Direct Formation of Planetary Embryos in Self-Gravitating Disks

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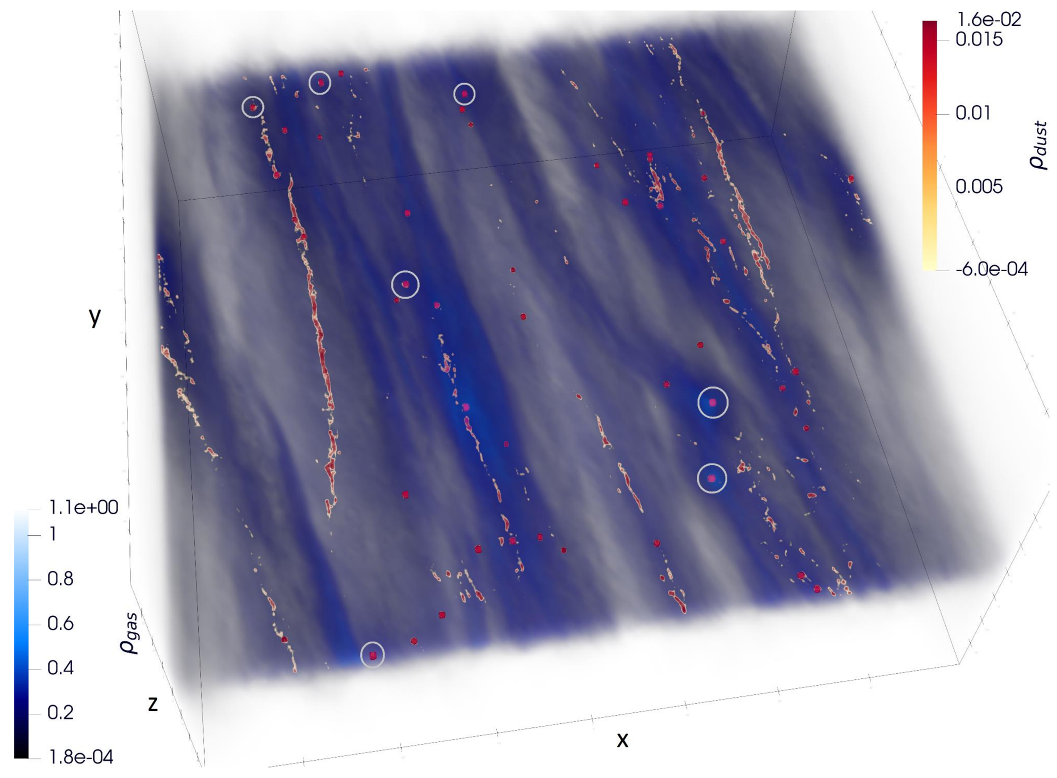
What happens to the dust in a self-gravitating disk?

Planet formation in self-gravitating disks typically focuses on the rapid collapse (fragmentation) of dense gas in the disk into gas giant planets. This is particularly effective at larger distances where the disk is cool [3]. Therefore, fragmenting disks are often used to explain direct imaging observations of gas giant planets at wide orbital separations. While the gas dominates the mass budget of a self-gravitating disk, the dust can concentrate into dense filaments when the disk is turbulent but does not fragment. Concentration occurs through the aerodynamic drag of the particles with respect to the gas and leads to density enhancements within the gas spirals [4]. At these densities, the dust can gravitationally collapse into bound clouds or clumps which can be seeds of planet formation.

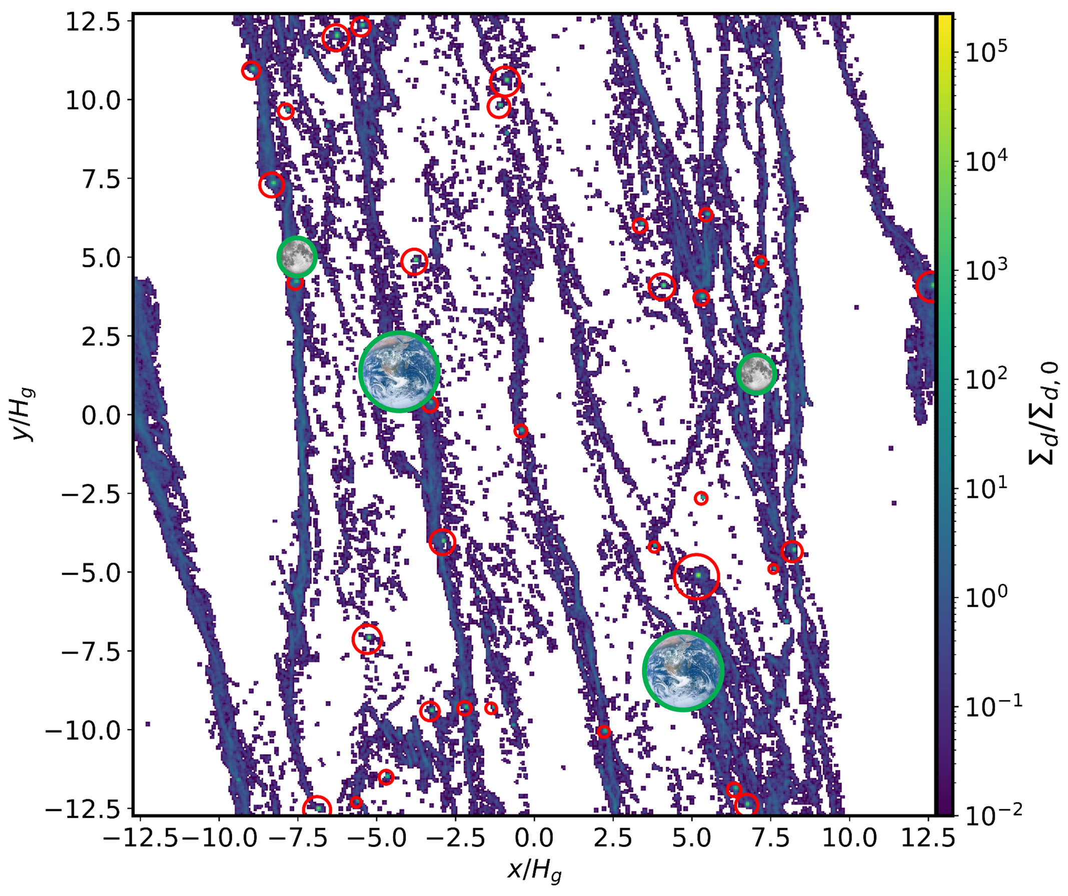
We conduct **3D simulations of dusty self-gravitating disks** to investigate the disk conditions and dust particle parameters which lead to the formation of these dense dust clumps. We find that these clumps can be up to **several Earth masses in size** and their formation is roughly consistent with a criterion where **turbulent diffusion of the dust counters the dust self-gravity.**

Marginally unstable disks can concentrate solid material

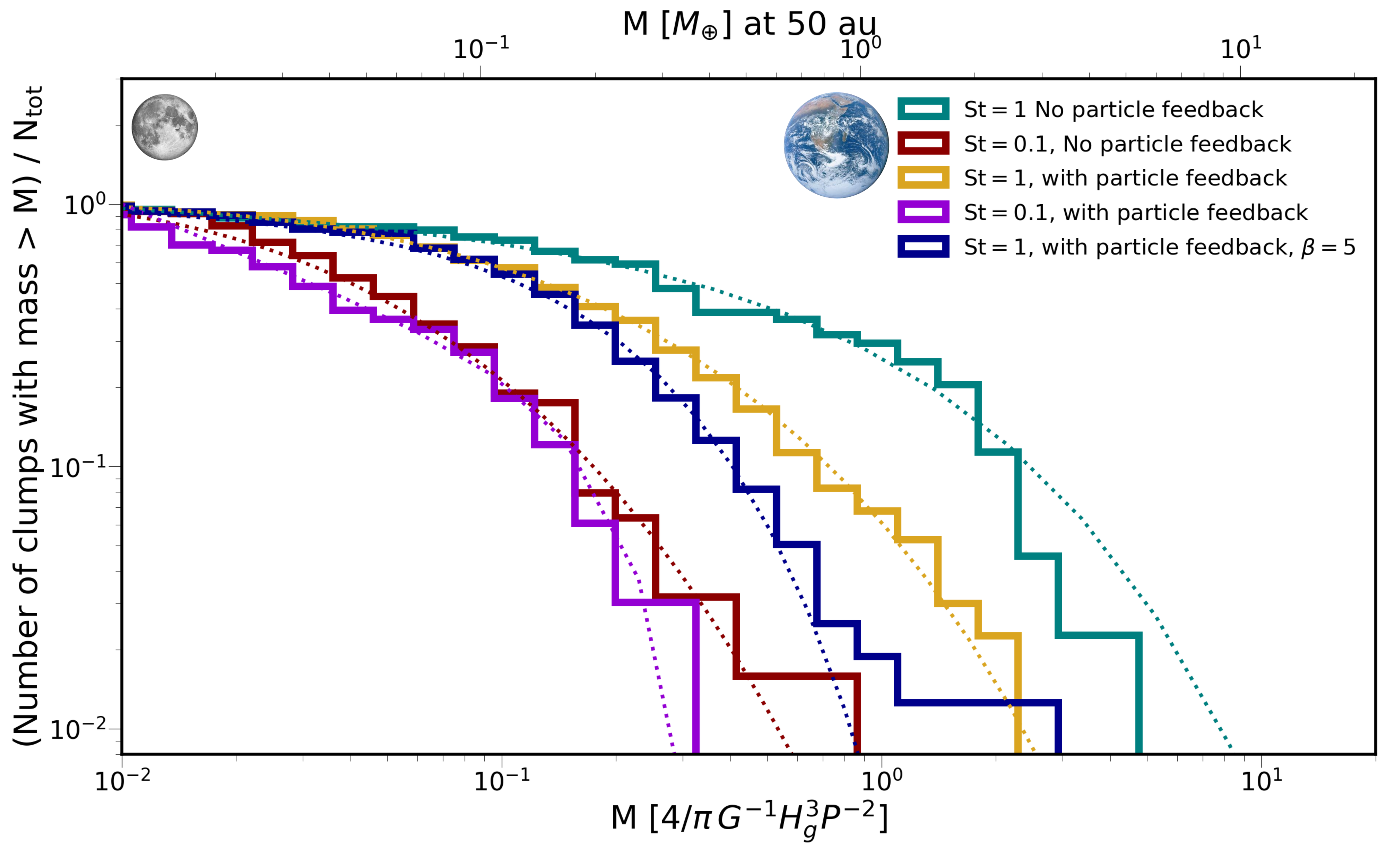
To the right we show two different views of the dense solids that form in our simulations. The top figure shows a 3D rendering of the high-density dust features (red to yellow) along with the gas structure (blue). The most massive clumps that are roughly an Earth mass and larger are circled.



The bottom figure shows the same data as above but viewing the enhancement of the vertically-integrated dust surface density from the initial condition. Here all clumps that are dense enough to be bound have red circles which are approximately the size of the Hill radius of the clump, which is an indication of the clump size (larger Hill radius = more massive clump).

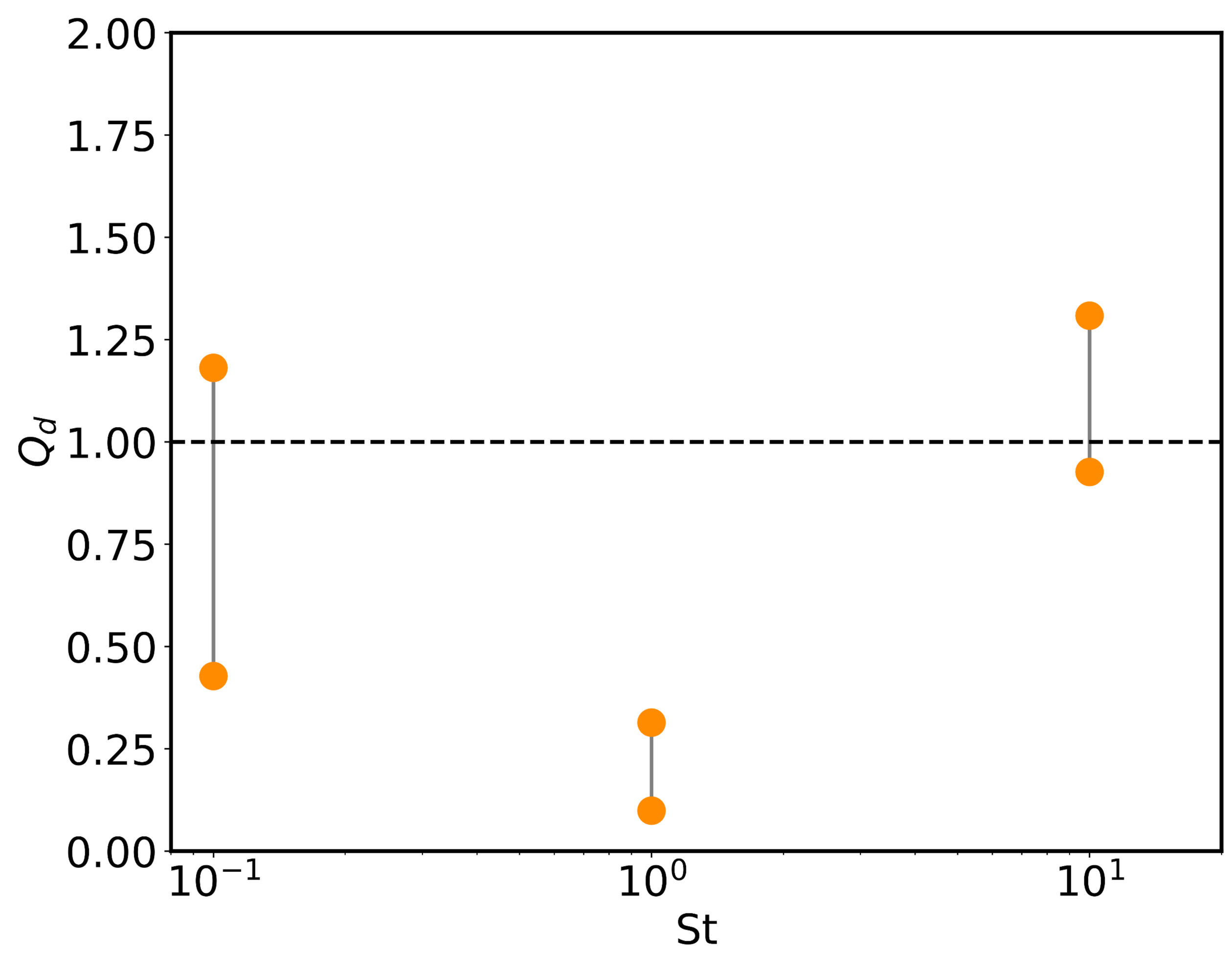


Check out the video of clumps merging and evolving here:



The mass distribution of bound clumps ranges up to a few Earth masses

The mass distribution of clumps that gravitationally collapse from the dusty filaments varies with a few key parameters. Simulations that include backreaction of the dust onto the gas produces fewer high mass objects but a larger number of smaller clumps of dust. More coupled dust (St ~ 0.1) is less likely to gravitationally collapse due to resistance from the internal turbulent diffusion of the particles and lower densities within filaments. Larger dust species (St ~ 1), which concentrates the most yields bound clouds of particles which can be over one Earth mass. No bound clumps form for even larger species (St ~ 10).



A collapse criterion for self-gravitating dust

For a few different particle sizes (St), clump formation within these simulations is consistent with a collapse criterion which considers that the turbulent diffusion δ of particles within the clump can suppress collapse [2]. If the dust concentrates above its initial metallicity Z by a factor of ϵ, this could accelerate the formation of large solid bodies that are the seeds of giant planets on wide orbits.

$$Q_d = \frac{3}{2}\frac{Q}{\epsilon Z}\sqrt{\frac{\delta}{\mathrm{St}}} < 1$$

References and Further Details

1. Baehr, H., Zhu, Z. and Yang, C.-C., "Direct Formation of Planetary Embryos in Self-Gravitating Disks", ApJ submitted, arXiv:2204.13310
2. Gerbig, K., Murray-Clay, R., Klahr, H., Baehr, H., "Requirements for Gravitational Collapse in Planetesimal Formation—The Impact of Scales Set by Kelvin-Helmholtz and Nonlinear Streaming Instability", 2020, ApJ, 895, 91
3. Gammie, C. F., "Nonlinear outcome of gravitational instability in cooling, gaseous disks", ApJ, 2001, 553, 174
4. Gibbons, P., Mamatsashvili, G., Rice, W. K. M., "Planetesimal formation in self-gravitating discs - the effects of particle self-gravity and back-reaction", MNRAS, 2014, 442, 361

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