Formation of planetesimals and planets

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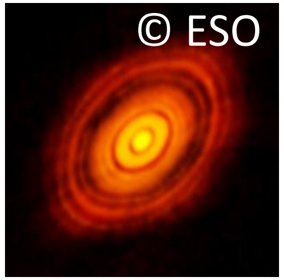
OUTLINE

- Introduction
- Part I: The formation of planetesimals and evidence within the Solar System (Blum)
- Part II: Evidence for planetesimal and planet formation beyond the Solar System (Najita)
- Summary of the main points and open questions

INTRODUCTION

Formation of planets in a nutshell

Protoplanetary Disks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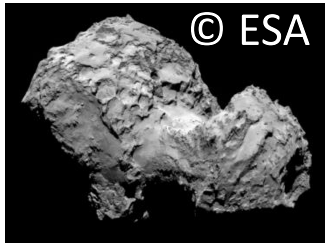
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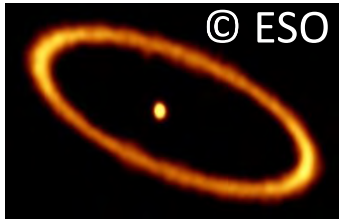
Cometary Nuclei

Debris Disks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Protoplanetary dust

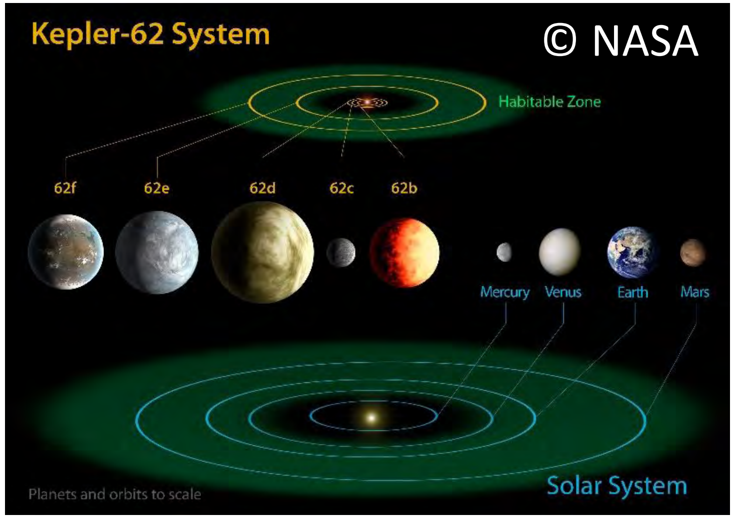
Dust “pebbles”

Planetesimals

Protoplanets

Giant planets

Terrestrial planets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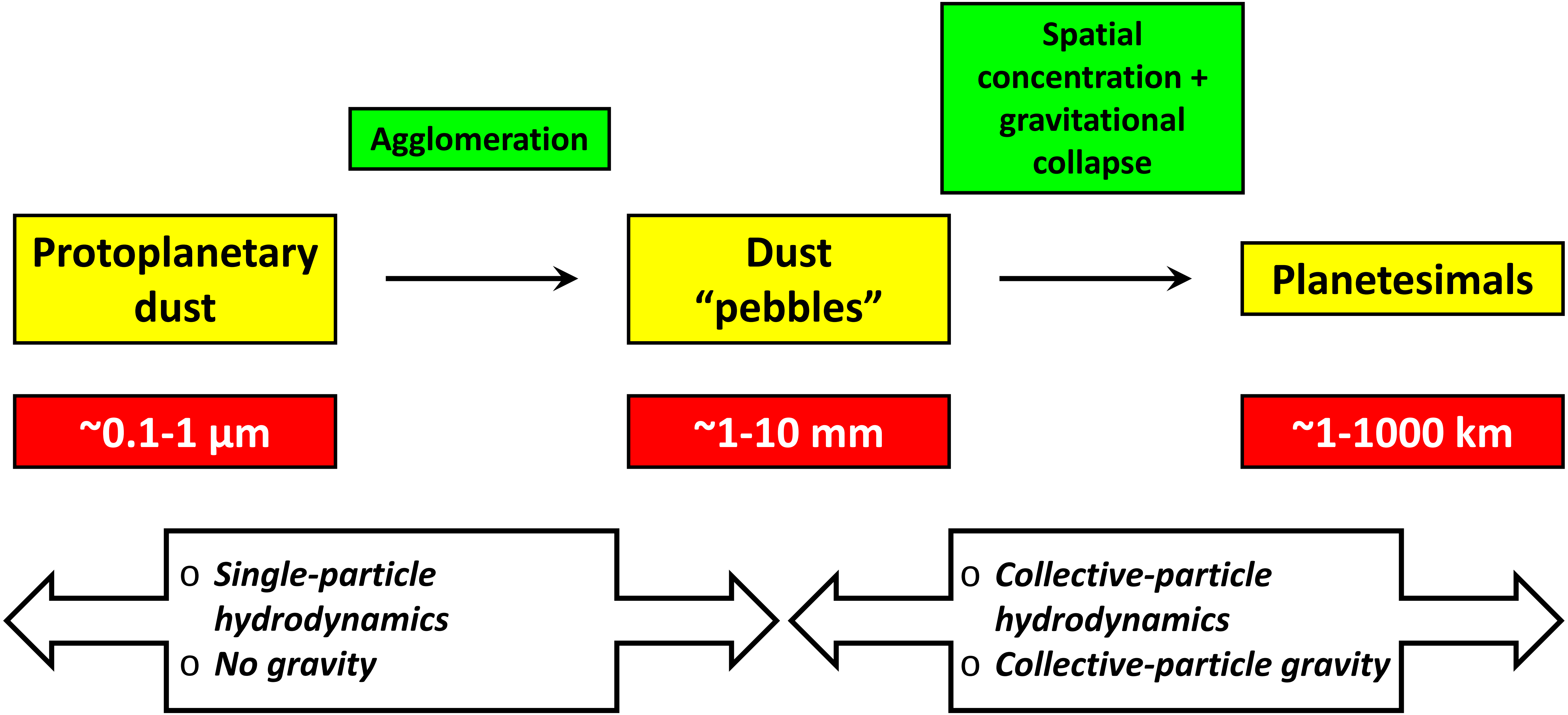
(Exo) Planetary Systems

(Exo) Zodiacal Light

THE FORMATION OF PLANETESIMALS
AND EVIDENCE WITHIN THE SOLAR SYSTEM

The two-stage process of planetesimal formation



Agglomeration

Spatial concentration + gravitational collapse

Protoplanetary dust → **Dust "pebbles"** → **Planetesimals**

~0.1-1 µm

~1-10 mm

~1-1000 km

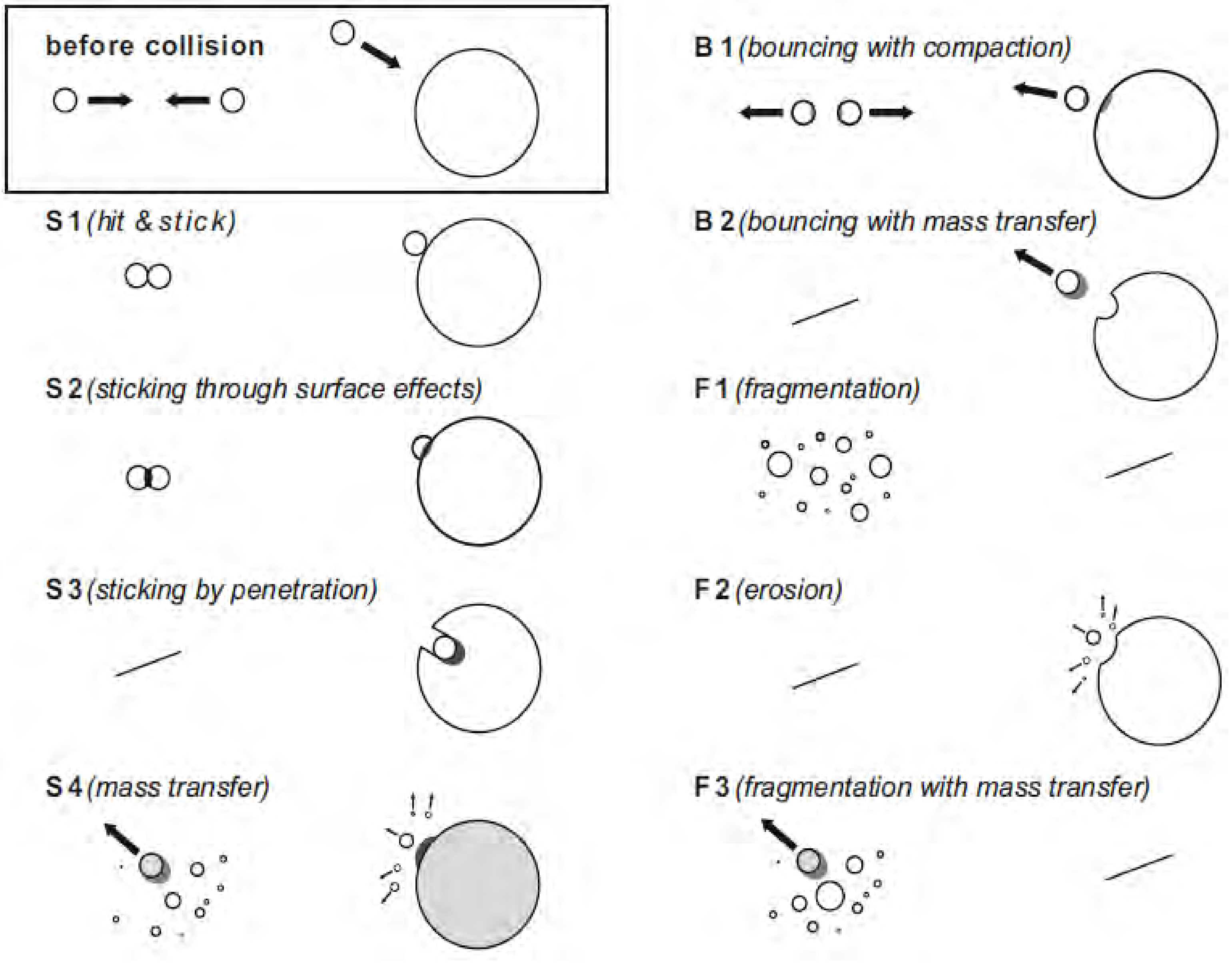
- ***Single-particle hydrodynamics***
- ***No gravity***

- ***Collective-particle hydrodynamics***
- ***Collective-particle gravity***

I.

“Pebbles” can form under PPD conditions – but nothing much bigger than that

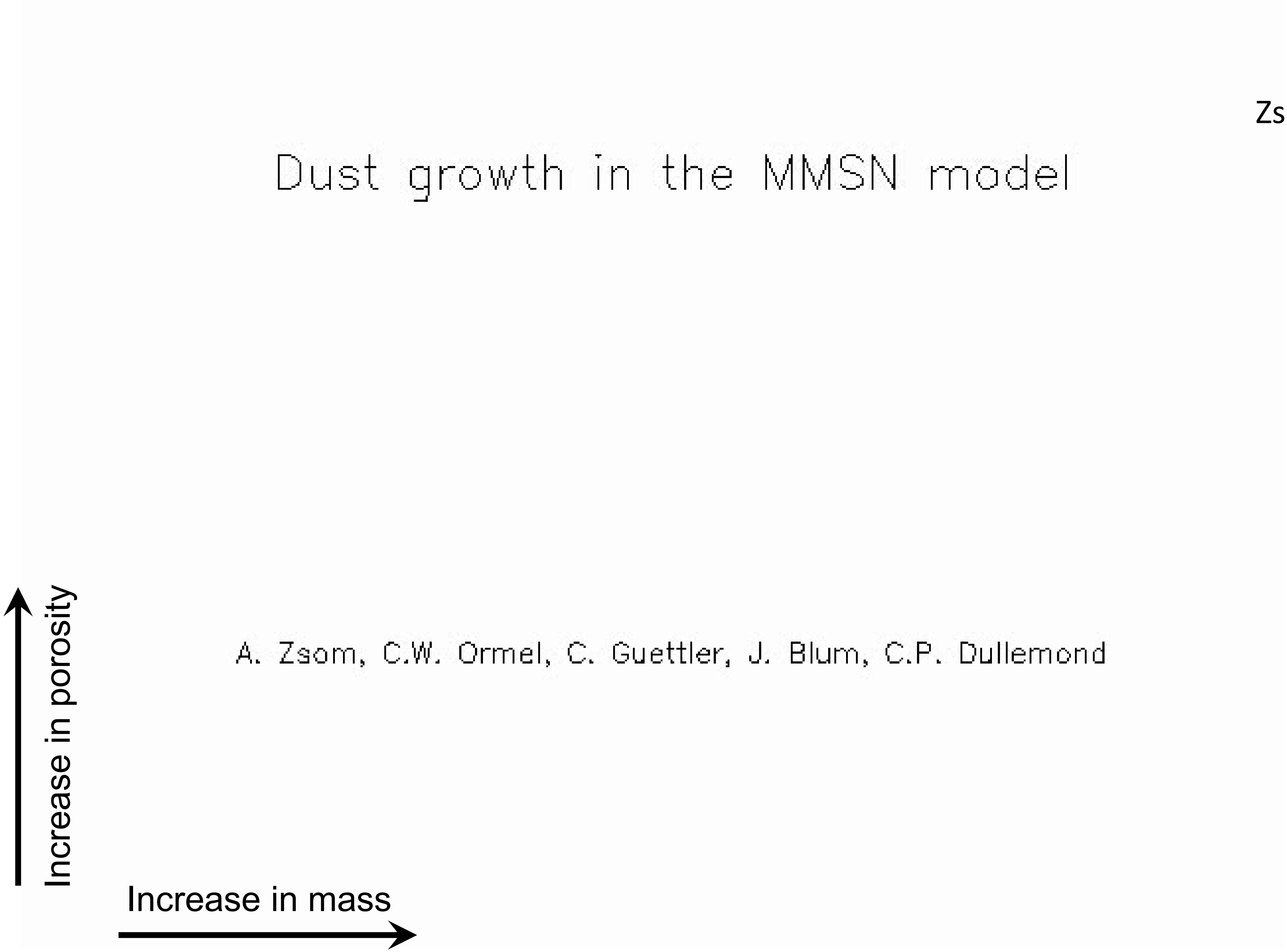
Evidence for dust "pebbles": laboratory and modeling (2010)



Güttler et al. 2010

Evidence for dust “pebbles”: laboratory and modeling (2010)

Zsom et al. 2010



Dust growth in the MMSN model

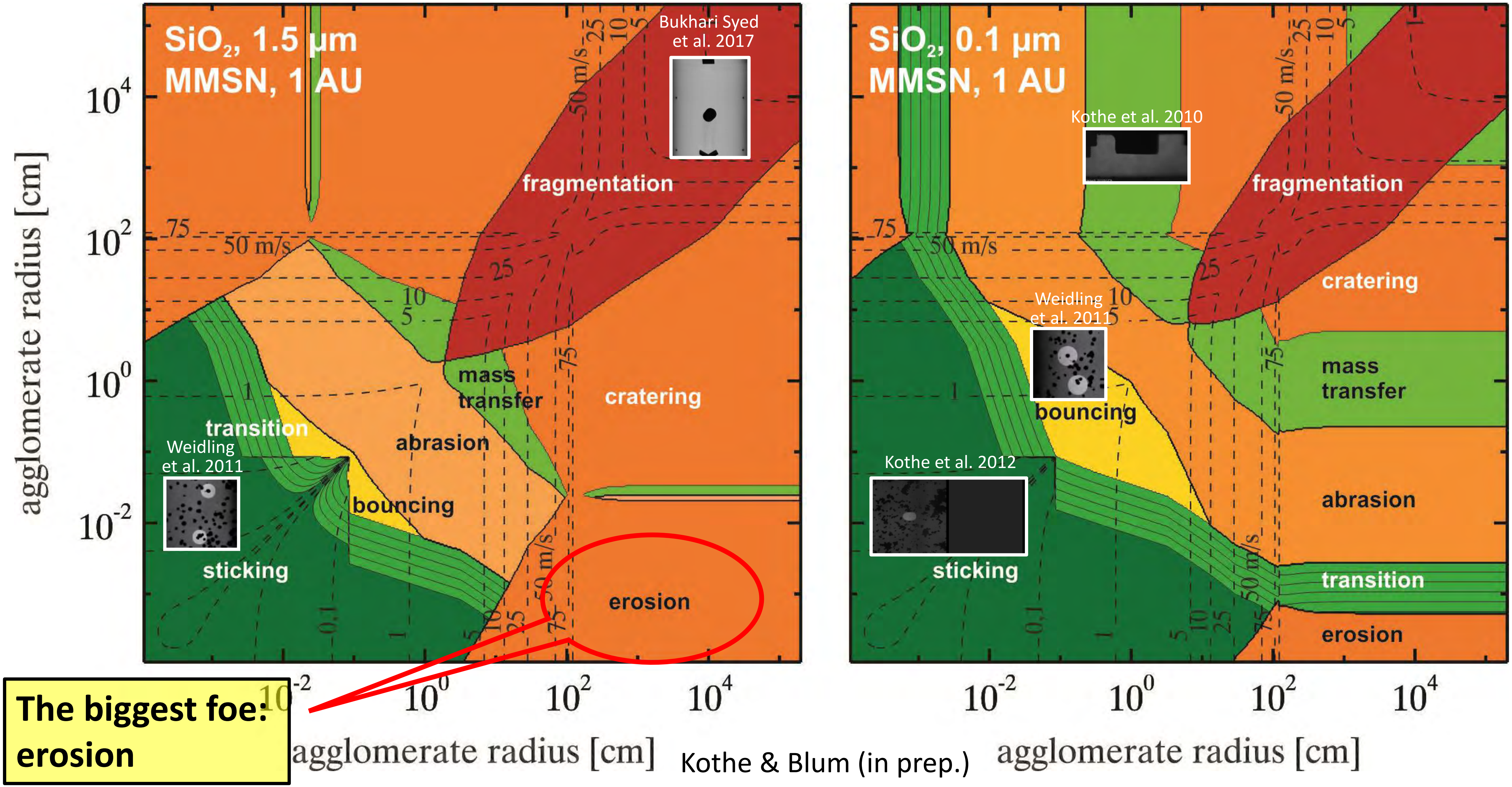
A. Zsom, C.W. Ormel, C. Guettler, J. Blum, C.P. Dullemond

Increase in porosity

Increase in mass

1.5 µm SiO_2
1 AU
MMSN
$\alpha = 10^{-4}$

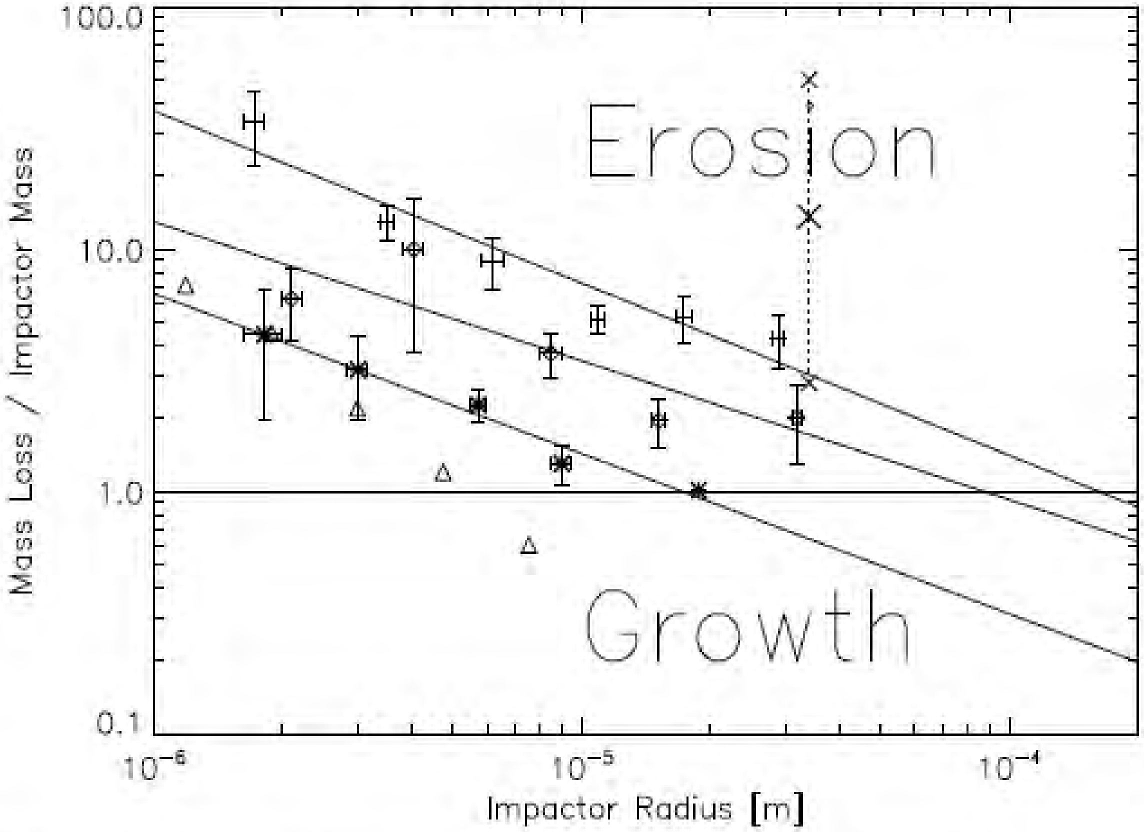
Evidence for dust “pebbles”: laboratory and modeling (2018)



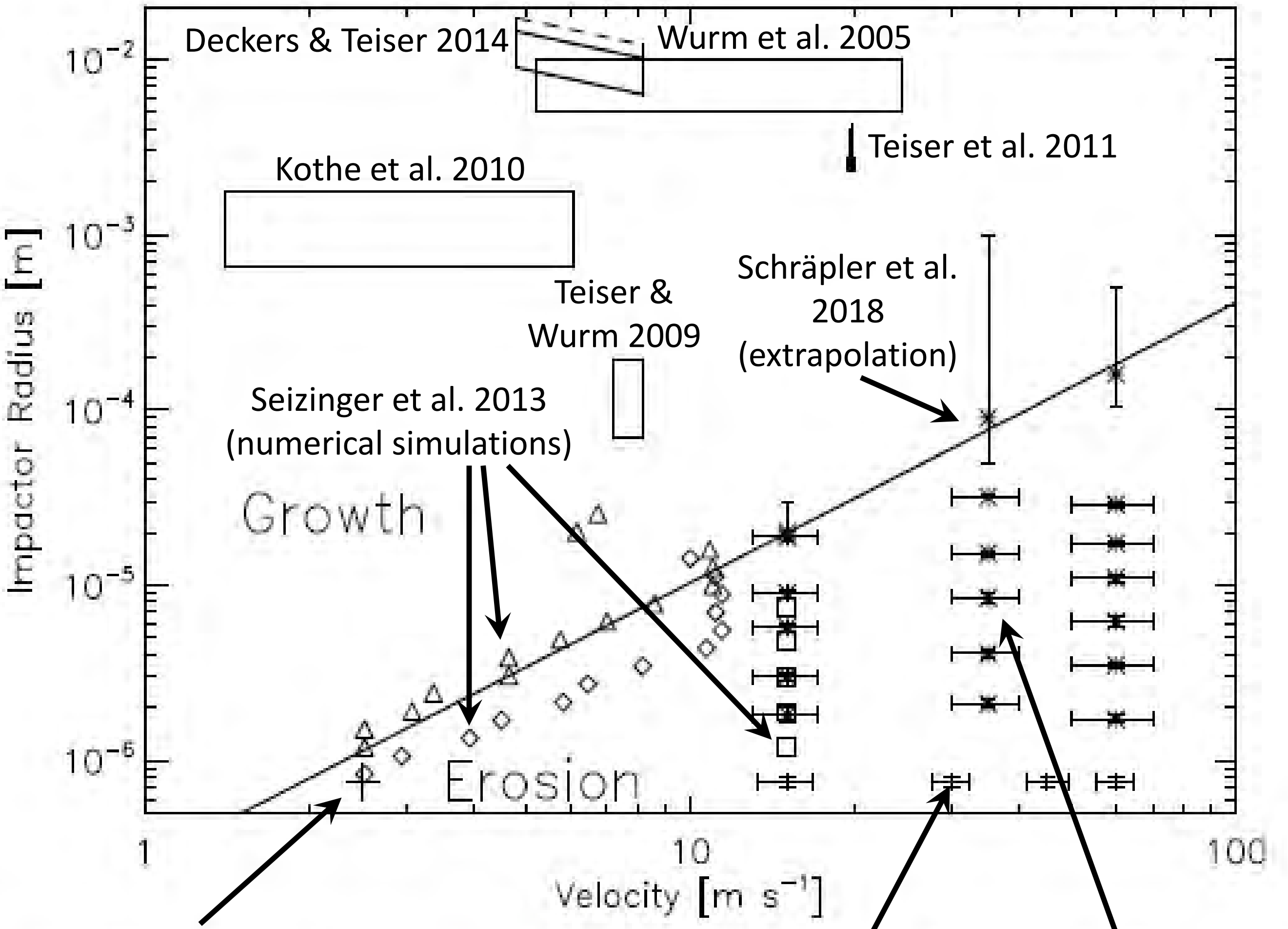
The biggest foe: erosion

Kothe & Blum (in prep.)

Empirical evidence for erosion



Schräpler et al. 2018



Deckers & Teiser 2014

Wurm et al. 2005

Teiser et al. 2011

Kothe et al. 2010

Teiser & Wurm 2009

Schräpler et al. 2018 (extrapolation)

Seizinger et al. 2013 (numerical simulations)

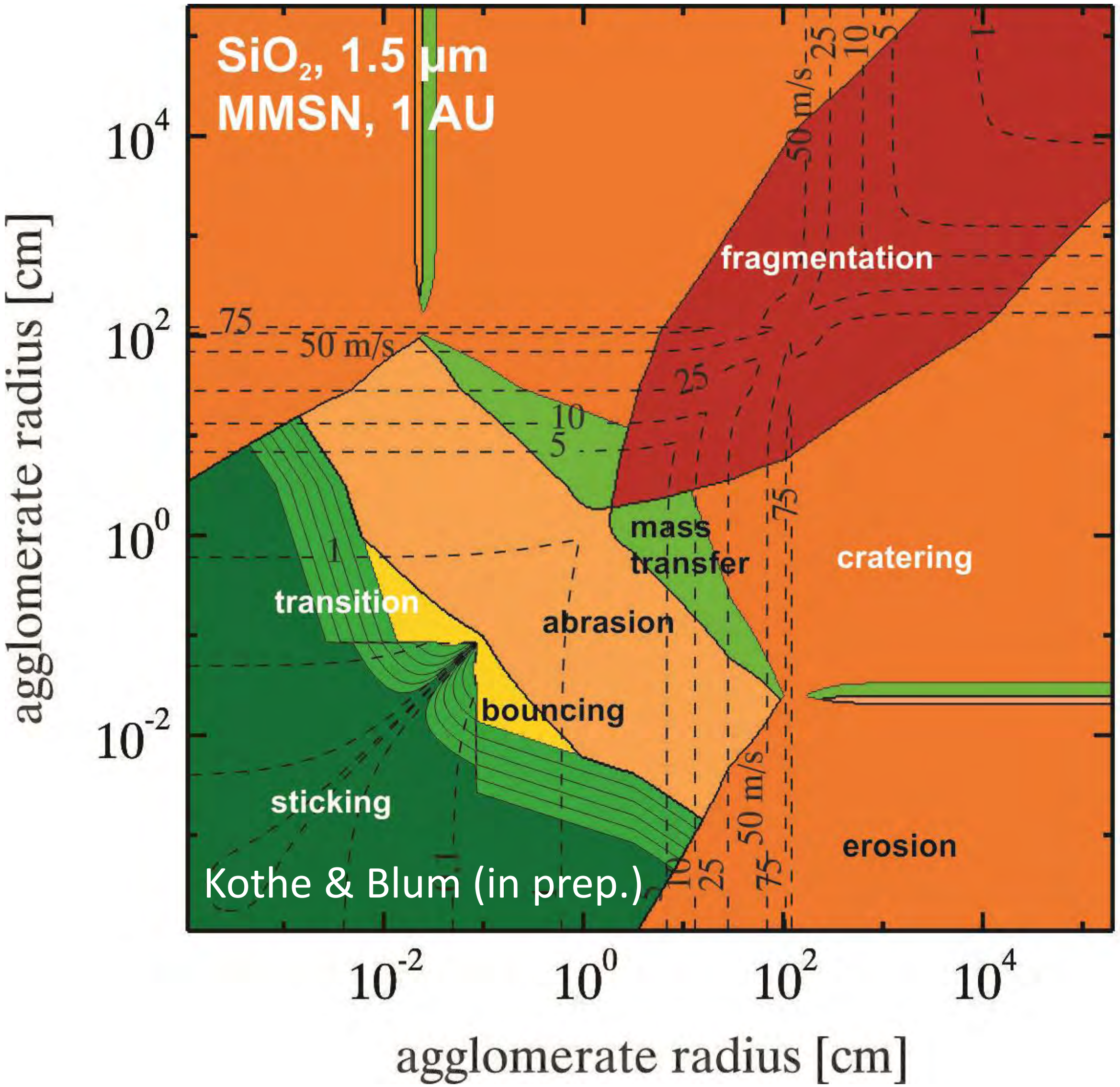
Schräpler & Blum 2011 (extrapolation)

Schräpler & Blum 2011

Schräpler et al. 2018

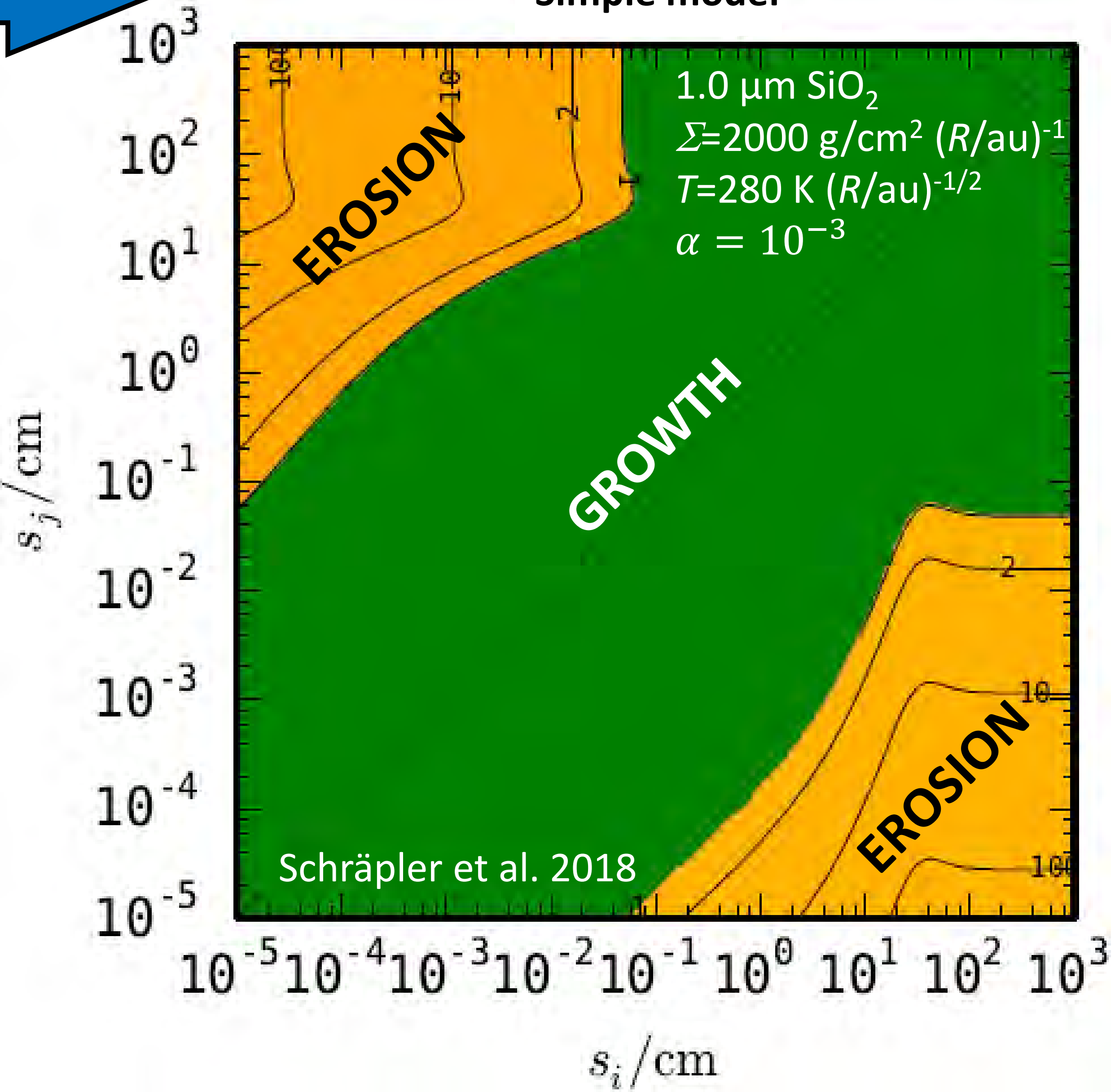
A simple growth-erosion model

Complex model



Kothe & Blum (in prep.)

Simple model



1.0 µm SiO_2

Σ=2000 g/cm^2 (R/au)$^{-1}$

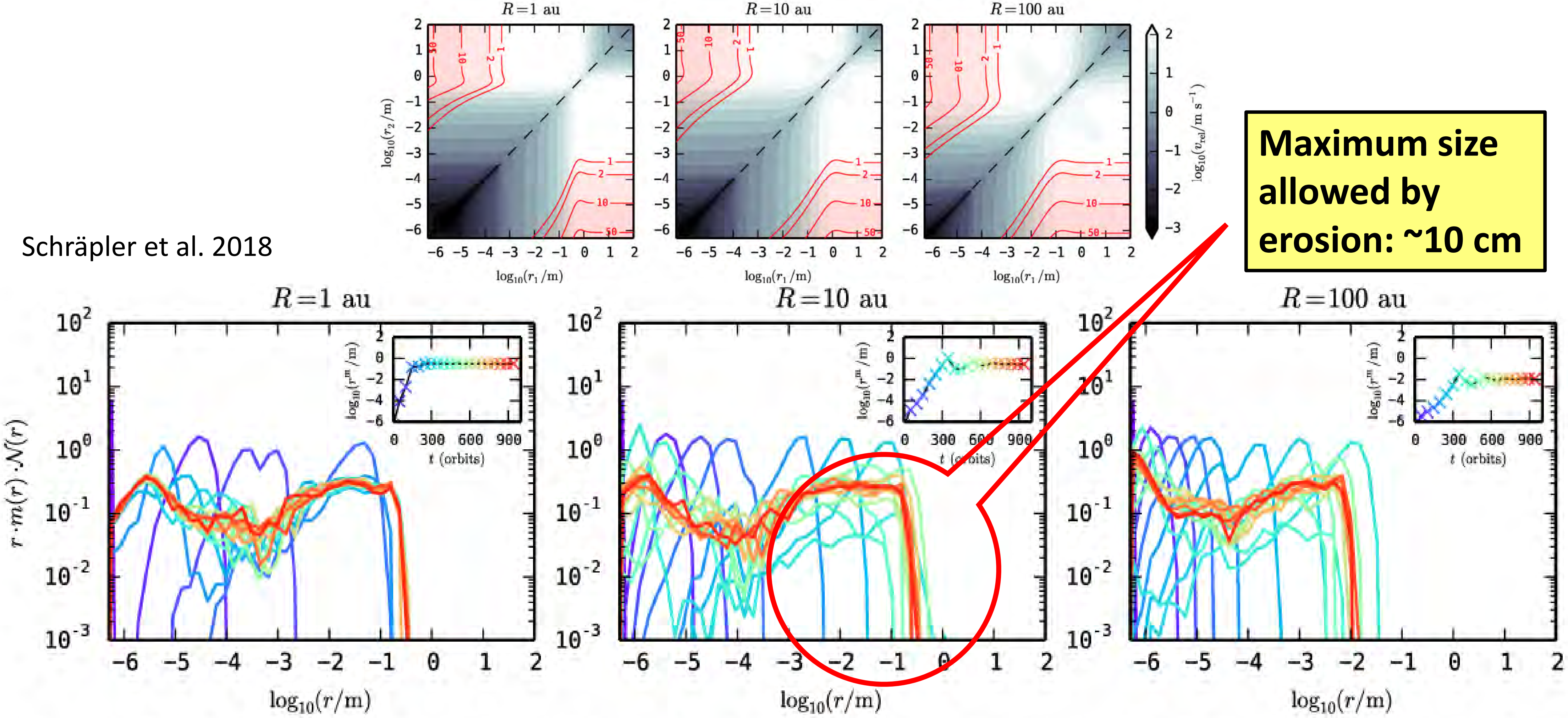
T=280 K (R/au)$^{-1/2}$

$\alpha = 10^{-3}$

Schräpler et al. 2018

A simple growth-erosion model

Schräpler et al. 2018



Maximum size allowed by erosion: ~10 cm

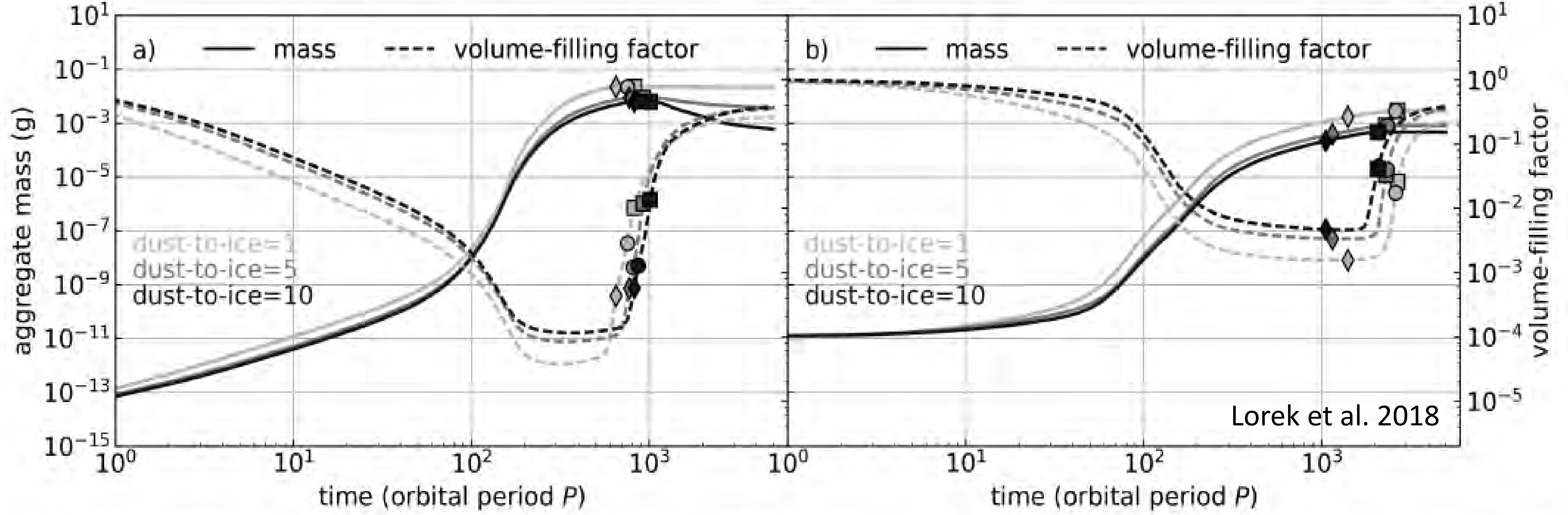
Figure 10. Results of the coagulation models discussed in Section 3.1 at 1, 10 and 100 au. The colored curves show normalized mass-weighted size distributions at different time steps (violet corresponds to $t = 0$, red to $t = 10^3$ orbits). The insets show the evolution of the maximum particle size r^m present in the simulation as a function of time.

Can planetesimals form by direct sticking?

I. Monomer size and dust-to-ice ratio

Monomer size: 0.1 µm

Monomer size: 1 µm



Lorek et al. 2018

Fig. 1. Aggregate mass and volume-filling factor versus time. The heliocentric distance is 30 au. The monomer size is **a)** 0.1 µm; and **b)** 1 µm. **The diamond (♦) and the circle (•) indicate when the system becomes drift-limited and bouncing-dominated, respectively.** A square (■) indicates when the aggregates reach $\mathrm{St}_{\min} = 1.5 \times 10^{-3}$ (Yang et al. 2016). Solid and dashed lines show the time evolution of aggregate mass and volume-filling factor, respectively.

Can planetesimals form by direct sticking?
II. Heliocentric distance

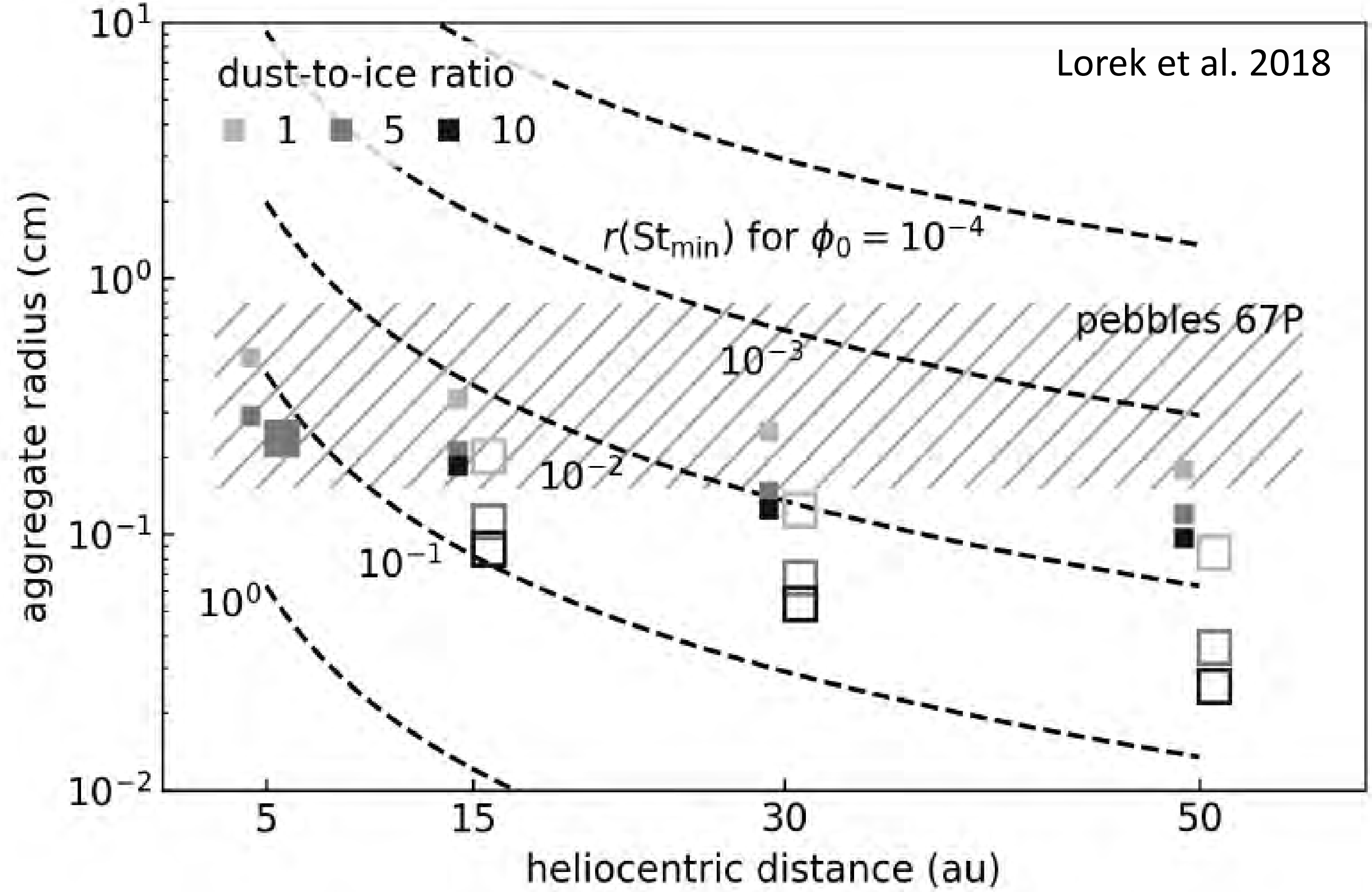
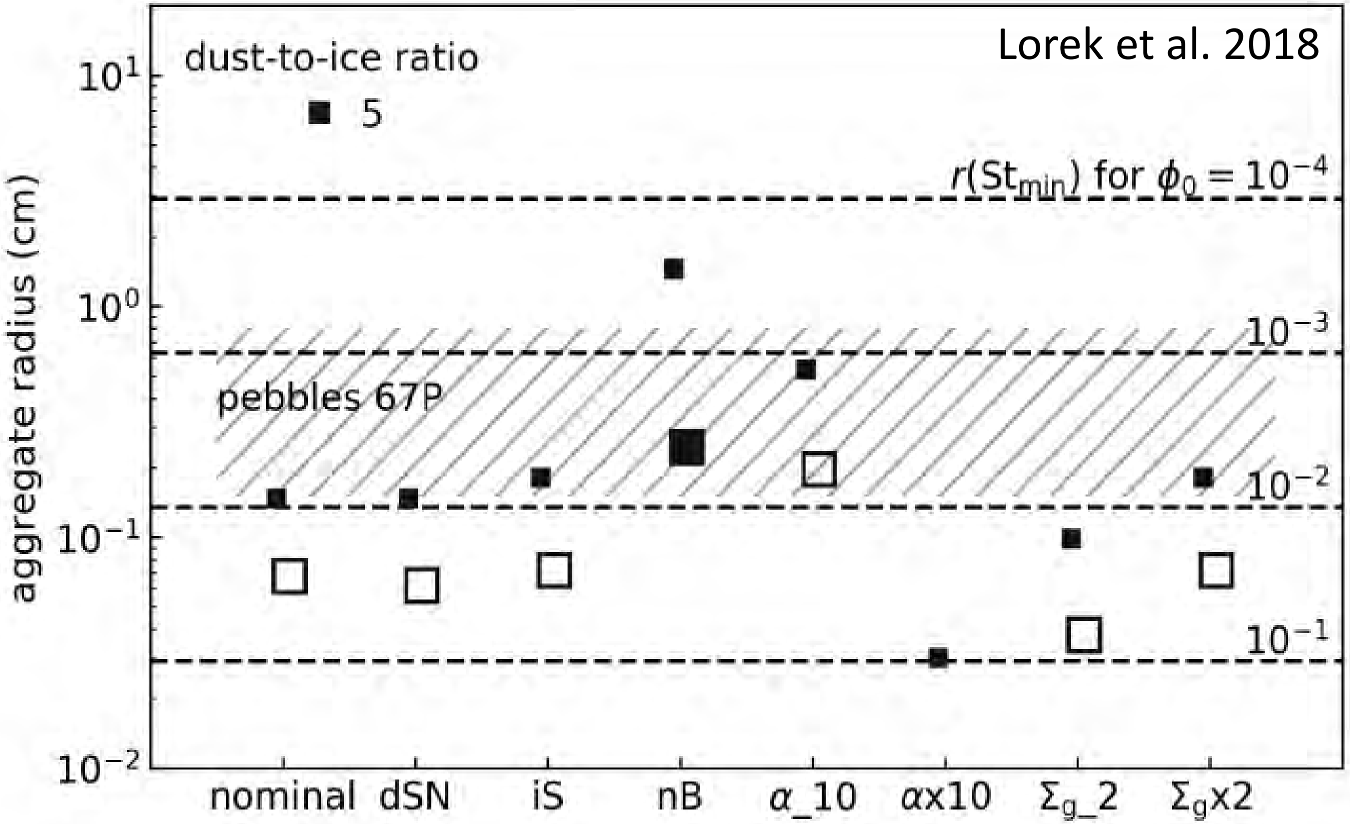
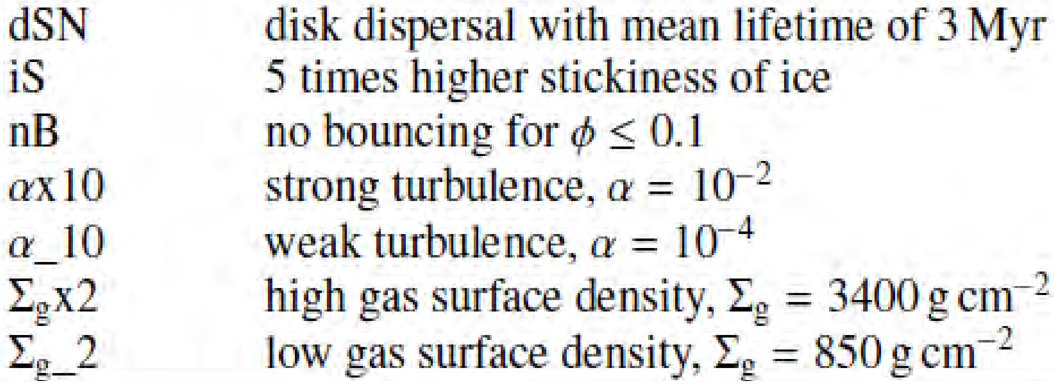


Fig. 10. Aggregate radius versus heliocentric distance. **The hatched area marks the range of pebble sizes measured on 67P by the CIVA camera on-board Rosetta/Philae (Poulet et al. 2016). Symbols (■) show aggregate sizes when reaching $\mathrm{St_{min}}$. Large and small symbols are for $1\,\mu$m- and $0.1\,\mu$m-sized monomers, respectively. Symbols are filled if aggregates would potentially trigger the streaming instability (Table 3). Dashed lines indicate the minimum size for aggregates with a given volume-filling factor to have $\mathrm{St_{min}}$. ϕ_0 refers to the initial aggregate porosity (i.e. before compression).**

Can planetesimals form by direct sticking?
III. Anything else?

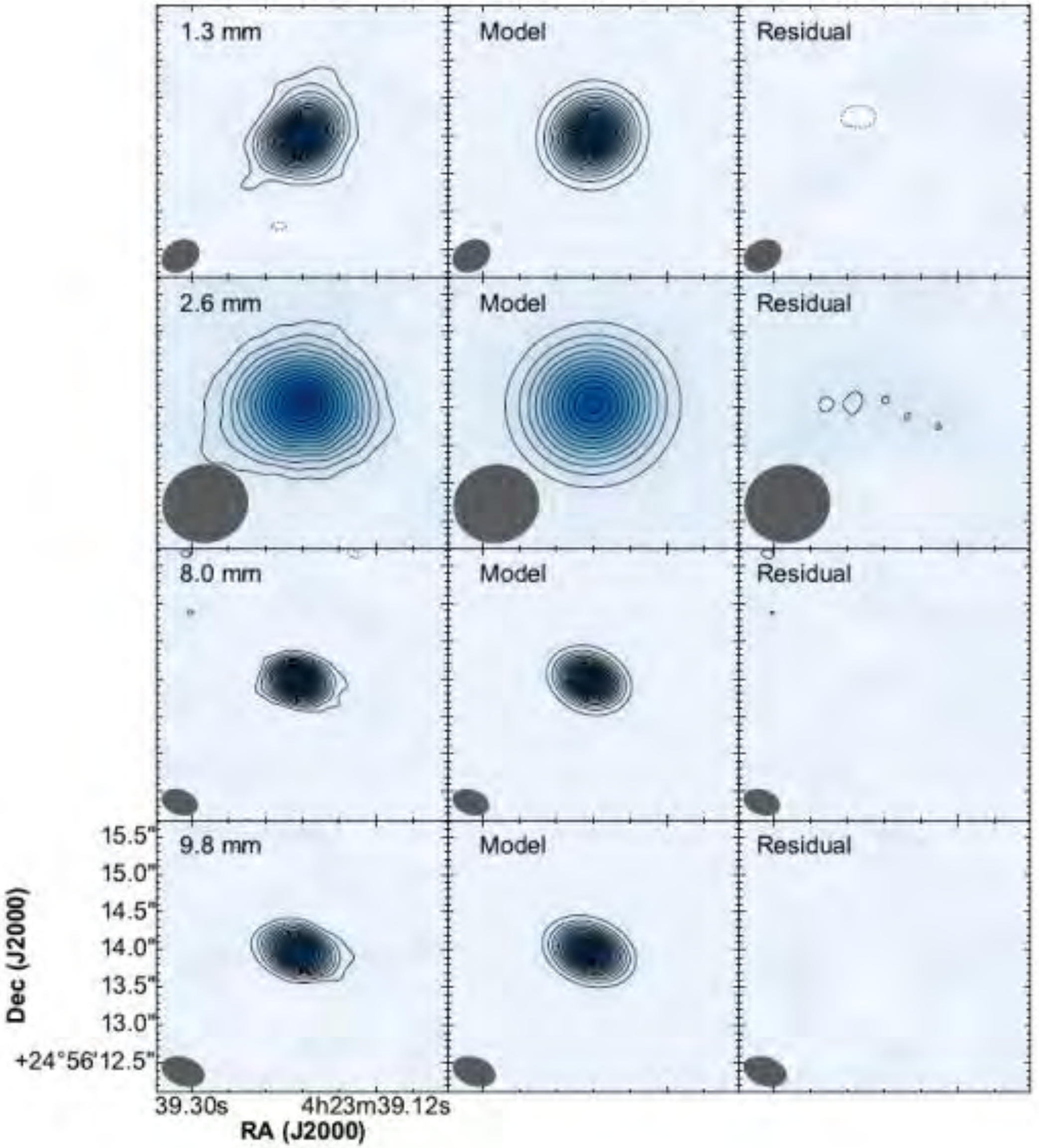




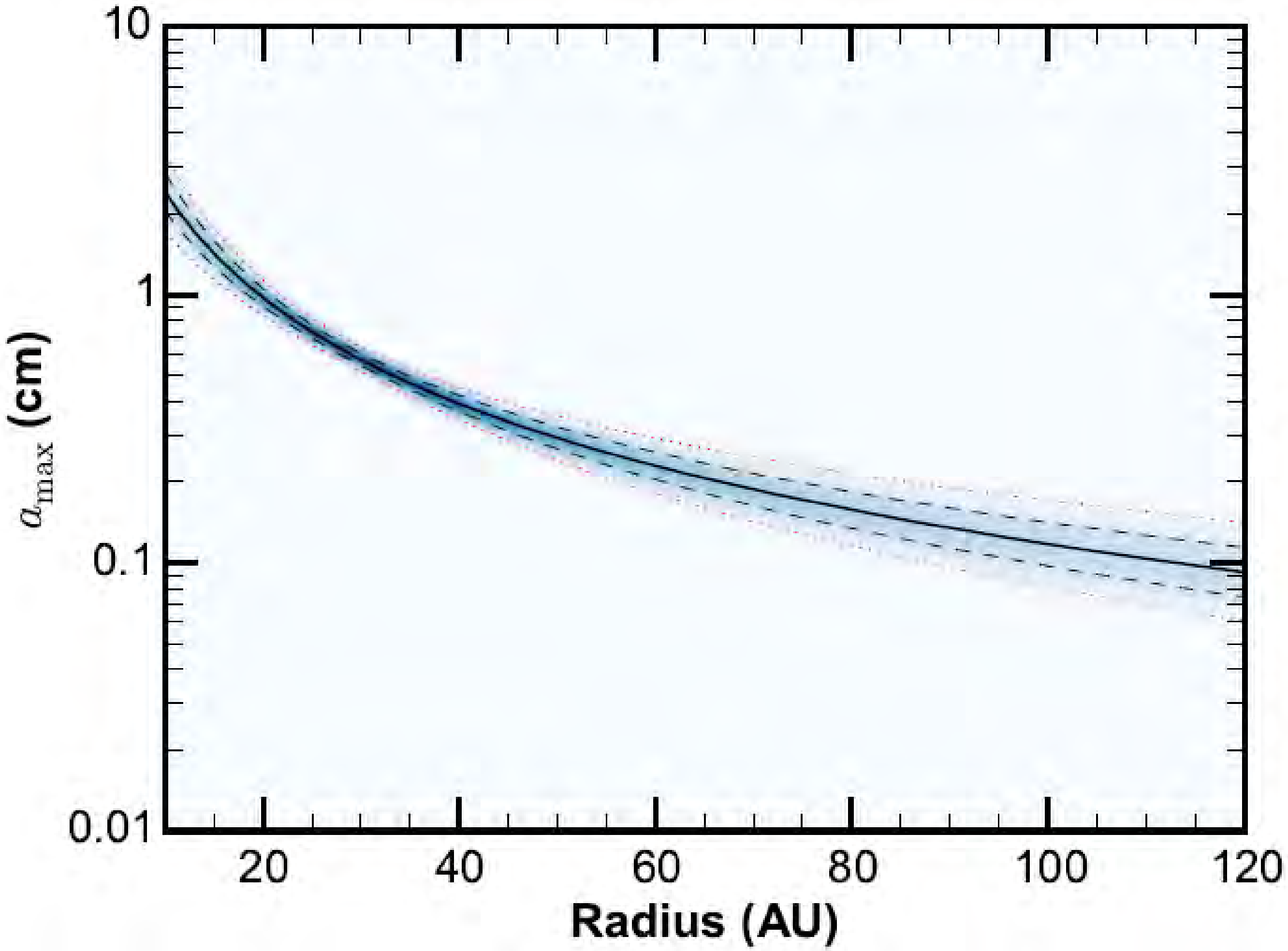
dSN	disk dispersal with mean lifetime of 3 Myr
iS	5 times higher stickiness of ice
nB	no bouncing for $\phi \leq 0.1$
αx10	strong turbulence, $\alpha = 10^{-2}$
α_10	weak turbulence, $\alpha = 10^{-4}$
Σ_gx2	high gas surface density, $\Sigma_g = 3400\,\mathrm{g\,cm^{-2}}$
Σ_g_2	low gas surface density, $\Sigma_g = 850\,\mathrm{g\,cm^{-2}}$

- ☐ Ice does not help (as long as it is not pure water ice with 0.1 µm monomer size)! (Kataoka et al. 2013)
- ☐ Small monomers result in larger aggregates!
- ☐ No bouncing helps to produce larger “pebbles” (but we have seen bouncing collisions among dust and ice aggregates in the lab, even for coordination number = 2).

Evidence for dust "pebbles": observations (example)



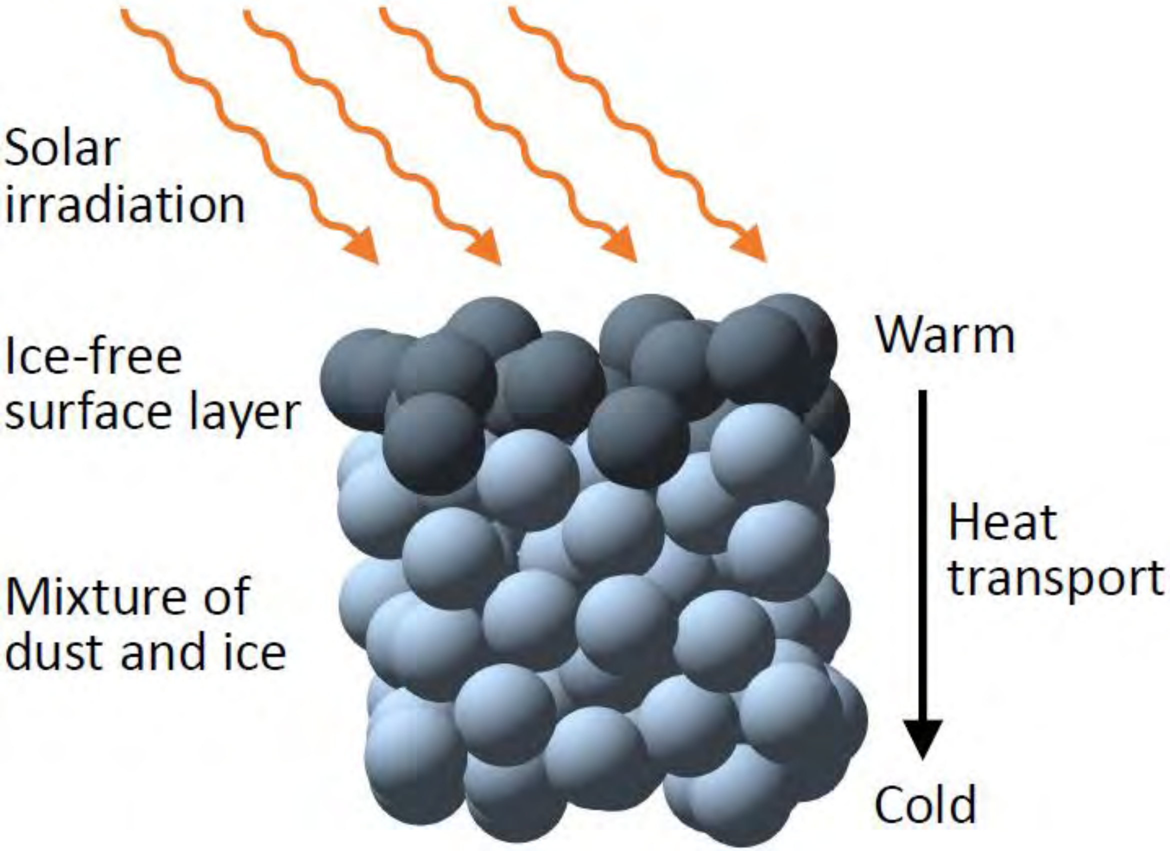
Tazzari et al. 2016



II.

Comet 67P consists of “pebbles”

Has comet 67P formed by the gravitational collapse of a “pebble” cloud?



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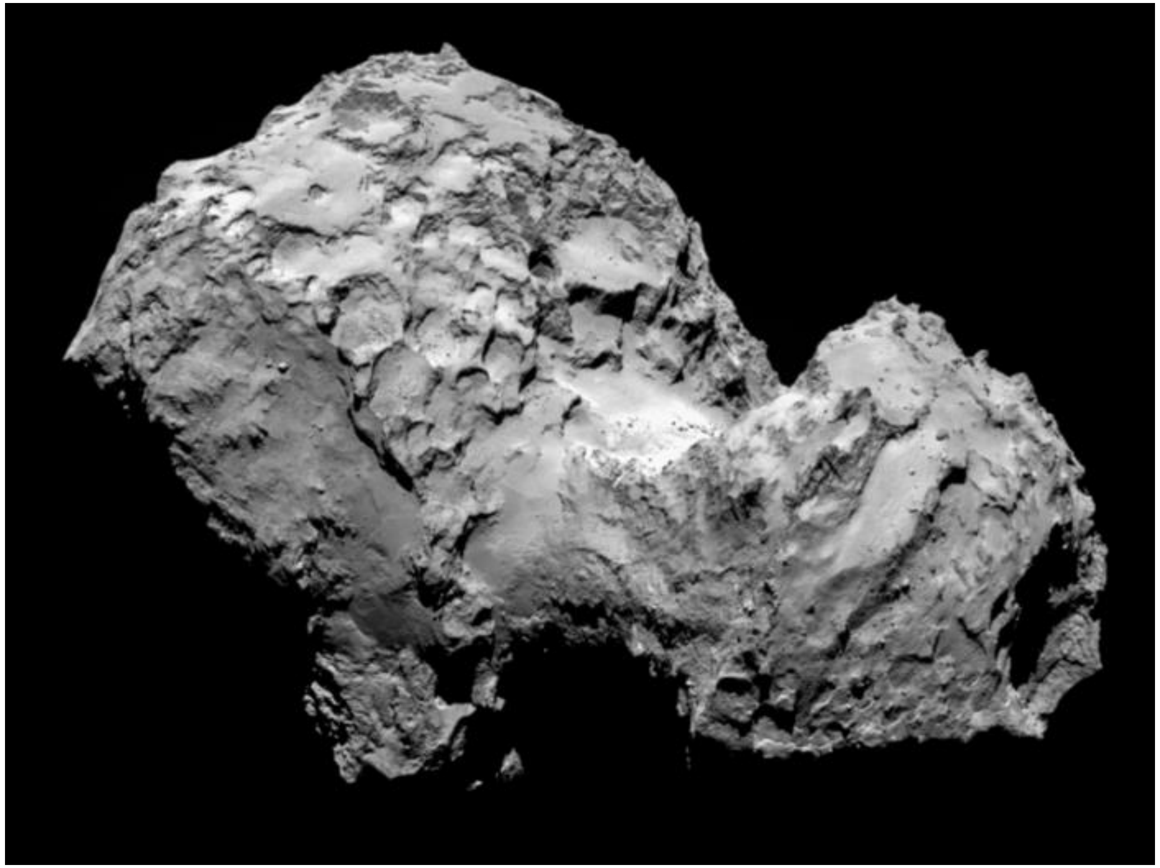
?



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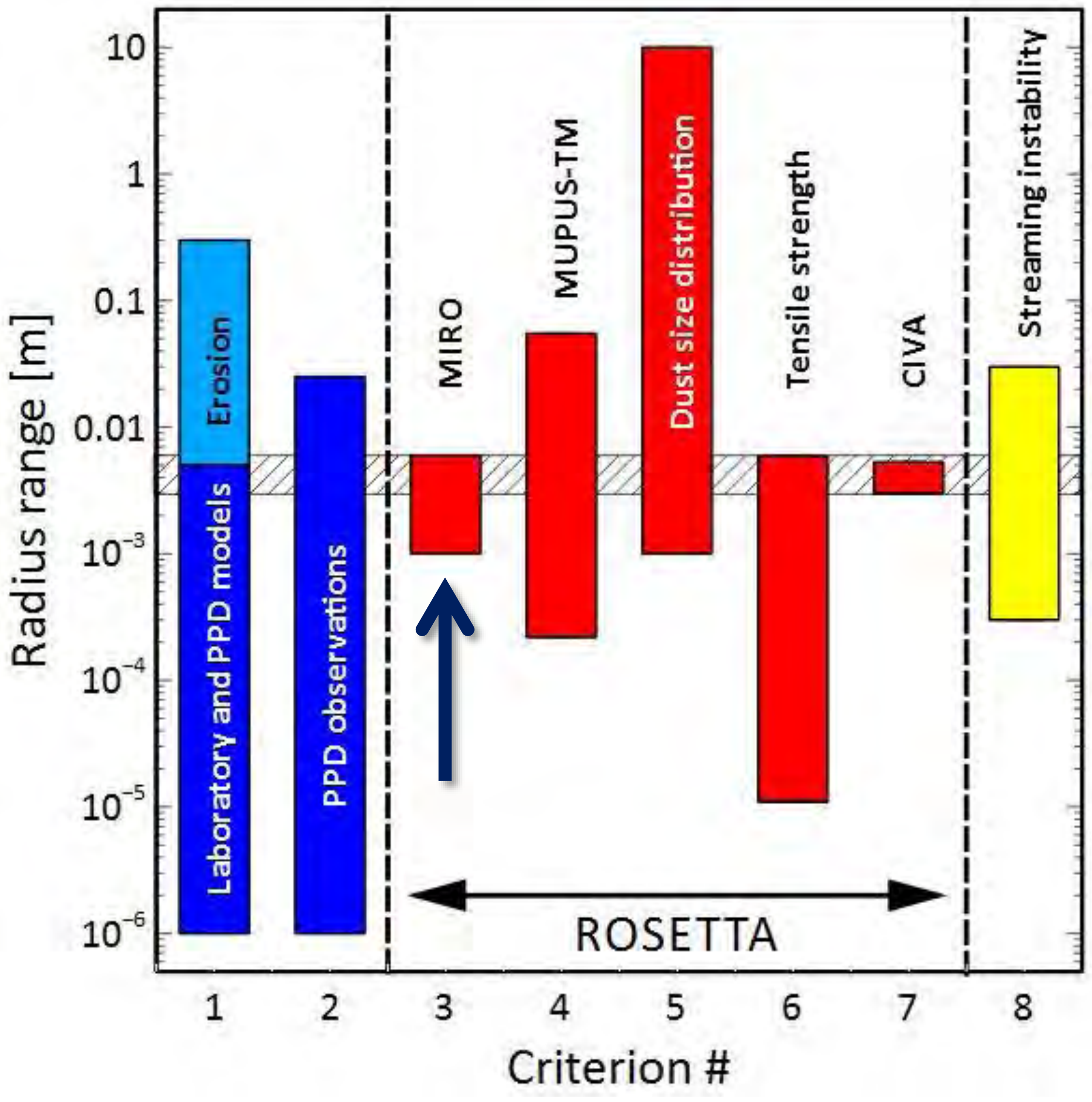
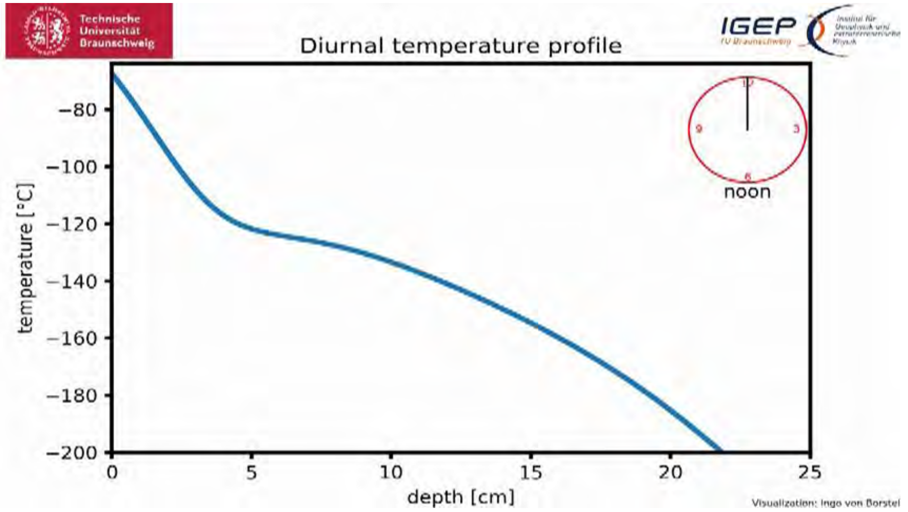
Evidence for dust “pebbles”: MIRO

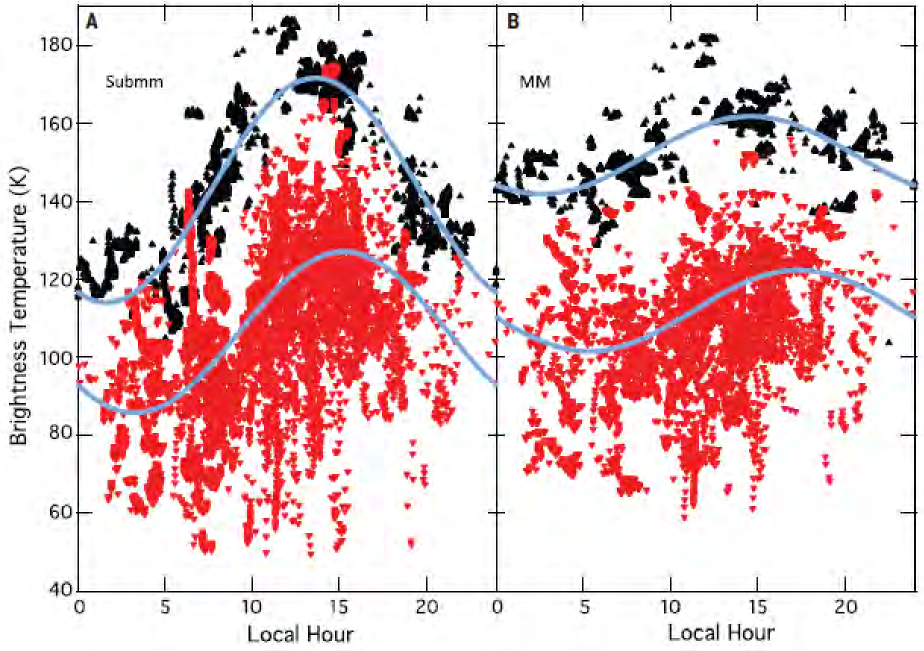


Blum et al. 2017

Thermophysical modeling of the subsurface temperature distribution of comet 67P and comparison to MIRO measurements

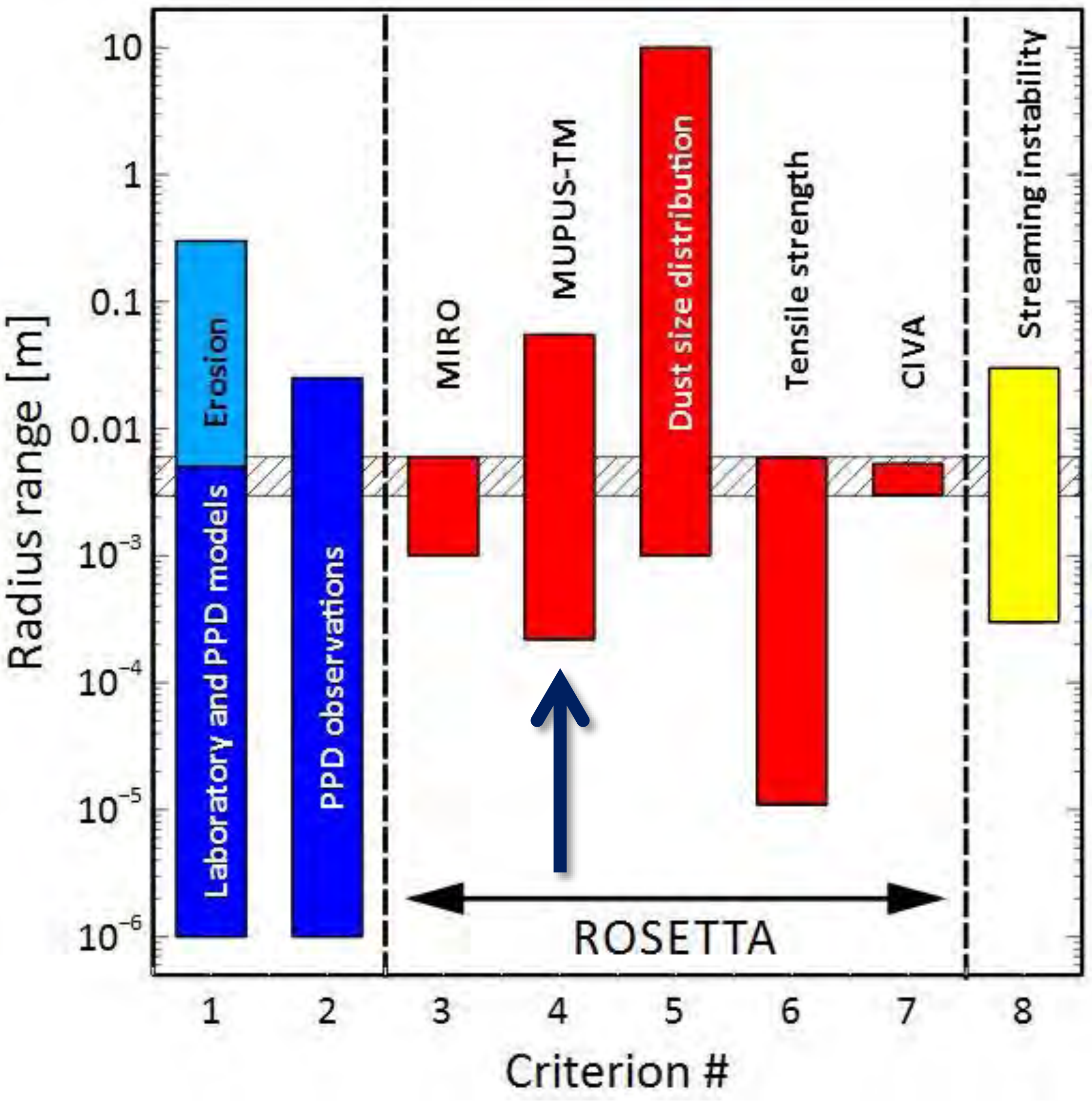


Diurnal changes of subsurface temperatures from Blum et al. 2017



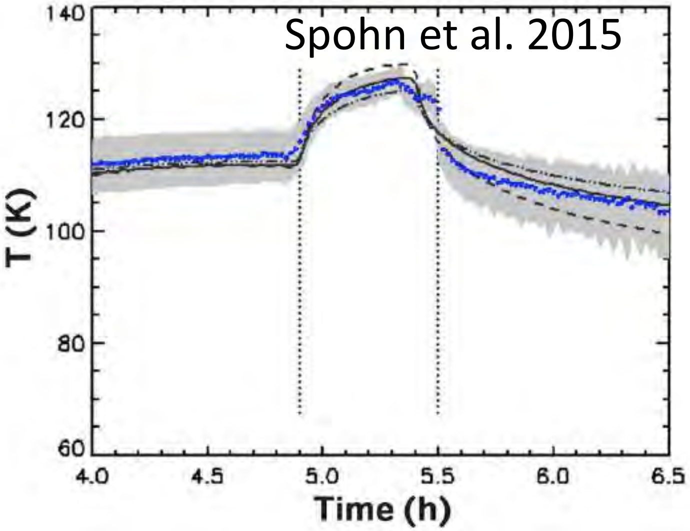
MIRO data from Gulkis et al. 2015

Evidence for dust “pebbles”: MUPUS-TM

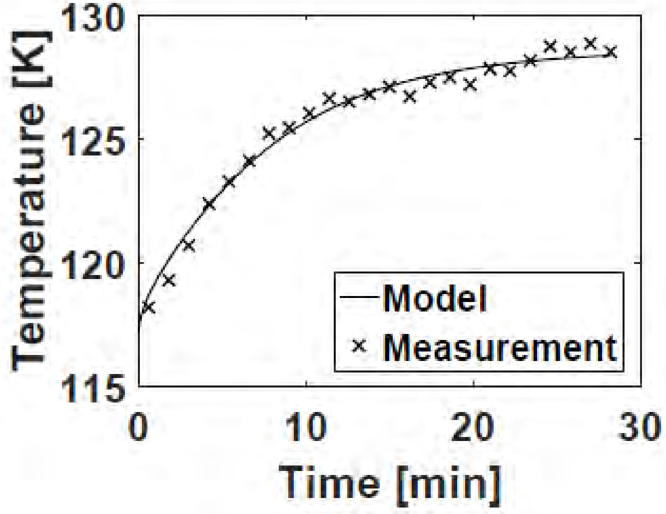


Blum et al. 2017

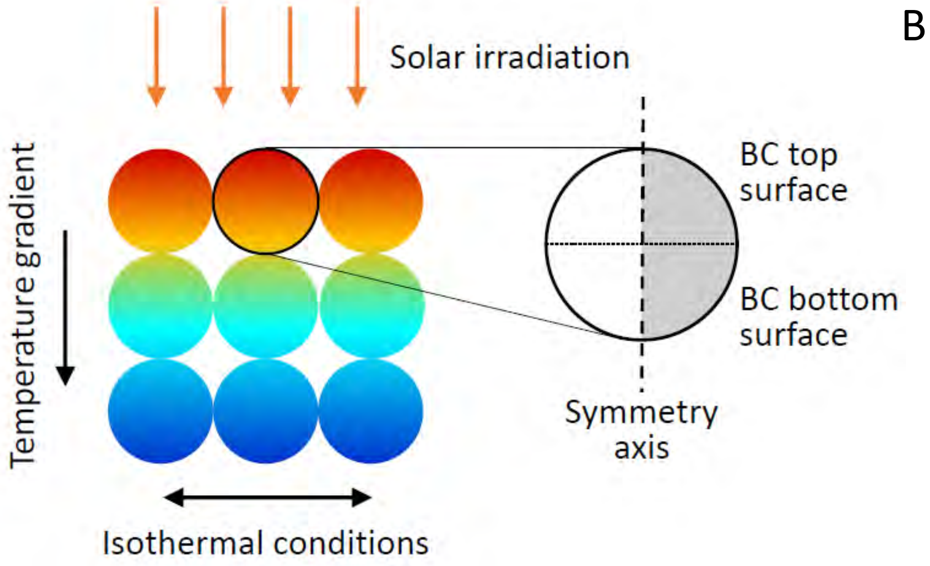
Thermophysical modeling of the surface temperature of comet 67P and comparison to MUPUS-TM measurements

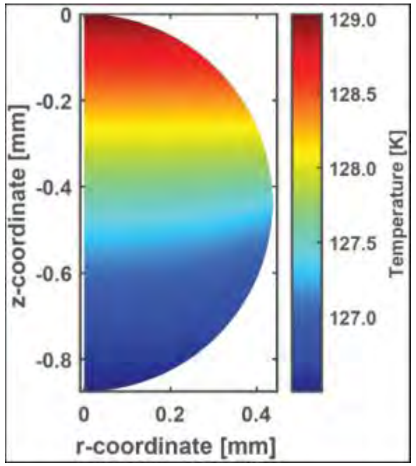


Spohn et al. 2015

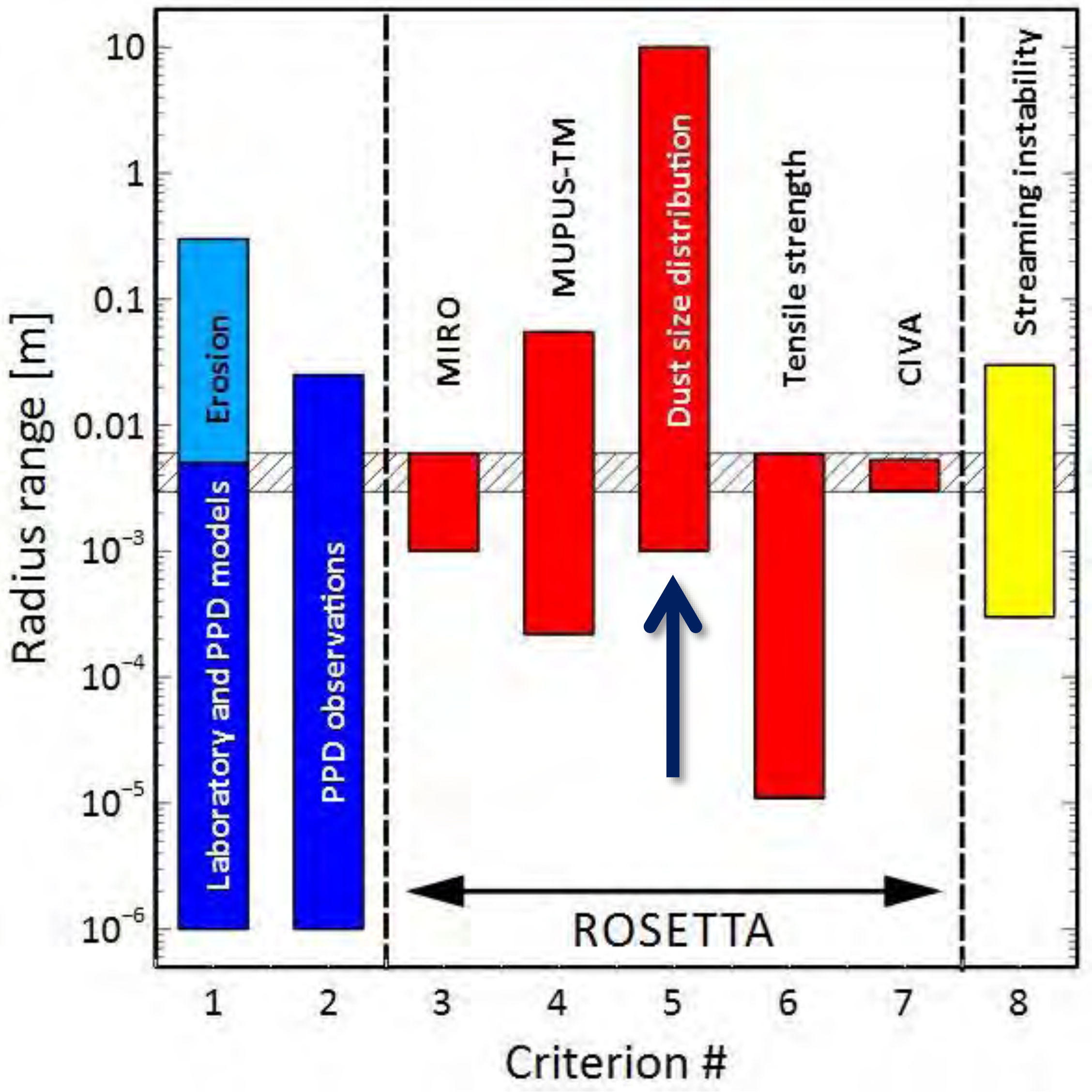


Blum et al. 2017



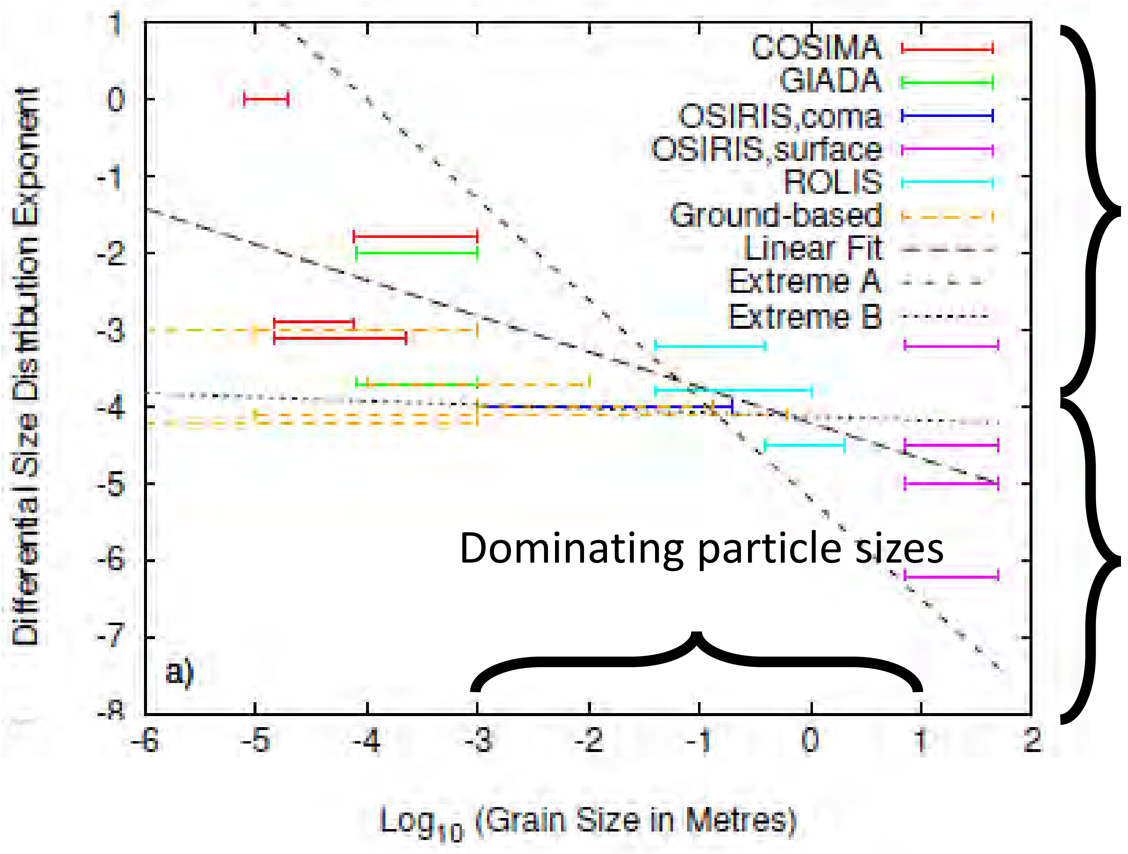


Evidence for dust “pebbles”: dust observations (various instruments)



Blum et al. 2017

Measurements of dust-size distributions on the surface and in the coma of comet 67P with various Rosetta instruments and from the ground

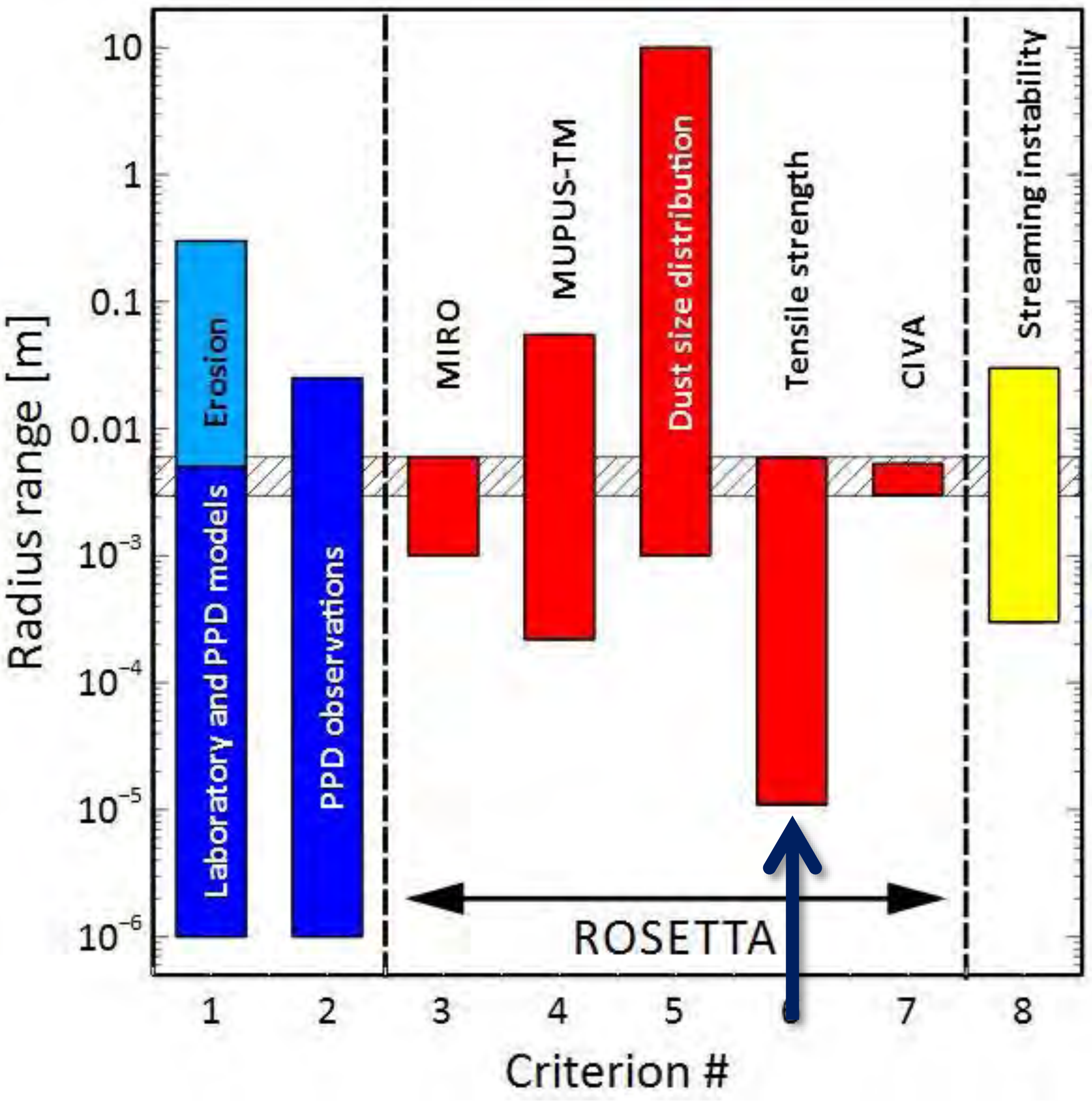


Mass domina-ted by <u>largest</u> particles

Mass domina-ted by <u>smallest</u> particles

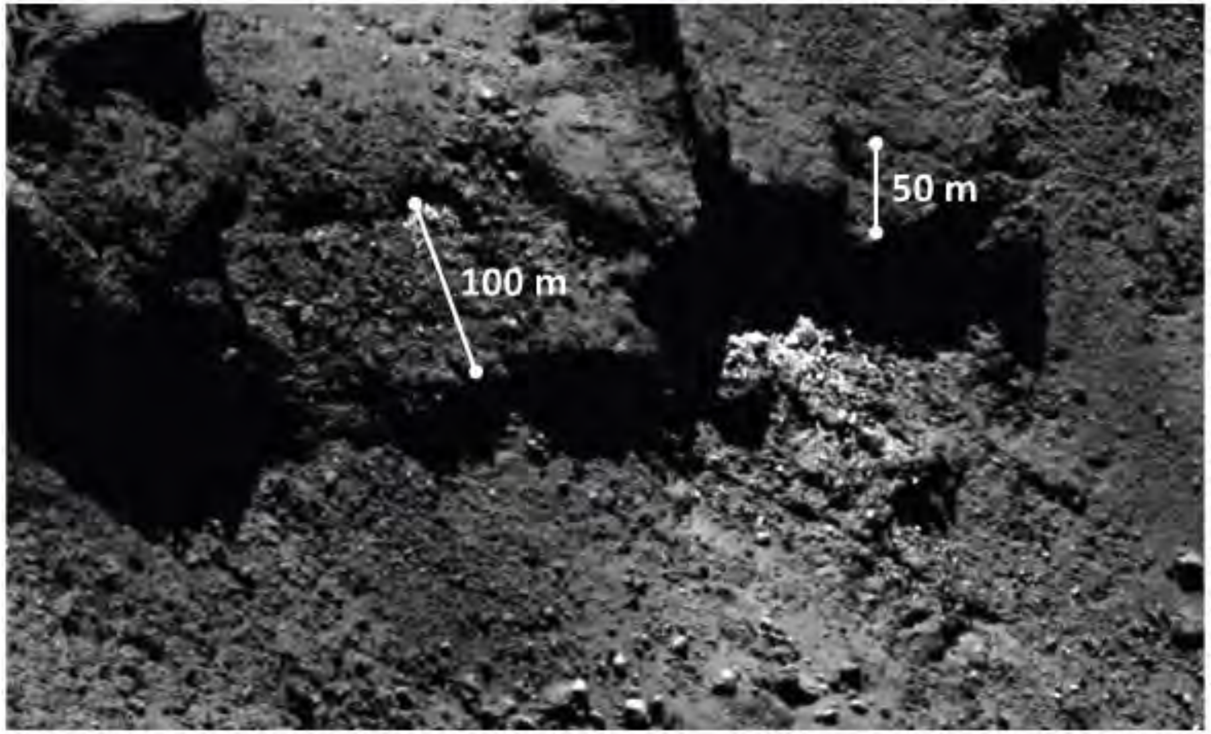
Blum et al. 2017

Evidence for dust “pebbles”: tensile strength



Blum et al. 2017

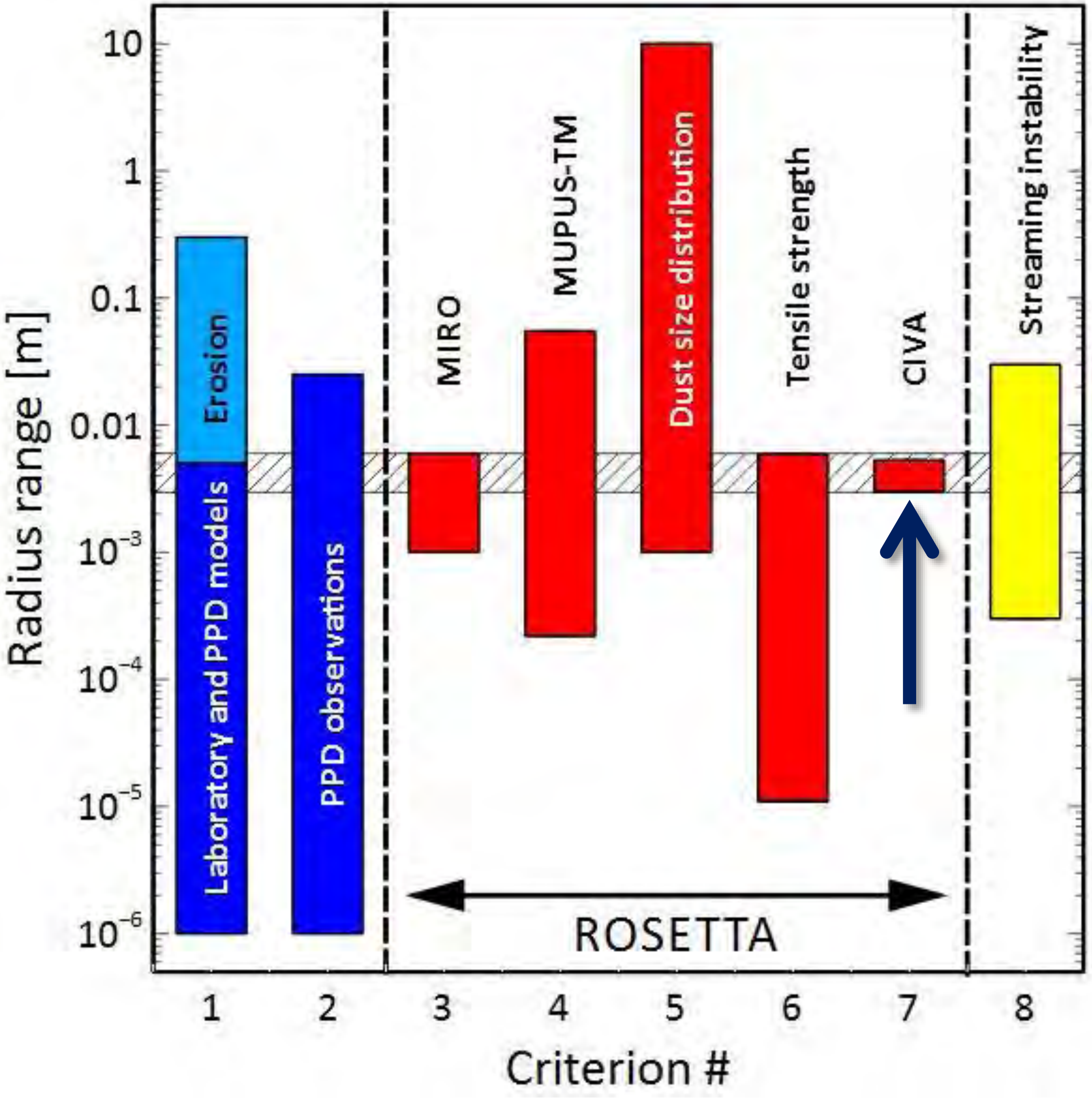
Determination of the tensile strength of the surface material of comet 67P and application of the strength model by Skorov & Blum 2012



→	$\sigma_T \approx 3 - 15$ Pa	Groussin et al. 2015
→	$\sigma_T \approx 10 - 20$ Pa	Thomas et al. 2015
→	$\sigma_T \approx 10 - 200$ Pa	Hirabayashi et al. 2016

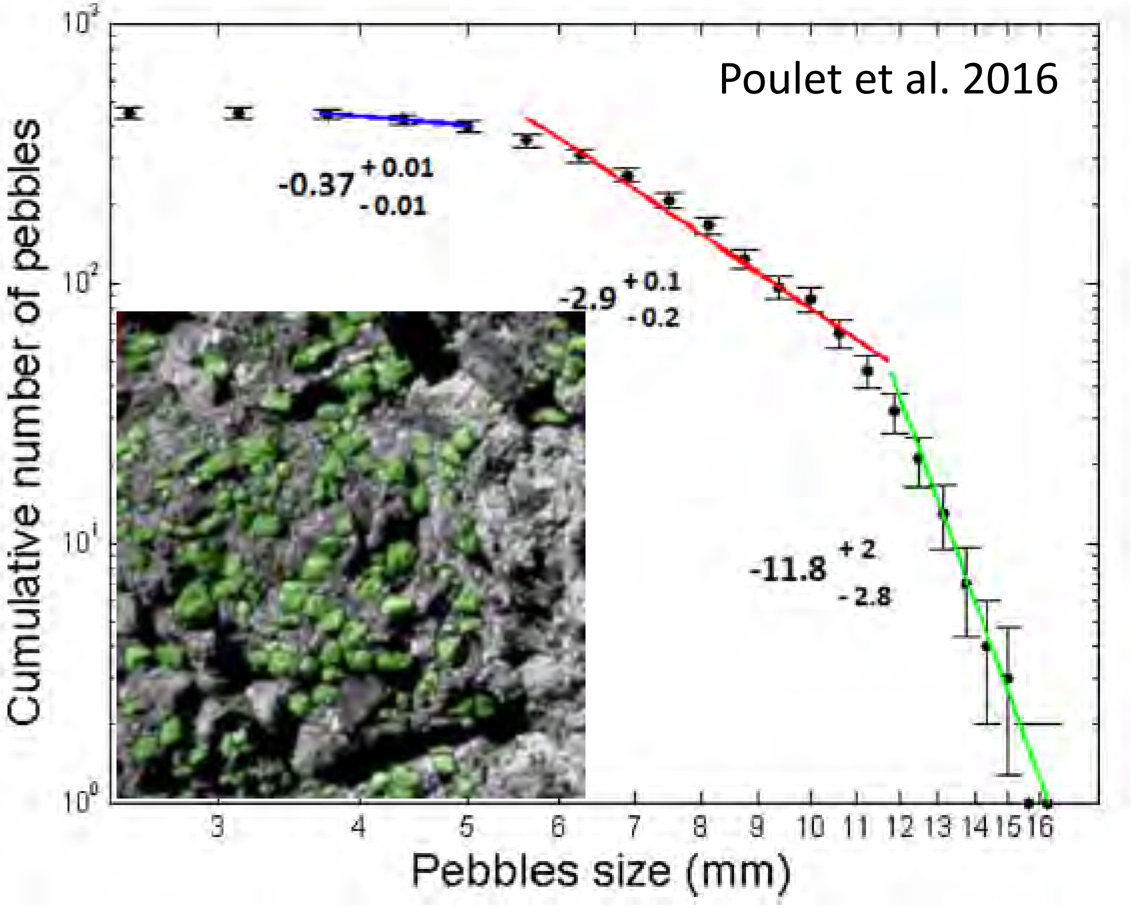
NEW VALUES: $\sigma_T \approx 0.1 - 2$ Pa — Attree et al. 2018

Evidence for dust "pebbles": CIVA



Blum et al. 2017

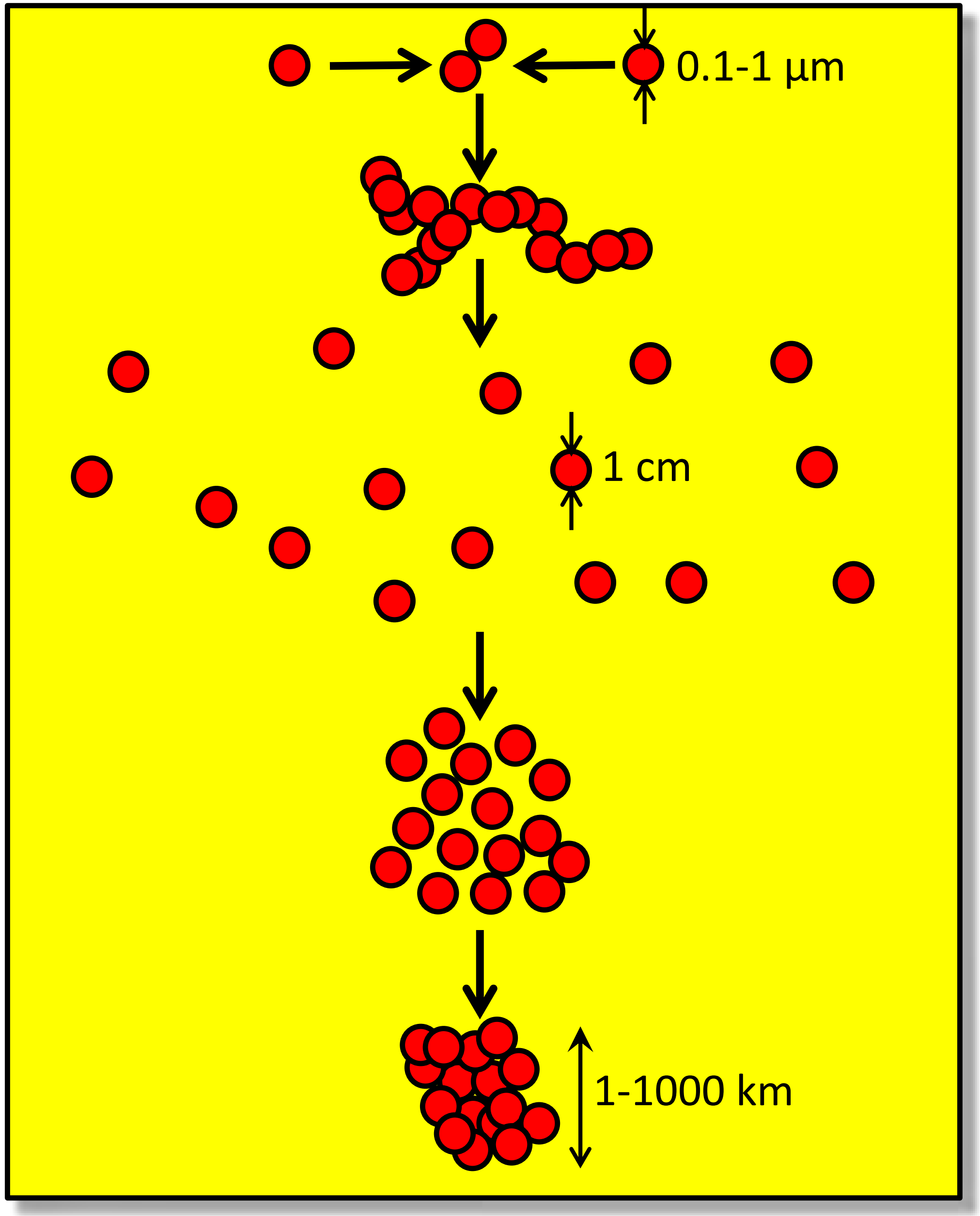
Direct observation of mm- to cm-sized surface granulation by the Philae camera CIVA



III.

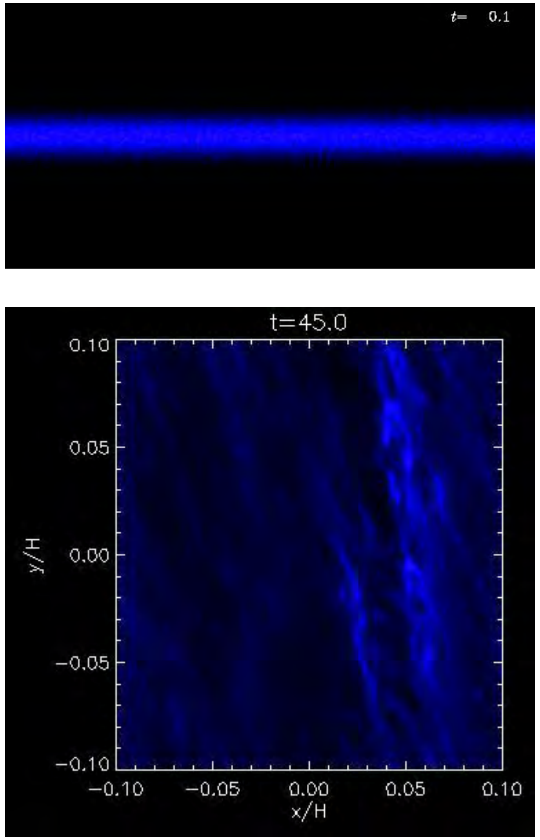
Planetesimal formation by streaming instability and gravitational collapse of “pebble” clouds

Planetesimal formation by streaming instability and gravitational collapse of “pebble” clouds



Dust grains
↓
Formation of cm-sized dust “pebbles” by sticking collisions[1]
↓
Bouncing barrier[1]
↓
No further growth by collisional sticking
↓
Spatial pre-concentration (e.g., by KHI or MRI)
↓
Further concentration by the streaming Instability[2]
↓
Gravitational collapse[3]
↓
Fragmentation of collapsing cloud ?
↓
Planetesimals

Johansen et al. 2007; 2009



References:

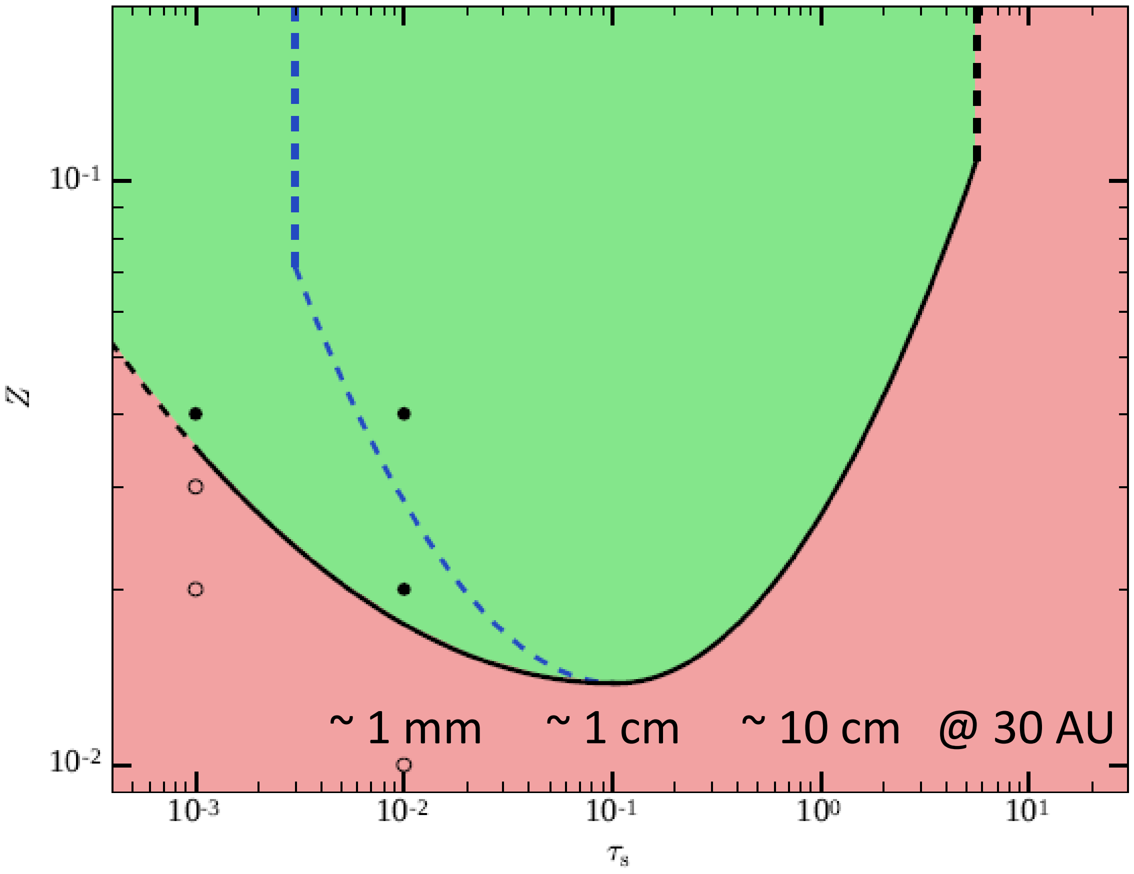
[1] Zsom et al. 2010

[2] Youdin & Goodman 2005

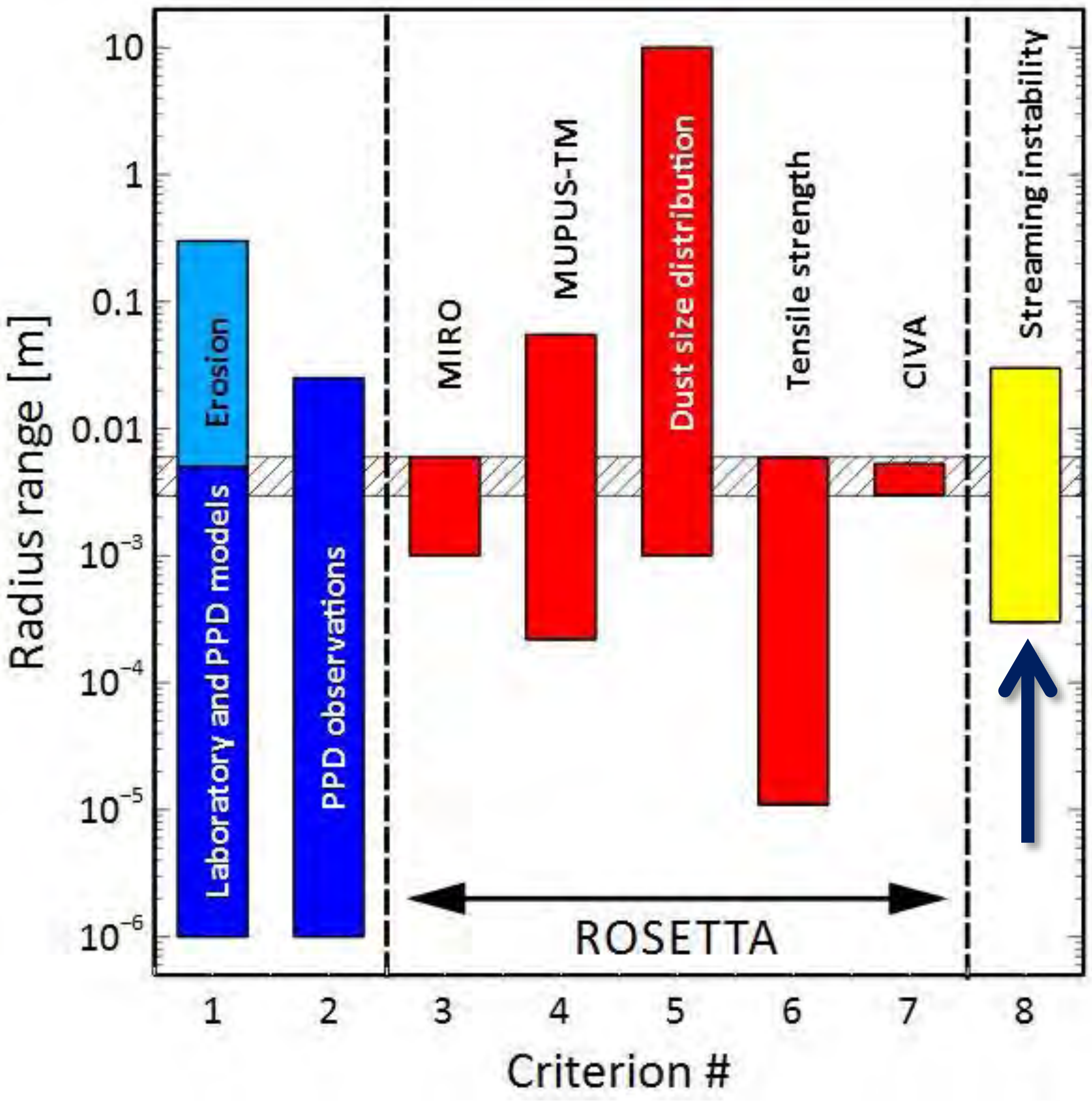
[3] Johansen et al. 2007

Conditions for the streaming instability to work

Onset of streaming instability with minimum metallicity (enhancement) for dust “pebbles” with $St \sim 0.1$, i.e., with sizes ~1 cm



Yang et al. 2017

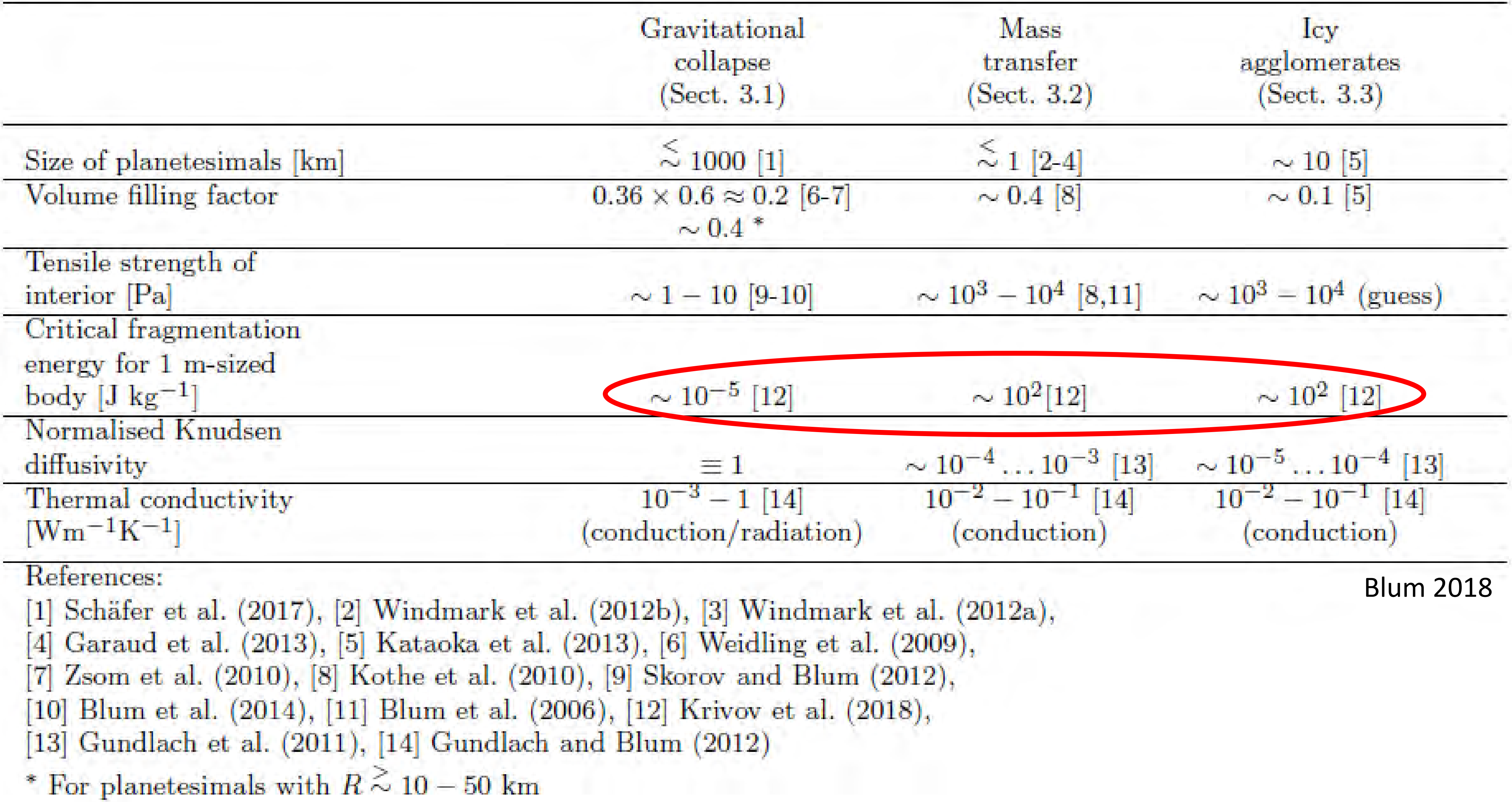


Blum et al. 2017

IV.

Properties of bodies formed by gravitational collapse of “pebble” clouds

How can we distinguish between different formation scenarios of planetesimals?



	Gravitational collapse (Sect. 3.1)	Mass transfer (Sect. 3.2)	Icy agglomerates (Sect. 3.3)
Size of planetesimals [km]	$\lesssim 1000$ [1]	$\lesssim 1$ [2-4]	~ 10 [5]
Volume filling factor	$0.36 \times 0.6 \approx 0.2$ [6-7] ~ 0.4 *	~ 0.4 [8]	~ 0.1 [5]
Tensile strength of interior [Pa]	$\sim 1 - 10$ [9-10]	$\sim 10^3 - 10^4$ [8,11]	$\sim 10^3 - 10^4$ (guess)
Critical fragmentation energy for 1 m-sized body [J kg^{-1}]	$\sim 10^{-5}$ [12]	$\sim 10^2$[12]	$\sim 10^2$ [12]
Normalised Knudsen diffusivity	$\equiv 1$	$\sim 10^{-4} \dots 10^{-3}$ [13]	$\sim 10^{-5} \dots 10^{-4}$ [13]
Thermal conductivity [Wm^{-1}K^{-1}]	$10^{-3} - 1$ [14] (conduction/radiation)	$10^{-2} - 10^{-1}$ [14] (conduction)	$10^{-2} - 10^{-1}$ [14] (conduction)

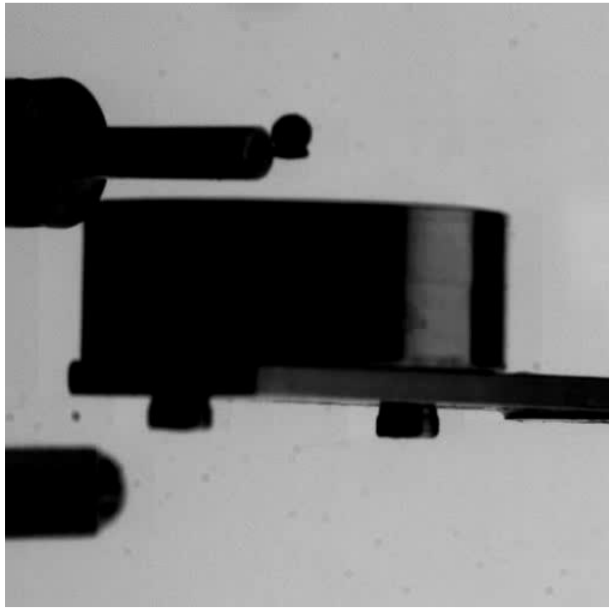
References:
[1] Schäfer et al. (2017), [2] Windmark et al. (2012b), [3] Windmark et al. (2012a),
[4] Garaud et al. (2013), [5] Kataoka et al. (2013), [6] Weidling et al. (2009),
[7] Zsom et al. (2010), [8] Kothe et al. (2010), [9] Skorov and Blum (2012),
[10] Blum et al. (2014), [11] Blum et al. (2006), [12] Krivov et al. (2018),
[13] Gundlach et al. (2011), [14] Gundlach and Blum (2012)

* For planetesimals with $R \gtrsim 10 - 50$ km

Blum 2018

Collision properties of planetesimals consisting of dust pebbles (experiments)

Sticking

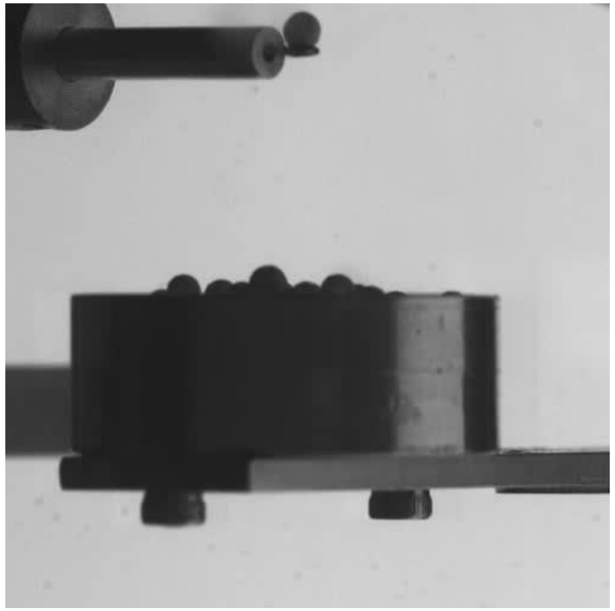


Whizin et al. 2017

$v_{\mathrm{im}} = 0.05\ \mathrm{m/s}$

$E_{\mathrm{im}} = 3 \times 10^{-9}\ \mathrm{J}$

Bouncing

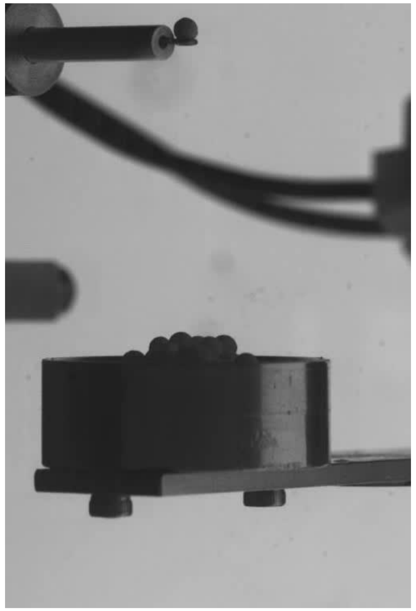


Whizin et al. 2017

$v_{\mathrm{im}} = 0.2\ \mathrm{m/s}$

$E_{\mathrm{im}} = 4 \times 10^{-8}\ \mathrm{J}$

Fragmentation

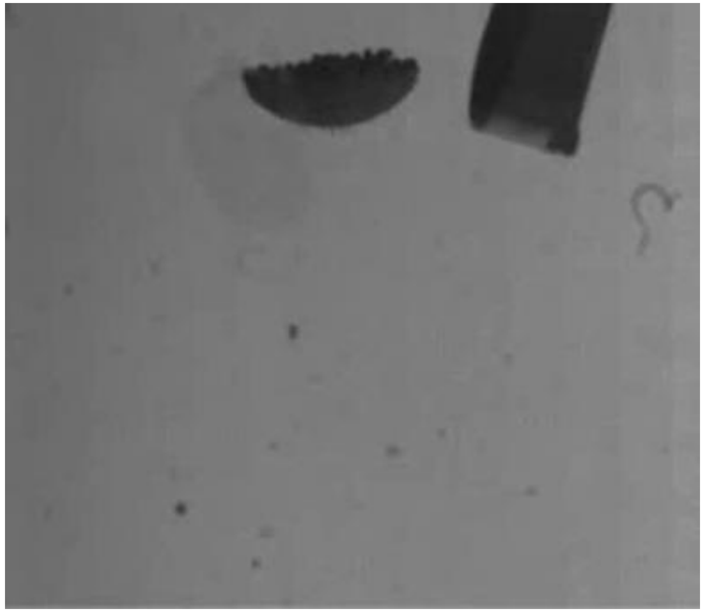


Whizin et al. 2017

$v_{\mathrm{im}} = 1\ \mathrm{m/s}$

$E_{\mathrm{im}} = 1 \times 10^{-6}\ \mathrm{J}$

Total disruption



Katsuragi & Blum (in prep.)

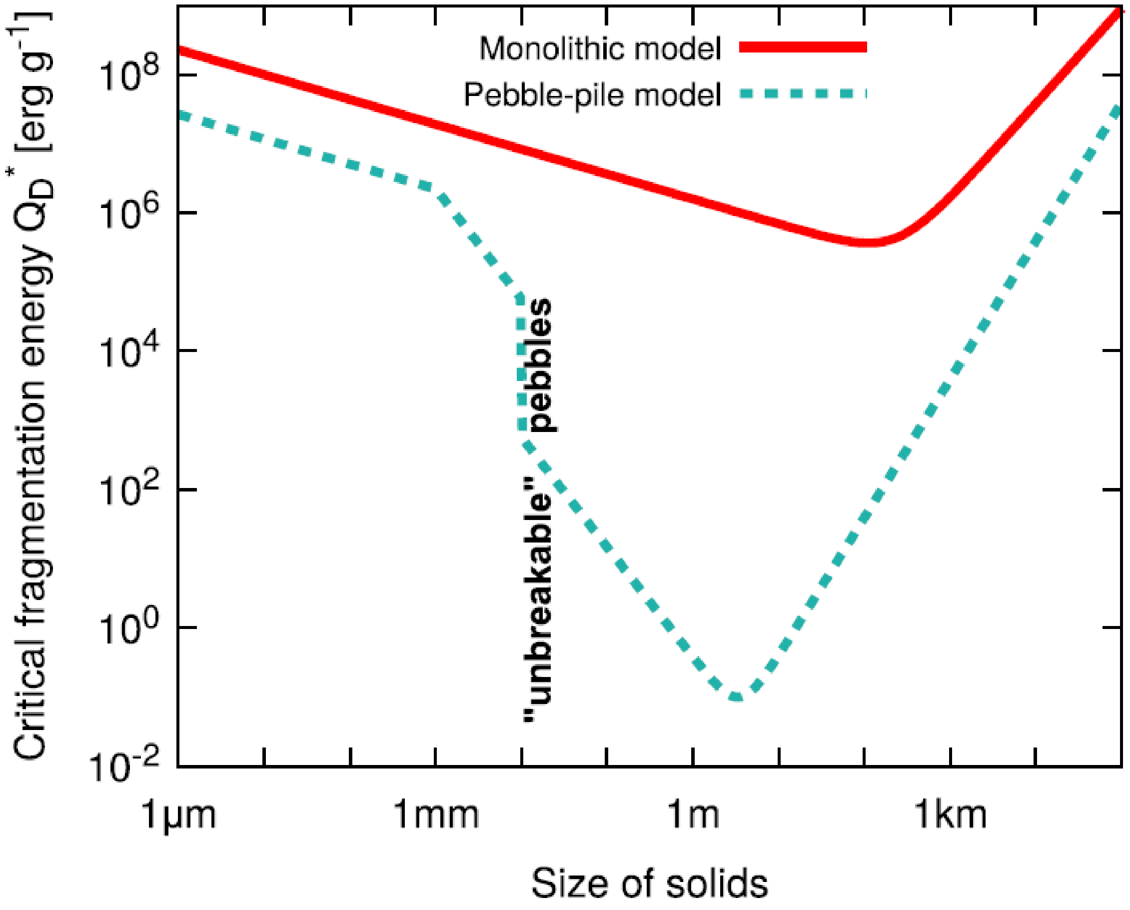
$v_{\mathrm{im}} = 0.8\ \mathrm{m/s}$

$E_{\mathrm{im}} = 9 \times 10^{-5}\ \mathrm{J}$

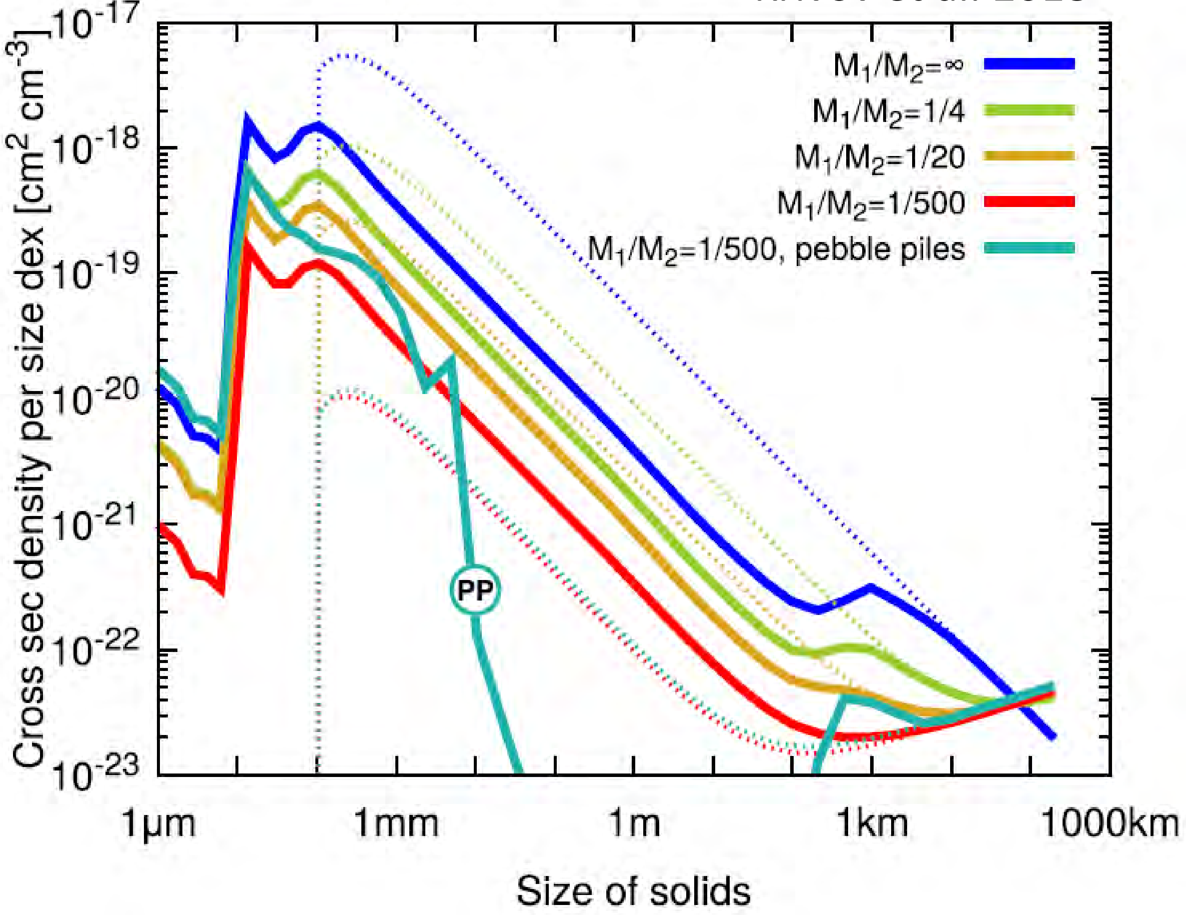
<u>Targets</u>: Clusters of dust aggregates with 1.0-1.6 mm diameter; dust aggregates consisting of 0.1-10 µm silica grains and having a volume filling factor ~0.4.
<u>Projectiles</u>: 1.0-1.6 mm dust aggregates (Whizin et al. 2017); 6 mm glass bead (Katsuragi & Blum, in prep.).

Collision properties of planetesimals consisting of dust pebbles (simulations)

Krivov et al. 2018

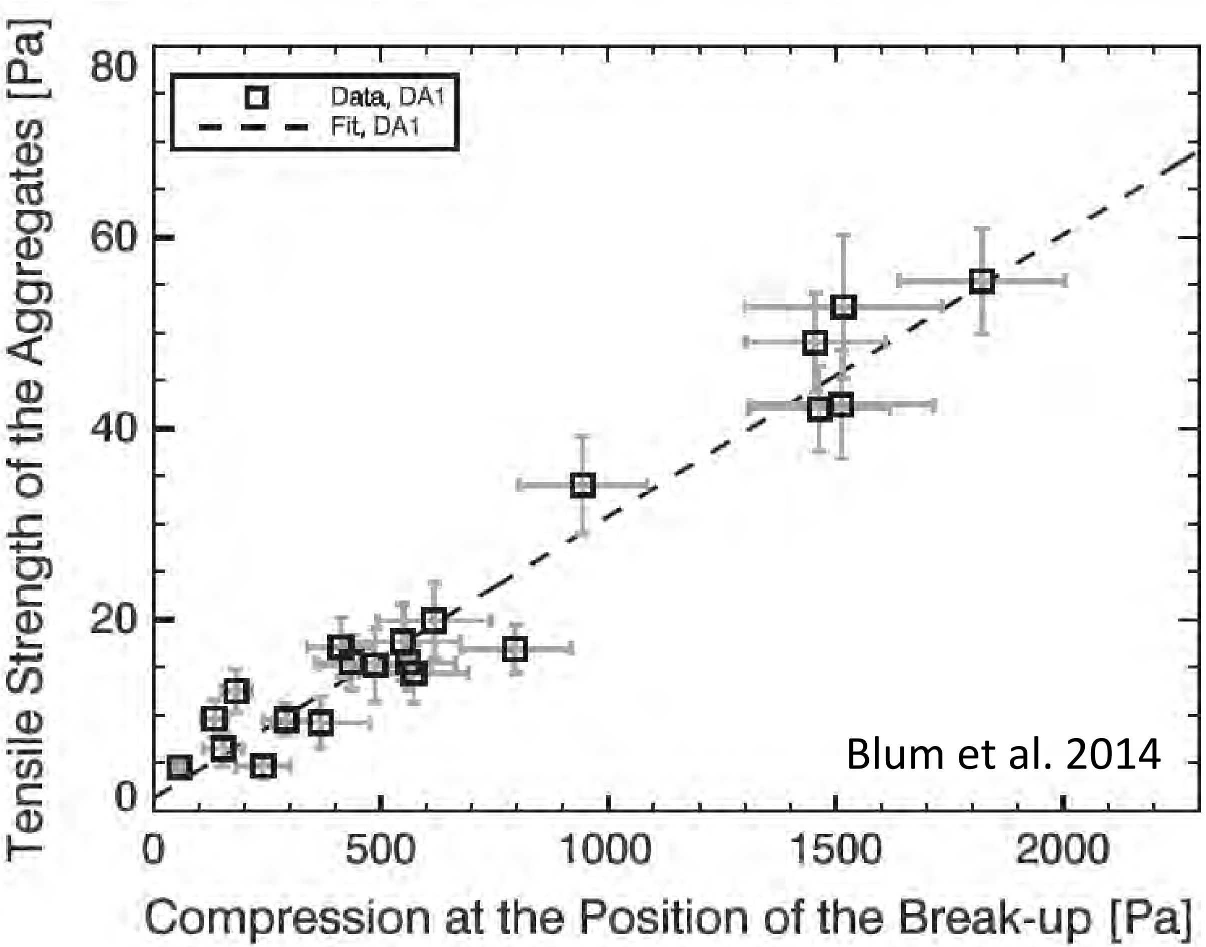


Krivov et al. 2018



BUT: ONLY IF PLANETESIMALS WERE BORN SMALL…

…IF PLANETESIMALS WERE BORN BIG: MEMORY EFFECT!



Blum et al. 2014

Average lithostatic stress:

$$\bar{p} = \frac{4}{15}\pi\rho^2 G R^2 \approx 14\ \mathrm{Pa}\left(\frac{R}{1\ \mathrm{km}}\right)^2$$

$R = 10\ \mathrm{km}$: $\bar{p} = 1.4\ \mathrm{kPa}$

→ $\bar{p} <$ crushing strength of pebbles

→ $\sigma_t = 40\ \mathrm{Pa}$

$R = 50\ \mathrm{km}$: $\bar{p} = 35\ \mathrm{kPa}$

→ $\bar{p} \gg$ crushing strength of pebbles

→ $\sigma_t > 1\ \mathrm{kPa}$

Additionally, the “pebbles” are starting to become collisionally destroyed during the gravitational collapse for *R* > 50 km.

(Wahlberg Jansson et al. 2017)

V. Conclusions of Part I

- Planetesimal formation by sticking collisions is very unlikely.
- Best planetesimal formation model: dust forms “pebbles” by coagulation, which form planetesimals by streaming instability and gravitational collapse.
- Empirical evidence for “pebble-pile” planetesimals: comet 67P.
- Small “pebble-pile” planetesimals possess very different properties than planetesimals formed by sticking collisions (e.g., collisional strength).

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DFG Deutsche Forschungsgemeinschaft

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