Type I migration in an optically thin disk

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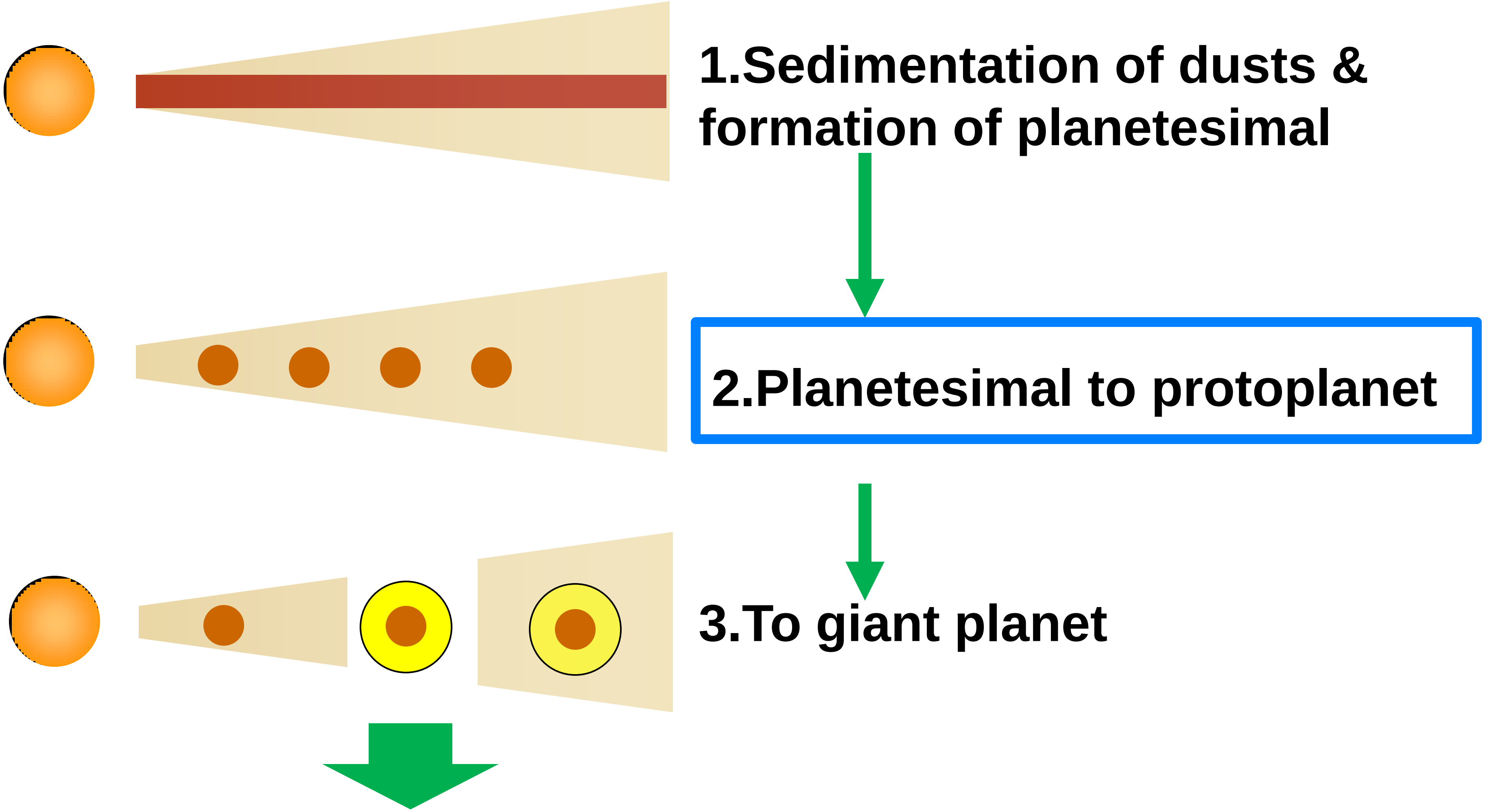
Abstract

We study Type I migration of a planet in a radiatively efficient disk using global twodimensional hydrodynamic simulations. The large positive corotation torque is exerted on a planet by an adiabatic disk at early times when the disk has the steep negative entropy gradient. The gas on the horseshoe orbit of the planet is compressed adiabatically during the change of the orbit from the slow orbit to the fast orbit, increasing its density and exerting the positive torque on the planet. The planet would migrate outward in the adiabatic disk before saturation sets in. We further study the effect of energy dissipation by radiation on Type I migration of the planet. The corotation torque decreases when the energy dissipates effectively because the density of the gas on the horseshoe orbit does not increase by the compression compared with the gas of the adiabatic disk. The total torque is mainly determined by the negative Lindblad torque and becomes negative. The planet migrates inwards towards the central star in the radiatively efficient disk. **The migration velocity is dependent on the radiative efficiency and is greatly reduced if the radiative cooling works inefficiently.**

Background



1.Sedimentation of dusts & formation of planetesimal

2.Planetesimal to protoplanet

3.To giant planet

4. Planetary system

Type I migration

A planet with ~1 earth mass drives spiral density waves in the surrounding gas disk.

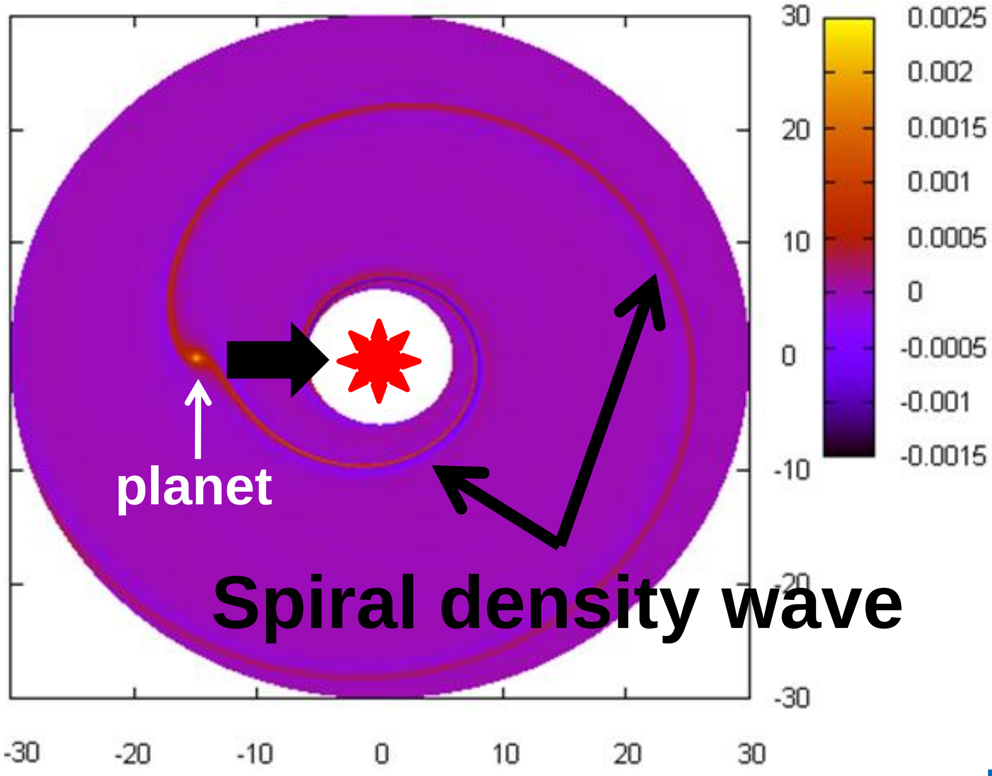
Gravitational interaction between planet and spiral waves causes the change of planet orbit.

Type I migration

Previous studies

Goldreich and Tremaine 1979, Tanaka et al.2002

In an isothermal disk, planet migrates inwards on timescales that are much shorter than the million-year lifetime of the disk.



planet

Spiral density wave

Recently…

In some Adiabatic disks, planets migrate outward.

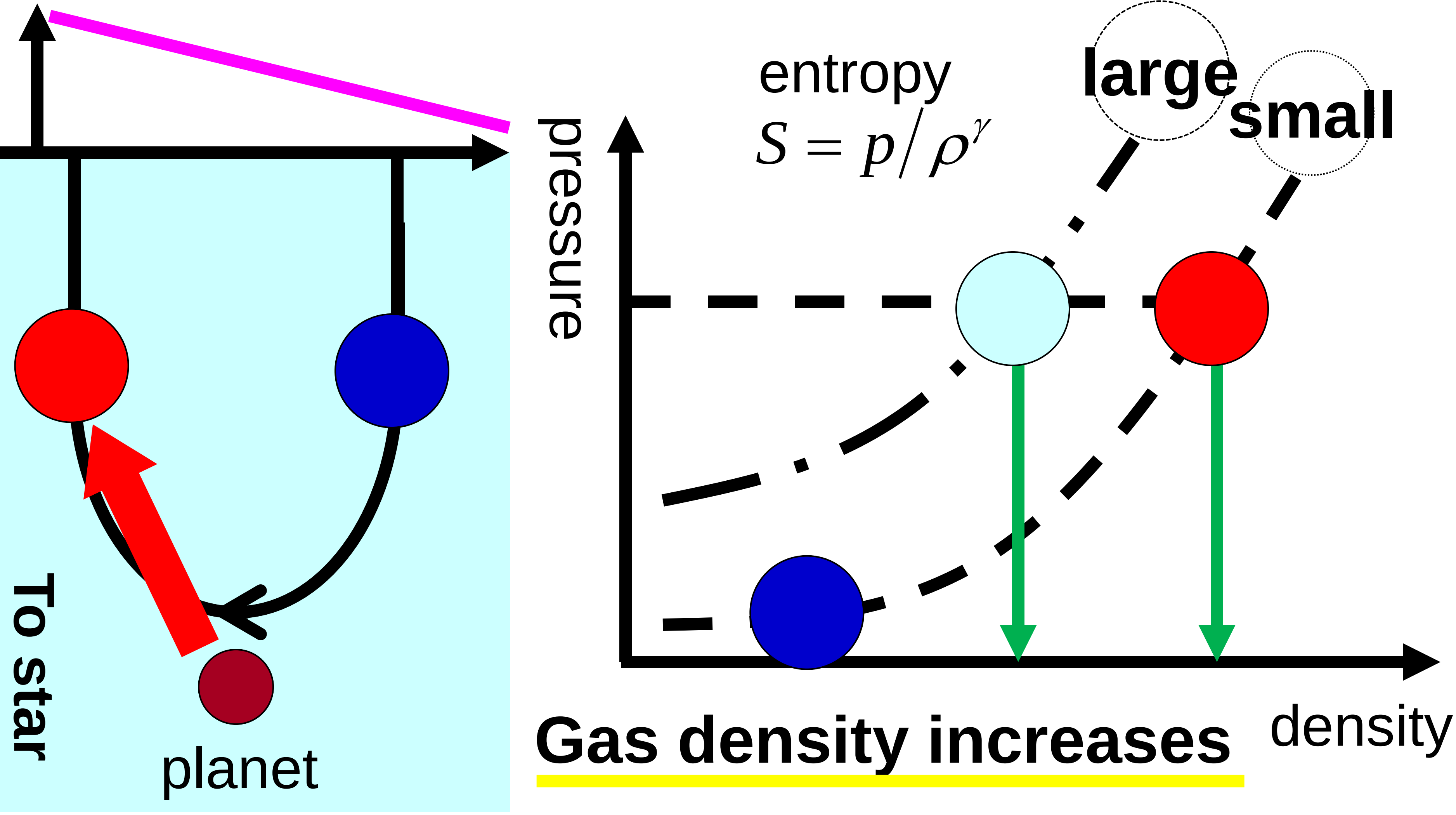
Baruteau & Masset(2008)、Paardekooper & Papaloizou(2008)

The direction and magnitude of the planet migration depends on the entropy gradient.

Positive gradient ⇒ planets move inward
Negative gradient ⇒ planets move outward

ここに次のスライドを貼る

In an adiabatic disk with
negative entropy gradient



Gas density increases

Isothermal disk ← **Ideal disk** → Adiabatic disk

Heat in the gas element escapes quickly.

Heat in the gas element does not escape.

In an actual disk, heat runs away gradually by radiation.

➡ Radiative cooling : **large ⇒ to isothermal disk**

shearing-box approximation calculation (Morohoshi & Tanaka 2003)

Planet migration in the disk with some dissipative effects

- Paardekooper & Papaloizou(2008) examine

  relationships between planet migration and the conductivity of disk

  ➡ conductivity : large ⇒ inward migration

- Kley & Crida(2008) examine

  planet migration using single optically thick accretion disk model with the density$\propto r^{-0.5}$ and temperature$\propto r^{-1.6}$

  ➡ they found the outward migration in the disk

A variety of disk structure

Imaging survey of protoplanetary disks around single T Tauri stars(Kitamura et al.,2003)

density$\propto r^{-p}$

$$0 < p < 1$$

$$0 < p < 0.5$$

Disk age > 10^6 years

$\longleftrightarrow$

temprature$\propto r^{-q}$

$$0.5 < q < 0.7$$

$$0.5 < q < 0.6$$

entropy $\propto r^{\underline{(\gamma-1)p-q}}$

➡ $-0.7 < (\gamma - 1)p - q < -0.1$

$$-0.6 < (\gamma - 1)p - q < -0.33$$

= negative gradient ⇒ planet may migrate outward!

Goal of our research

- adiabatic and isothermal disks⇒ ideal disk model

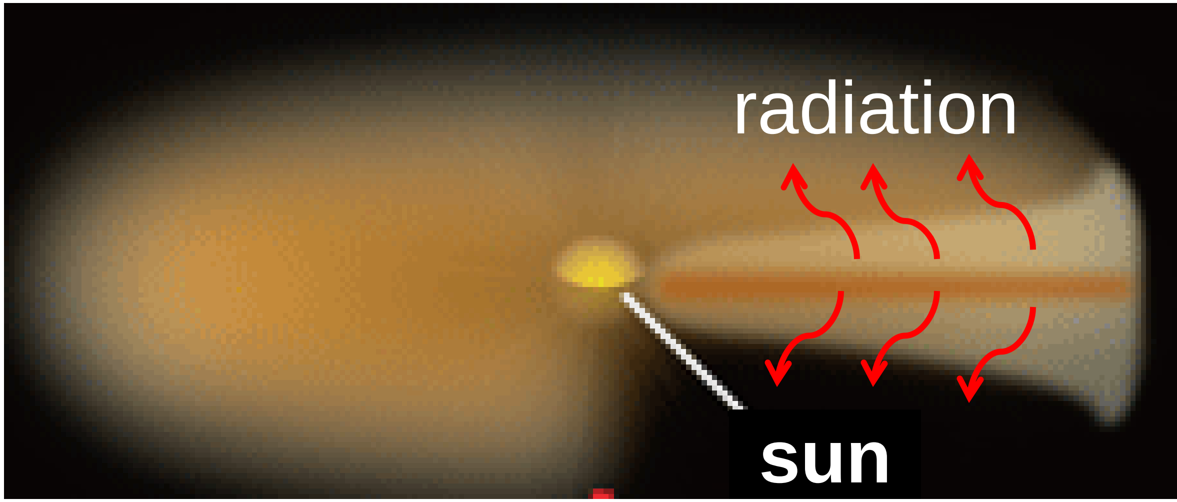
  ➡ Heat escapes by radiation from a disk

- observation

  ➡ Various disk structures

Gooooal!

Gooooal!



we systematically examine the total torque acting on a planet by radiatively efficient discs with various values of the opacity and reveal how the total torque depends on the efficiency of the cooling by radiation as well as the structure of a disk.

Set up of calculation

2 D disk (thin disk approximation)

The disk is optically thin

Planet mass＝5M$_{\mathrm{earth}}$@15AU

Mesh number:576 × 3072 $\begin{cases} \Delta r_{\mathrm{r}} / r_{\mathrm{H}} = 0.12 \\ \Delta r_{\theta} / r_{\mathrm{H}} = 0.12 \end{cases}$

Initial condition $\begin{cases} \text{density} \propto r^{-p} \\ \text{temperature} \propto r^{-q} \end{cases}$

Basic Equations

- **mass conservation equation**
- **Euler equations**
- **energy conservation equation**

$$\frac{\partial E}{\partial t}+\nabla\left[\mathbf{v}\left(E+p\right)\right]=-\Sigma\mathbf{v}\cdot\nabla\Phi-\overset{\text{Radiative term}}{\boxed{4\kappa\Sigma\sigma_{\mathrm{SB}}\left(T^{4}-T_{0}^{4}\right)}}$$

The source terms are computed with a **second-order Runge-Kutta scheme**, while the advective terms are calculated by a second-order MUSCL-Hancock scheme and exact Riemann solver

The angular momentum of the disk gas is transferred to the planet. The transfer rate of the angular momentum from the gas at r to the planet:

$$T_r=\int_0^{2\pi}\left(\mathbf{r}'\times\nabla\Phi\right)\Sigma\cdot\mathbf{e}_z r'\,\mathrm{d}\theta$$

Cooling time VS Passing time

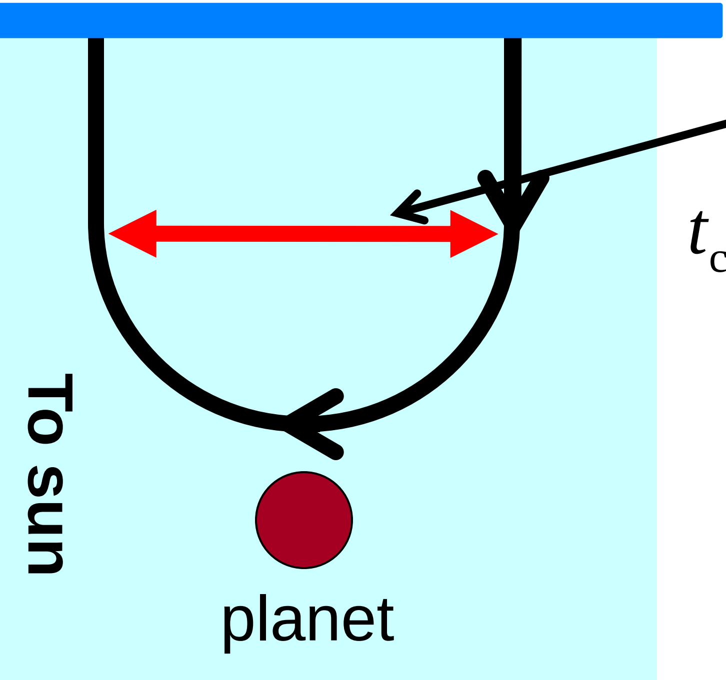
Radiation

$$\frac{\partial E}{\partial t}+\nabla\left[\mathbf{v}\left(E+p\right)\right]=-\Sigma\mathbf{v}\cdot\nabla\Phi-\boxed{4\kappa\Sigma\sigma_{\mathrm{SB}}\left(T^4-T_0^4\right)}$$

Cooling time

$$t_{\mathrm{cool}}=\frac{c_V T}{16\sigma_{\mathrm{SB}}T^4\kappa}=0.7\mathrm{yr}\left(\frac{\kappa}{0.0075\,\mathrm{cm}^2/\mathrm{g}}\right)^{-1}\left(\frac{r}{15\mathrm{AU}}\right)^{3q}$$

※1cm dust



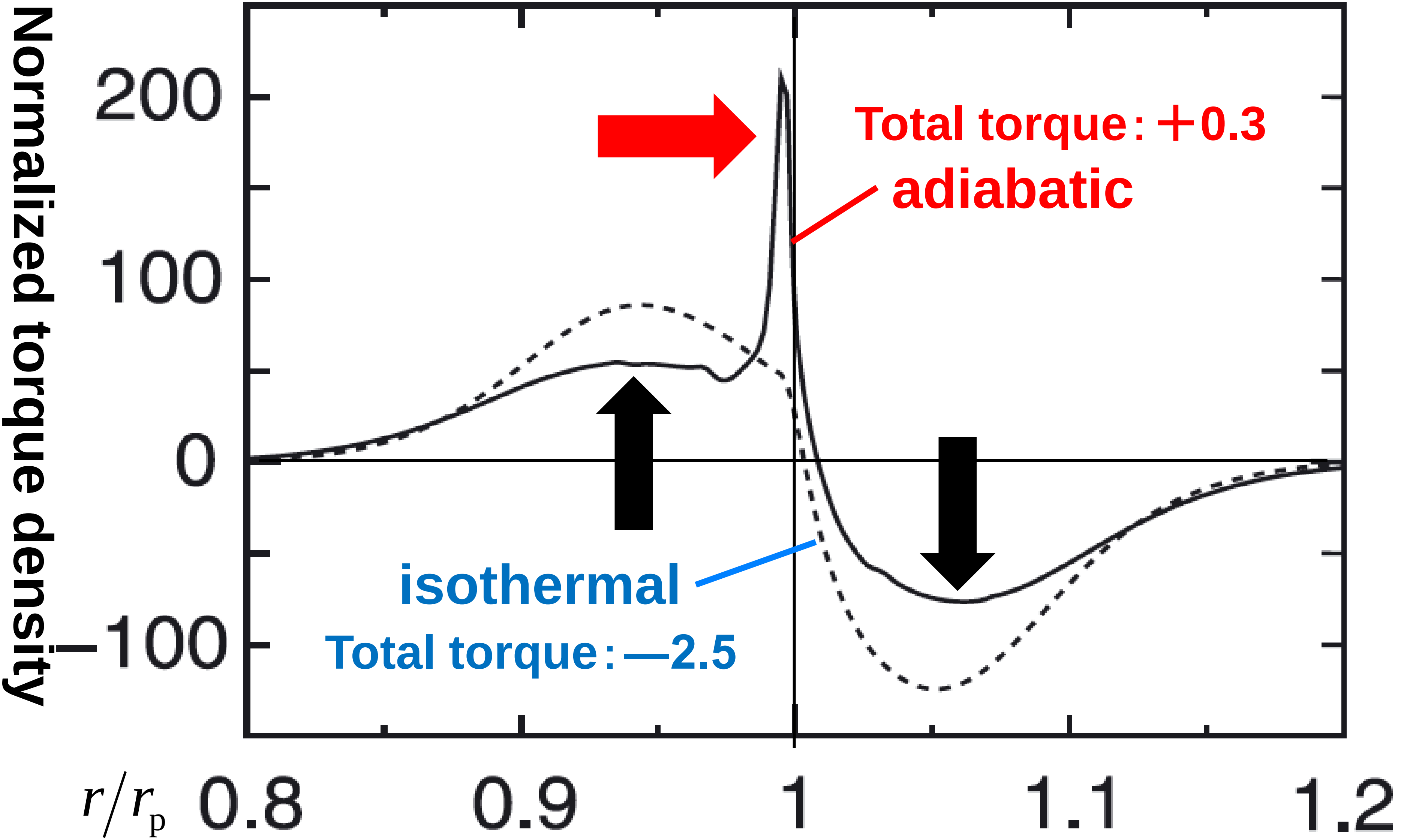
Passing time

$$t_{\mathrm{comp}}=\frac{2r_H}{\frac{3}{2}\Omega_P r_H}=\frac{4}{3\Omega_P}=12.3\mathrm{yr}\left(\frac{r}{15\mathrm{AU}}\right)^{3/2}$$

$$\boxed{\zeta}=\frac{t_{\mathrm{comp}}}{t_{\mathrm{cool}}}=18\left(\frac{\kappa}{0.0075}\right)\left(\frac{r}{15}\right)^{\frac{3}{2}-3q}$$

Adiabatic VS Isothermal disk

20kepler times@15AU



Total torque：＋0.3

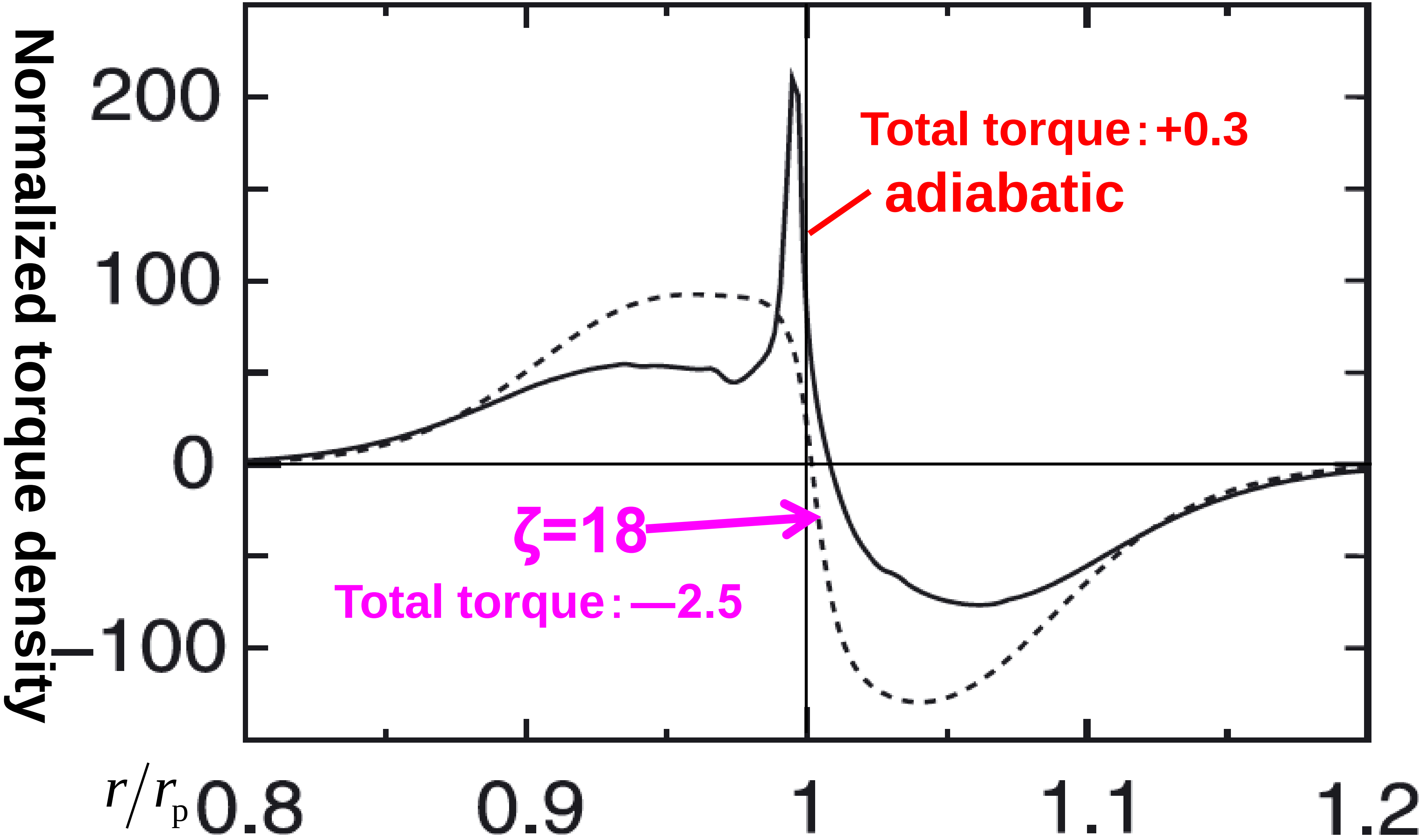
adiabatic

isothermal

Total torque：—2.5

Radiative disk

20kepler times@15AU



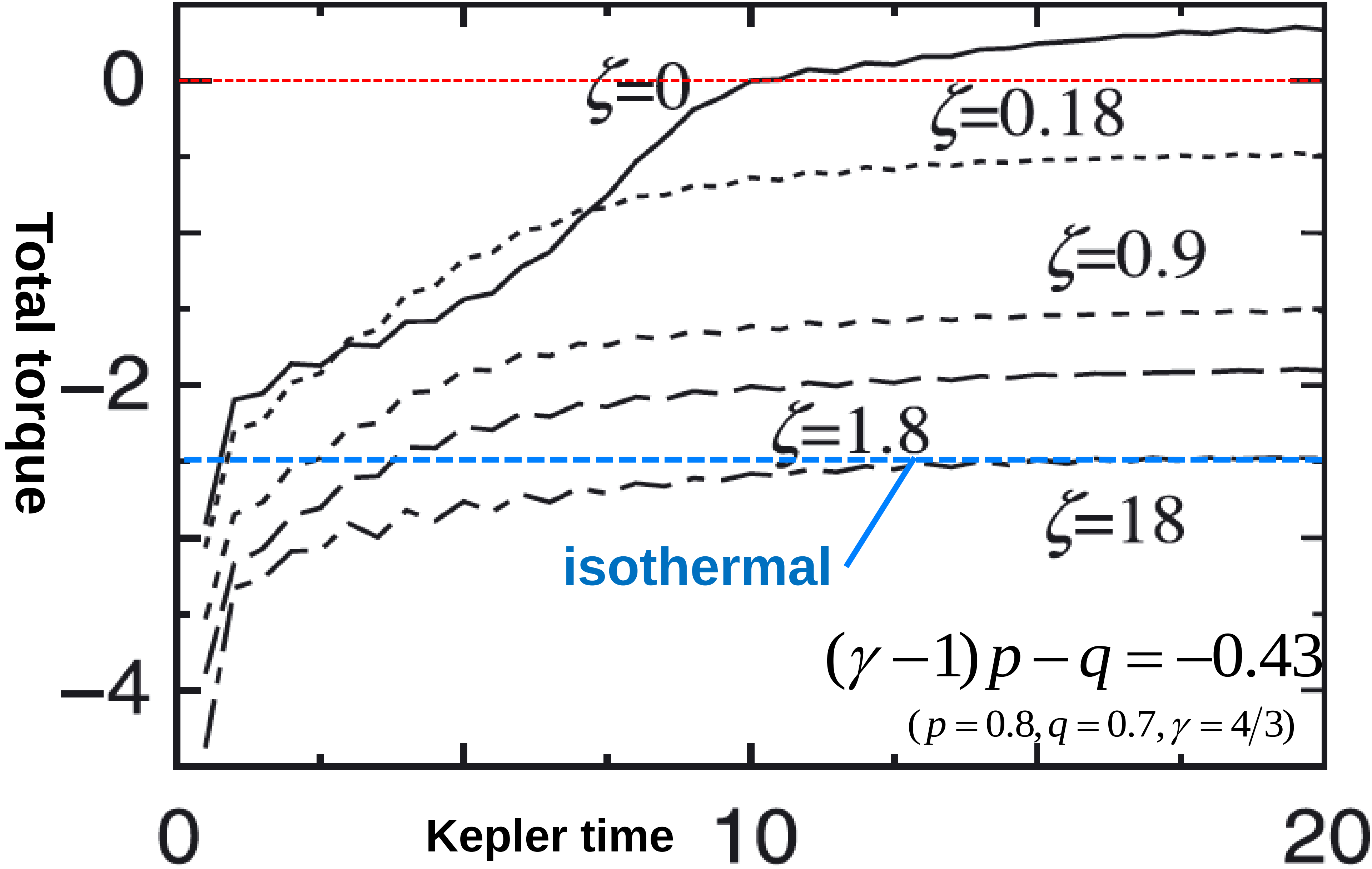
Total torque：+0.3

adiabatic

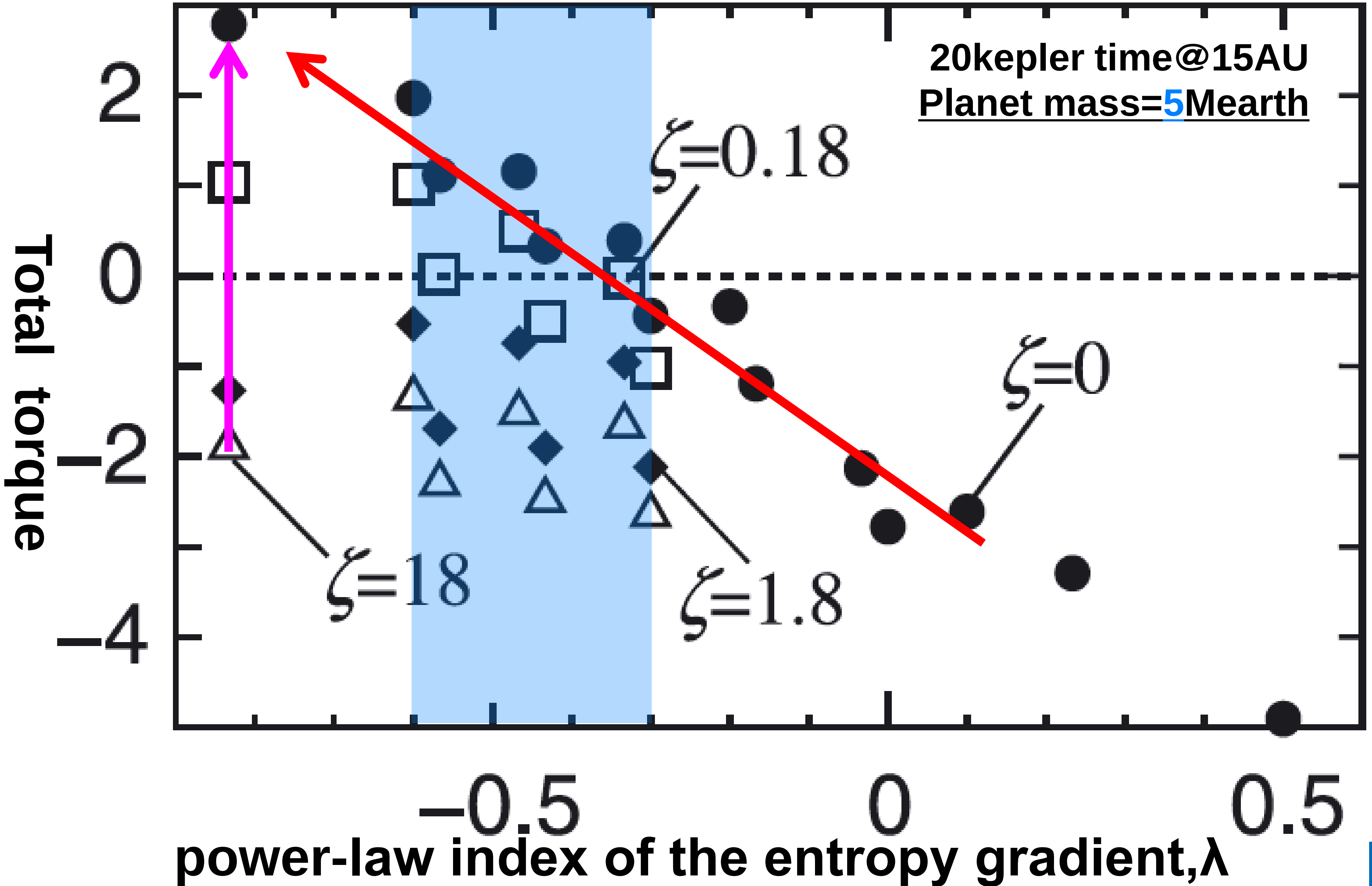
ζ=18

Total torque：—2.5

Planet migration in radiative disks



Total torque VS entropy gradient



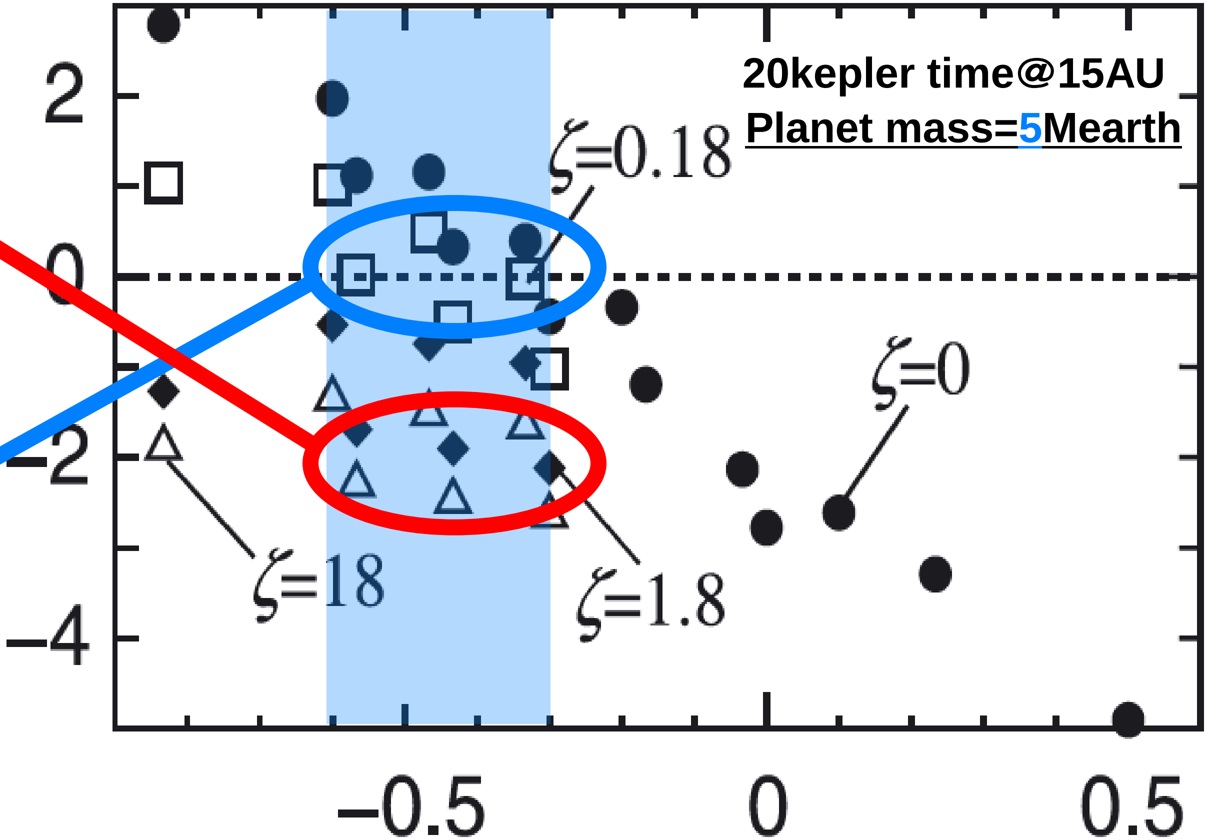
Summary & Discussion

Migration speed
～－2AU/10^5years

Migration time
～7.5x10^5years

Migration speed
～ 0.5AU/10^5years

Migration time
～ 3x10^6years



dust opacity：small ⇒ critical core mass of giant planet: small

(Inaba et al 2006)

A disk with a small number of dust is advantageous to the formation of the giant planet.

end