

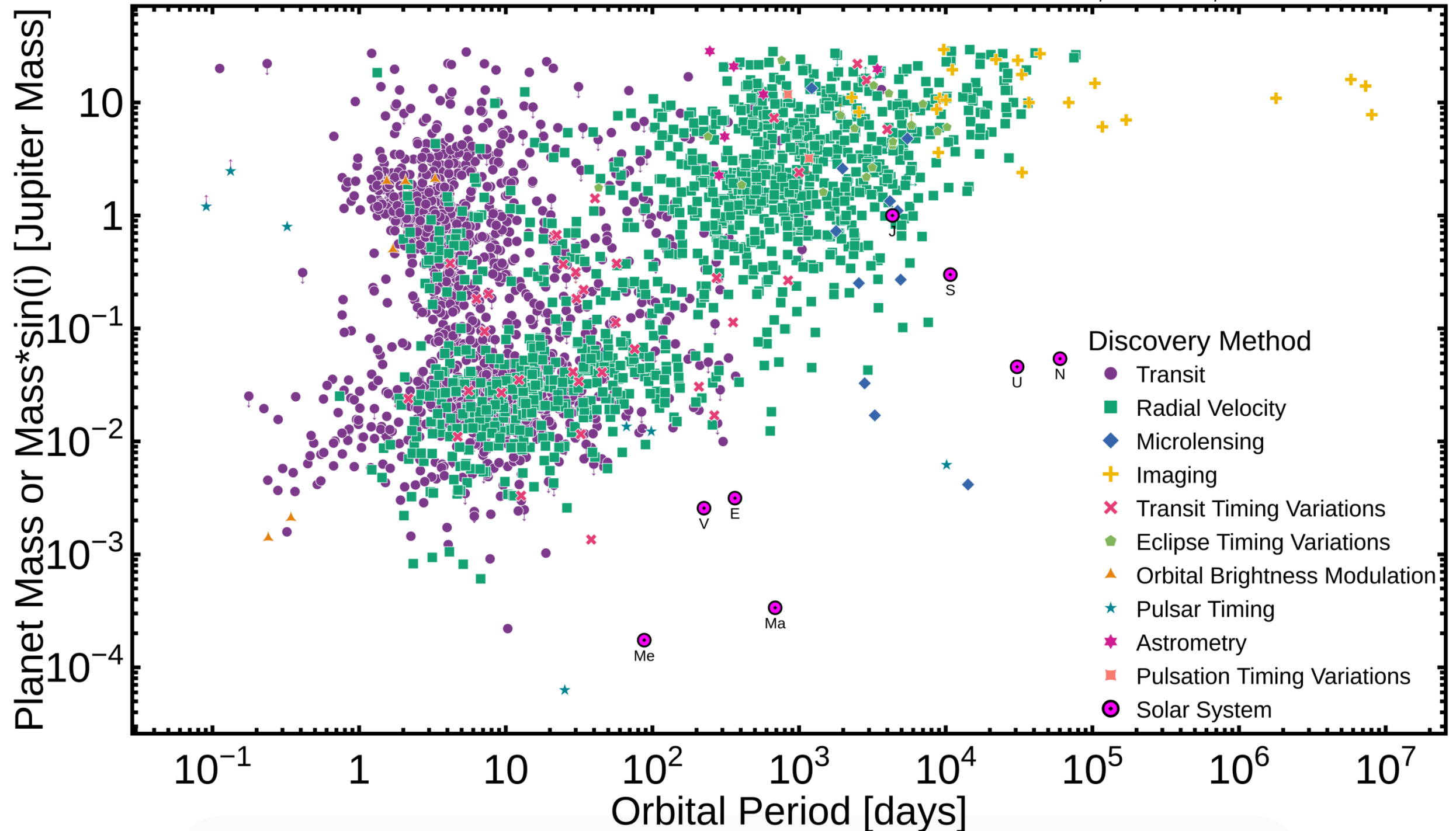
Planet Formation I

Jake Simon
Iowa State University

Exoplanets

Planet Mass or Mass* $\sin(i)$ vs Orbital Period

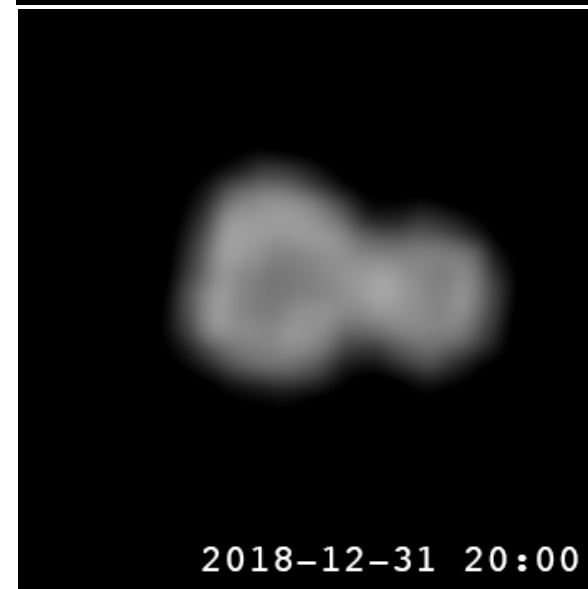
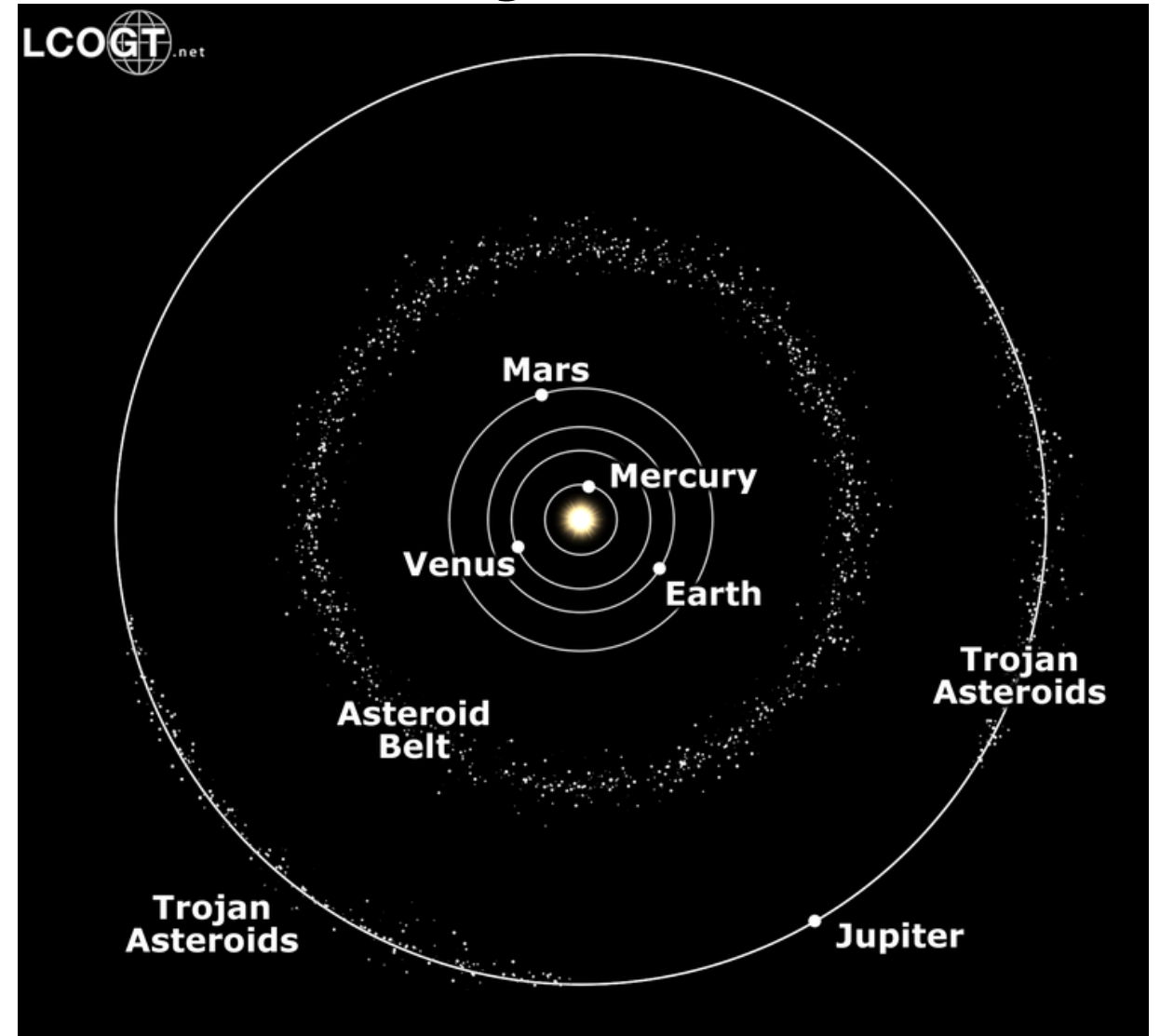
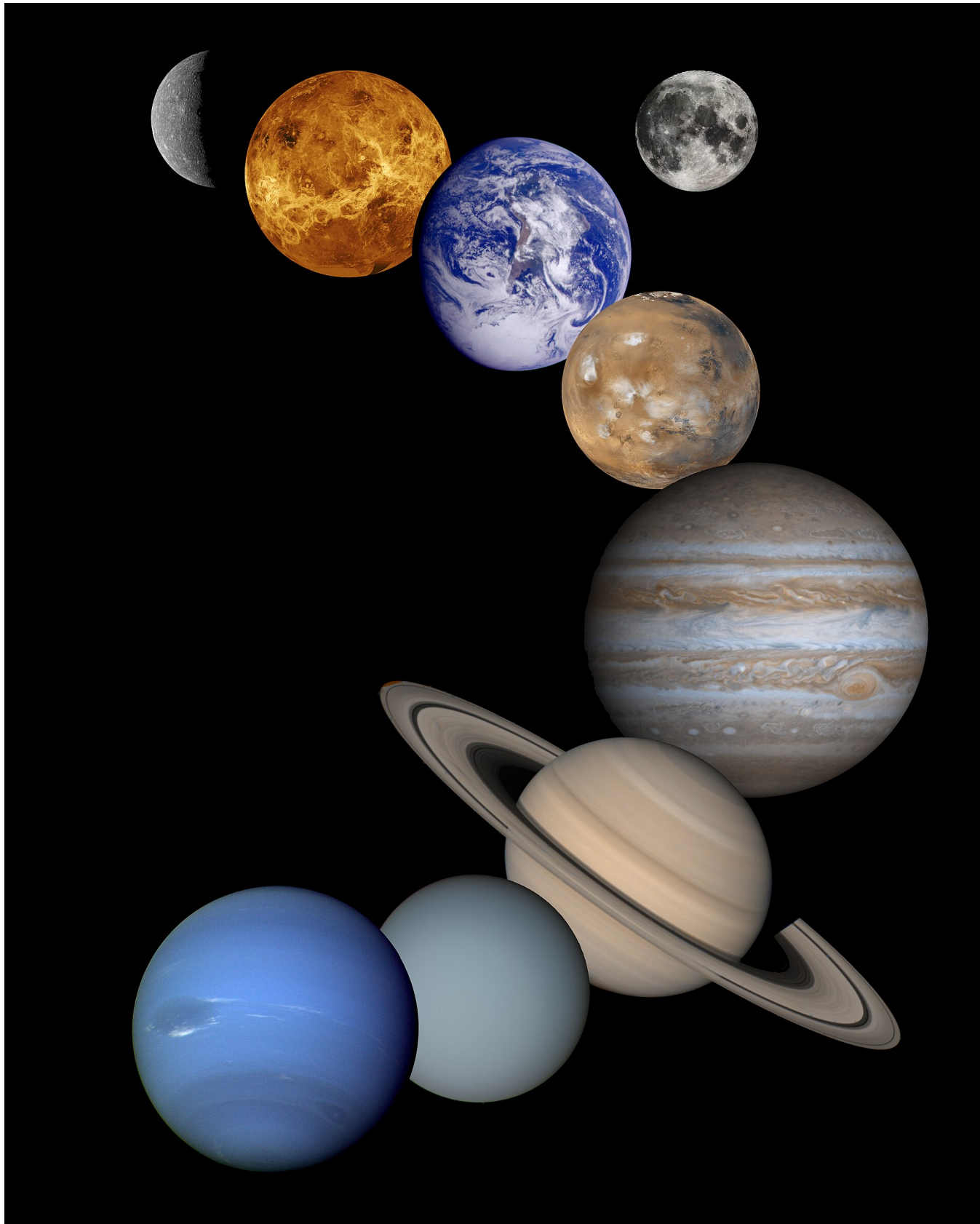
exoplanetarchive.ipac.caltech.edu, 2026-07-09



- We know a lot about different types of planetary systems
- But very little about each system

Solar System

We know a lot about one system!



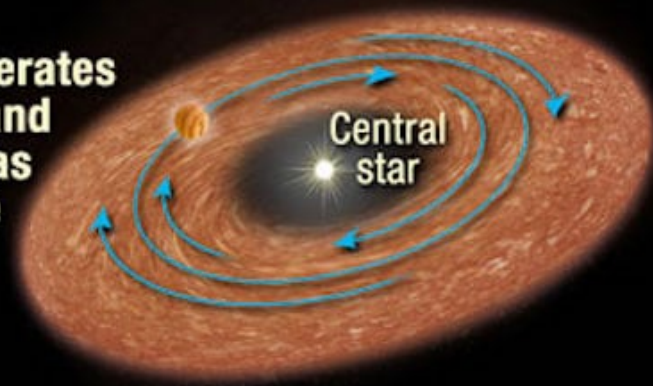
Two primary modes of planet formation:

Gravitational Instability and Core Accretion

Formation Scenarios for Planetary-Mass Companion

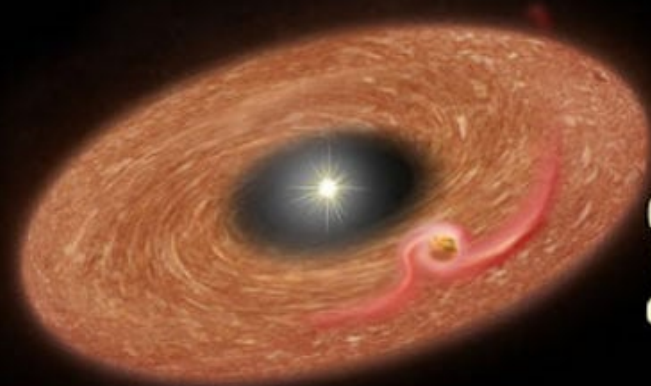
Core Accretion Model

Planet agglomerates from dust and attracts gas envelope



Disk Instability Model

Clump of gas collapses in circumstellar disk



- For many years, the GI or disk instability model was not favored
- Recent observations have reinvigorated the idea

Gravitational Instability (GI)

(“Top down”)

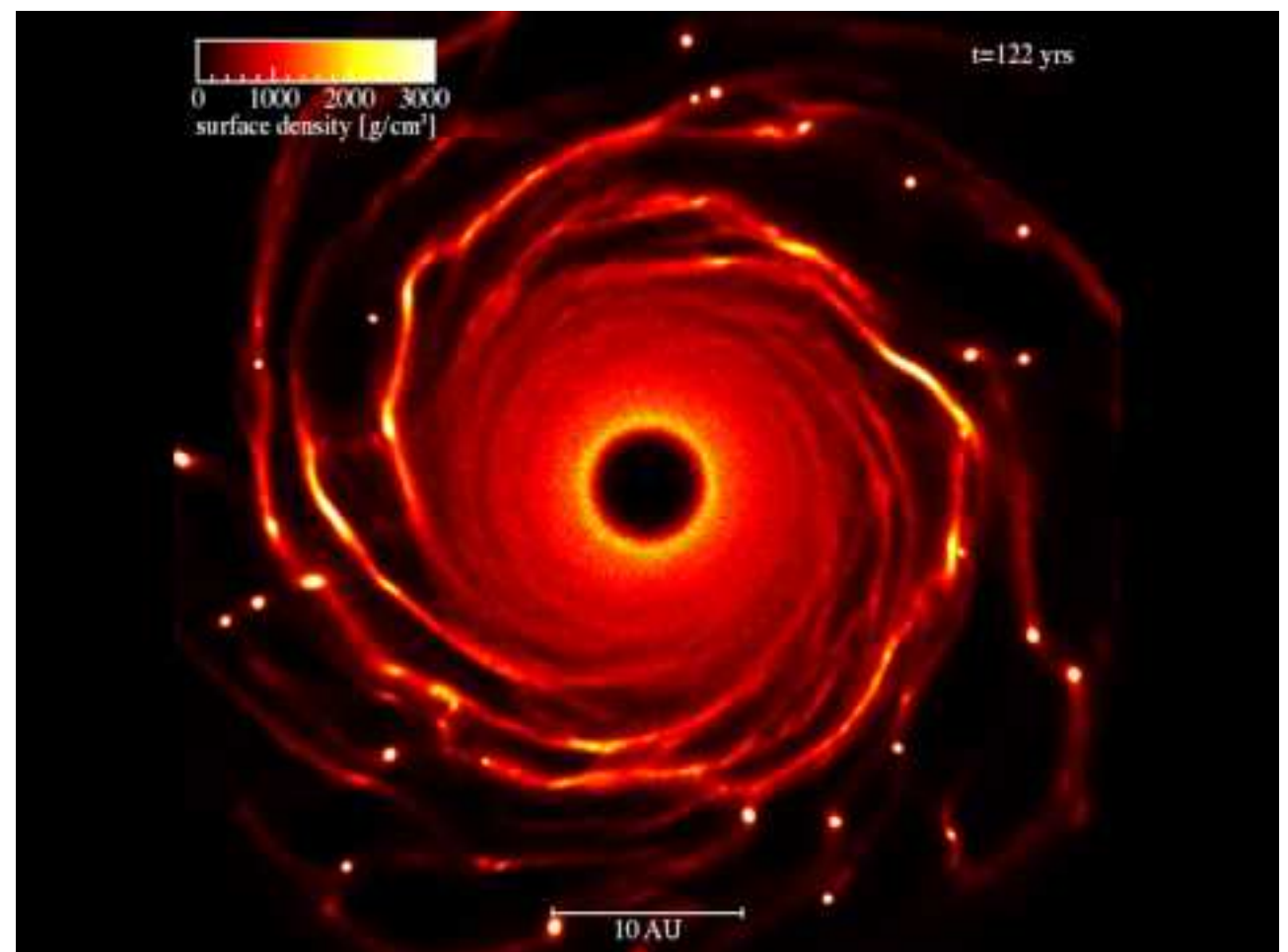
- Some disks can be gravitationally unstable (Zhaohuan’s lectures)
- Condition for this:
- **Rapid cooling (on dynamical timescale!!) is necessary to overcome negative feedback mechanism (more on this tomorrow)**

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} \lesssim 1$$

- **But also needs to cool sufficiently rapidly**
- **Necessary cooling timescale:**

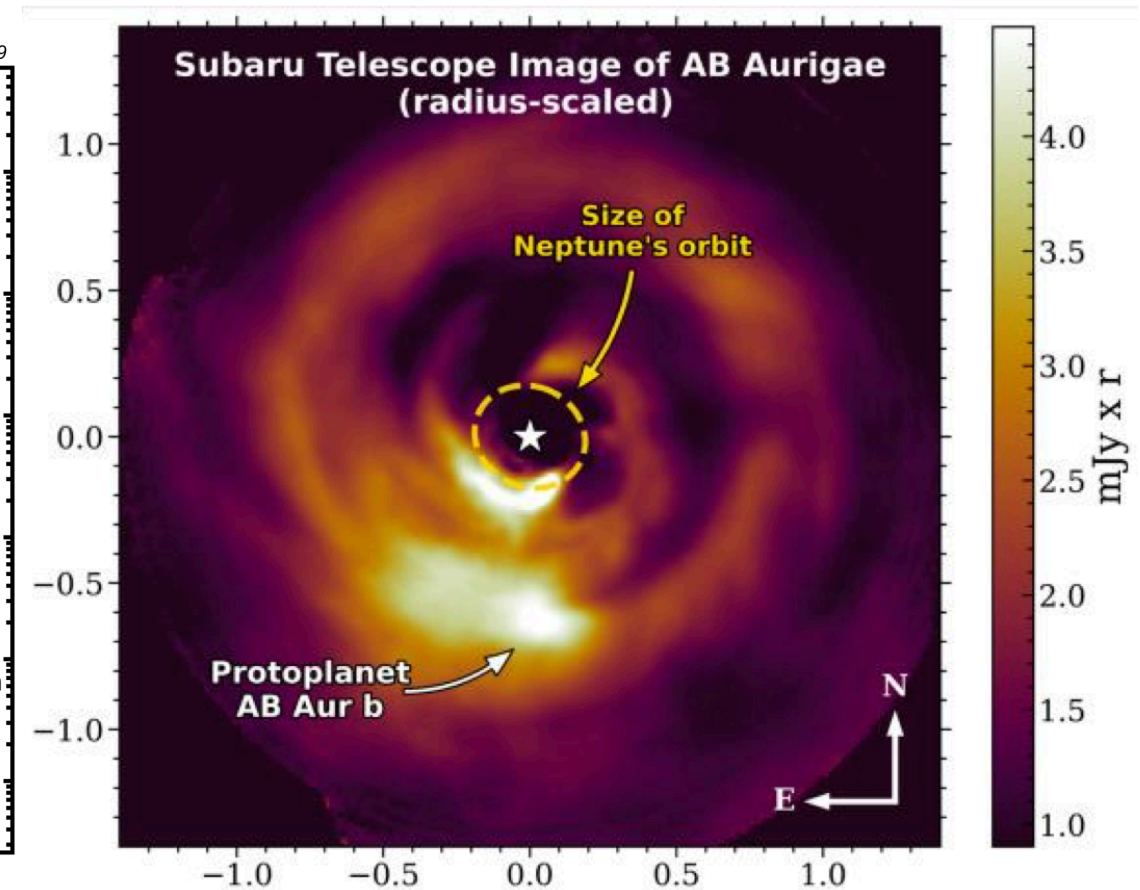
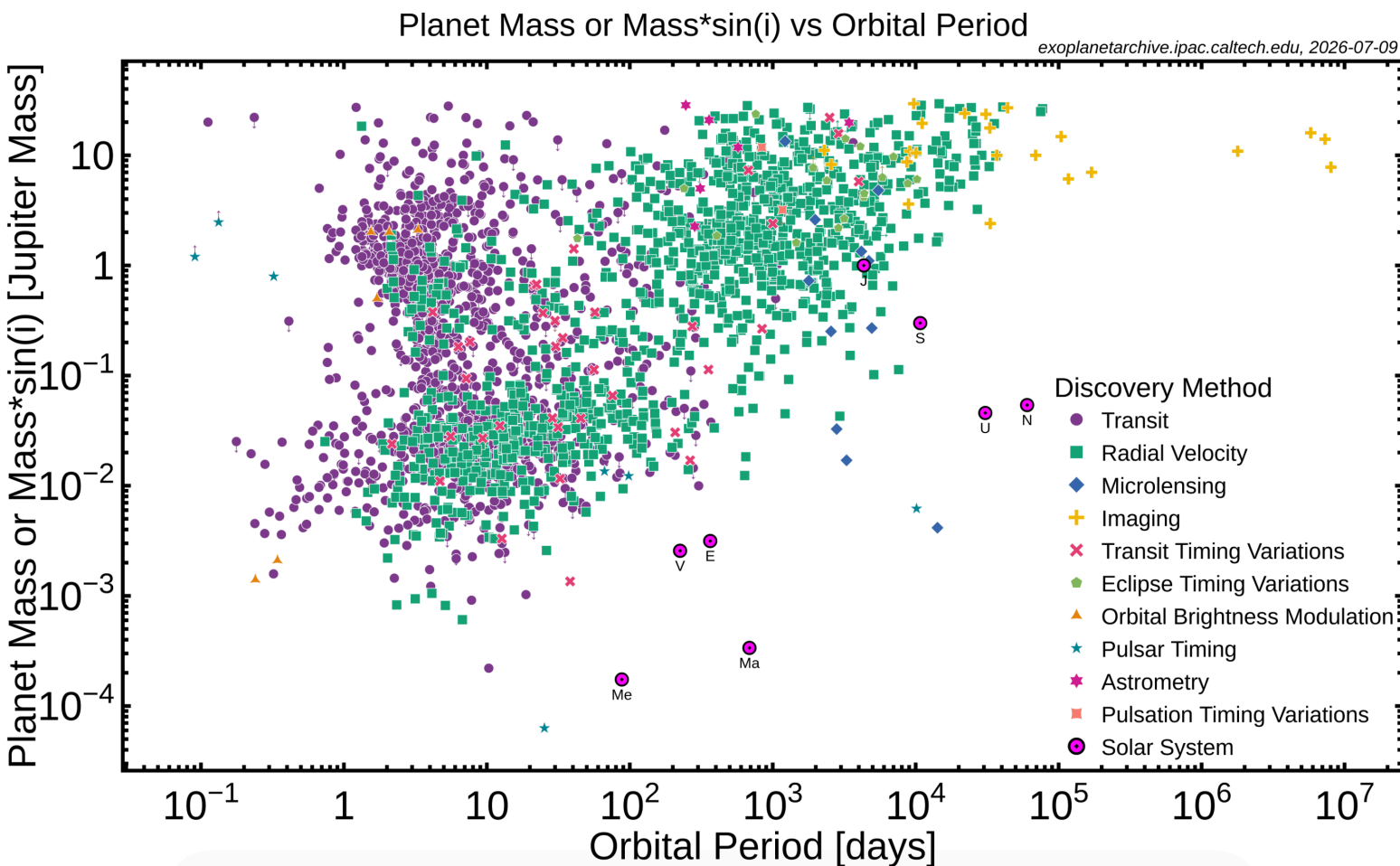
$$\tau_{\text{cool}} \approx 3\Omega^{-1}$$

(determined by numerical simulations)



Daniel Price - Gravitationally unstable disk that fragments into bound objects

GI - may explain massive planets at large distances

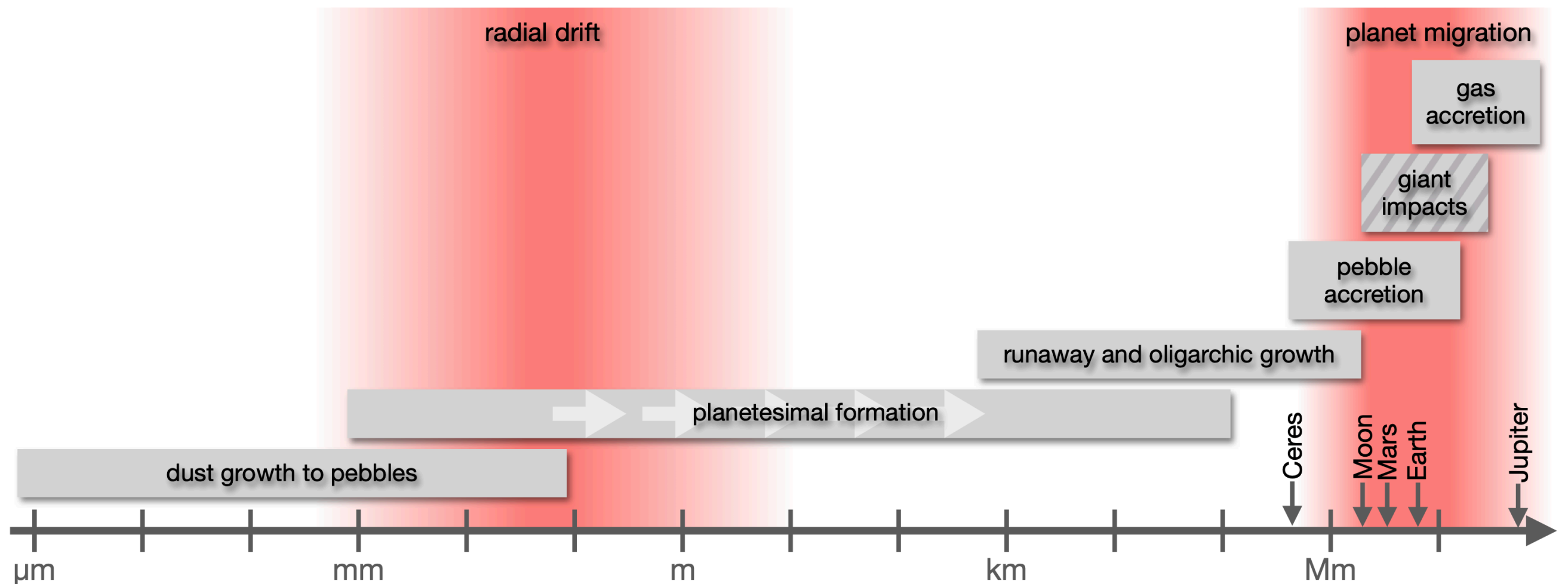


Currie et al. (2022)

- Some planets form very far from their host star (AB Aur b at 93 AU)
- Core accretion not efficient at large distances from star
- Conversely, disk is more gravitationally unstable at large distances

Core Accretion

(“Bottom up”)

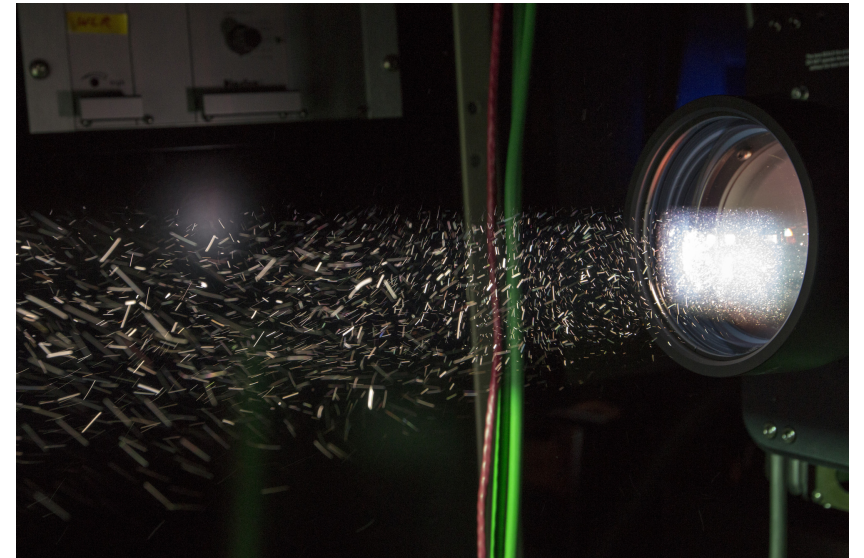


Drazkowska et al. (2023), PPVII chapter

1. Dust grains grow, fall and settle on the disk mid-plane;
2. Planetesimals form in the mid-plane by gravitational instabilities (different than the GI mechanism!) in the dense mid-plane of the protoplanetary disk.
3. Planetesimals grow to planetary embryos through collisional growth
4. Embryos accrete remaining pebbles or other planetesimals (or even other embryos) to grow to planetary cores
5. For gas giants: once critical mass is reached, atmosphere is accreted

Dust and Gas Interact

- How they interact depend on the gas density (ρ_{gas}), the material density of the solids (ρ_{mat}), and the particle size (a)
- Real world example:
 - Dust in the air gets easily lofted up because the grains are small
 - Dust can grow to larger “agglomerates”, such as “dust bunnies”. These do not easily get lofted into the air, but settle down more easily



$St \ll 1$



$St \gg 1$

$$St \approx \frac{\rho_{\text{mat}}}{\rho_{\text{gas}}} \frac{a}{c_s} \Omega$$

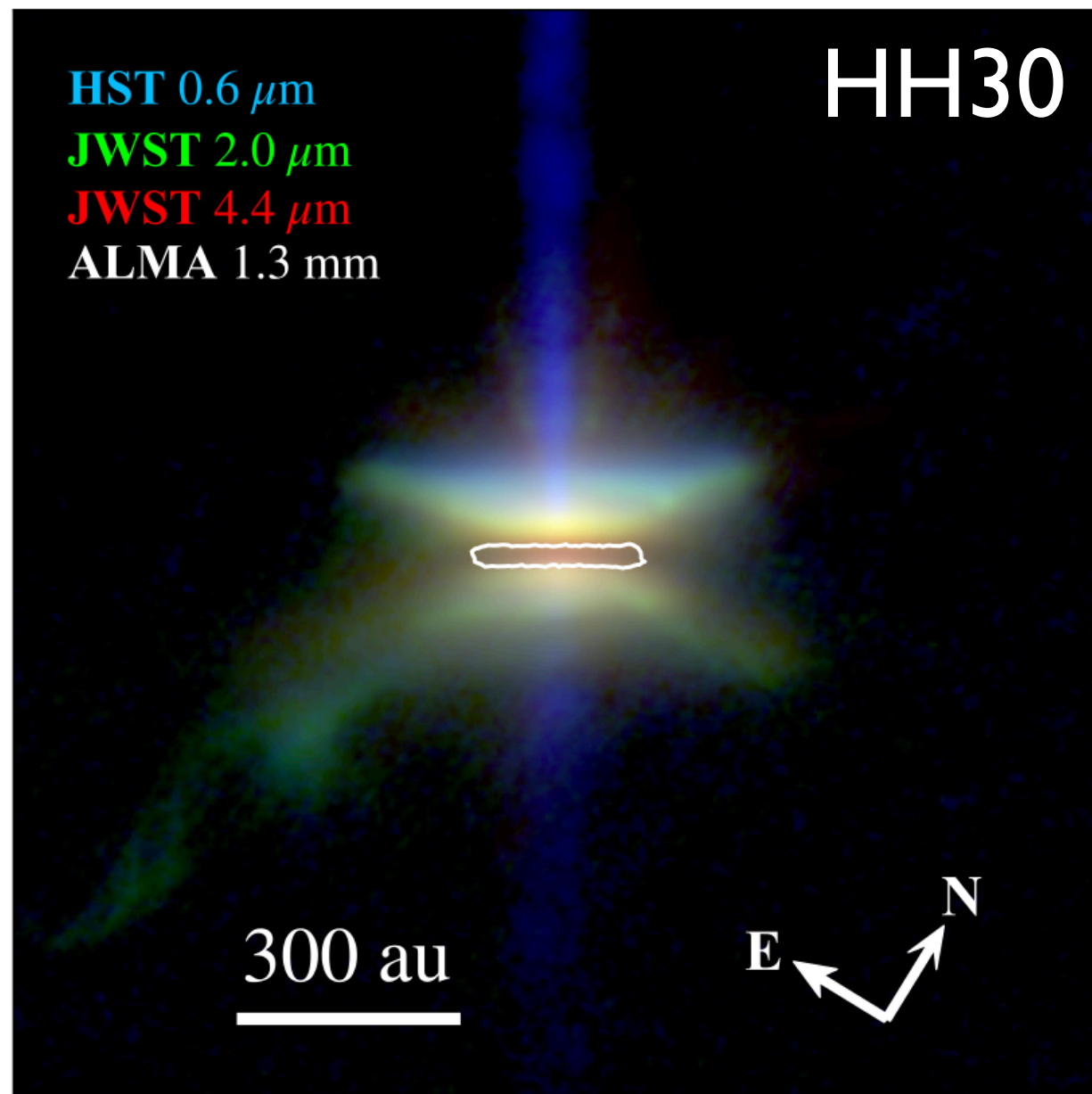
In Epstein regime ($a \ll l_{\text{mfp}}$ where l_{mfp} is mean free path of gas)

Dust Settling and Growth

Dust Settling and Growth

Chalkboard Time

Dust grains in real disks



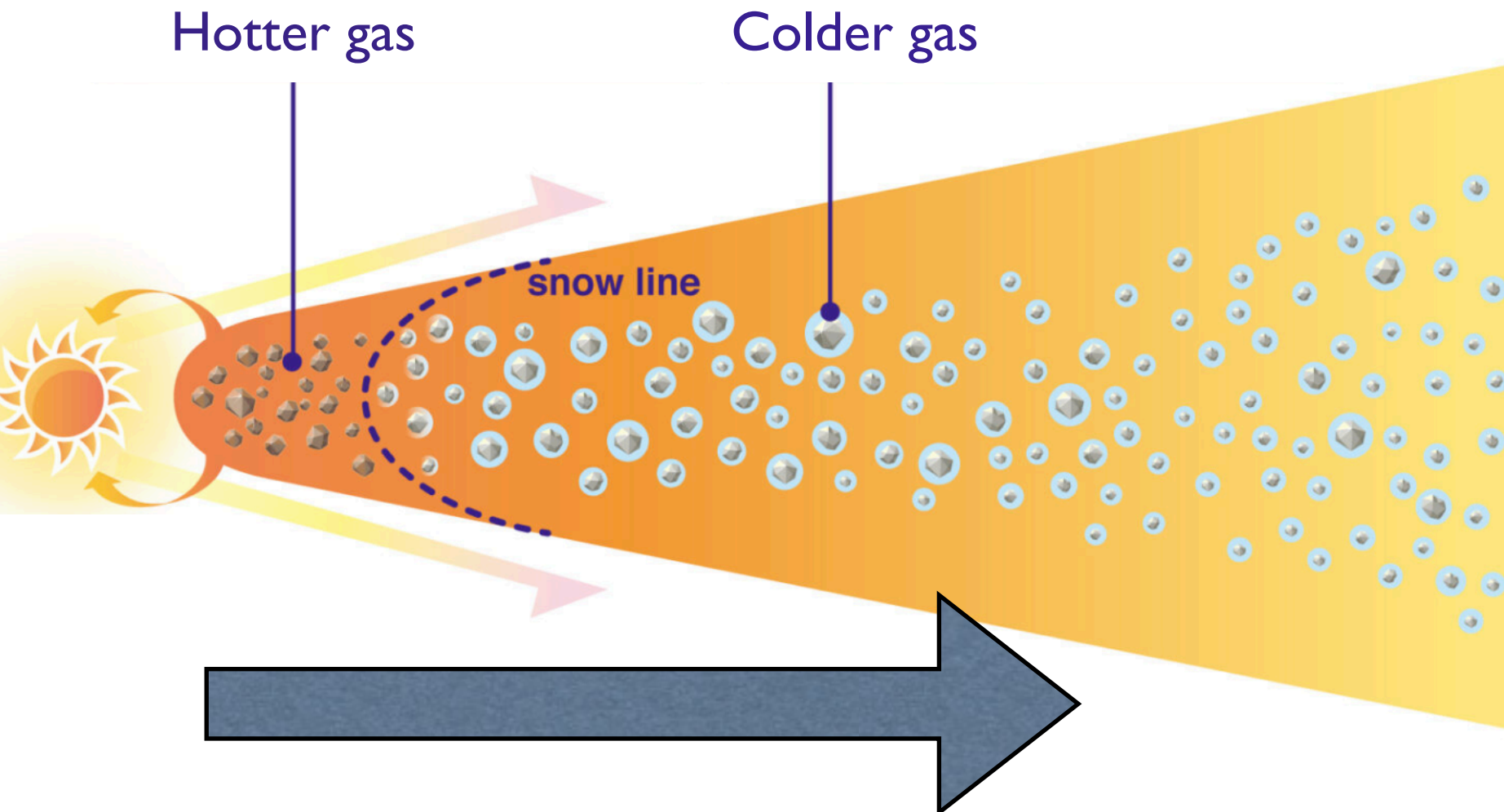
Tazaki et al. (2025)

$$H_d = H \sqrt{\frac{\alpha}{\text{St} + \alpha}}$$

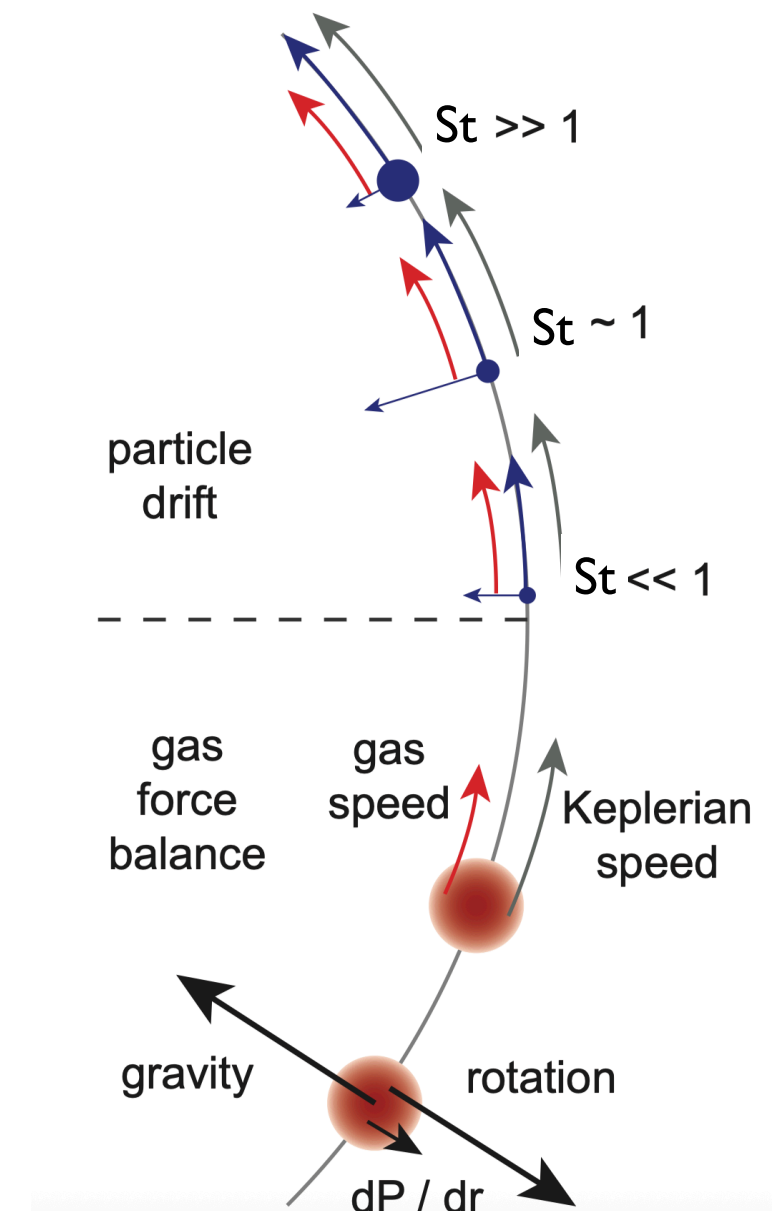
$$\alpha \sim \frac{v_{\text{turb}}^2}{c_s^2}$$

- Dust preferentially scatters light of wavelength $\sim$ grain size
- HST shows grains with $a \sim 0.6 \mu\text{m}$
- JWST shows slightly larger grains
- ALMA (radio telescope) shows grains of size $\sim 1 \text{ mm}$
- **As a increases, the thickness of the disk decreases!**
- H_d increased by smaller St or larger α (i.e., stronger turbulence)

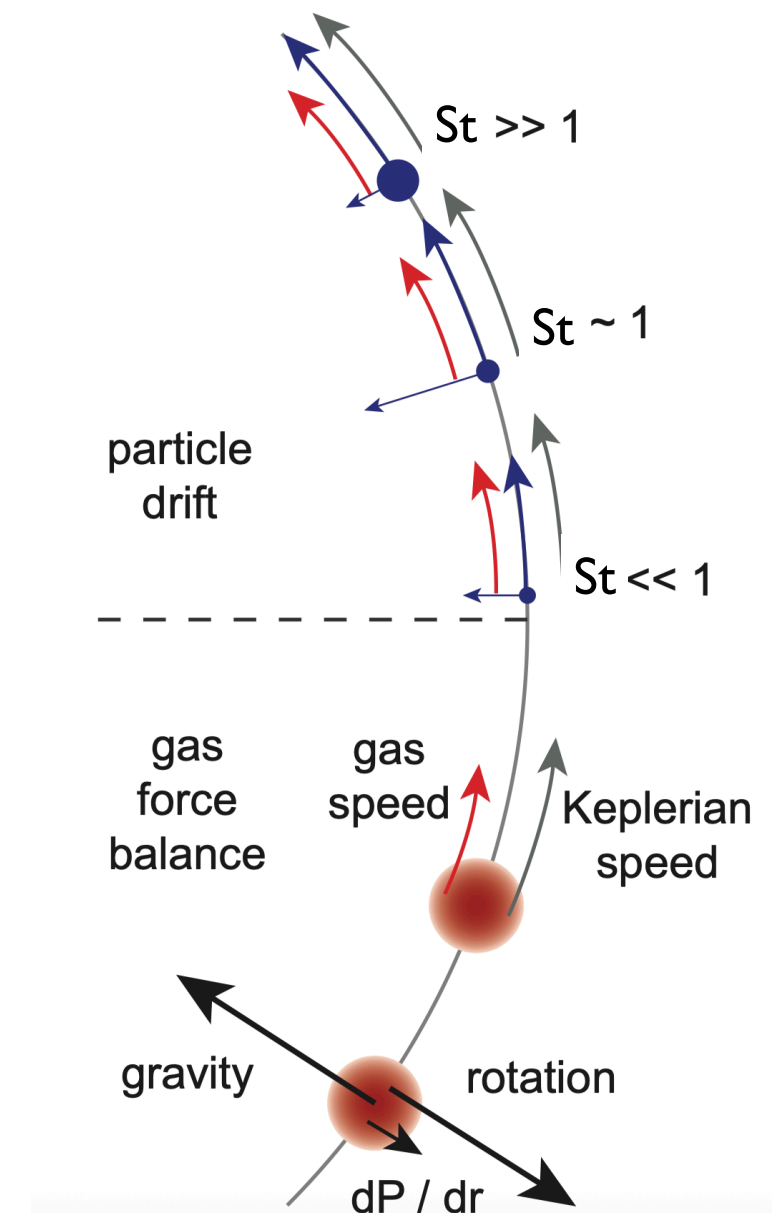
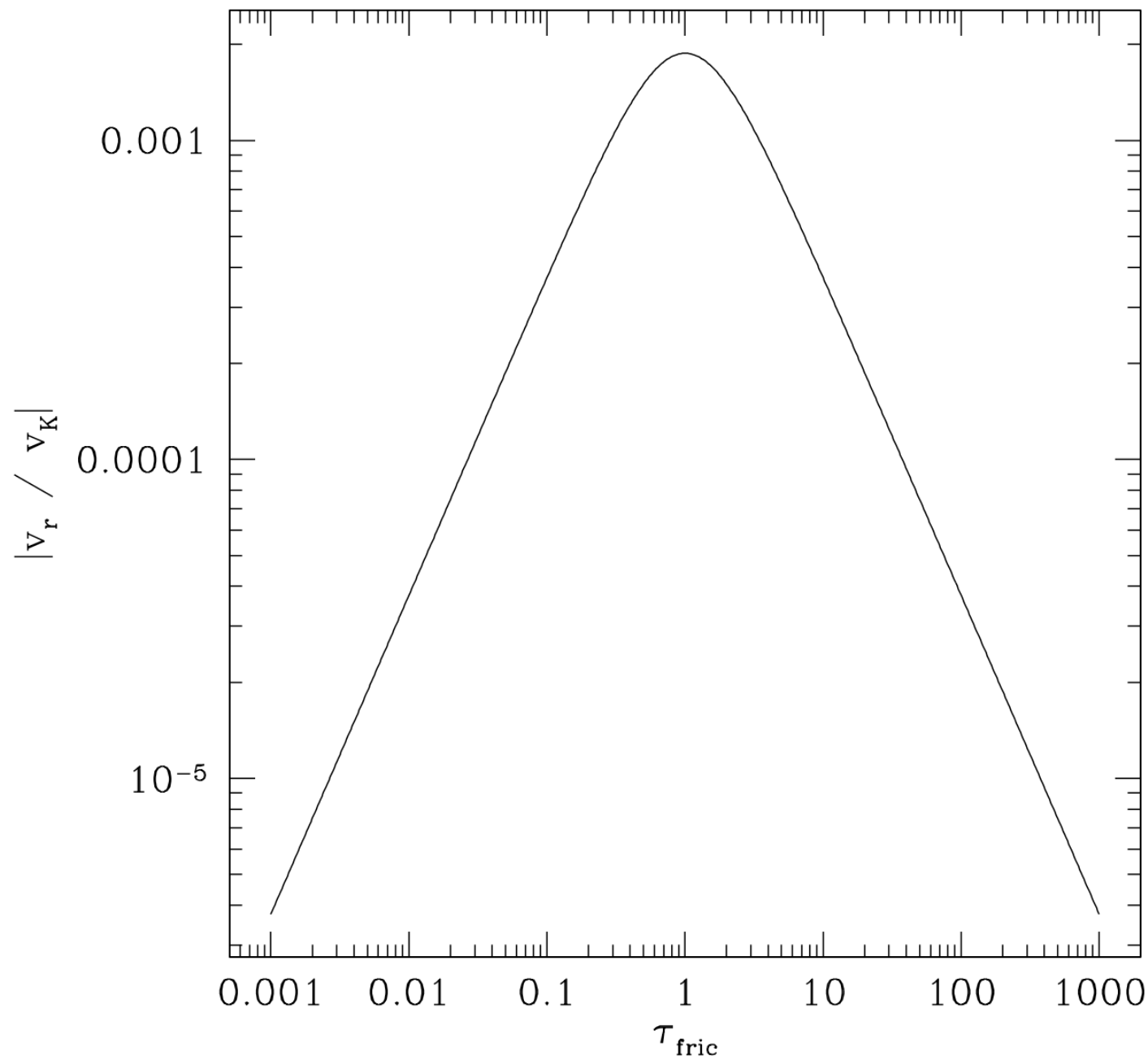
Radial Pressure Gradient and Dust Drift



- Temperature and density decrease outward
- Pressure decreases outward; $\frac{dP}{dr} < 0$
- **Supports gas against gravity**
- Dust is not supported by pressure; rotates faster
- **Causes inward drift of grains**

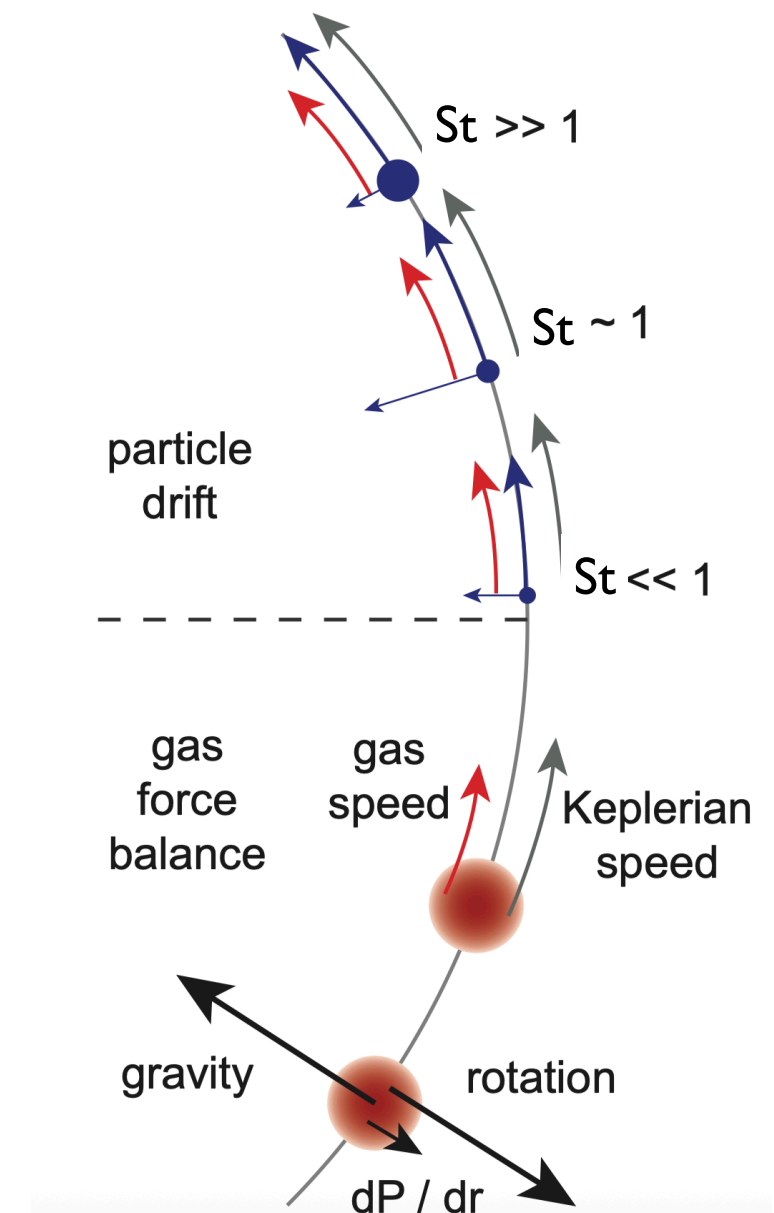
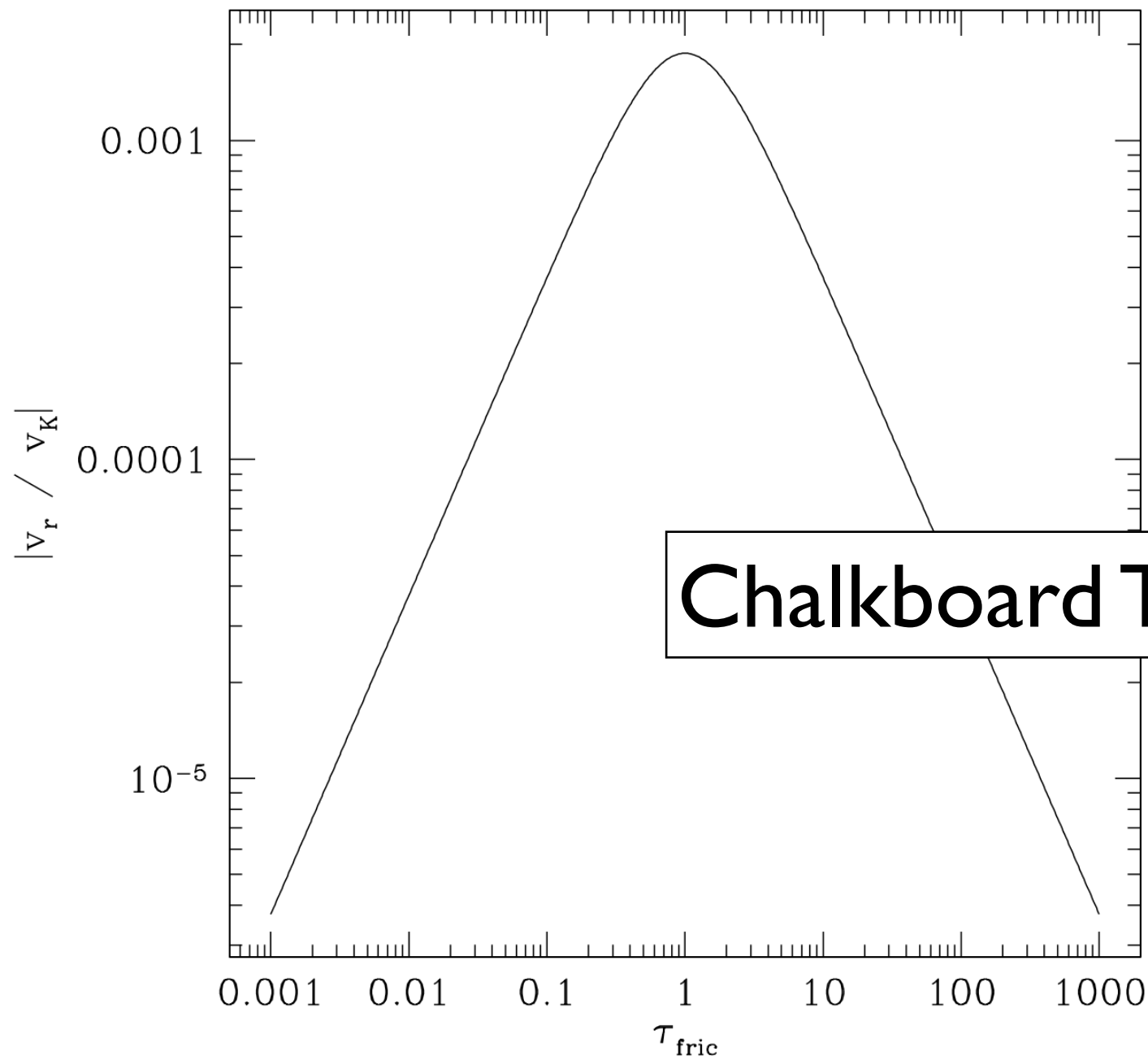


Radial Pressure Gradient and Dust Drift



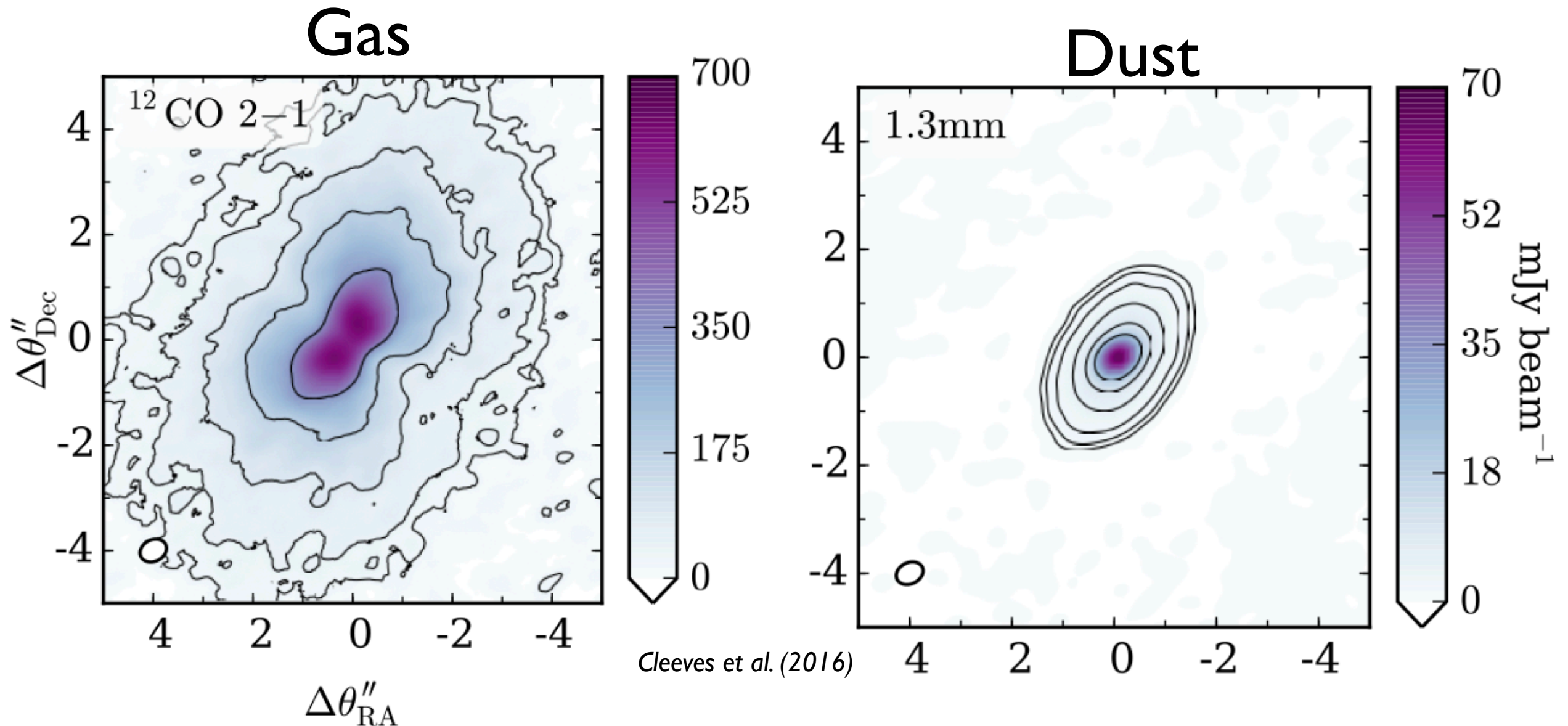
- Maximum drift rate is for marginally coupled particles: $St \sim 1$
- Drift can be very rapid (e.g., ~30 years at 1 AU!)

Radial Pressure Gradient and Dust Drift



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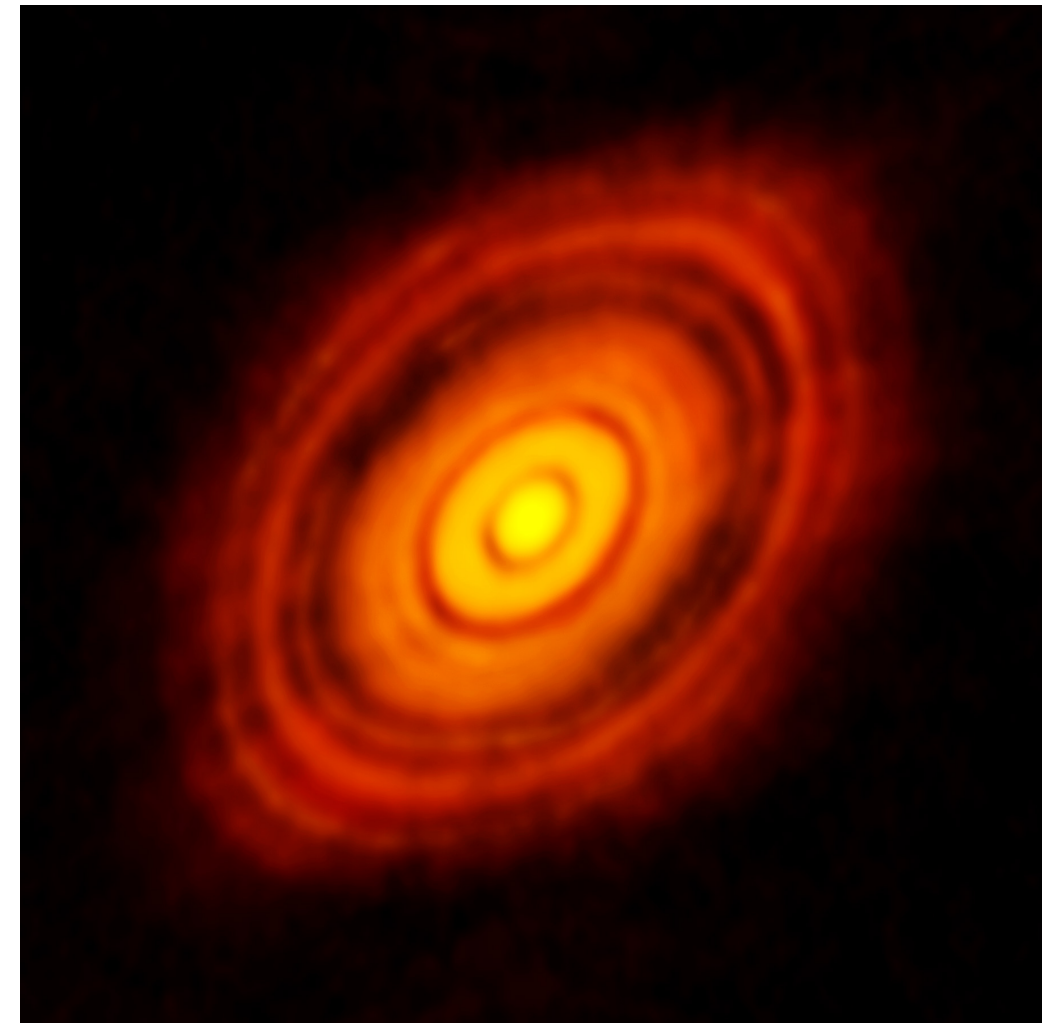
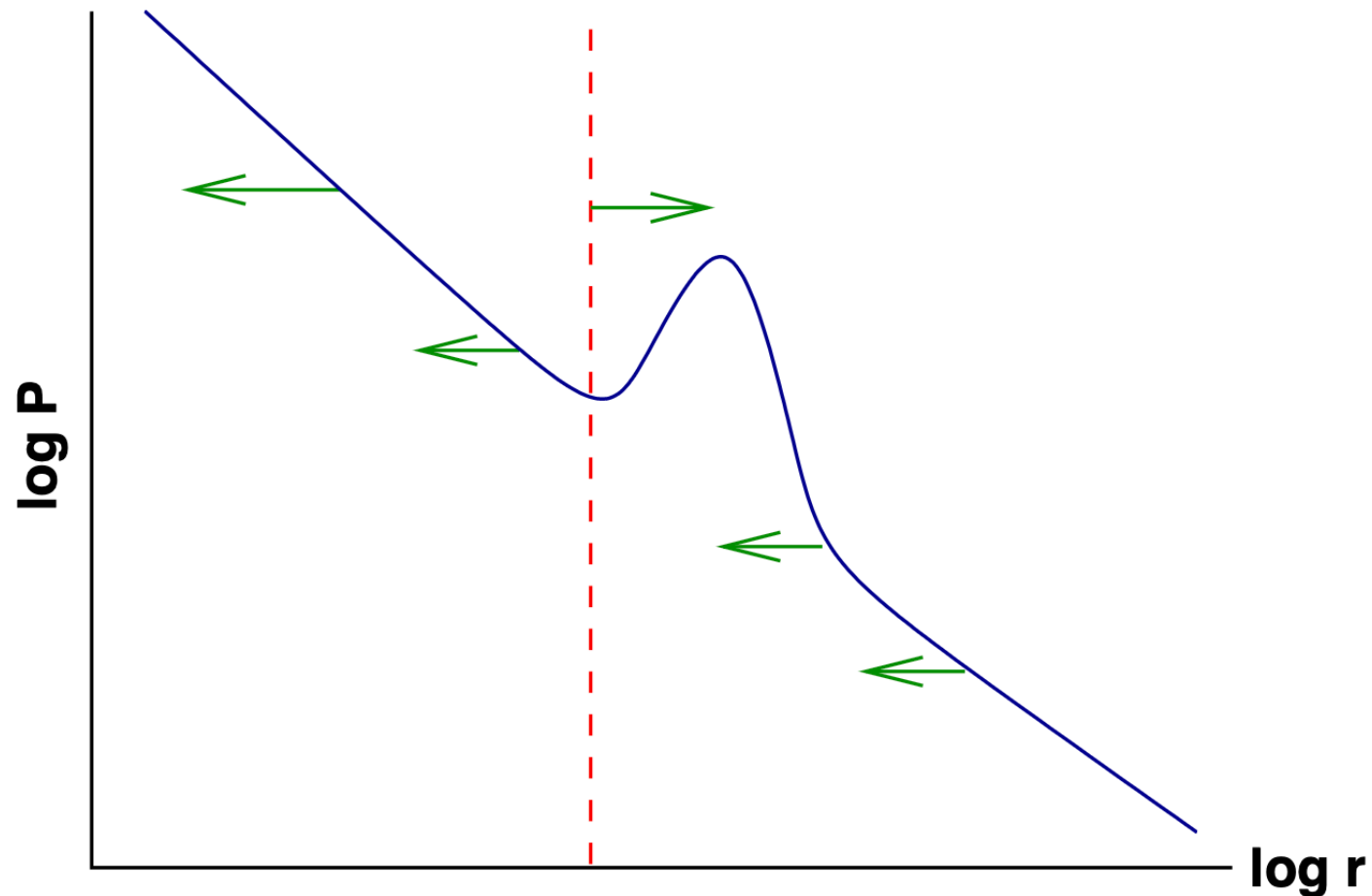
Evidence for radial drift in disks



- The **dust components of disks are more compact than the gas** component - clear signature of radial drift
- Why does the dust not completely drain onto the star? We're not entirely sure, but... (see next slide)

Pressure bumps

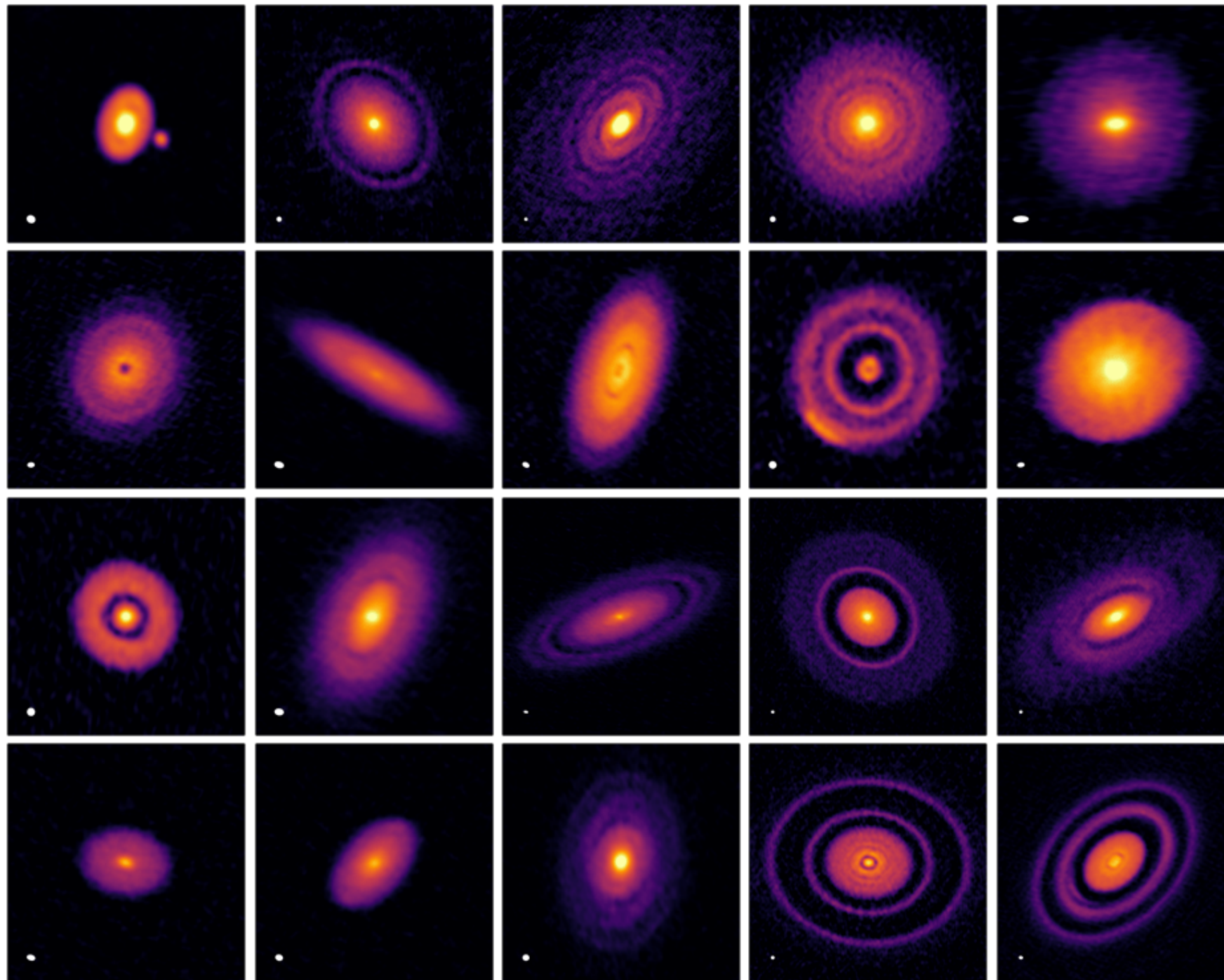
HL Tau



By ALMA, CC BY 4.0, <https://commons.wikimedia.org/w/index.php?curid=36643860>

- **Pressure bumps can reverse** (or at the very least slow down) **radial drift!**
- **Dust can be “trapped” at pressure maxima!** Could explain the rings of disks like HL Tau
- If not trapping, the change in pressure gradient can slow down the drift - **a traffic jam effect!**

These pressure bumps appear to be very common in disks!



DSHARP Collaboration

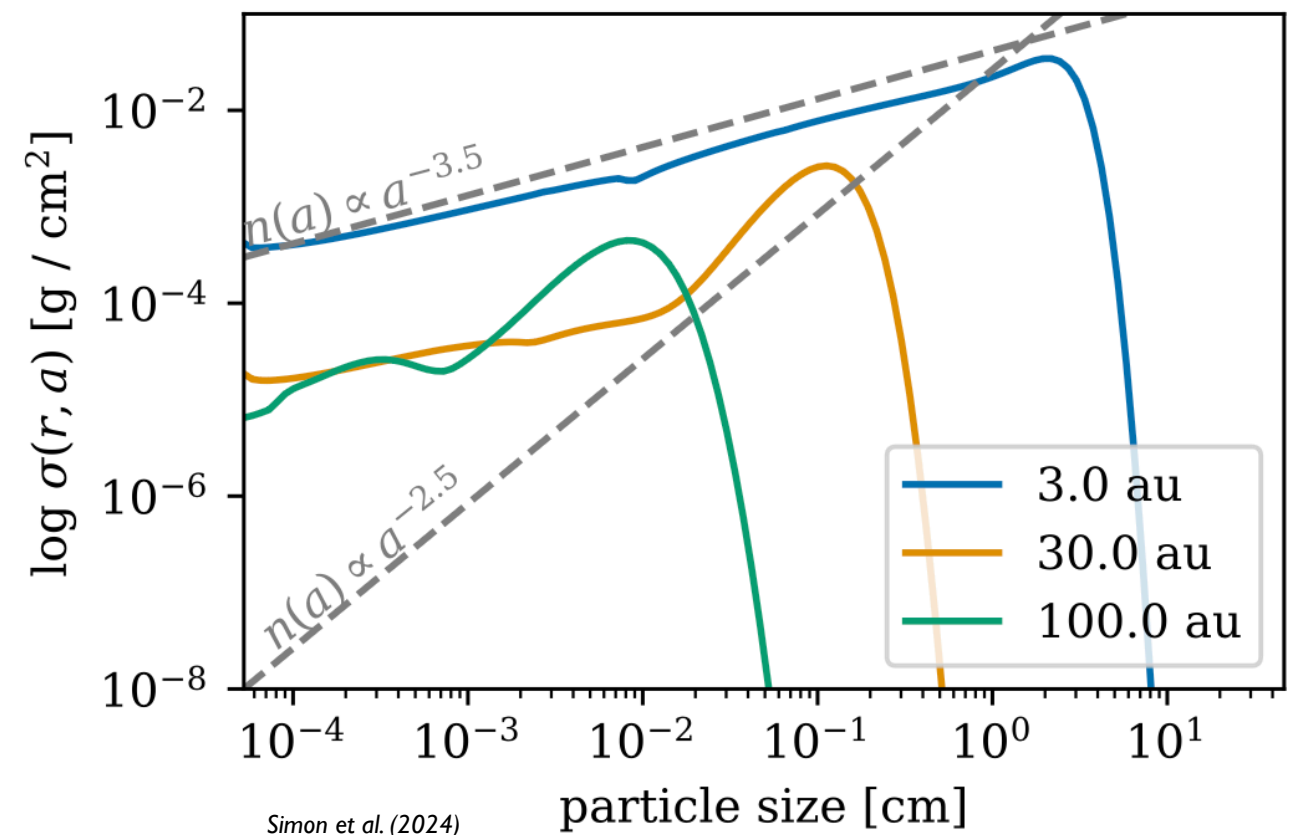
- Nearly all Class II (protoplanetary) disks show some “substructure”
- Often in the form of rings
- Evidence for pressure bumps and radial drift!

All the while, dust grains interact with each other

Have to solve Schmoluchowski equation numerically

$$\frac{\partial n(x, t)}{\partial t} = \frac{1}{2} \int_0^x K(x - y, y) n(x - y, t) n(y, t) dy - \int_0^\infty K(x, y) n(x, t) n(y, t) dy.$$

- Collisions lead to a number of different effects
- Grains can **stick** and “**coagulate**”
- They can also **bounce apart** and not stick
- They can also **fragment** into smaller grains
- All depends on properties of the grains, their relative speeds, etc.



Laboratory Astrophysics



Drop Tower in Bremen, Germany

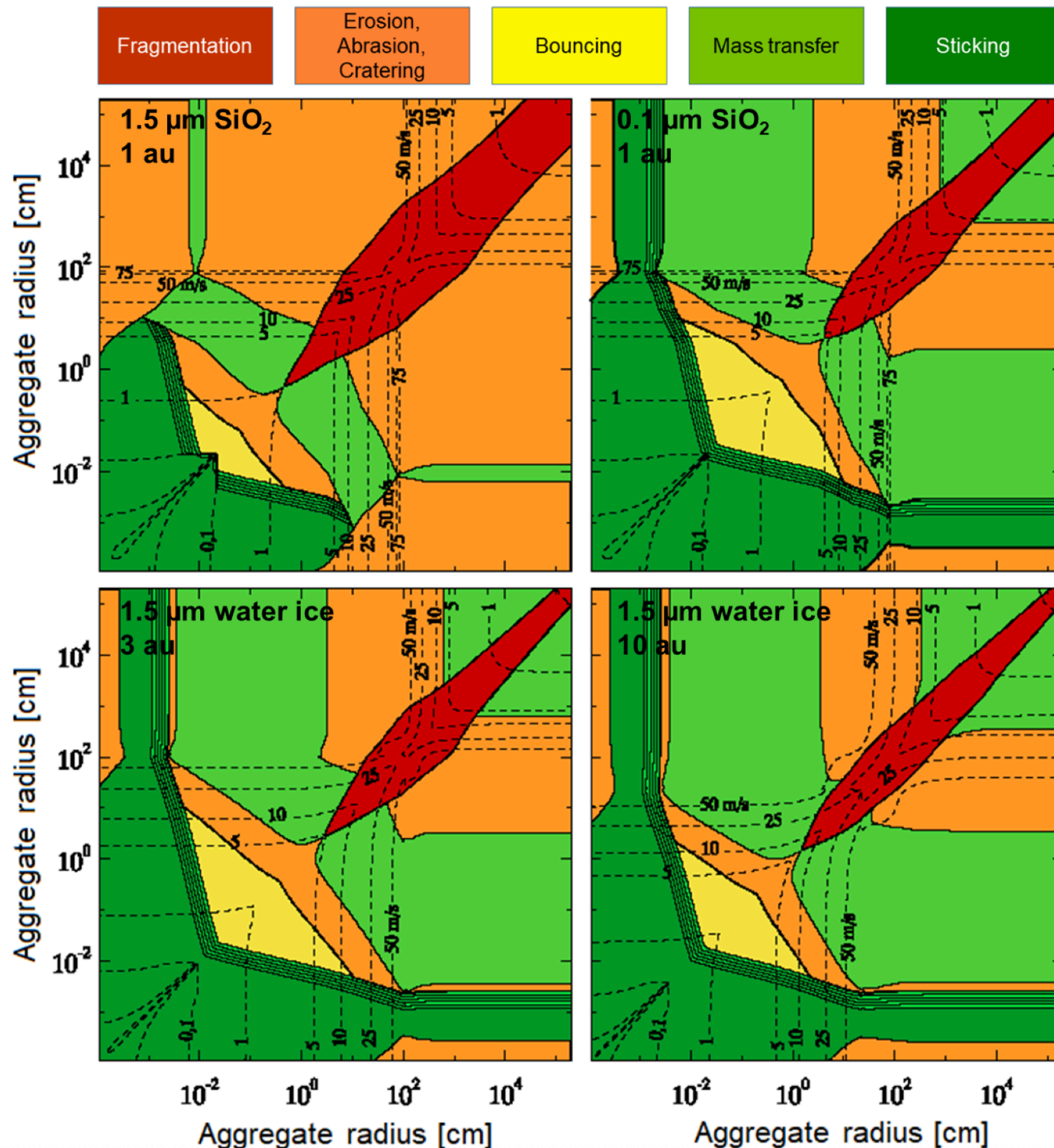
<https://sciences.ucf.edu/physics/microgravity/trace/>



Collision of two cm-sized aggregates at $\sim 1\text{m/s}$ in microgravity condition

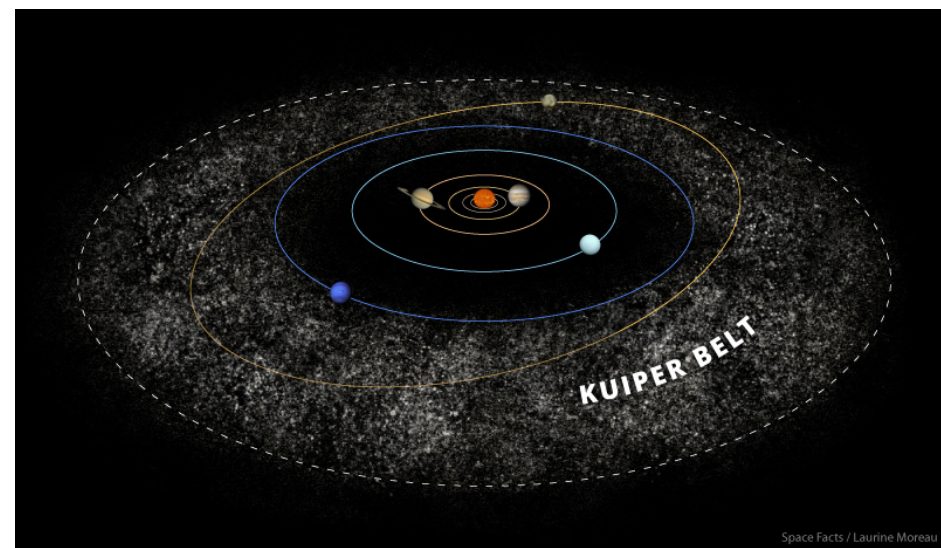
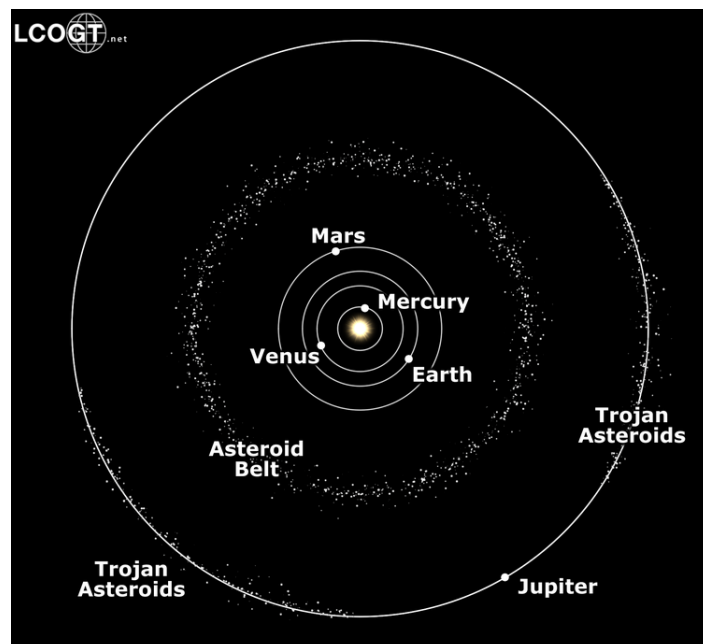
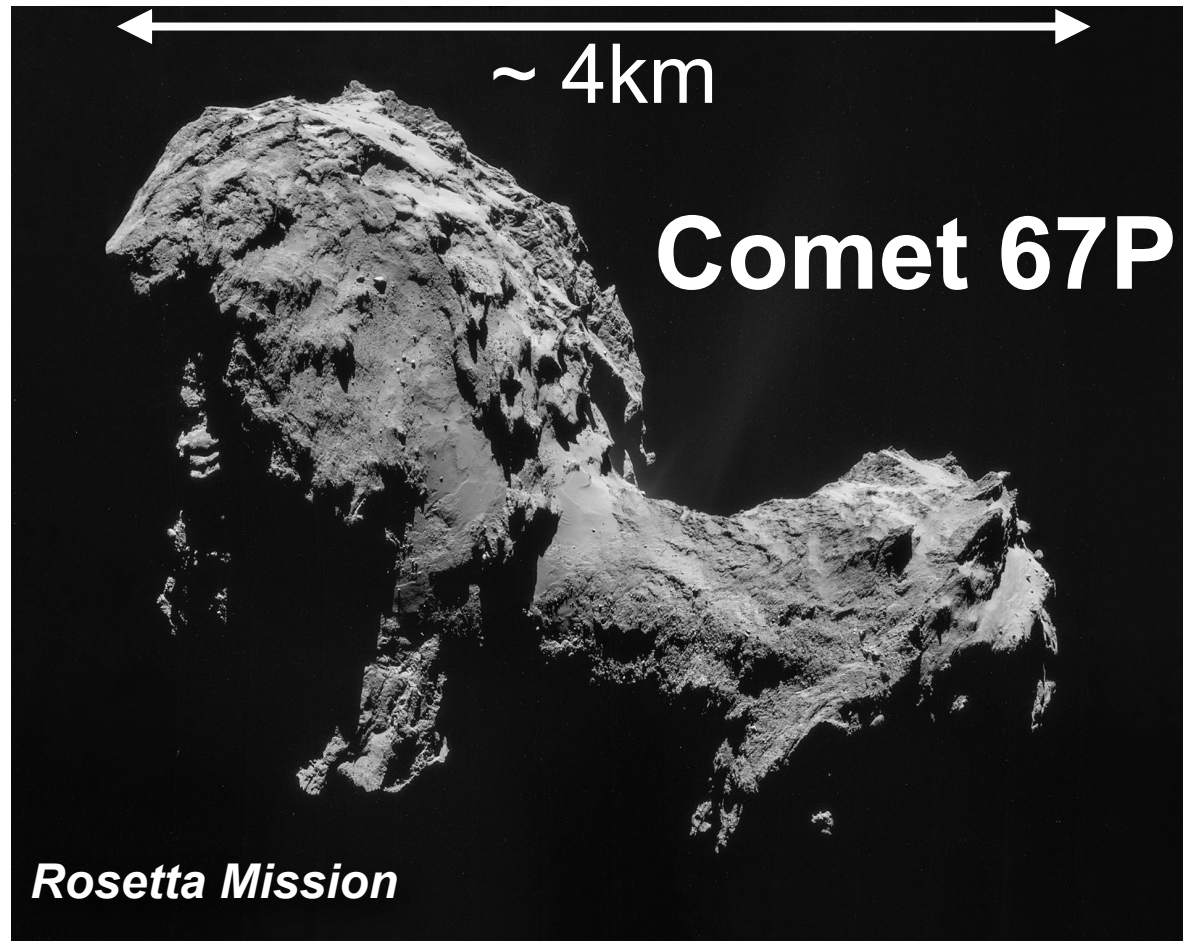
- Beyond modeling, one can actually run laboratory experiments
- Simulate microgravity with drop tower or suborbital flights

Results of lab experiments



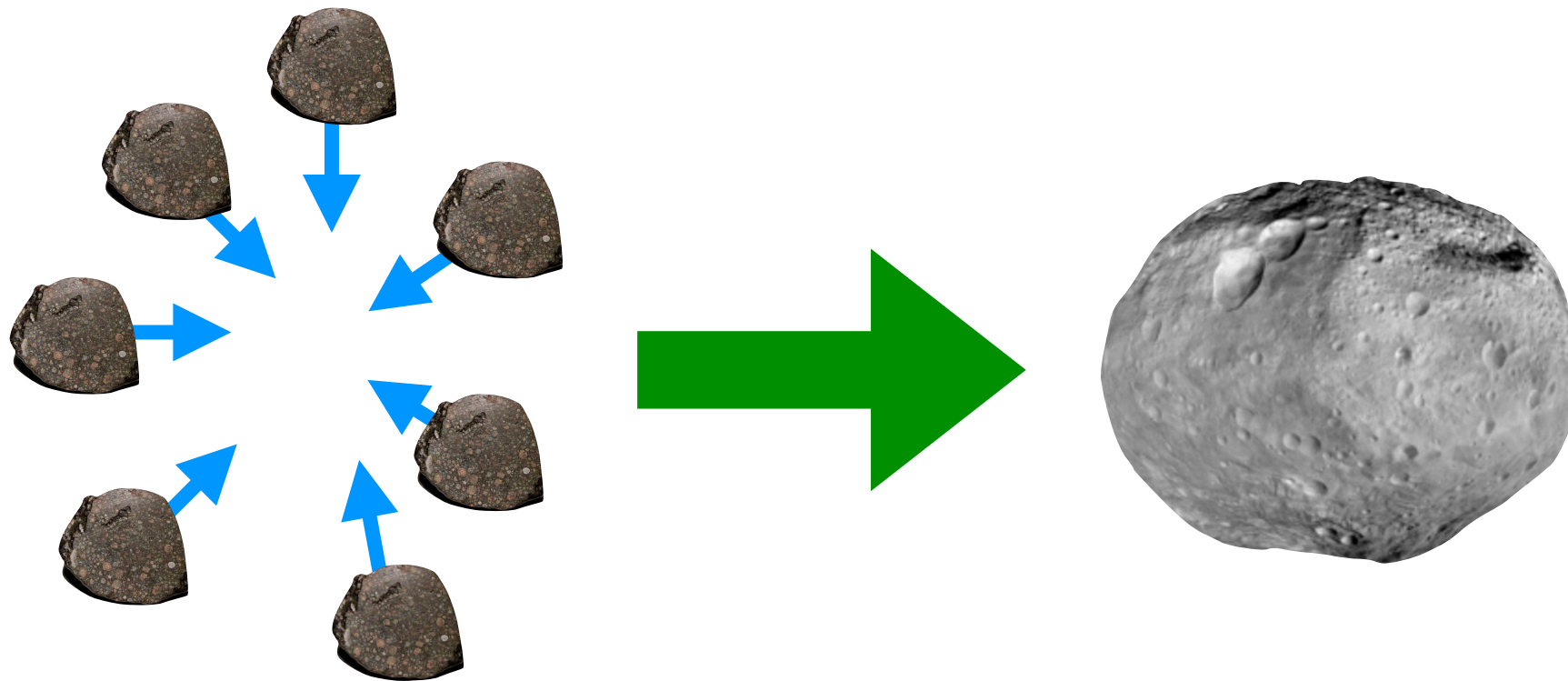
- Exact results depend on many parameters
- But very roughly, a simple trend for similar size particles colliding
 - **At small sizes, particles stick** (through molecular forces like Van der Waals)
 - **Intermediate sizes - bouncing dominates!**
 - **Larger sizes - particles fragment** back into smaller particles
- Bottom line: **particles tend to not grow beyond mm-cm sizes**

Next stage: Planetesimals (1-100 km sized bodies)



How do we grow beyond mm-cm sizes?

Gravitational instabilities!



(not to scale)

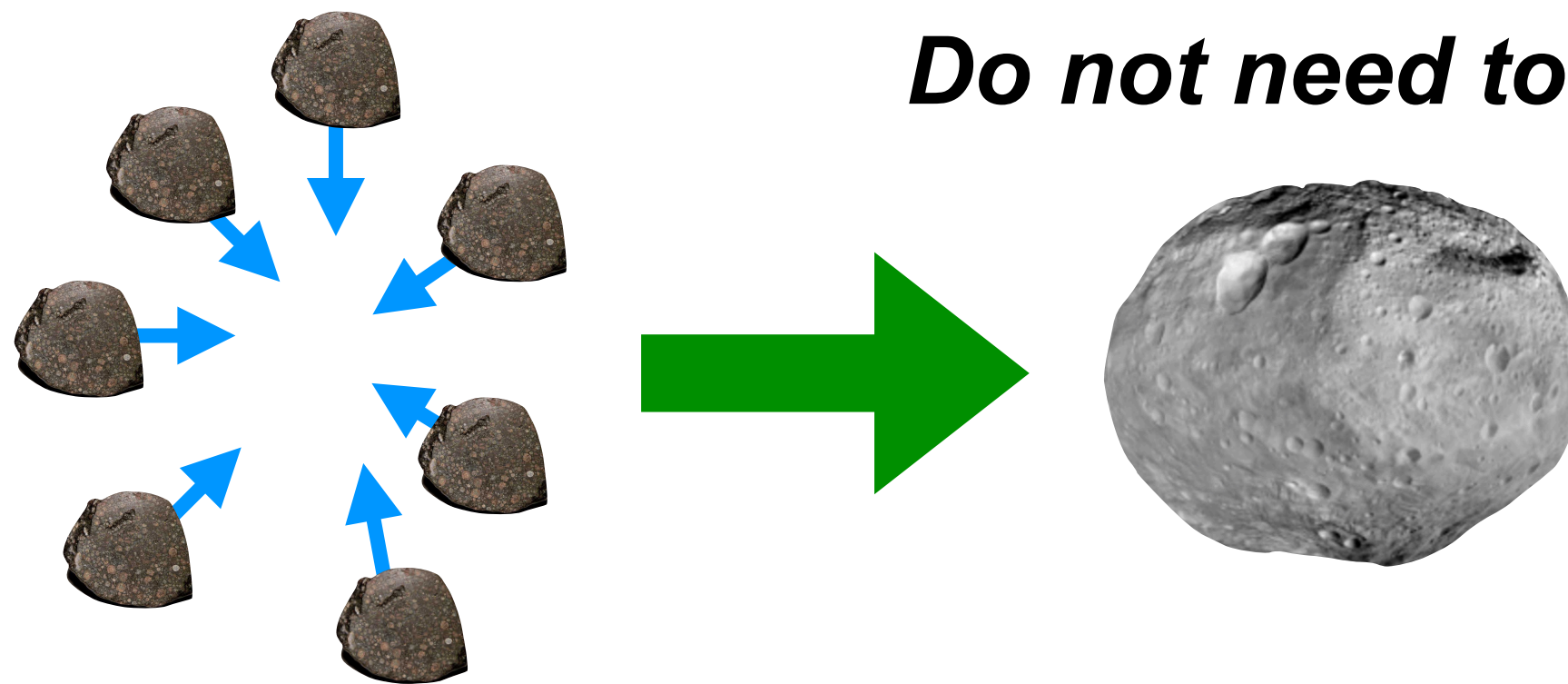
Critical criterion for gravitational collapse: density of planetesimal exceeds Roche density

$$\rho_{\text{planetesimal}} > \rho_{\text{Roche}} \equiv 3.5 \frac{M_{\text{star}}}{r^3}$$

r is distance from star to the planetesimal

How do we grow beyond mm-cm sizes?

Gravitational instabilities!



Do not need to collisionally stick!

(not to scale)

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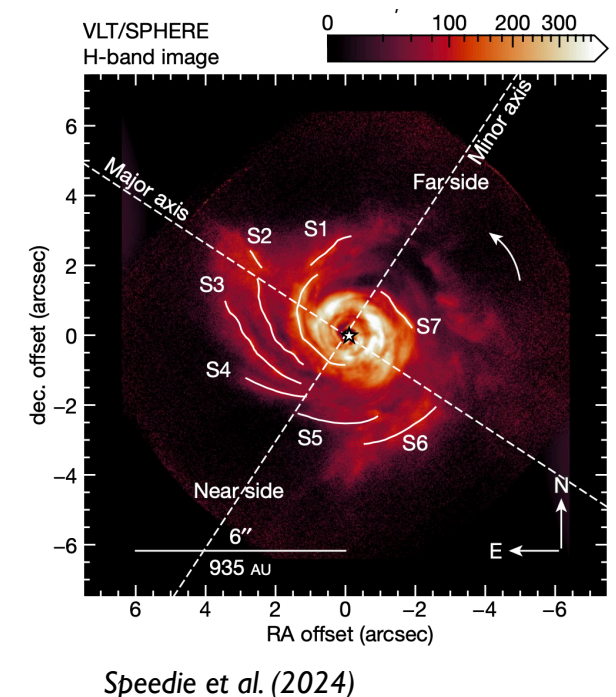
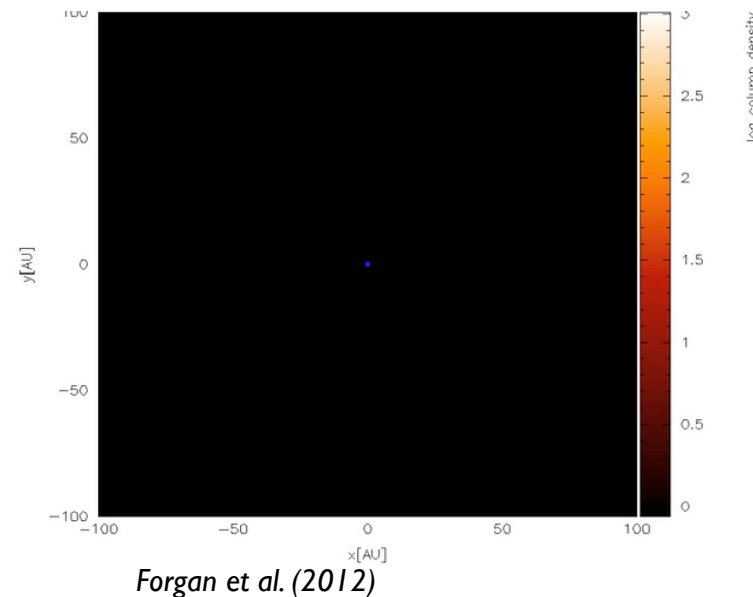
Toomre Q parameter

- Have to also account for velocity dispersion of pebbles; equivalent to a **Jeans criterion for pebbles**
- **Toomre Q encapsulates both the Jeans criterion and the Roche density:** planetesimal must be sufficiently massive to overpower both tidal forces and disruptive dispersion of pebbles (i.e., the pebble cloud being “kicked apart”)

$$Q_{\text{gas}} = \frac{c_s \Omega}{\pi G \Sigma_{\text{gas}}}$$

$$Q_{\text{peb}} = \frac{\sigma_p \Omega}{\pi G \Sigma_{\text{peb}}}$$

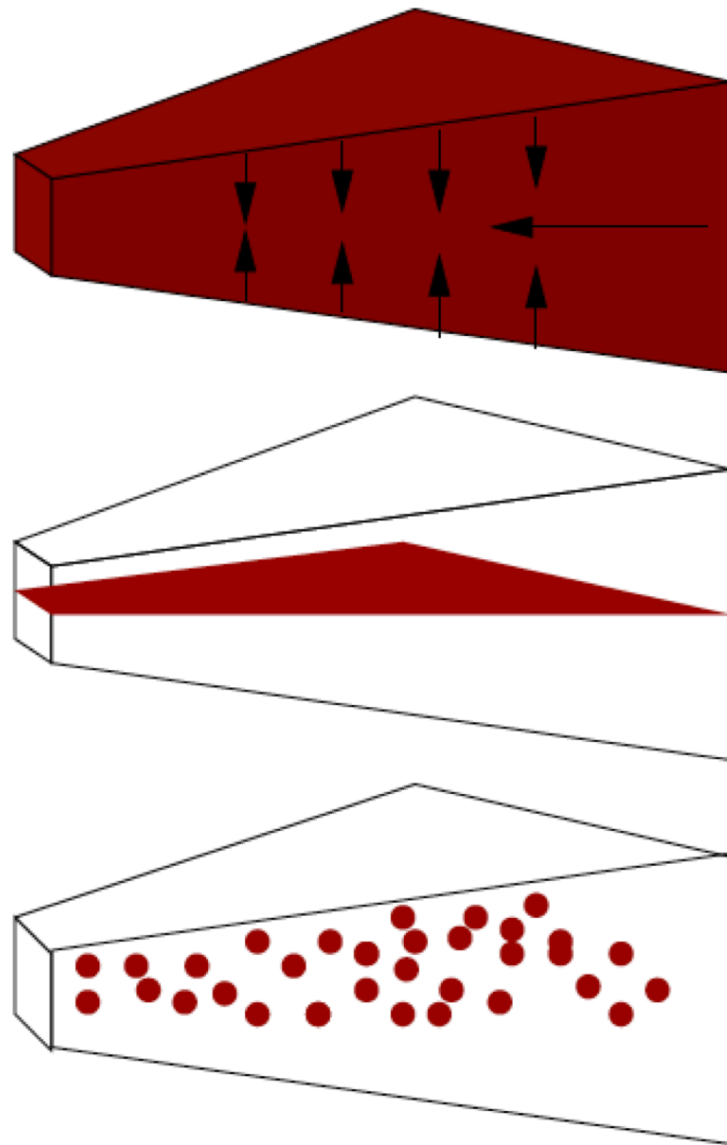
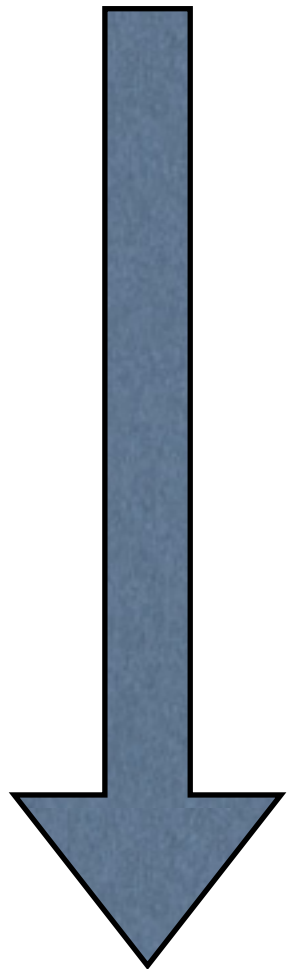
σ_p is pebble velocity dispersion



- When $Q < 1$, collapse can proceed
- Collapse may not happen for gas because cooling is also important
- But no cooling for a pebble clump - pebbles are not gas particles!

Goldreich-Ward Mechanism

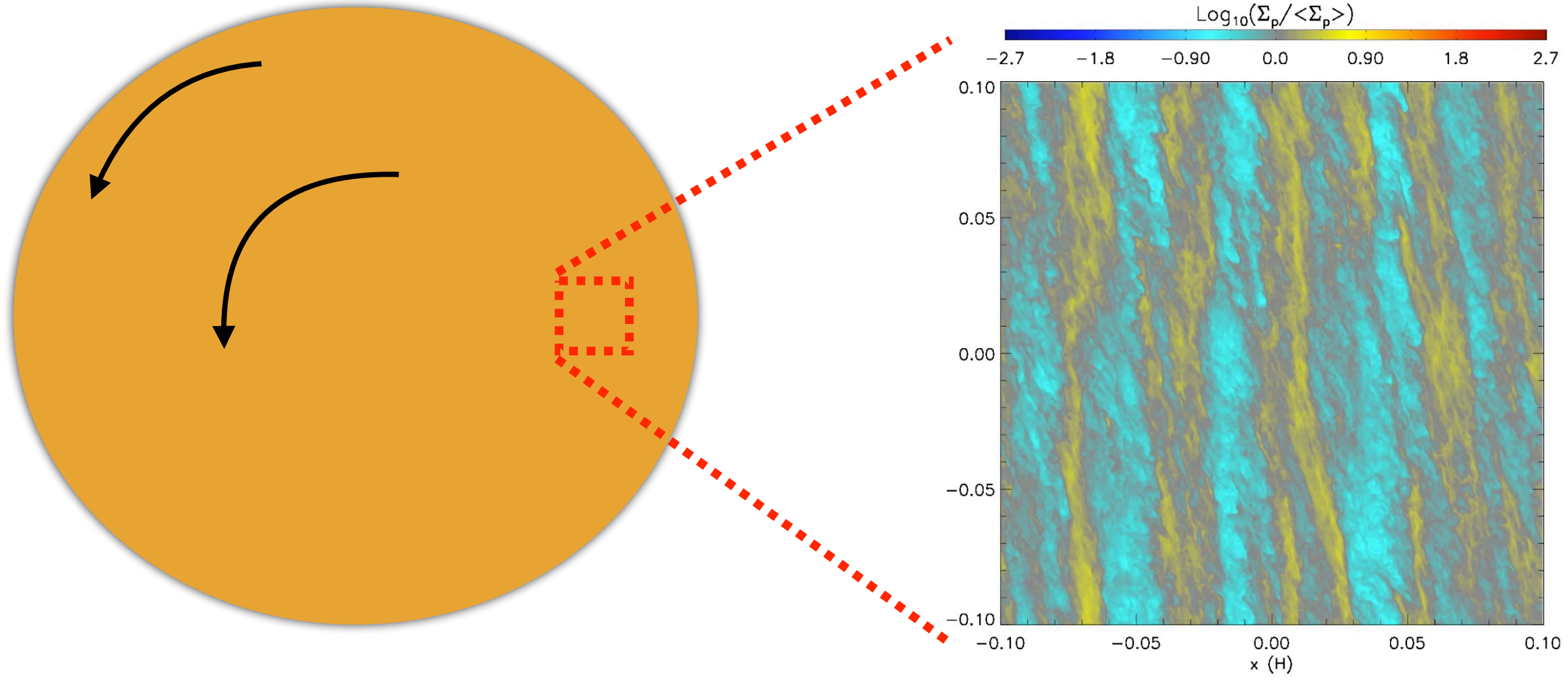
Time



- Settling to mid-plane
- One possible way to get $Q_{\text{peb}} < 1$:
 - If there is enough mass in the pebbles, Σ_{peb} can become large
 - If particle layer is sufficiently settled, σ_p can become small
- But this doesn't work!
- Why?

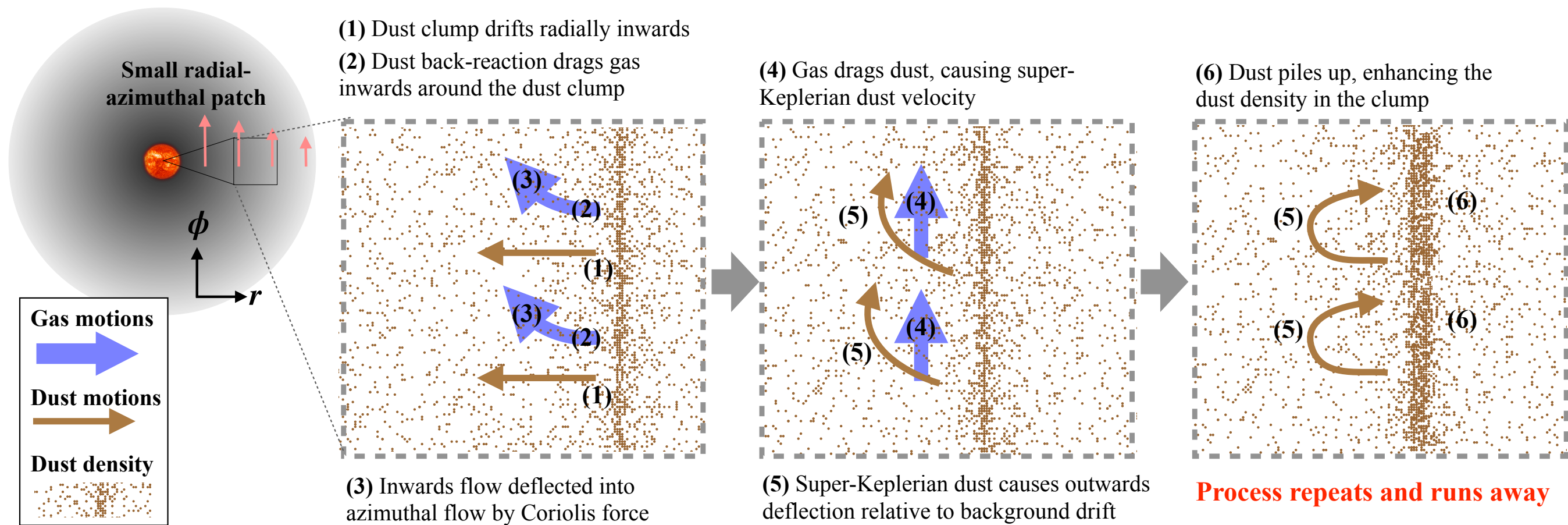
Chalkboard Time

Streaming Instability



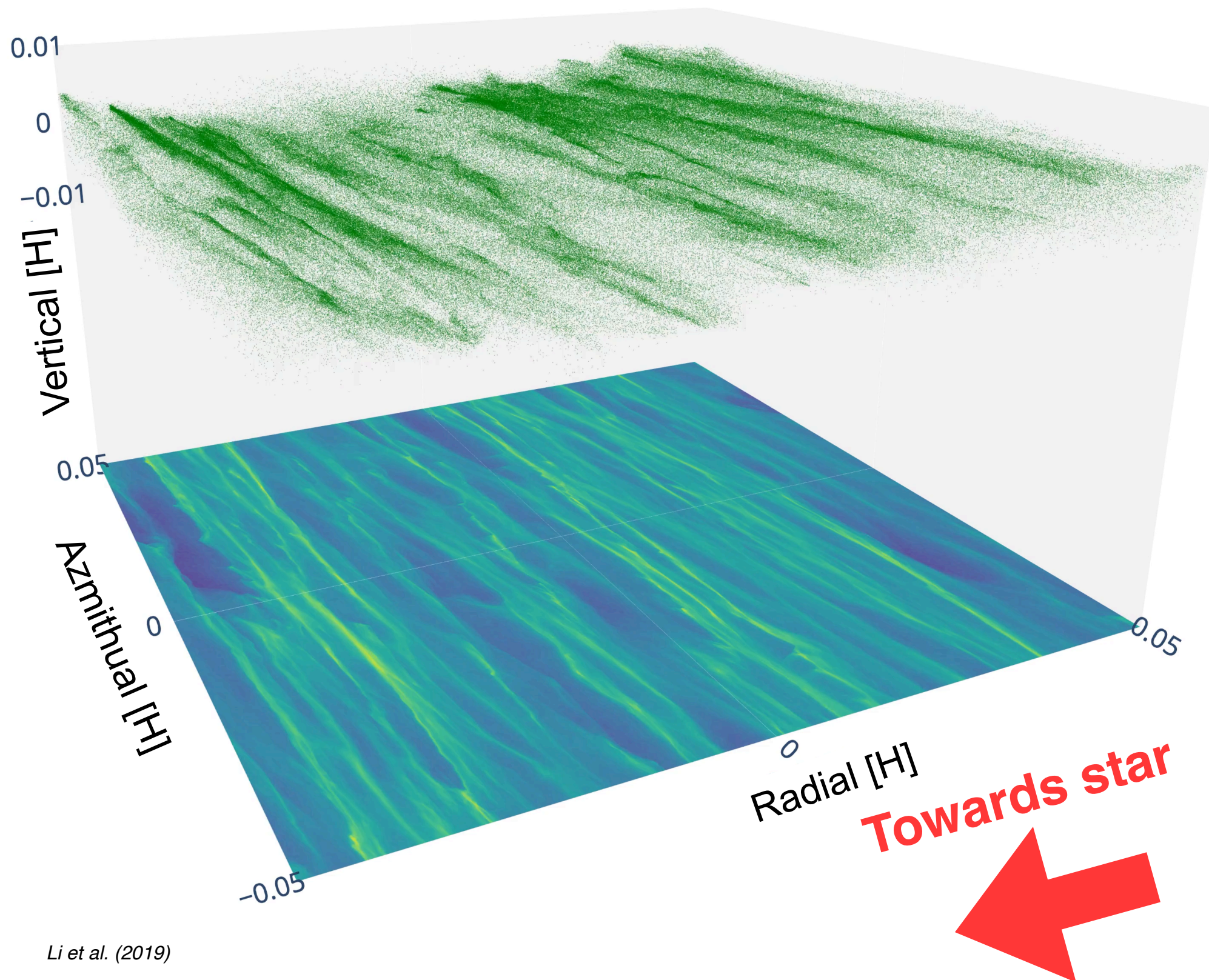
- When one accounts for not only gas drag on particles, but pushback on gas *from particles* a new process emerges: **the streaming instability**
- **Also, radial drift slows down!**
- **Streaming instability concentrates pebbles into filaments**
- Gravity eventually takes over; **collapse into ~100 km sized objects**

Basic Mechanism for the Streaming Instability



- Intuitive description of linear growth
- Not complete picture - instability actually requires vertical dimension (see papers by Squire and more recently Magnan)
- Another way to think about it (at least for dust-to-gas < 1): resonance between drift frequency and inertial mode frequency

End result: gravitationally bound objects

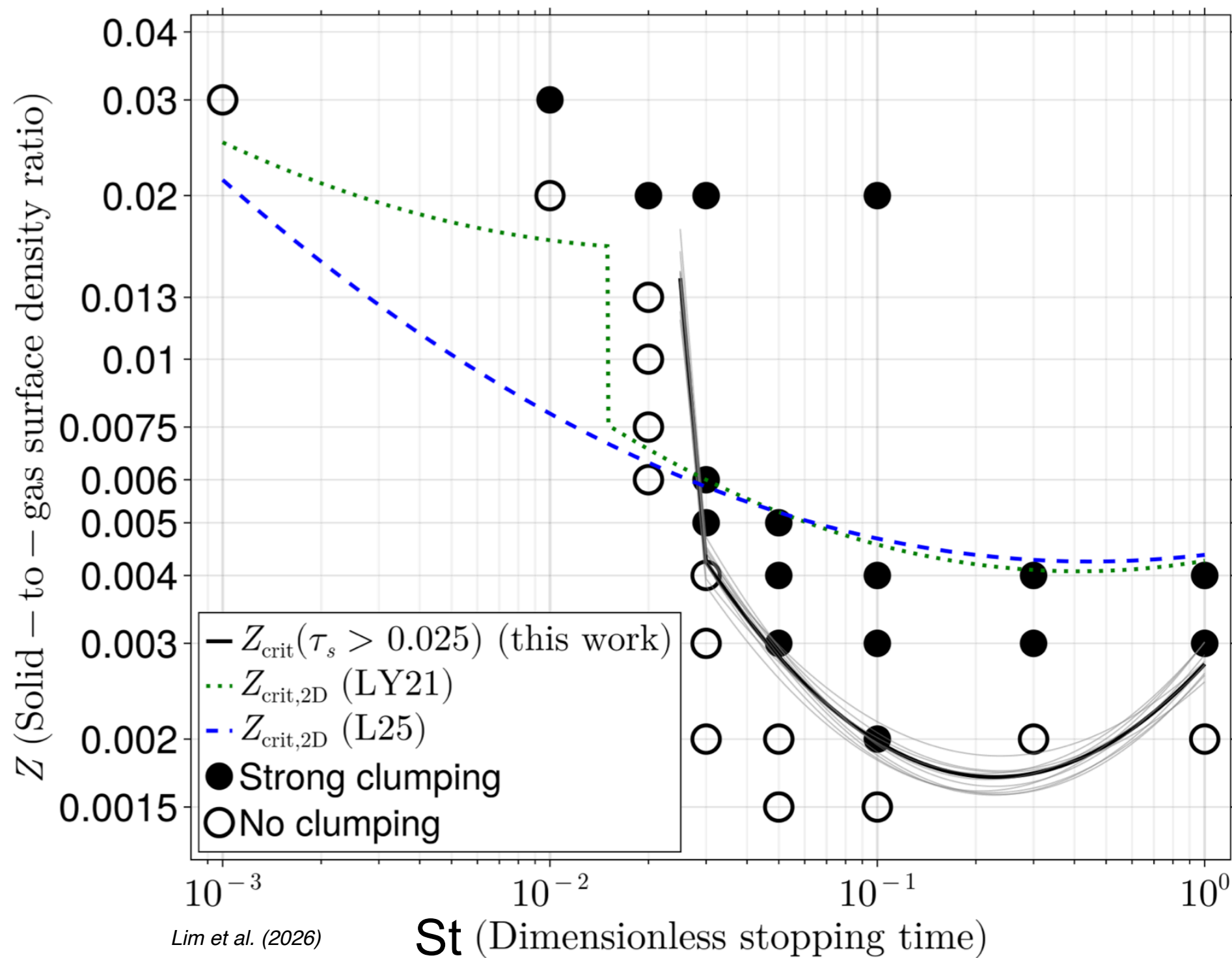


Li et al. (2019)



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Under what conditions does the streaming instability produce “strong clumping”?



- 2D and 3D critical curves differ
- 3D more expensive, but necessary
- Smaller St requires larger Z to produce strong clumping
- **VERY** difficult to deal with small St and large Z - equations become very stiff

What does stiff mean here?

$$\frac{\partial \rho_g}{\partial t} - q\Omega x \frac{\partial \rho_g}{\partial y} + \mathbf{u} \cdot \nabla \rho_g + \rho_g \nabla \cdot \mathbf{u} = 0,$$

Gas continuity eqn.

$$\begin{aligned} \frac{\partial \mathbf{u}}{\partial t} - q\Omega x \frac{\partial \mathbf{u}}{\partial y} + \mathbf{u} \cdot \nabla \mathbf{u} = & a_x \hat{\mathbf{e}}_x + g_z(z_k) \hat{\mathbf{e}}_z - c_s^2 \nabla \ln \rho_g \\ & - 2\boldsymbol{\Omega} \times \mathbf{u} + q\Omega u_x \hat{\mathbf{e}}_y + \sum_j \frac{\tilde{\epsilon}_{kj}(\mathbf{v}_j - \mathbf{u})}{t_s}, \end{aligned}$$

Gas momentum eqn.

$$\frac{d\mathbf{r}_{p,j}}{dt} = -q\Omega x_{p,j} \hat{\mathbf{e}}_y + \mathbf{v}_j,$$

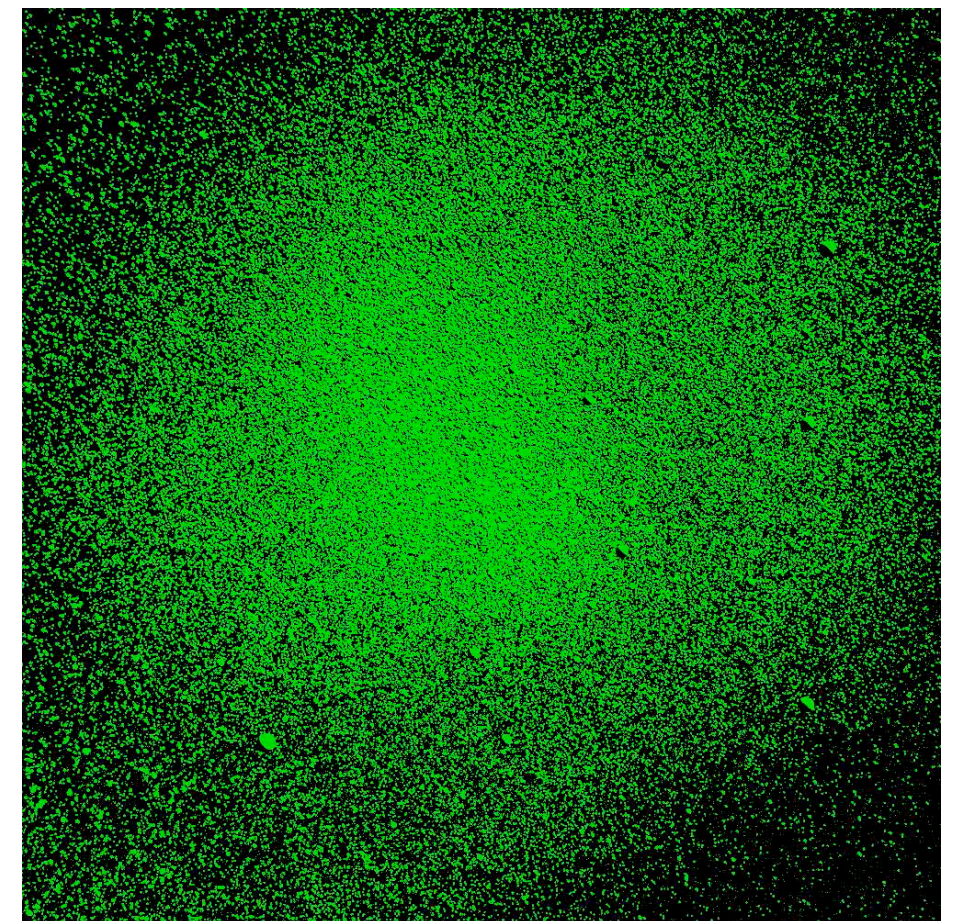
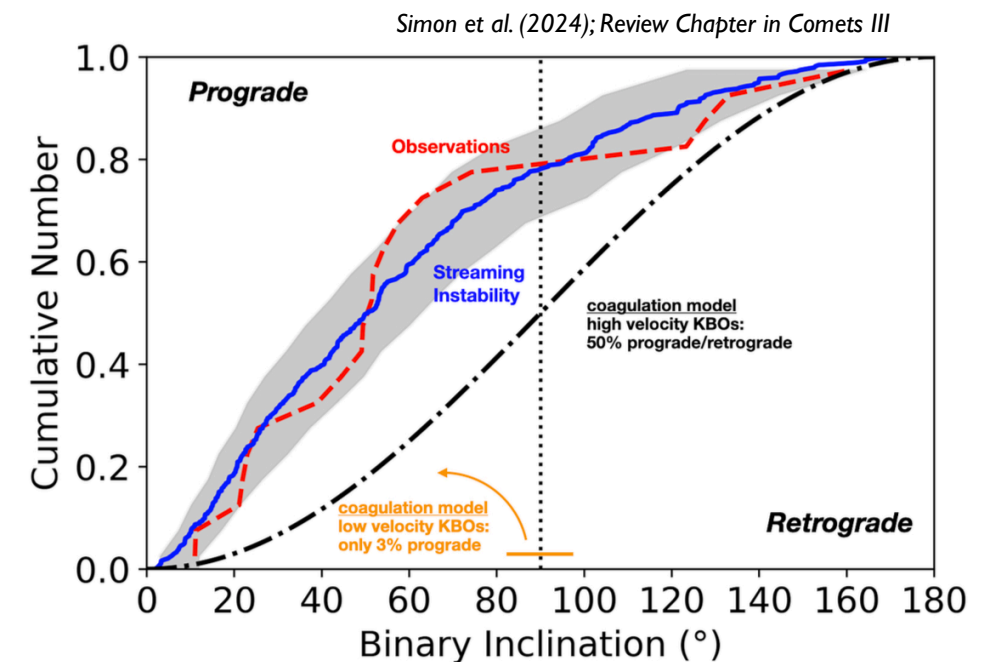
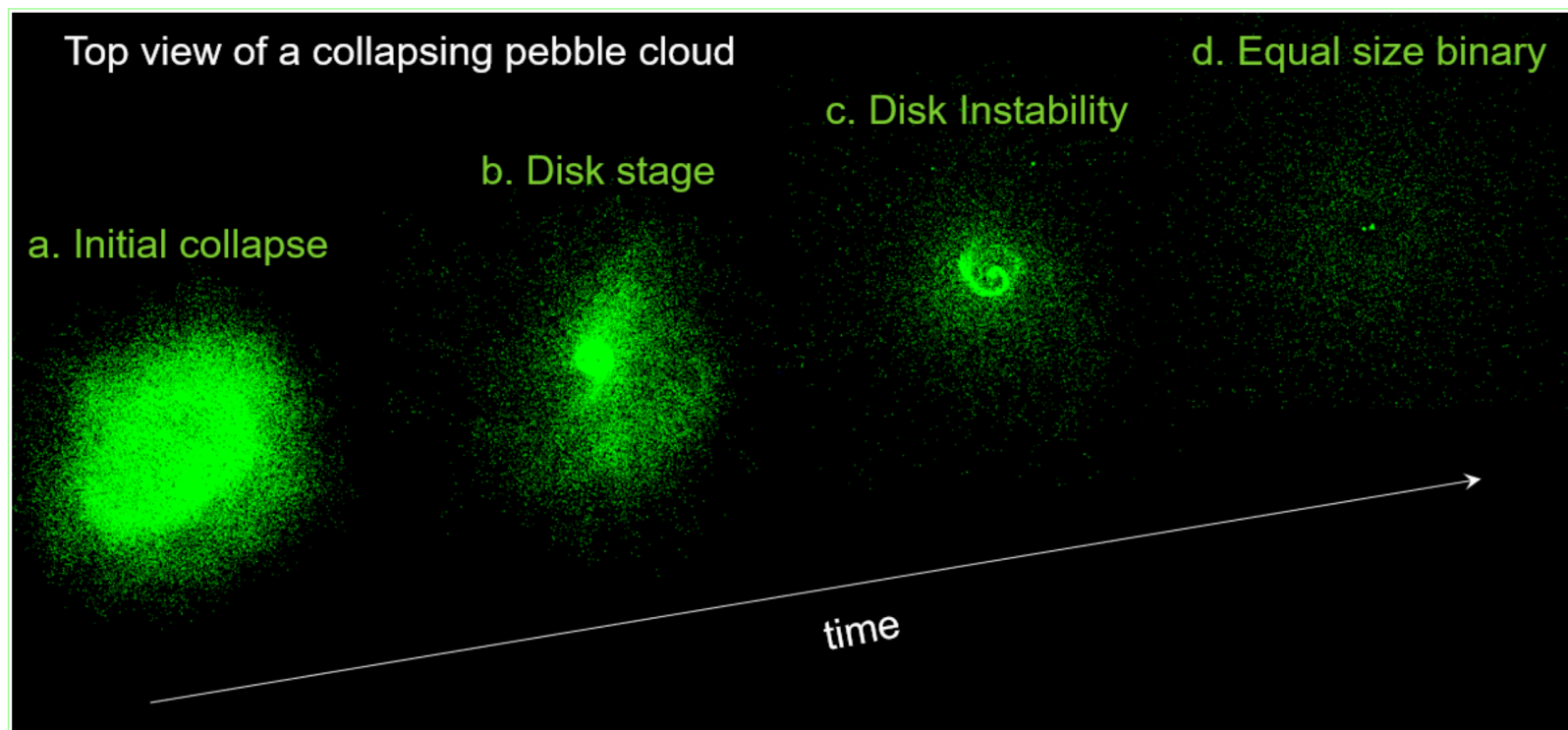
Particle eqns of motion

$$\frac{d\mathbf{v}_j}{dt} = g_z(z_{p,j}) \hat{\mathbf{e}}_z - 2\boldsymbol{\Omega} \times \mathbf{v}_j + q\Omega v_{j,x} \hat{\mathbf{e}}_y + \frac{\tilde{\mathbf{u}}_j - \mathbf{v}_j}{t_s}.$$

Stiffness condition:

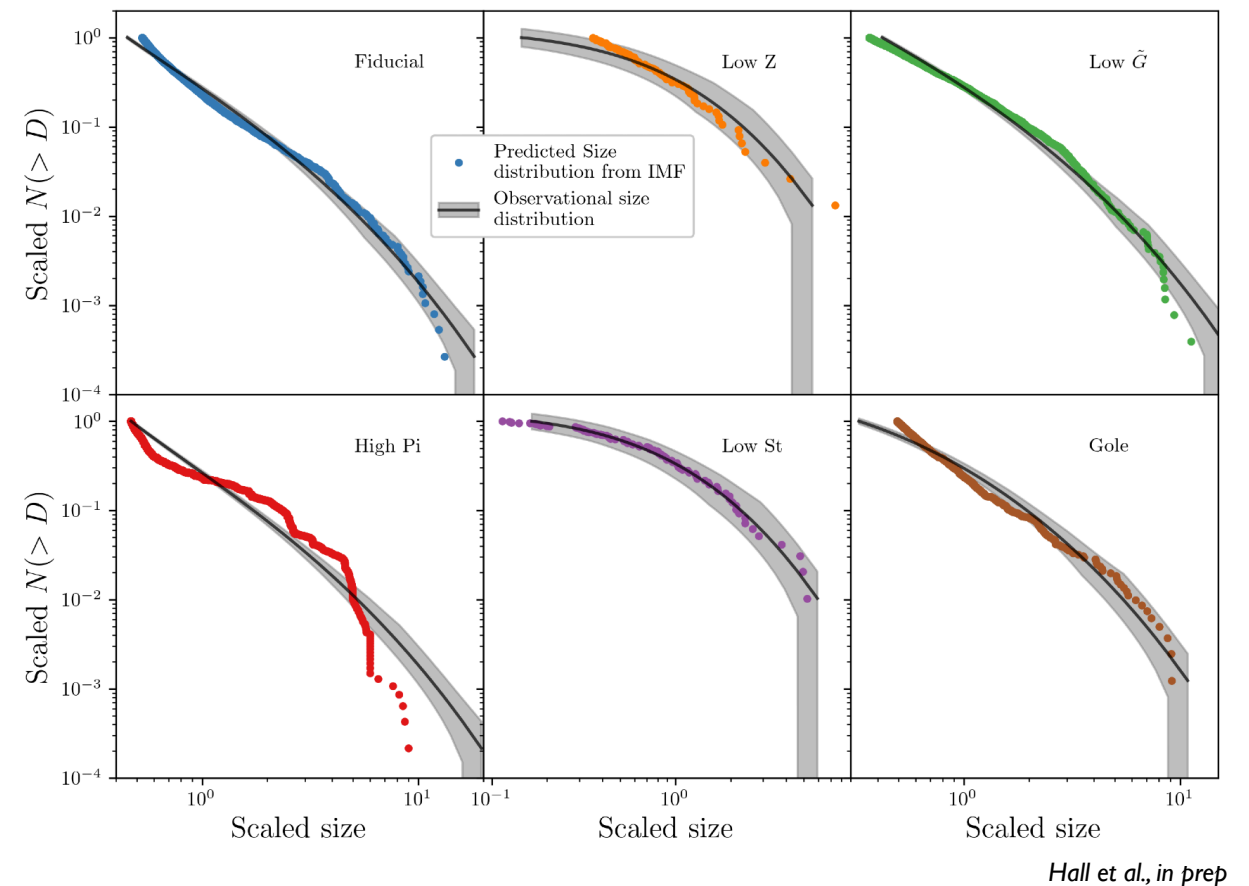
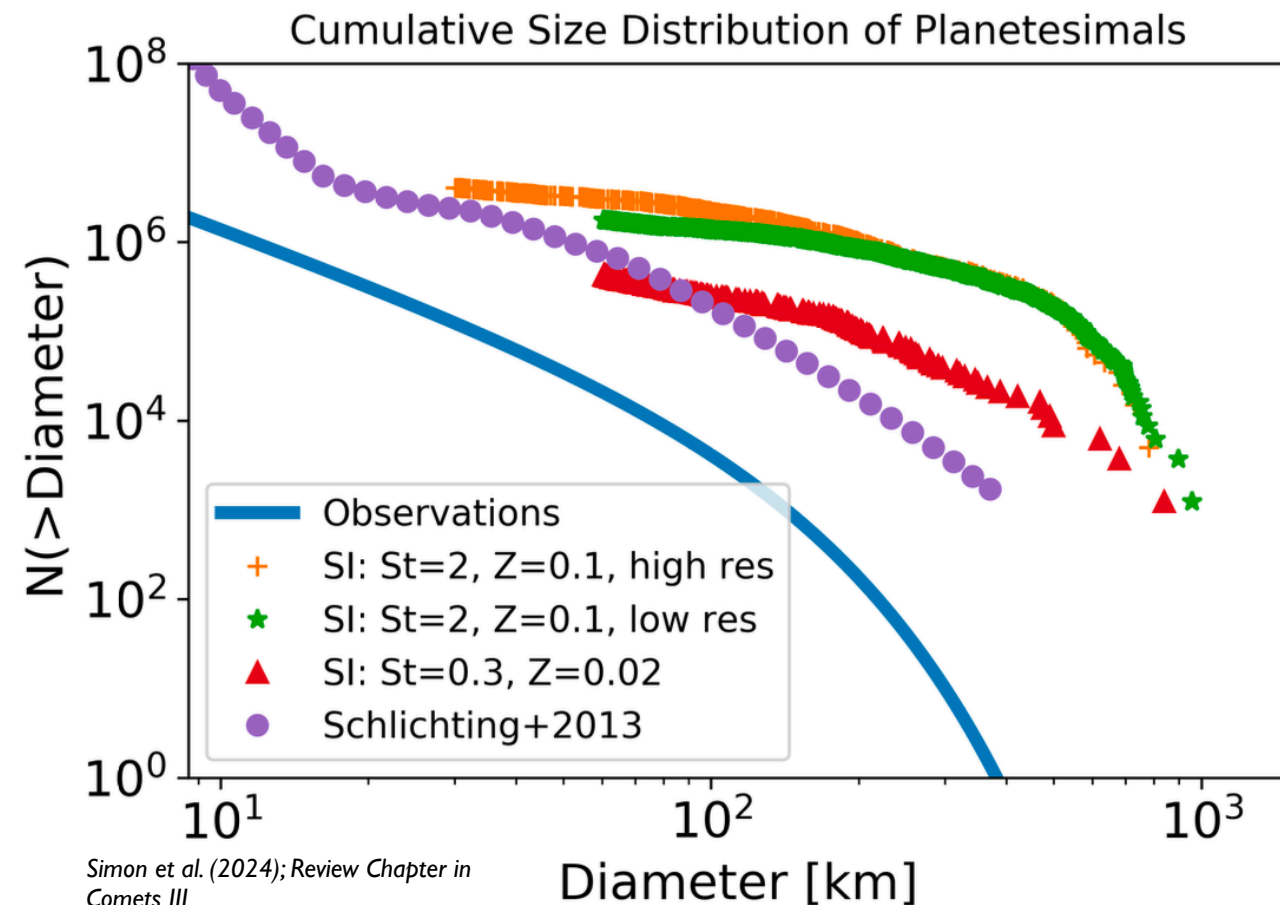
$$\Delta t > \frac{t_s}{1 + \epsilon}$$

Tests of the Streaming Instability: Binary KBO properties



- Pebble clouds initially have a lot of angular momentum
- **Leads to binary formation** (too much spin for a single body to stay bound)
- Binary properties **strongly agree with Kuiper Belt binaries!**

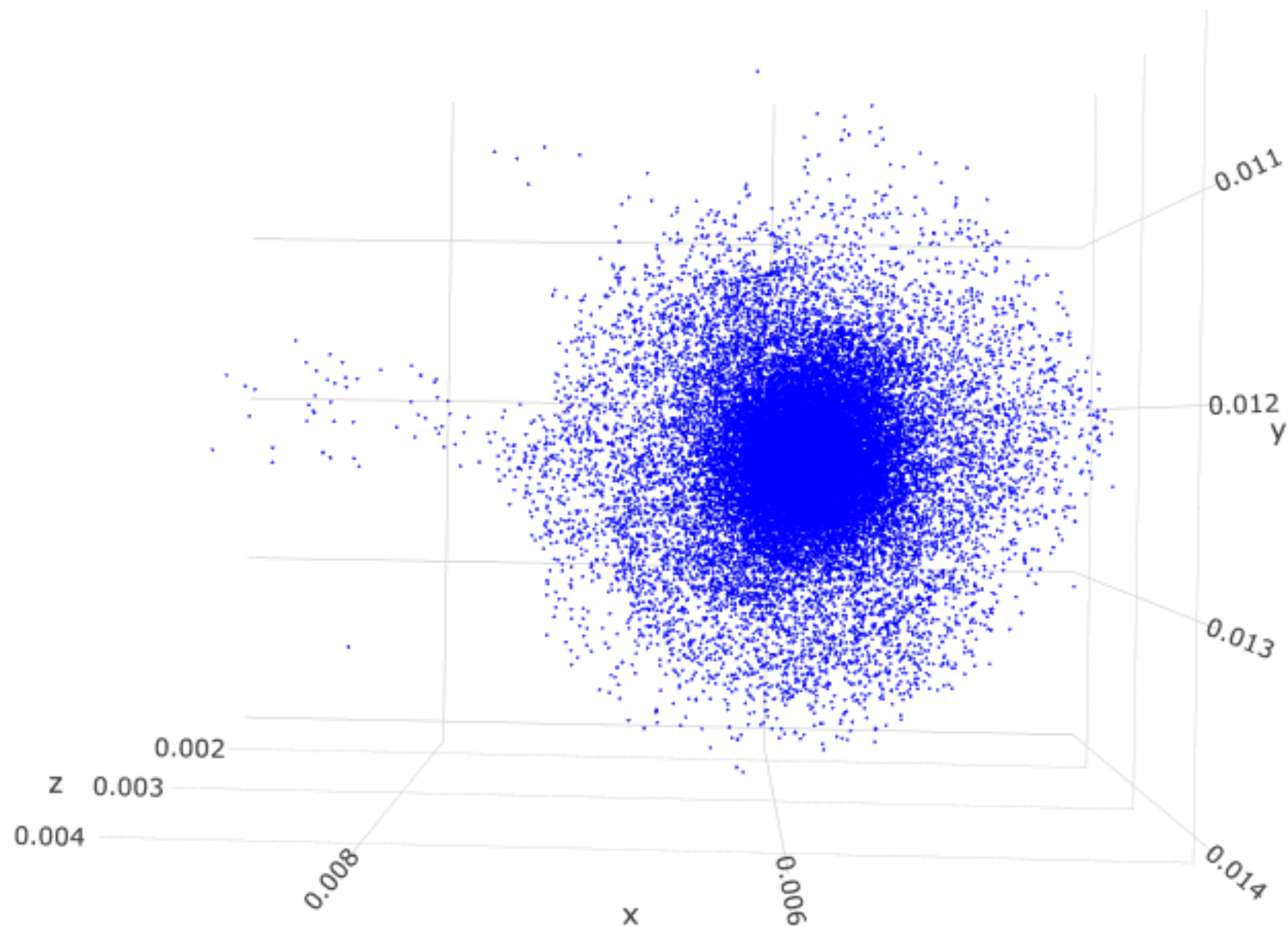
Tests of the Streaming Instability: Size Distribution



- Compare with cold classical Kuiper Belt (pristine!)
- Earlier work: Shape of (cumulative) size distribution doesn't agree
- Newer work (by graduate student Weston Hall) - **shapes strongly agree!!!**
- **But still issues to resolve:**
 - Can only test large-size end of distribution ($D \gtrsim 50$ km)
 - Very idealized setups (no MHD, no self-consistent substructures)
 - “Planetesimals” are actually uncollapsed pebble clouds
 - Stiffness issue - what happens at small St and large Z ??

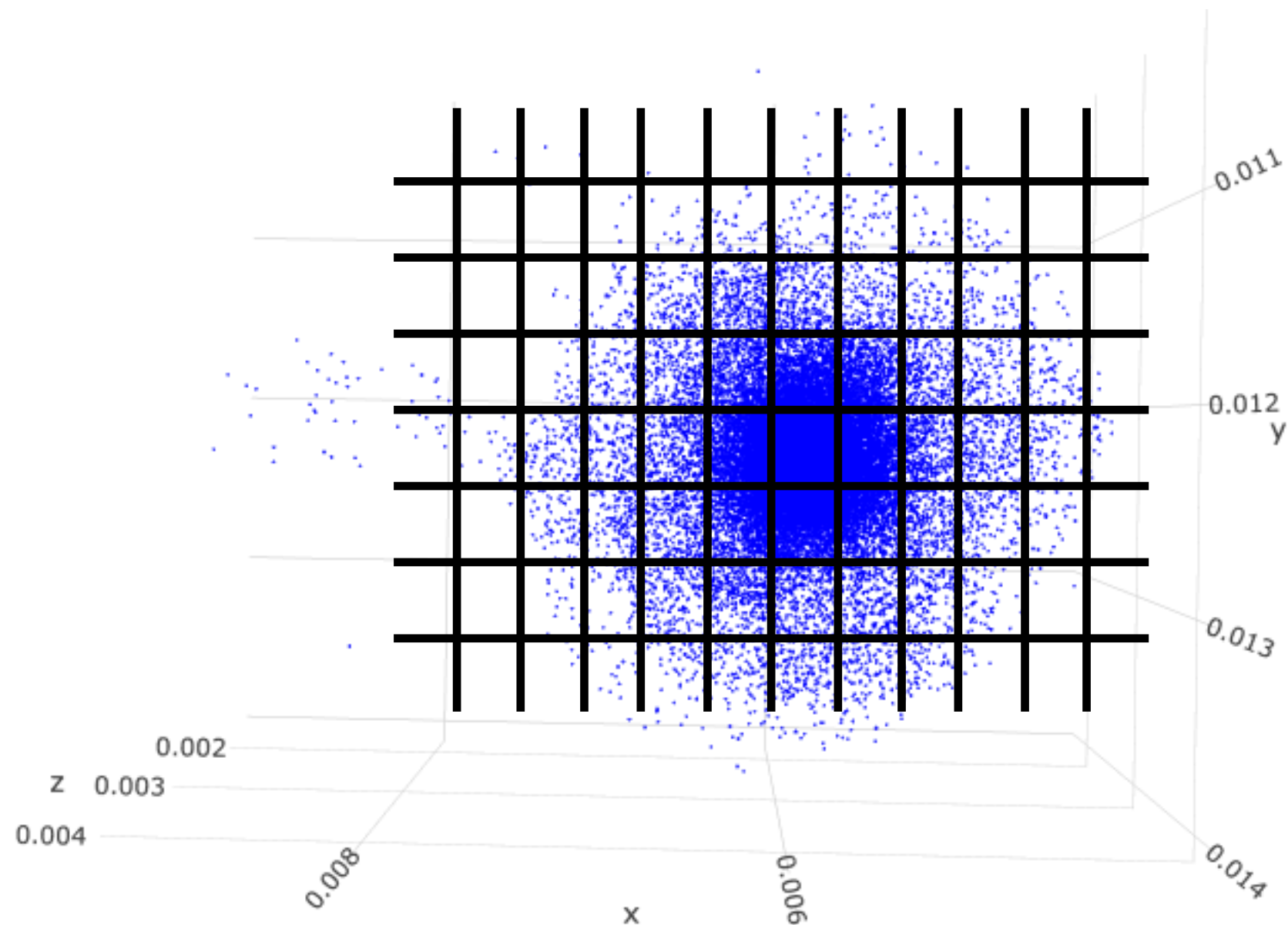
Uncollapsed pebble cloud limited by grid scale

(Poisson solver only resolves gravity on grid scale)



Uncollapsed pebble cloud limited by grid scale

(Poisson solver only resolves gravity on grid scale)



AthenaK Plans

1. Simplest problem to address: explore small St and large Z
(We're putting in a new particle integrator, either using implicit or analytic approach)
2. Larger shearing boxes with MHD turbulence, non-ideal effects (diffusion, Hall), substructures (zonal flows) and influence on the streaming instability
(takes advantage of GPU capability)
3. *Use AMR* to resolve pebble cloud collapse (need at least 11 levels of refinement)
4. *Use AMR* to probe small size end of the distribution (only requires ~ 7 levels of refinement)