Conditions for Strong Clumping by the Streaming Instability

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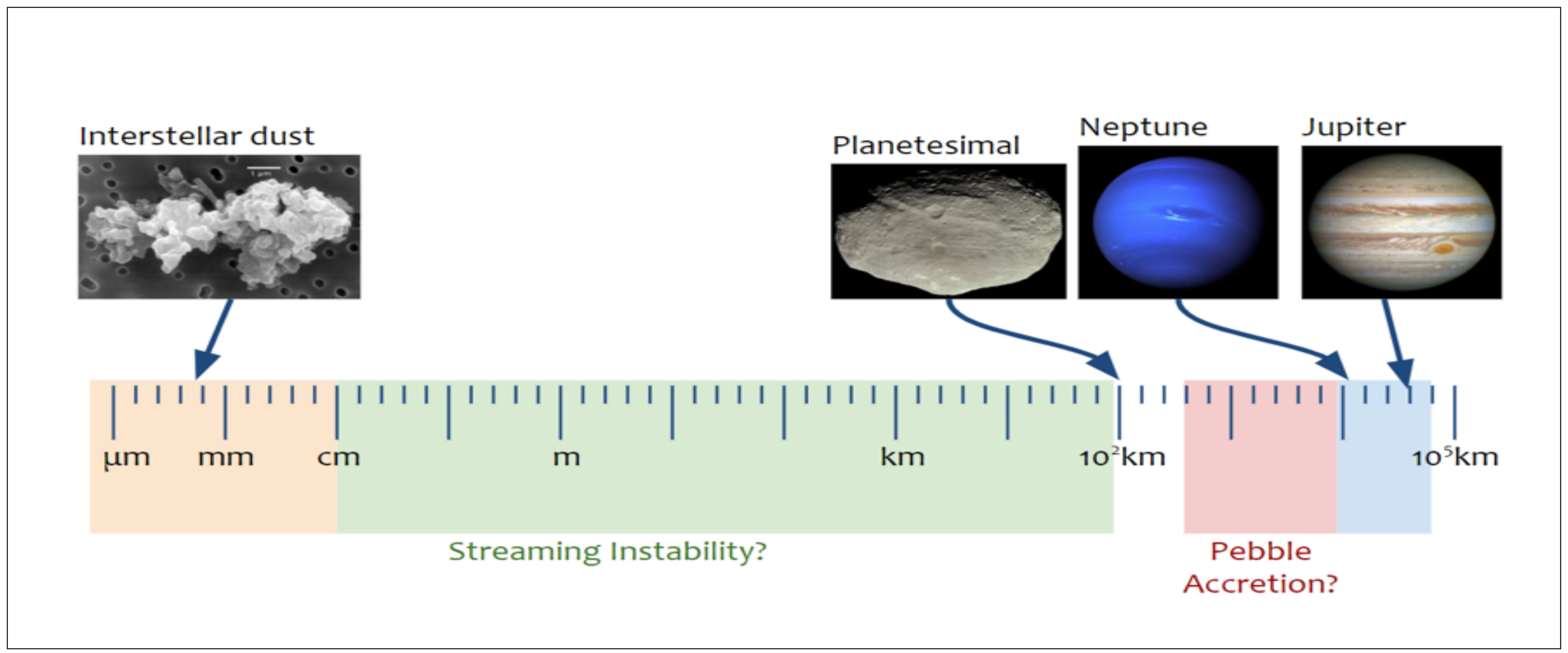
Motivations

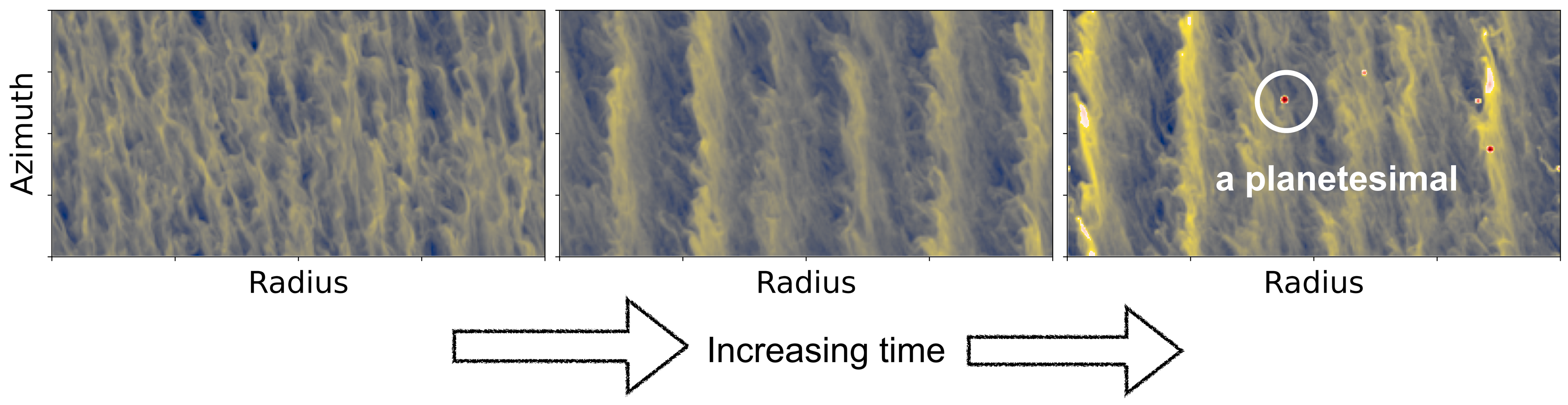


How do mm-cm sized pebbles grow into planetesimals? Answering this question is one of the biggest challenges in all of planet formation. The difficulties lie with several growth barriers that prevent pebbles from sticking together to grow in size.

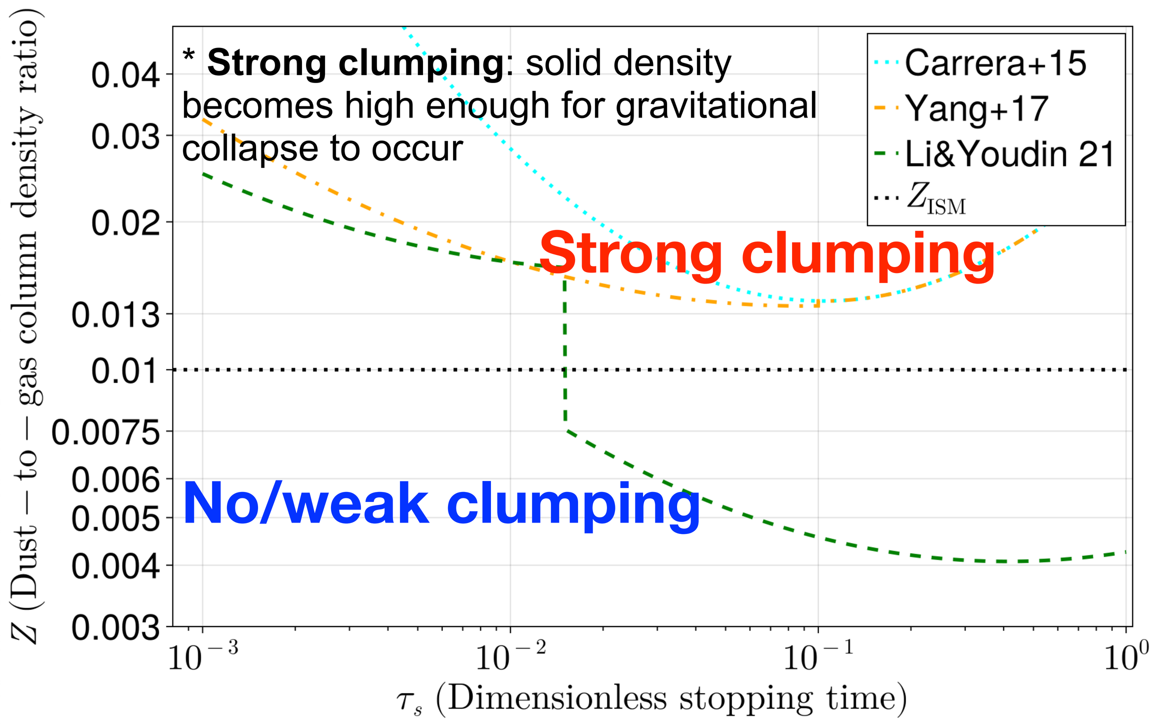
Streaming Instability (SI)

The SI is one of the most promising mechanisms for planetesimal formation, as it offers a robust and rapid pathway that circumvents growth barriers. The SI is driven by angular momentum exchange between gas and solids through aerodynamic drag. This interaction leads to the rapid concentration of solids, and **under favorable conditions**, the resulting overdensities can become large enough for gravitational collapse, forming planetesimals.

Dust density (top-down view)



Conditions for strong clumping by the SI



Previous studies have sought to identify the conditions under which SI-driven concentration becomes strong enough to trigger planetesimal formation.

Although effective for $\tau_s > 0.01$, **the SI needs $Z > Z_{\rm ISM} = 0.01$ for smaller solid particles (i.e., $\tau_s \lesssim 0.01$)**

Moreover, **those previous studies used 2D axisymmetric models.**

To build more realistic conditions for strong clumping, we simulate two different models with ATHENA code and the shearing box approximation.

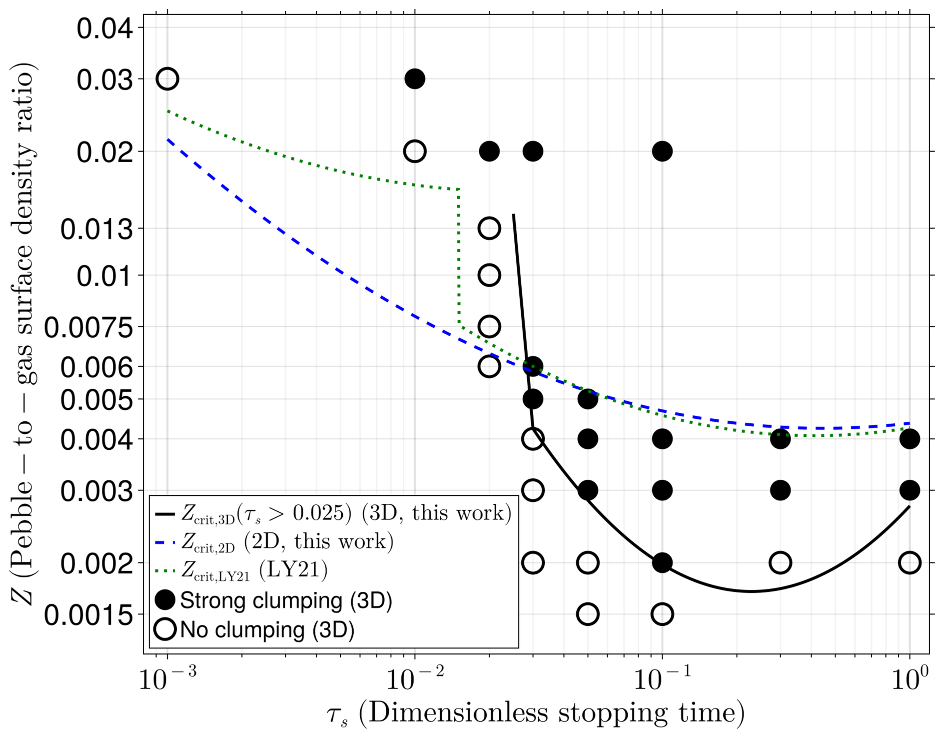
1. **2D axisymmetric models** (already published; Lim et al. 2025)
   - focus on $\tau_s = 10^{-3} - 10^{-2}$.
   - use *Z*=0.0075, 0.01, and 0.013 for $\tau_s = 10^{-2}$ and *Z*=0.02 for $\tau_s = 10^{-3}$.
   - use high grid resolutions (up to 5120 cells per gas scale height *H*) than most of previous simulations.
2. **Full 3D models** (in preparation)
   - cover a wider range of τ_s: $10^{-3} \leq \tau_s \leq 1.0$.
   - use grid resolution of 640 cells/*H* used for most of the simulations.

Results 1: Conditions for Strong Clumping

$$\log(Z_{\rm crit}) = A(\log \tau_s)^2 + B(\log \tau_s) + C$$

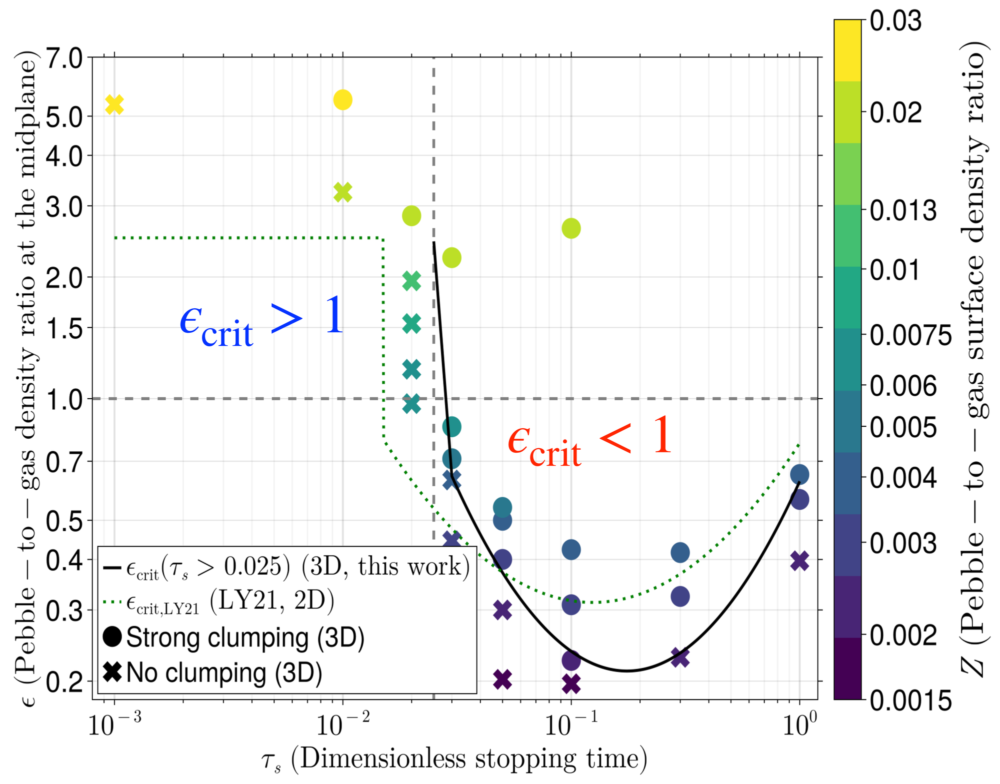
A=0.10, *B*=0.07, *C*=-2.36 (2D, blue curve)

_A_=0.51, _B_=0.65, _C_=-2.56 (3D, black curve, $\tau_s > 0.025$)



- Our 2D simulations with high grid-resolutions show strong clumping for *Z*=0.01 and 0.013 when $\tau_s = 10^{-2}$.
- For $\tau_s = 10^{-3}$, we did not see strong clumping even with the highest grid resolution (5120/*H*).
- As a result, we lower $Z_{\rm crit}(\tau_s = 0.01)$ below 0.01, making the smooth transition of the curve between $\tau_s = 0.01$ and 0.02 (compare green and blue curves).

- Our 3D simulations show even lower $Z_{\rm crit}$ for $\tau_s > 0.02$, with $Z_{\rm crit} \sim 2 \times 10^{-3}$ for $\tau_s = 0.1$.
- However, for $\tau_s \lesssim 0.02$, we find that strong clumping becomes less efficient compared to 2D simulations, resulting in a sharp transition in $Z_{\rm crit}$ between $\tau_s = 0.02$ and 0.03.
- Due to the sharp transition, we provide the best-fit to $Z_{\rm crit,3D}$ for $\tau_s > 0.02$ only.



ϵ : the dust-to-gas density ratio at the midplane

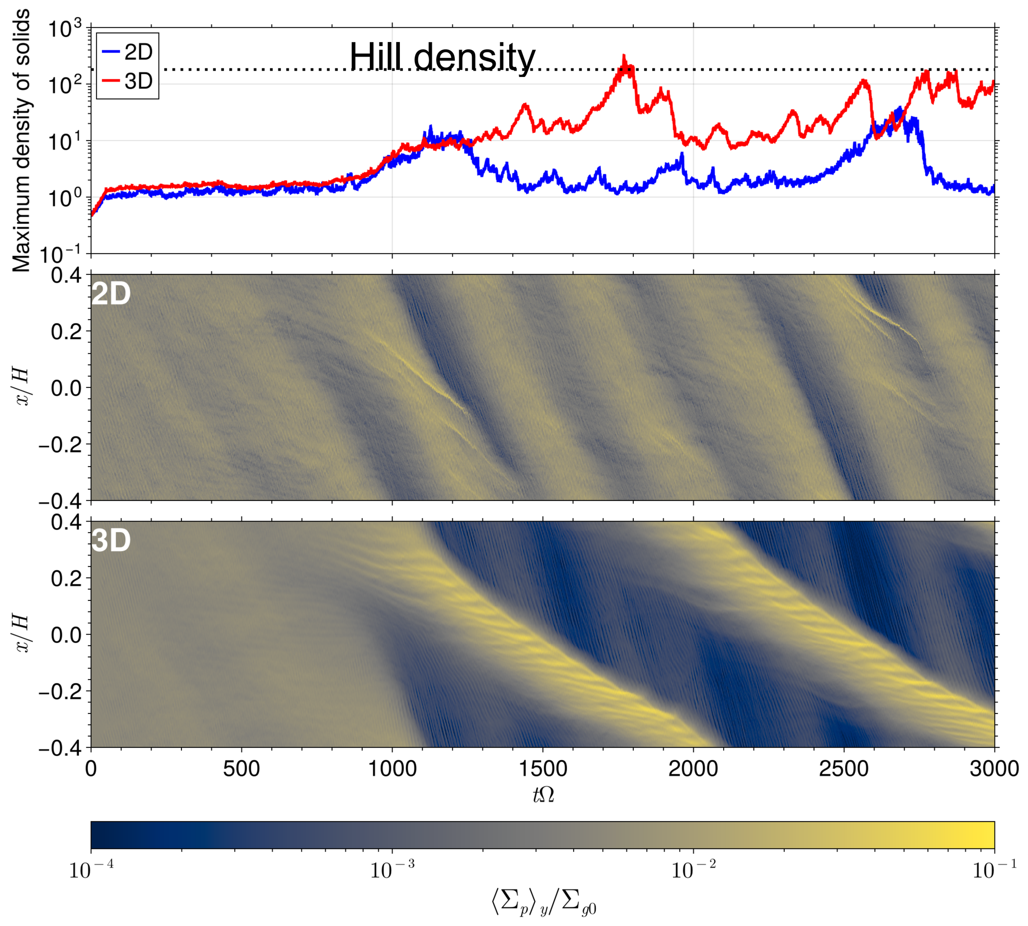
$$\log(\epsilon_{\rm crit}) = A(\log \tau_s)^2 + B(\log \tau_s) + C$$

_A_=0.82, _B_=1.24, _C_=-0.2 (3D, black curve, $\tau_s > 0.025$)

- When $\epsilon_{\rm crit} < 1$, 3D simulations show **more** efficient strong clumping compared to 2D (i.e., $Z_{\rm crit,3D} < Z_{\rm crit,2D}$)
- When $\epsilon_{\rm crit} > 1$, 3D simulations show **less** efficient strong clumping compared to 2D (i.e., $Z_{\rm crit,3D} > Z_{\rm crit,2D}$)

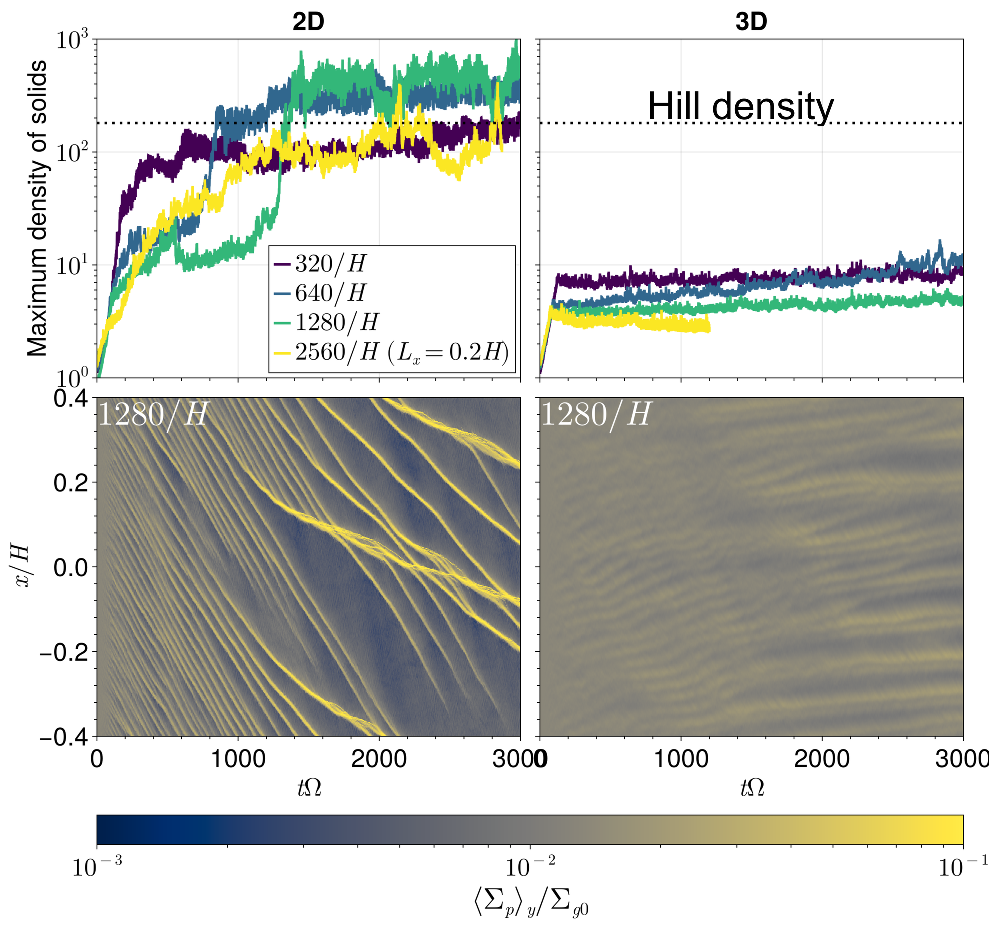
Results 2: Comparison between 2D and 3D Models

$\tau_s = 0.03$, $Z = 5 \times 10^{-3}$ ($\epsilon < 1$)
grid resolution: 640/*H*



- The 3D case shows filaments-in-filaments structure, where the large parent filament contains multiple subfilaments within.
- Those subfilaments occasionally merge, increasing maximum solid density beyond the Hill density.
- The parent filament induces a traffic-jam effect where solid particles drift faster than the parent filament and thus join the filament.
- This results in the persistent filaments-in-filaments structure, with larger density contrast between inside and outside the structure compared to that in the 2D case.

$\tau_s = 0.02$, $Z = 1.3 \times 10^{-2}$ ($\epsilon > 1$)
grid resolution: 320/*H* - 2560/*H*



- Contrary to $\epsilon < 1$ case, 2D runs show much stronger concentration in all resolutions considered.
- The temporal evolution of filaments is remarkably different between 2D and 3D.
- In 2D, filaments drift radially inward (i.e., moving toward negative *x*) and merge each other, promoting strong clumping.
- By contrast, filaments in 3D simulations do not appear to drift radially inward.
- Moreover, the concentration becomes weaker with increasing resolution in 3D cases.