Modelling the disks in AGE-PRO with substructures

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Abstract

ALMA large program AGE-PRO targets 30 disks from three distinct regions, spanning ages from 0.1 to 10 Myr. These disks represent different evolutionary phases: the embedded disk phase, middle age, and the final stages of disk evolution. The visibilities have been fitted using FRANKENSTEIN[1], revealing that approximately half of these disks exhibit substructures. By employing a novel approach AGE-PRO has obtained well-constrained gas disk masses. This, along with follow-up observations in Bands 5 and 3, high angular resolution studies, and JWST observations that are completed or forthcoming, provides a comprehensive dataset. Together, they create an exceptional opportunity to test models with substructures, offering a unique laboratory for advancing our understanding of dust dynamics and terrestrial planet formation viability.

The disks were modelled using the dust evolution code DustPy[2]. Substructures were modelled as rings and gaps in gas surface density formed by planets embedded in the disk [3]. For each disk, we explored different values of the turbulence parameter (α) and fragmentation velocity (v_{frag}). Modelling the substructures allows us to trace the radial drift of pebbles across various disk ages. Using these dust distributions, we generated synthetic images with RADMC[6] and compared them with ALMA observations. By comparing the synthetic images with ALMA data, we aim to constrain α and v_{frag}.

Example: Disk in Upp Sco

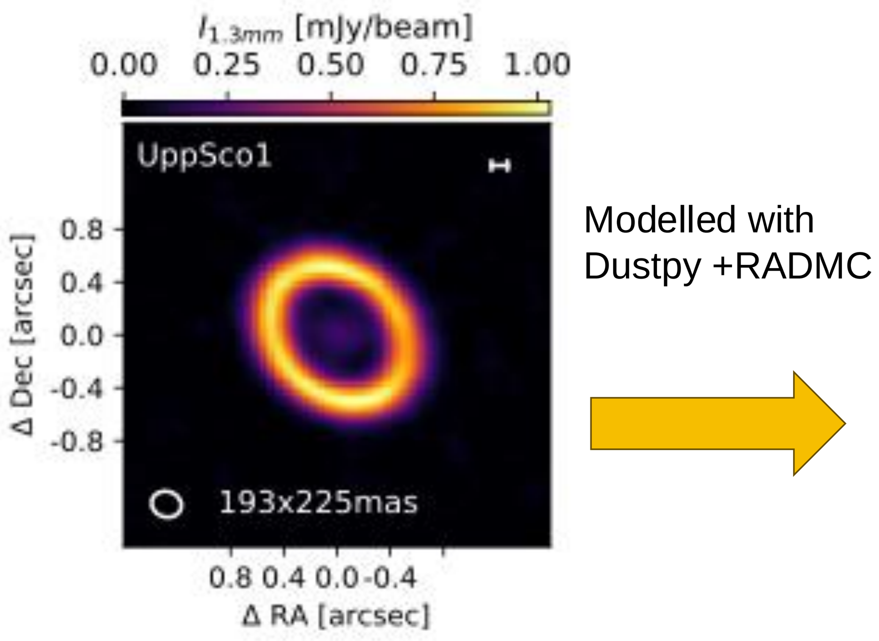

Fig. 1. ALMA observation of Upp_Sco 1 at 1.3mm, a transitional disk with a planet candidate[4]. Courtesy AGE-PRO collaboration.

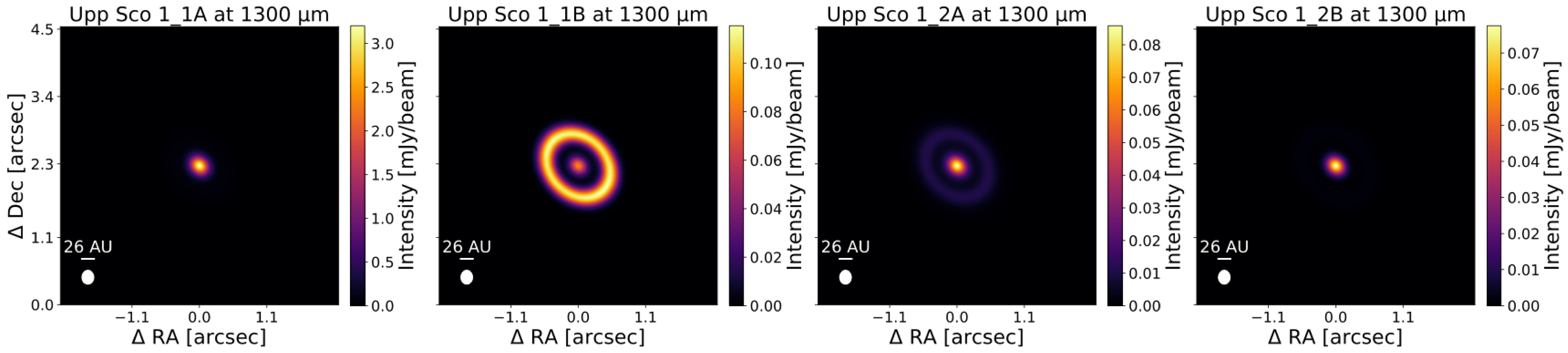

Fig. 2. The RADMC images of the different dustpy models of Upper Scorpius 1. Only configuration 1B and 2A replicates the large outer ring. The best match is 1B, which has low v_{frag} and α.

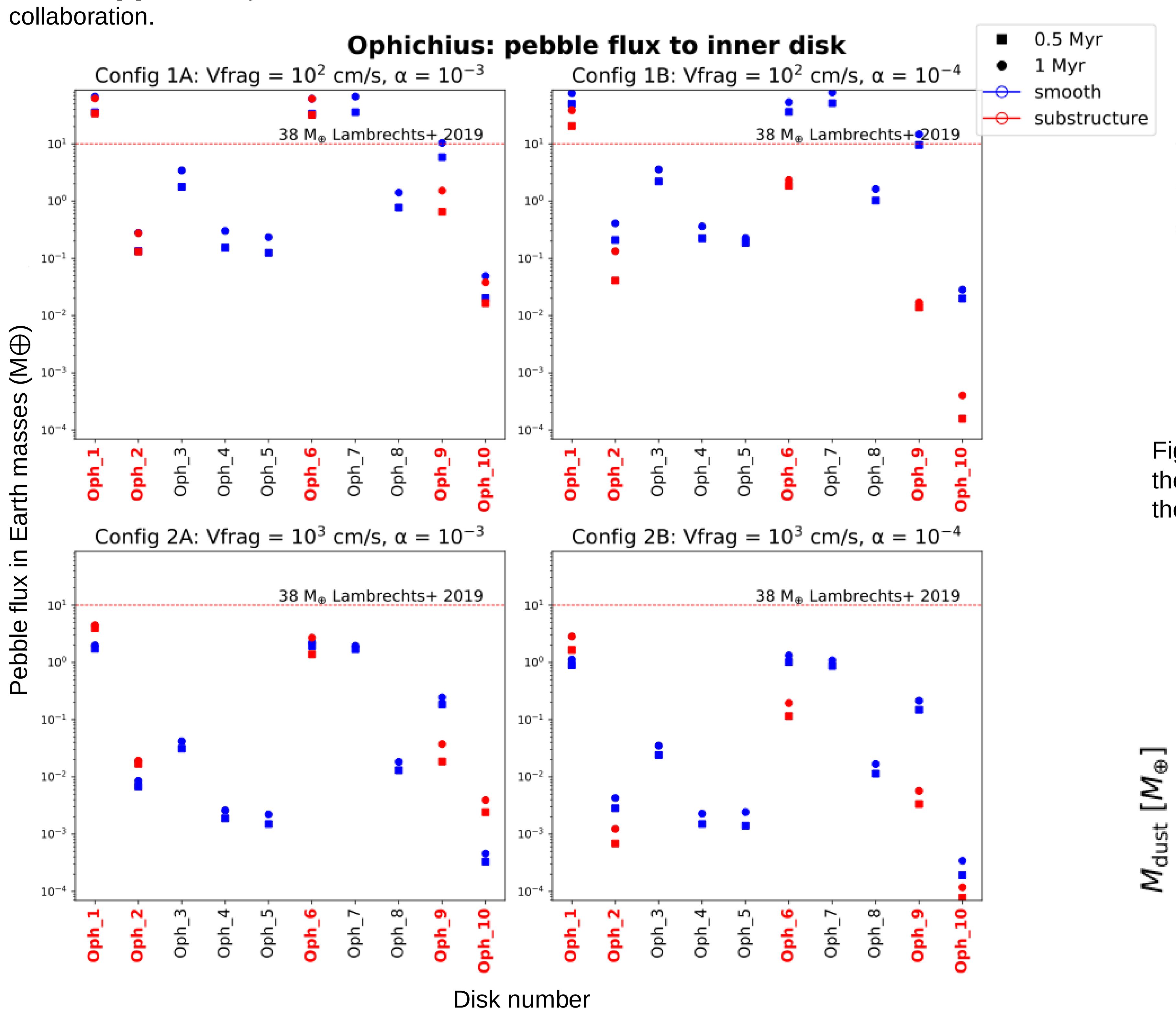

Fig. 4. Cumulative pebble flux of the young disks (Ophichius) into the inner disk (5AU), where terrestrial planets could form. The horizontal dashed line is the threshold for how much flux is required to form mars sized planets. The blue color denotes a smooth disk model while red are the substructured disks.

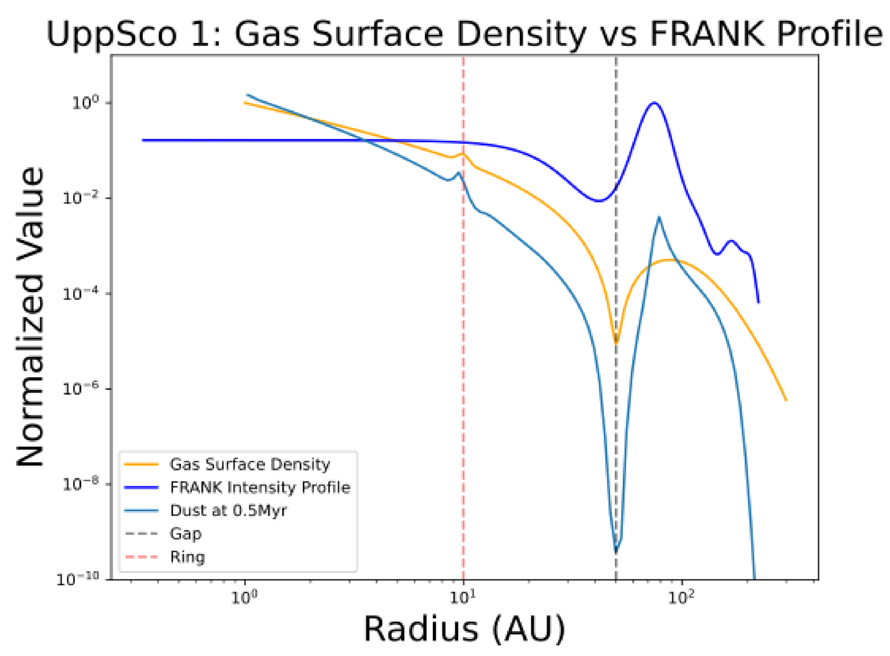

Fig. 3. We modelled the disk substructure as a perturbation in the gas surface density, matching the FRANK profile. We plot the resulting dust surface density from the dustpy simulation.

Configuration	v_{frag}	α
1A	1m/s	10^{-3}
1B	1m/s	10^{-4}
2A	10m/s	10^{-3}
2B	10m/s	10^{-4}

Table 1. Configurations for the 4 different disk models.

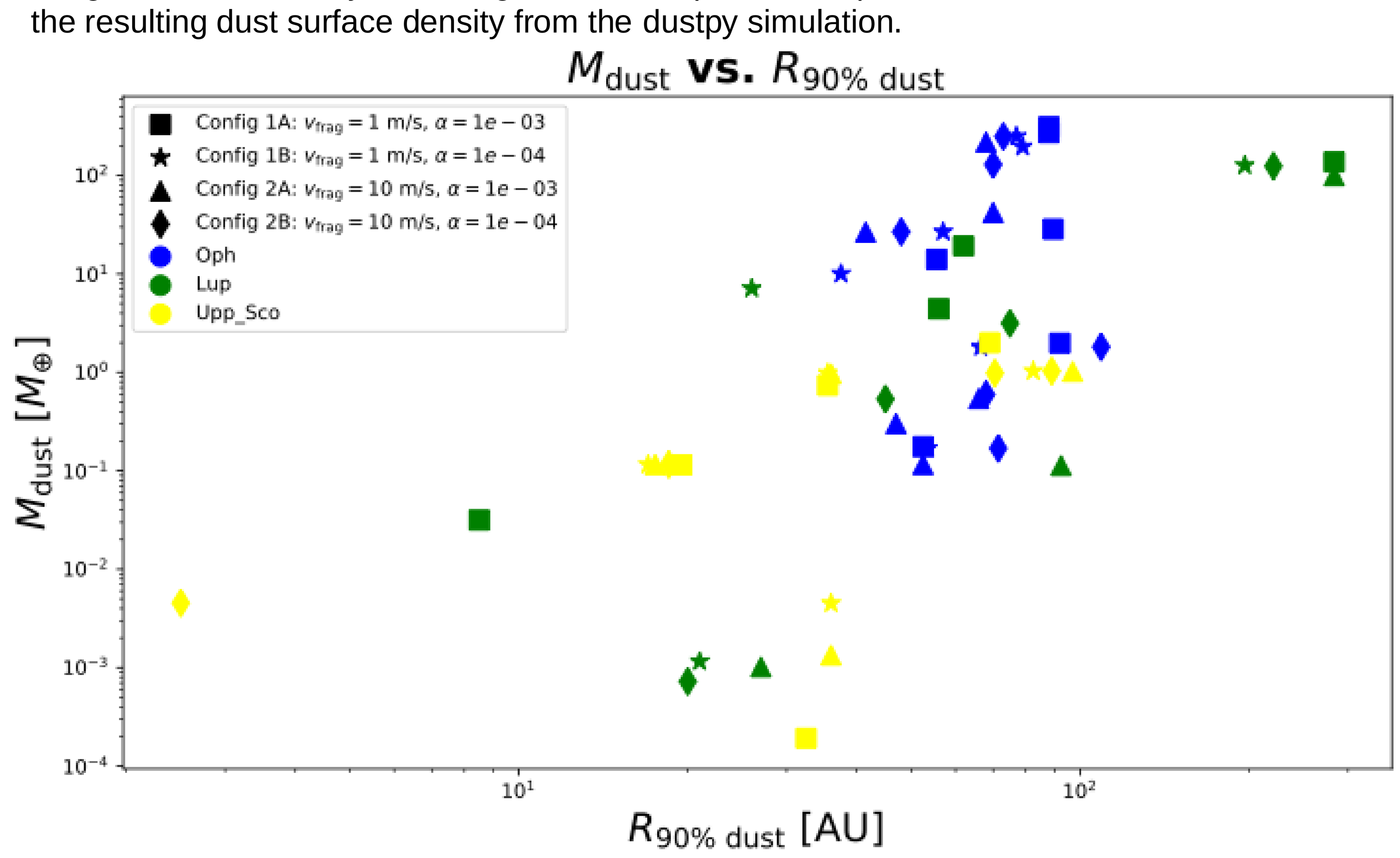

Fig. 5. Shows the relationship between total dust mass (Mdust) and the radius enclosing 90% of the dust mass (R90%) for disks in the Oph, Lup, and Upp Sco regions.

Discussion

We modelled 13 disks with substructures. For the young disks (Ophichius) pebble flux is around 1-100 Earth masses (M⊕). According to pebble accretion models, (e.g., [5]), such flux would only allow the formation of Mars-sized planets. No specific values of fragmentation velocity (v_{frag}) and turbulence parameter (α) seem to be universally favored across all disks. We observe a steady decrease in pebble flux in the Lupus and Upper Scorpius regions, which correspond to the middle and later stages of disk evolution.

Future goals

Upcoming JWST observations (Zhang et al., in prep) reveal the presence of cold water within 1-10 AU in Ophiuchus. We will use our models to interpret these observations, to assess the efficiency of water and dust delivery into the terrestrial-planet-forming regions. This will have implications for understanding how substructures influence the delivery of dust and volatiles to regions where terrestrial planets form.

We will leverage our dust distribution to obtain new disk gas mass estimations accounting substructures using thermochemical models, crucially providing the community with correction factors (if needed) in the case of disks with substructures.

References:

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[4]Sierra, Anibal, et al. "Hints of planet formation signatures in a large-cavity disk studied in the AGE-PRO ALMA Large Program." arXiv preprint arXiv:2407.16651 (2024).

[5] Lambrechts, Michiel, et al. "Formation of planetary systems by pebble accretion and migration-How the radial pebble flux determines a terrestrial-planet or super-Earth growth mode." Astronomy & Astrophysics 627 (2019): A83.