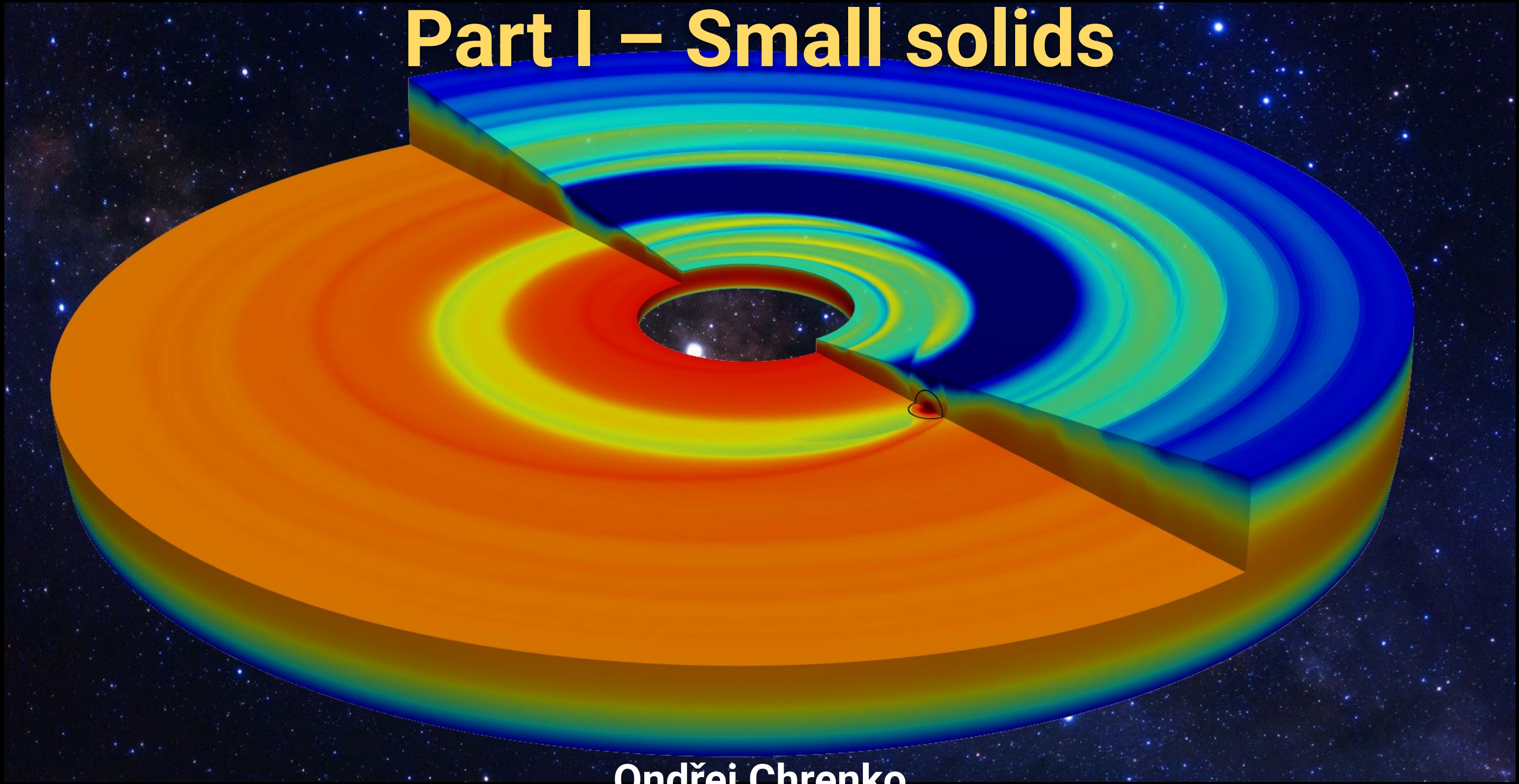
Exoplanets II – Planet formation
Part I – Small solids



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2026

Outline

Lecture plan

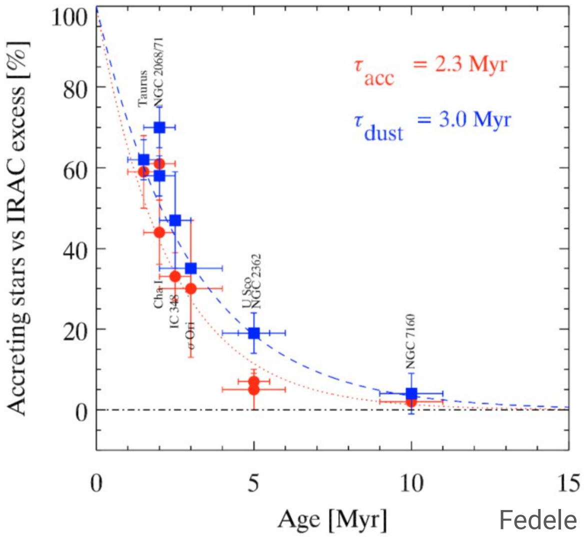
- 1–2: Small solids in protoplanetary disks
- 3: Accretion processes
- 4–6: Planet-disk interactions
- (7: Formation scenarios of planetary systems)

Today

- The role of dust; gas disk stratification & rotation; dynamics of dust grains (drift and settling)

Planet-forming environment

- Protoplanetary accretion disks: by-products of collapsing molecular clouds during star formation (ang. mom. conserved)
- If derived from ISM: 1% of disk mass in sub-micron dust grains
- Lifetime rather short!

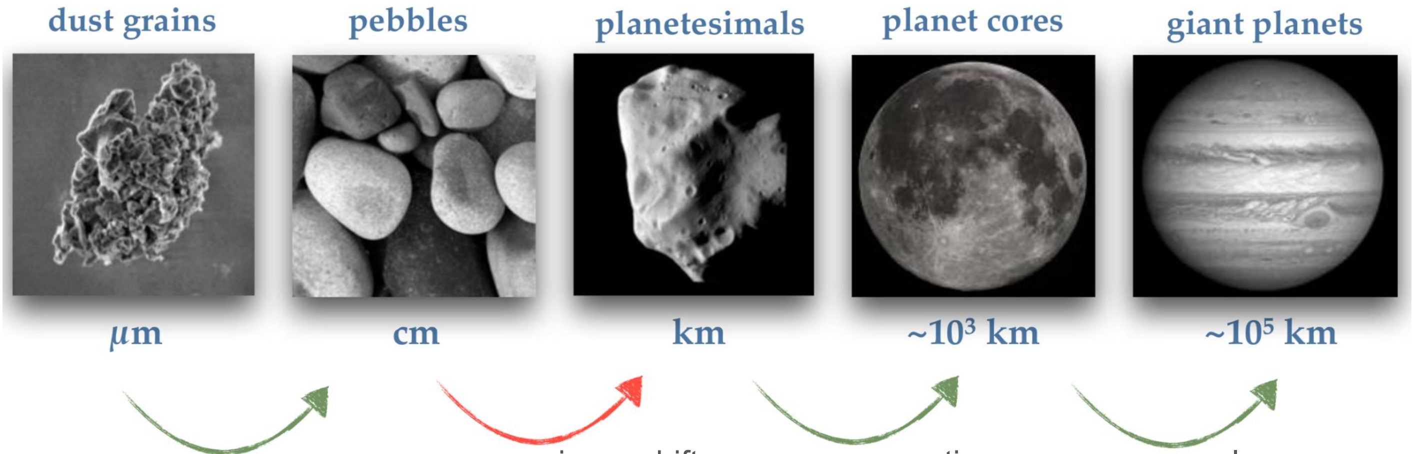


Fedele et al. (2010)

movie credit: M. Bate

A not-so-long but winding road to planets

- Planets form within the disk lifetime (gas giants; sub-Neptunes with primordial H/He envelopes; observable protoplanets), despite many barriers:



- drift
- fragmentation
- bouncing

- maximum drift
- how to trigger grav. collapse of clumps

- accretion not very efficient

- envelope mass vs core mass

- Note: order-of-magnitude differences in terms of mass even more pronounced!
- Don't forget: solar-system terrestrial planets; post-disk evolution (outgassing, atmospheric loss, …)

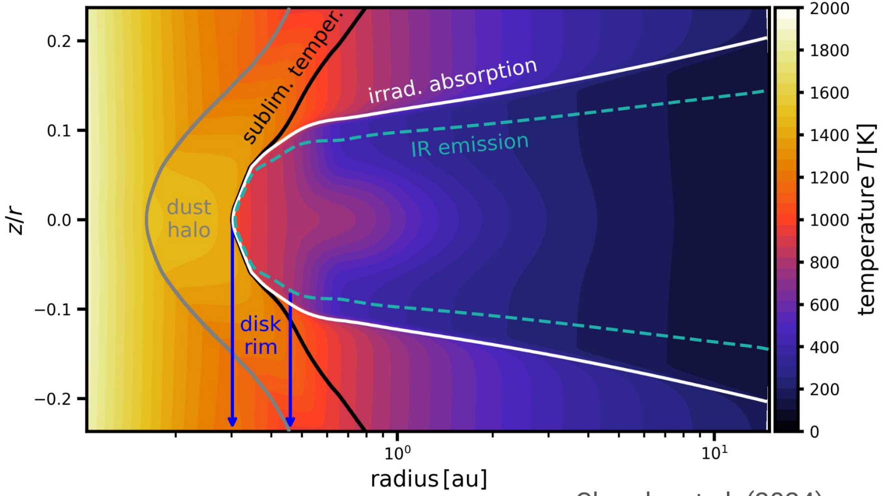
Dust grains are not just building blocks

RADIATION TRANSFER

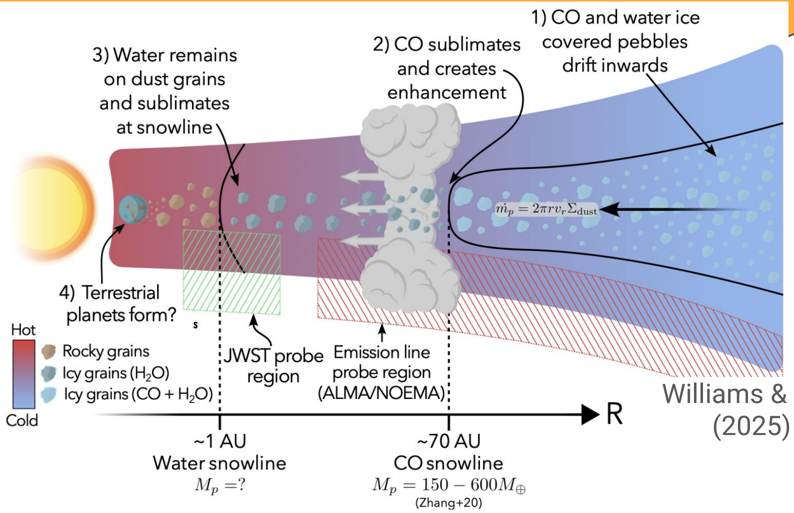
- grains dominate continuum opacity
- determine where starlight is absorbed/scattered
- disks' thermal emission & scattered light
- disk temperature -> hydrostatic structure
- cooling rate -> hydrodynamic processes

CHEMISTRY

- UV shielding (e.g. Jonkheid et al. 2004)
- solid surface acts as catalyst on which complex reactions are enabled (Garrod & Herbst 2006)
- `conveyor belt' for volatile redistribution (e.g. Krijt et al. 2016)



Chrenko et al. (2024)



Williams & Krijt (2025)

Dust grains are not just building blocks

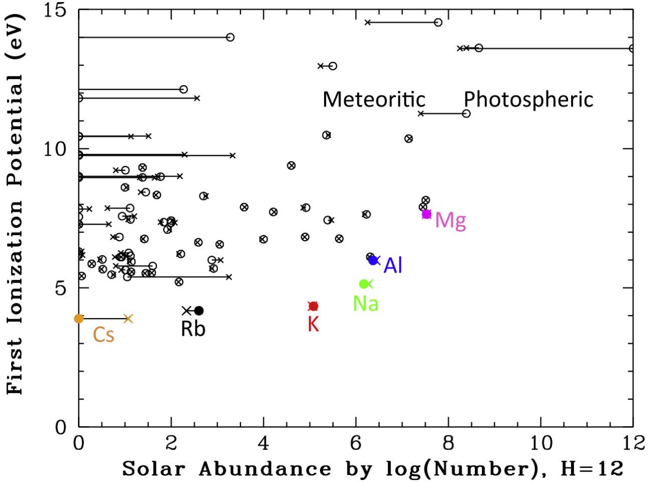
Pure-gas ionization

- mostly thermal (T>1000 K) as high-energy radiation cannot easily penetrate disks
- collisional ionization of gas-phase K atoms

$$H_2 + K^0 \rightarrow H_2 + K^+ + e^-$$

being in detailed balance with gas-phase recombination

$$H_2 + K^+ + e^- \rightarrow H_2 + K^0$$



Asplund et al. (2005), Desch & Turner (2015)

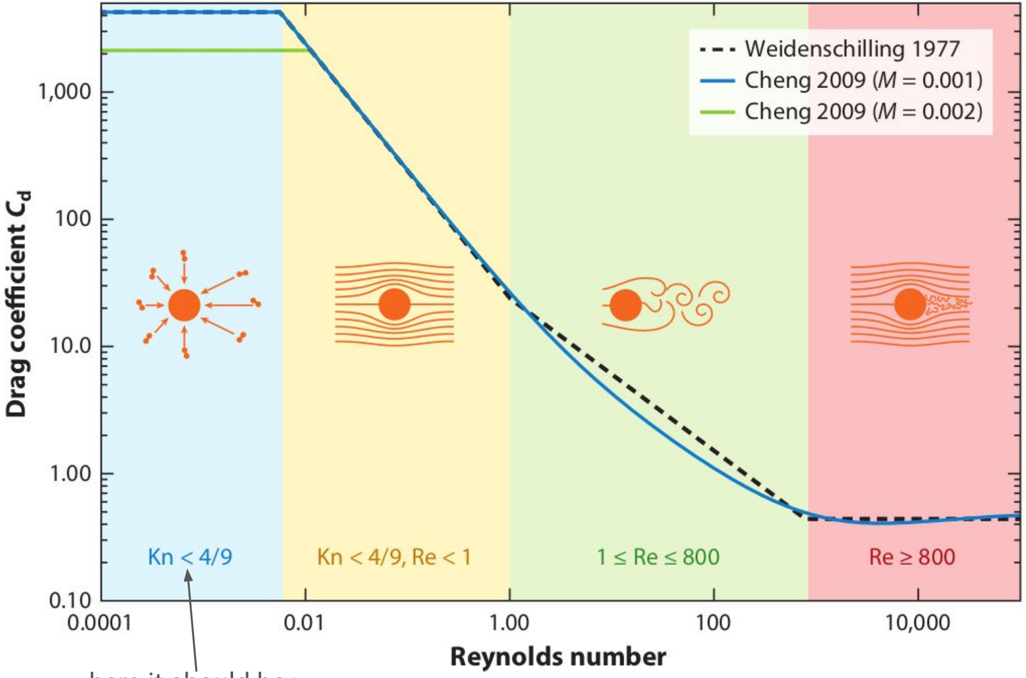
NON-LTE DISK IONIZATION

- grain surfaces mop up (adsorb) charges, those quantum-tunnel across the surface, recombine, neutral K can leave the grain (Sano et al. 2000)
- thermionic emission: inverse process, grains emit electrons/ions when heated (T > 500 K; Desch & Turner 2015) and restore neutrality in collisions with neutral atoms
- instead of the FIP, the work function of grains becomes important

Note for dust growth: grain charging can prevent sticking

Gas background & dust dynamics: The basics

- Dust grains important in many contexts => let's discuss their dynamics on blackboard
- Governing role: aerodynamic friction forces (drag)

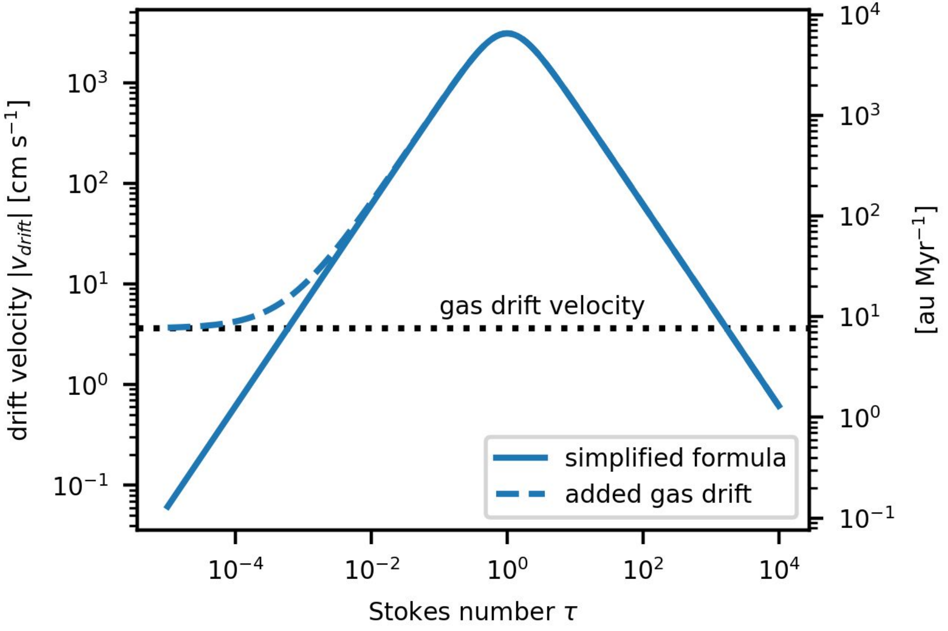


Birnstiel (2024)

here it should be >

Implications of dust drift

- Continuous mass flux of small solids towards the star occurs in smooth power-law disks
- Dust drift >> gas accretion
- Drift barrier of dust growth (St ~ size): as dust grows to pebbles, the drift becomes so efficient that it removes pebbles before they can grow further

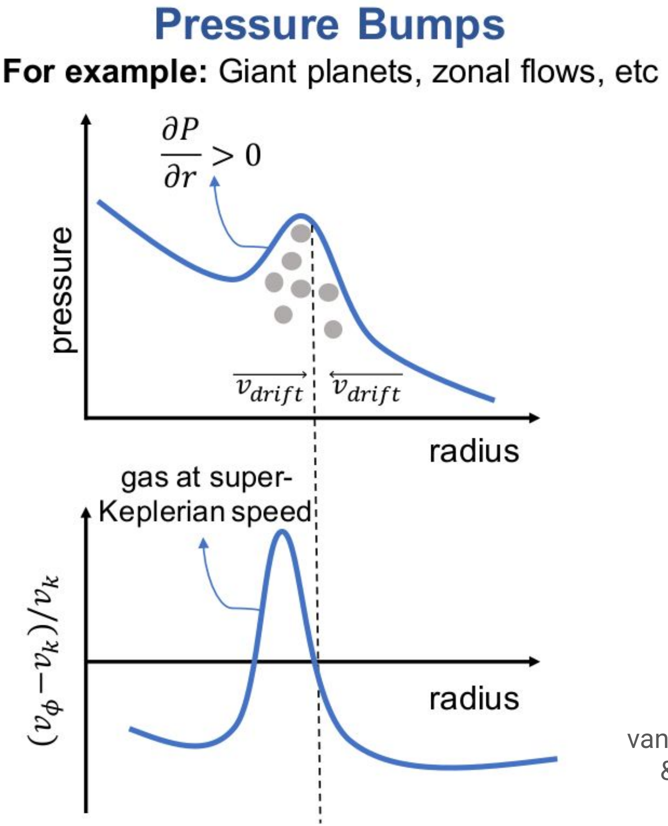


Disk model in the figure based on Brauer et al. (2008):

- $\alpha = 10^{-3}$
- surface density ~$r^{-0.8}$, temperature ~$r^{-0.5}$
- ηv_K independent of r in this example

Implications of dust drift

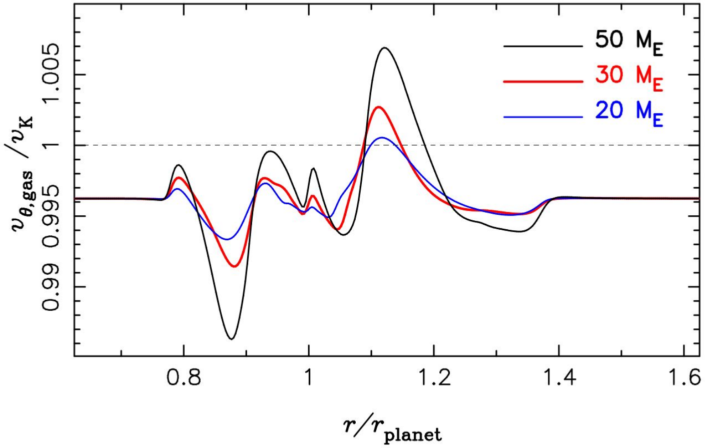
- If disks become structured and develop pressure inversions, the gas rotation becomes locally super-Keplerian
- Dust drifts outwards in such regions
- Outward/inward drift region inevitably separated by a dust-accumulating radius
- ! In viscously evolving disks, Stokes numbers < α still cross the bump



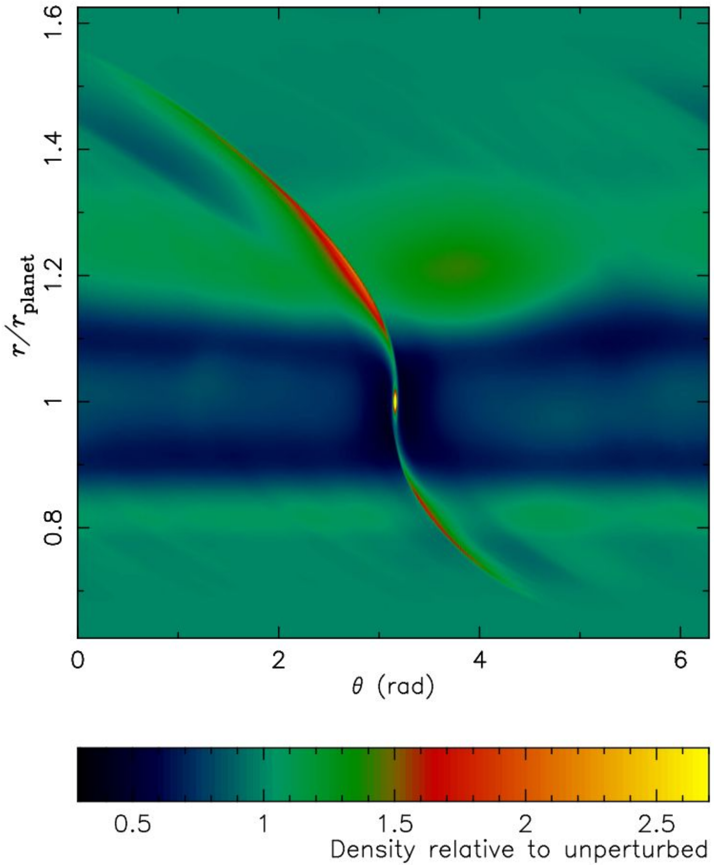
van der Marel & Pinilla (2024)

(Some) possibilities of forming a pressure bump

- Growing planets modifying the gas disk structure and rotation



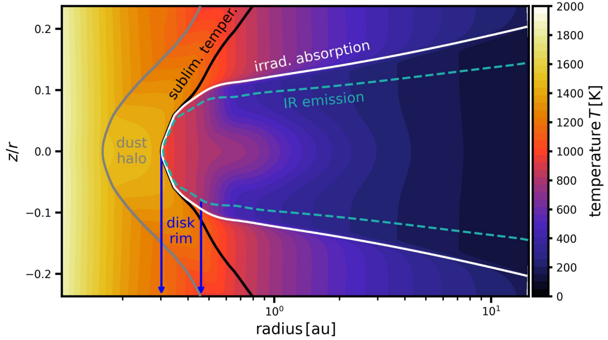
Lambrechts et al. (2014)



(Some) possibilities of forming a pressure bump

- Change in the turbulent activity -> gas surface density transition -> pressure bump
- Hypothesized at the inner disk rim

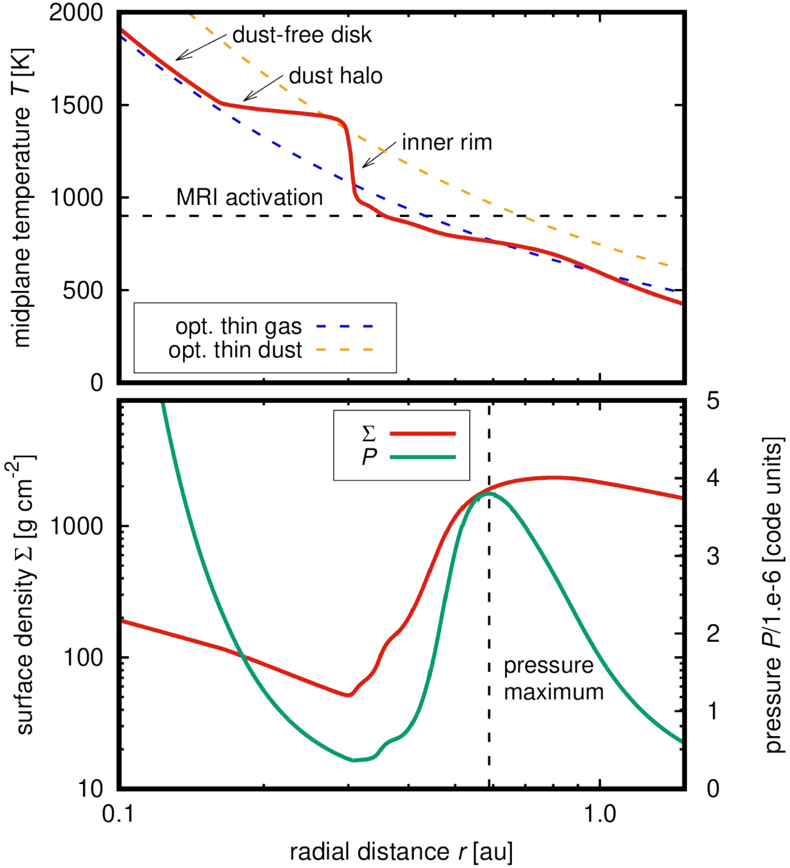
Fig. from Chrenko et al. (2024), shown previously...



$$\dot{M} = 3\pi\nu\Sigma \quad \text{and} \quad \nu = \alpha c_s^2/\Omega_K$$

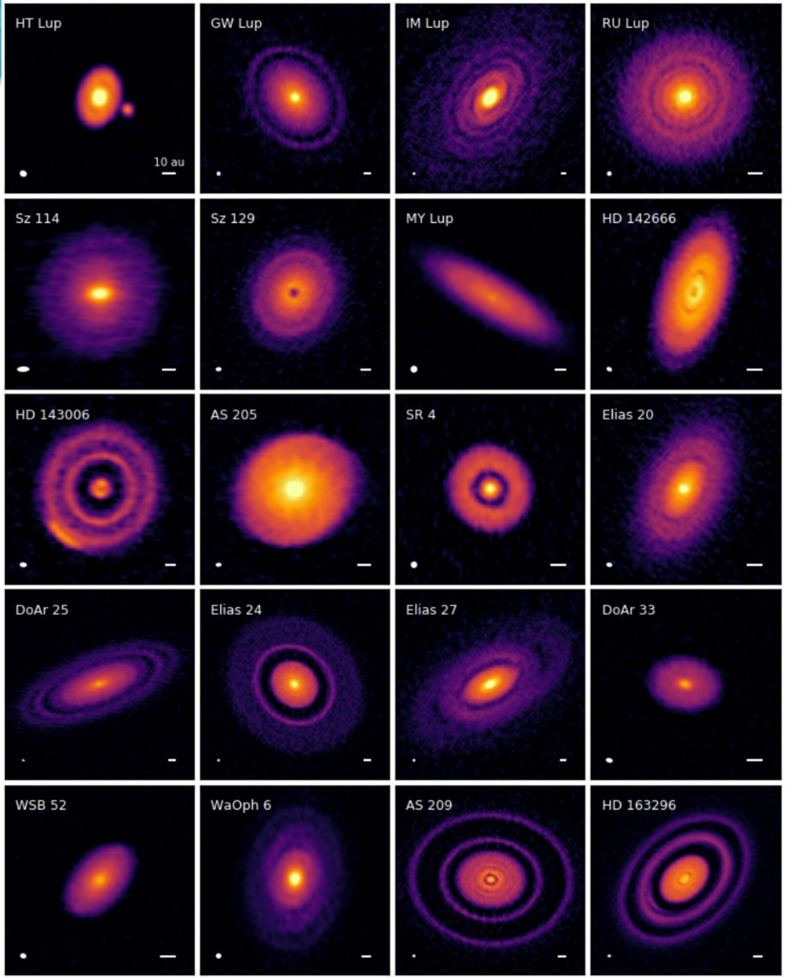
uniform

varying at T~900 K



Rings in resolved ALMA images?

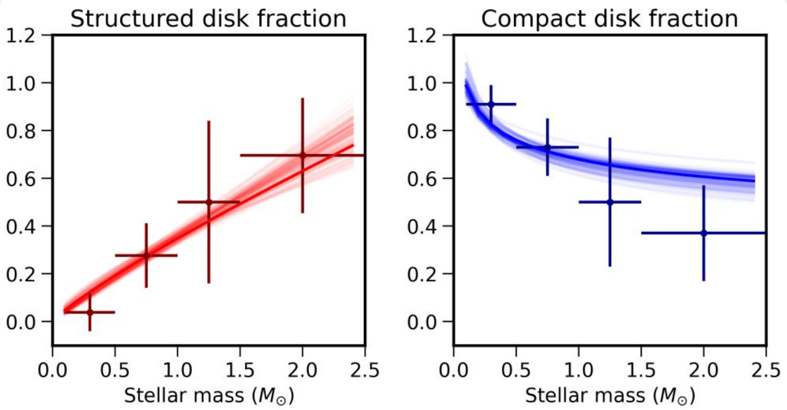
- Interpreted as pressure bumps, clear indication that dust can be protected against inward drift
- Open questions:
  - How many of them are due to planets?
  - Are they really so common?



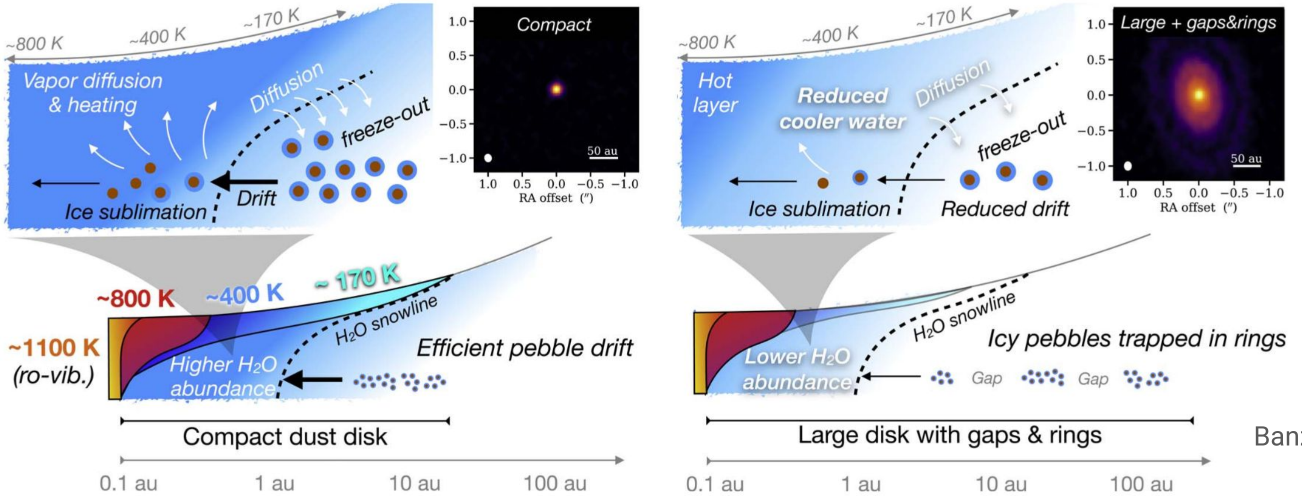
DSHARP survey, Andrews et al. (2018)

Rings in resolved ALMA images?

- Disks around low-mass stars more compact (so the dust disk has to shrink; no pressure bumps opposing this)
- H_2O content suggests efficient dust transport with no traps (sublimation -> elevated water content -> JWST spectra)



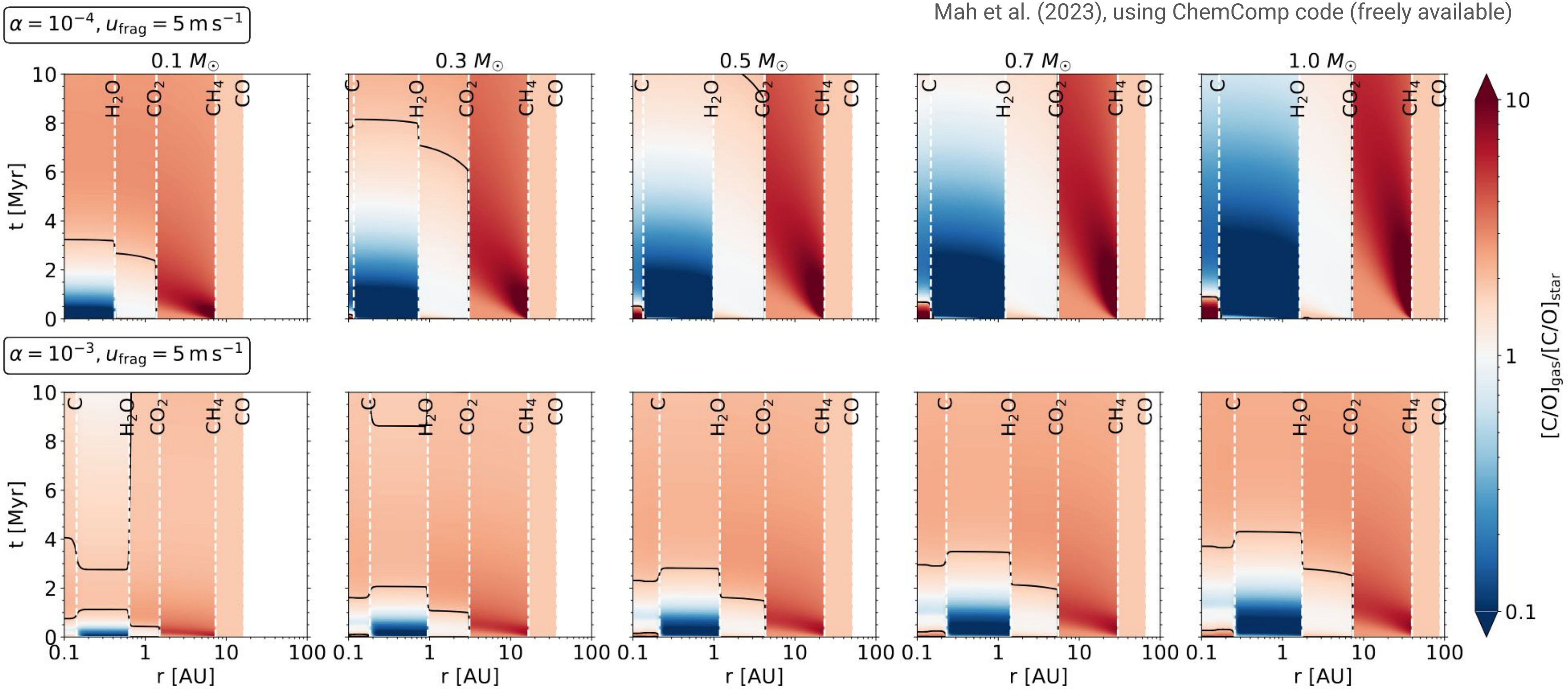
van der Marel & Pinilla (2024), based on v.d. Marel & Mulders (2021)



Banzatti et al. (2023)

C/O ratio in the inner disk

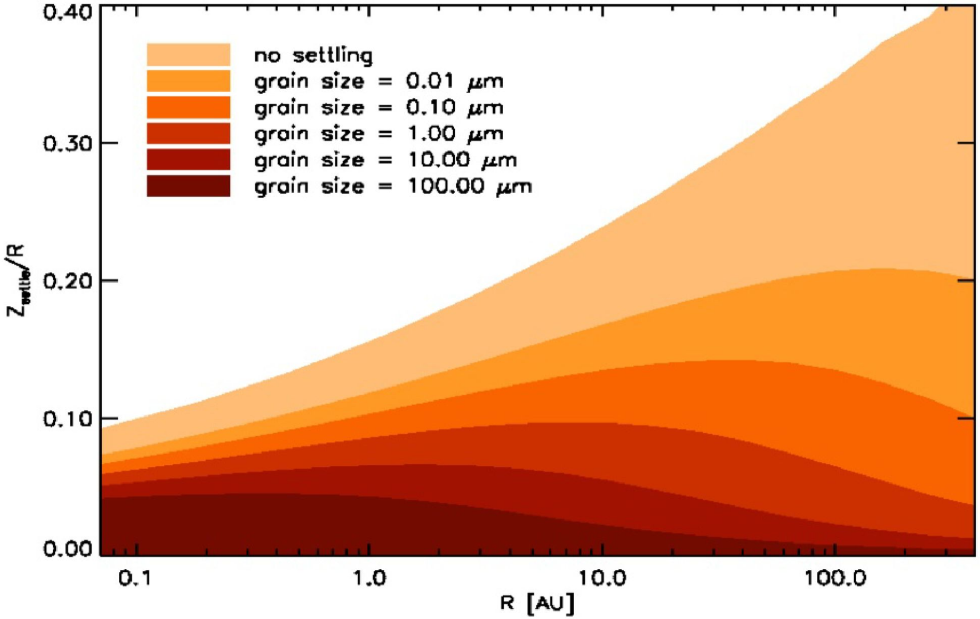
Mah et al. (2023), using ChemComp code (freely available)



Implications of dust settling

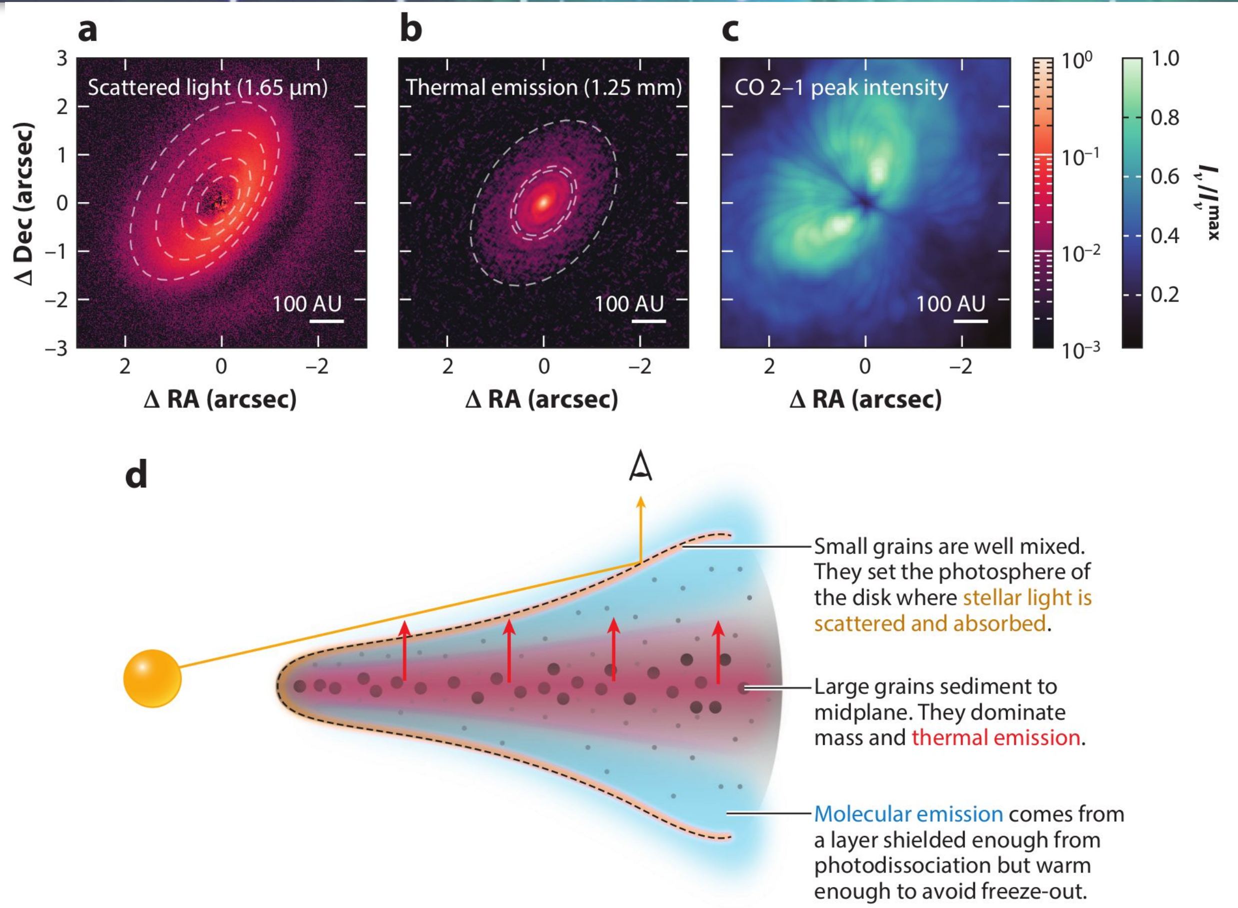
- Settling is opposed by turbulence, leading to the equilibrium scale height of dust grains (e.g. Youdin & Lithwick 2007, Dominik 2015)

$$H_{\rm dust} = H_{\rm gas}\sqrt{\frac{\alpha}{\alpha+\tau}}$$



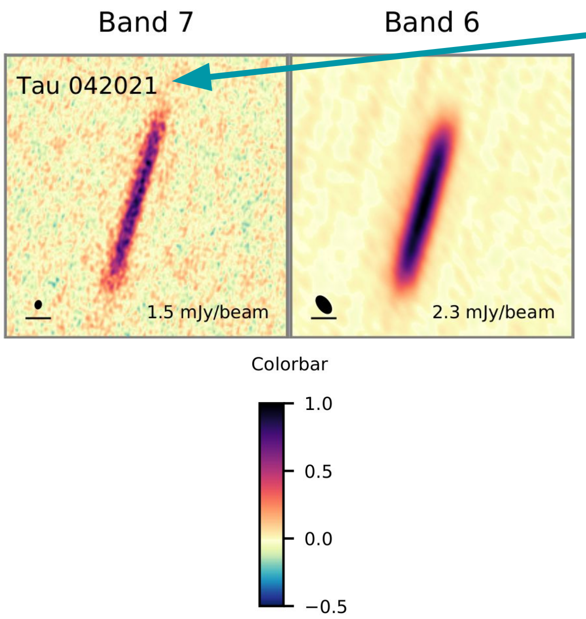
Dominik (2015)

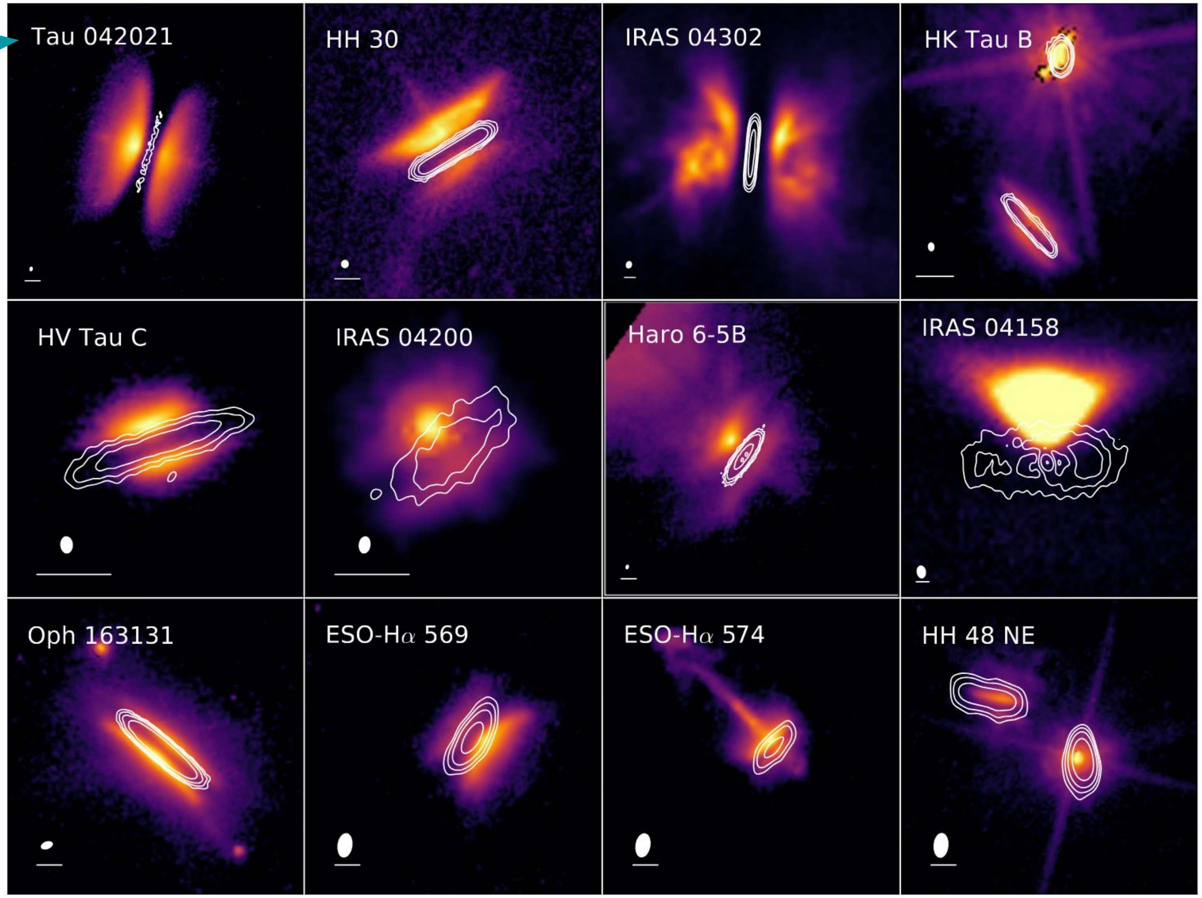
Implications of dust settling



IM Lupi (Avenhaus+18, Andrews+18, Law+21, Birnstiel 24)

Edge-on disks

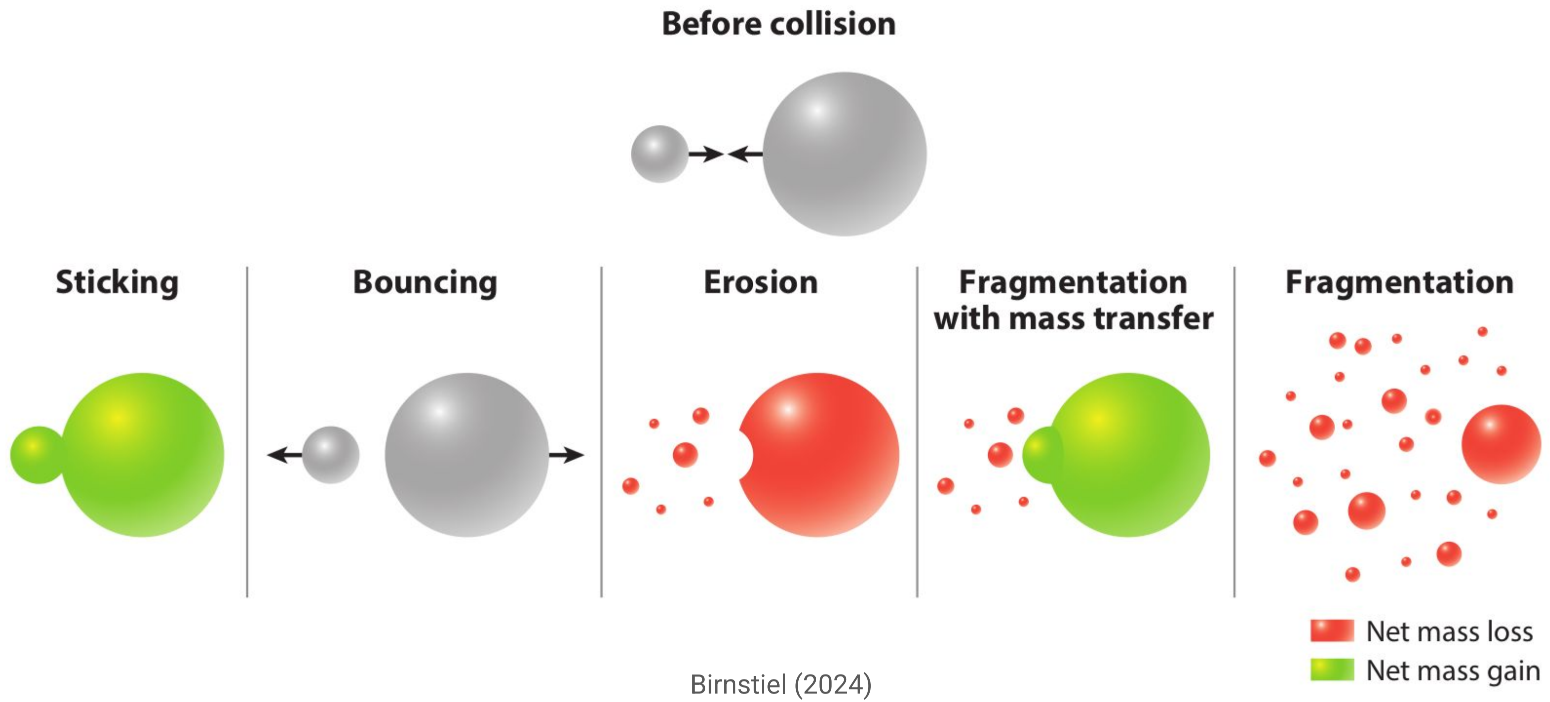




Villenave et al. (2020)

Collisional evolution

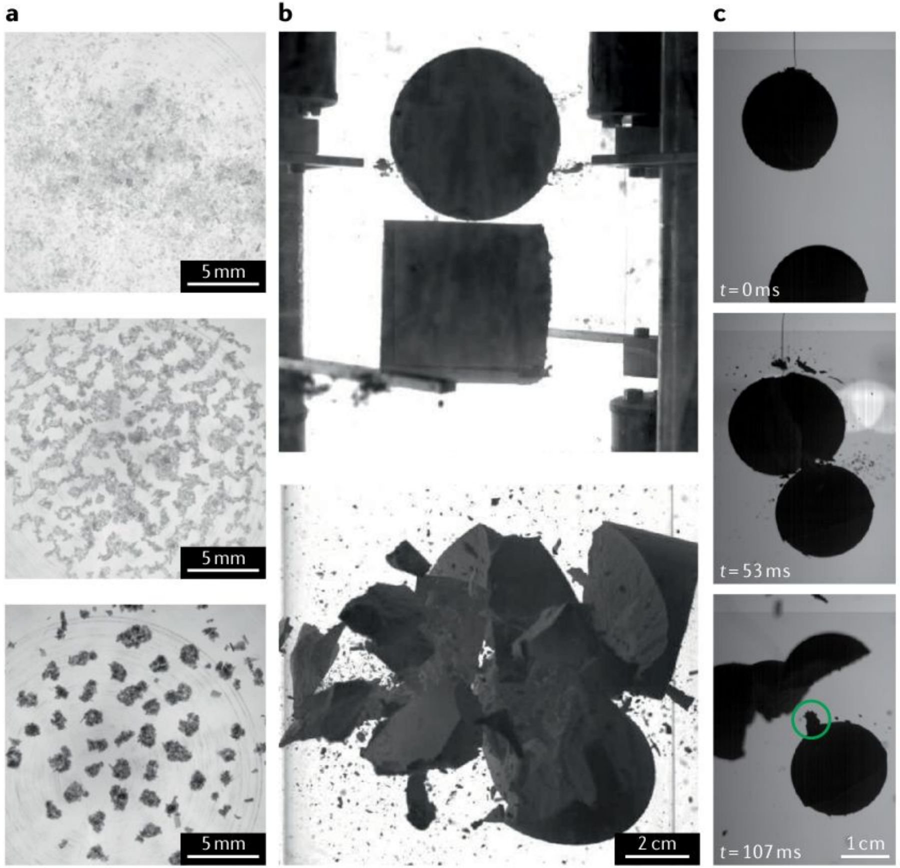
- Mutual collisions are needed to grow dust to pebbles ⟵ process of coagulation



Birnstiel (2024)

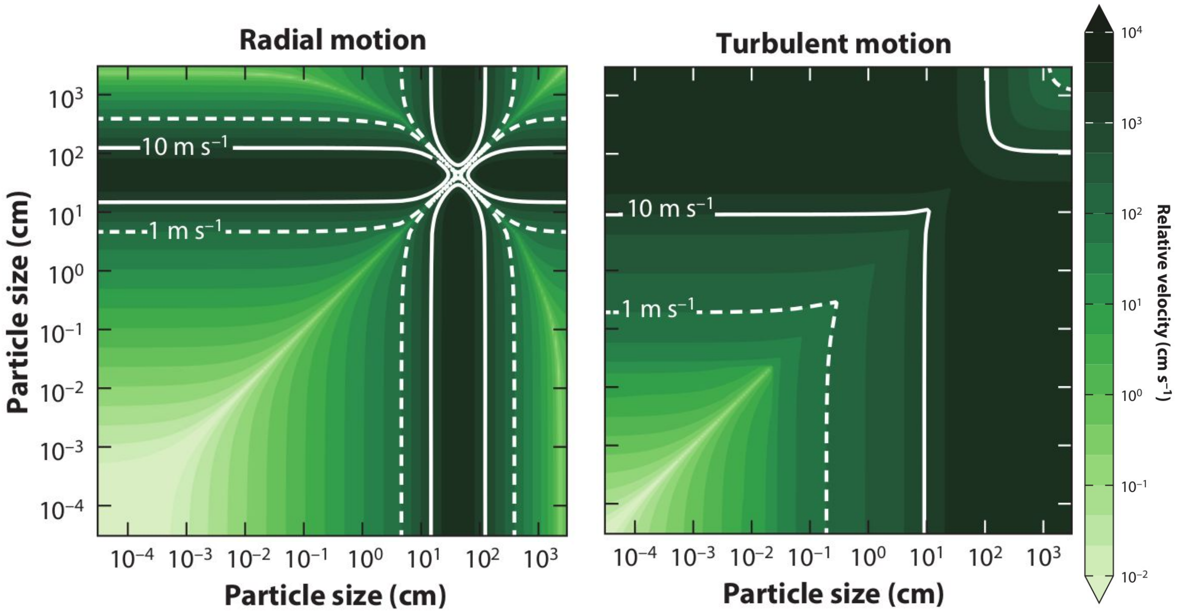
Microgravity experiments

- Collision outcomes studied by laboratory measurements in microgravity (drop towers, suborbital flights, onboard ISS, …)
- Fig from Wurm & Teiser (2021):
  - a - growth from 10-micron agglomerates to mm-sizes at the bouncing barrier
  - b - total fragmentation
  - c - fragmentation with mass transfer



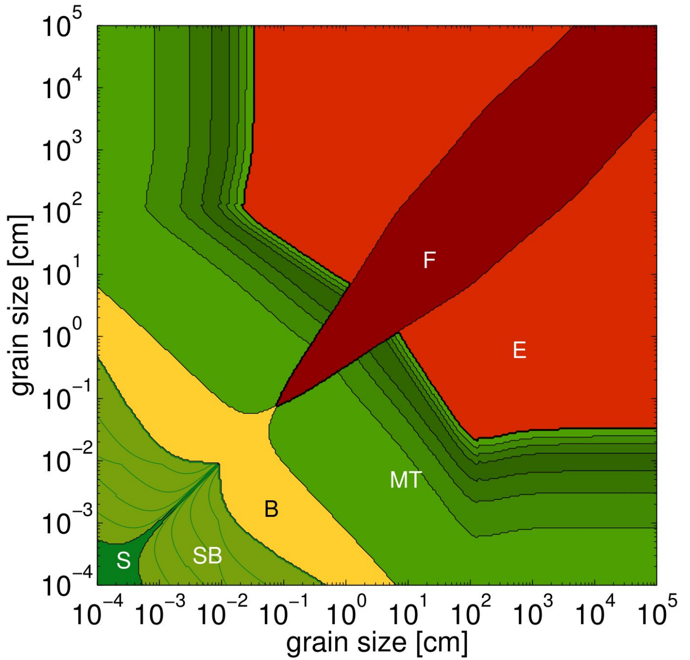
Relative velocities vs collision outcomes

- Relative velocities between particle pairs



Birnstiel (2024)

- Mapping of collisional outcomes between particle pairs



Windmark et al. (2012)

Smoluchowski equation

- Master equation in models of dust coagulation

time evolution of the number density for the grain mass *m*

gain term

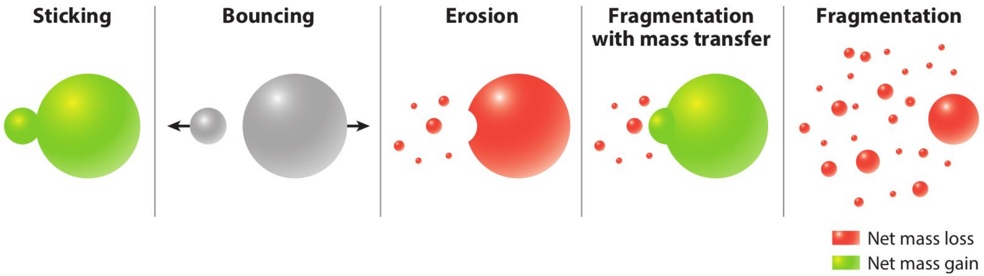
loss term

$$\frac{\partial n(m)}{\partial t} = \int_0^\infty \int_0^{m_1} K(m, m_1, m_2) R(m_1, m_2) n(m_1) n(m_2) \mathrm{d}m_1 \mathrm{d}m_2 - n(m) \int_0^\infty R(m, m_1) n(m_1) \mathrm{d}m_1$$

- *R* … collision rates
- *K* … collision outcomes (kernel)
- loss ~ bookkeeping of events: collision happened -> particle removed
- gain ~ bookkeeping of products: collision happened between m_1+m_2 (found by *R*) -> how does it contribute to the population of particles *m* ? (set by *K*)

Smoluchowski equation

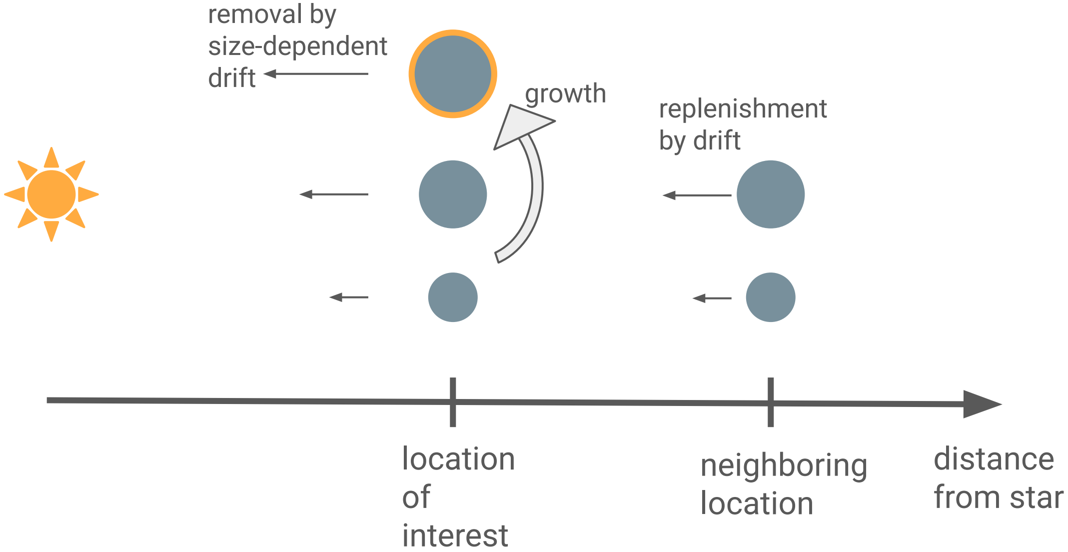
- $K(m, m_1, m_2)$ needs to capture:



- $R(m_1, m_2)$ needs to capture:
  - pairwise cross-sections: spherical | fractal | charged grains
  - distribution of relative velocities due to:
    - relative motion (size-dependent drift): radial | azimuthal | vertical
    - Brownian thermal motion in gas (mostly affects small grains)
    - turbulent gas motion (mostly affects large grains)

Main growth barriers

- Fragmentation barrier: maximum size the particles can grow before v_{rel} is so high that destructive collisions stunt further growth
- Drift barrier: grain size which is lost faster to inward drift than dust flux from outer regions + growth can resupply it



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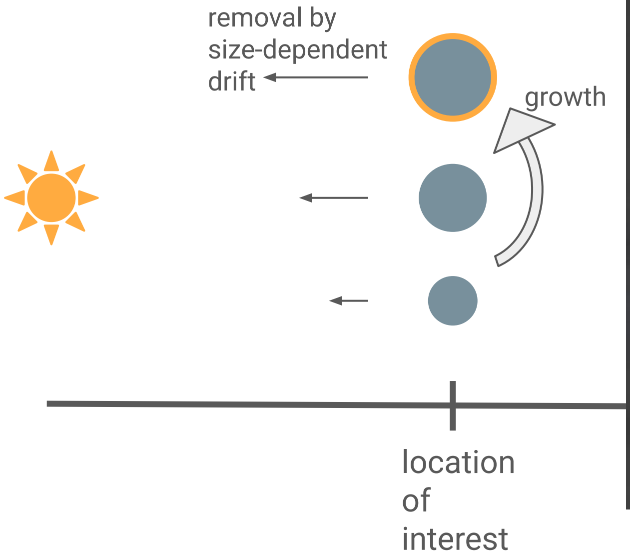
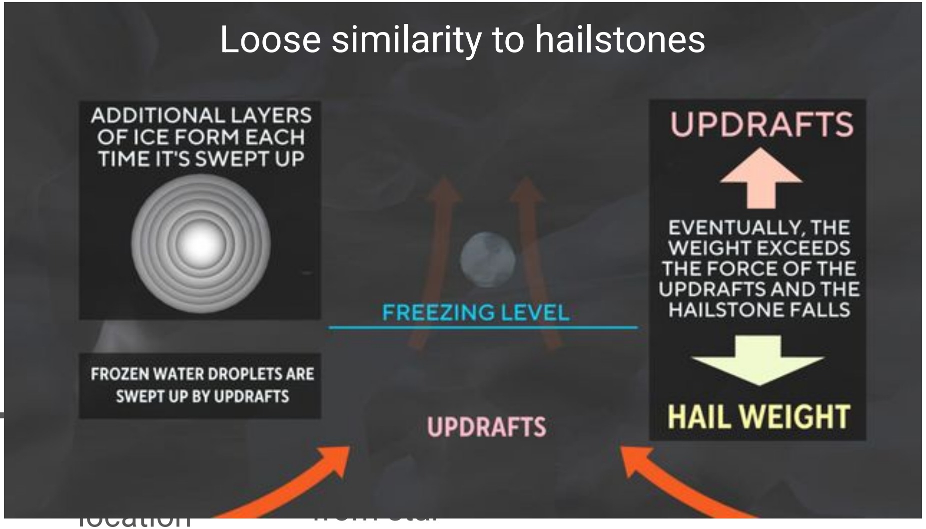




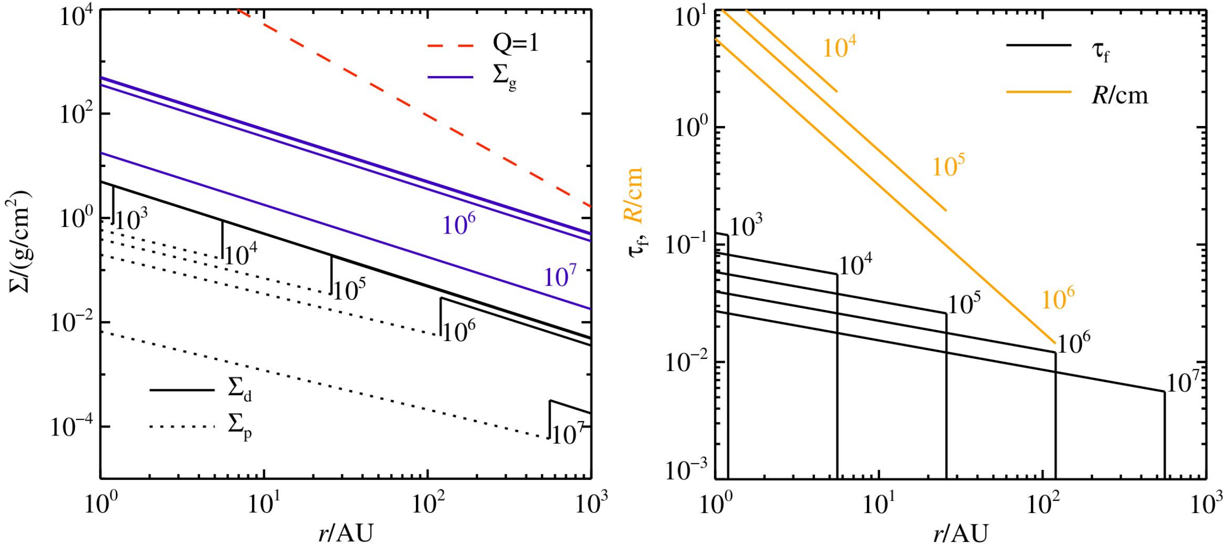
Dust growth vs pebble flux

- We will later derive: the growth timescale & the drift-limited size

$$t_{\rm grow} \simeq \frac{1}{Z\Omega_{\rm K}}$$

$$a_{\rm drift} = \frac{\Sigma_{\rm d}}{\pi \rho_{\rm s} \eta}$$

- Simple dust evolution models with drift and coagulation predict:
  - inside-out growth of dust to pebbles (pebble-production front moving outward)
  - pebble flux decreasing with time as the disk gets depleted



Lambrechts & Johansen (2014)

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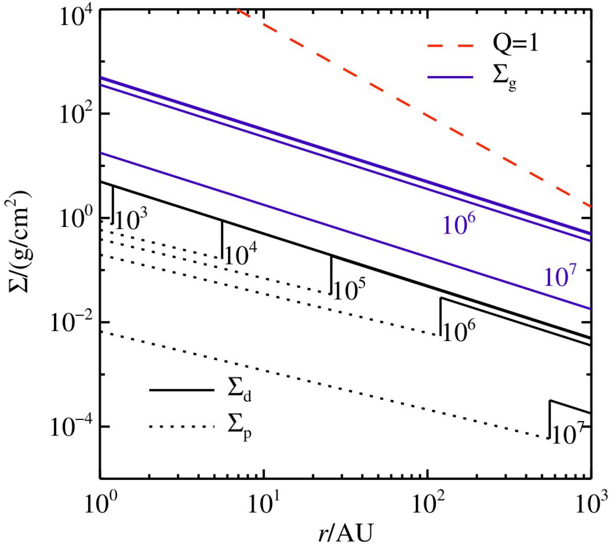


Lambrechts & Johansen (2014)

$$\dot{M}_{\mathcal{F}} = 2\pi r(-2\tau\eta v_{\rm K})\Sigma_{\rm p}$$

$$\dot{M}_{\mathcal{F}} \approx 10^{-4} \exp\left(-\frac{[t]_{\rm Myr}}{3\,{\rm Myr}}\right) M_\oplus\,{\rm yr}^{-1}$$

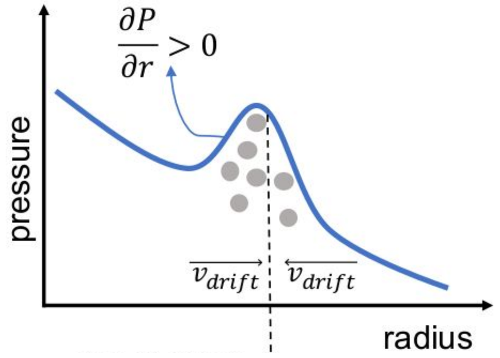
e.g. Lambrechts et al. (2019)

Dust fragmentation vs dust rings

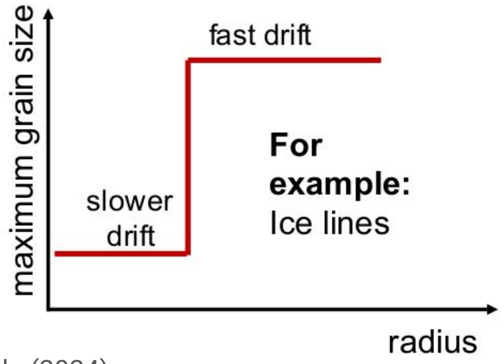
- We will later derive the fragmentation-limited dust size $$a_{\rm frag} = \frac{2\Sigma_{\rm g}}{3\pi\alpha\rho_{\rm s}}\left(\frac{v_{\rm frag}}{c_{\rm s}}\right)^2$$
- Traffic jam principle: pebbles reach an ice line → volatile (e.g. water ice) evaporates → leftover material more brittle (lower velocity sufficient for fragmentation) → max. size decreases (if fragmentation-limited) → Stokes number drops → slower drift → mass flux formula dictates increasing surface density, hence sudden pebble accumulation $$\dot{M}_{\mathcal{F}} = 2\pi r(-2\tau\eta v_{\rm K})\Sigma_{\rm p}$$

Pressure Bumps

For example: Giant planets, zonal flows, etc



Traffic Jams



$$v_{\rm frag} = C\left(\frac{a_0}{0.1\,\mu{\rm m}}\right)^{-5/6}$$

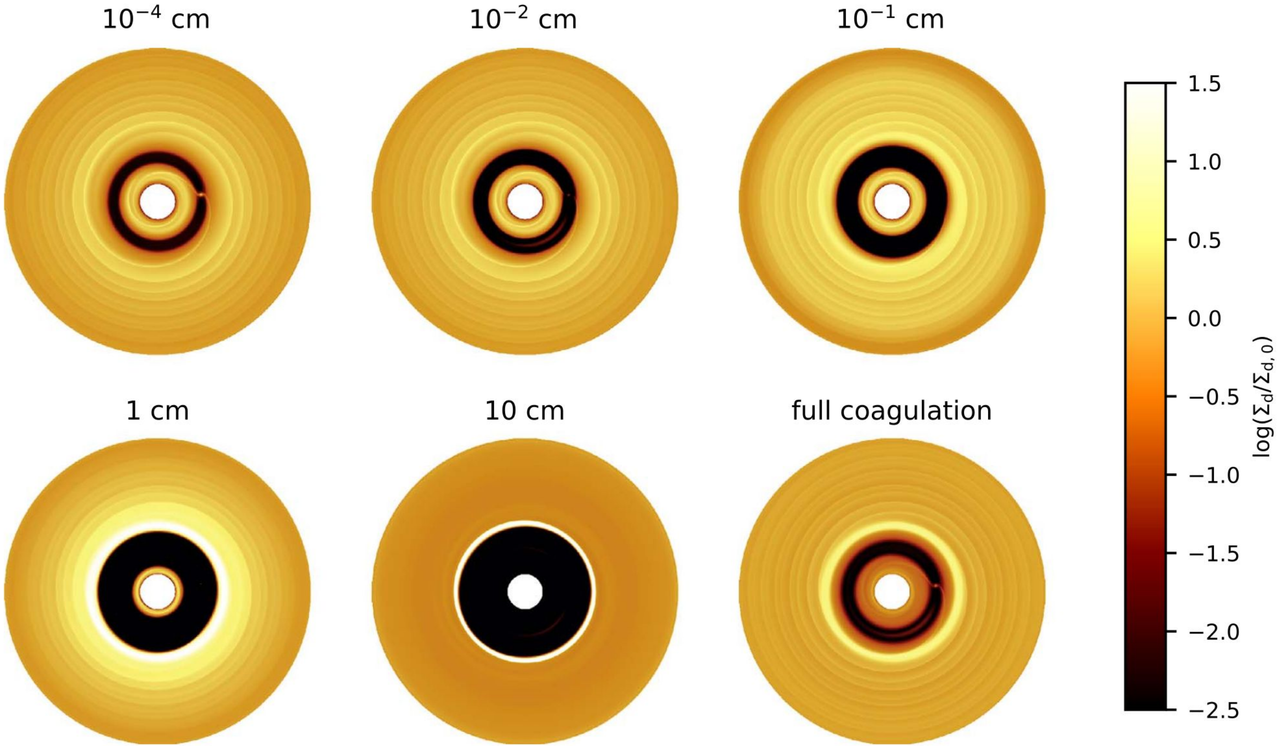
$$C \simeq \begin{cases} 80\,{\rm m/s}, & \text{water ice} \\ 8\,{\rm m/s}, & \text{silicates} \end{cases}$$

Wada et al. (2013)

van der Marel & Pinilla (2024)

Dust fragmentation vs dust rings

- Drazkowska et al. (2019), Pfeil et al. (2024): dust size in a pressure bump always limited by fragmentation → small fragments not stopped by the bump (they follow gap-crossing gas flows) → pressure bumps are leaky and small dust can continue growing in the inner disk



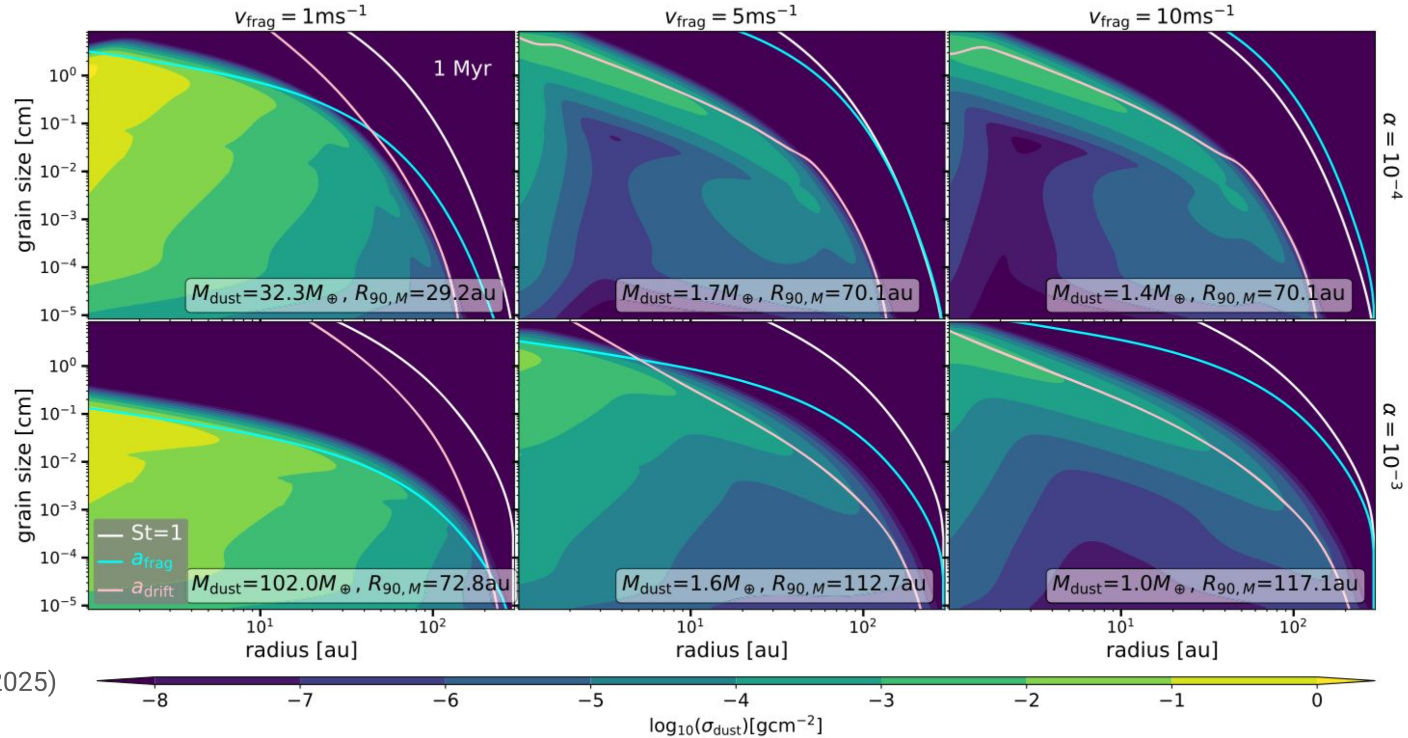
Drazkowska et al. (2019)

Dust evolution solvers & typical outcomes

- DustPy (https://stammler.github.io/dustpy/), TriPodPy (https://github.com/tripod-code/tripodpy), Two-Pop-Py (https://github.com/birnstiel/two-pop-py), cuDisc (https://github.com/cuDisc/cuDisc)

$$a_{\mathrm{drift}} = \frac{\Sigma_{\mathrm{d}}}{\pi \rho_{\mathrm{s}} \eta}$$

$$a_{\mathrm{frag}} = \frac{2\Sigma_{\mathrm{g}}}{3\pi\alpha\rho_{\mathrm{s}}} \left(\frac{v_{\mathrm{frag}}}{c_{\mathrm{s}}}\right)^2$$



Pinilla (2025)

- Installing and running DustPy:

```
pip install dustpy
ipython
from dustpy import Simulation
sim = Simulation()
sim.initialize()
sim.run()
```

- Plotting results:

```
from dustpy import plot
plot.ipanel("data")
```