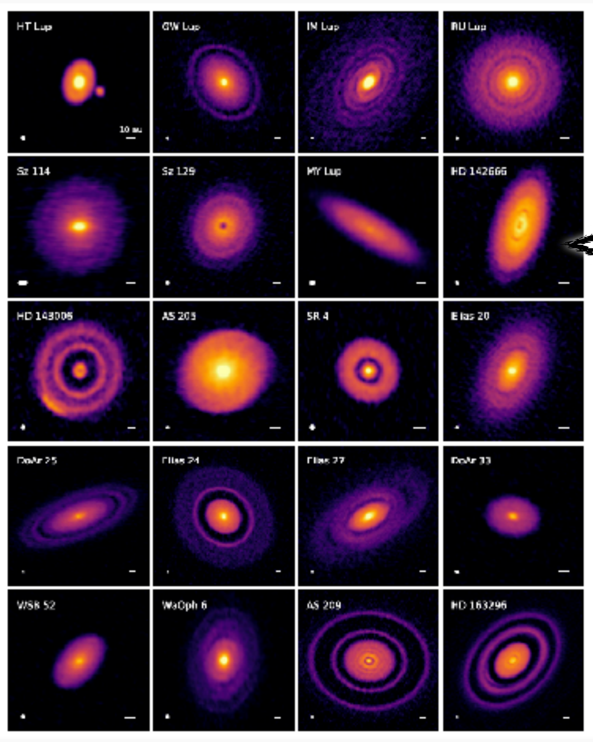
Dust growth toward planetesimals via coagulation instability and secular gravitational instability in protoplanetary disks

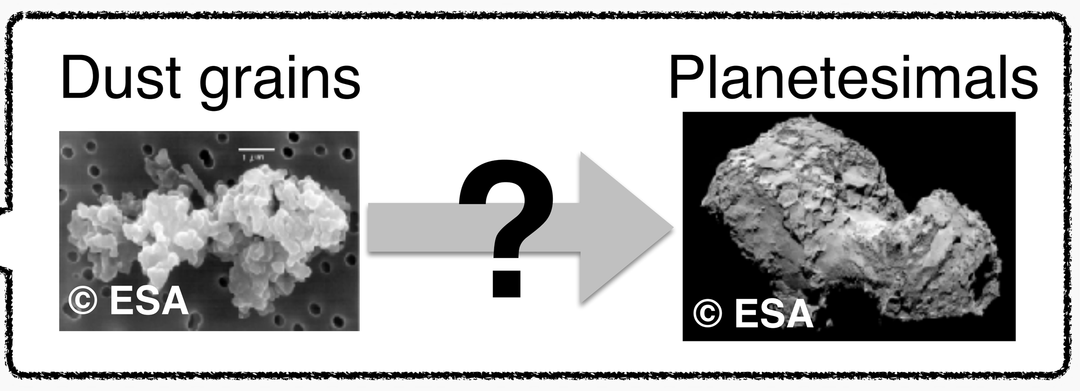
Ryosuke T. Tominaga[*1], H. Tanaka[*2], H. Kobayashi[*3], S. Z. Takahashi[*4,5] & S. Inustuka[*3]

*1: RIKEN, *2: Tohoku University, *3: Nagoya University, *4 Kagoshima University, *5 NAOJ

1. Introduction



DSHARP, Andrews et al. (2018)



Dust evolution is one key process in the disk evolution and planet formation.

- coagulation (e.g., Okuzumi et al. 2012)
- dust-gas instabilities (e.g., Youdin & Goodman 2005)

Dust evolution via dust-gas instabilities

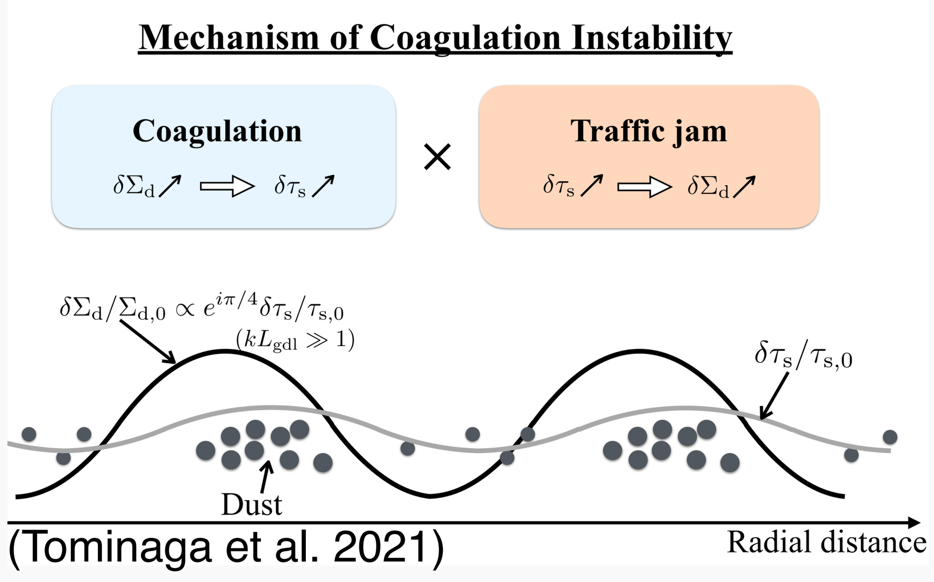
- streaming instability (SI) (e.g., Youdin & Goodman 2005; Johansen & Youdin 2007; Johansen et al. 2007)
- secular gravitational instability (secular GI) (e.g., Ward 2000; Youdin 2011; Takahashi & Inutsuka 2014,2016)

D/G ≥ 10^{-2} & large dust sizes are required for SI/secular GI.
→ dust trapping at pressure bumps/snowline… is necessary.

This work proposes a new instability free from the prerequisite dust trapping!

2. Coagulation Instability (CI): linear growth

Tominaga et al. (2021): "Coagulation + Radial drift" triggers CI!



(Tominaga et al. 2021)

Basic equations:
(see Sato et al. 2016)

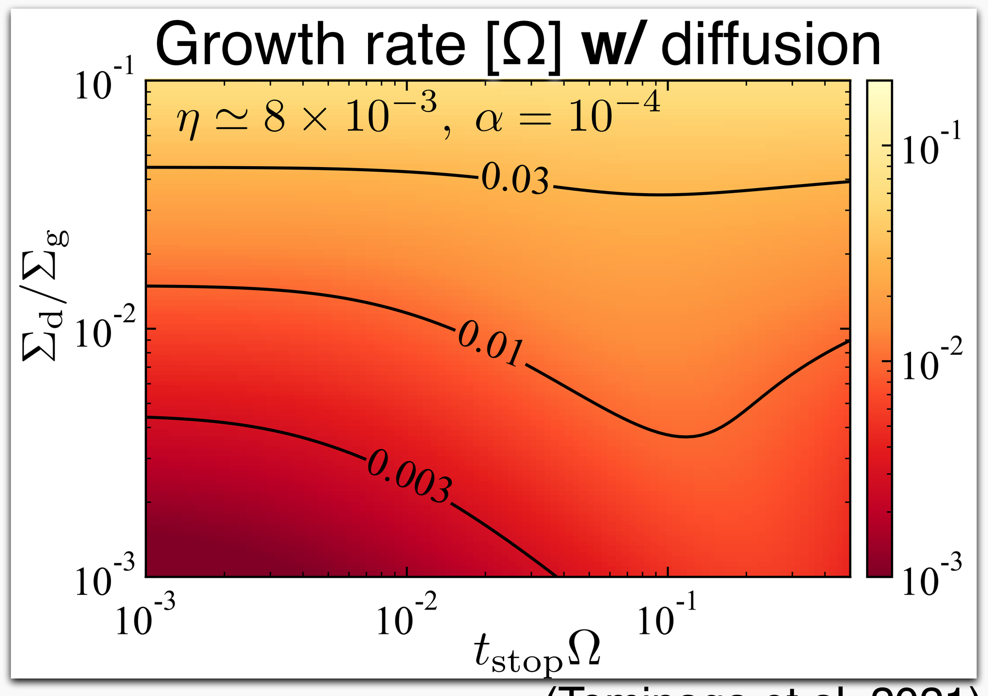
$$\frac{\partial \Sigma_d}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left[r v_r(r, m_p)\Sigma_d\right]$$

$$\frac{\partial m_p \Sigma_d}{\partial t} = \frac{2\sqrt{\pi}a^2 \Delta v_{pp}}{H_d}\Sigma_d - \frac{1}{r}\frac{\partial}{\partial r}\left[r m_p v_r(r, m_p)\Sigma_d\right]$$

$$v_r = v_{drift} + F_{diff}/\Sigma_d$$

↑ Diffusion flux

*Two-fluid analyses show little difference. -> CI is essentially one-fluid instability.



(Tominaga et al. 2021)

In contrast to SI & secular GI, **CI operates even for low D/G!**

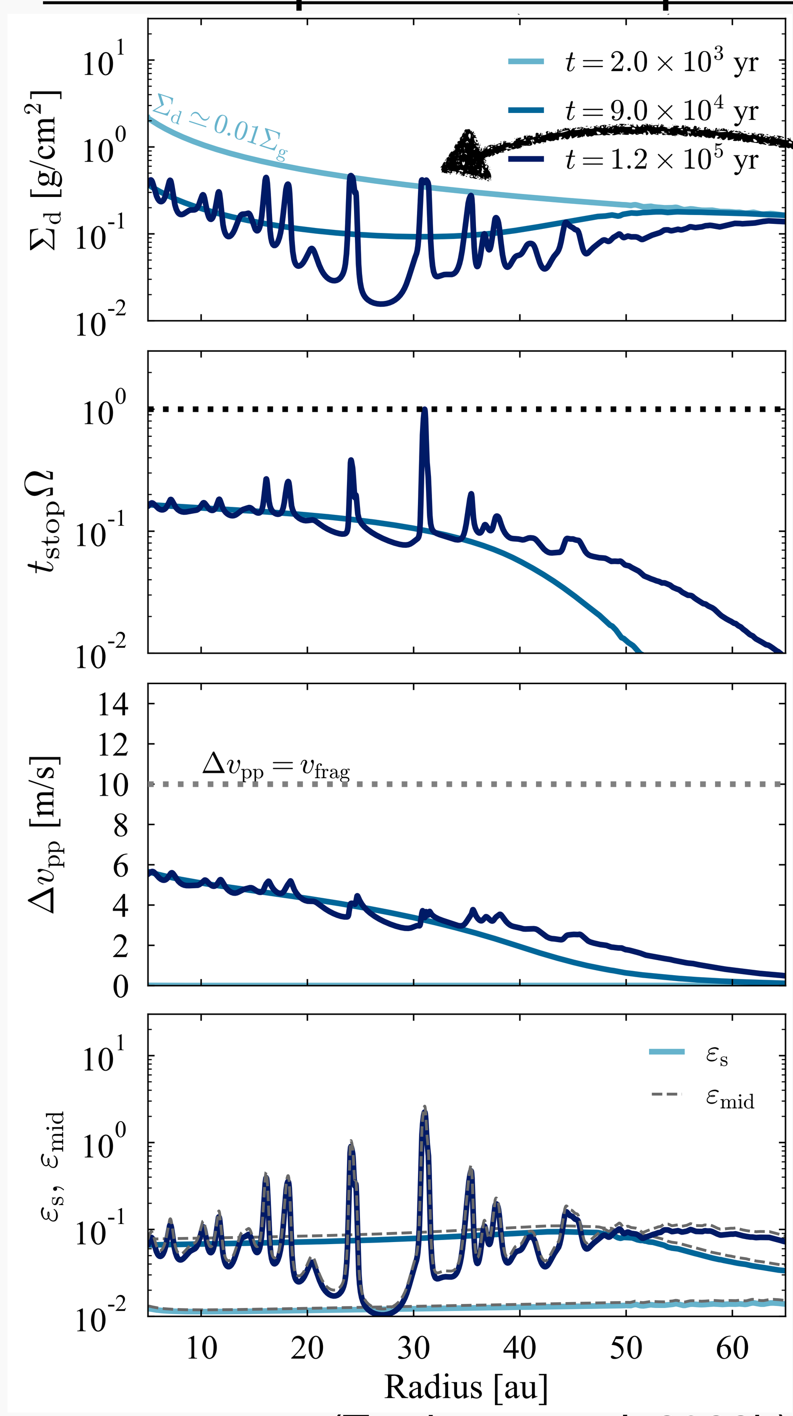
CI timescale ~ tens of T_{Kep}, even with dust diffusion (α~10^{-4})

$$\lambda_{max} \sim H\left(\frac{\alpha}{10^{-4}}\right)^{2/3}\left(\frac{\Sigma_d/\Sigma_g}{10^{-3}}\right)^{-1/3} \times \left(\frac{|v_{drift}|/c_s}{0.02}\right)^{-1/3}$$

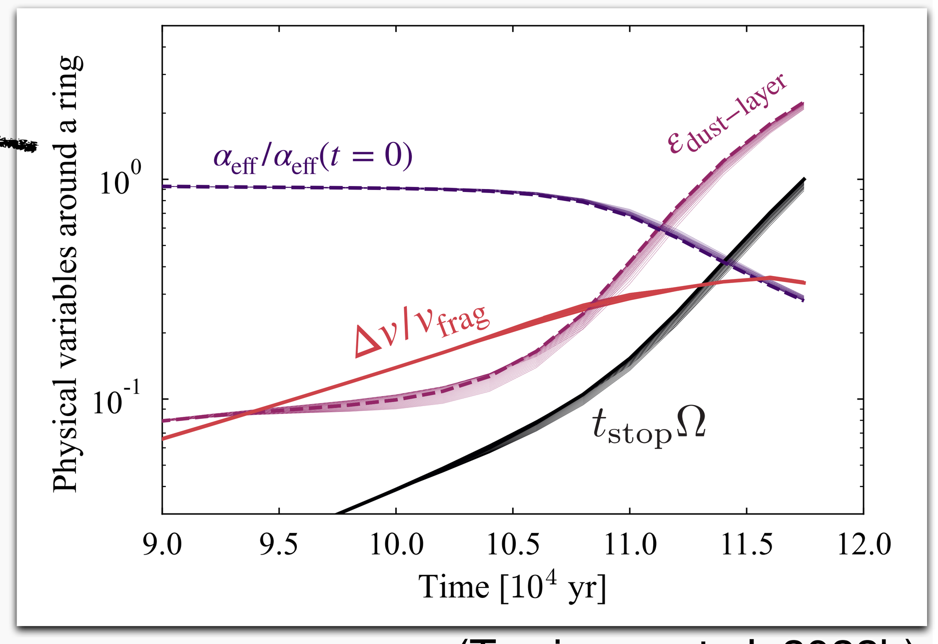
3. Numerical simulations of CI

Tominaga et al. (2022a,b): Nonlinear CI accelerates dust growth!

Note: **no** pressure bump assumed!



(Tominaga et al. 2022b)

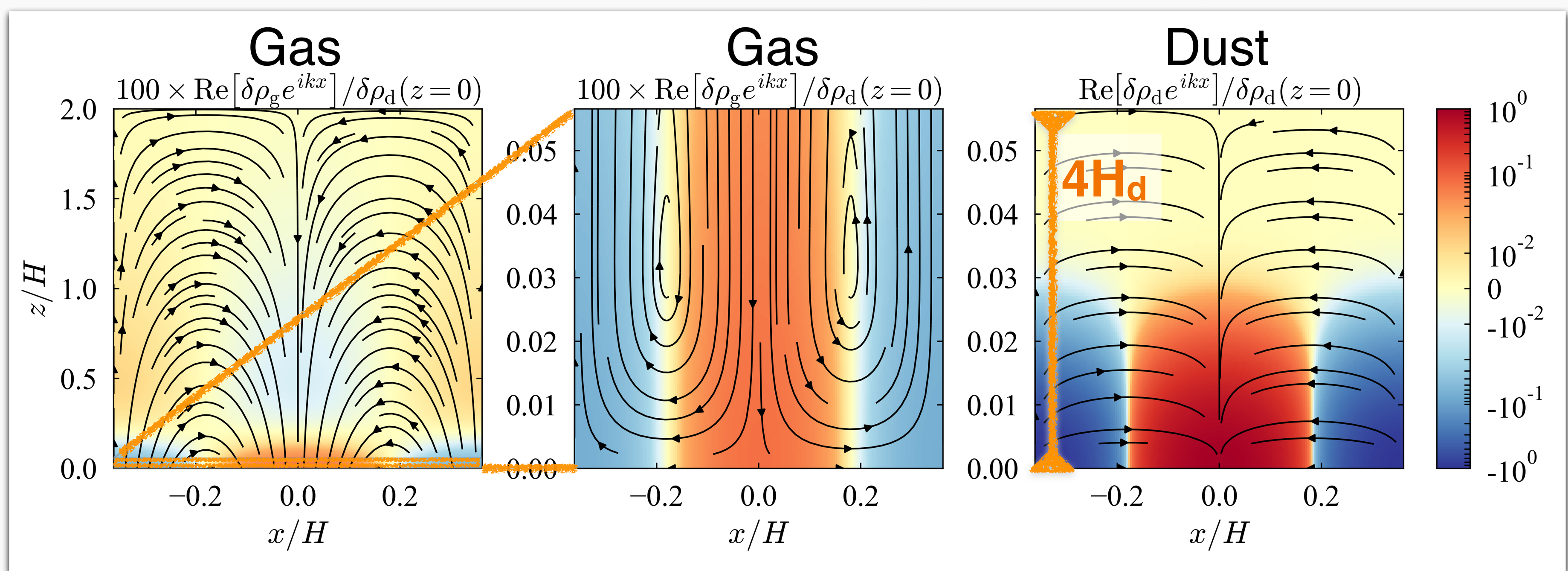


(Tominaga et al. 2022b)

- Σ_d increases until $\rho_d/\rho_g \sim 1$
- The backreaction reduces the dust collision velocity (see also Hyodo et al. 2019; Ida et al. 2021) -> dust avoids fragmentation once CI operates in a disk!
- **The resulting dust-rich regions are preferable sites for SI and/or secular GI to develop!**

4. Secular GI after CI: toward planetesimal formation

Tominaga et al. (2023): 2.5D linear analyses to study secular GI in vertically stratified disks



(Tominaga et al. 2023)

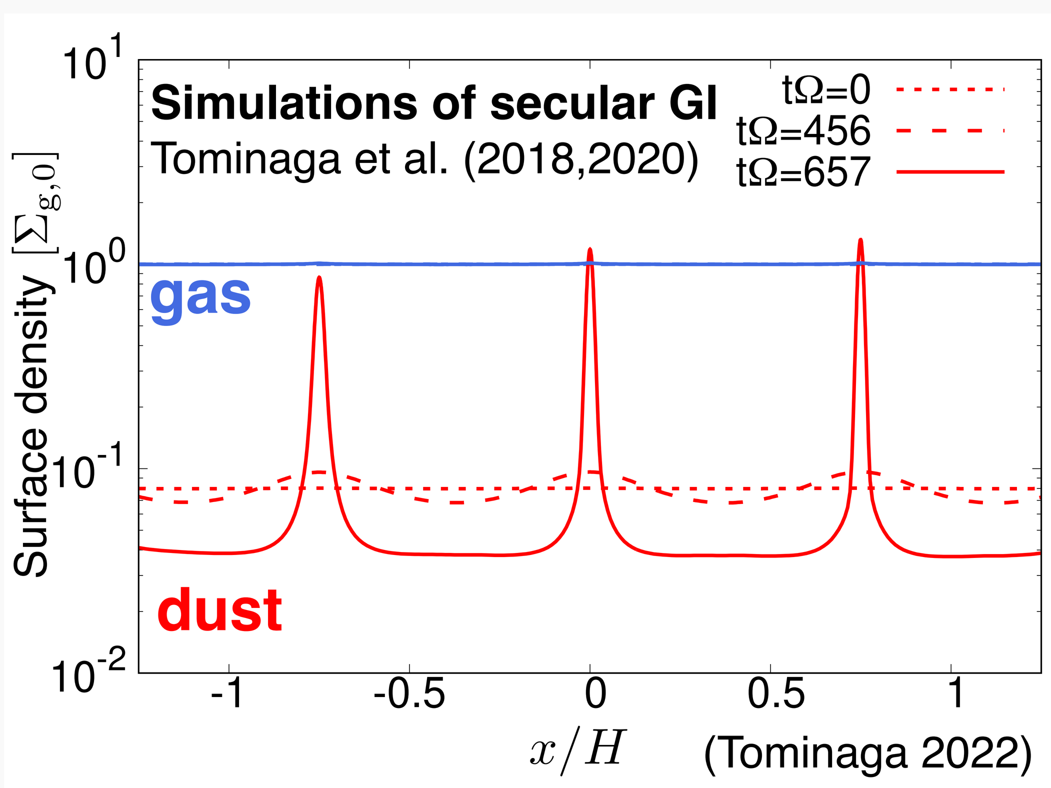
The growth condition for secular GI (found similar to 1D analyses)

$$\pi R^2 \Sigma_d > 3\times10^{-4} M_* \left(\frac{\Sigma_d/\Sigma_g}{10^{-2}}\right)^{0.5}\left(\frac{H/R}{0.1}\right)\left(\frac{\tilde{D}_r/t_{stop}\Omega}{10^{-3}}\right)^{0.5}$$

$\tilde{D}_r \equiv D_r/c_s H$: radial dust diffusivity

(see also Takahashi & Inutsuka 2014; Latter & Rosca 2017; Tominaga et al. 2019)

Secular GI may operate more easily in younger (massive) disks. (e.g., Tobin et al. 2020; Andrews 2020)



(Tominaga 2022)

Nonlinear secular GI results in self-gravitational collapse of dust rings (Tominaga et al. 2020) or Rossby wave instability (Pierens 2021). Clumps forming via "dust-ring GI" will exhibit prograde spin (Visser & Brouwers 2022; Takahashi et al. 2023), which can explain the observed high frequency of prograde binaries among the TNOs (see also Nesvorný et al. 2019).
Therefore, a combination of CI and secular GI is one promising mechanism to explain planetesimal formation in protoplanetary disks!