Streaming Instability and Turbulence: Conditions for Planetesimal Formation

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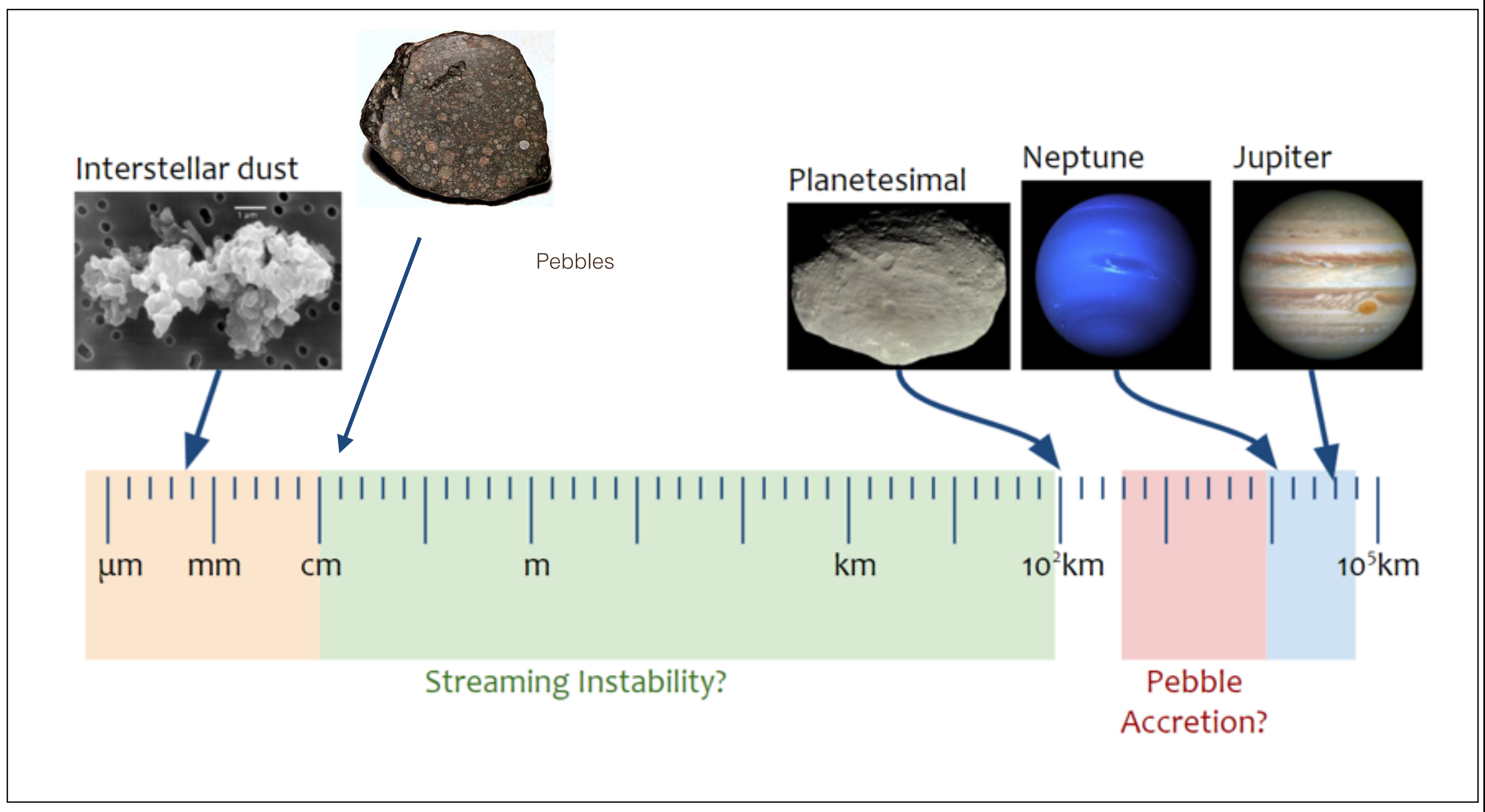
Motivating Questions

1. How do mm- to cm-sized pebbles grow into km-sized planetesimals in protoplanetary disks?
2. How would conditions for planetesimal formation be different between laminar and turbulent disks?
3. Does a smaller dust scale height necessarily mean weaker turbulence?

Background

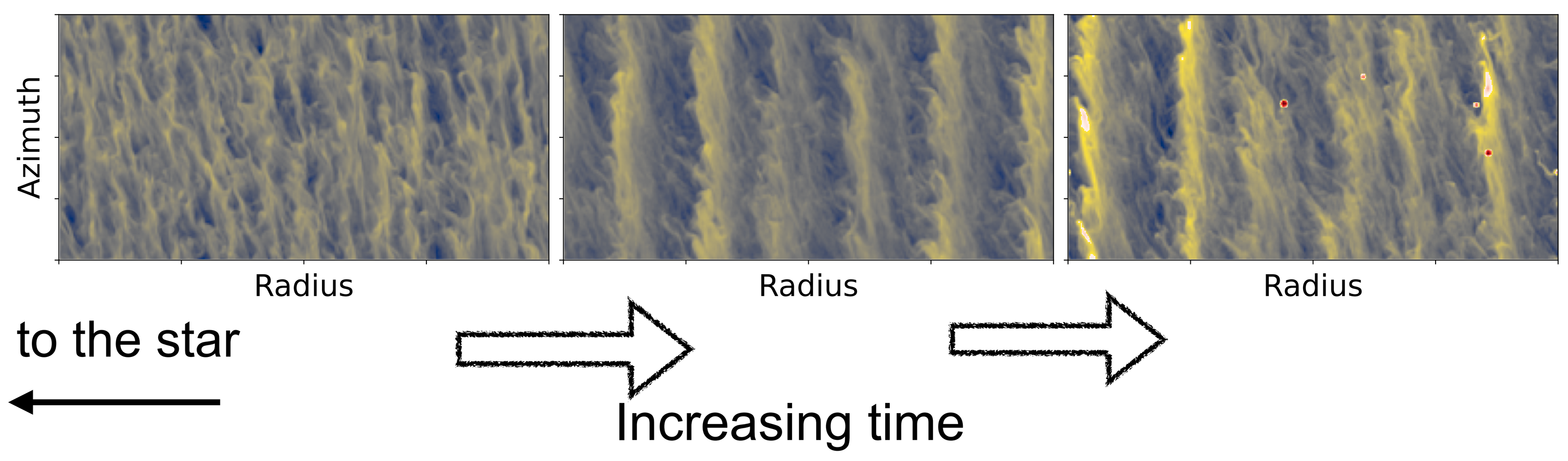


How mm-cm sized pebbles grow into planetesimals? Answering to this question is one of the biggest questions in all of planet formation. The difficulties lie with several growth barriers that prevent pebbles from sticking together to grow in size.

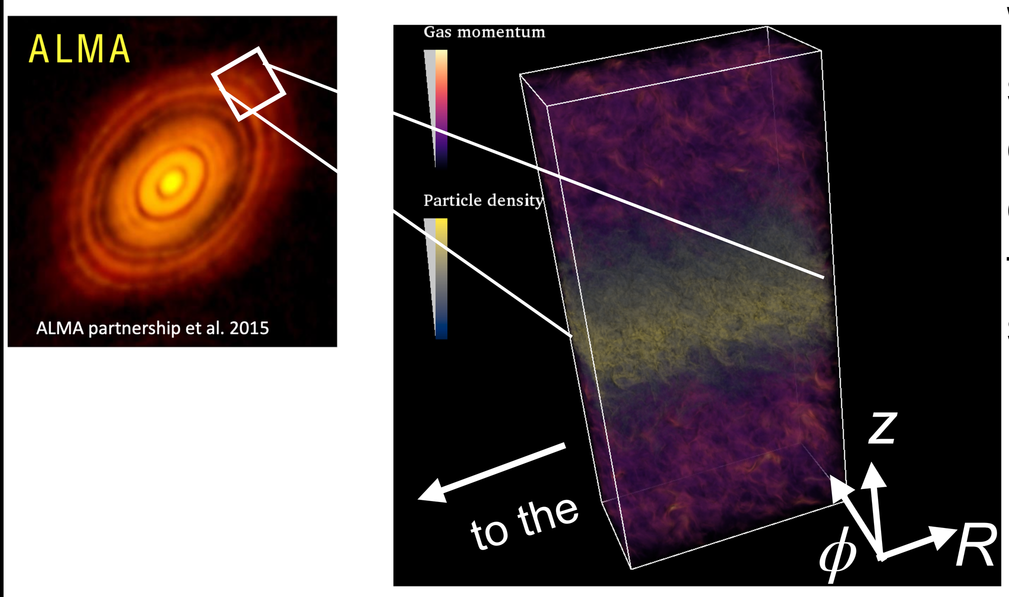
Streaming Instability

The streaming instability (SI) is one of the most promising mechanisms for planetesimal formation as it provides a robust and rapid path around the growth barriers. The SI arises from angular momentum exchange between gas and solid particles via aerodynamic coupling in protoplanetary disks. The SI leads to rapid concentration of the particles in narrow filaments, and under some circumstances, these filaments can reach sufficiently high particle densities that gravitational collapse ensues, producing planetesimals.

Particle density (top-down view)



Numerical method: Shearing box



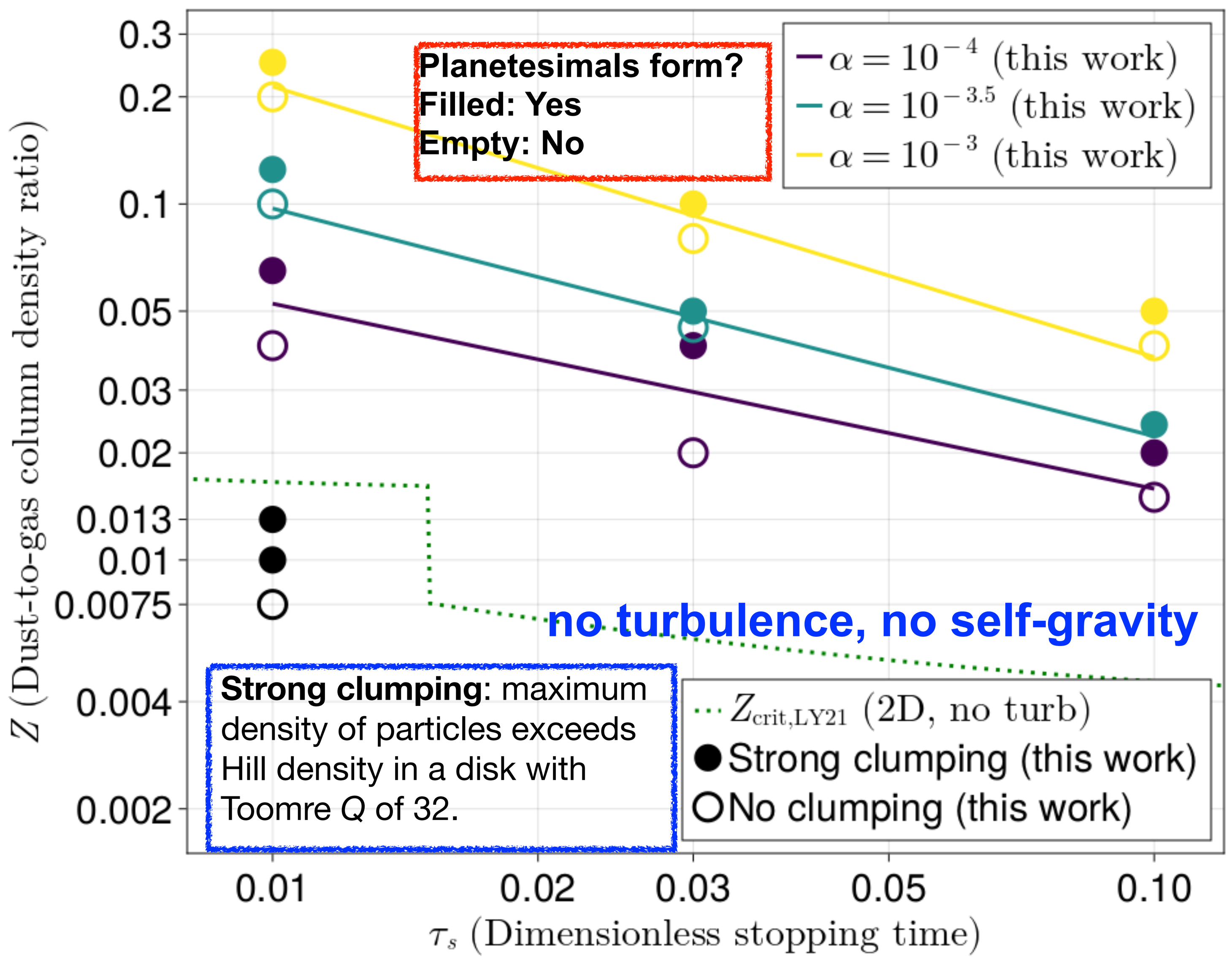
We carry out shearing box simulations using the *Athena* code. We explore the conditions for planetesimal formation in two different setups:

1. **2D** axisymmetric (r-z) laminar disk with **larger domain and higher resolution than any previous studies.**
2. **Full 3D** with **turbulence forcing** and **self-gravity of particles** implemented.

***Shearing box**: A co-rotating patch of a disk sufficiently small such that the domain can be treated in Cartesian coordinates without curvature effects.

Result 1. Conditions for Planetesimal Formation

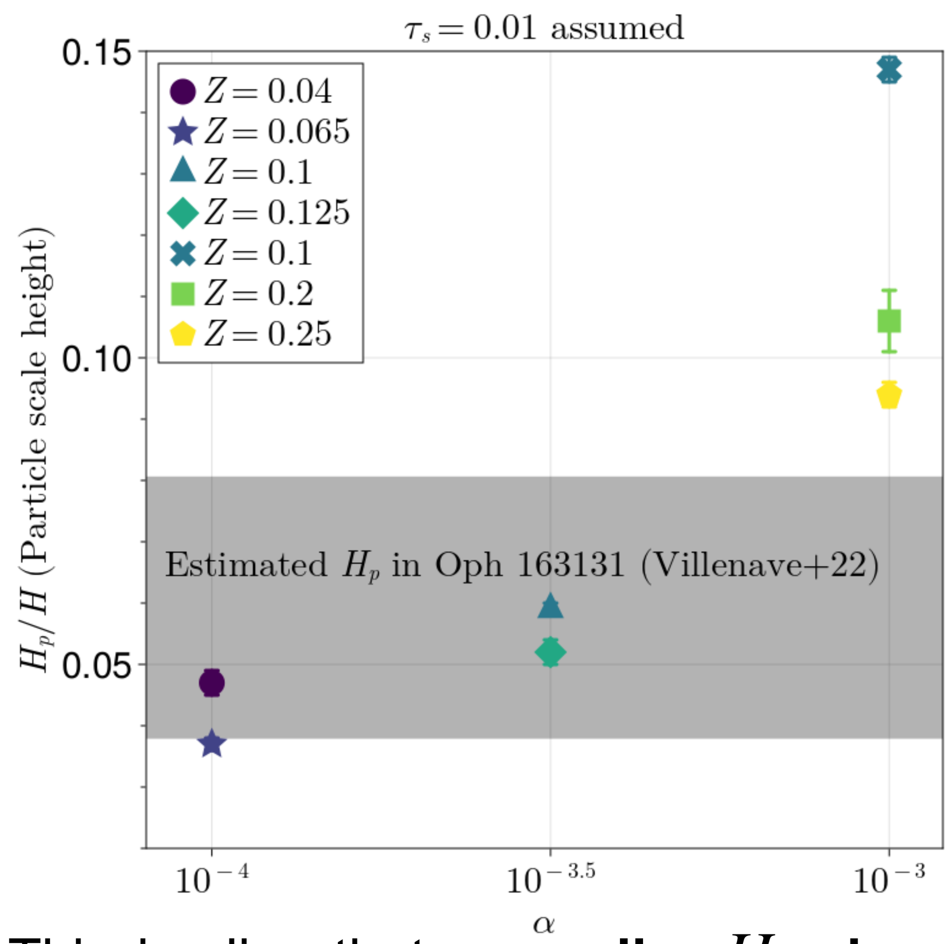
Turbulent forcing and particle self-gravity included



*τ_s can be translated to particle sizes. For example, τ_s = 0.01 corresponds to ~ mm sizes at 50 au in a standard disk model. The solid lines show critical Z values for three different α values above which planetesimals form. In the runs marked as black circle at $\tau_s = 0.01$, we were looking at the pure SI case

- Even modest level of turbulence **makes it harder for the SI to form planetesimals**. When $\alpha = 10^{-3}$, the SI requires **a factor of ~10 enhancement in Z** (far above the ISM value; see the three solid lines in the plot above).
- It implies that if a disk is modestly turbulent, **dust rings or vortices**, which can strongly concentrate pebbles, may be the **only regions** where planetesimal formation via the SI can occur.
- In our 2D axisymmetric simulations, we found that a **critical Z value at $\tau_s = 0.01$ lies below 0.01**. This is a factor of ~ 2 smaller than LY21's $Z_{\rm crit}$ and results in a smooth transition between τ_s = 0.02 and 0.01.
- Overall, our results are a significant refinement of the criteria necessary for planetesimals to form, under a range of disk conditions from purely laminar to moderately turbulent gas.

Result 2. The effect of particle mass on the thickness of dust disks



We found that as particle density increases near the midplane, the particle scale height (H_p) decreases. More quantitively, we propose an estimation for H_p that accounts for both turbulence and the particle-to-gas density ratio ($\epsilon \equiv \rho_p/\rho_g$):

$$H_p \sim \frac{H}{\sqrt{\epsilon+1}}\sqrt{\frac{\alpha}{(\alpha+\tau_s)}}$$

This implies that a **smaller H_p does not necessarily indicate weaker turbulence** because H_p depends on ϵ as well as α (i.e., is H_p small because of weak turbulence or large dust mass?). For example, Villenave+22 estimated $\alpha \lesssim 10^{-5}$ for a thin, edge-on disk (Oph 163131). We found a similar range of H_p **but for $\alpha \gtrsim 10^{-4}$ when Z is sufficiently high (see the figure above).**