Planetesimal formation by gravitational instability

\[
\frac{GM_* R}{a^2 \mu} \sim \frac{G(\rho R^3)}{R^2} \quad \Rightarrow \quad \text{Roche} \quad \rho \sim \frac{M_*}{a^3}
\]

\[
\rho_{\text{Roche}} \sim 200 \rho_{\text{MMSN}} \quad \Leftrightarrow \quad \mu \equiv \frac{\rho_{\text{dust}}}{\rho_{\text{gas}}} \sim 200
\]

Assumed starting conditions

- \(1 - 10 \rho_{\text{MMSN}}\)
- particle size \(s < 1 \text{ cm}\)
- bulk metallicity \(Z \equiv \Sigma_{\text{dust}}/\Sigma_{\text{gas}} \sim 0.01 - 0.1\)
Streaming Instability
Two-fluid aerodynamic clumping mechanism in disks

- always present
- most effective when particles are marginally coupled to gas: $t_{\text{stop}} \sim \Omega^{-1}$

$\tau_s \equiv \Omega t_{\text{stop}} \sim 1$

see also Yang #3.27

Johansen & Youdin 07

Bai & Stone 10
Streaming Instability

- works for outer disk (~100 AU)
- problematic for inner disk: but see Meru #3.20
- but turbulent concentration of particles is general and promising
- also promising is concentration of $\tau_s \sim 1$ in vortices: see Meheut #3.19
Vertical Settling

- Dust settles quickly even for $\tau_s \ll 1$ ($10^3$ yr for mm grains)
- Turbulence (of all forms) is a problem

Kelvin-Helmholtz (KH) instability
Vertical Settling

- If $Z \sim 0.06$ (4 x solar), then $\max \mu \sim 30$
- Results so far omit self-gravity, whose inclusion should only increase $\mu$
- But streaming instability might prevent vertical settling
- Computationally expensive to simulate thin sublayers
Vertical Settling

Only small clumps with big particles can collapse against gas pressure

If $t_{\text{stop}} < \ell/c$:

- Dust-gas mixture acts as a tightly coupled suspension

$$c = \frac{c_s}{\sqrt{1 + \mu}} \quad \ell = \frac{1}{\sqrt{G\rho_{\text{Roche}}}}$$

Roche-density suspensions are Jeans-stable

Cuzzi et al. 08
Shi & EC 13

If $t_{\text{stop}} > \ell/c$:

- Dust and gas decouple; loss of pressure support

$$t_{\text{collapse}} \sim \frac{\ell}{v_{\text{term}}} \sim \frac{1}{\Omega \tau_s} \sim 10^3 \Omega^{-1}$$

Collapse is slowed by drag; turbulence could stop it

Lee, EC+ 10b
Secular Gravitational Instability

- overdense rings of dust attract more dust
- modes grow even for $\rho \ll \rho_{\text{Roche}}$
- accretion rate limited by terminal velocity

Drag-mediated gravitational collapse is slow and sensitive to turbulence

![Graph showing maximal particle diffusivity](image)
Outlook

Particle concentration in both passive and active disks

- Nonlinear and non-axisymmetric development of secular GI
- Can $\tau_s \sim 10^{-3}$ stick up to $\tau_s \sim 1$? Also need to extend Garaud et al. (2013) to global drift models.
- How thin is thin for $\tau_s \sim 10^{-3}$? How vertically settled can disks be with streaming instability?
- How dead is dead?
Shearing box simulation of dusty sublayer

KH-unstable

KH-stable

Lee, EC+ 10b