ASTR 405
Planetary Systems
<u>Dust, Pebbles, and Planetesimals</u>

Fall 2025

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Supplementary Readings: **formation.pdf Section III A** on Canvas

Lecture Notes on the Formation and Early Evolution of Planetary Systems by Armitage

Module II: Exoplanet Demographics and Planet Formation

- **Protoplanetary Disks:** Gas–dust disks around young stars; evolve on Myr timescales, set the initial conditions for planet formation

- <u>**Dust, Pebbles, and Planetesimals:** Dust grains stick → pebbles (mm–cm); rapid drift & instabilities lead to km-scale planetesimals</u>

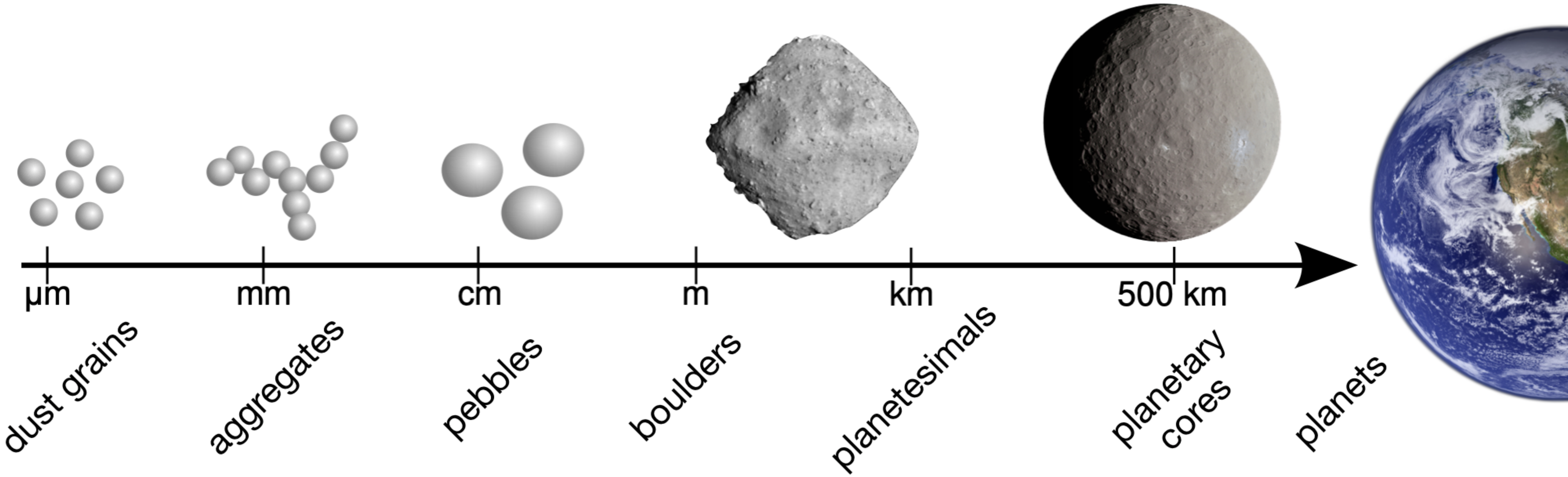
- **Planet Formation: Terrestrial and Giant Planets**

  Terrestrials: runaway/oligarchic growth → embryos → giant impacts

  Giants: ~10 $M_\oplus$ cores accrete gas before disk dispersal or via disk instability

- **Evolution of Planetary Systems:** Migration, resonances, and instabilities sculpt exoplanet architectures

Phases of Planet Formation



Credit: J. Drazkowska

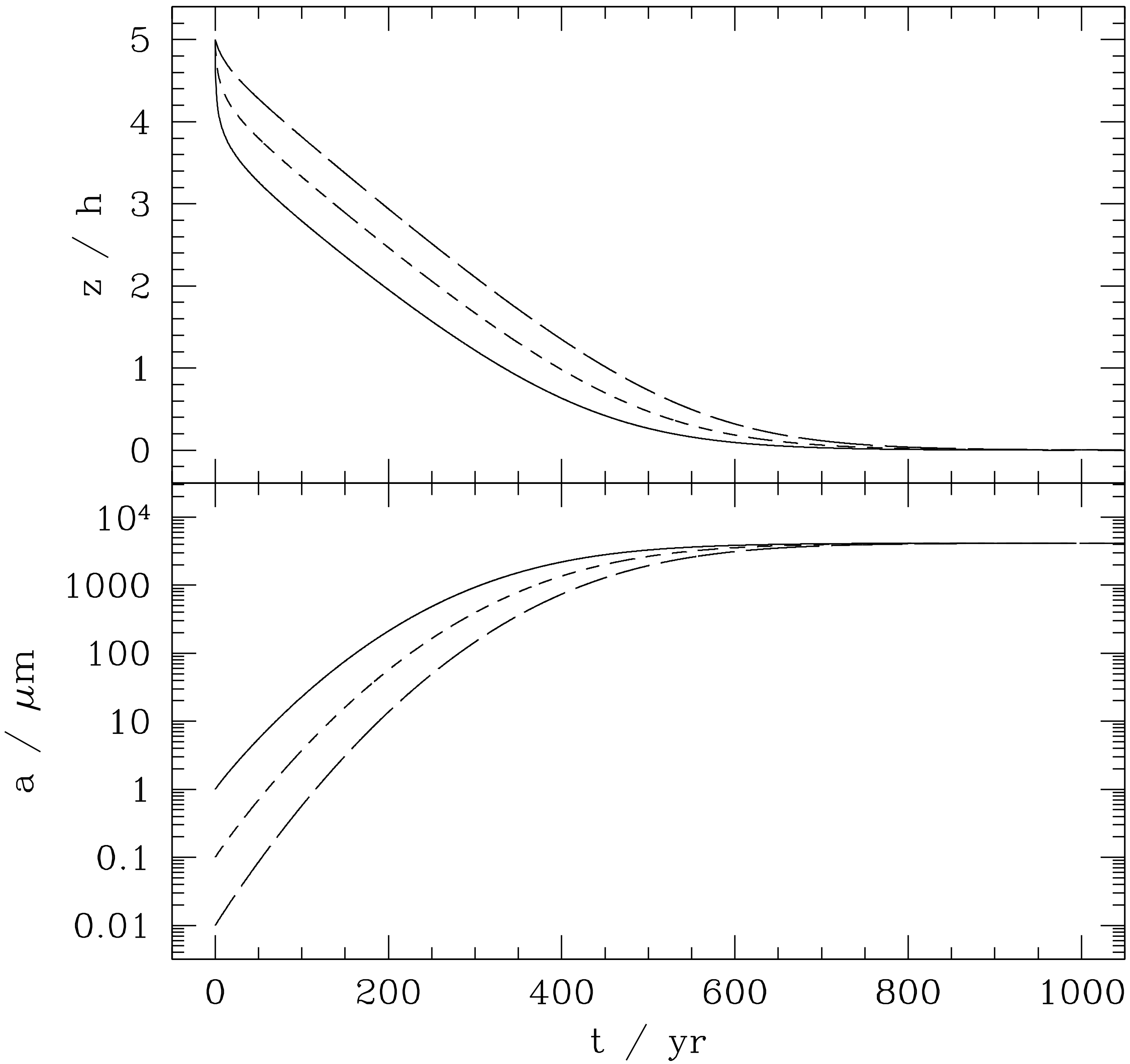
1. Dust Growth → Pebbles

- Sub-micron dust grains collide and stick via electrostatic forces.
- Growth proceeds through pairwise collisions to form cm–m sized pebbles.

2. Pebbles → Planetesimals

- Growth past the **meter-size barrier** likely requires gravitational instability of solids (e.g., the streaming instability).
- Once planetesimals form, they grow efficiently by **accreting pebbles** through radial drift and **gravitational focusing**.

Dust Settling and Coagulation



Vertical settling and resulting growth of particles (Armitage 07).

Disk Dynamics

The radial force balance for the gas in a protoplanetary disk is largely between three forces: the centrifugal force, pressure gradients, and gravity.

$$\frac{v_\phi^2}{r} = \frac{1}{\rho}\frac{dp}{dr} + \frac{GM_\star}{r^2}$$

Assuming that the pressure follows $p = p_0(r/r_0)^{-n}$, we get

$$v_\phi = v_K\sqrt{1 - n\frac{h^2}{r^2}}$$

For $dp/dr < 0$, the velocity of the gas will be **sub-Keplerian**. This is critical for determining **the motions of dust particles in the disk**.

Radial Drift of Dust in Disks

Large particles / "rocks" ($s \gtrsim 1$ m)

- Orbit at the **Keplerian** speed.
- Gas moves slower → particles feel a headwind.
- The headwind removes angular momentum, causing inward drift.

Small particles ($s \lesssim 1$ cm)

- Well-coupled to the gas.
- Orbit slightly **sub-Keplerian**, but lack pressure support.
- Experience a net inward force → spiral toward the star at a terminal radial velocity.

Dust Coupling

Stopping (friction) time $t_{\rm fric}$ quantifies **how tightly dust couples to gas**.

- Defined as

$$t_{\rm fric} = \frac{mv}{F_D} \quad \text{and} \quad \tau_{\rm fric} = t_{\rm fric}\Omega \ ,$$

  where m is the mass of a dust particle, v is the relative velocity of the dust grain to the gas disk, F_D is the drag force, and Ω is the orbital frequency.

- In the Epstein regime (for small particles $s \sim \mu m$),

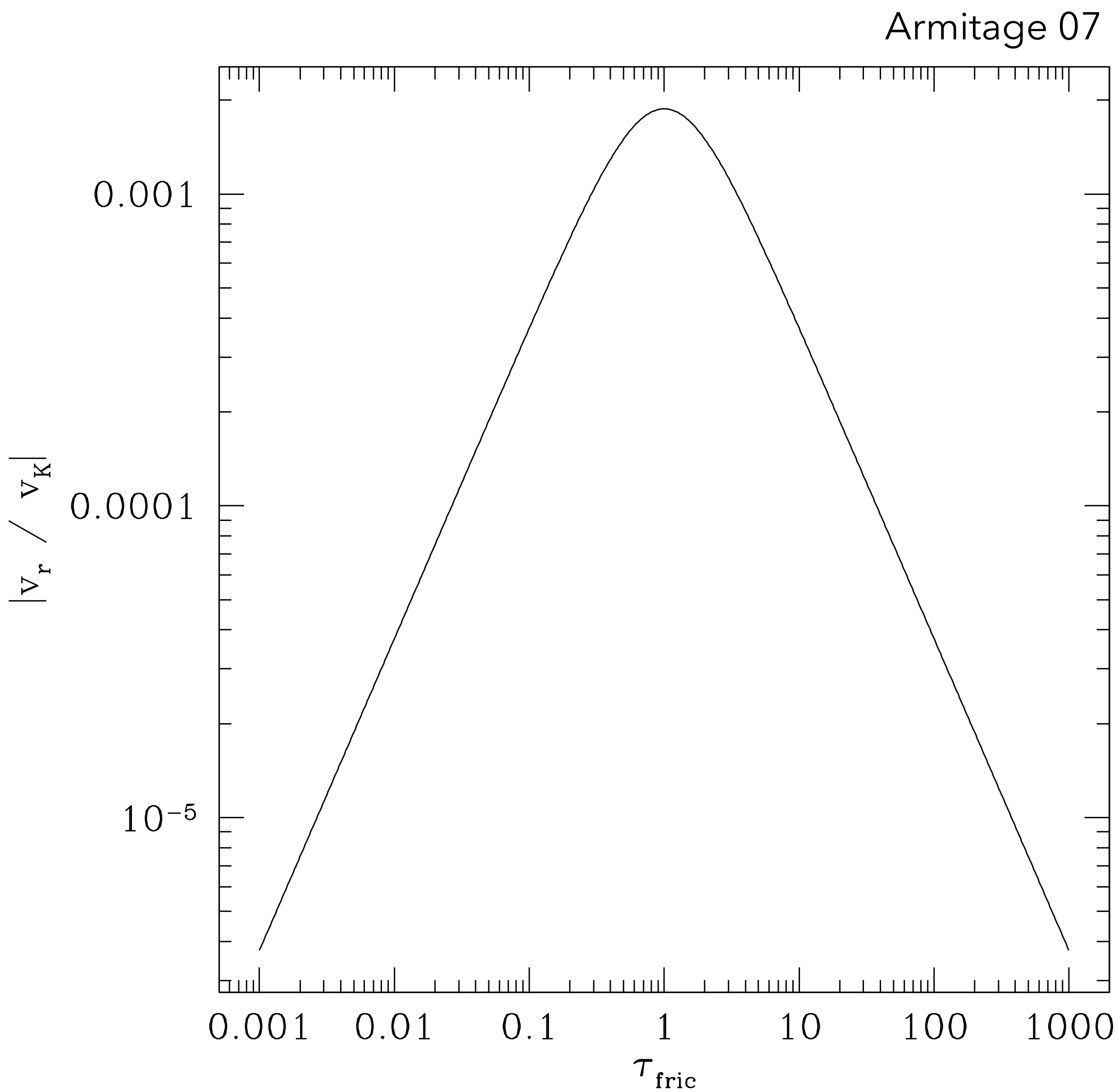
$$F_D = -\frac{4\pi}{3}\rho s^2 v_{\rm th} v \ ,$$

  where ρ is the gas density, s is the size of dust grain, and $v_{\rm th} = \sqrt{\frac{8k_BT}{\pi\mu m_p}} = \sqrt{\frac{8}{\pi}}c_s$ is the mean thermal velocity in the gas.

In-Class Activity

Radial Drift of Dust Particles

The "Meter-Size Barrier"



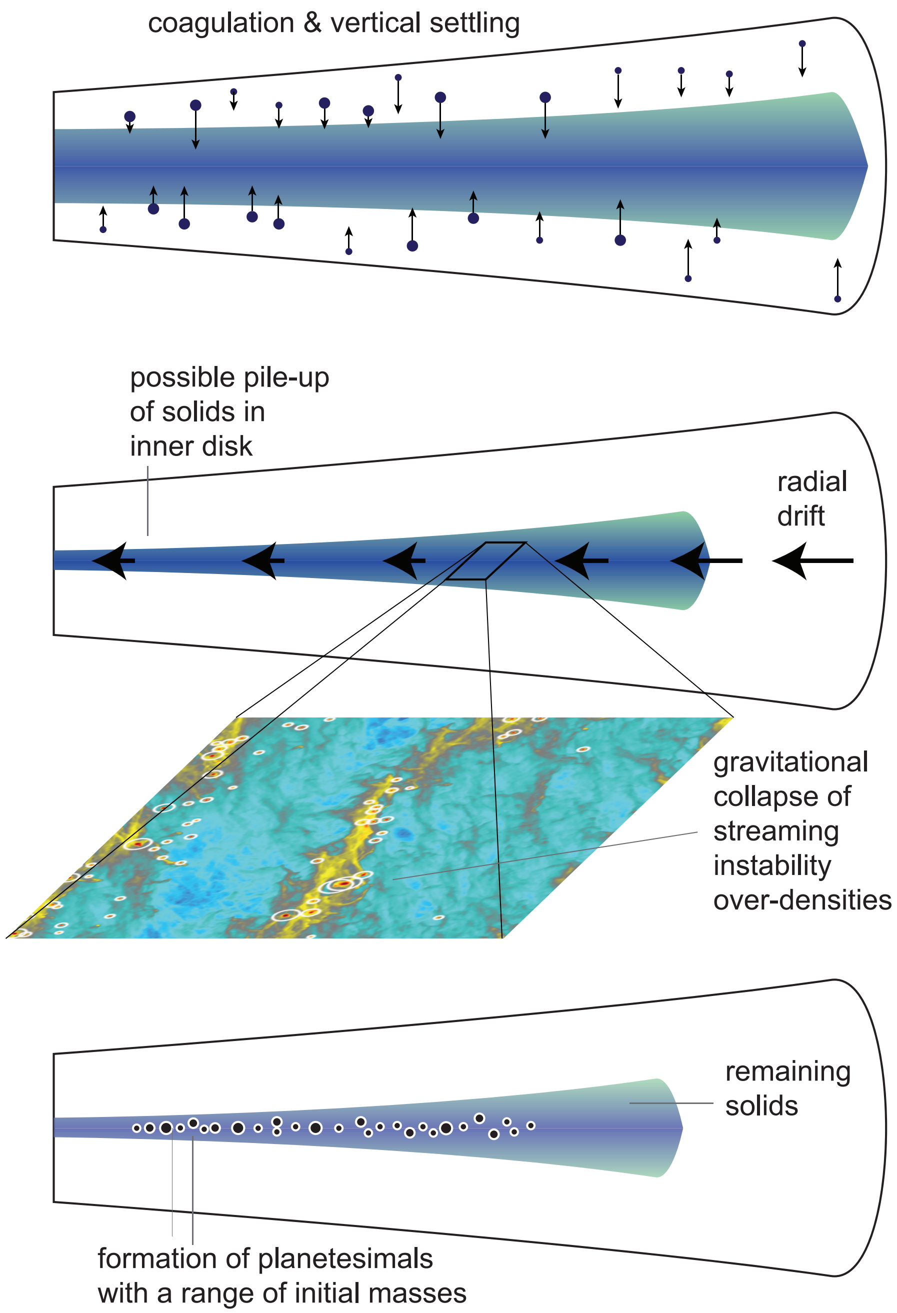
- Radial drift velocity of a dust particle

  $$\frac{v_r}{v_K} = \frac{-\eta}{\tau_{\rm fric} + \tau_{\rm fric}^{-1}},$$

  where $v_{\phi,\,{\rm gas}} = v_K(1-\eta)^{1/2}$.

- Radial velocity peaked at $\tau_{\rm fric} = 1$
- At 1 au, $\eta v_K \sim 25{-}50\ {\rm m\,s^{-1}}$ ⇒ meter-scale bodies drift inward on ~100 yr, far shorter than disk lifetimes
- Solids near cm–m sizes are rapidly lost to the star unless they can jump this size range quickly.

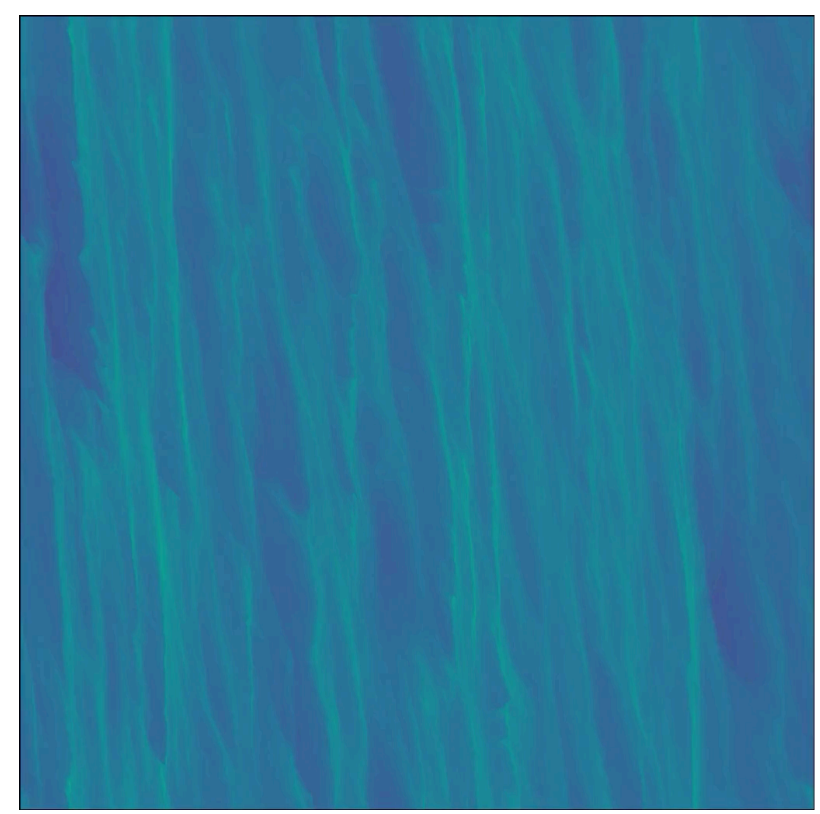
A Way Around the "Meter-Size Barrier"
Streaming Instability



Armitage 07

Streaming Instability (SI): Pebbles → Planetesimals

- If enough pebbles pile up, their drag on the gas slows the drift locally.
- This feedback makes pebbles clump together into dense filaments.
- These clumps can collapse under gravity to form planetesimals directly.



Credit: Rixin Li