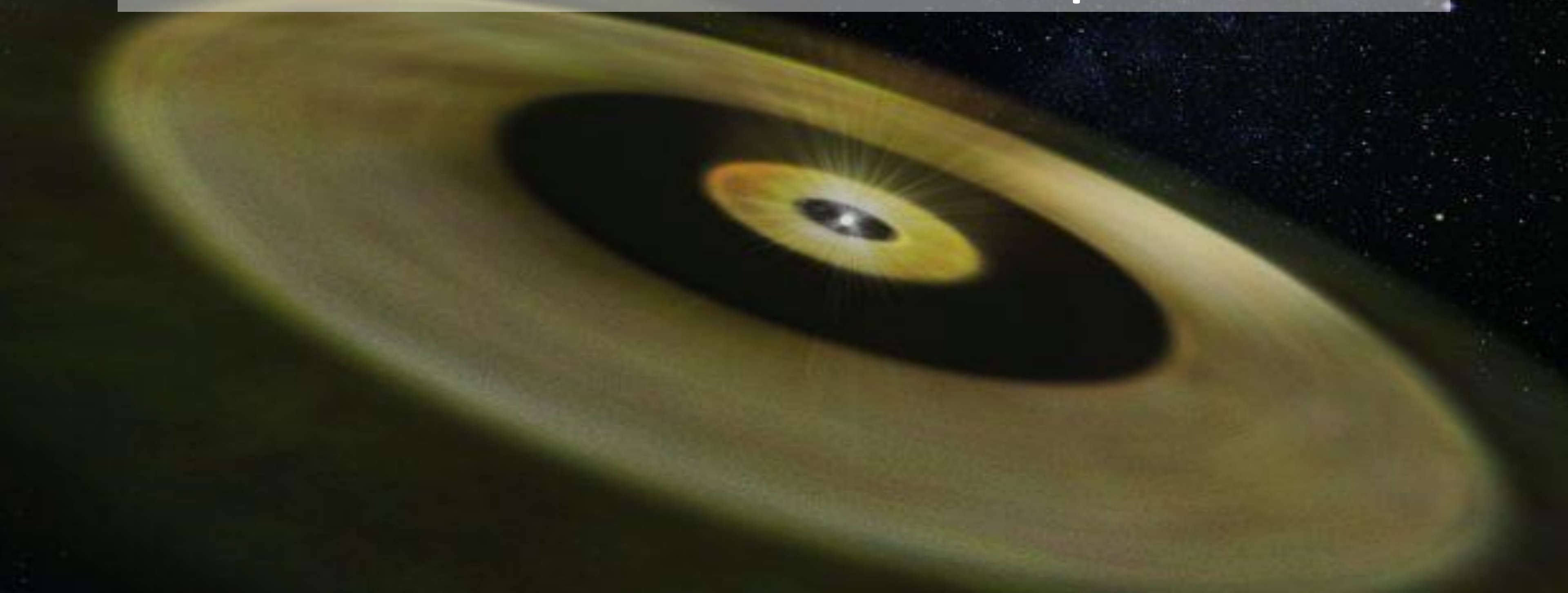
# Effects of dust feedback on evolutions of disks and planets



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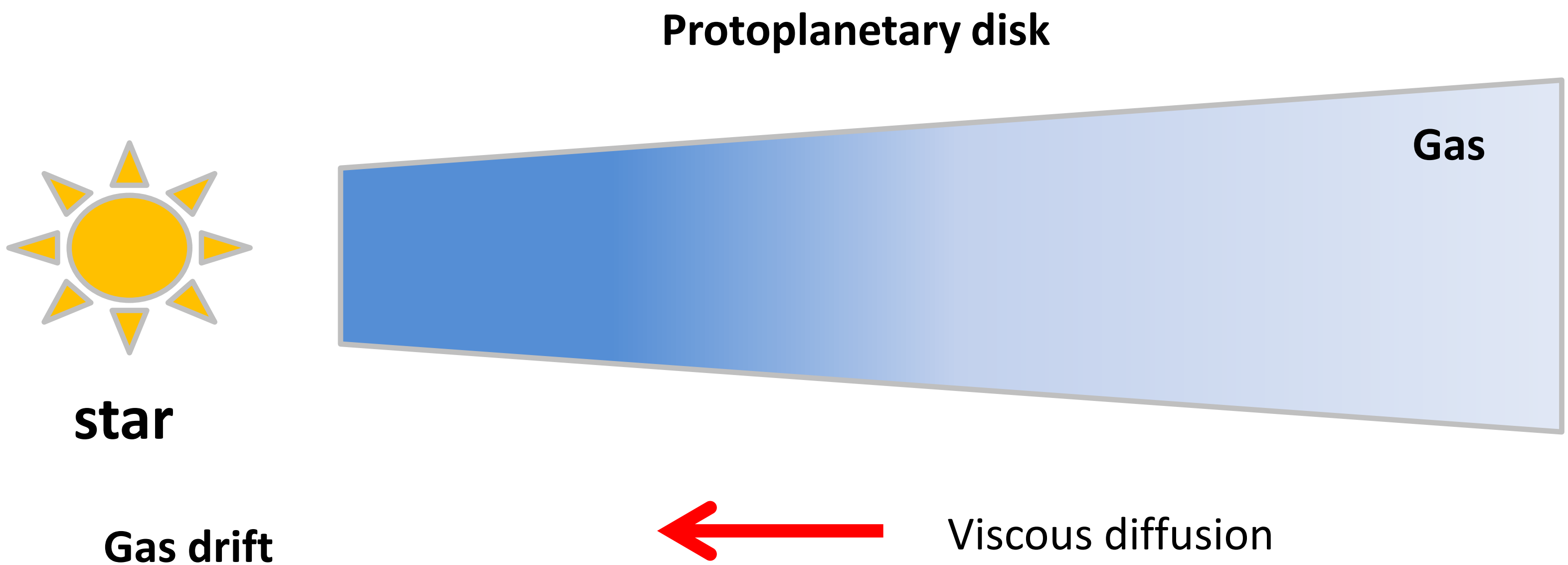
25 July 2019

Great Barriers in planet formation @Palm Cove, Queensland, Australia

# Viscous evolution of a gas disk



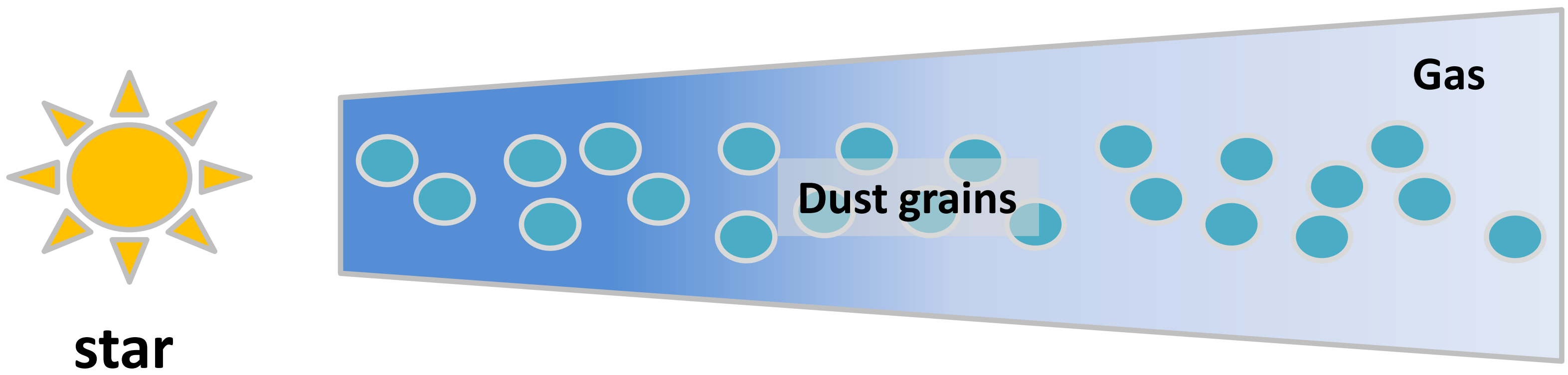

$$V_{\rm vis} \simeq -\frac{3\nu}{R}$$

# Gas-dust friction vs. Viscous evolution

$$\Omega_{\rm gas} = \Omega_{\rm K}\sqrt{1-\eta} \qquad \eta = -\frac{1}{2}\left(\frac{h}{R}\right)^2 \frac{\partial \ln P}{\partial \ln R}$$

$$\Omega_{\rm dust} = \Omega_{\rm K}$$

η > 0 in a usual case




**Dust drift** — Gas-dust friction

**Gas drift**
- Feedback from drifting dust
- Viscous diffusion

# Basic equations

## Equations of motions of dust grains and disk gas

For the dust grains

Gas-dust friction

$$\cancel{\frac{\partial v_{\rm R}}{\partial t}} + (\vec{v}\cdot\nabla)\, v_{\rm R} - \frac{v_\phi^2}{R} = -\frac{GM_*}{R^2} - \boxed{\frac{v_{\rm R}-V_{\rm R}}{t_{\rm stop}}},$$

$$\cancel{\frac{\partial v_\phi}{\partial t}} + (\vec{v}\cdot\nabla)\, v_\phi + \frac{v_{\rm R} v_\phi}{R} = \boxed{-\frac{v_\phi - V_\phi}{t_{\rm stop}}},$$

$T_{stop}$: stopping time

For the disk gas

Viscosity

Dust feedback

$$\cancel{\frac{\partial V_{\rm R}}{\partial t}} + \left(\vec{V}\cdot\nabla\right) V_{\rm R} - \frac{V_\phi^2}{R} = -\frac{c_s^2}{\rho_{\rm g}}\frac{\partial\rho_{\rm g}}{\partial R} - \frac{GM_*}{R^2} + \boxed{\frac{f_R}{\rho_{\rm g}}}$$

$$\cancel{\frac{\partial V_\phi}{\partial t}} + \left(\vec{V}\cdot\nabla\right) V_\phi + \frac{V_{\rm R} V_\phi}{R} = \boxed{-\frac{f_\phi}{\rho_{\rm g}}}$$

$f_R$, $f_\phi$: viscous forces acting unit area in radial and azimuthal directions.

# Dust and gas velocities in steady state

- Gas velocity

Dipierro+17, Kanagawa+17

$$V_{\mathrm{R}}(R,z) = \frac{2St'}{St'^2+1}\frac{\rho_{\mathrm{d}}}{\rho_{\mathrm{g}}+\rho_{\mathrm{d}}}\eta V_K + \left(1 - \frac{1}{St'^2+1}\frac{\rho_{\mathrm{d}}}{\rho_{\mathrm{g}}+\rho_{\mathrm{d}}}\right)V_{\mathrm{vis}},$$

$$V_{\phi}(R,z) = V_K + \left(\frac{1}{St'^2+1}\frac{\rho_{\mathrm{d}}}{\rho_{\mathrm{g}}+\rho_{\mathrm{d}}} - 1\right)\eta V_K + \frac{St'}{St'^2+1}\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}+\rho_{\mathrm{d}}}V_{\mathrm{vis}},$$

First term: Gas-dust friction, Second term: Gas viscosity

$$V_{\mathrm{vis}} = -\frac{3\nu}{R}\left[p + \frac{2q}{3} + 2\left(\frac{z}{h_{\mathrm{g}}}\right)^2\left(\frac{5q+9}{6}\right)\right]$$

$$\Omega_{\mathrm{g}} = \Omega_{\mathrm{K}}\sqrt{1-2\eta},$$

$$\eta(R,z) = -\frac{1}{2}\left(\frac{h_{\mathrm{g}}}{R}\right)^2\left(p + q + \frac{q}{2}\frac{z^2}{h_{\mathrm{g}}^2}\right).$$

$$St' = \rho_{\mathrm{g}}/(\rho_{\mathrm{g}}+\rho_{\mathrm{d}})St$$

$$St = t_{\mathrm{stop}}\Omega_{\mathrm{K}}$$

- Dust velocity

$$v_{\mathrm{R}}(R,z) = -\frac{2St'}{St'^2+1}\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}+\rho_{\mathrm{d}}}\eta V_K + \frac{1}{St'^2+1}\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}+\rho_{\mathrm{d}}}V_{\mathrm{vis}},$$

$$v_{\phi}(R,z) = V_K + \frac{1}{St'^2+1}\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}+\rho_{\mathrm{d}}}\eta V_K - \frac{St'}{St'^2+1}\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{g}}+\rho_{\mathrm{d}}}V_{\mathrm{vis}},$$

# Gas radial velocities in steady state

$V_{vis}$: Viscous drift velocity, $V_K$: Keplerian rotation velocity

Dipierro+17, Kanagawa+17

Gas-dust friction

Viscosity

$$V_\mathrm{R}(R,z) = \boxed{\frac{2St'}{St'^2+1}\frac{\rho_\mathrm{d}}{\rho_\mathrm{g}+\rho_\mathrm{d}}\eta V_K} + \boxed{\left(1-\frac{1}{St'^2+1}\frac{\rho_\mathrm{d}}{\rho_\mathrm{g}+\rho_\mathrm{d}}\right)V_\mathrm{vis},}$$

$$V_\mathrm{vis} \simeq -\frac{3\nu}{R}$$

$$St' = \rho_\mathrm{g}/(\rho_\mathrm{g}+\rho_\mathrm{d})St$$

Push the gas outward

Push the gas inward

$$St = t_\mathrm{stop}\Omega_\mathrm{K}$$

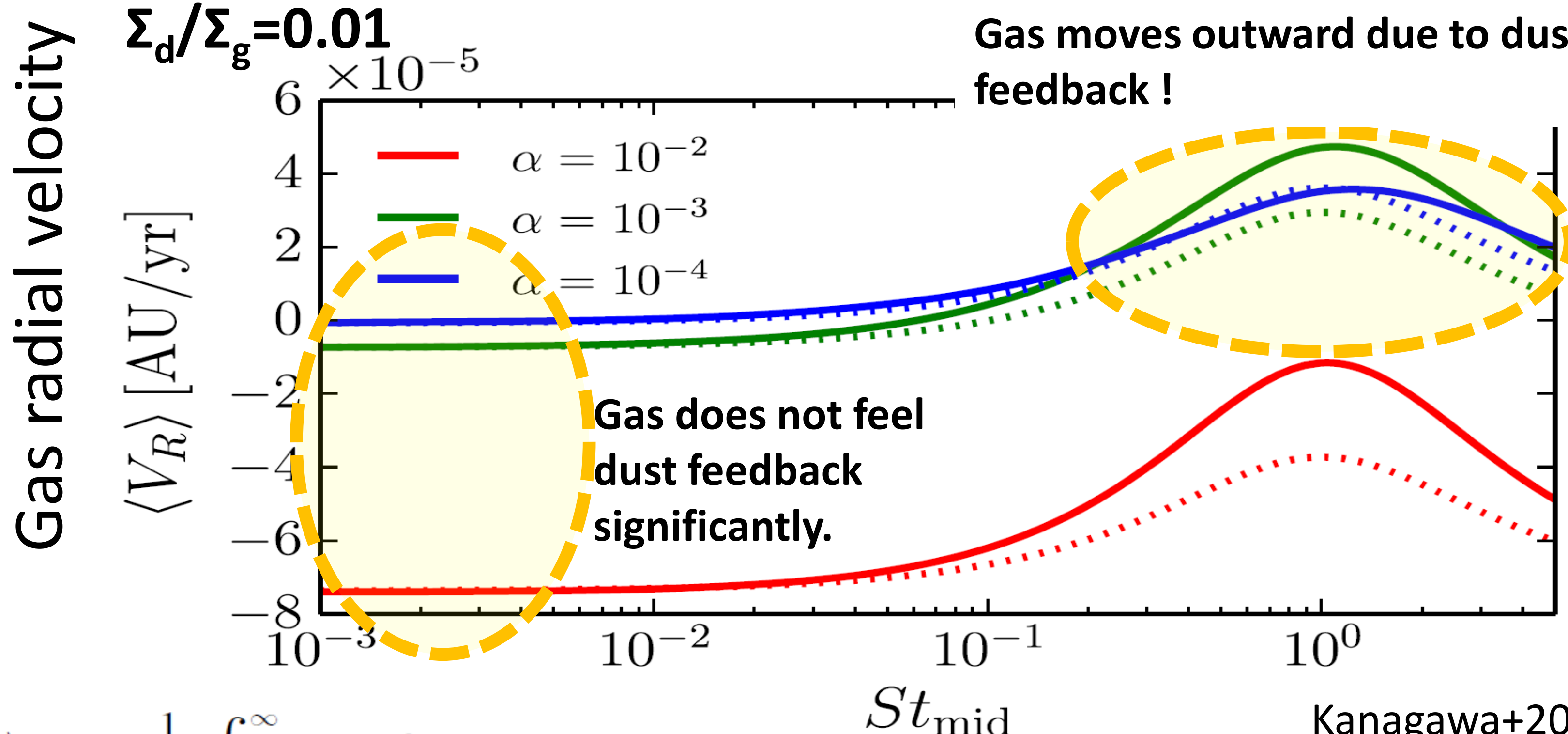
- Inward drift due to gas viscosity slows down due to dust feedback
- When the gas-dust friction term is larger than the viscous term, the gas can move outward against viscous diffusion.

# Drift velocities of gas

Solid: Vertical averaged velocity (3D), Dotted: 2D disk (ignore vertical structure)

**$\Sigma_d/\Sigma_g$=0.01**

**Gas moves outward due to dust feedback !**



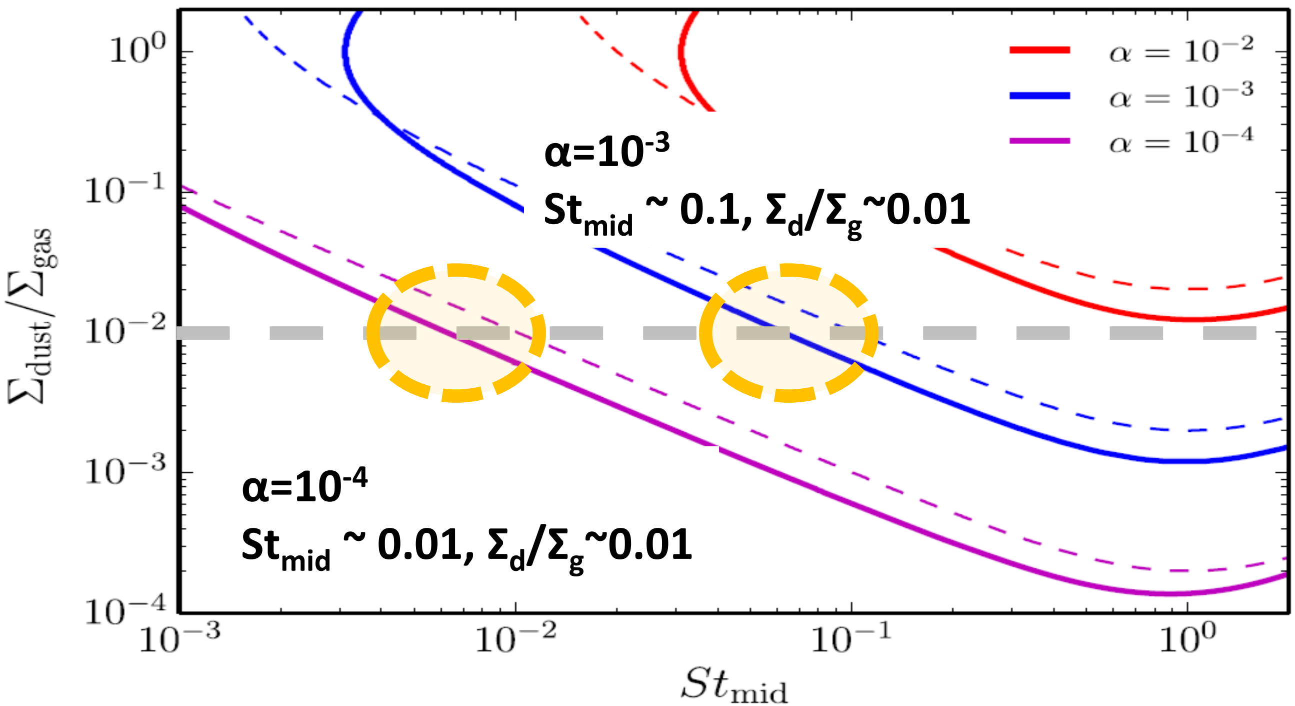

Kanagawa+2017 ApJ

$$\langle V_{\rm R}\rangle (R) = \frac{1}{\Sigma_{\rm g}} \int_{-\infty}^{\infty} V_{\rm R}\, \rho_{\rm g}\, dz.$$

Stokes number at the midplane

# When can the dust feedback overcome viscosity ?

Above the line, the gas drift velocity is positive (gas move outward)




Solid: Vertical averaged velocity (3D)
Dotted: 2D disk (ignore vertical structure)

Kanagawa+2017 ApJ

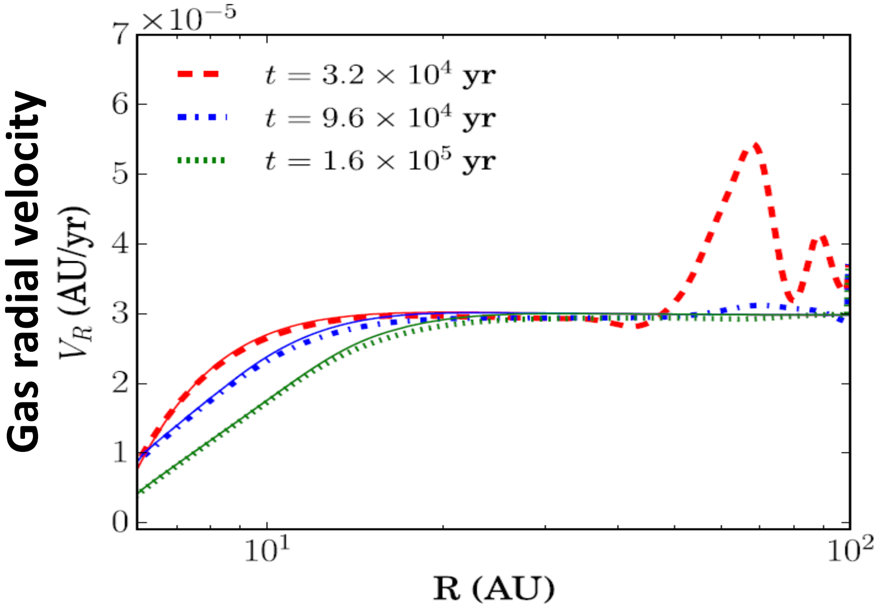
# Hydrodynamic simulations

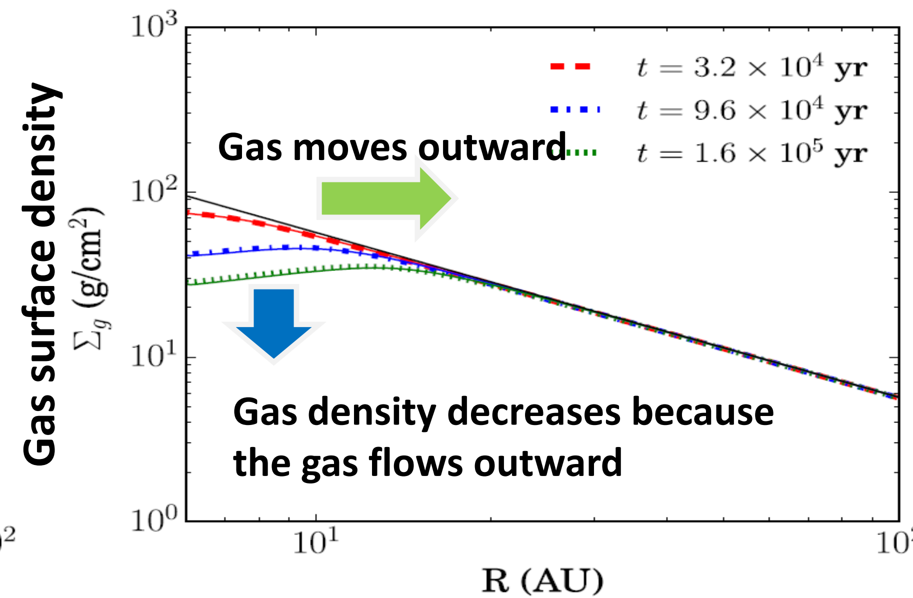
- 2D (R,ϕ) simulations by FARGO extended into gas-dust fluid.
  - Ignore the vertical structure of the disk (dust setting, etc)
- Commutating domain (6AU < R < 100AU) divided by radially 512 and azimuthally 128 meshes.
- Initial gas density $\Sigma_g$=540 g/cm$^2$ (R/1AU)$^{-1}$.
- Initial dust/gas ratio, $\Sigma_d/\Sigma_g$=0.01.
- Gas aspect ratio: h/R = 0.028 (R/1AU)$^{1/4}$
- Constant size of dust grains (3cm)
  - Initially St=0.1 at 10AU
  - no growth, no fragmentation, no planetesimal formation
- Assuming that the disk size is large enough (dust and gas are supplied from the outside during the simulation)

# Effect on viscous disk evolution

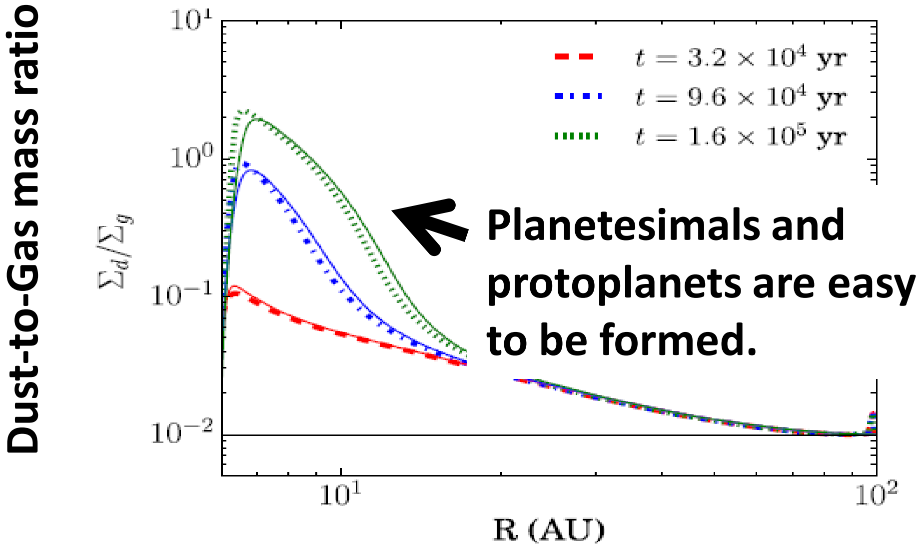
Kanagawa+2017 ApJ

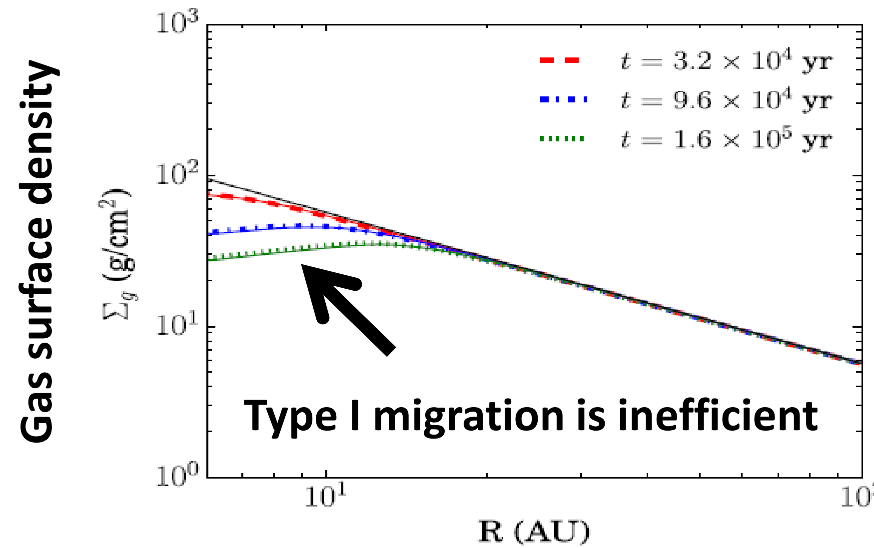
**α = $10^{-3}$, $\Sigma_d/\Sigma_g$ = 0.01, dust size = 3cm (initially St =0.1 at 10 AU)**



# Implication for planet formation



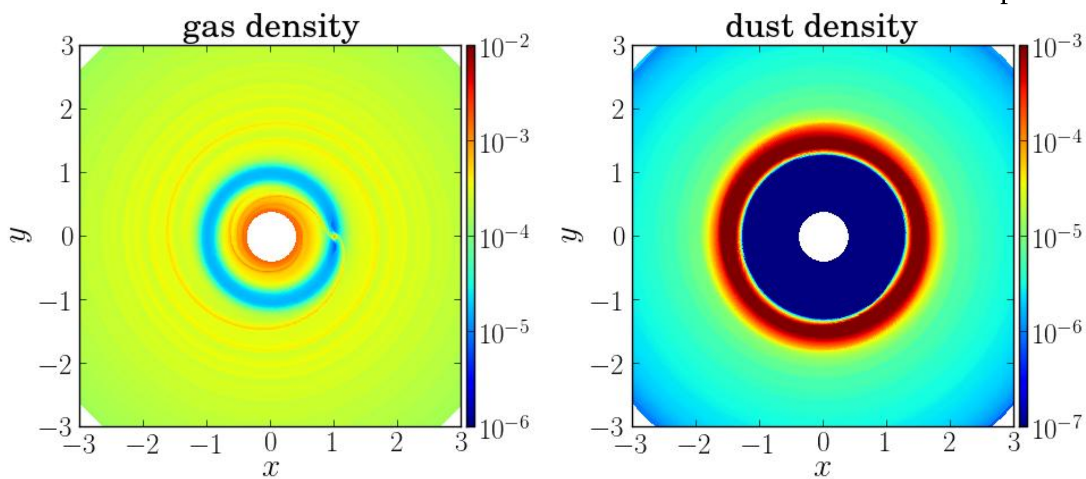

But, … we did not consider

- Size distribution of dust (Dipierro+18)
- 3D simulations (Gonzalez+15,17)
- Dust growth/fragmentation and planetesimal formation (Drążkowska+16, Drążkowska&Alibert 17)

# Dust feedback can change a shape of a planet-induced gap

When a large enough protoplanet forms, it would be a giant planet which forms a gap.

Dust size: 3 cm (constant), $\alpha=4\times10^{-3}$, $h/R=0.05$, $M_p/M_*=10^{-3}$



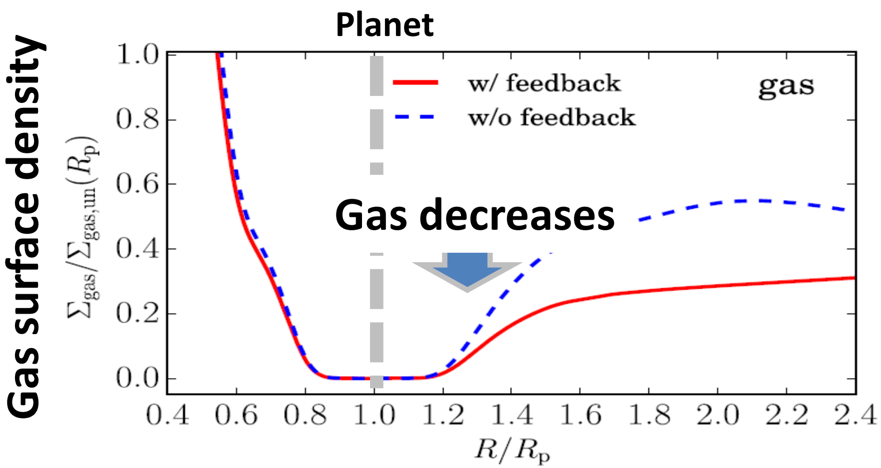

Dust grains are highly accumulated at the outer edge → Dust feedback must be effective.

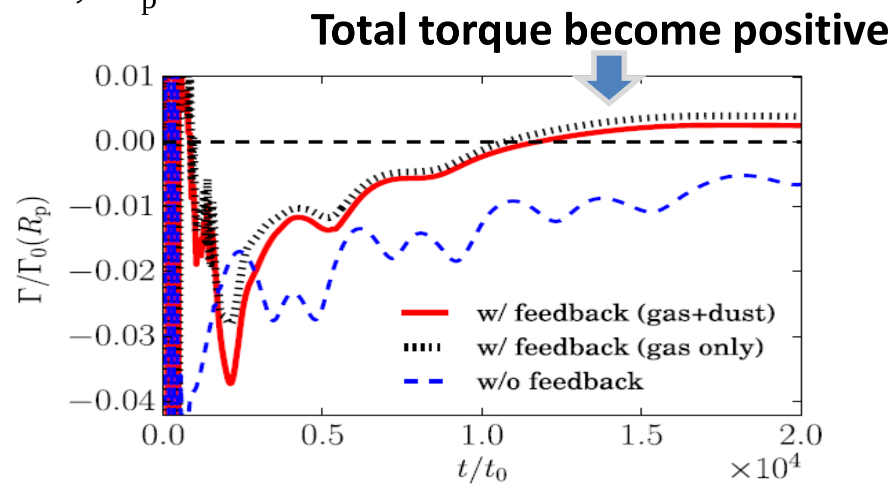
# Effect of dust feedback on migration of a gap-opening planet

**2D hydrodynamic simulations (with a migrating planet)**

Kanagawa 2019 ApJL

Dust size: 3 cm (constant), $\alpha=3\times10^{-4}$, h/R=0.05, $M_p/M_*=10^{-3}$




Since the gas density at the outer disk decreases due to the dust feedback, torque exerted from the outer disk decreases.

# Effect of dust feedback on migration of a gap-opening planet

**2D hydrodynamic simulations (with a migrating planet)**

Kanagawa 2019 ApJL

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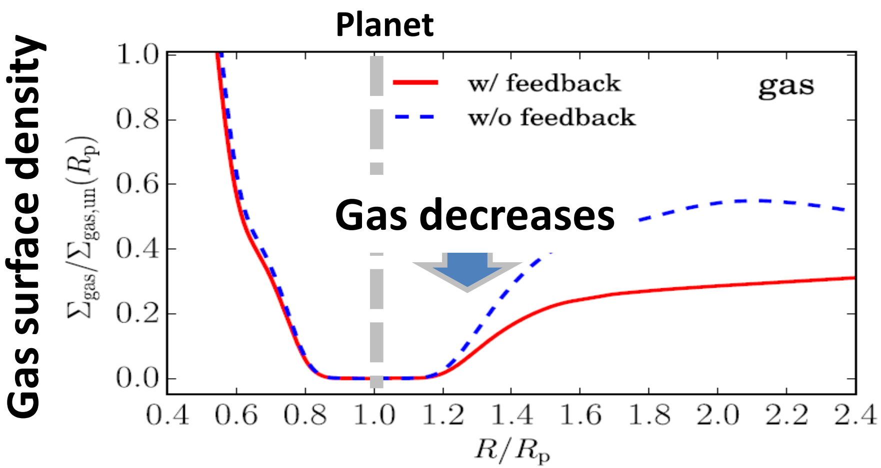


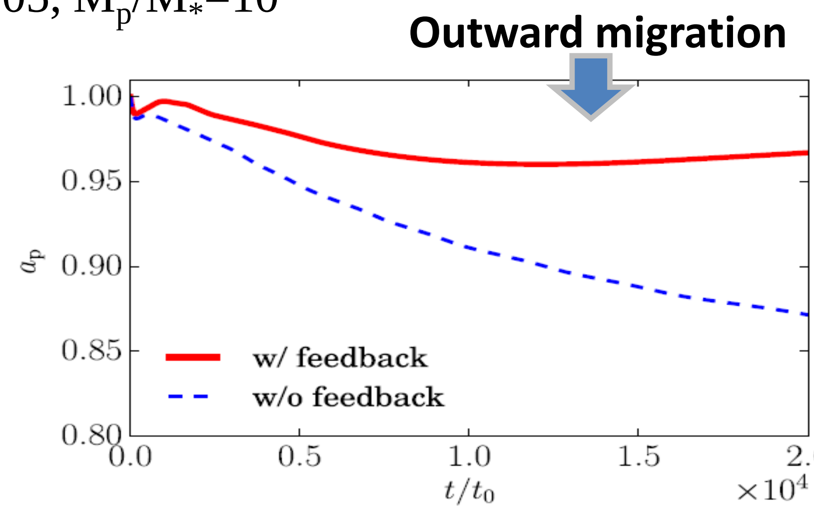


Because of weaker negative torque from the outer disk, the planet can migrate outward.

# Summary

- **Dust feedback can help to make planets and save them from fast inward migration**.
- The gas surface density within 10 AU can decrease due to the dust feedback.
  - Since the dust-to-gas mass ratio decreases, planetesimals and protoplanets could easy to be formed.
  - Since Type I migration is inefficient, the planets which are formed in this region can avoid too fast inward migration.
- Dust feedback reduce the torque exerted from the outer disk
  - The gap-opening planet can migrate outward when the planet is massive (Jupiter size) and viscosity is relatively low.
  - The gap-opening planet can survive for a long time.