Steady dust concentration and planetesimal formation at the super/sub-Keplerian flow boundary created by non-uniform growth of MRI

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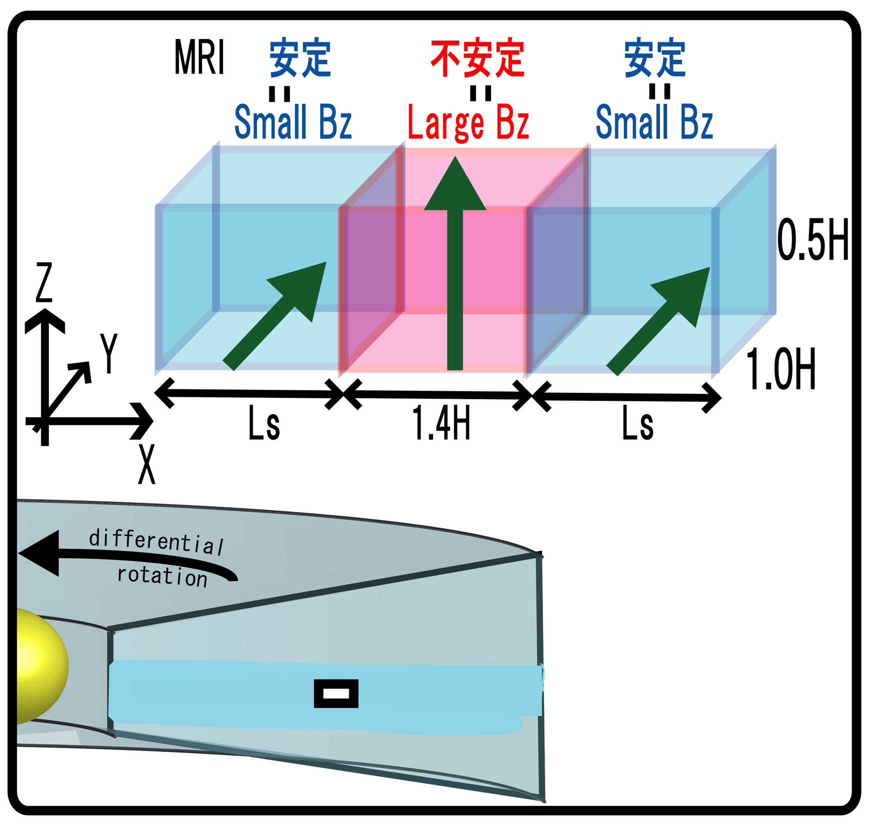
1. Abstract

We study how the planetesimals are formed from tiny dust particles in a proto-planetary disk before the dust particles in-fall to the central star. In our previous work (Kato et al. 2009) we have shown that a steady angular velocity profile that consists of a super-Keplerian and a sub-Keplerian part to appear through nonuniform excitation of Magneto-Rotational Instability (MRI). Then, we study if this radial structure of the angular velocity leads to prevention of in-fall and furthermore to accumulation of dust particles, and how the feedback from concentrated dust particles onto gas work on the dust concentration. Treating the dust particles as super-particles, we found that the particles can be stopped in-fall and concentrated around the outer-edge of the super-Keplerian region. In the most favorable cases (larger MRI-stable region and 1m size dust particles), the maximum dust density is around high as 10 times the gas density and the velocity dispersion of the concentrated particles is too small. So, it is highly likely to cause the gravitational instability and this result suggests a possible route to planetesimal formation via non-uniformly excited MRI in a weakly ionized part of a disk.

2. Model

The growth rate of MRI depends on the ionization degree of gas and the strength of the magnetic field(San&Miyama, 1999). In our model, the magnetic resistivity is uniform but the vertical magnetic component is non-uniform in the radial direction. Both the unstable and stable region exist next to each other.



*common setup

angular velocity (dust) $v_y = v_{kep} = -2/3\cdot\Omega x c_s$

(gas) $u_y = v_{kep} + \frac{1}{2\rho}\frac{\partial P_g}{\partial r}$

global pressure $\frac{1}{\rho}\frac{\partial P_g}{\partial r} = -0.04 c_s \Omega$

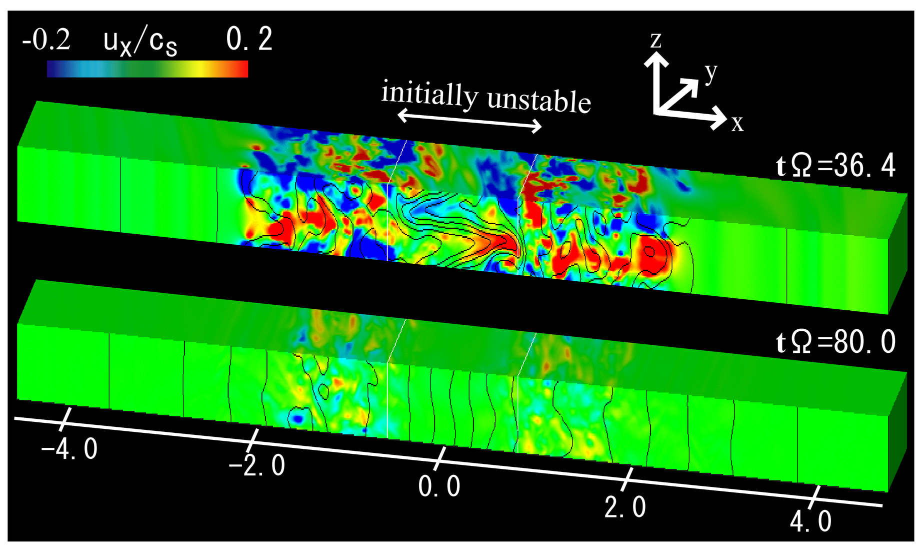
The local pressure and the distribution of particles are uniform.
The vertical gravity is ignored.

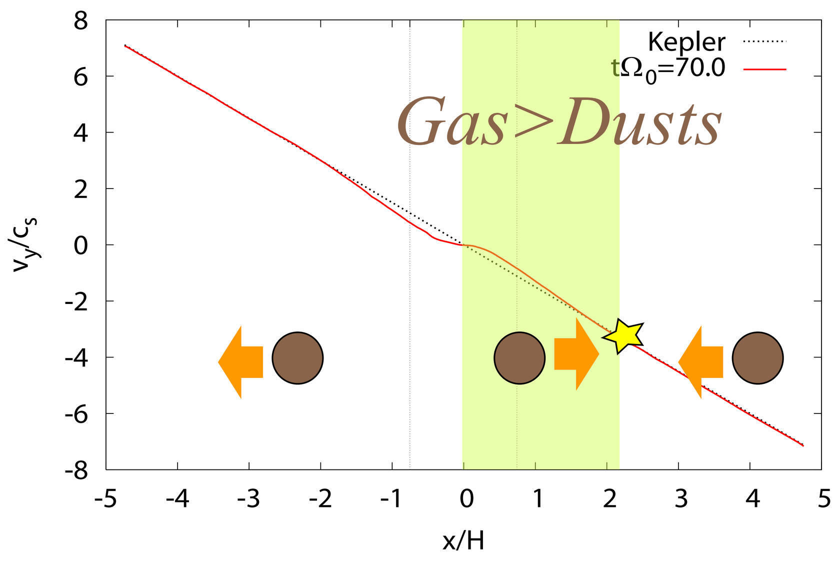
*parameter

- The radial width of the initail stable region; Ls=0.5H、4.0H
- The friction time; $\tau_f\Omega$=0.1(cm)、1.0(m)
- The initial dust-to-gas density ratio ; ε_0=0.01、0.10

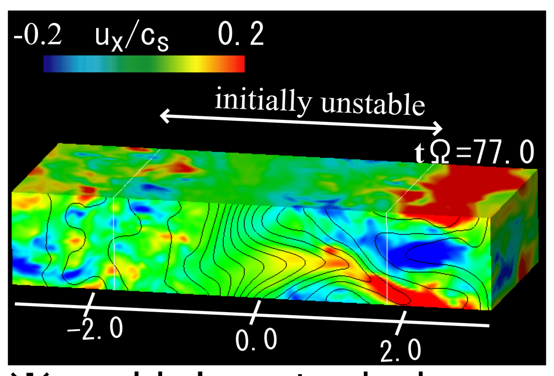
3. The quasi-steady state by MRI

*Ls=4.0H

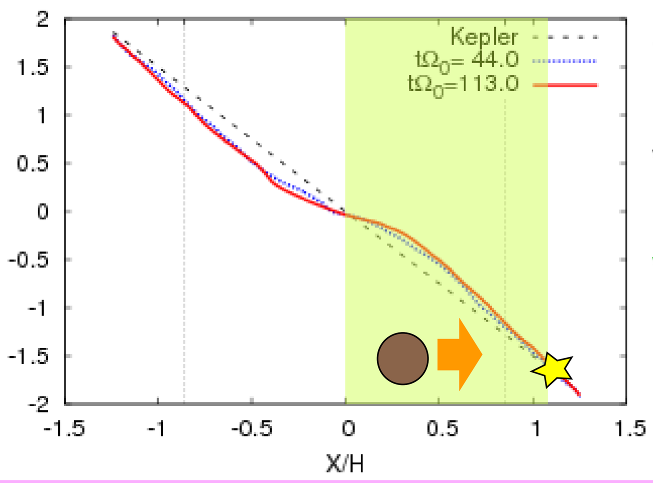




*Ls=0.5H

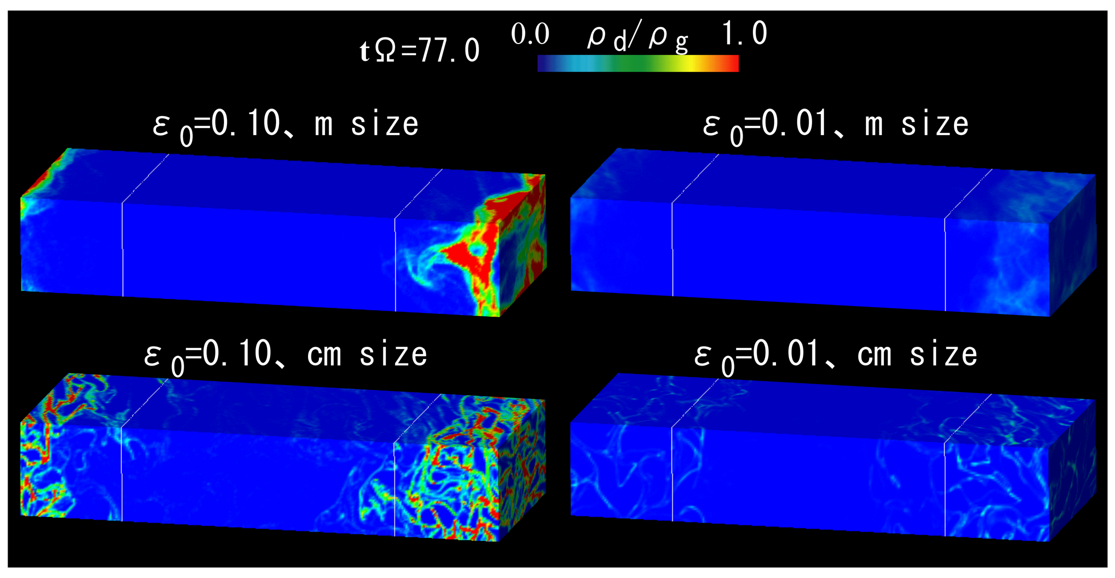


※small Ls→turbulence tends to remain.

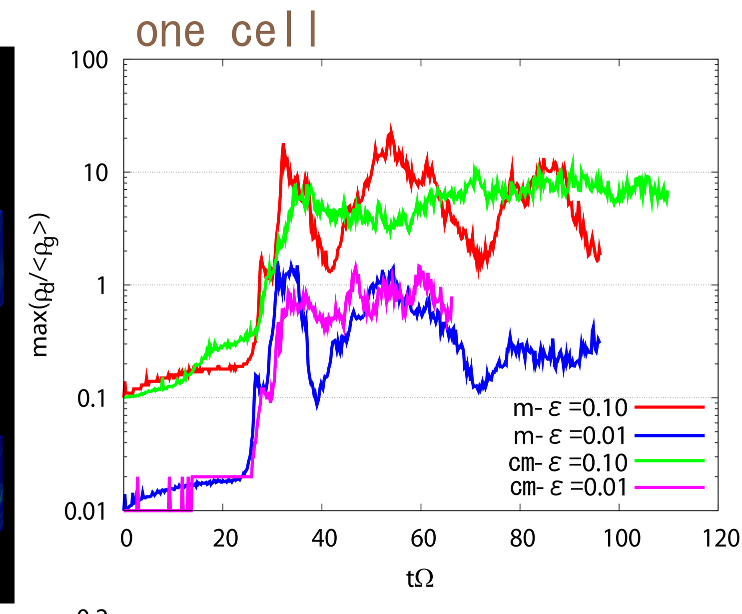


The angular velocity and the pressure shift non-uniformly. They balance with each other.
→The quasi-steady state with the super-Keplerian region is created!
⇒Do the dust particles assemble steadily?

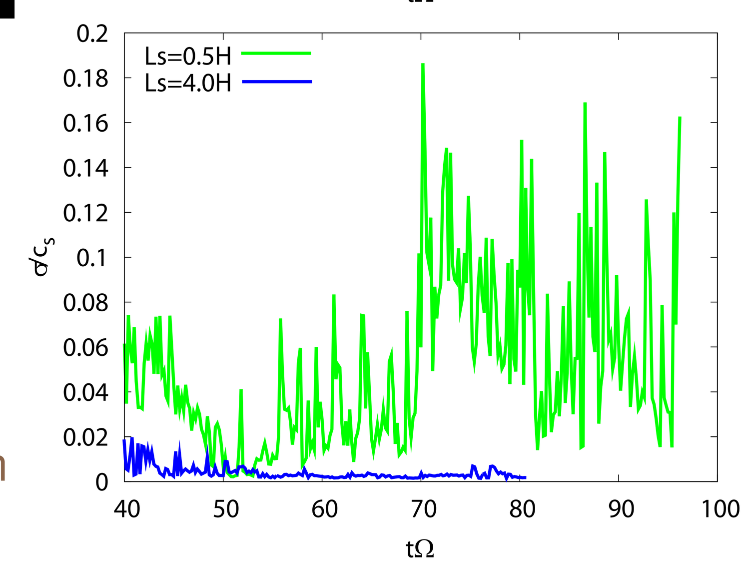
4. Result (Ls=0.5H)



↓The time change of the maximum dust density in one cell



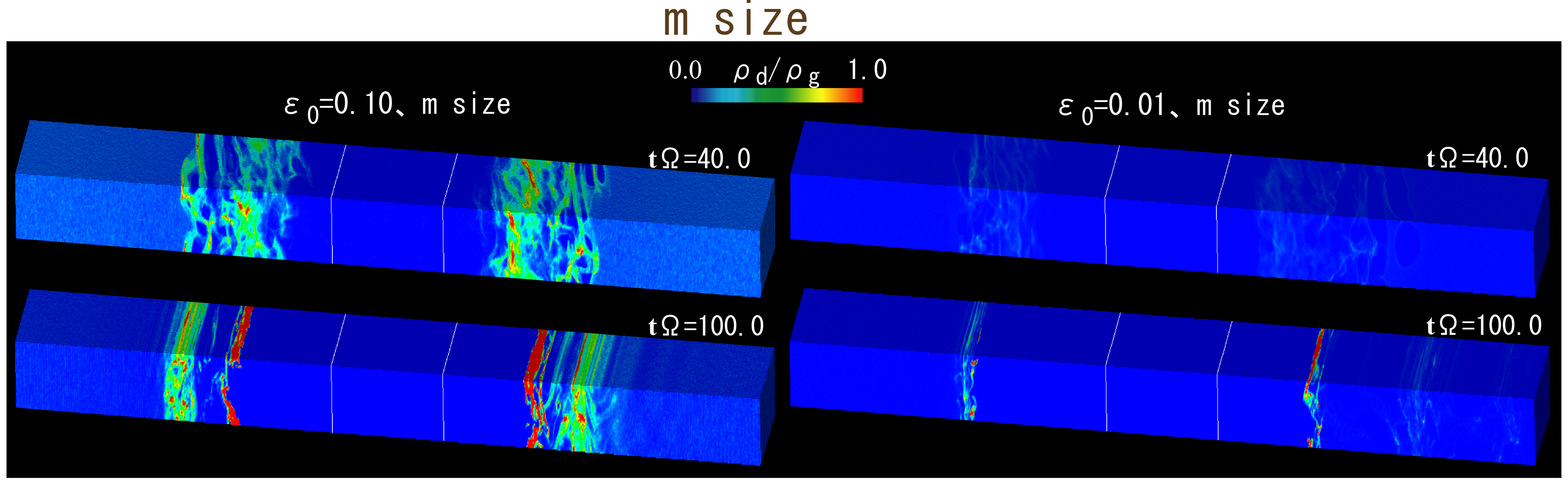
The condensed area in which the turbulence is dominant is created around the Keplerian region. The smaller particles keep its maximum density higher. But the velocity dispersion is larger than the more steady concentration case. →Some clumps are dissipated but others are formed in the other area.



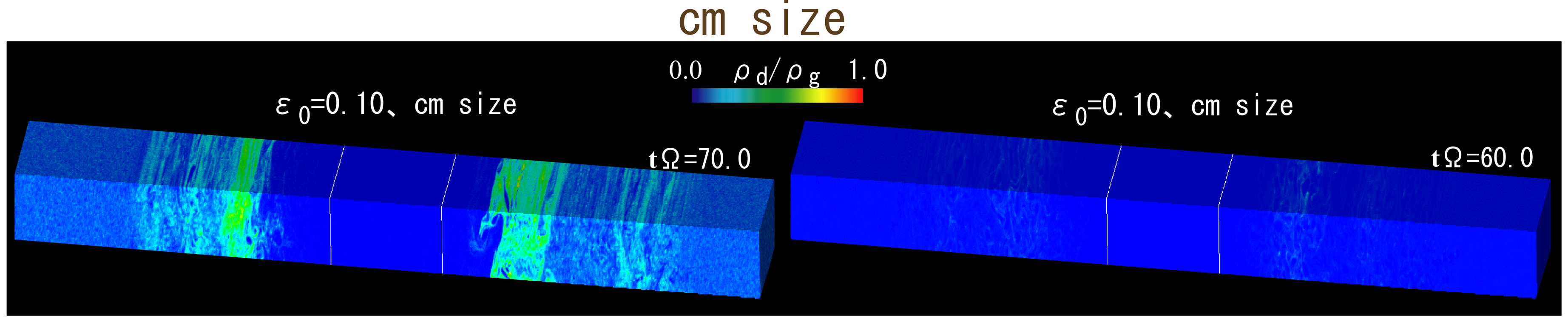
→The velocity dispersion of the particles in the densest grid (ε_0=0.10、cm-size)

5. Result (Ls=4.0H)

m size

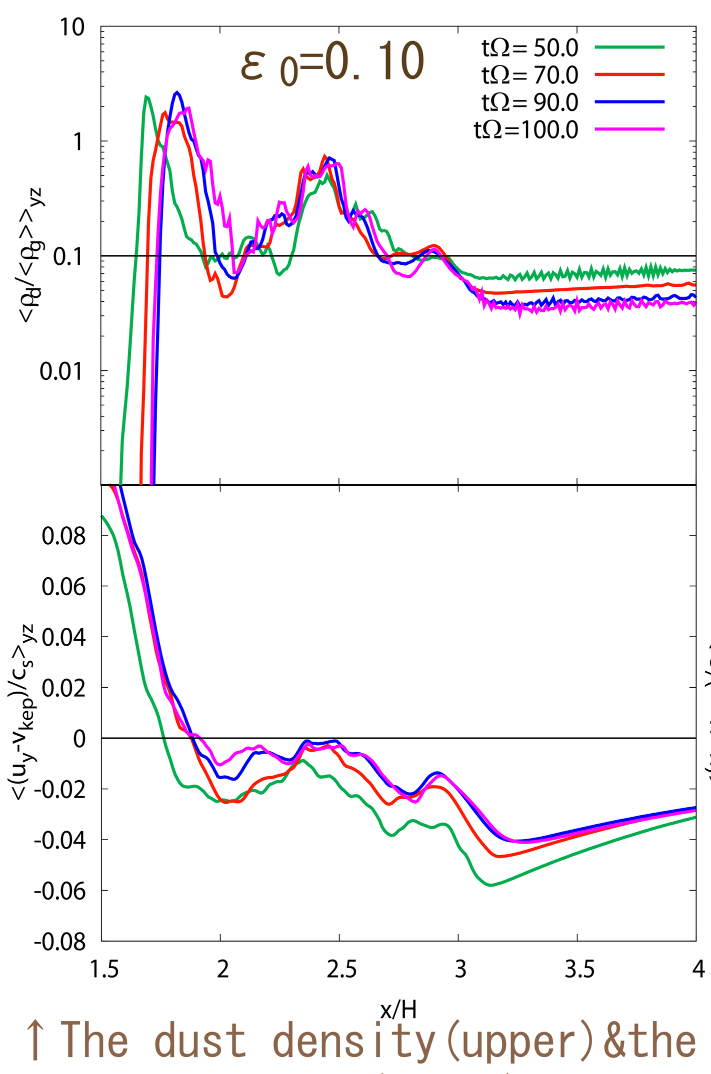


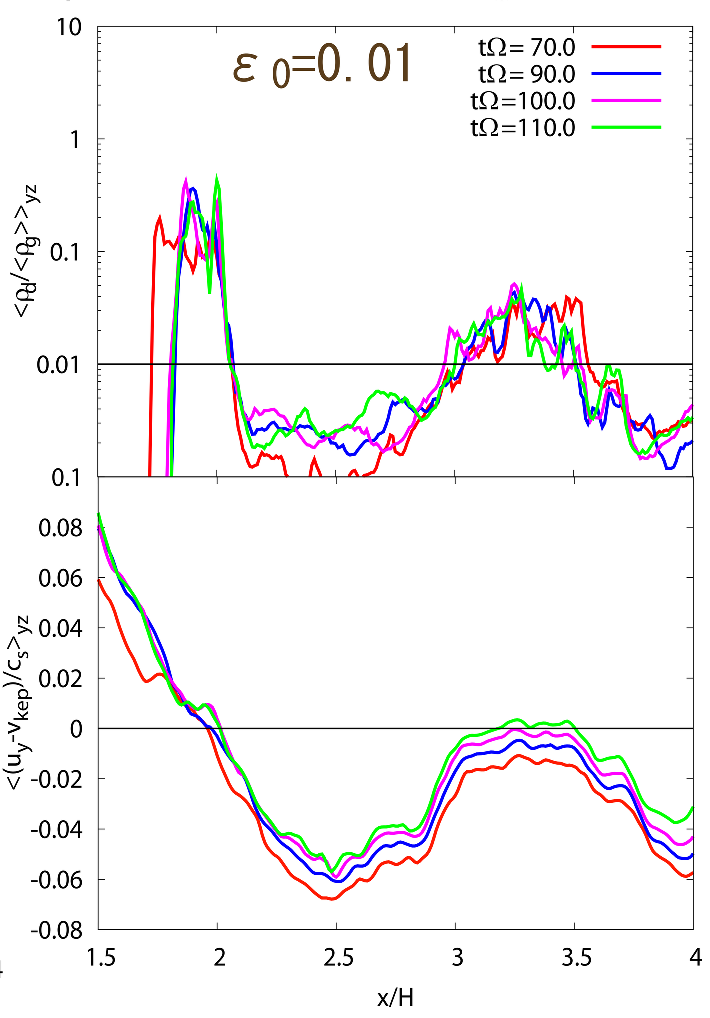
cm size



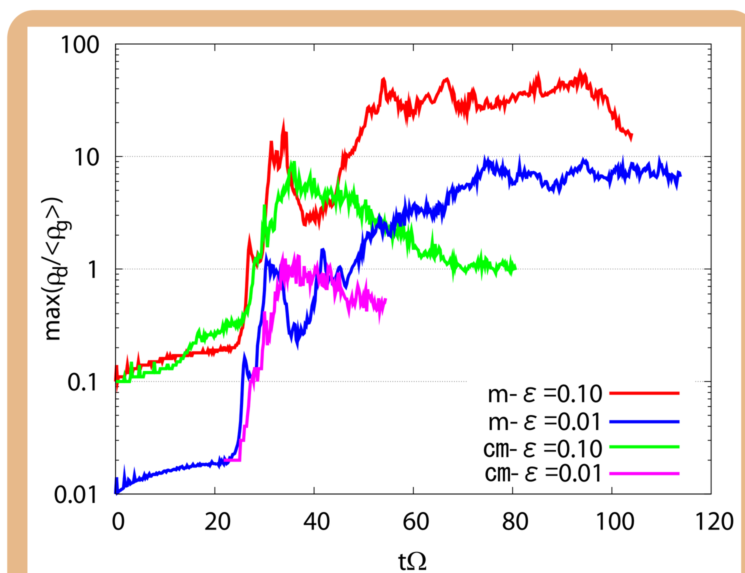
When the friction time is smaller, the particles is more sensitive to gas. So, their migration speed resulted from the difference in rotation (vf) is down and that is why the weak turbulence is dominant in the whole region.
*vf is smaller than the radial velocity by the drag of radial gas flow, vt.

①The density around the Keplerian region becomes higher due to the MRI flow.
②The particles settle down into the Keplerian region steadily.
*The concentrated particles in the outer area of the Keplerian region cause the gas to rotate at *Vkep*.
③The concentrate area extends radially.
→The particle cannot assemble onto the inner densest grid!
*small ε_0→The extending starts at the later stage. The feeding from the outer area is possible for a longer time.





↑The dust density(upper)&the difference between gas *uy* and *Vkep* ∝ dust *vy*(lower) around the densest grid.

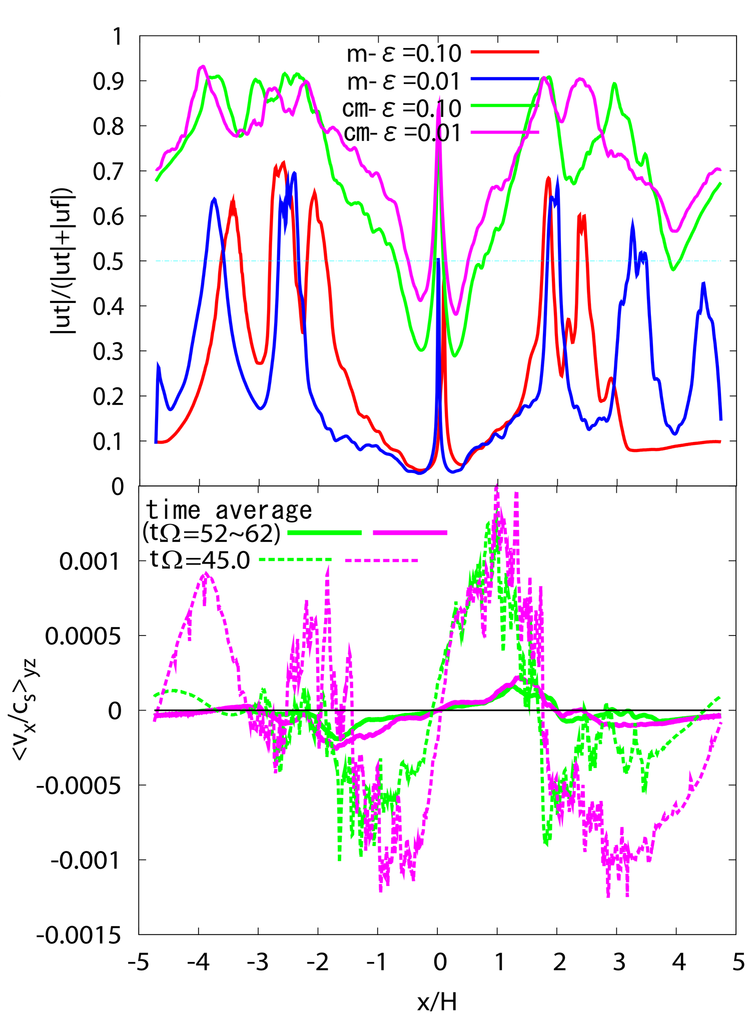


*The average of the particle radial velocity(*vx*) approaches zero. →It is difficult to concentrate particles in the more local region.

←The time change of the maximum dust density in one cell

m size ― The maximum value is saturated because of the extending of the Kepler region.
cm size ― The maximum value decrease because of the weak turbulence.
*But the condenset area is crated by the MRI flow at the early stage. Is it possible to form larger particles?

* The planetesimal formation
The concentration in the quasi-steady state can
→keep the high density in the particular region.
→let the velocity dispersion keep too small(<0.01cs).
⇒It is highly possible to form a planetesimal via gravitational instability, especially in the m-sized case.



↑The ratio of vt to vx(upper) & the averaged value of vx (lower). The value of vt and vf is estimated from motion eq.

6. Future Work

★How do the self-gravity work? ★The sedimentation on the midplane should be calculated at the same time. ★How can the initial condition of our model is generated. ★The time evolution of the magnetic resistivity should be considered when the gas (and dust) density changes.