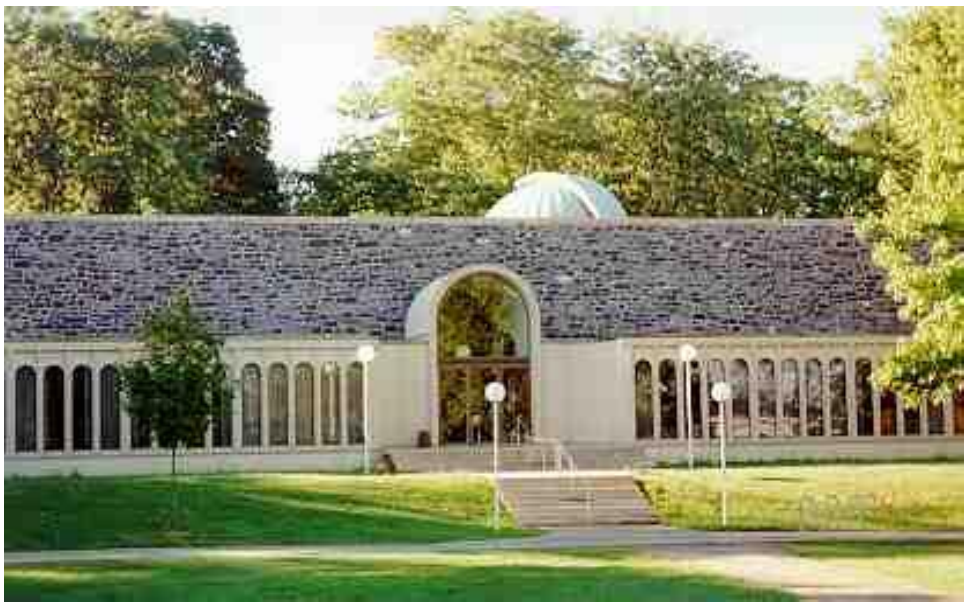
Streaming Instability in Protoplanetary Disks: Implications for Planetesimal Formation



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Planetesimal Formation in Protoplanetary Disks

Micron sized dust suspending in the gaseous disk

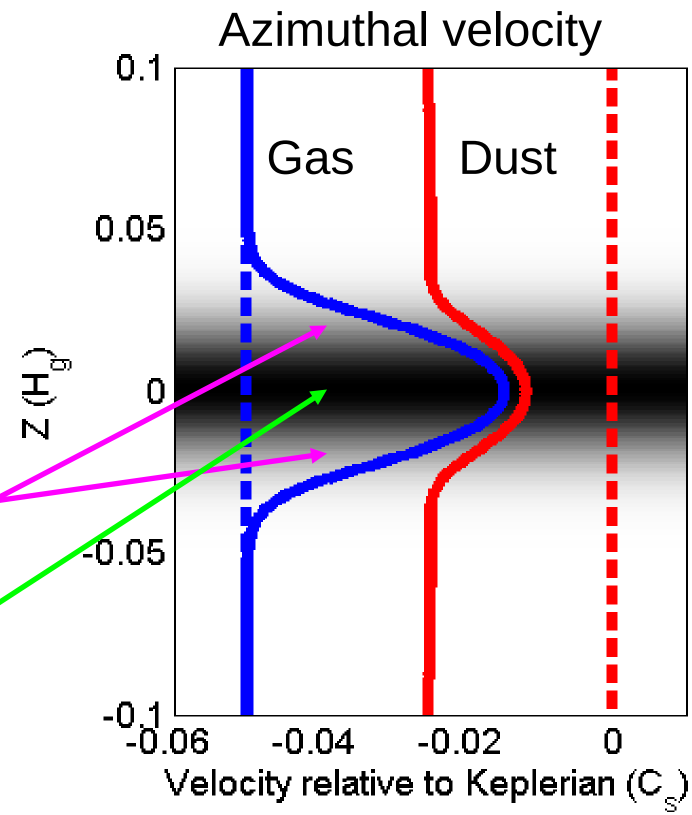
Coagulation by sticking

Radial drift

Settle to disk mid-plane

Kelvin-Helmholtz and/or Streaming instability

Gravitational collapse ⇨ **Planetesimal**



Assume in the dead zone, no MRI

Scientific Motivation and Goals

Previous Work:

Johansen et al. 2007, 2009:

Fully 3D simulations on planetesimal formation by streaming instability
But particle size distribution was narrow, didn't investigate KHI

Chiang 2008, Barranco 2009:

Fully 3D simulations, search criteria for the onset of KHI
But dust was assumed to be perfectly coupled to gas

This Work:

Isolate streaming instability from KH instability:

Streaming instability: most prominent in the ***r-z*** plane
KH instability: requires the azimuthal dimension

Effect of a wide particle size distribution:

From strongly coupled dust grains to pebbles/rocks/boulders

Numerical Method and Model Setup

Athena MHD code (Stone et al. 2008) for gas dynamics with

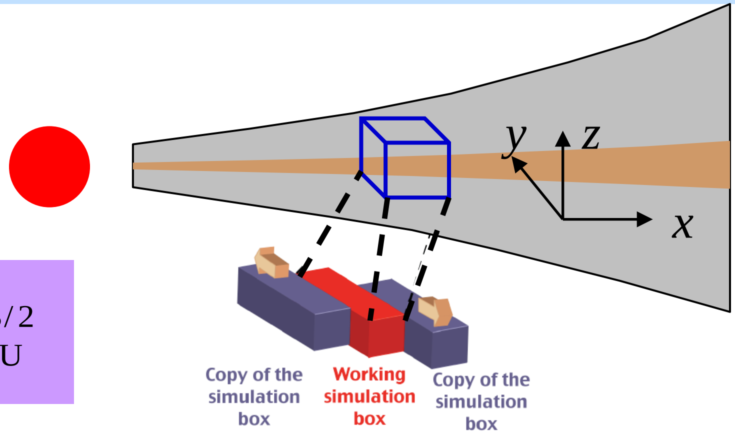
- Lagrangian super-particles coupled to gas via aerodynamic drag (with feedback)

Parameters in the problem:

Sub-Keplerian velocity: $\eta V_k \approx 0.05 r_{\rm AU}^{1/4} c_s$

Total Metalicity: Z = 0.01-0.03

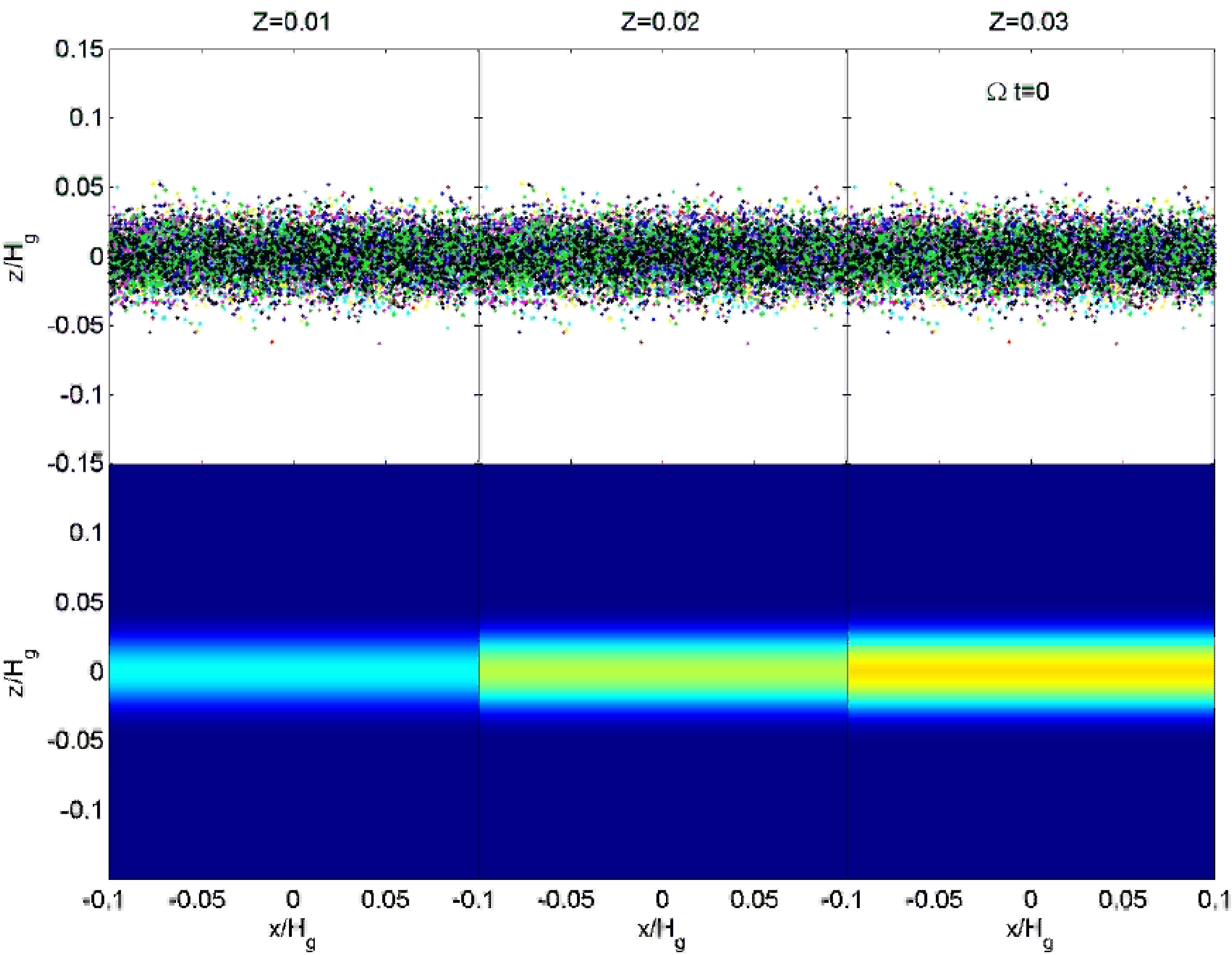
Dust composition: $\tau_i \equiv \Omega t_{{\rm stop},i} \approx 5\times10^{-3} a_{i,{\rm cm}} r_{\rm AU}^{3/2}$



Model Setup: <u>Local shearing box simulation with vertical gravity</u>

- 2D (***r-z*** plane, only SI, no KHI) and 3D
- No magnetic field, no self-gravity, isothermal EoS, reflection vertical BC
- Particle size distribution is uniform (in log) spanning 1 ~ 3 orders of magnitude
- Change size range and metalicity (~30 runs)
- Initially partially settled $H_d = 0.015 H_g$, run for 50-100 orbits until saturation

Dust and Gas Dynamics in Disk Mid-Plane



$L_x = L_y = 0.2H_g;\ L_z = 0.3H_g;$

$\eta V_k = 0.05c_s;\ \tau_s = 10^{-3} - 1$

Top:

Evolution of particles

Color marks particle with different τ_s ; big black dot in Z=0.03 panel marks the densest clump.

Bottom:

Gas azimuthal velocity

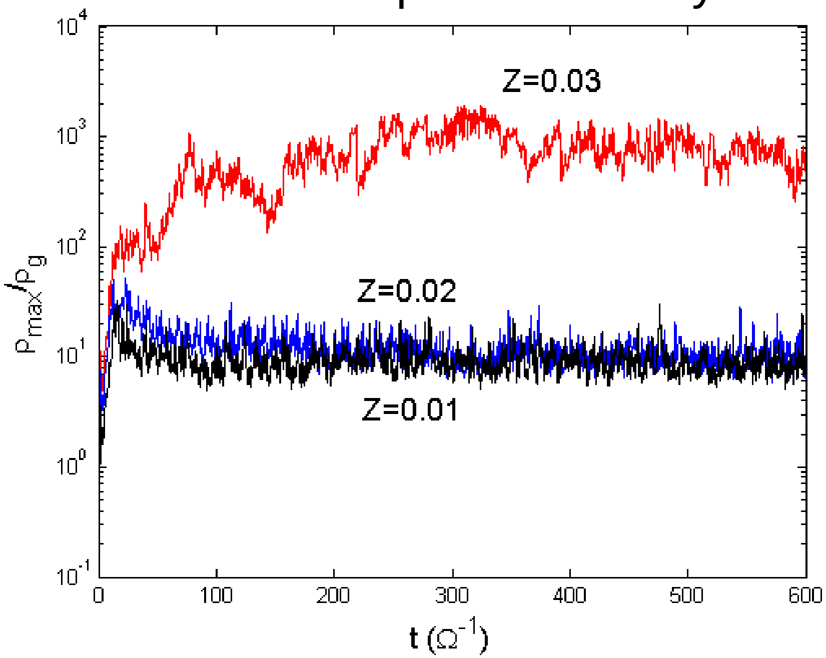
Larger metalicity -> weaker turbulence

Implications for Planetesimal Formation

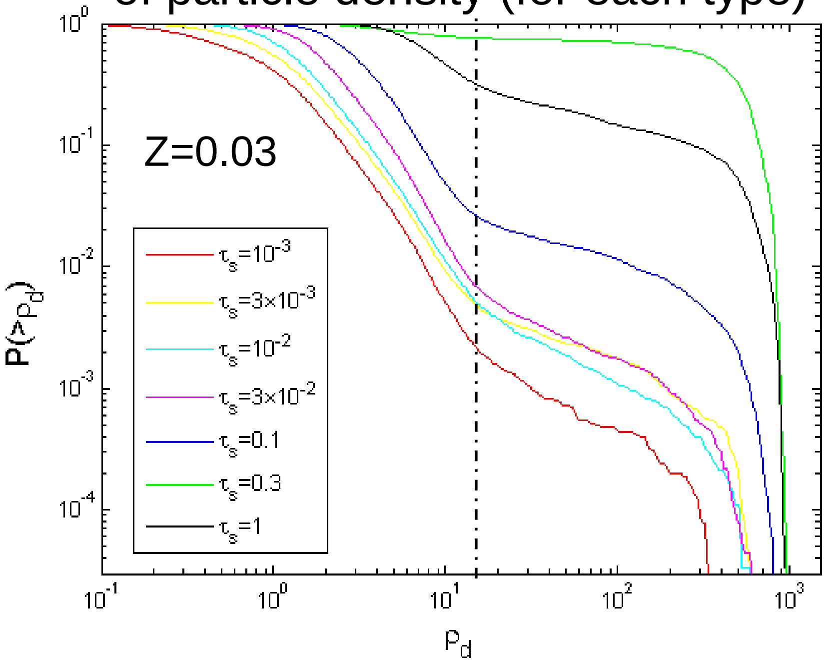
- Concentration of particles
- Can Kelvin-Helmholtz instability occur?
- Vertical diffusion
- Radial drift
- Radial mixing
- Collision velocity

Concentration of Particles

Maximum particle density



Probability distribution function of particle density (for each type)



Threshold metalicity:

Above which rapid planetesimal formation via streaming instability is possible (Johansen et al. 2009)

Composition of dense clumps:

Mostly made of particles undergoing strongest streaming instability, but other particles are also trapped

Can Kelvin-Helmholtz Instability Occur ?

Mass loading:

$$\rho_g \le \rho^{\rm eff} \equiv \rho_g \frac{\eta V_k}{\Delta u_y} \le \rho_g + \rho_d$$

Generalization from the strong coupling regime

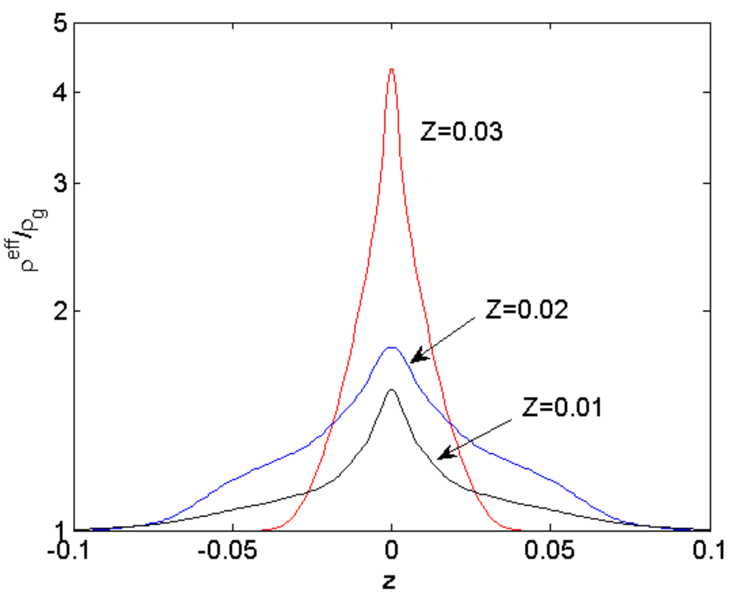
Richardson number:

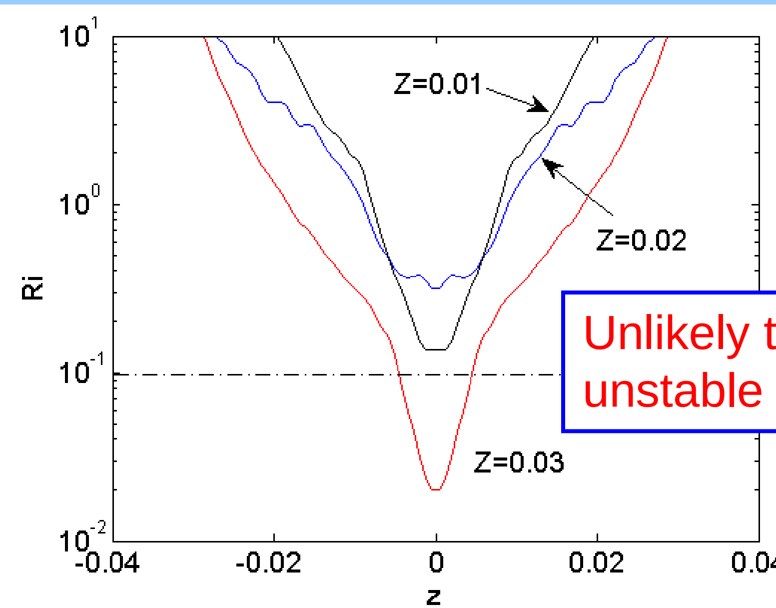
$$Ri \equiv -\frac{\Omega^2 z}{\rho^{\rm eff}} \frac{\partial \rho^{\rm eff} / \partial z}{(\partial u_y / \partial z)^2} \approx \frac{-\Omega^2 z}{\Delta u_y (\partial u_y / \partial z)}$$

Onset of KH instability: (necessary but not sufficient)

No rotation: $Ri < 1/4$ (Chandrasekhar 1961)

Keplerian shear: $Ri \le 0.1$ (Chiang 2008)

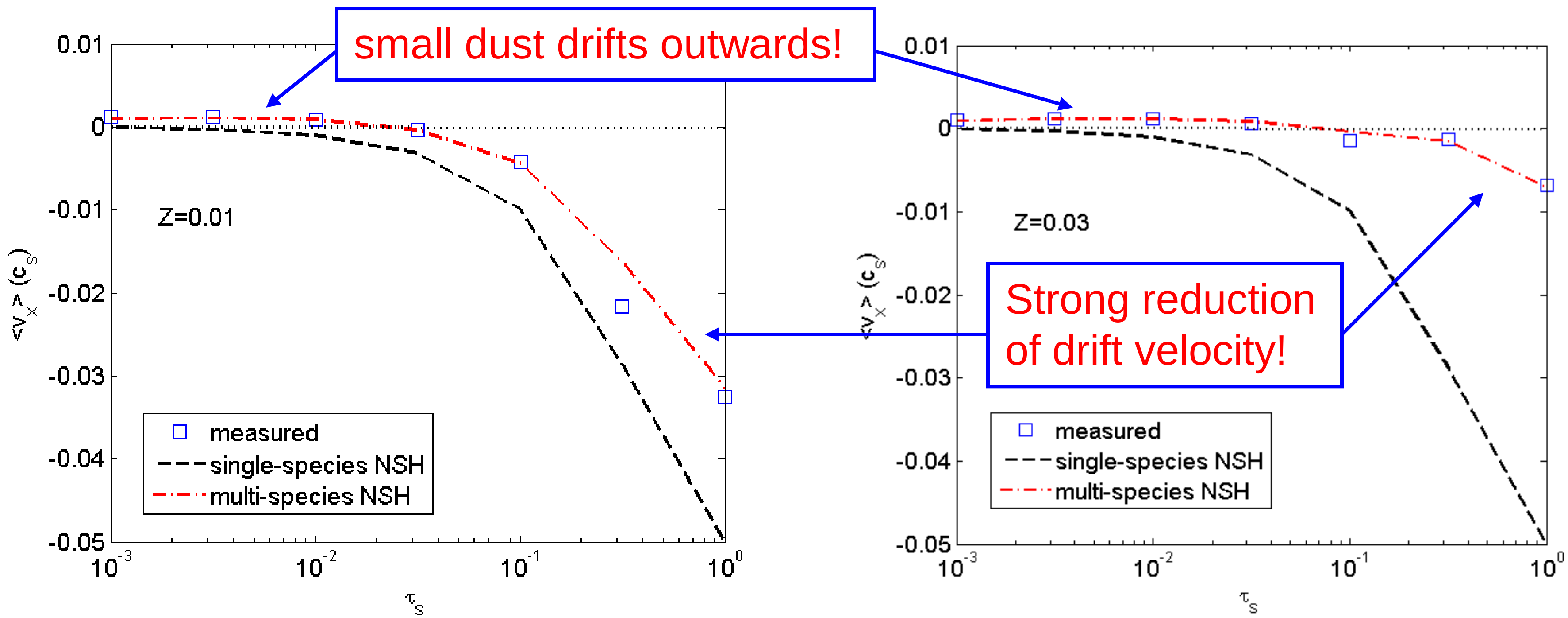




Unlikely to be unstable to KHI

Radial Drift Velocity

Multi-species of dust will modify the NSH equilibrium, which is derived from single dust species. This effect reduces the radial drift velocity significantly.



Streaming instability is known to reduce the radial drift velocity (Johansen & Youdin 2007), however, it appears to be much less pronounced in stratified simulations with multi-species of dust particles.

Conclusions

- Formation of dense clumps by streaming instability strongly depends on metalicity, and its composition is dominated by big particles.
- The turbulence generated from streaming instability is strong enough to prevent KH instability from setting in. KH instability appears to be relevant only when all dust particles are strongly coupled to gas.
- Vertical diffusion coefficient depends on height, and the profile is more extended than Gaussian, probably better given by Lorenzian or Viogt.
- Dust drift velocity is strongly reduced in the disk mid-plane, and is well described by multi-species NSH equilibrium solution.
- Radial diffusion due to the streaming instability is generally very weak, and is more efficient for big particles.
- Collision velocity is largest for big-small particle collisions, major contribution comes from differential radial drift.

Thank you for your attention!