PEBBLES

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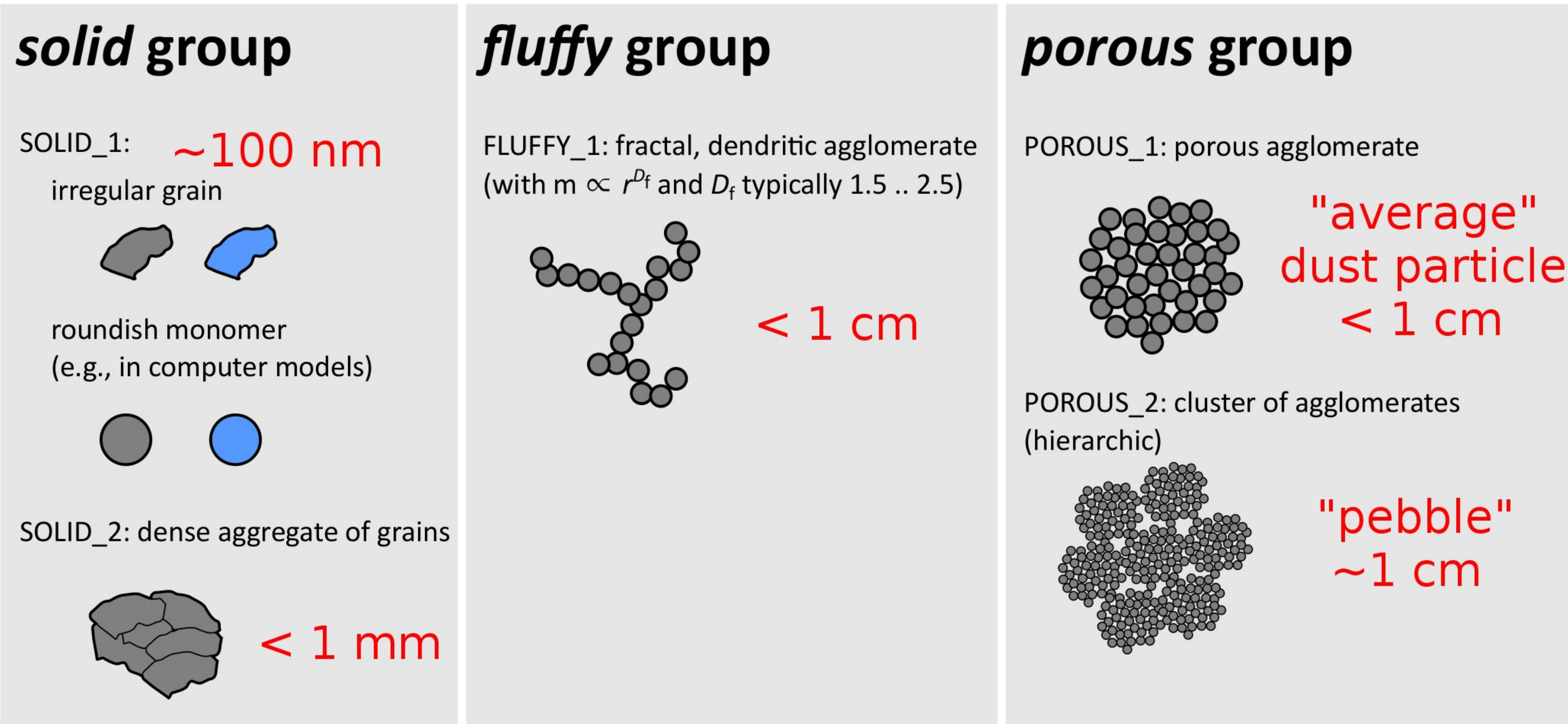
Pebbles (if any) must be made of (icy) dust particles

Dust classification after IDPs, Rosetta, Stardust (Güttler et al 2019 AA 630, A24)



From classification to samples

Fig. 9: Rosetta/MIDAS AFM image at best resolution: grains (monomers) of a size peak at 100 nm
Fig. 5: Bigger aggregates of grains, typical volume filling factor = 0.6 (v.f.f. = 1 – porosity)
Fig. 6: Rosetta/MIDAS and Rosetta/COSIMA images, sizes from few micron to sub-mm
Lower left: most particles are mixtures of rocks and porous aggregates, Stardust sample:
[SOLID_2 = sulfide (lower right) + silicate (middle)] + [POROUS] (Güttler et al 2019 AA 630, A24)

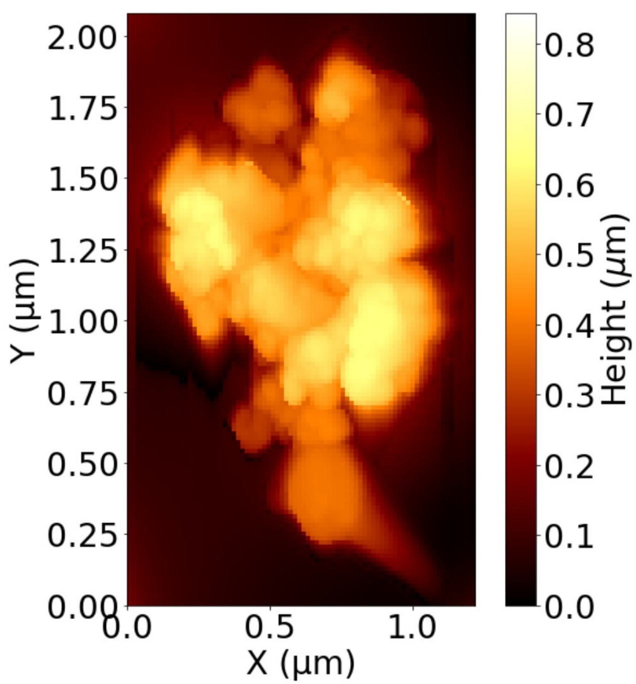


Fig. 9. MIDAS image of an agglomerate particle sticking to the side of a tip that was acquired using a calibration target with sharp spikes (Mannel et al. 2019). The smooth round feature at the bottom is the tip apex, and the straight line to the bottom right corner is a structure supporting the tip. The image has a pixel resolution of about 15 nm and was acquired on 8 December 2015.

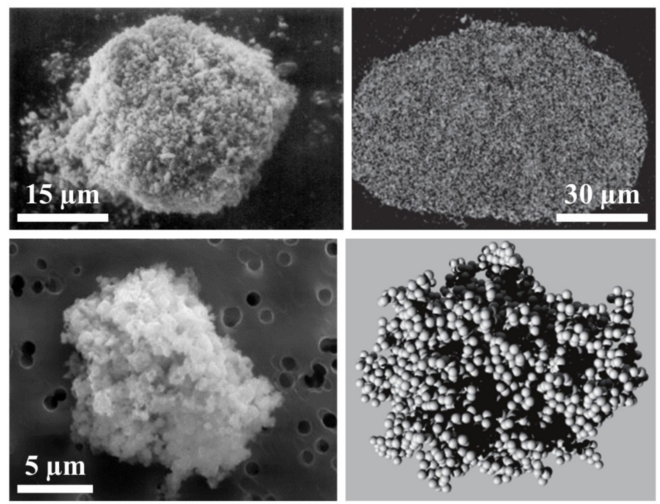


Fig. 5. Agglomerates from the POROUS_1 type in Fig. 1. SEM image of a laboratory analog agglomerate (*top left*), an IDP (*bottom left*), a tomographic cross section (*top right*), and a computer model (*bottom right*; references in the text).

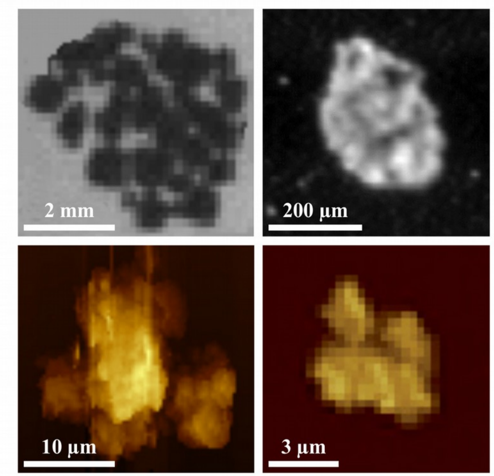
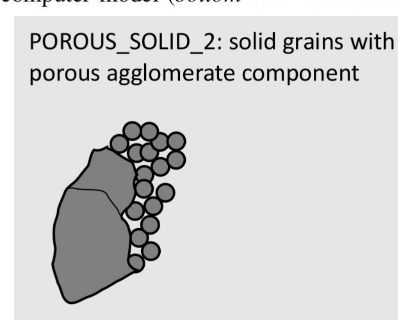
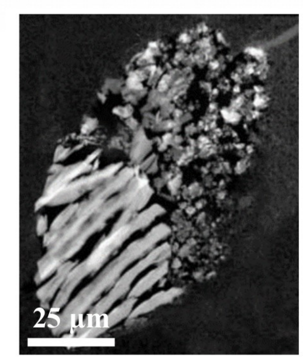


Fig. 6. Clusters of agglomerates from the POROUS_2 type in Fig. 1. Sample grown under microgravity (*top left*), Rosetta/ COSIMA (*top right*), and Rosetta/MIDAS samples (*bottom*; references in the text).





Fluffy particles require pebbles to survive

Fractal particles cannot form on comets: heritage of the first dust accretion in the presolar cloud
Both MIDAS and GIADA infer a fractal dimension ~1.7, consistent with primordial growth
Fractal dust of size <1 cm requires storage in voids among much more robust cm-sized pebbles
Comets did not undergo catastrophic collisions completely reshuffling the structure of nuclei

Fulle & Blum 2017 MNRAS 469, S39

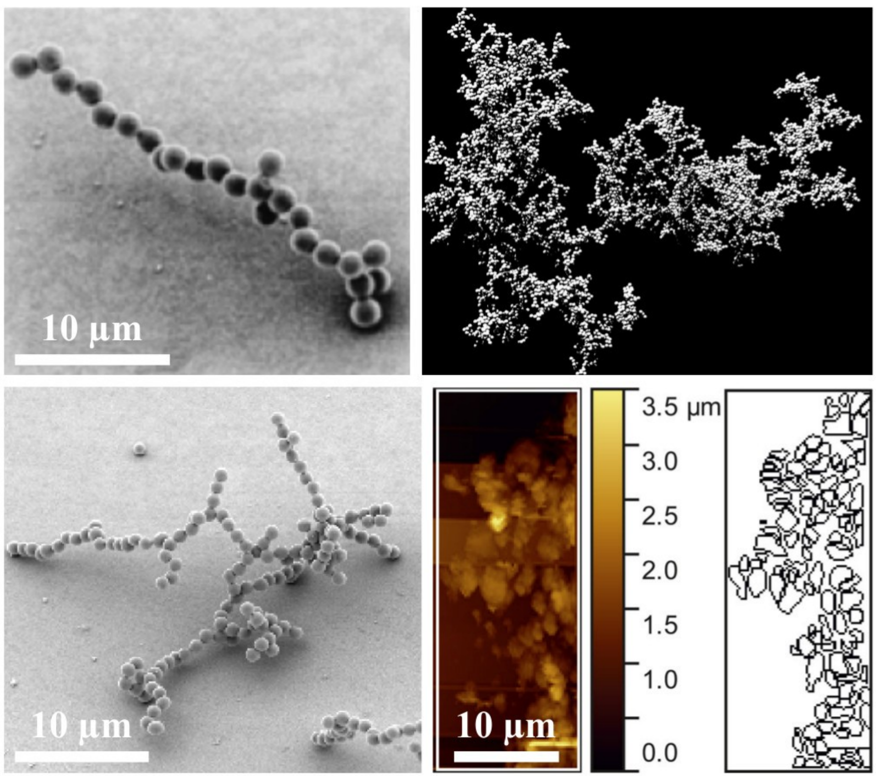
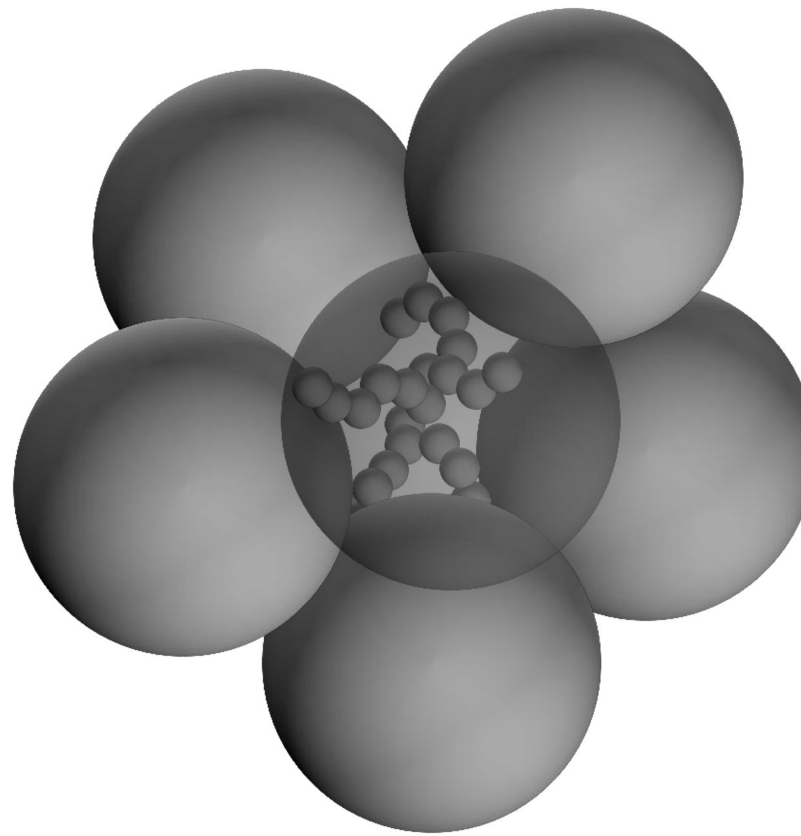


Fig. 4. Fractal particles from laboratory experiments (*left*), computer simulation (*top right*), and Rosetta/MIDAS (*bottom right*, left and right of the scale bar; references in the text). The color code and scale bar for the bottom right image denotes height.



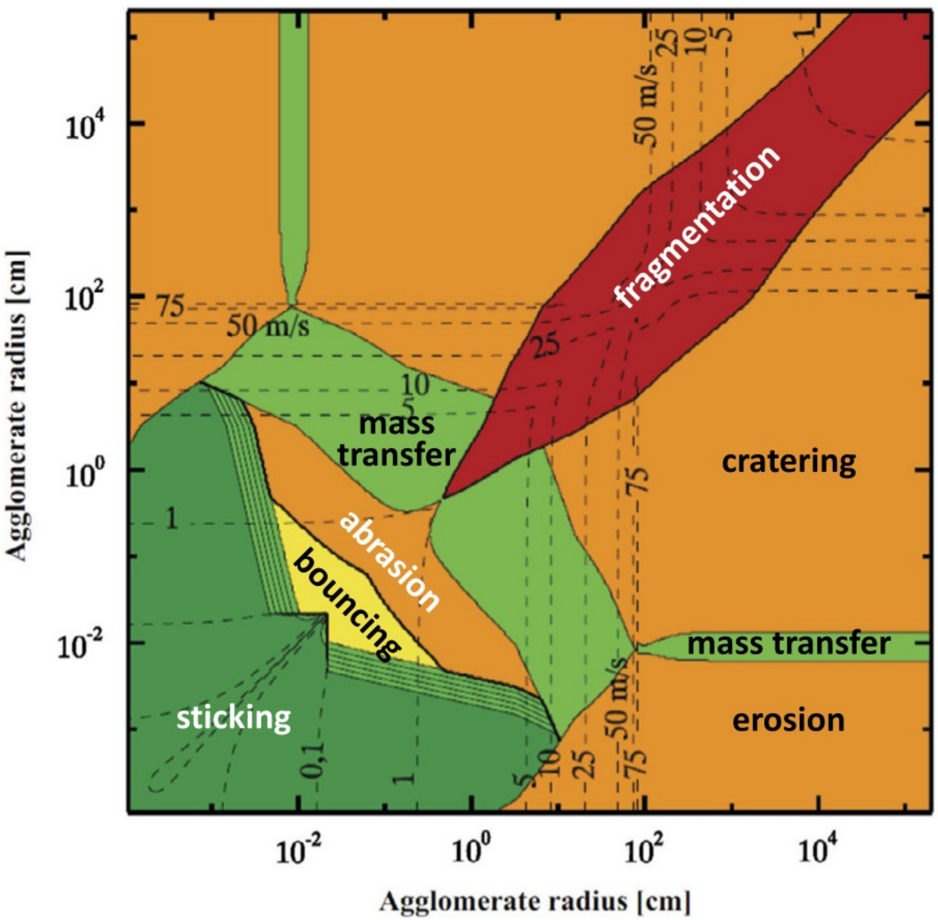
Evolution from Grains to Pebbles to Planetesimals

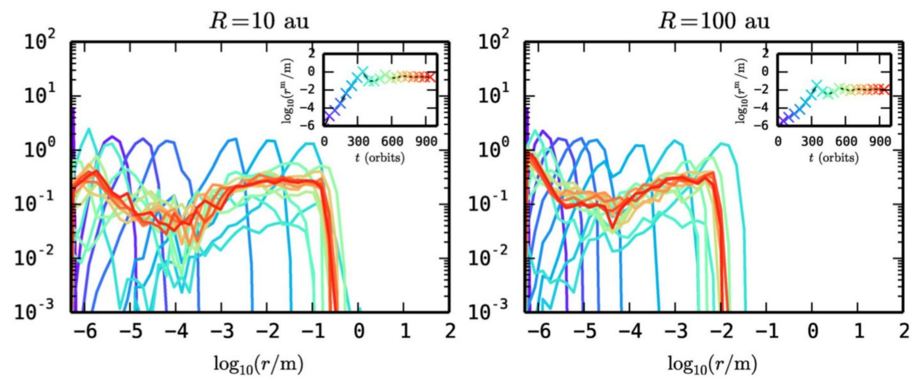
Dominant Process	Evolutionary Step	v.f.f.	Size
	Presolar grain	~1	~100nm
Sticking	Grains → Fractal particles	<0.01	<1 cm
Sticking + bouncing	Fractals → Porous particle	~0.4	~1 mm
Disc mixing + sticking	Porous → Rocks+Porous	~0.6	<1 cm
Erosion barrier	Particles → Pebbles + fractals	~0.4	~1 cm
Disc instability + gravity	Pebbles → Planetesimals	~0.25 - 1	1-1000km

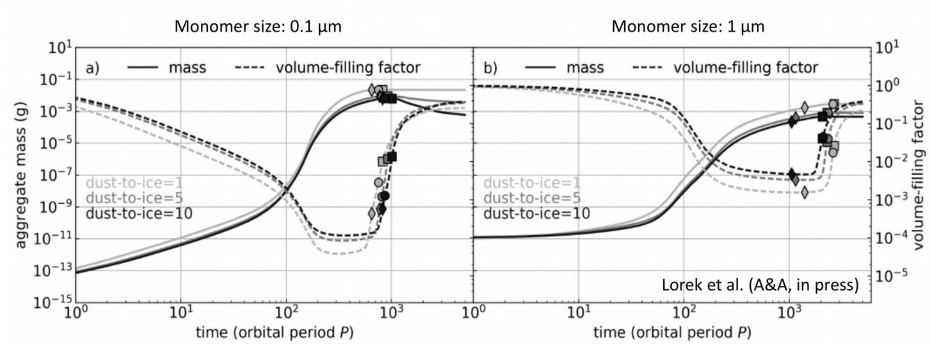
If the planetesimal size <100 km, then pebbles are not destroyed by self-gravity and radio decays (in which case v.f.f. ~ 1) → COMETS of v.f.f. ~ 0.25

Erosion barrier: no growth above ~10 cm

Left: Dust collision experiments (lab. and low gravity) + models (Blum 2018, SSR 214,52)
Upper right: Erosion stops any planetesimal growth above 10 cm (Schrapler et al. 2018, ApJ 853, 74)
Lower right: ice does not help, its larger sticking has no effects (Lorek et al. 2018, AA 611, A18)

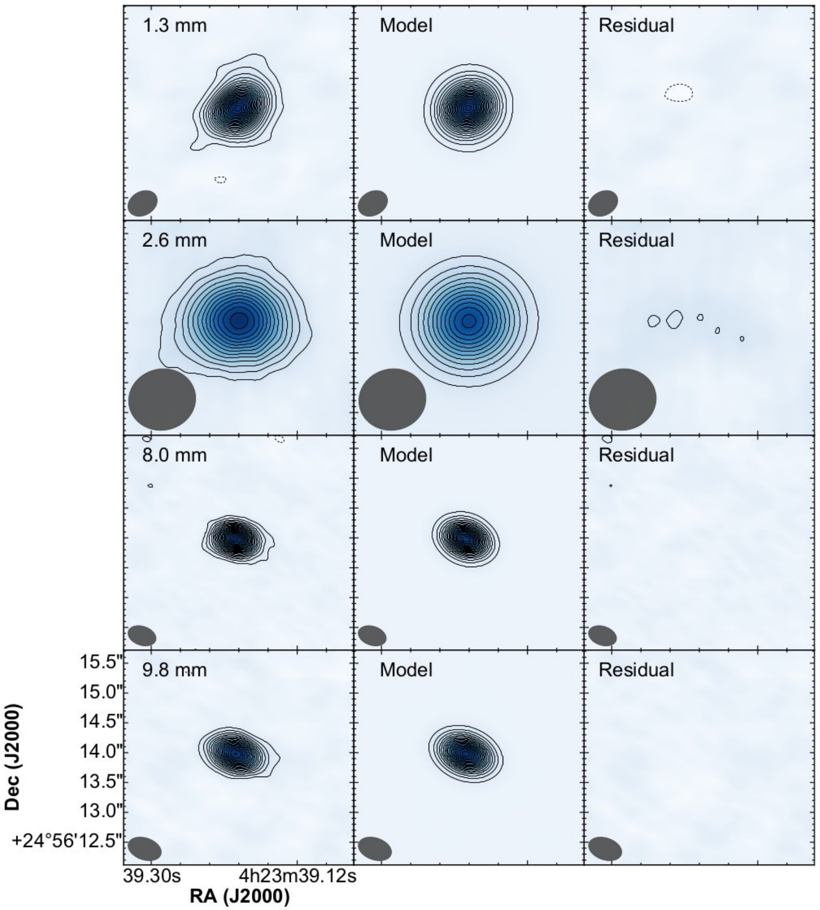


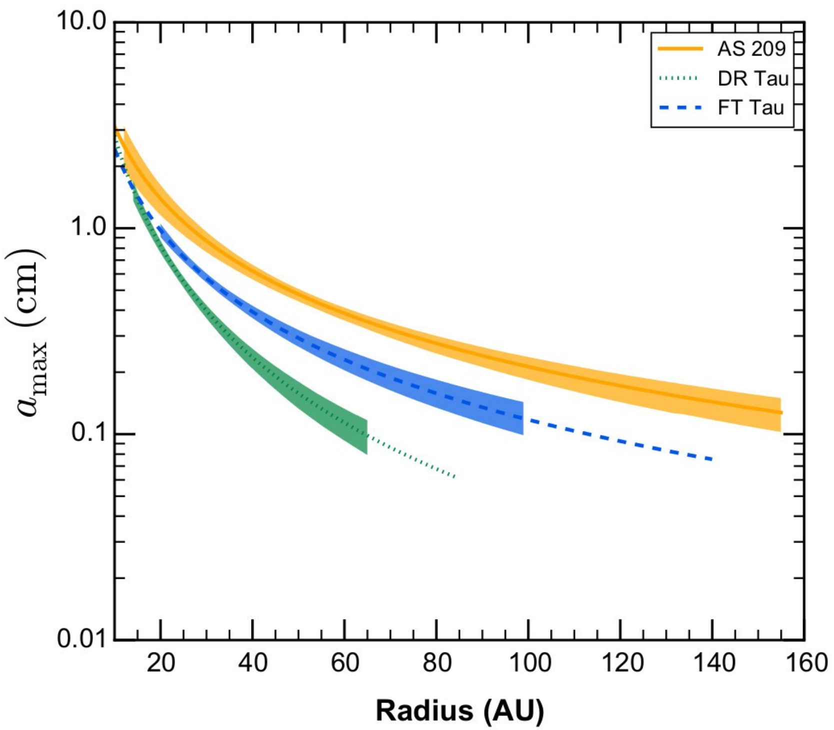




Protoplanetary discs are made of pebbles

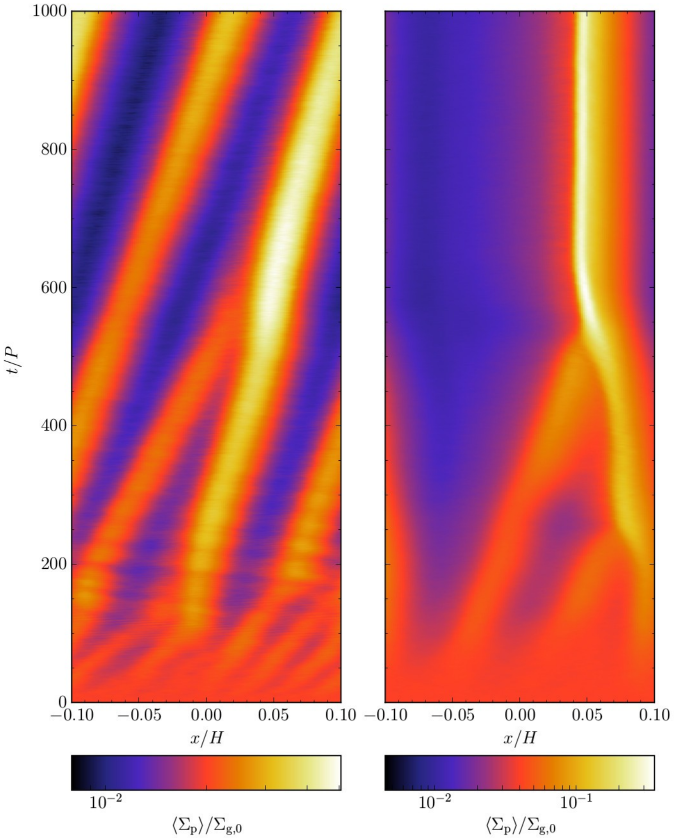
Tazzari et al. 2016, AA 588, A53

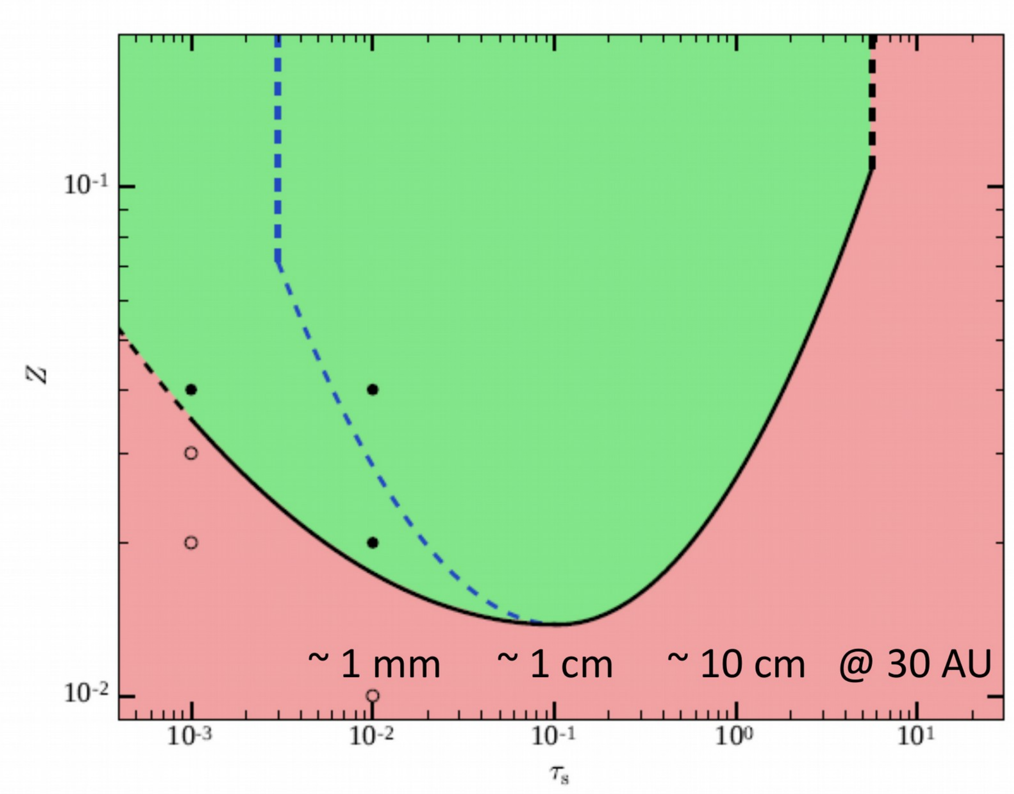




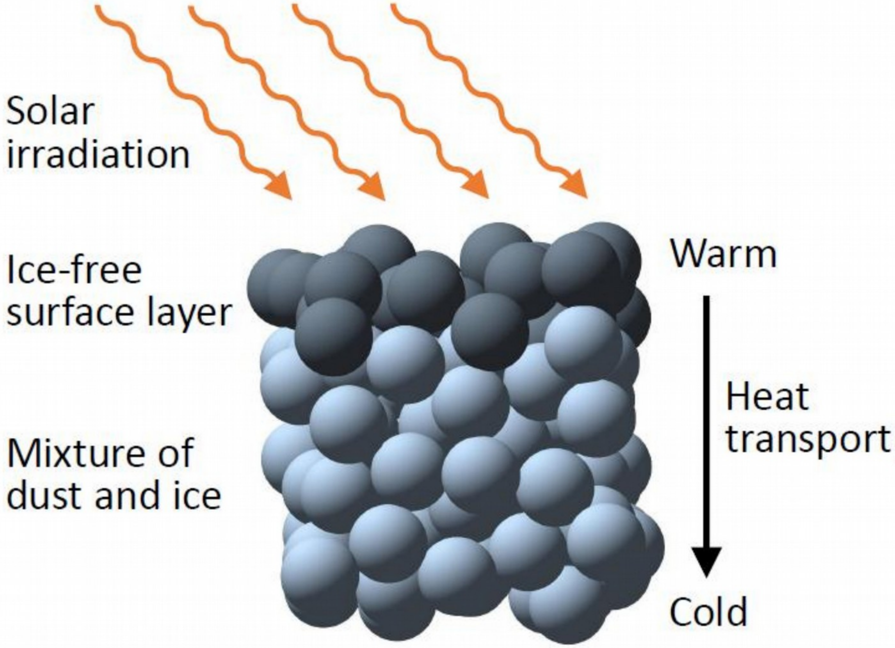
Streaming Instability most efficient at ~1 cm

Yang et al. 2017, AA 606, A80





Are comets made of pebbles ?



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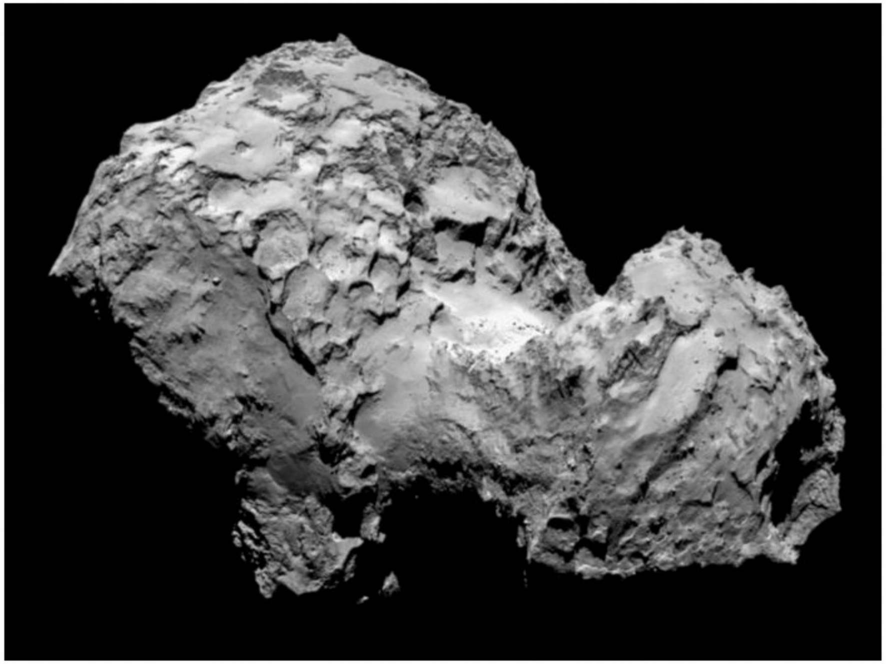

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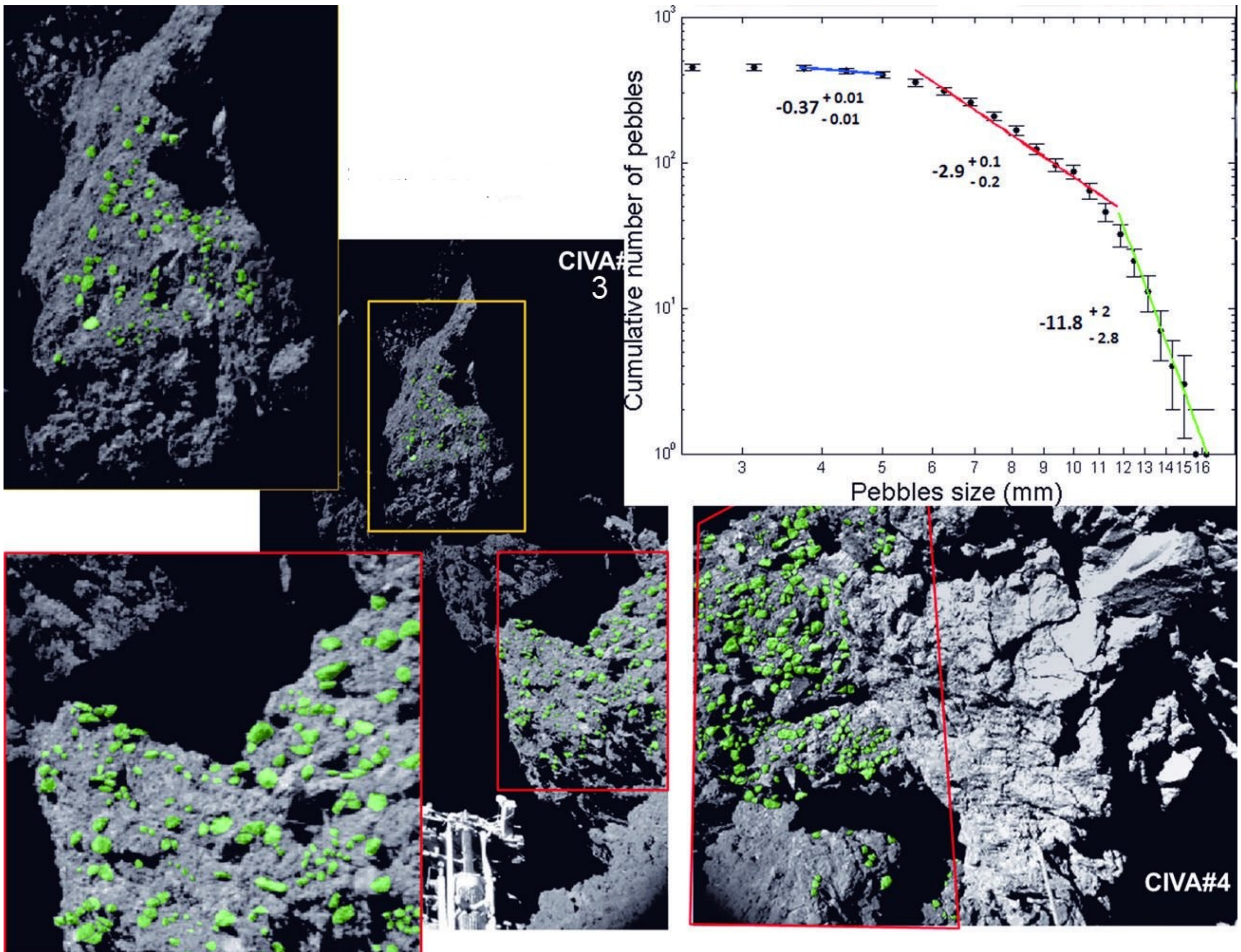
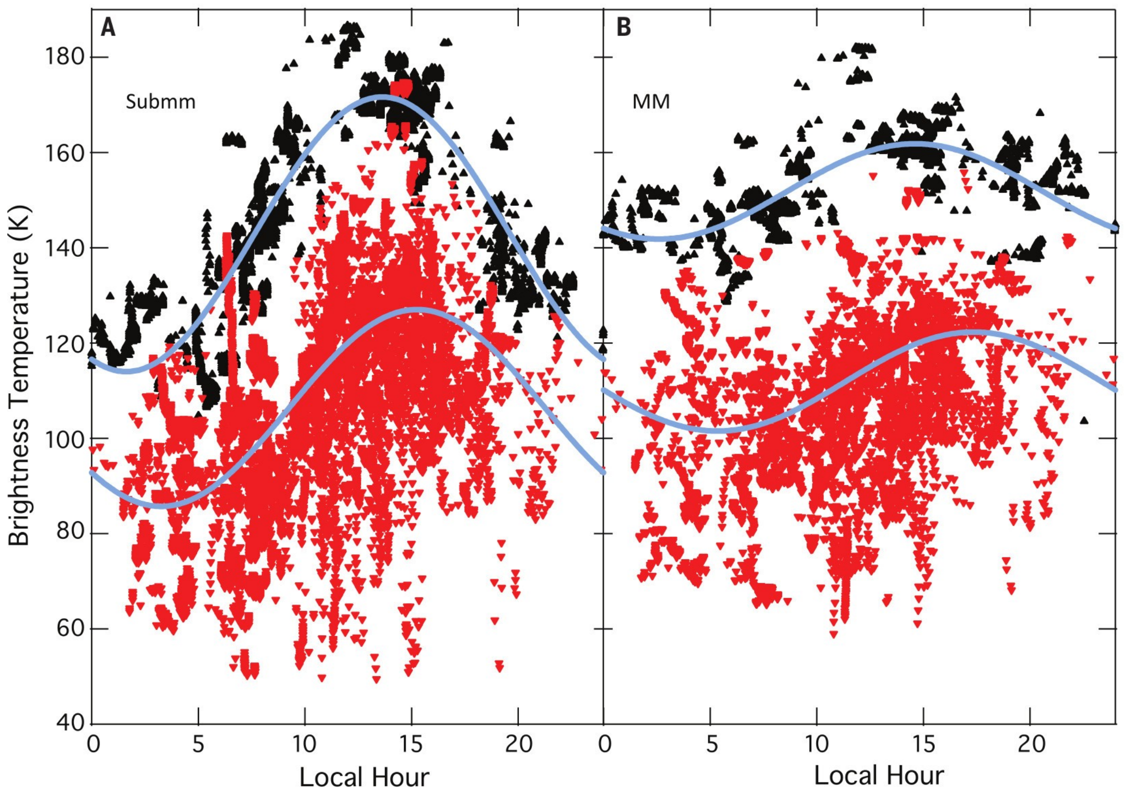
Philae/CIVA direct observation of cm-sized pebbles

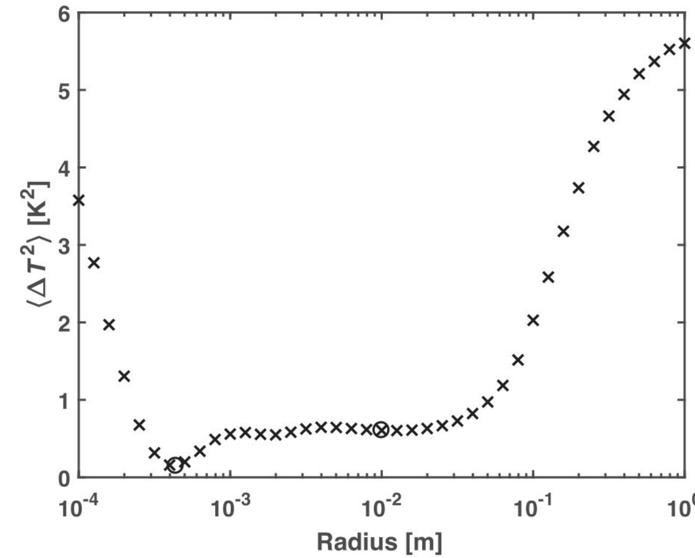
Poulet et al. 2016, MNRAS 462, S23

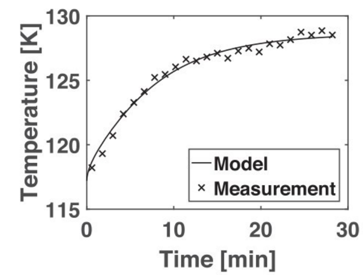


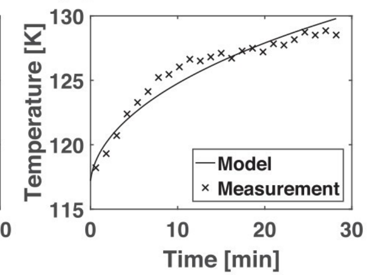
Thermal model of 67P pebble-made nucleus

Fit of orbiter (MIRO) and lander (MUPUS) thermal data (Blum et al. 2017, MNRAS 469, S755)



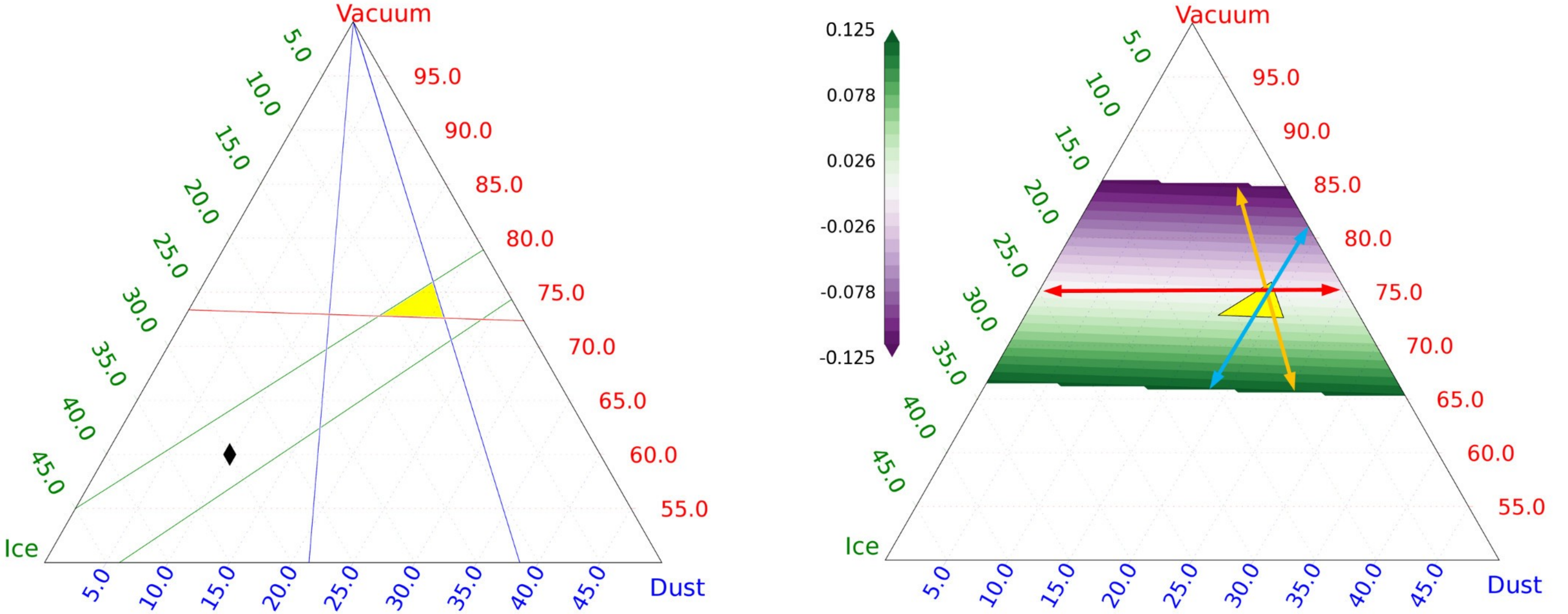






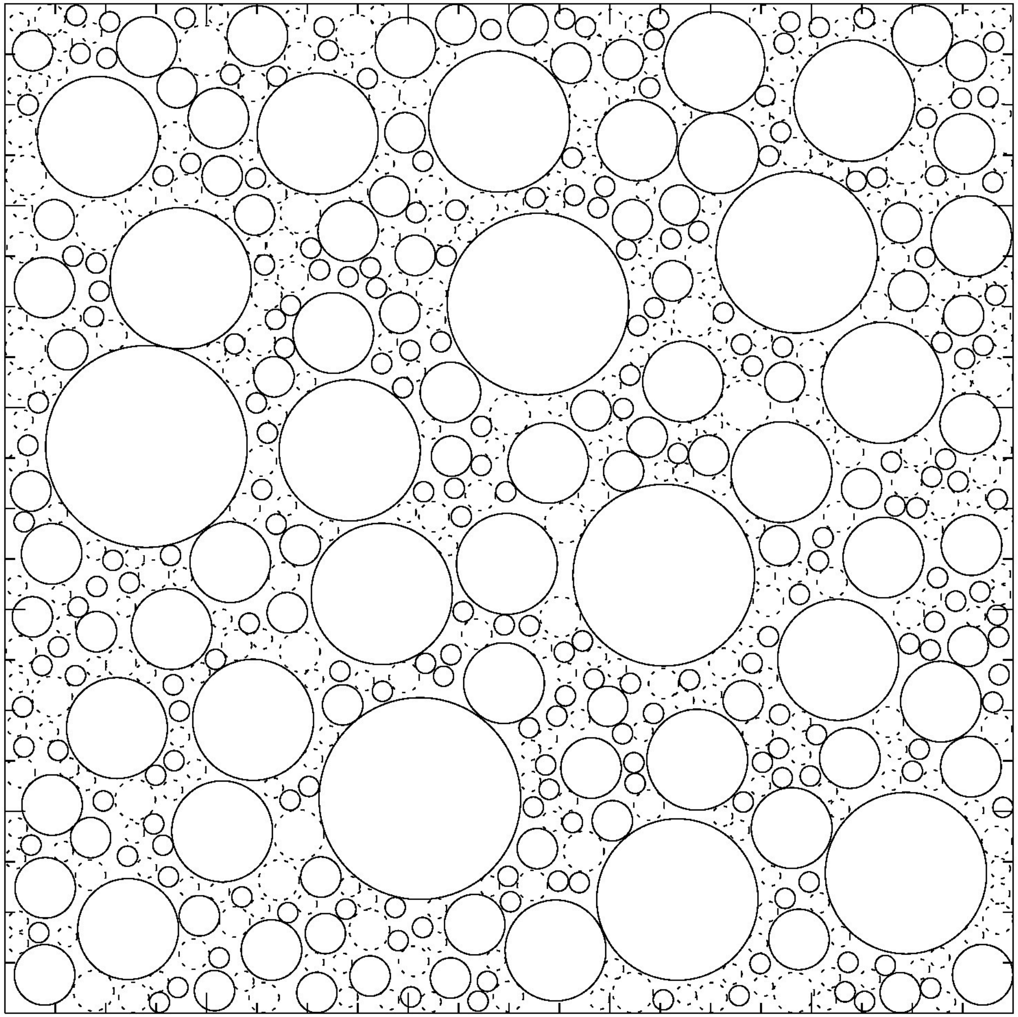
67P nucleus tomography finds a pebble-made nucleus

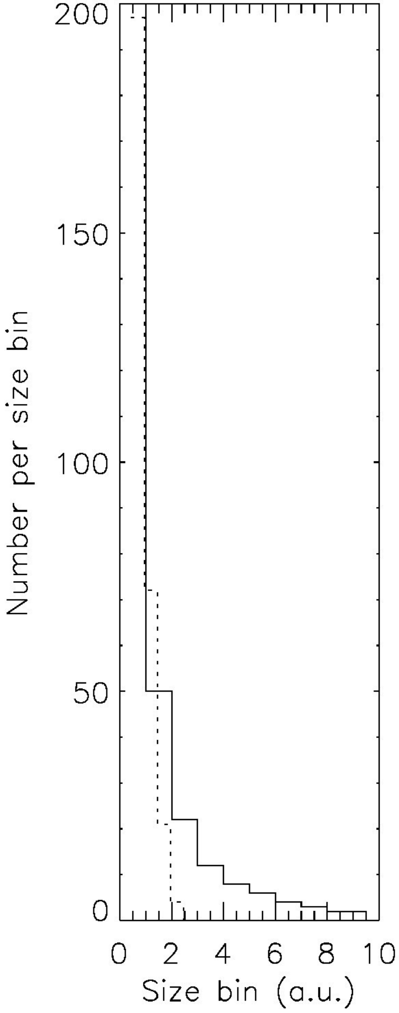
Rosetta/CONSERT data (red line) are only consistent with porosity heterogeneities at lengths <1m;
at larger scales, porosity changes <10%; refractory-to-ice ratio >3 (Herique et al. 2019, AA 630, A6)
Green lines: bulk density range (RSI); Blue lines: refractory-to-ice mass ratio = 2 (left) and 6 (right)



Gas diffusion inside a dust-made pebble

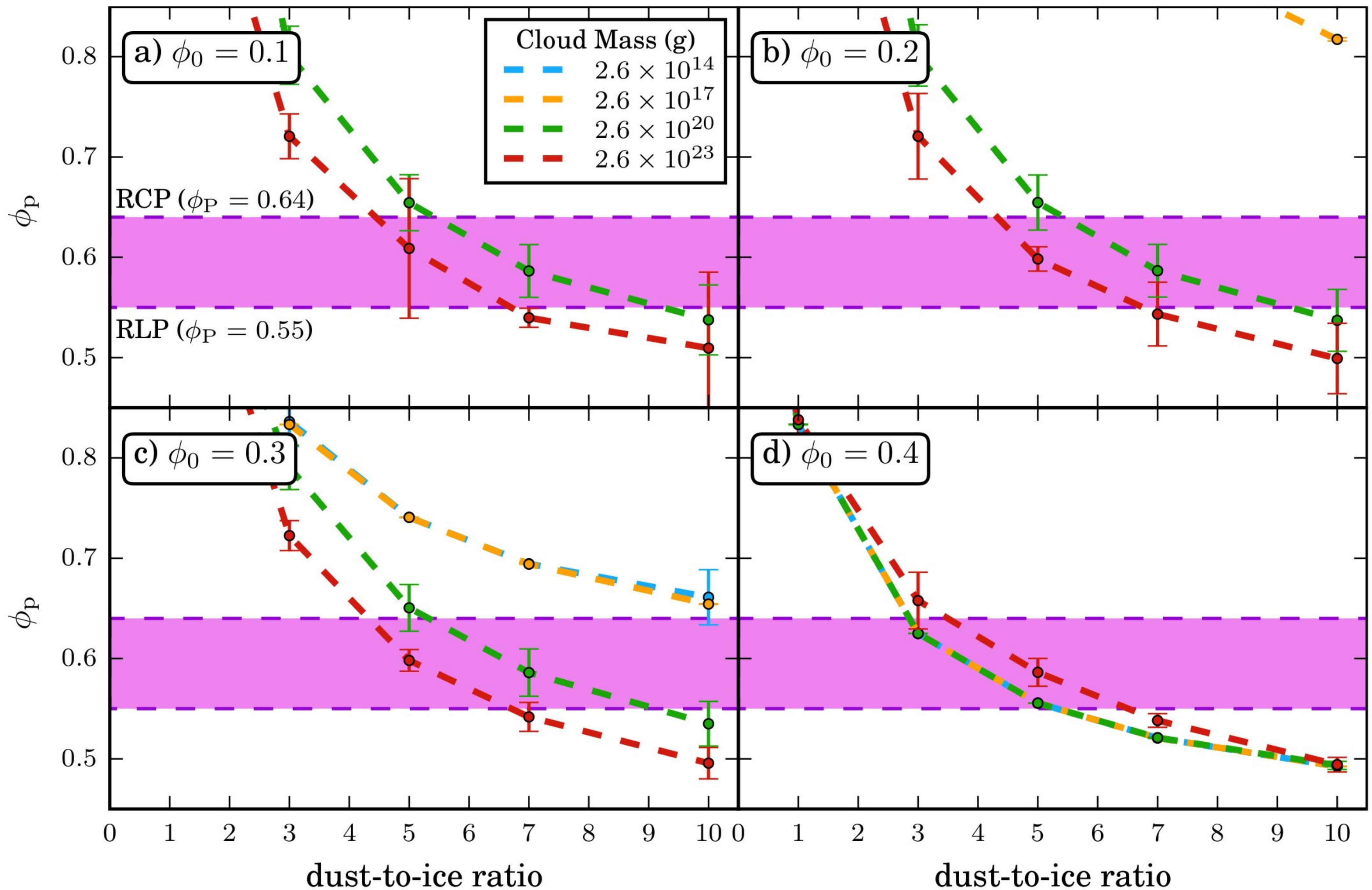
The dust size spectrum constrains that of pores → Knudsen diffusivity (Fulle et al. 2019, ApJ 879, L8)
If pebbles >10 cm, then diffusion time scale >0.5hr: never observed any such activity delay at sunrise
Gas diffusion model from ice sublimation inside dust fits all 67P activity data (Fulle et al. 2020, subm.)





The pebble model fixes the refractory-to-ice ratio

Pebble-made comets must have refractory-to-ice > 3 (Lorek et al. 2019, AA 587, A128)
All cometary data confirm refractory-to-ice ratio > 3 (Fulle et al. 2019, MNRAS 482, 3326)



Conclusions

……..…up to now, pebbles only explain “everything”……….