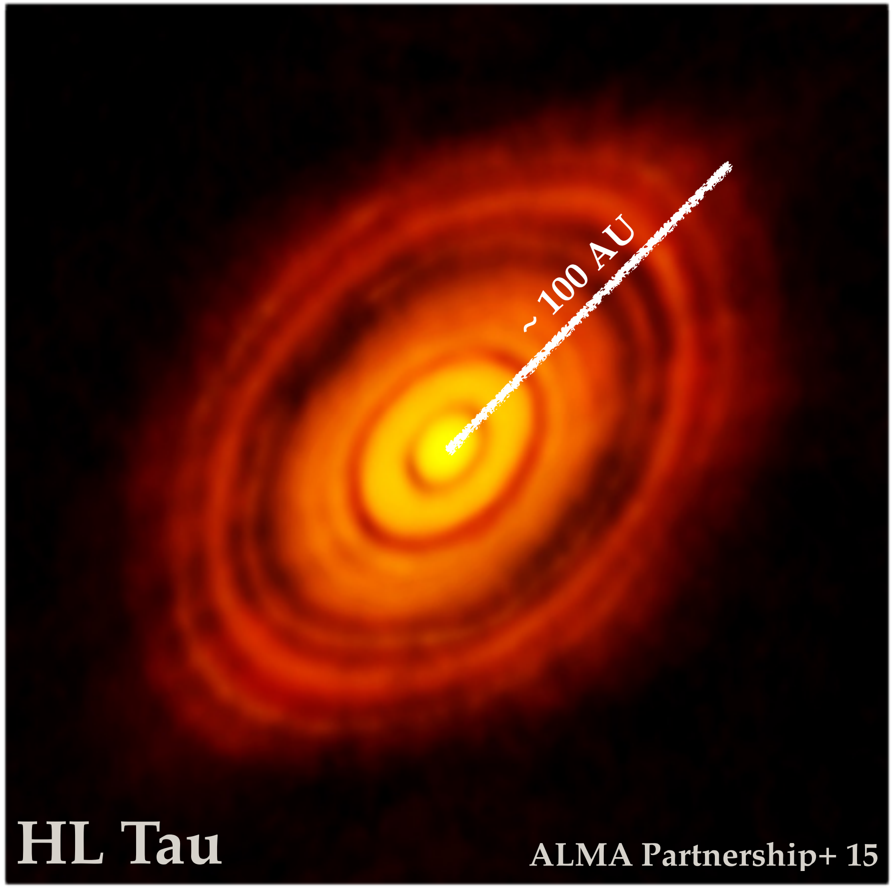
Lecture 3: dust dynamics in protoplanetary disks

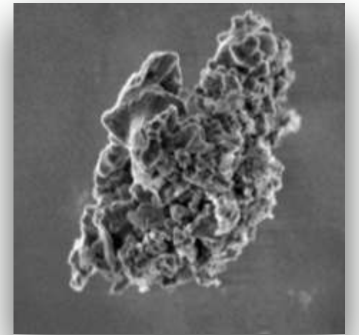


Suggested references:

- Armitage 2011, ***Lecture notes on the formation and early evolution of planetary systems***
  arxiv.org/abs/astro-ph/0701485
- Johansen et al. 2014, ***The multifaceted planetesimal formation process***
  arxiv.org/abs/1402.1344

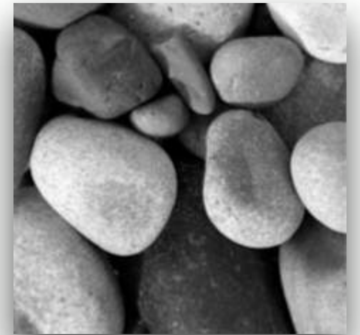
From dust to planets

dust grains



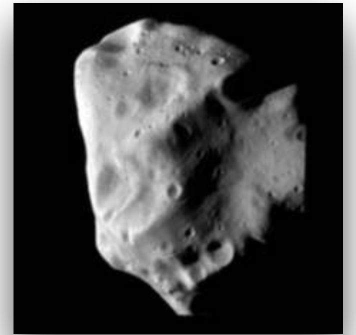
μm

pebbles



cm

planetesimals

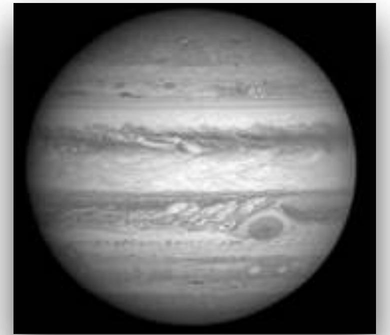


km

planet cores

~10^3 km

giant planets



~10^5 km

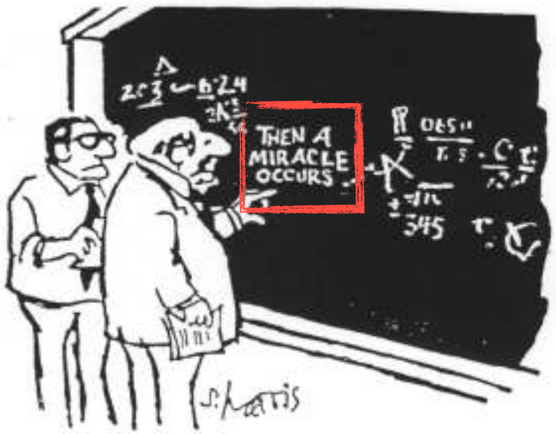
grains growth

planetesimals formation

planetesimals growth to protoplanets

growth/accretion to gas giants

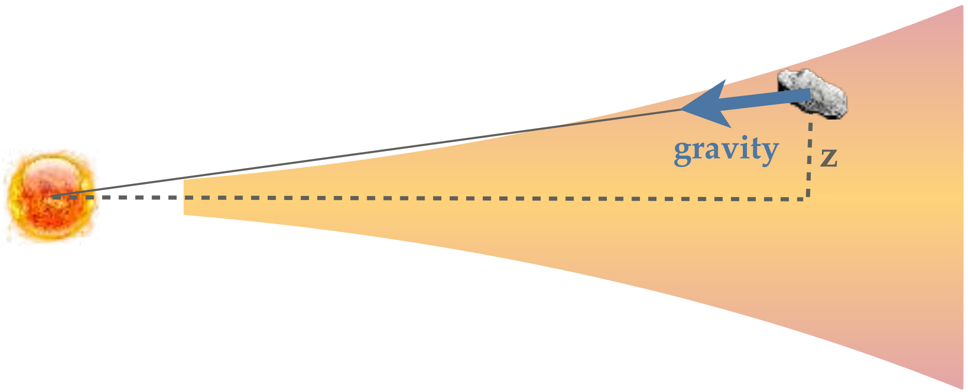
surface forces



I think you should be a little more specific, here in Step 2

gravity

Vertical settling of dust particles



- Dust feels vertical stellar gravity and gas drag (but no pressure):

$$\ddot{z} = -\Omega_K^2 z - \frac{\dot{z} - \cancel{v_{z,\mathrm{gas}}}}{\tau_{\mathrm{stop}}} \quad [1]$$

$\rightarrow$ damped harmonic oscillator

solution is $z(t) = z_0 e^{-\frac{t}{2\tau_{\mathrm{stop}}}} e^{\pm i \Omega_K t \sqrt{1 - \frac{1}{4\mathrm{St}^2}}}$ if $\mathrm{St} = \tau_{\mathrm{stop}} \Omega_K > 1/2$

$\rightarrow$ large grains have a **settling time** ~ $\tau_{\mathrm{stop}} \equiv \frac{\mathrm{St}}{\Omega_K}$

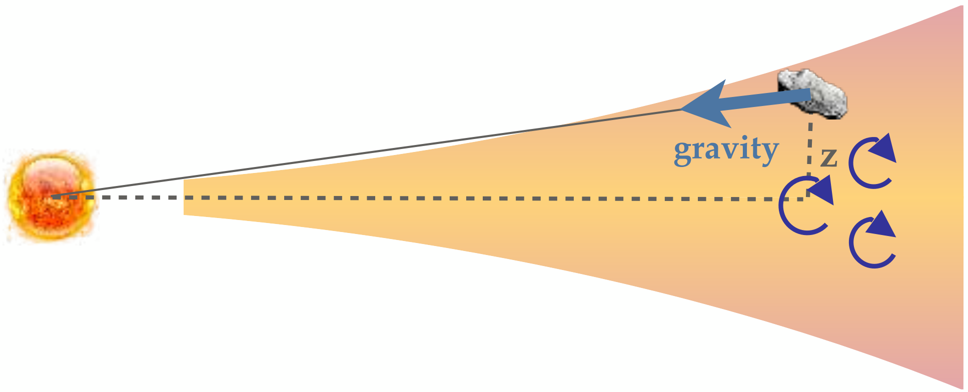
if $\mathrm{St} \ll 1$ approximate [1] as $0 = -\Omega_K^2 z - \frac{\dot{z}}{\tau_{\mathrm{stop}}} \rightarrow z(t) = z_0 e^{-\Omega_K^2 \tau_{\mathrm{stop}} t}$

$\rightarrow$ small grains have a **settling time** ~ $(\Omega_K^2 \tau_{\mathrm{stop}})^{-1} \equiv \frac{1}{\mathrm{St}\Omega_K}$

- Solids **drift** to the **midplane** on a **settling timescale** such that $\boxed{\Omega_K \tau_{\mathrm{sett}} \sim \mathrm{St} + \mathrm{St}^{-1}}$

… which is fastest for St ~ 1 solids and only of order the orbital period (1 yr at 1 AU)!

Vertical settling of dust particles



- So how to keep dust up in the air?

  → turbulence! (if really effective…)

turbulent diffusion prevents solids from settling indefinitely, and occurs on a timescale

gas turbulent viscosity

$$\tau_{\rm diff} \sim \frac{z^2}{D_{\rm dust}} \quad \text{with} \quad D_{\rm dust} \sim \frac{D_{\rm gas}}{1+{\rm St}^2}$$

Youdin & Lithwick 2007

Settling proceeds down to a **height** H_d until turbulent diffusion starts acting against settling. That height is thus where the **settling** and **diffusion timescales** are roughly **equal**:

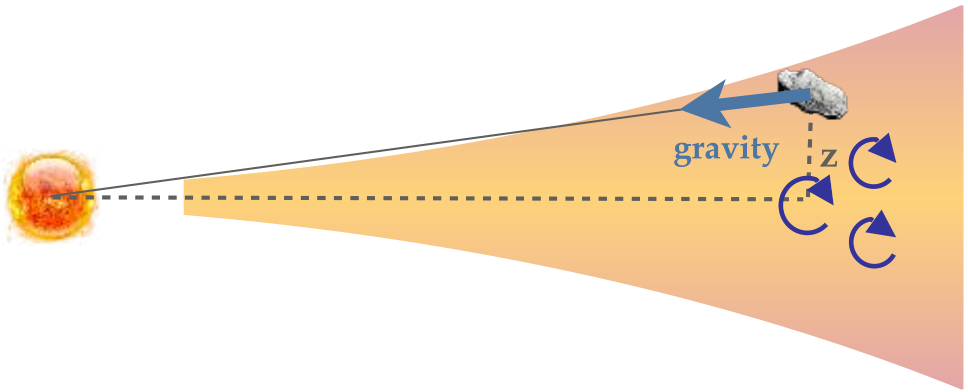
$$H_{\rm d} \sim \sqrt{\frac{D_{\rm gas}}{\Omega_{\rm K}{\rm St}}}$$

Writing $D_{\rm gas} \equiv \nu = \alpha c_{\rm s} H = \alpha H^2 \Omega_{\rm K}$ we obtain the dust-to-gas scale height ratio

$$\frac{H_{\rm d}}{H} \sim \sqrt{\frac{\alpha}{\rm St}}$$

NB: calculation of H_d is actually a little more involved since St depends on z…

Vertical settling of dust particles



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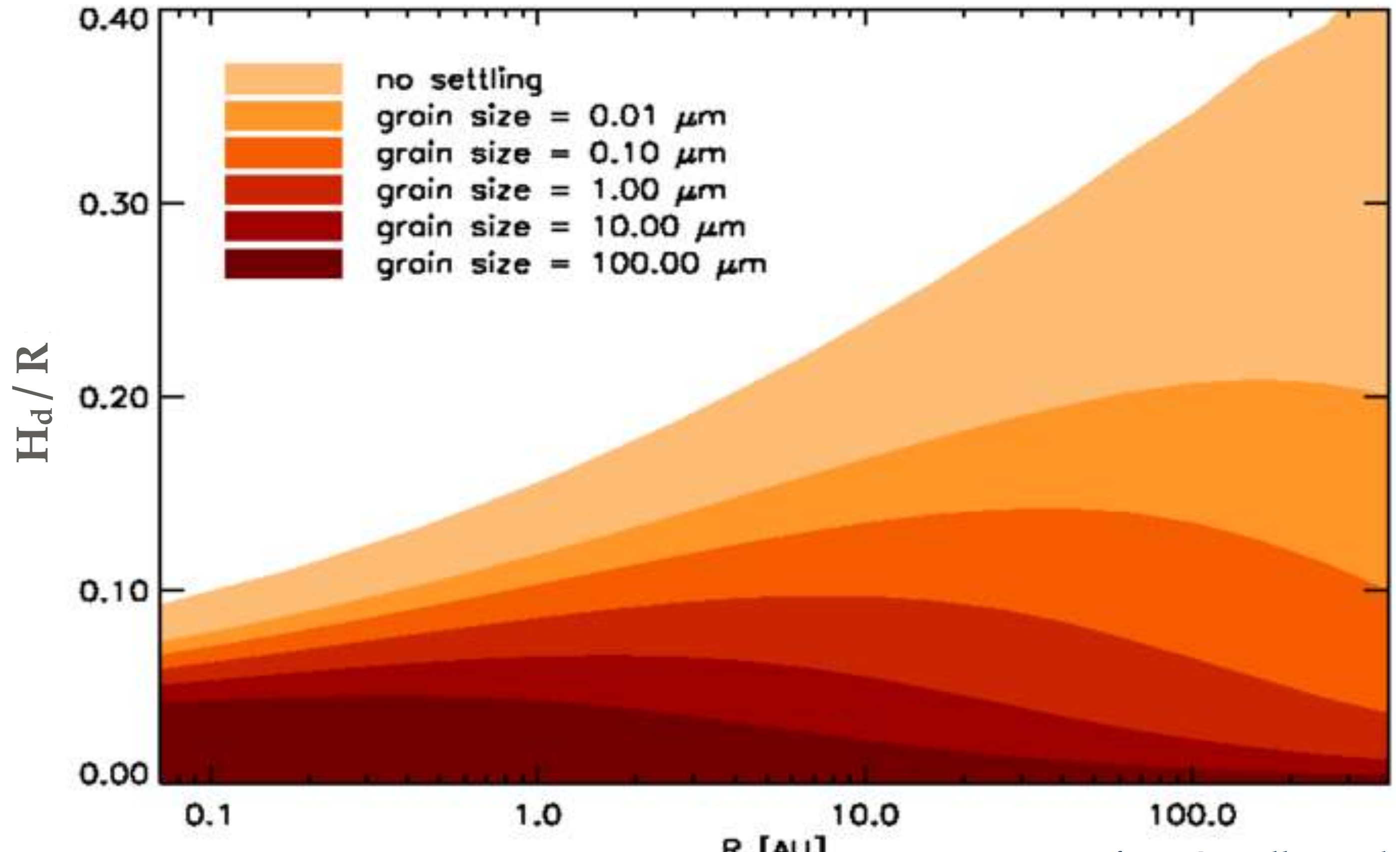


from C. Dullemond

acting against settling.

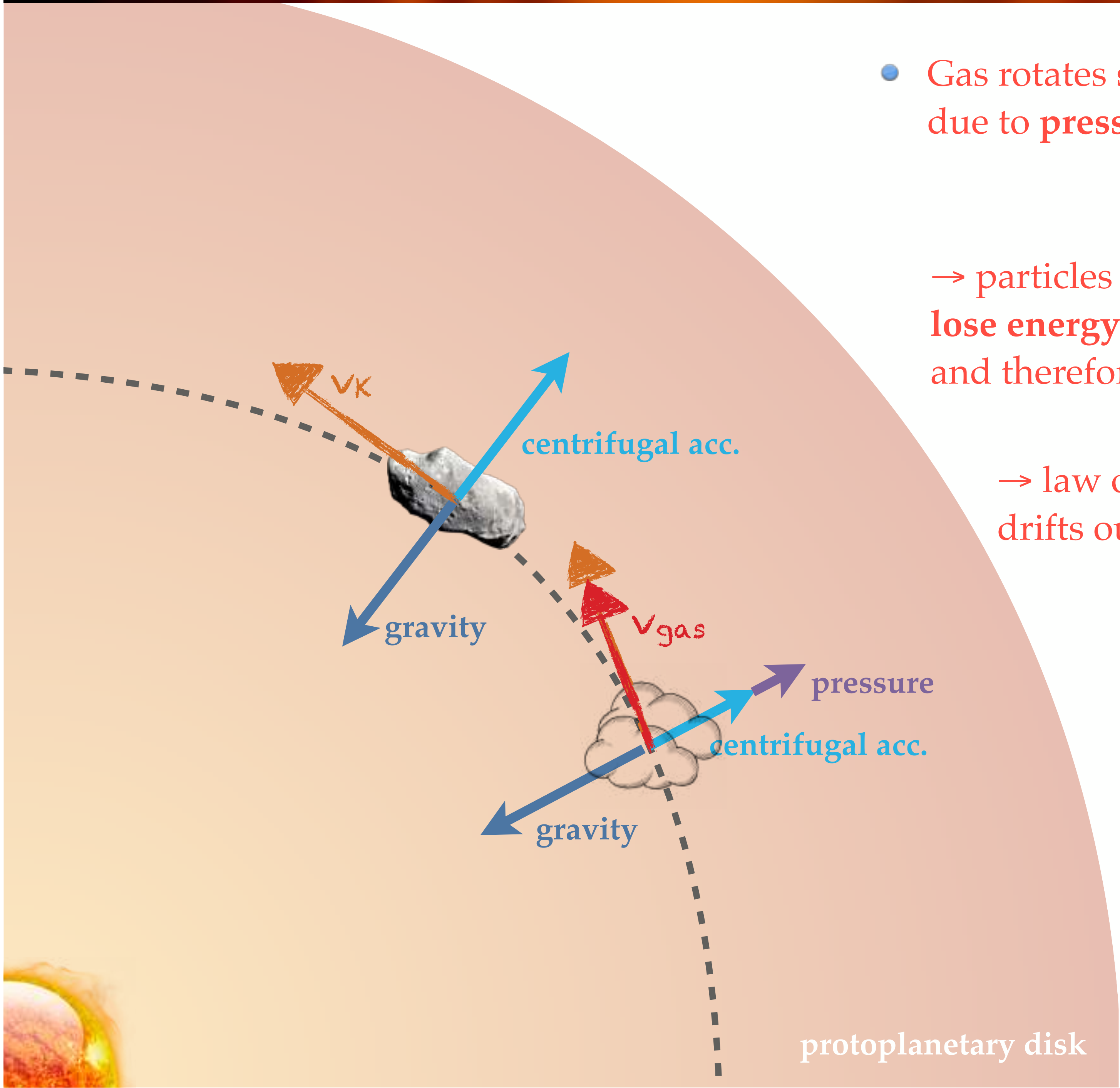
ughly **equal**:

ght ratio

$$\frac{H_{\rm d}}{H} \sim \sqrt{\frac{\alpha}{\rm St}}$$

s on z…

Radial drift of dust particles



- Gas rotates **slower** than solid particles due to **pressure support**

→ particles feel the gas like a **headwind**, **lose energy** and **angular momentum**, and therefore **drift towards the star**

→ law of action-reaction: gas slowly drifts outwards

- **drag acceleration on dust:**

$$a_{\mathrm{drag}} = -\frac{v_{\mathrm{dust}} - v_{\mathrm{gas}}}{\tau_{\mathrm{stop}}}$$

- **dust Stokes number:**

$$\mathrm{St} = \tau_{\mathrm{stop}}\Omega$$

(depends on dust size, gas Σ)

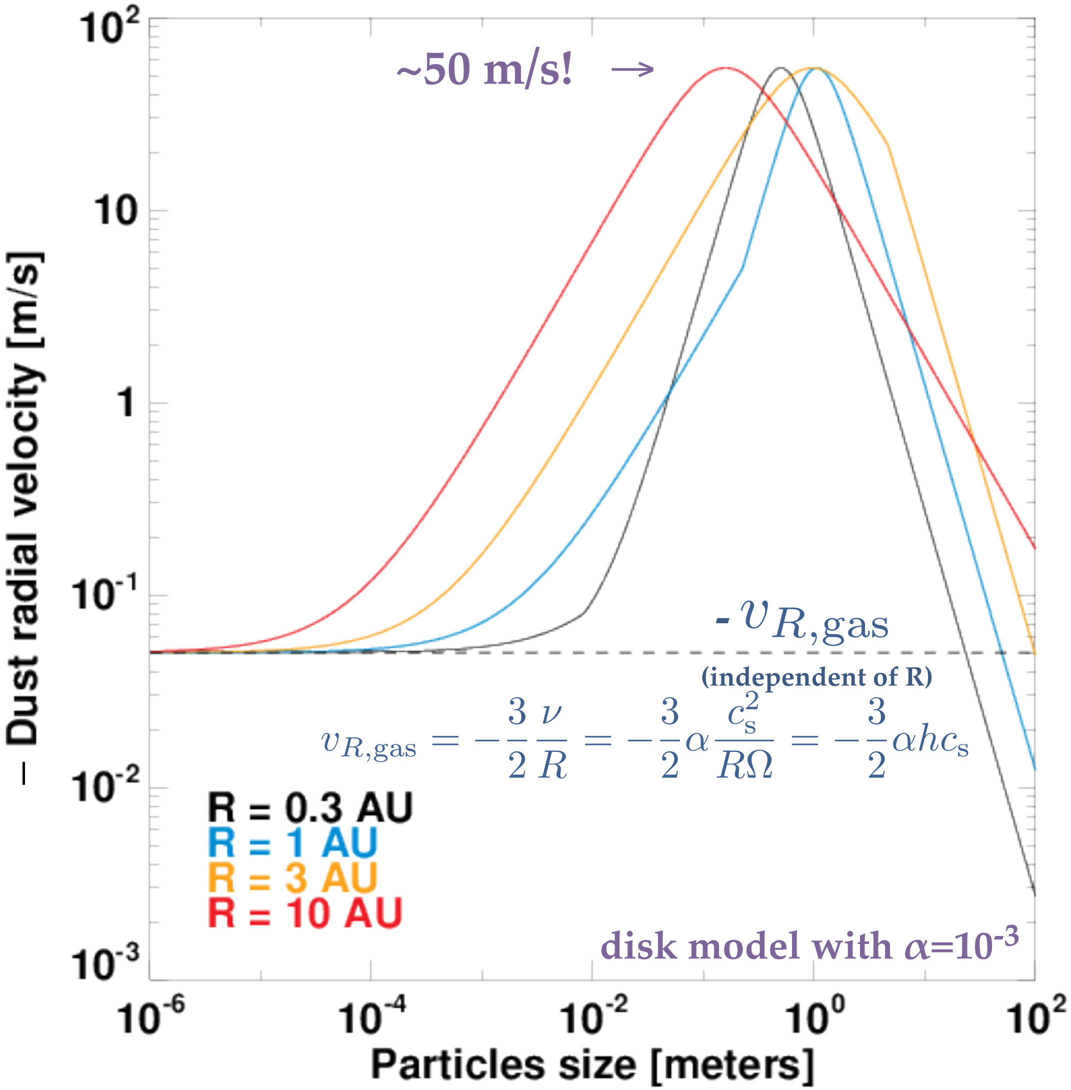
Radial drift of dust particles

For small dust-to-gas density ratios, $v_{R,\mathrm{dust}} = v_{R,\mathrm{gas}} \frac{1}{1+\mathrm{St}^2} + h^2 v_{\mathrm{K}} \left(\frac{\partial \log p}{\partial \log R}\right) \frac{1}{\mathrm{St}+\mathrm{St}^{-1}}$

means that the gas drags the solid particles, but we neglect the fact solid particles may drag the gas as well

maximum for St=1

e.g., Armitage 2015



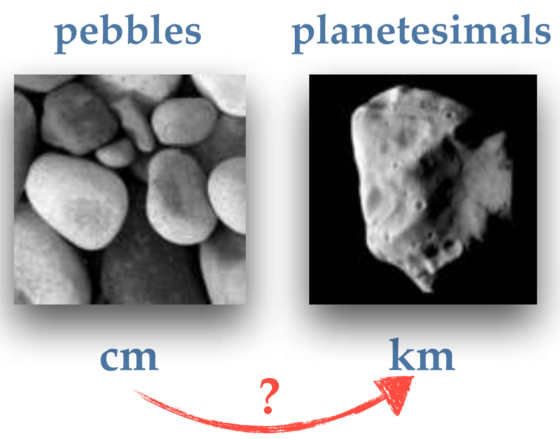
→ Meter-sized bodies only take ~100 years to reach the star from a distance of 1 AU!

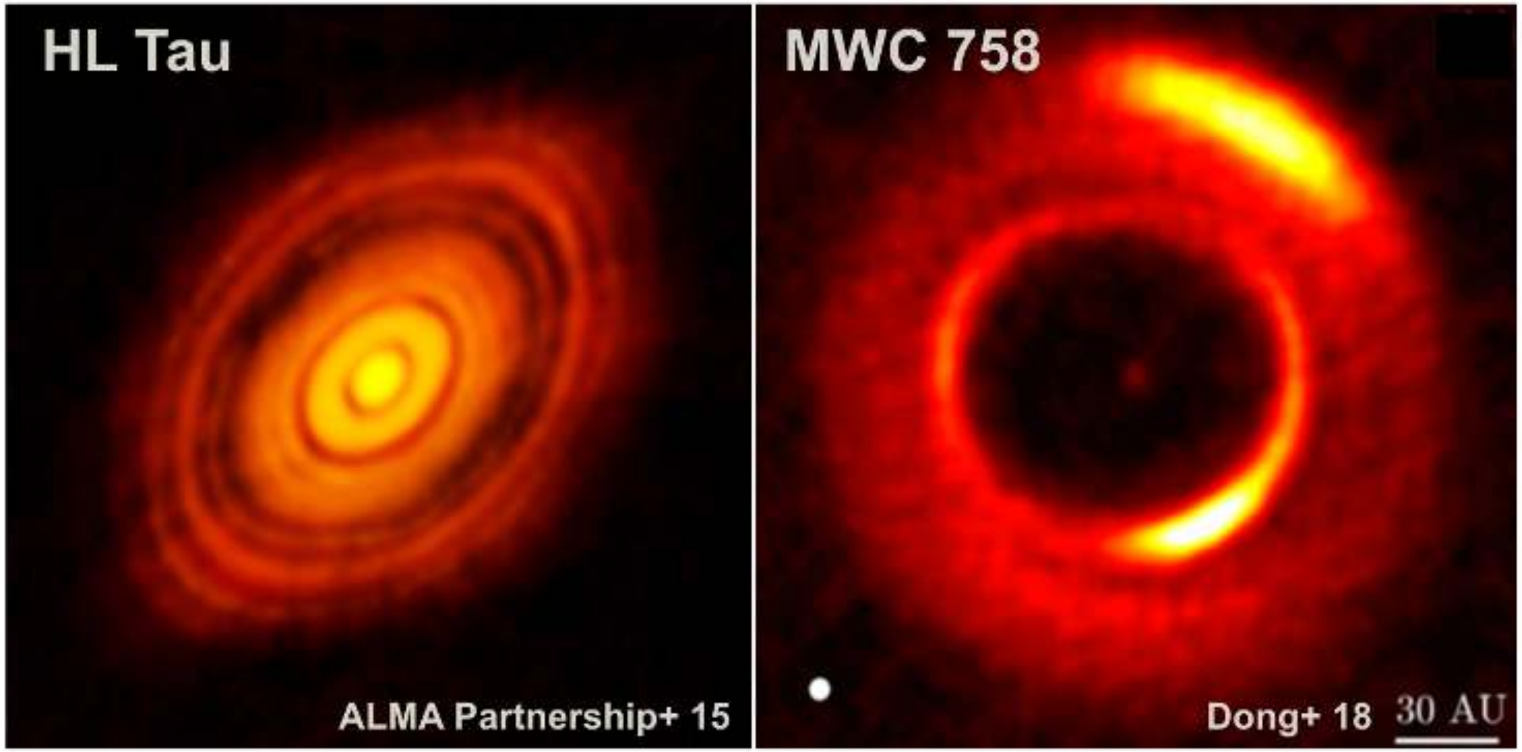
→ severe constraint on the timescale for planetesimal formation!

Radial drift of dust particles

- So how do we not lose all the cm / meter-sized solids and **build** planetesimals?
  - invoke **pressure maxima** in the disk to trap dust?

    → observational support?

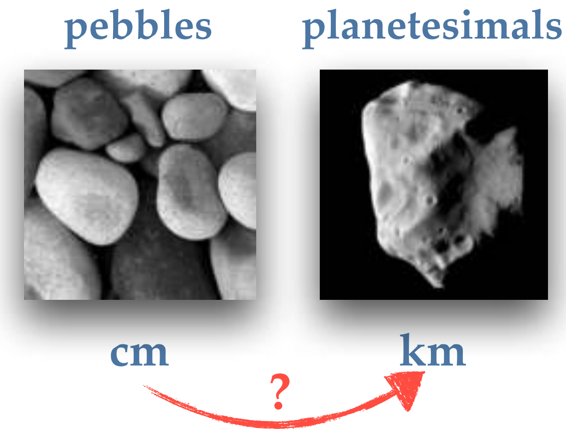


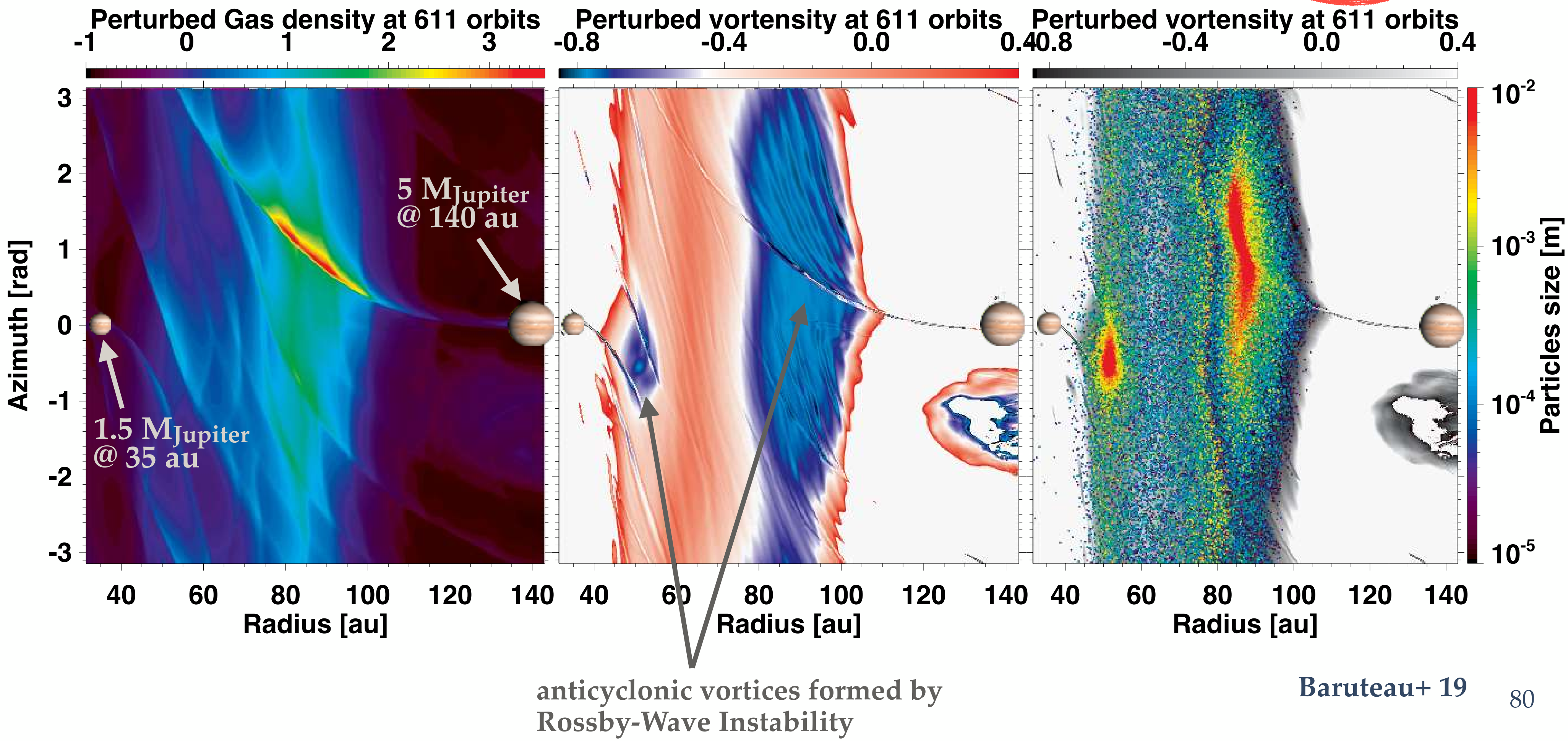


Radial drift of dust particles

- So how do we not lose all the cm/meter-sized solids and **build** planetesimals?
  - invoke **pressure maxima** in the disk to trap dust?

→ observational support? a modelling example:





Baruteau+ 19

Radial drift of dust particles

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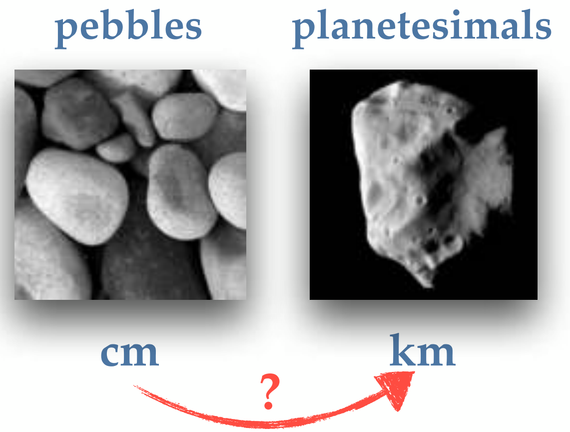

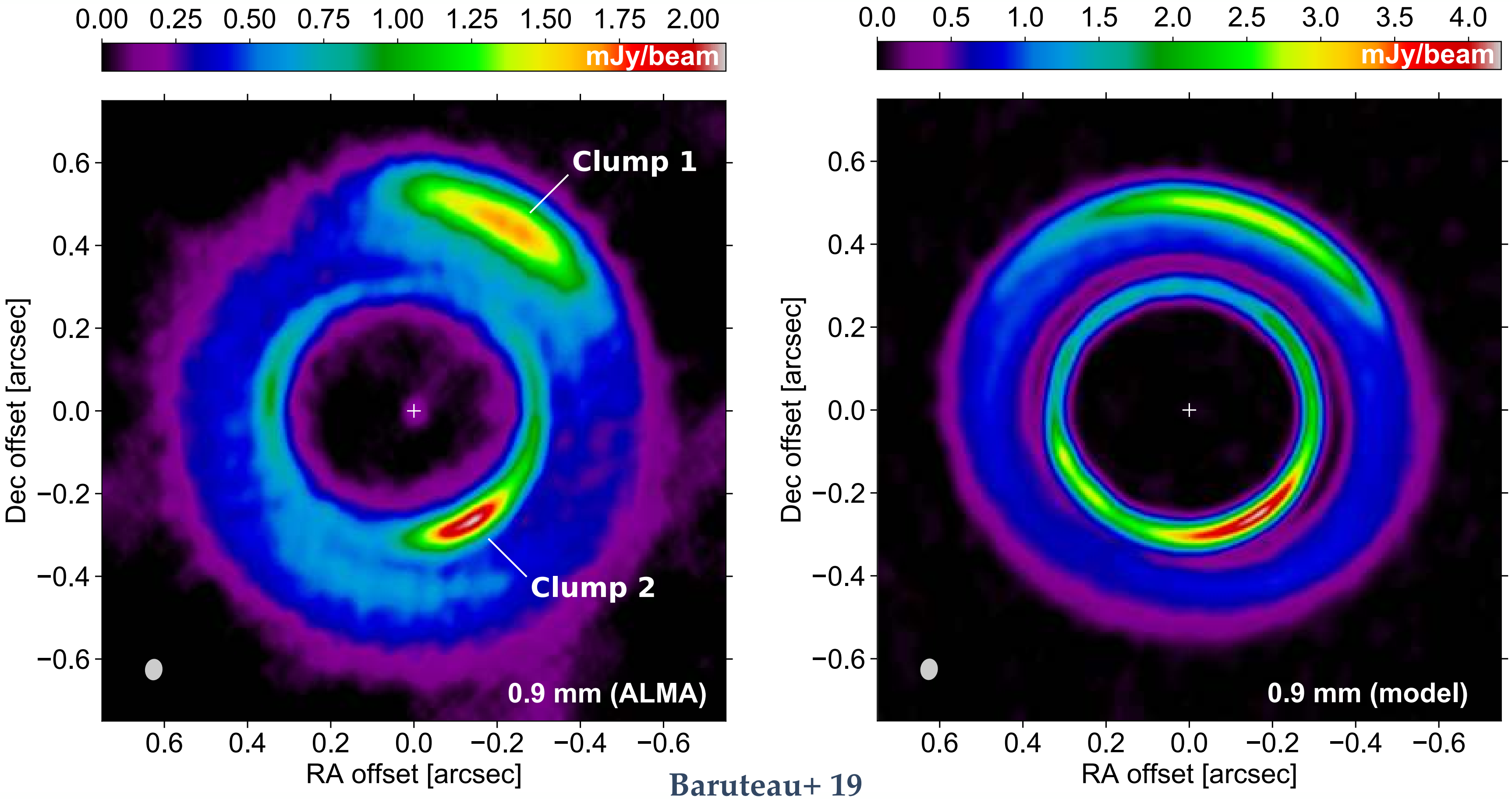

Baruteau+ 19

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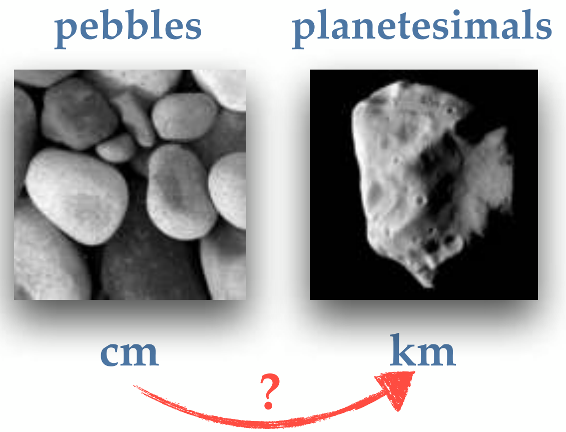
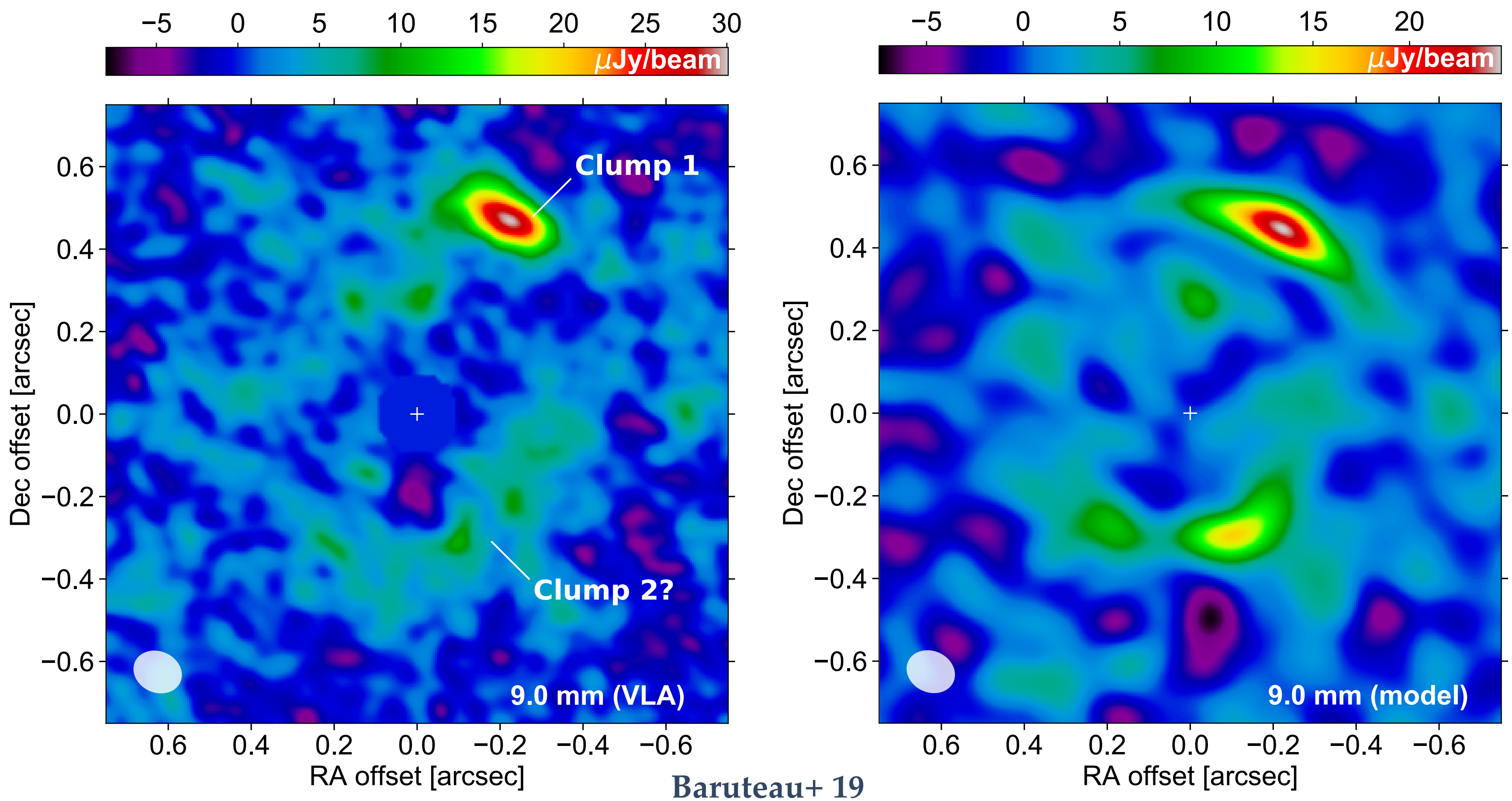




Baruteau+ 19

Radial drift of dust particles

- So how do we not lose all the cm / meter-sized solids and **build** planetesimals?
  - invoke **pressure maxima** in the disk to trap dust?

    → observational support? a modelling example:

    → but how efficient is dust growth at these locations?

pebbles **planetesimals**

cm **?** **km**

Radial drift of dust particles

- So how do we not lose all the cm / meter-sized solids and **build** planetesimals?
  - invoke **pressure maxima** in the disk to trap dust?
  - invoke very **efficient** size **growth**?

  → **bouncing** at **low** relative velocities

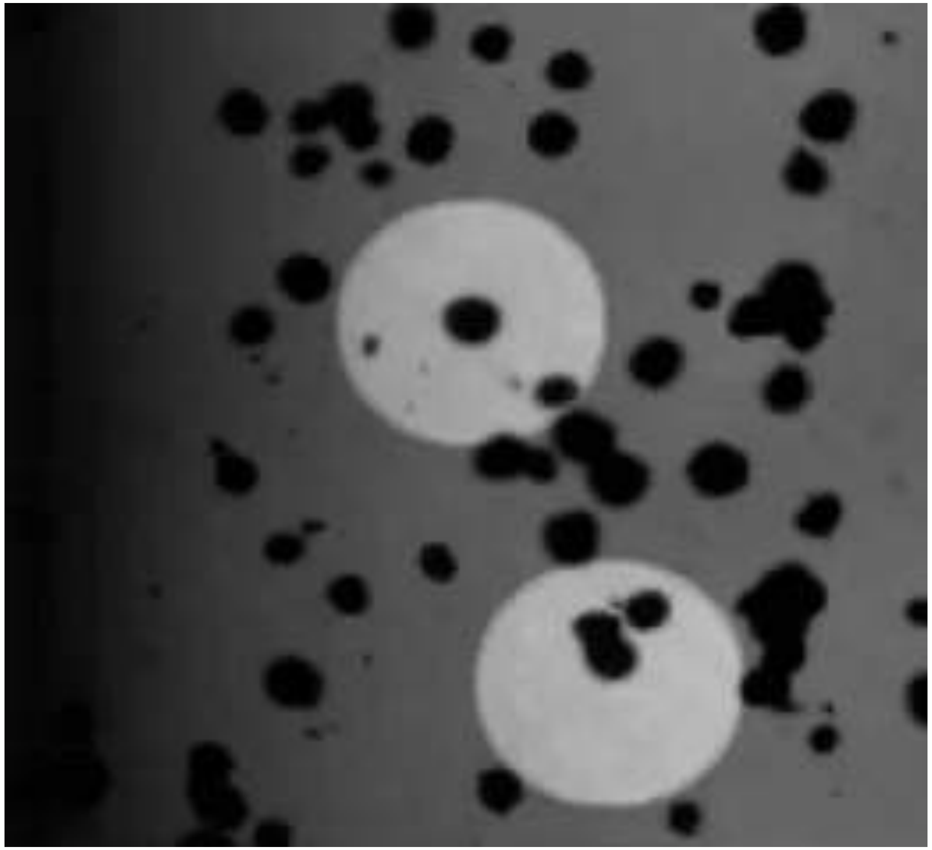
pebbles

cm

planetesimals

km

?



Weidling+ 2012 (mm-sized particles @ ~0.1 m/s)

Radial drift of dust particles

- So how do we not lose all the cm / meter-sized solids and **build** planetesimals?
  - invoke **pressure maxima** in the disk to trap dust?
  - invoke very **efficient** size **growth**?

  → **bouncing** at **low** relative velocities, **fragmentation** at **large**

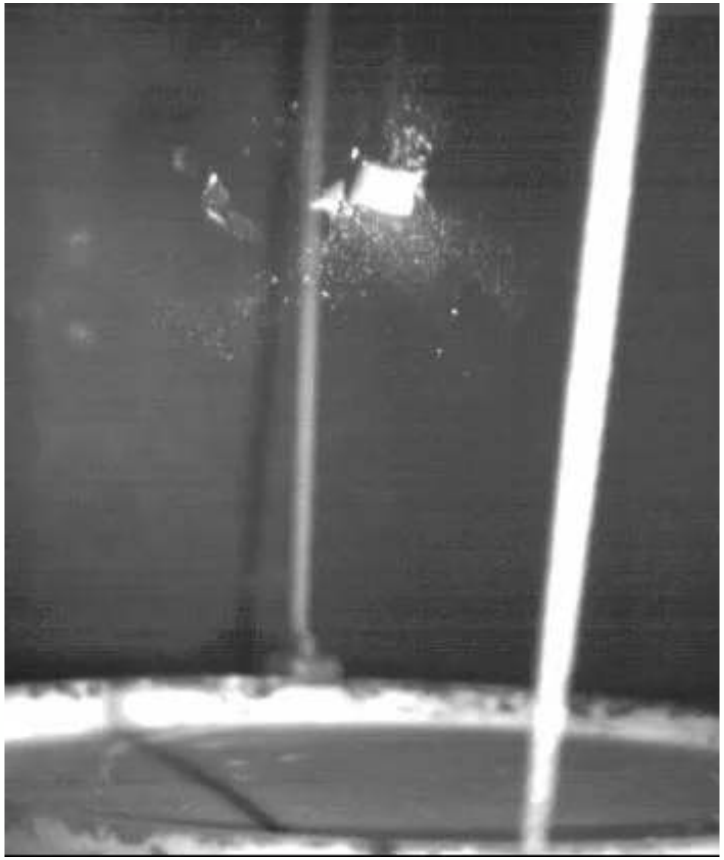
pebbles

cm

planetesimals

km

?



Guettler+ 2010 (mm-sized particles @ ~40 m/s)

Radial drift of dust particles

- So how do we not lose all the cm / meter-sized solids and **build** planetesimals?
  - ✤ invoke **pressure maxima** in the disk to trap dust?
  - ✤ invoke very **efficient** size **growth**?
    - → **bouncing** at **low** relative velocities, **fragmentation** at **large**
    - → **mass transfert** due to repeated collisions with smaller dust?

pebbles

cm

planetesimals

km

?

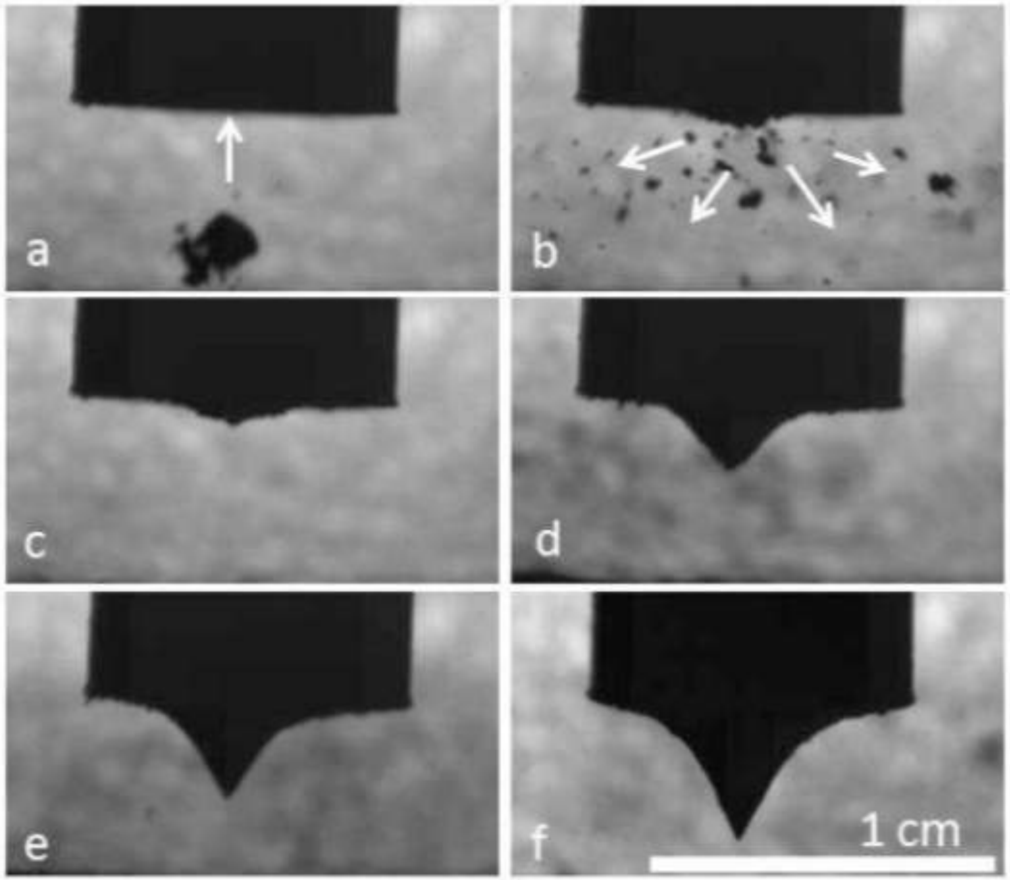


Fig. 10.— Experimental example of mass transfer in fragmenting collisions. All experiments were performed in vacuum. (a) A mm-sized fluffy dust aggregate is ballistically approaching the cm-sized dusty target at a velocity of 4.2 m/s. Projectile and target consist of monodisperse SiO_2 spheres of 1.5 μm diameter. (b) Shortly after impact, most of the projectile's mass flies off the target in form of small fragments (as indicated by the white arrows); part of the projectile sticks to the target. (c) - (e) The same target after 3 (c), 24 (d), 74 (e) and 196 (f) consecutive impacts on the same spot. Image credit: Stefan Kothe, TU Braunschweig.

Johansen+ 2014

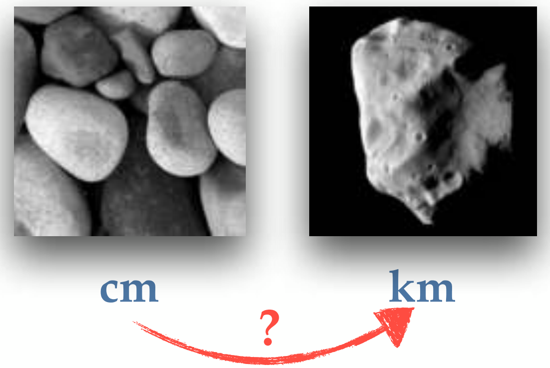
Radial drift of dust particles

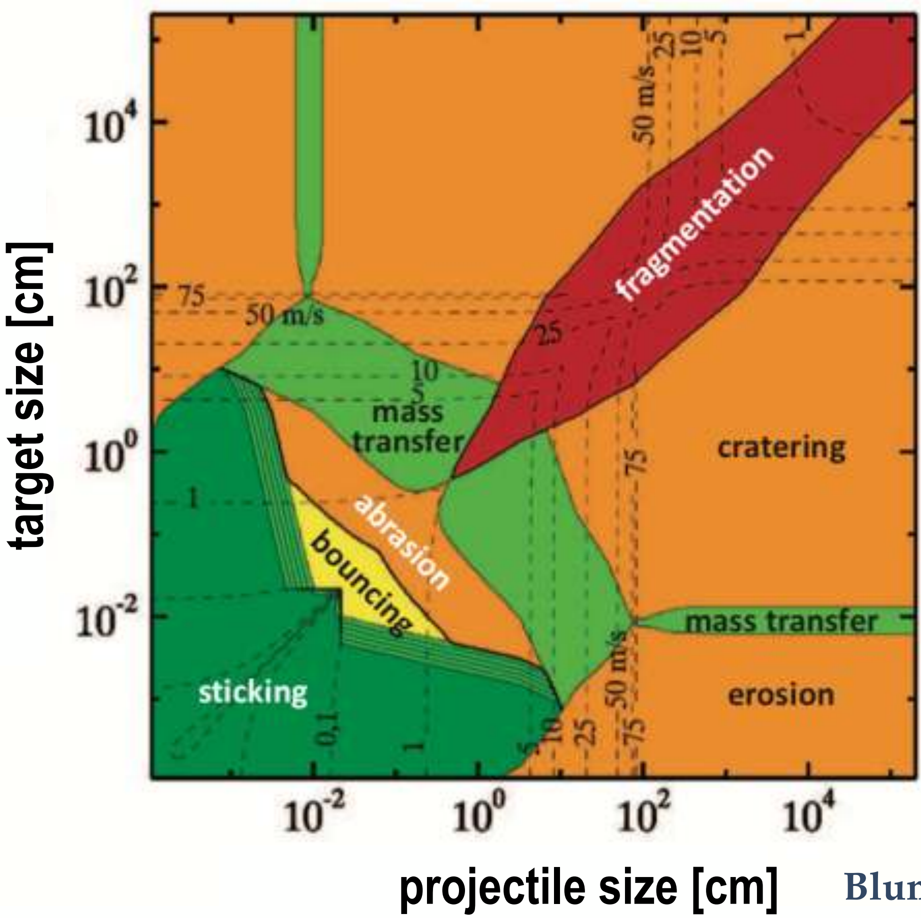
- So how do we not lose all the cm / meter-sized solids and **build** planetesimals?
  - ✣ invoke **pressure maxima** in the disk to trap dust?
  - ✣ invoke very **efficient** size **growth**?

→ **bouncing** at **low** relative velocities, **fragmentation** at **large**

→ **mass transfert** due to repeated collisions with smaller dust?

pebbles planetesimals

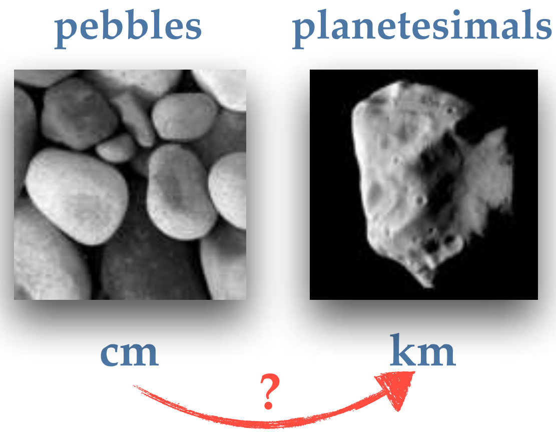




Blum 2018

Radial drift of dust particles

- So how do we not lose all the cm/meter-sized solids and **build** planetesimals?
  - invoke **pressure maxima** in the disk to trap dust?
  - invoke very **efficient** size **growth**?
  - invoke effects of **dust drag onto the gas**?



→ for any **dust-to-gas density ratio ϵ**, $v_{R,\mathrm{dust}} - v_{R,\mathrm{gas}} \approx h^2 v_\mathrm{K} \left(\frac{\partial \log p}{\partial \log R}\right) \frac{1}{\mathrm{St} + \mathrm{St}^{-1}(1+\epsilon)^2}$

Youdin & Goodman 2005

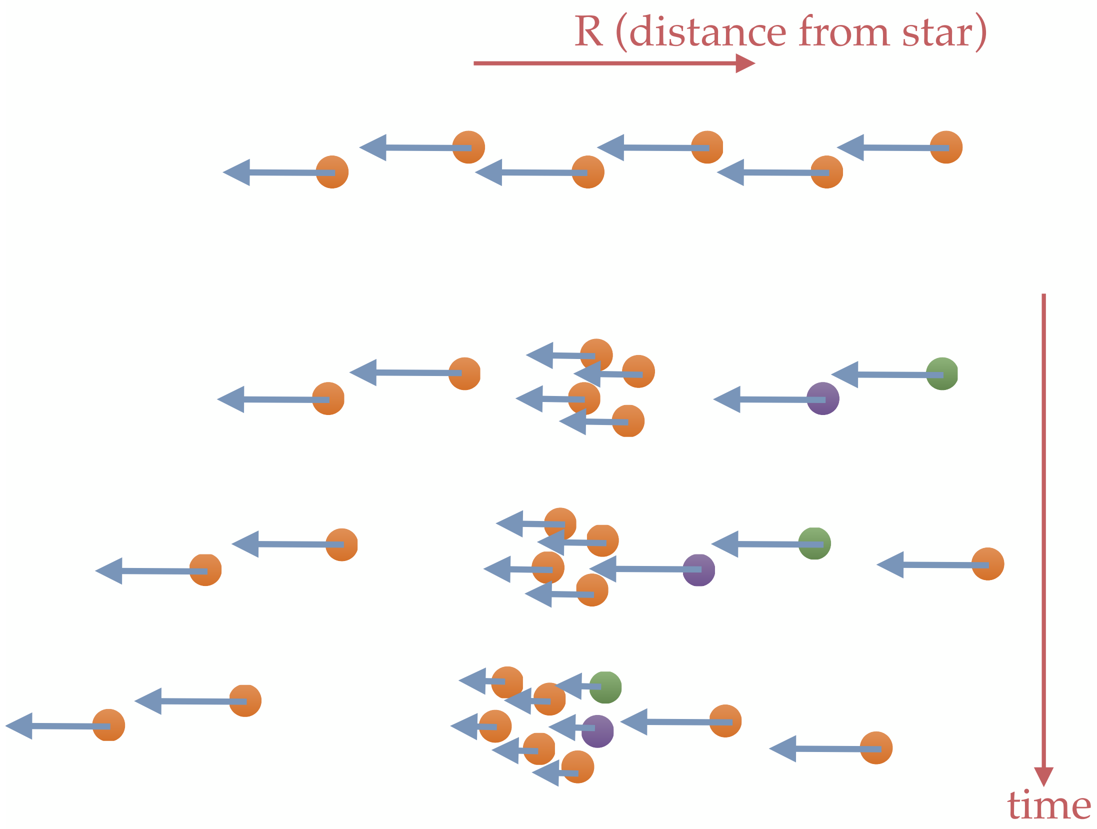
so $v_{R,\mathrm{dust}}$ becomes less negative as $\epsilon = \rho_\mathrm{dust}/\rho_\mathrm{gas}$ increases. But can $\epsilon \gg 1$?

→ may trigger the **streaming instability**

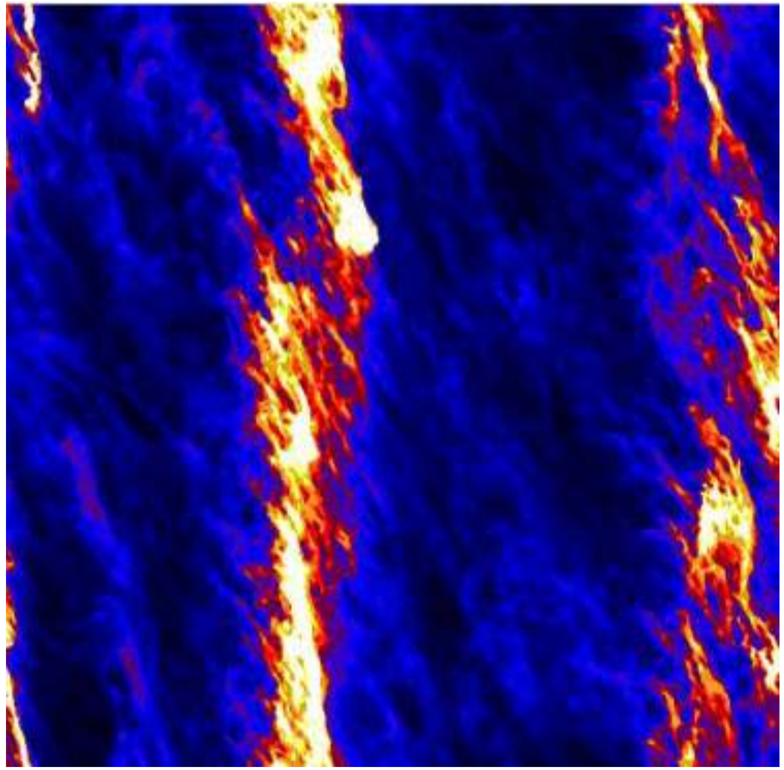
Streaming instability

- **Linear instability** due to dust drag on the gas ("dust feedback") **Youdin & Goodman 2005**

  → forms of **dust filaments** with a very large concentration of solids



sort of dust traffic jam!



Formation of dust filaments by the streaming instability
The dust-to-gas density ratio can reach a few x 1000

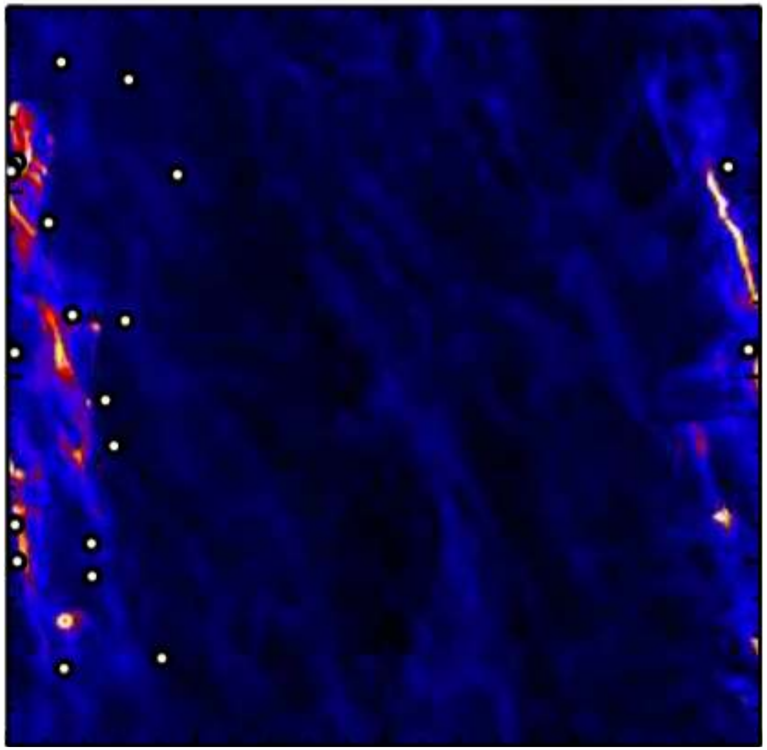
Johansen+ 2014

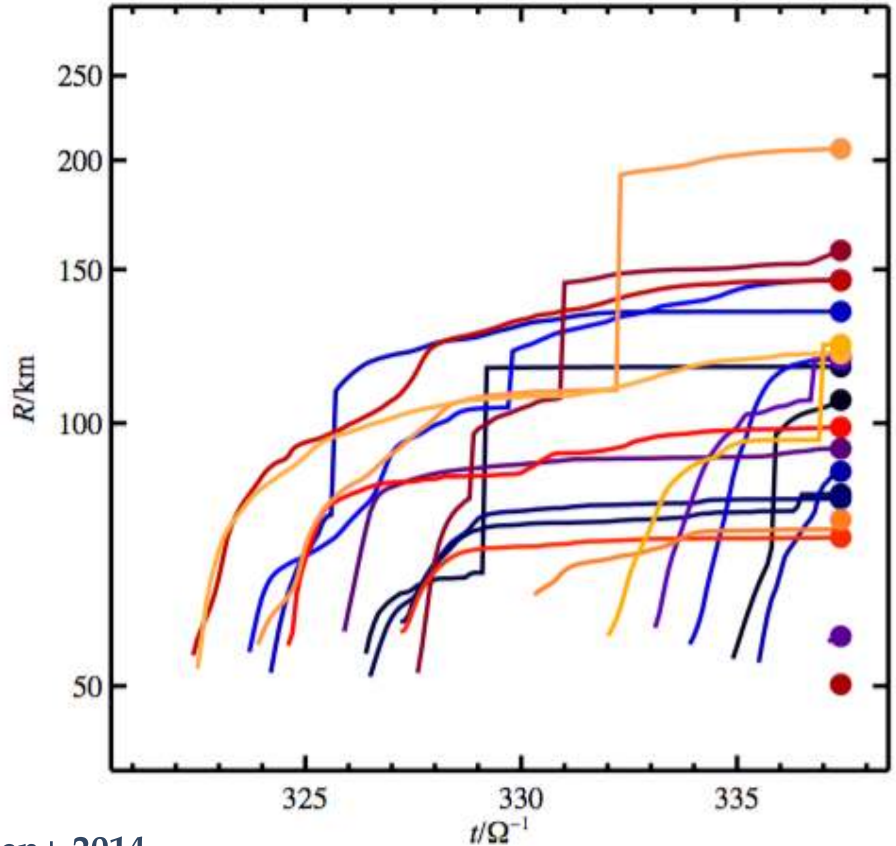
Streaming instability

- **Linear instability** due to dust drag on the gas ("dust feedback") **Youdin & Goodman 2005**

→ forms of **dust filaments** with a very large concentration of solids

→ dust's self-gravity causes the dust filaments to **collapse** which, with the help of collisions, can typically **form** ~100 km-sized **planetesimals**





Johansen+ 2014

→ very active field of research!

A few summary points

- Solid particles **drift** towards **pressure maxima** (radial drift towards the star, vertical settling towards disk midplane, anticyclonic vortices…)

- Drift is **fastest** for dust **marginally** coupled to the gas (with Stokes number~ 1), which corresponds to cm-sized pebbles at a few AU from the star

- Collisions cause dust to **stick** up to pebble (cm) sizes; beyond, **bouncing** and **fragmentation** become dominant

- Formation of (km-sized) **planetesimals** is thought to occur in the regime of strong dust-gas interaction through the **streaming instability**