A Closer Look at the Erosion Barrier in Protoplanetary Discs

Marco Agolzer[1], Sebastiaan Krijt[1]
[1]University of Exeter

Context

The first step of planet formation in the core accretion paradigm involves pair-wise growth of (sub)microscopic dust grains through a process known as dust coagulation [1].

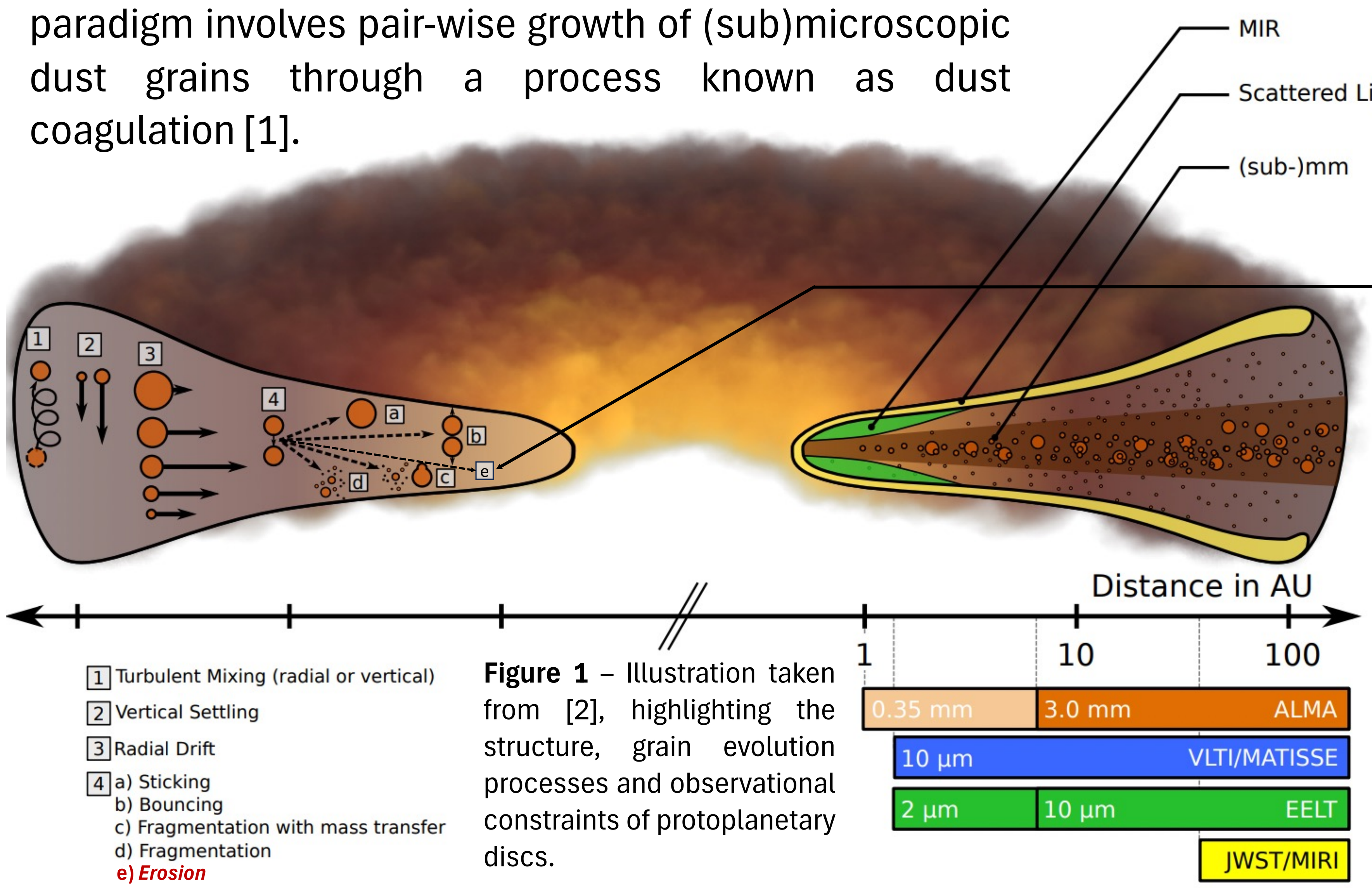


Figure 1 – Illustration taken from [2], highlighting the structure, grain evolution processes and observational constraints of protoplanetary discs.

There are several barriers preventing the resulting mm- and cm-sized "pebbles" from growing further:

- ***Fragmentation*** – Relative velocity of like-sized pebbles ($0.1 < \frac{m_1}{m_2} < 1$) increases as they grow, and they disintegrate during collisions [3].
- ***Drift*** – Pebbles are removed from certain disc regions by radial drift faster than they can grow/replenish [4].
- ***Erosion*** – Mass-loss of larger dust grains resulting from frequent high-velocity impacts of small impactors ($\frac{m_{target}}{m_{impactor}} > 10$).

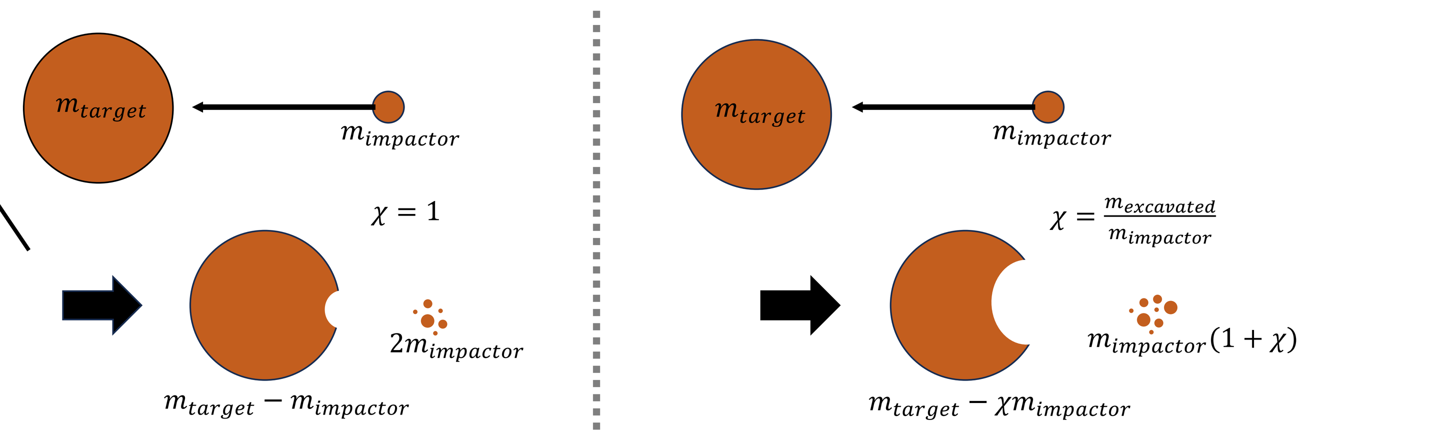


Figure 2 – Diagrams illustrating the effects of erosion (with different efficiencies χ) on dust grains.

- **a (left)** – Impactors excavate at most exactly the equivalent of their own mass during collisions.
- **b (right)** – Experimental work has shown erosion can have efficiencies as large as ~10-100 [5].
- χ is referred to as both 'erosion efficiency' or excavated mass ratio.

Motivation

Current simulations of dust coagulation highlight mostly the growth barriers associated with fragmentation and radial drift, but erosion can play a major role.

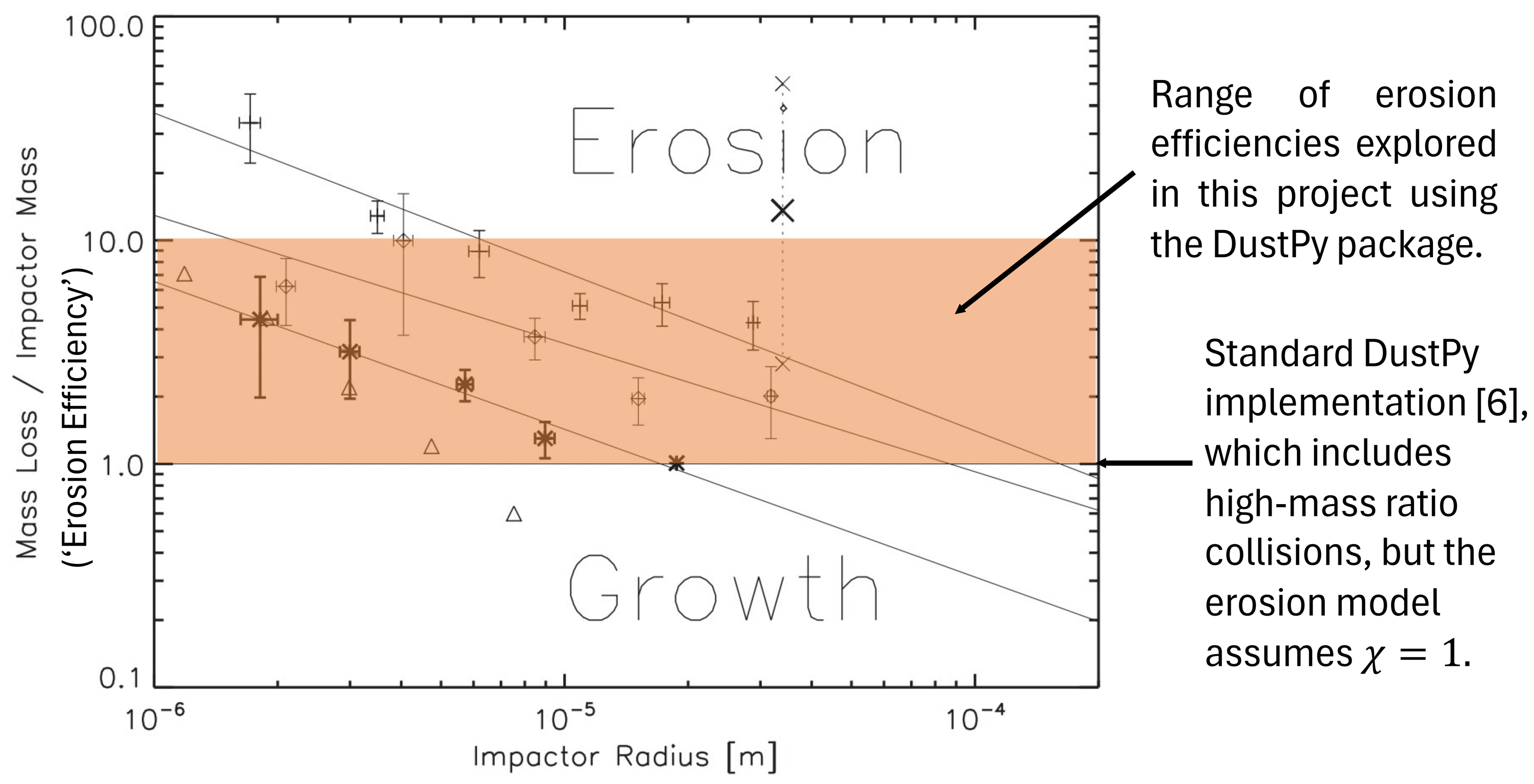


Figure 3 – Experimental results from [5] showing erosion efficiencies of ~10-100 (i.e. erosion could halt local dust coagulation before any other barriers).

Method

We run a suite of DustPy simulations of protoplanetary discs ($0.1-1\ Myr$), exploring different values of several parameters to shed light on how erosion impacts maximum particle size and the shape of the dust size distribution.

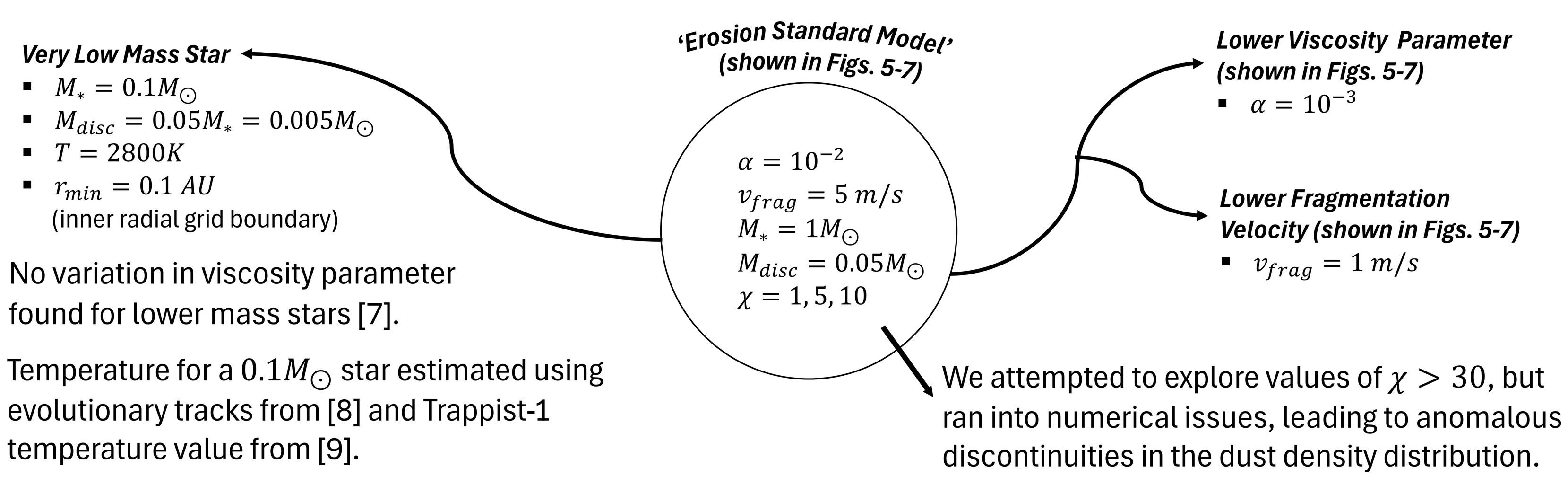


Figure 4 – We define an 'Erosion Standard Model' separate to the default DustPy values, from which we can vary the necessary parameters as desired.

Results

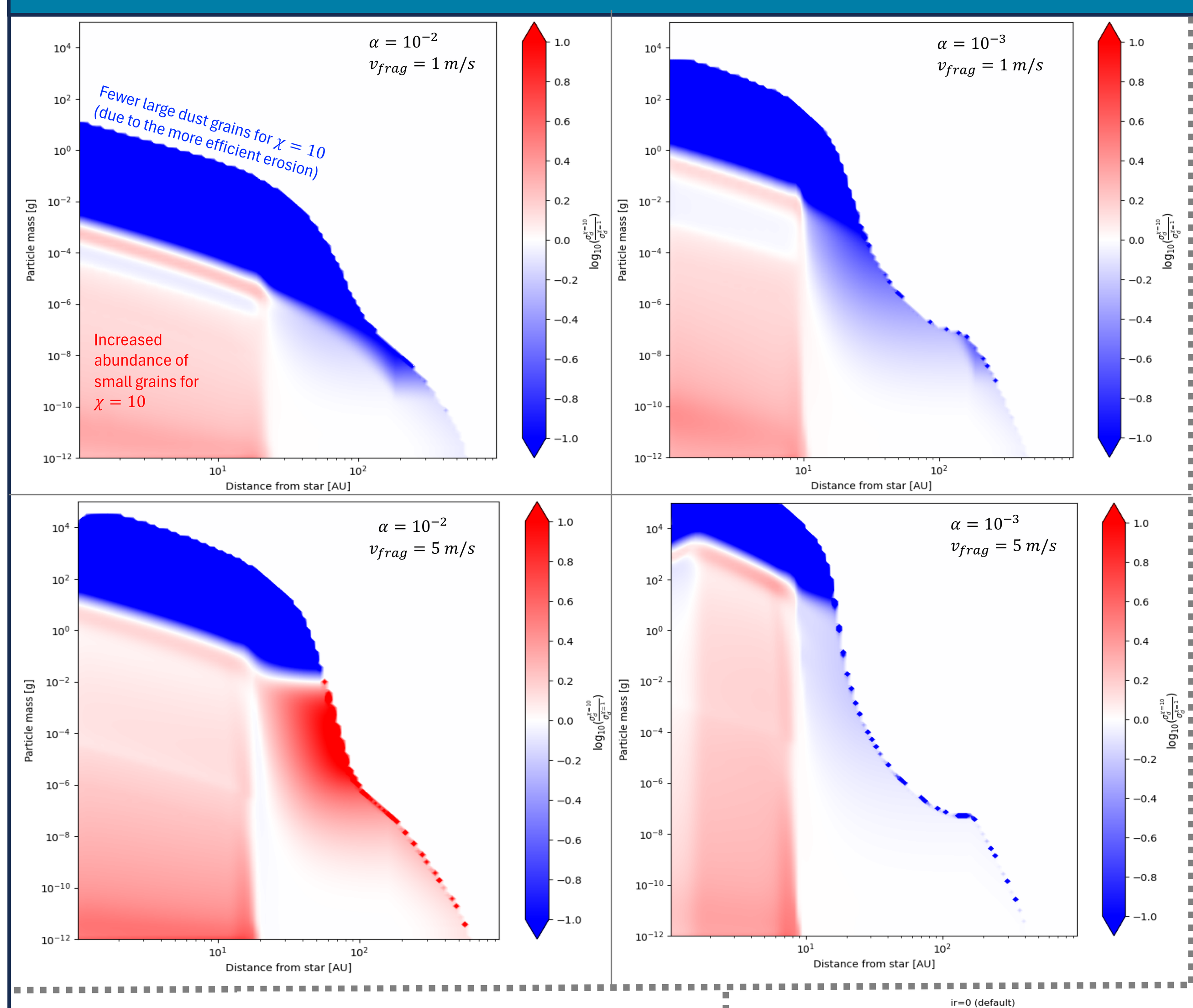


Figure 5 (left) – Ratio of dust density distributions ($\chi = 10$ & $\chi = 1$).

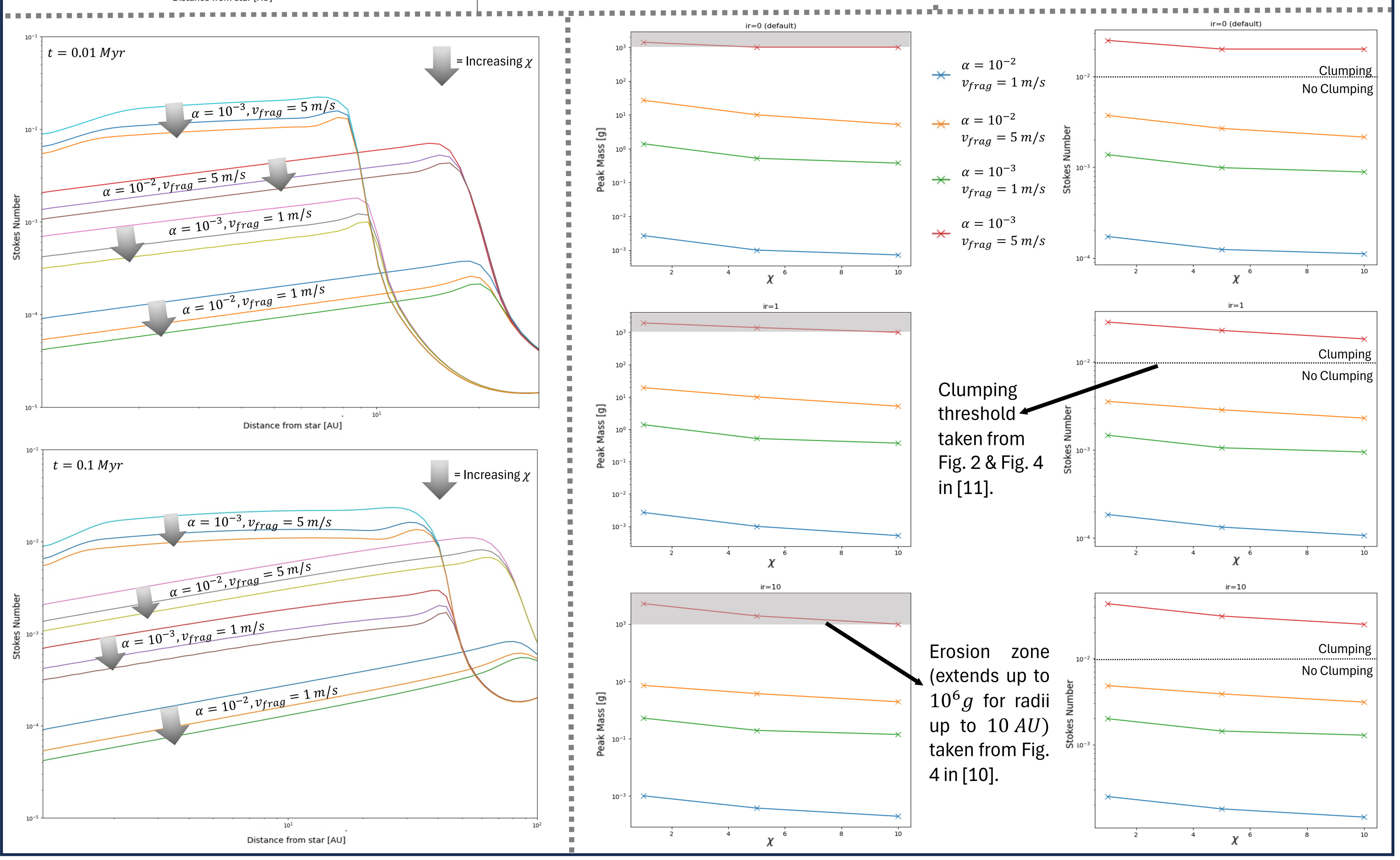
- Disc after $0.01\ Myr$ shown; trends continue for discs after 0.1-$1\ Myr$.

Figure 6 (bottom left) – Radial profile for weighted arithmetic mean Stokes numbers with varying χ, α and v_{frag}

- **a, b** (top to bottom) – Discs after 0.01 & $0.1\ Myr$ shown; trend continues for disc after $1\ Myr$.

Figure 7 (bottom right) – Peak dust grain mass **(left)** and Stokes number **(right)** as a function of χ at different distances (in AU) from star.

- Disc after $0.01\ Myr$ shown; trends continue for disks after 0.1-$1\ Myr$.
- $ir = 50$ does not yield relevant results as the disc does not fully develop there within these timescales.



Key Conclusions & Future Steps

Increasing χ from 1 to 10:

- Reduces peak mass of dust grains.
- Reduces peak and weighted arithmetic mean Stokes numbers of the dust grains.
- Increases amount of small grains present in the size distribution.

Decreasing v_{frag} :

- Decreases peak mass by a factor of $\sim 10^3$ and the Stokes numbers by a factor of ~ 20.

Decreasing α:

- Increases peak mass by a factor of $\sim 10^3$ and the Stokes numbers by a factor > 10.

Results look similar for protoplanetary discs around low mass stars (not presented in the section above).

Experimental results from [5] approximated the excavated mass ratio (seen in Fig. 3) as being described by:

$$f_{excav} = \left(\frac{r_{impactor}}{2 \cdot 10^{-5}\ m}\right)^{-0.62} \left(\frac{v_{impactor}}{15\ m/s}\right)$$

Future work should investigate non-constant erosion efficiency by implementing f_{excav} into the DustPy code.

References

[1] – Armitage, P. J., *Astrophysics of Planet Formation*, Cambridge University Press, 2010, p. 144
[2] – Testi, L. *et al*, "Dust Evolution in Protoplanetary Disks". In *Protostars and Planets VI*, Tucson: University of Arizona Press, 2014
[3] – Birnstiel, T. *et al*, 2011, A&A, 525, A11
[4] – Birnstiel, T. *et al*, 2012, A&A, 539, A148
[5] – Schräpler, R. *et al*, 2018, *ApJ*, **853**, 74
[6] – Stammler, S.M. & Birnstiel, T., 2022, ApJ, **935**, 35
[7] – Mulders, G.D. & Dominik, C., 2012, A&A, 539, A9
[8] – Pinilla, P., 2022, *Eur. Phys. J. Plus.* **137**, 1206
[9] – Agol, E. *et al*, 2021, *Planet. Sci. J.*, **2**, 1
[10] – Xu, W., Armitage, P.J., 2023, *ApJ.*, **946**, 94
[11] – Li, R. & Youdin, A. N., 2021, *ApJ*, **919**, 107

Acknowledgement

The work presented here was supported by an Undergraduate Summer Bursary provided by the Royal Astronomical Society.

Contact
Marco Agolzer
University of Exeter
ma1109@exeter.ac.uk