Disk-planet interaction and gap formation induced by a giant planet in protoplanetary disks

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Kanagawa et al. (2015), MNRAS
Kanagawa et al, (2015), ApJL in press
(arXiv: 1501.05422)

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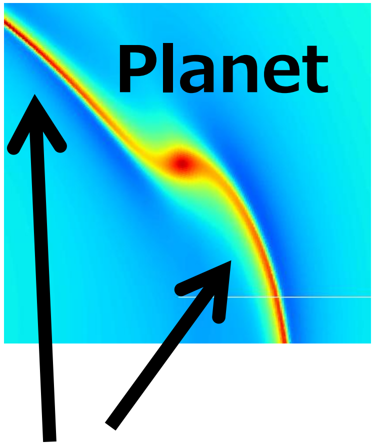
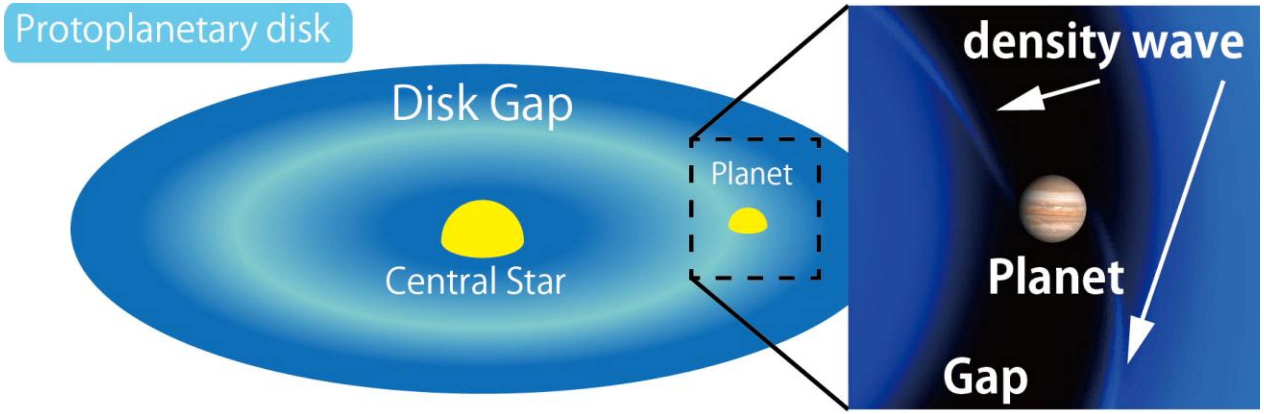
Planet induced structure in a disk

(A) planet(s) embedded in a disk perturbs the disk due to gravitation interaction.





Density waves excited by a planet

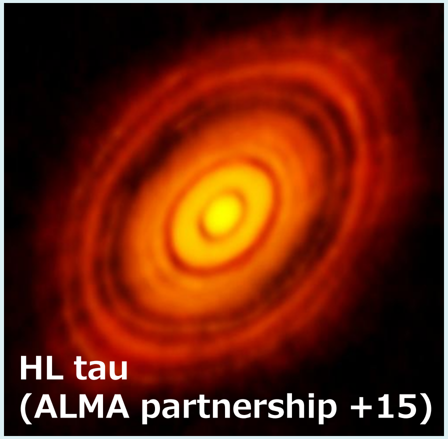
Giant planet can create a density gap with the planetary orbit

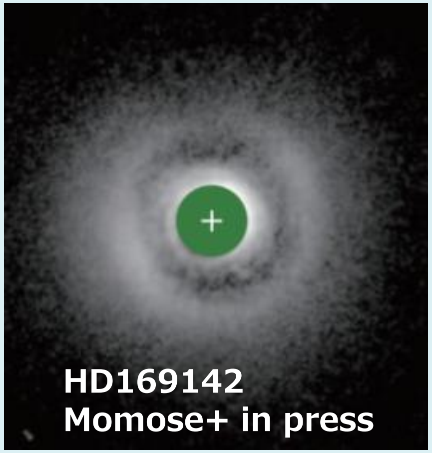
Spiral waves and Gaps are critical to the planetary migration.

Observations of protoplanetary disks

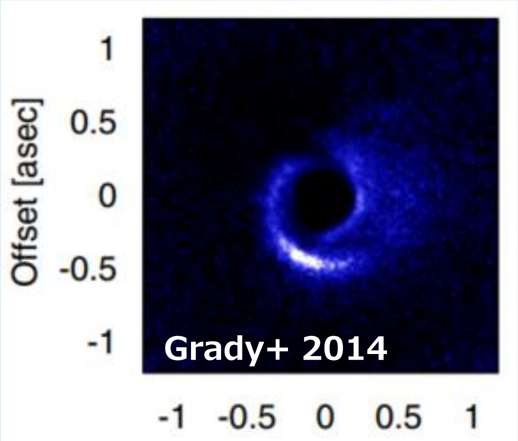
Gaps and spirals are discovered in protoplanetary disks.

Gaps





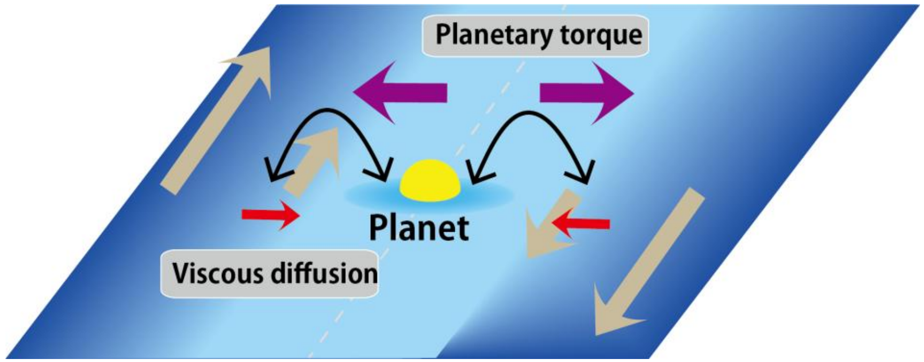
Spiral



These structures may indicate existance of planet embedded in the disks.

How are gaps and spirals related to planets?

Gap opening process



Planetary torque to open the gap

vs

Viscous diffusion to close the gap

$$T_0 \propto \left(\frac{M_p}{M_*}\right)^2 \left(\frac{h}{R}\right)^{-3} R_p^4 \Omega_K^2 \Sigma_0$$

$$F_{0,\nu} \propto \alpha \left(\frac{h}{R}\right)^2 R_p^4 \Omega_K^2 \Sigma_0$$

Gap structure depends on:

- Planet's mass (M_p)
- Disk aspect ratio (h/R), or T
- Disk viscosity (α)

$$K \equiv \alpha^{-1} \left(\frac{M_p}{M_*}\right)^2 \left(\frac{h}{R}\right)^{-5}$$

Important parameter for gap shape

Angular momentum conservation

A planet gives the angular momentum the surrounding gas due to the disk-planet interaction

Angular momentum conservation

$$F_J(R_e) = F_J(R_p) + T_{\rm LB}.$$

Gap edge

Gap bottom (planet location)

Planetary torque

This relation always has to be satisfied

Angular momentum flux on viscous disk

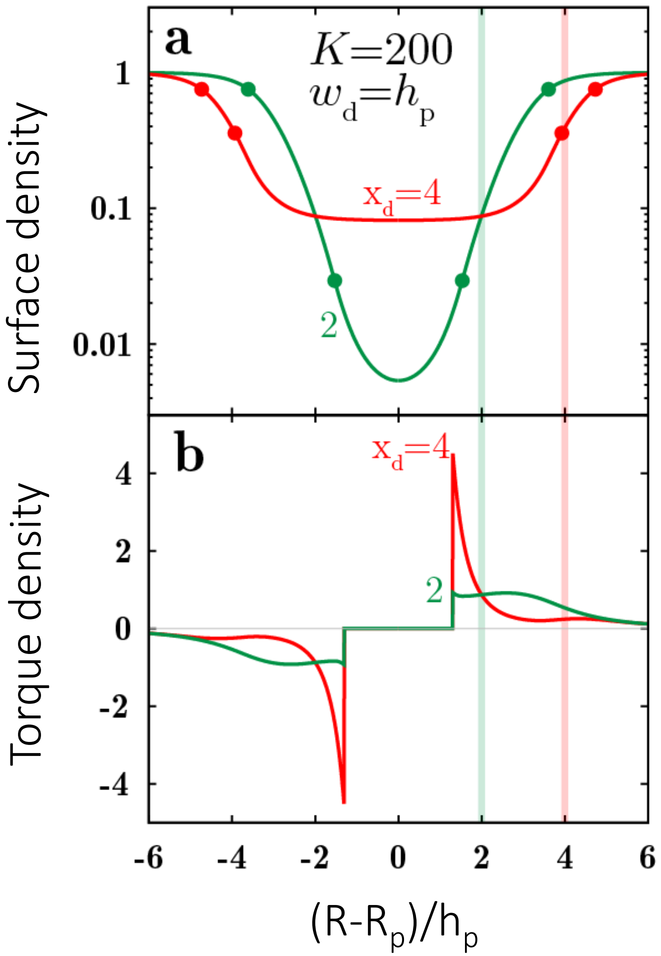
$$F_J(R) = R^2\Omega F_M - 2\pi R^3 \nu \Sigma \frac{\partial \Omega}{\partial R},$$

advection

viscosity

Wide-limit gap model

Assumption: A planet exerts only on the gap bottom ($\Sigma \sim \Sigma_p$)



If the gap is sufficiently wide, this assumption is valid.

In this case, the planetary torque is given as

$$\begin{aligned} T_{\rm LB} &= \int_{R_p+\Delta}^{\infty} 0.80\pi \left(\frac{M_p}{M_*}\right)^2 R_p^3 \Omega_p^2 \Sigma_p \left(\frac{R_p}{R-R_p}\right)^4 dR \\ &= 0.12\pi \left(\frac{M_p}{M_*}\right)^2 h_p^{-3} R_p^4 \Omega_{\rm p}^2 \Sigma_p, \end{aligned}$$

It is proportional to the surface density of gap bottom Σ_p

Relation between planet mass and gap depth

Angular momentum conservation (wide-limit gap):

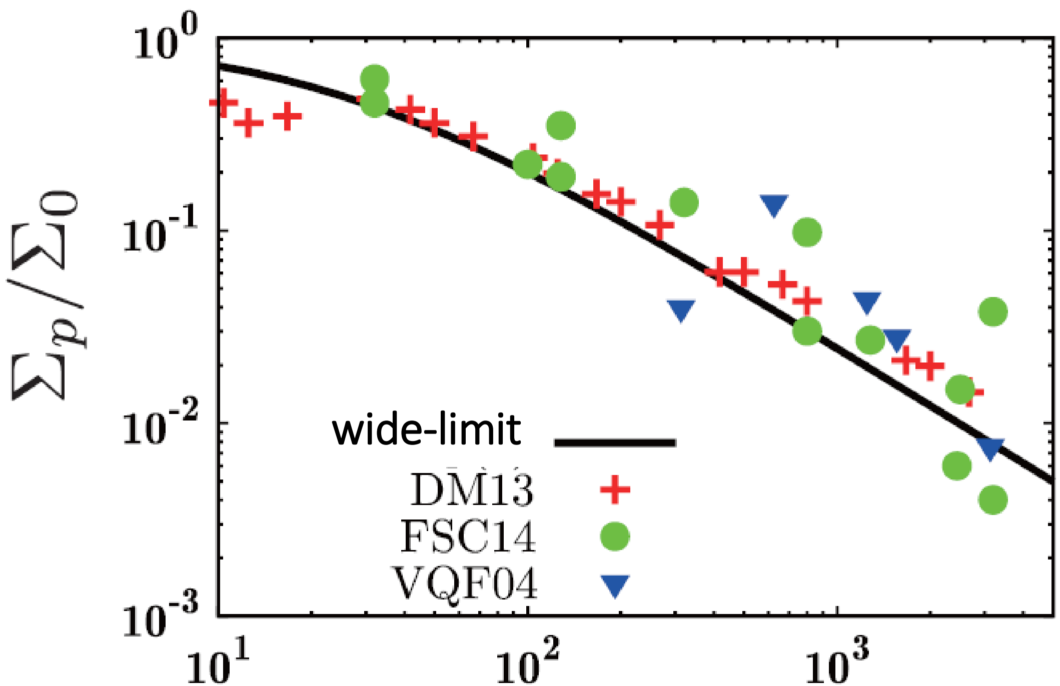
$$\underbrace{\cancel{R_e^2\Omega_e F_M} + 3\pi\alpha h_e^2 R_e^4\Omega_e^2\Sigma_0}_{\text{AMF at Gap edge}} = \underbrace{\cancel{R_p^2\Omega_p F_M} + 3\pi\alpha h_p^2 R_p^4\Omega_p^2\Sigma_p}_{\text{AMF at Gap bottom}} + \underbrace{0.121\pi R_p^4\Omega_p^2\left(\frac{M_p}{M_*}\right)^2 h_p^{-3}\Sigma_p}_{\text{Planet torque}}.$$

Gap depth (wide-limit gap model)

$$\frac{\Sigma_{\rm p}}{\Sigma_0} = \frac{1}{1+0.04\,K}, \qquad K \equiv \alpha^{-1}\left(\frac{M_{\rm p}}{M_*}\right)^2\left(\frac{h}{R}\right)^{-5}$$

This relation is very similar to empirical formula given by high-resolution hydrodynamic simulations (Duffell&MacFardyen 2013, Fung et al. 2014)

vs. Hydrodynamic simulations



$$K = \left(\frac{M_p}{M_*}\right)^2 h_p^{-5}\alpha^{-1}.$$

Gap depth obtained by the wide-limit gap

$$\frac{\Sigma_\mathrm{p}}{\Sigma_0} = \frac{1}{1 + 0.04\,K},$$

This relation is in a good agreement with previous hydrodynamic simulations !!

Assumptions of wide-limit gap

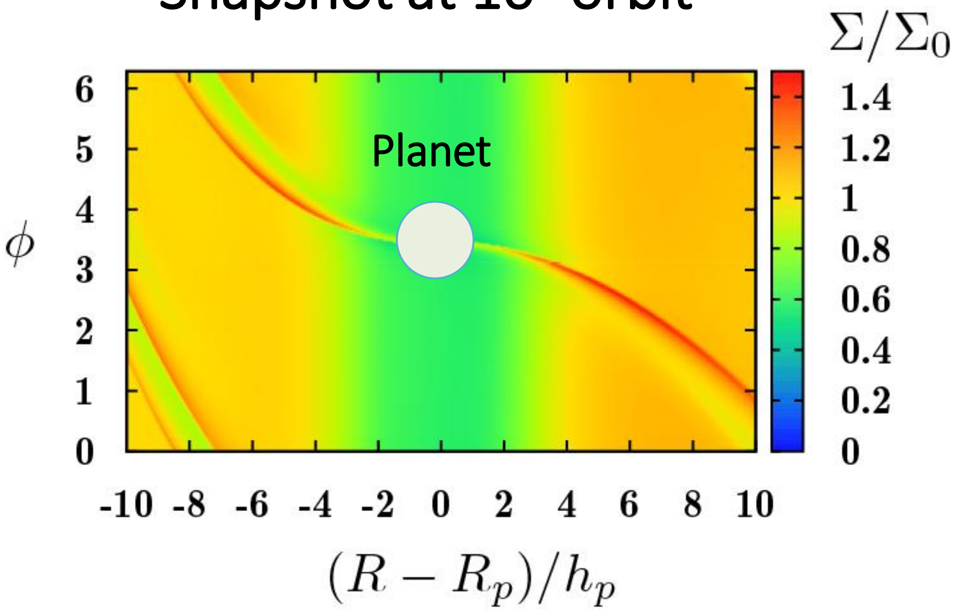
- Gap is in steady state
- **Planetary torque is distributed only within the gap bottom**

Torque distribution (small K)

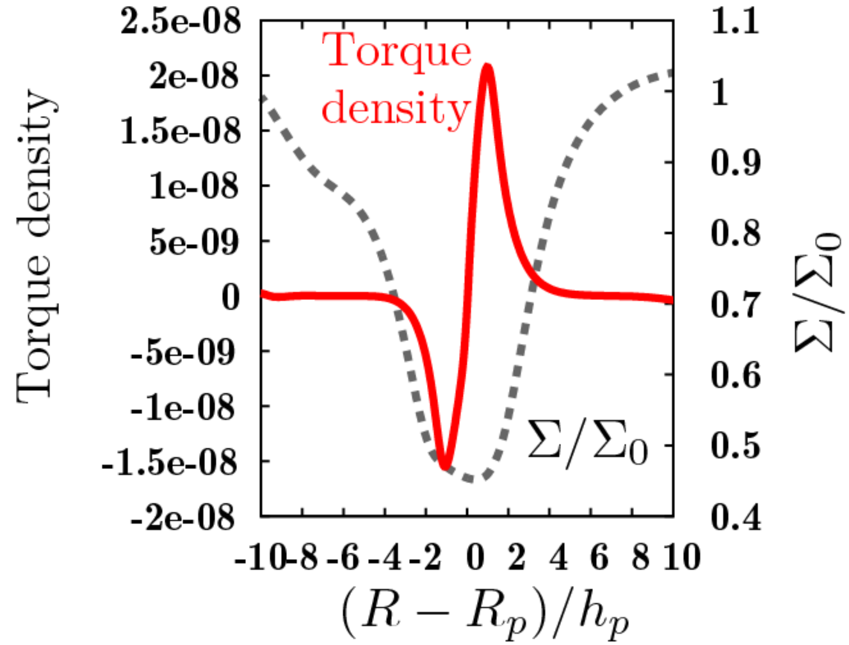
Where does the planet exert the gravitational torque ?

Hydrodynamic simulation using FARGO.
$M_p/M_* = 10^{-4}$, $h/R = 0.05$, $\alpha = 10^{-3}$ (K=32)

Snapshot at 10^4 orbit



Torque density



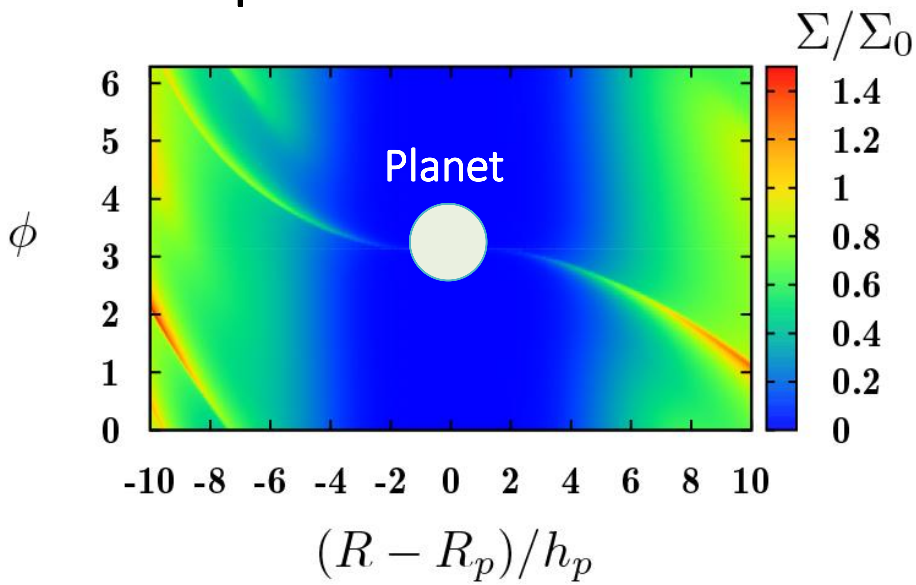
The torque density mainly distributes within the gap.
Wide-limit gap would be valid in this case.

Torque distribution (large K)

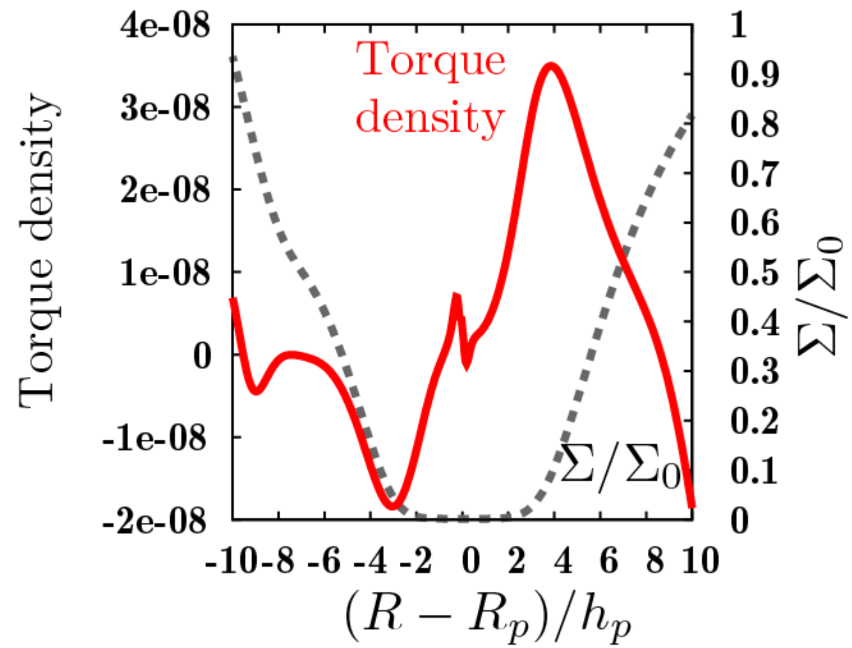
Where does the planet exert the gravitational torque ?

Hydrodynamic simulation using FARGO.
$M_p/M_* = 10^{-3}$, $h/R = 0.05$, $\alpha = 10^{-3}$ (K=3200)

Snap shot at 10^4 orbit



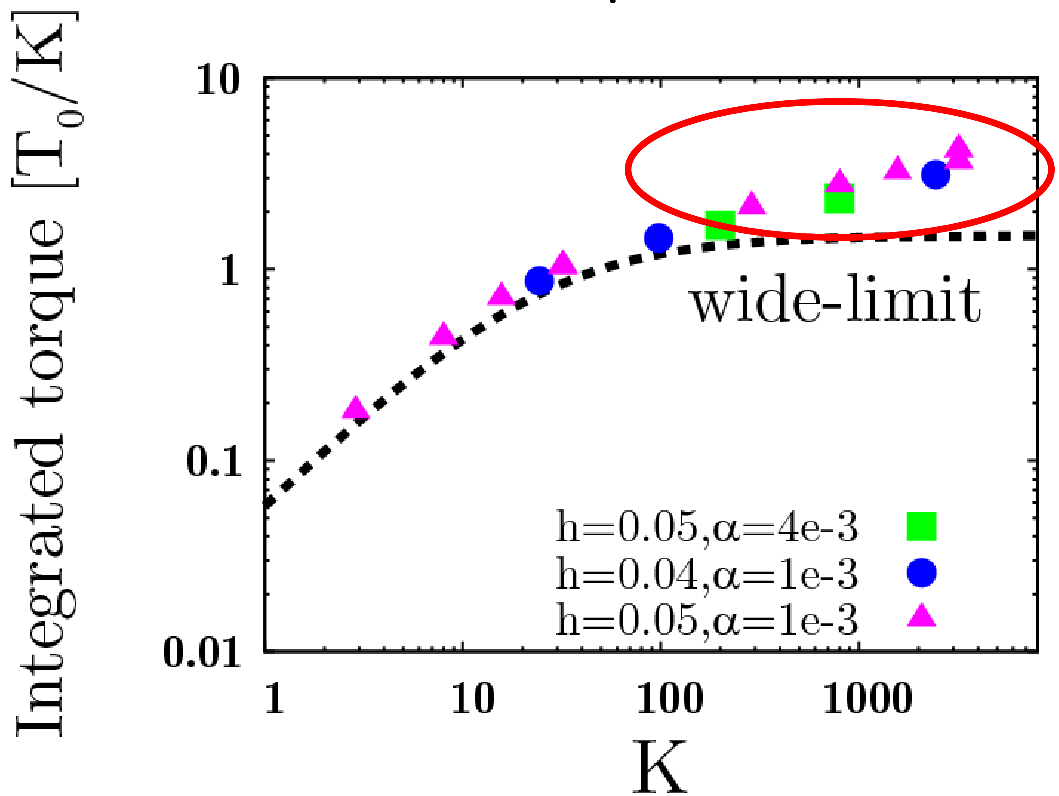
Torque density



The torque density distributes not only the gap bottom , but also the gap edge.
Wide-limit gap is valid ?

Planetary torque

Planetary torque (exerted on $R>R_p$) given by hydrodynamic simulations with various parameters

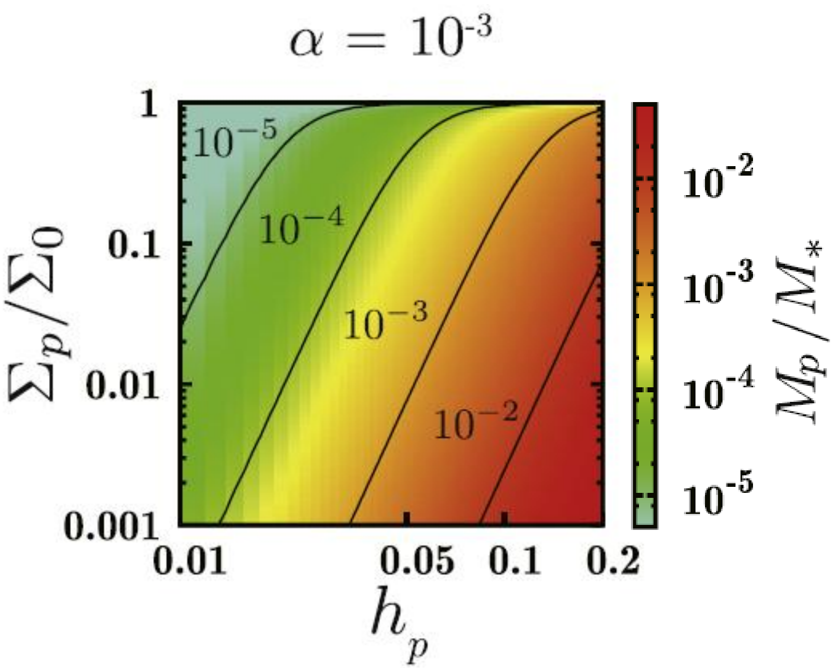


For large K, the one-sided torque is only 2-3 times larger than that of wide-limit gap !

The wide-limit gap model seems to good model for the gap formation.

Relation between gap depth and planet mass

Wide-limit gap can be used to estimate the planet mass in observed gap.

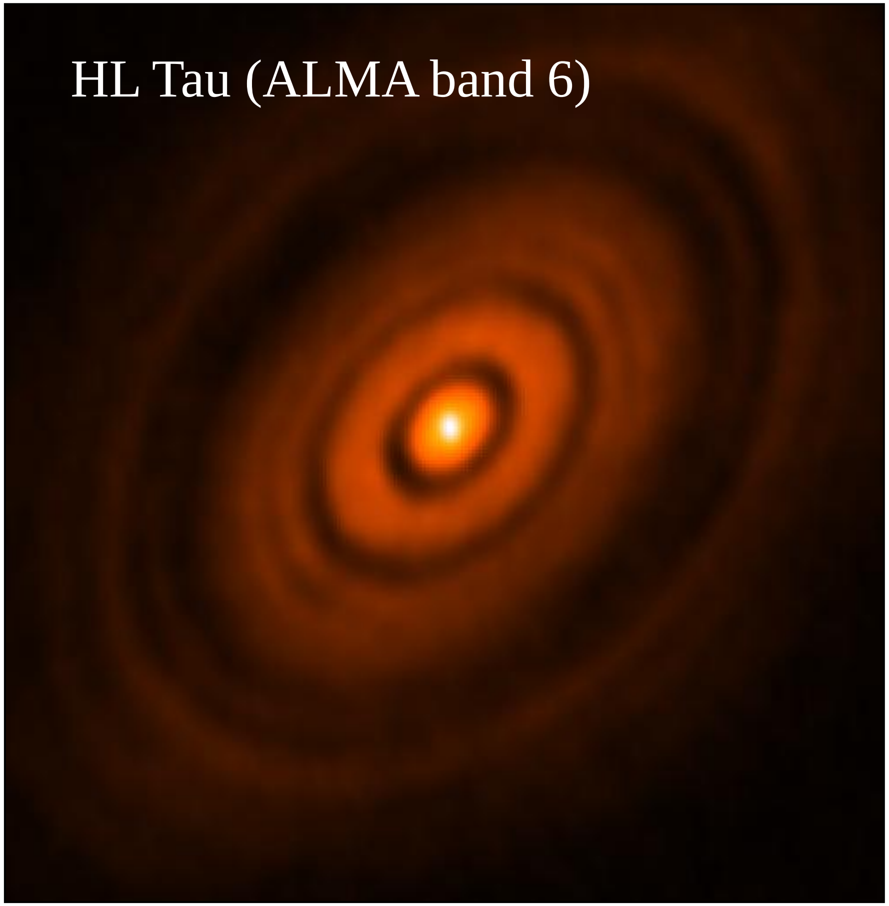


If the gap depth, disk aspect ratio (temperature) are observed, the planet mass can be obtained.

$$\frac{\Sigma_{\rm p}}{\Sigma_0} = \frac{1}{1+0.04\,K}, \qquad K \equiv \alpha^{-1}\left(\frac{M_{\rm p}}{M_*}\right)^2\left(\frac{h}{R}\right)^{-5}$$

$$\frac{M_p}{M_*} = 5\times 10^{-4}\left(\frac{1}{\Sigma_p/\Sigma_0}-1\right)^{1/2}\left(\frac{h_p}{0.1}\right)^{5/2}\left(\frac{\alpha}{10^{-3}}\right)^{1/2}$$

Example: HL Tau



Stellar mass: ~ 1Msun
Distance from the sun: ~ 140 pc

There are three observed gaps:
1st gap: ~ 15 AU
2nd gap: ~ 30 AU
3rd gap : ~ 90 AU

Using data of band6(230GHz) and band7(345GHz), we can obtain an optical depth and disk temperature.

$$\boxed{T_{\rm br6}} = T\left(1 - e^{-\tau_6}\right) \qquad \tau_7 = \tau_6(\nu_7/\nu_6)^{\beta}$$

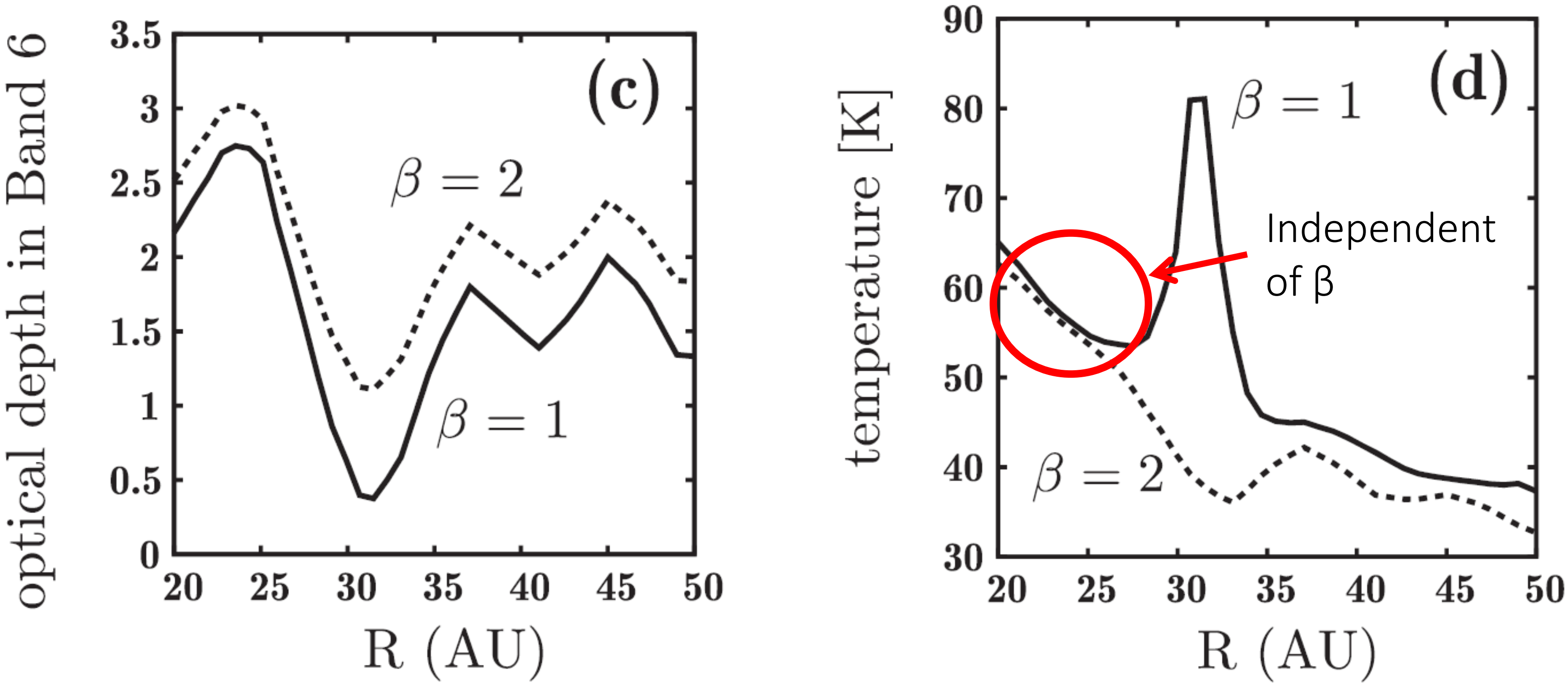
$$\boxed{T_{\rm br7}} = T\left(1 - e^{-\tau_7}\right),$$

observables

Optical thickness and gas temperature

$$T_{\mathrm{br6}} = T\left(1 - e^{-\tau_6}\right) \qquad T_{\mathrm{br7}} = T\left(1 - e^{-\tau_7}\right), \qquad \tau_7 = \tau_6(\nu_7/\nu_6)^{\beta}$$

Optical depth and temperature around the 2nd gap



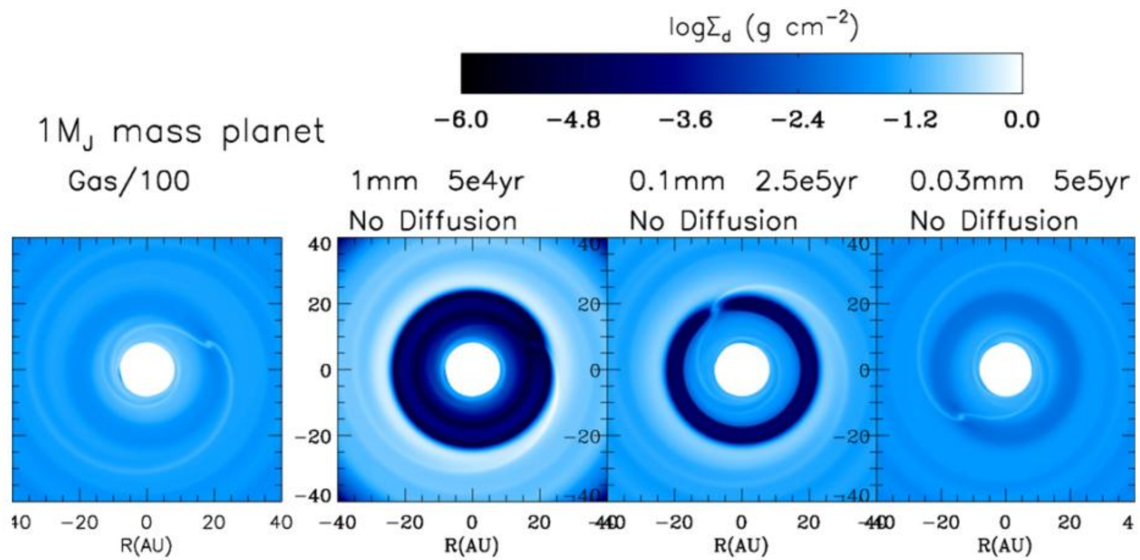
Gap depth is estimated as ~1/3– 1/7.
(if gas and dust are well-mixed)

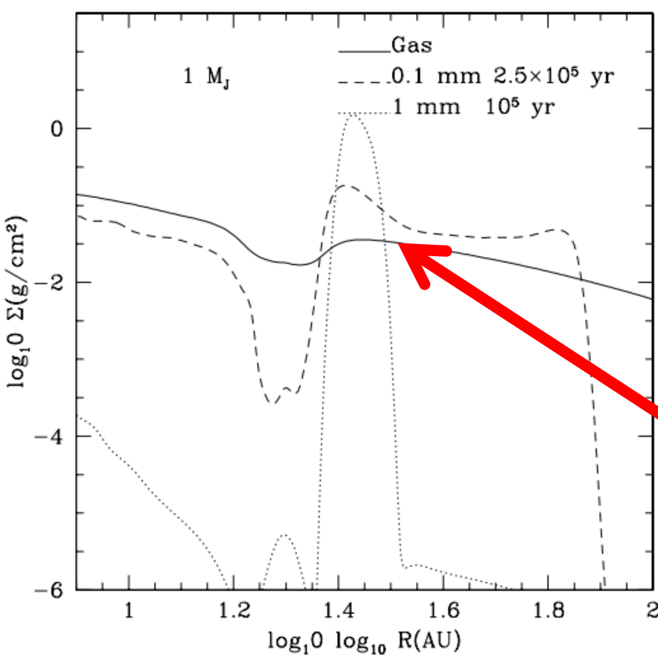
Temperature can be estimated as 55 K
(h/R ~ 0.07)

Dust filtration

The dust and gas distribution becomes different due to the difference of their rotation speed .

Result of hydrodynamic simulation done by Zhu et al. (2012)



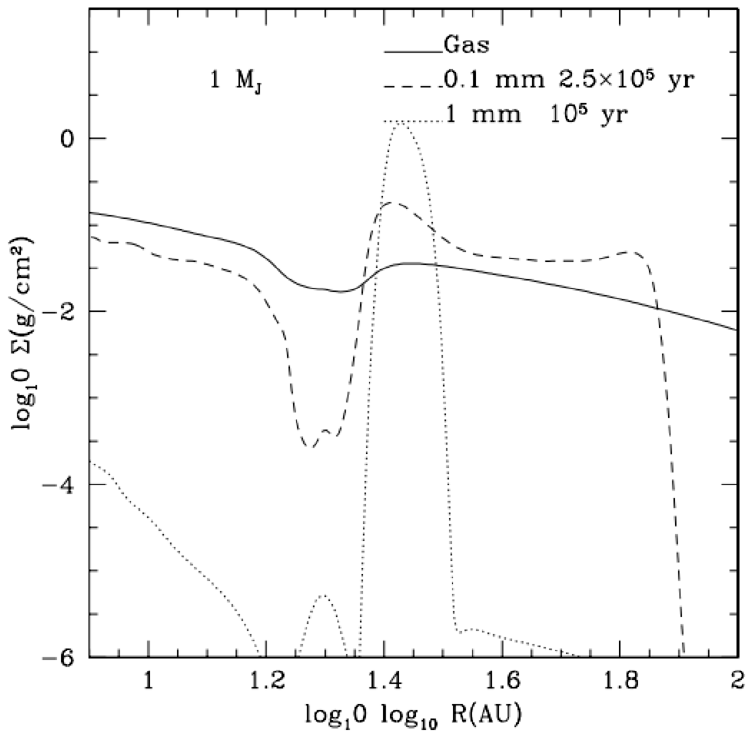


The distribution of only large size dust is much different from that of gas.
(small grains have almost same distribution of gaseous matter)

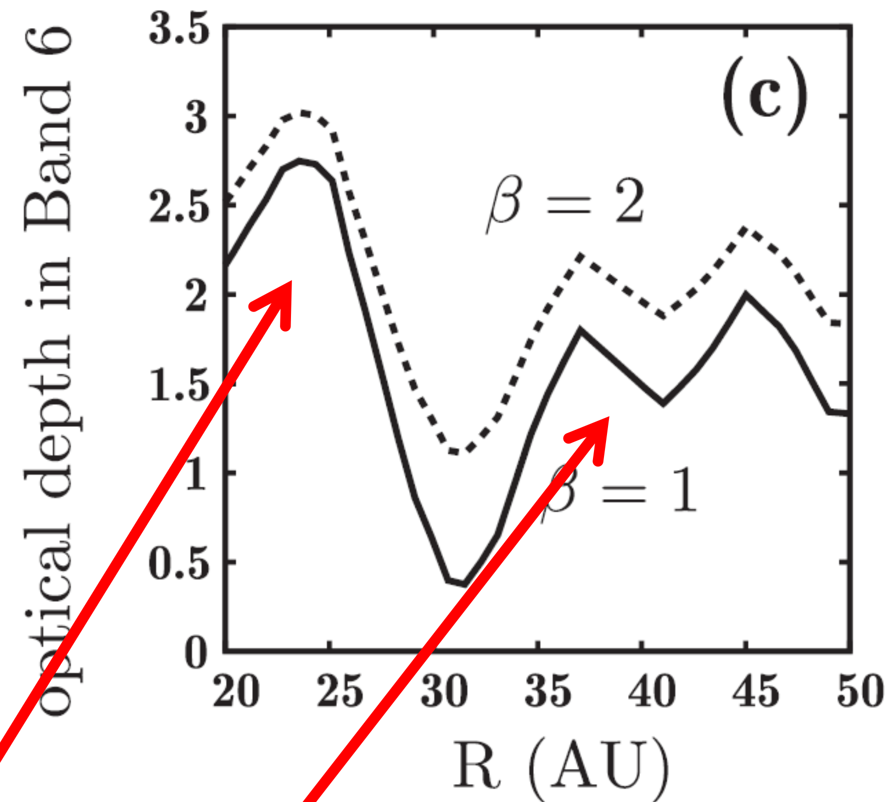
If the dust filtration is critical, the dust particles are pilling up at the gap edge.

HL tau’s case

Simulation (Zhu et al. 2012)



HL tau’s data



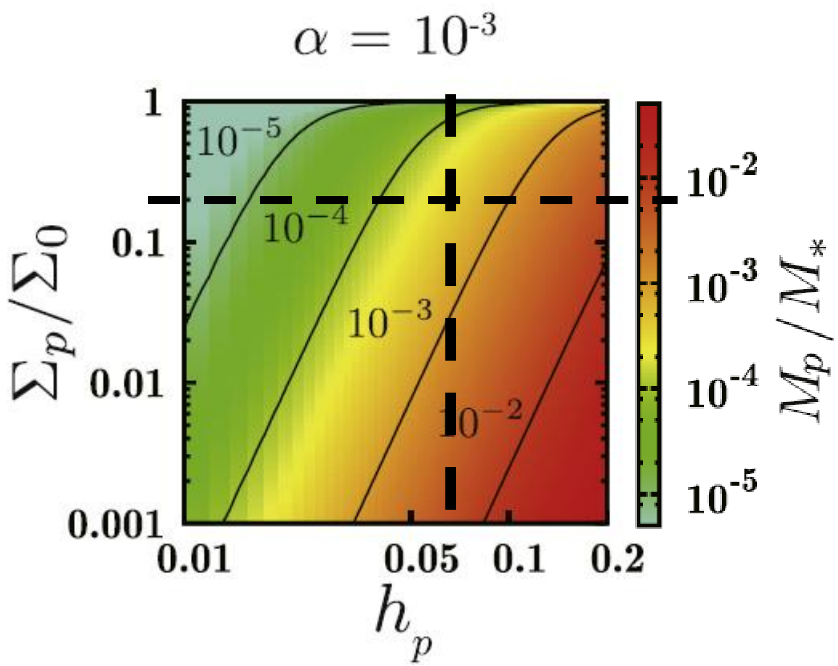
No decreasing of density

No pilling up

Estimated planet mass of HL tau

The planet mass in 2nd gap of HL tau's disk is about 0.3 M_J if exists.

(we assume that gas and dust are well-mixed)



$\Sigma_{min} \sim 0.3\ \Sigma_0$

T=55K (h/R=0.07)

$$\frac{M_p}{M_*} = 3 - 5 \times 10^{-4} \left(\frac{h_p}{0.07}\right)^{5/2} \left(\frac{\alpha}{10^{-3}}\right)^{1/2}$$

Summary

- We derive the analytic formula between the planet mass, disk parameters, and the observed gap depth.
- This relation can reproduce the gap depth given by numerical simulations.
- The planet mass in the observed gap can be estimated by this relation between the planet mass and the gap depth.
- We estimated the planet mass in 2nd gap of HL Tau's disk as about sub Jupiter mass, if the planet exists.