周惑星円盤のガス降着メカニズムについて

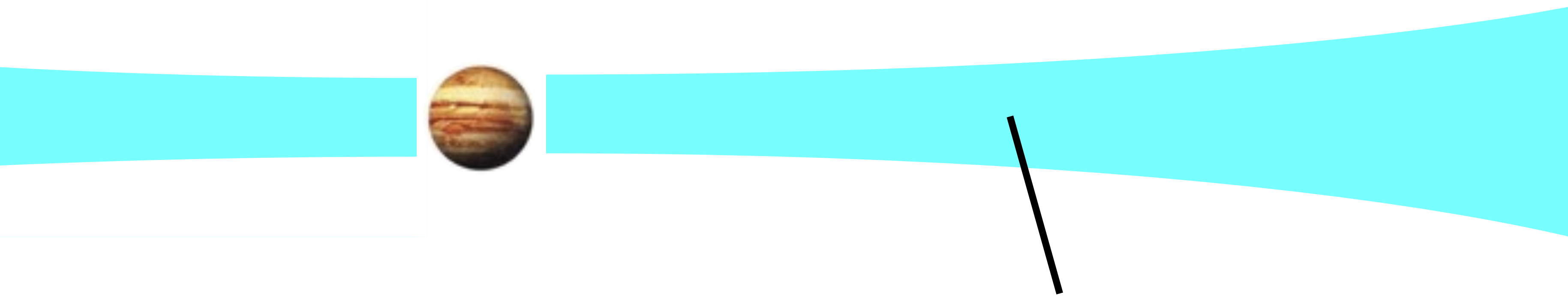
藤井悠里[1]

奥住聡[2], 谷川貴行[3], 犬塚修一郎[1], 高橋実道[14]

[1]名古屋大学, [2]東京工業大学, [3]北海道大学, [4]京都大学

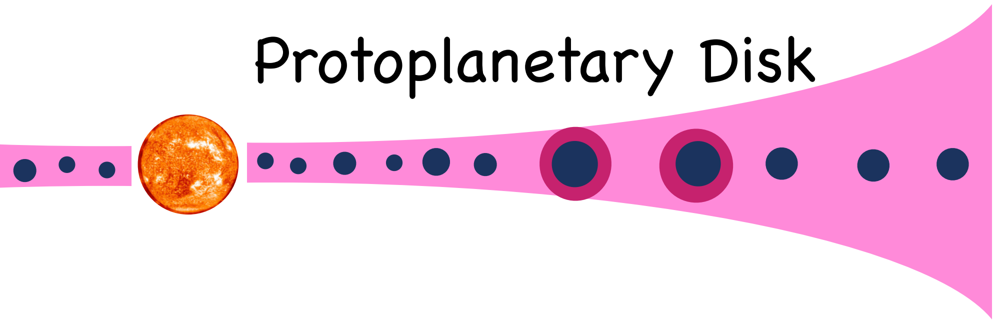
周惑星円盤

周惑星円盤

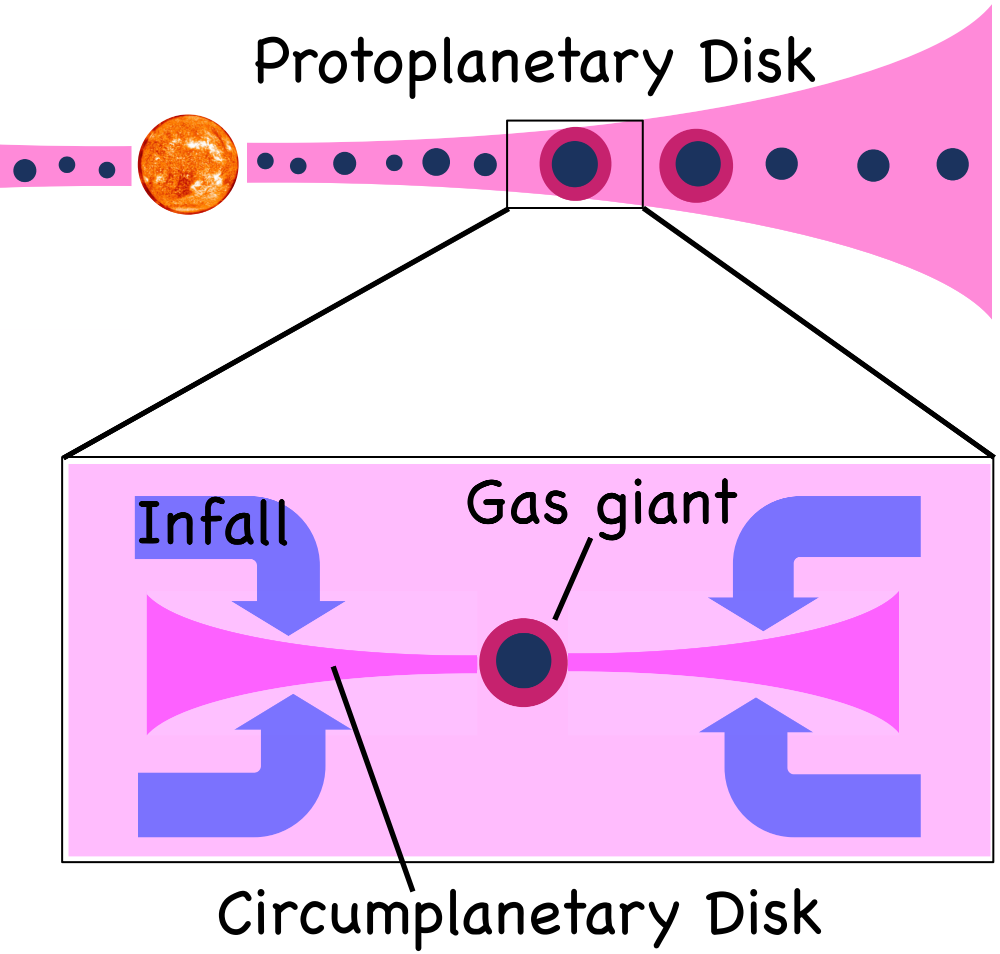


ガス降着率？
面密度？
温度構造？

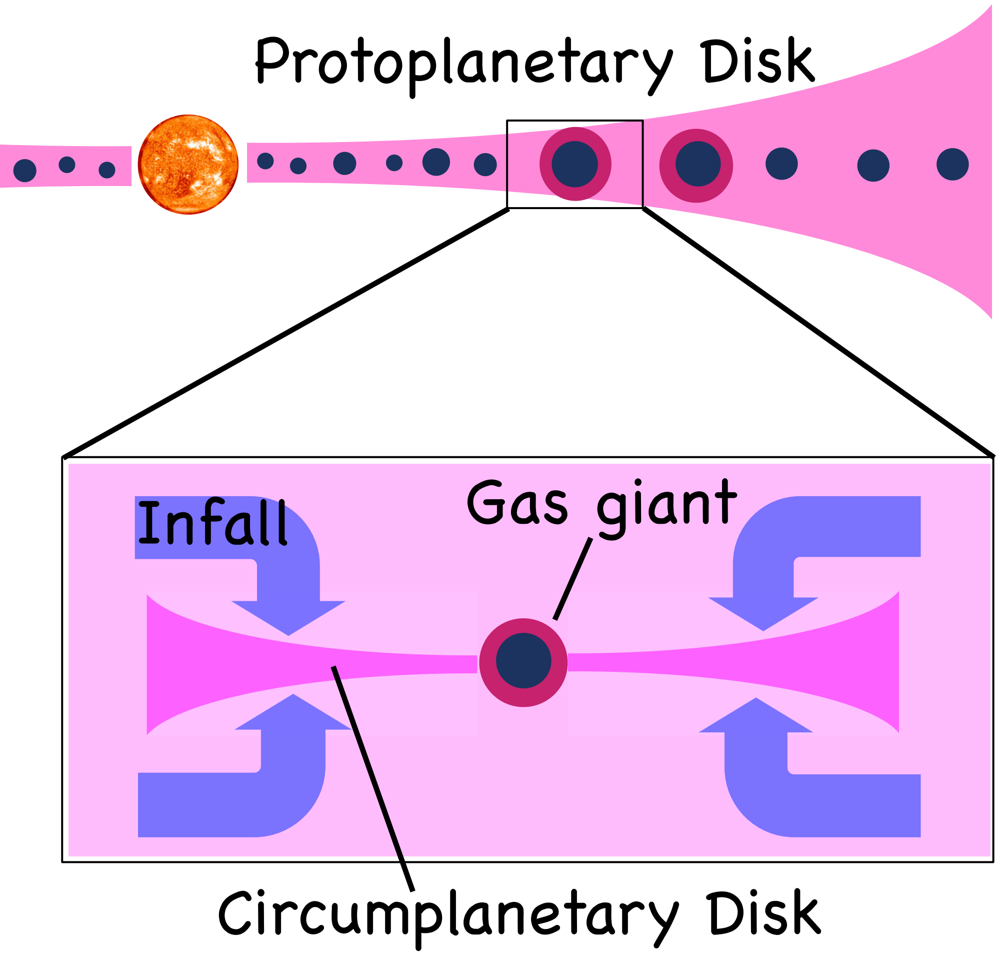
周惑星円盤の形成



周惑星円盤の形成


Protoplanetary Disk
Infall
Gas giant
Circumplanetary Disk

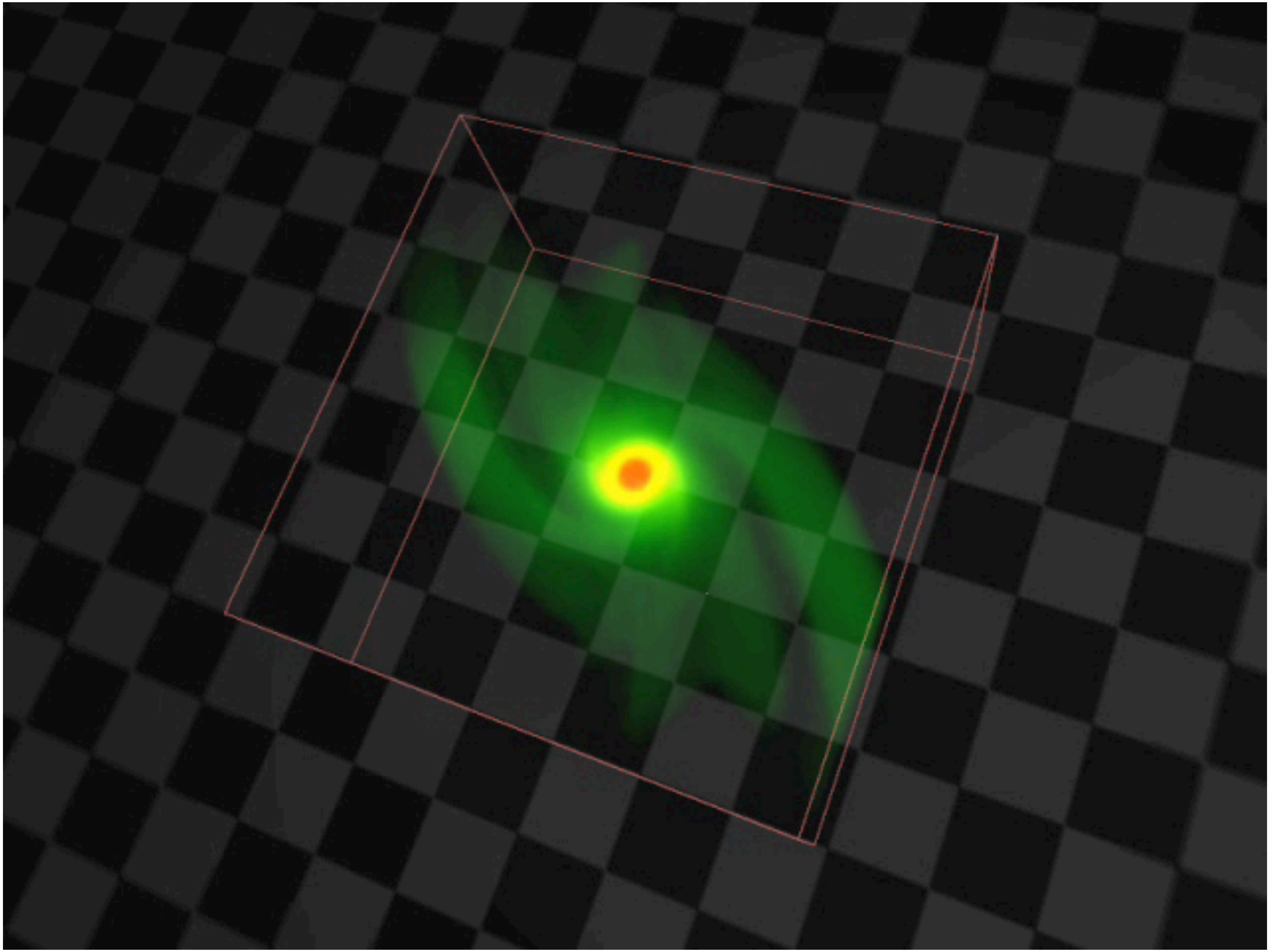
周惑星円盤の形成



原始惑星系円盤からの
ガス流入のシミュレーション

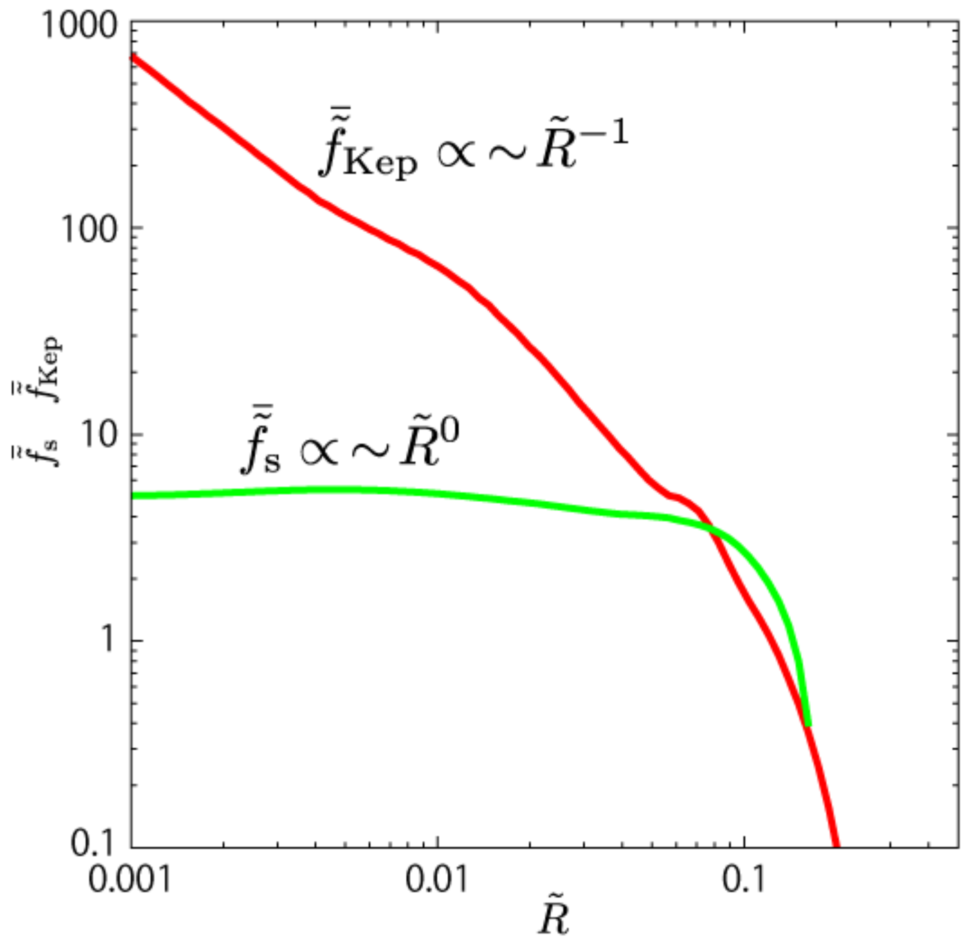
- Ayliffe & Bate (2009)
- Machida et al. (2010)
- Tanigawa et al. (2012)
- Uribe et al. (2013)

Tanigawa et al. (2012), Move: by T. Takeda (4D2U, NAOJ)



Tanigawa et al. (2012), Move: by T. Takeda (4D2U, NAOJ)

ガスの流入率

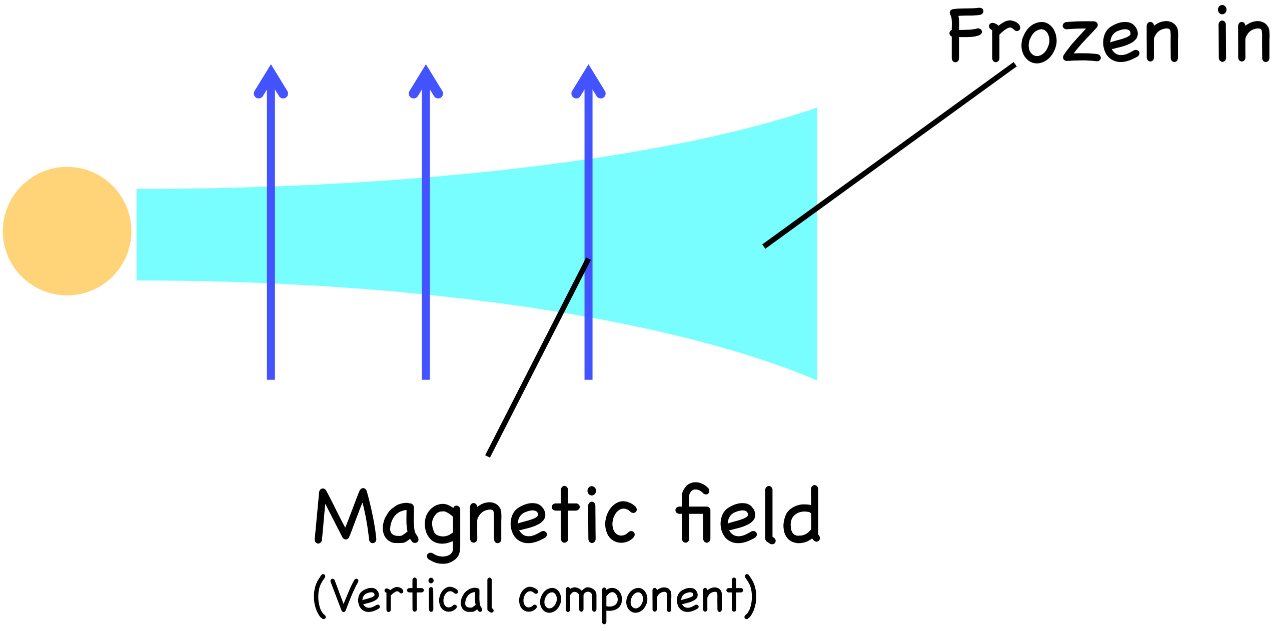


Tanigawa, Ohtsuki, & Machida (2012)

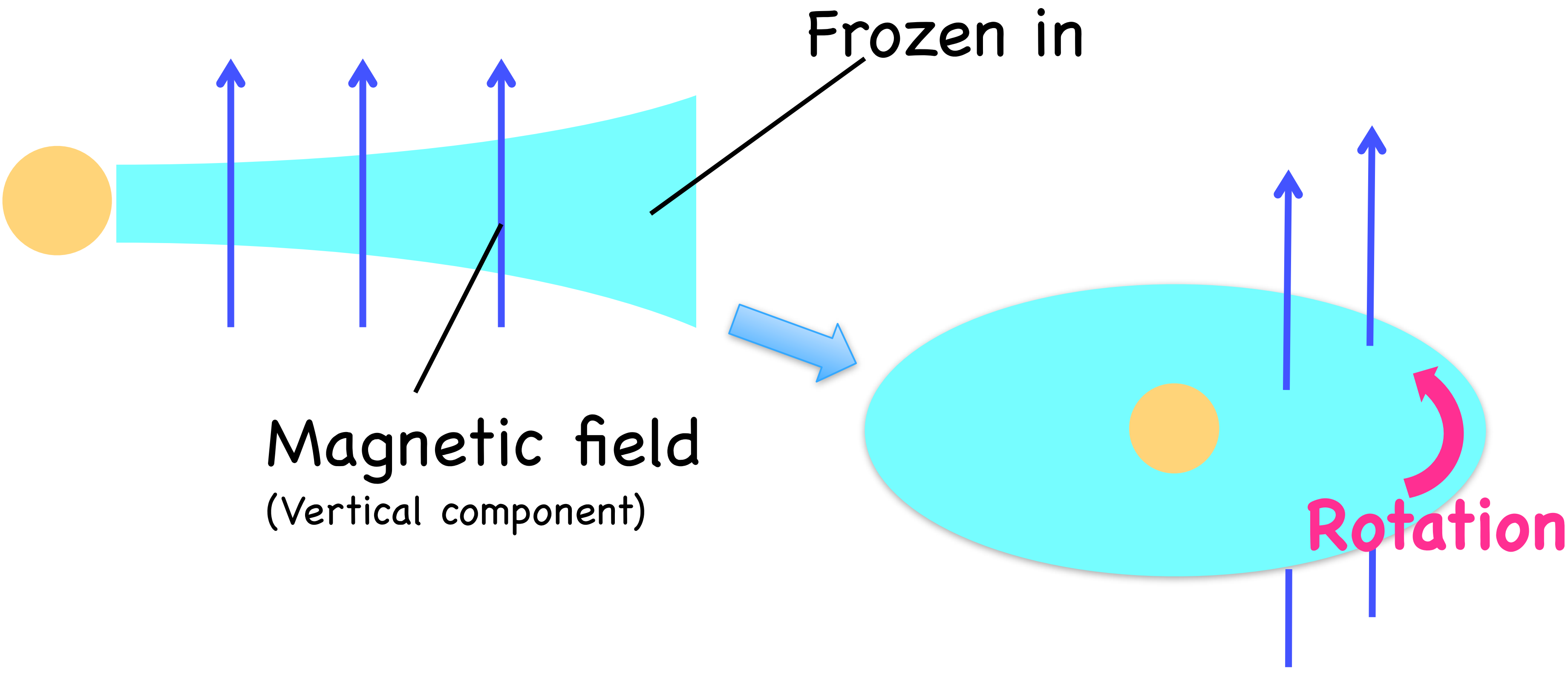
Most Promising Gas Accretion Mechanism:

Magnetorotational Instability (MRI)

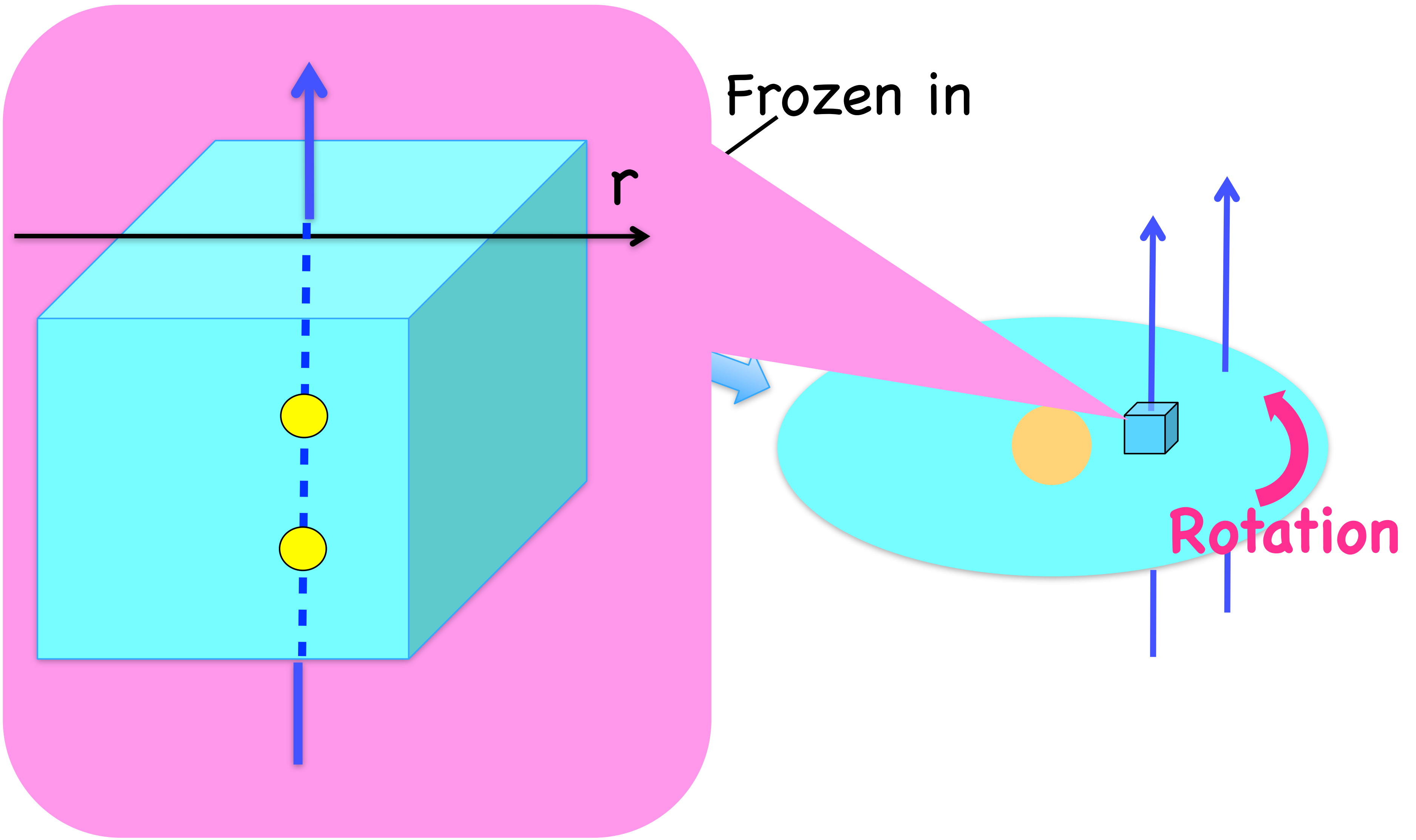
MRI



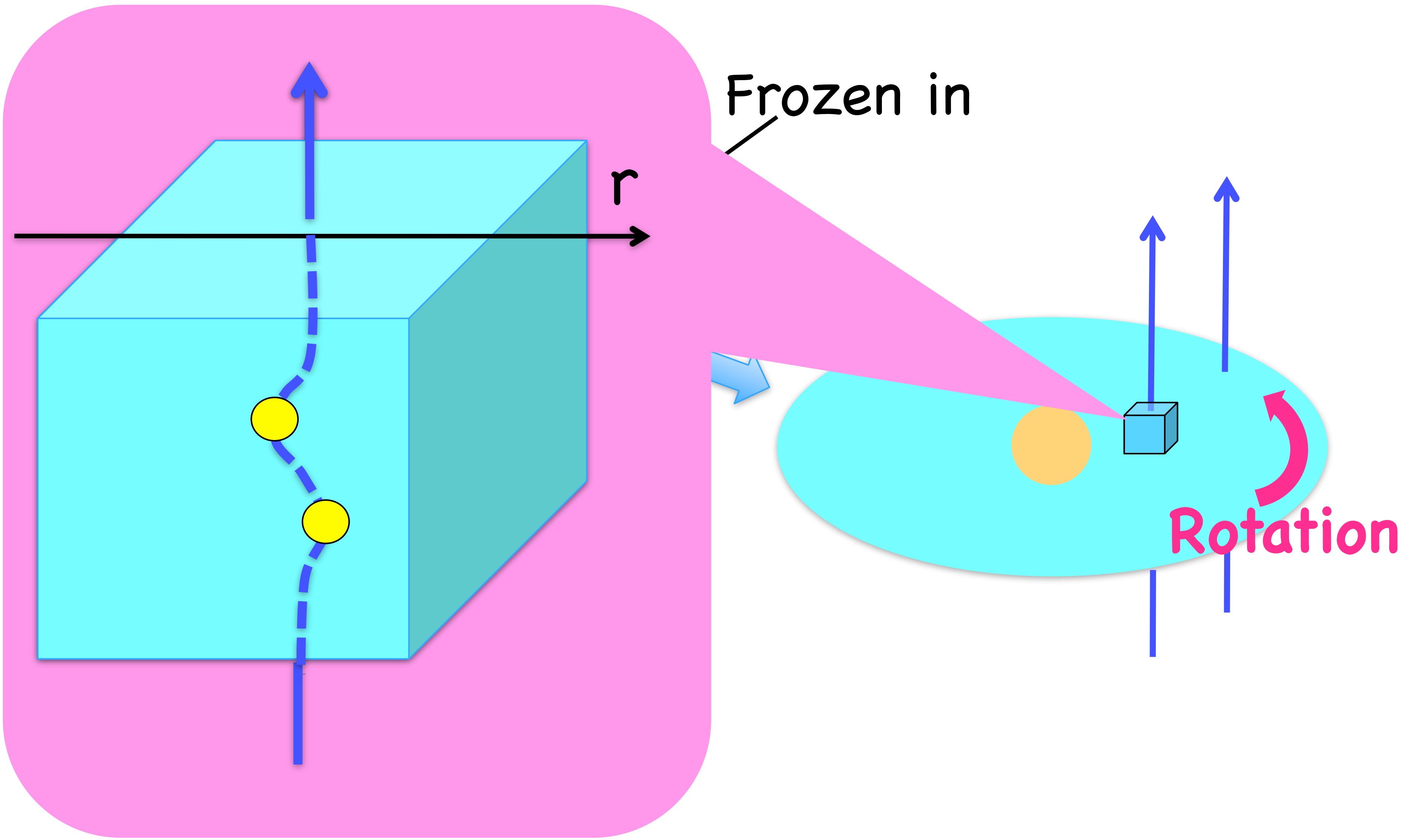
MRI



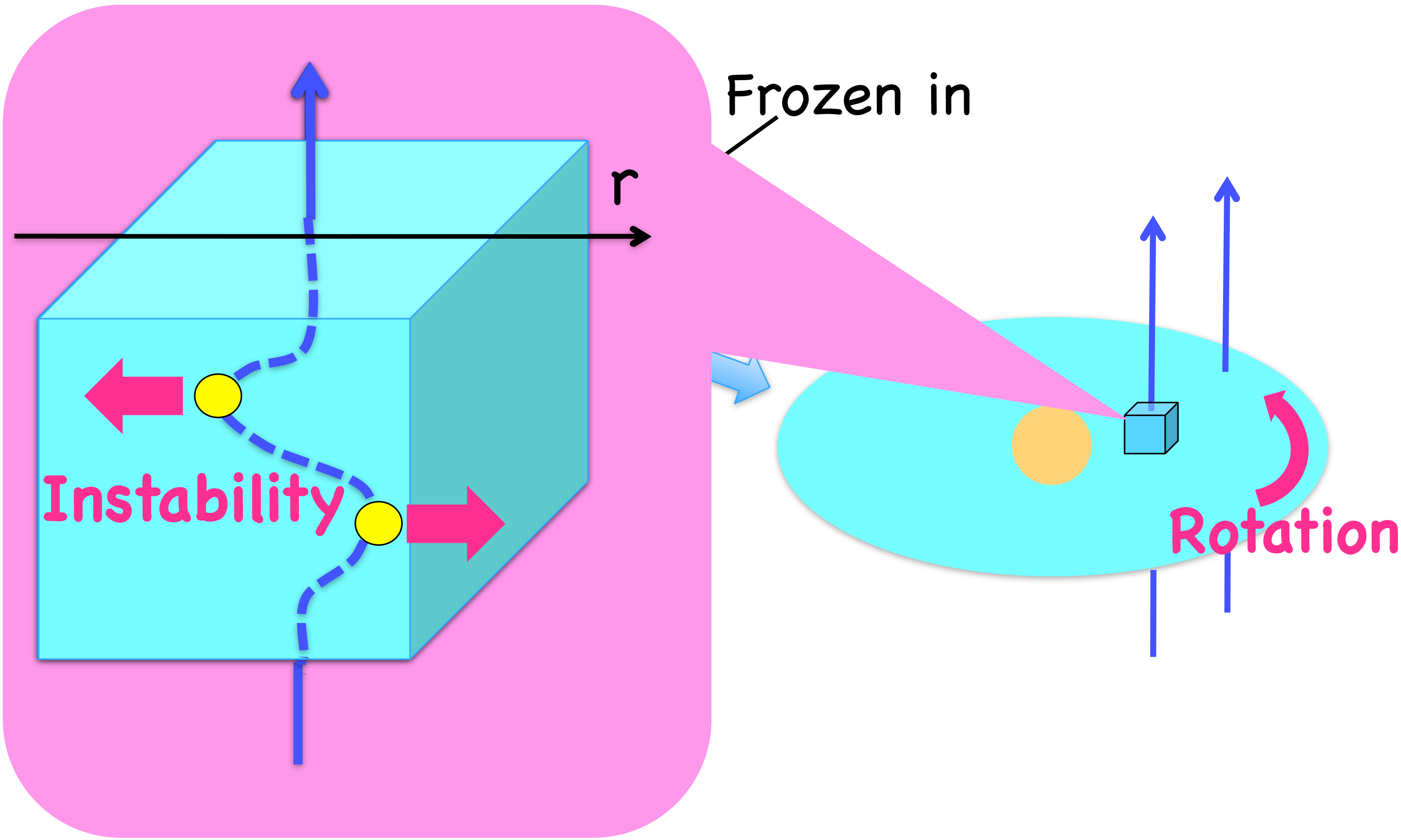
MRI



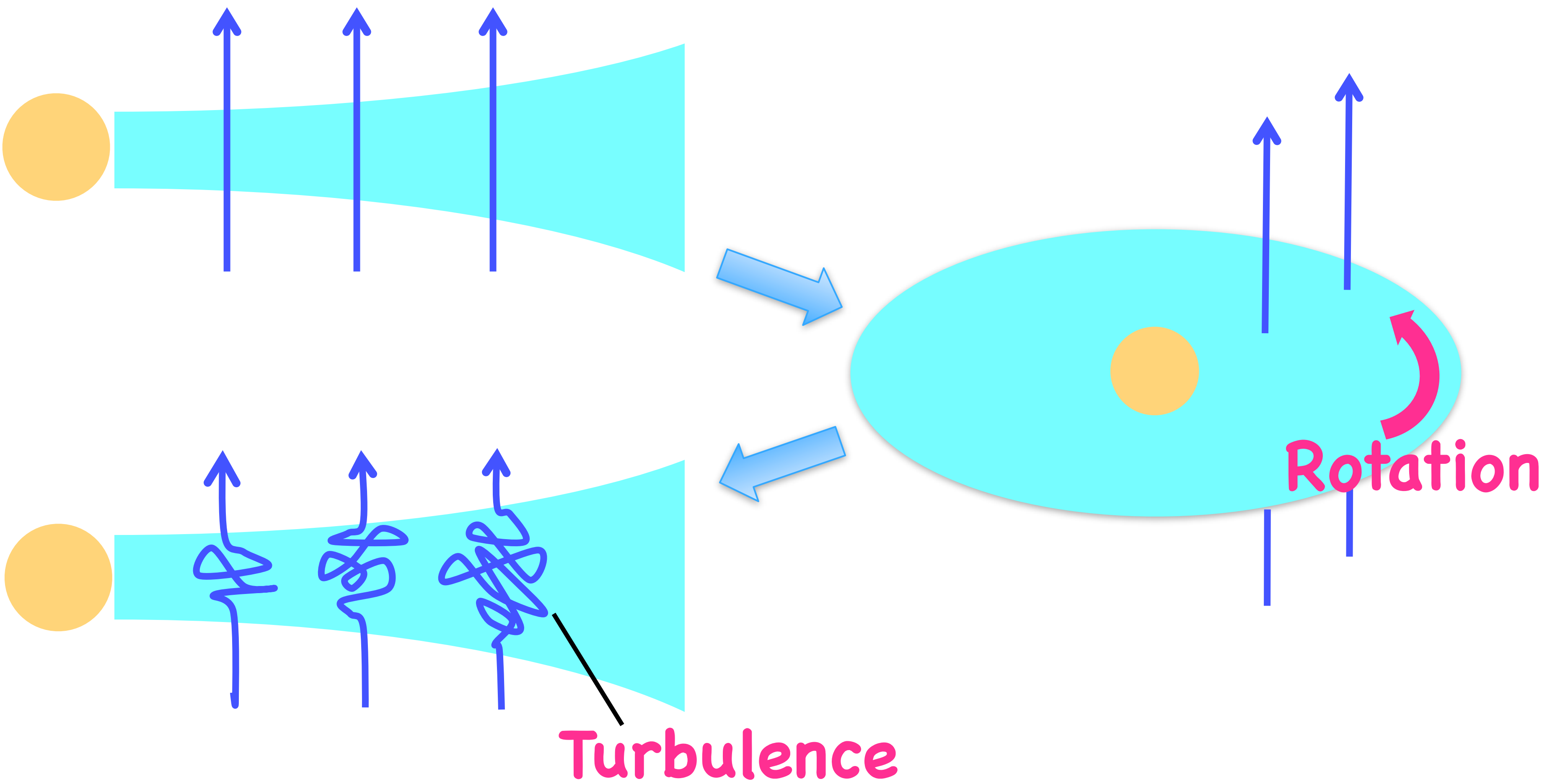
MRI

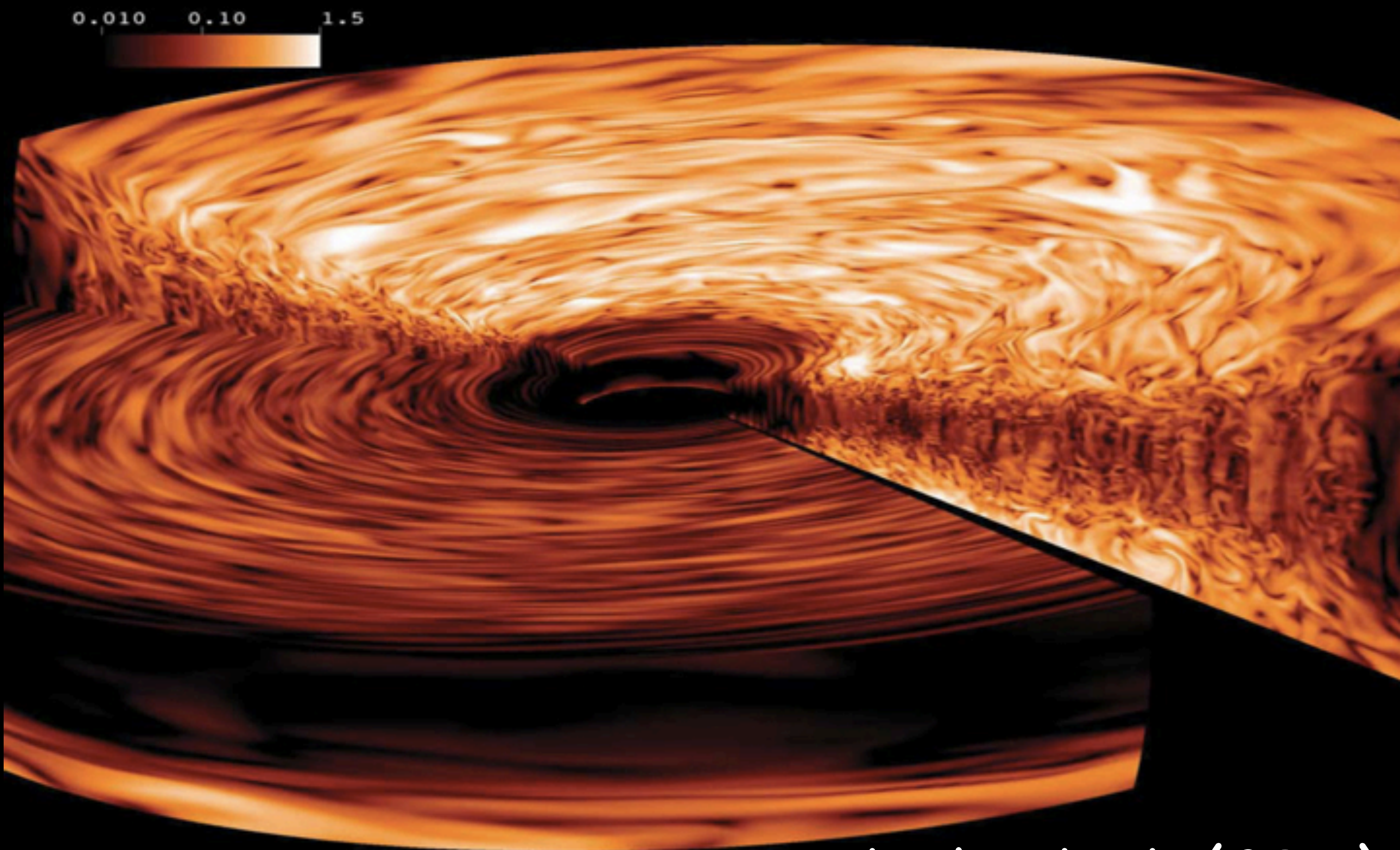


MRI



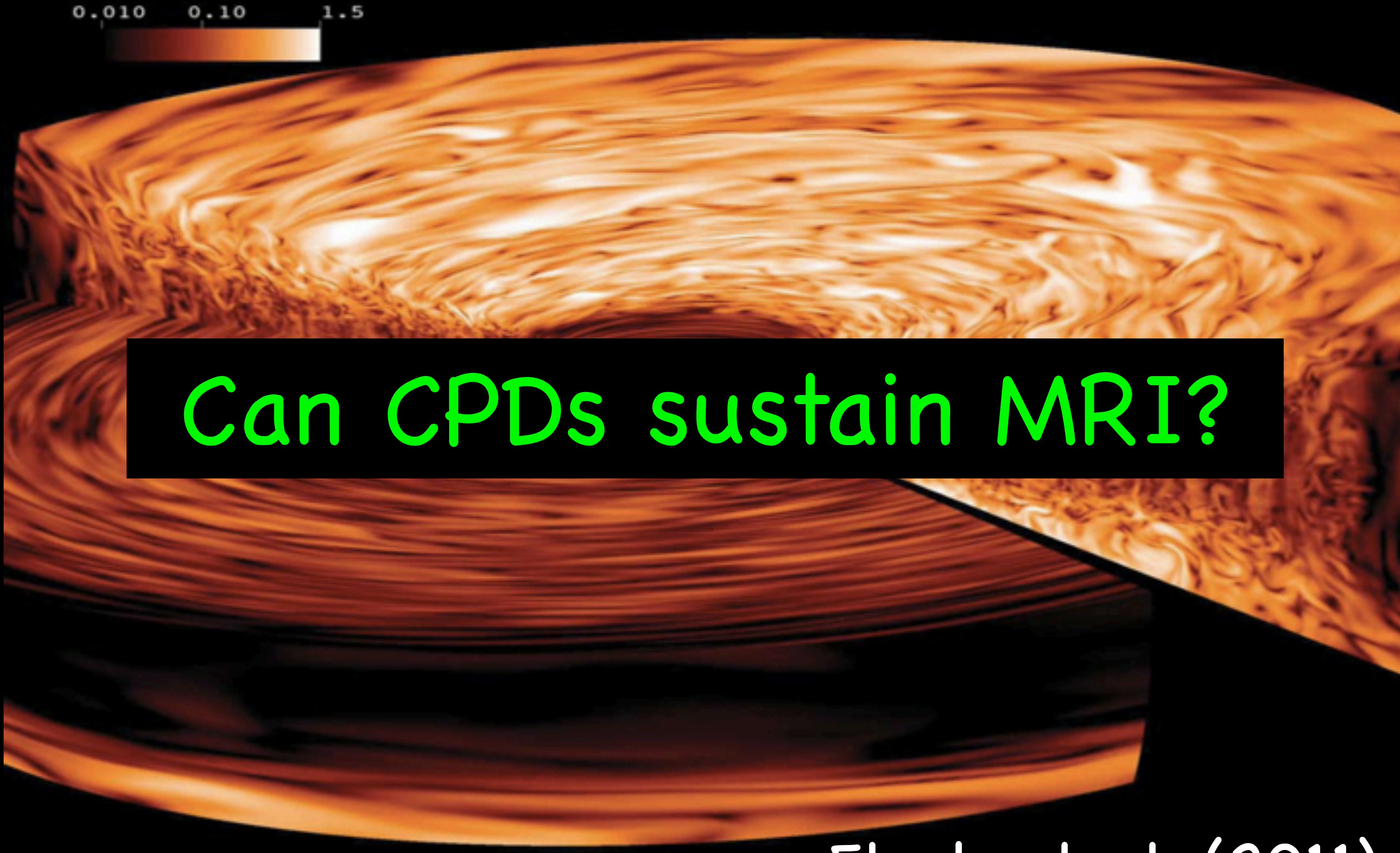
MRI





Flock et al. (2011)

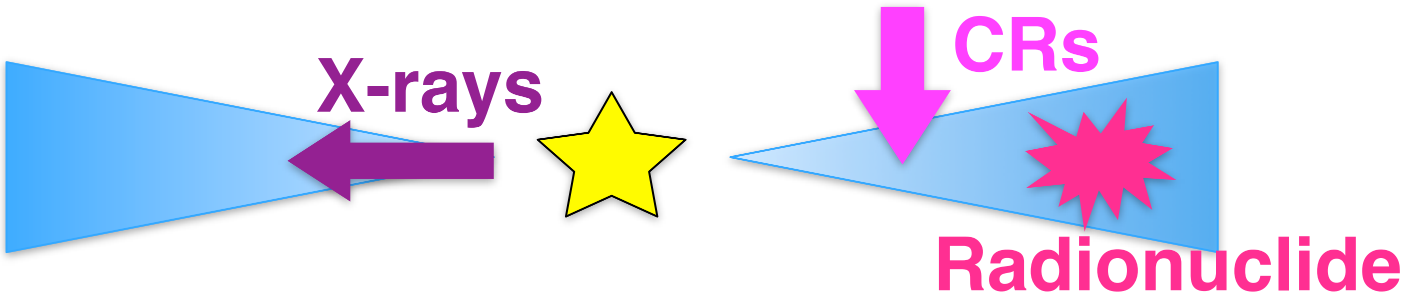
Can CPDs sustain MRI?



Flock et al. (2011)

Ionization & MRI

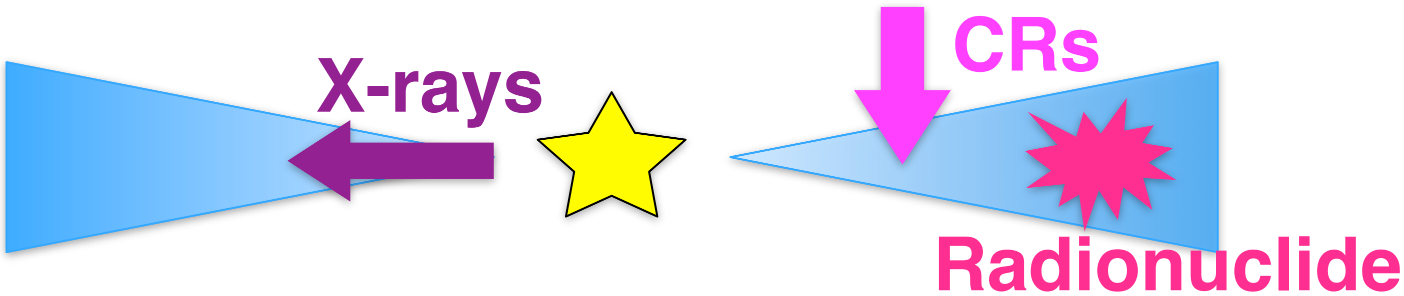
- Protoplanetary disks



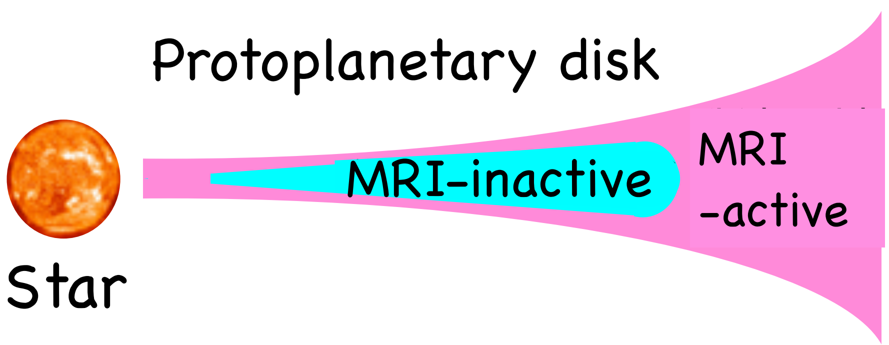
Weakly ionized ⇒ MRI ⇒ Accretion

Ionization & MRI

- Protoplanetary disks

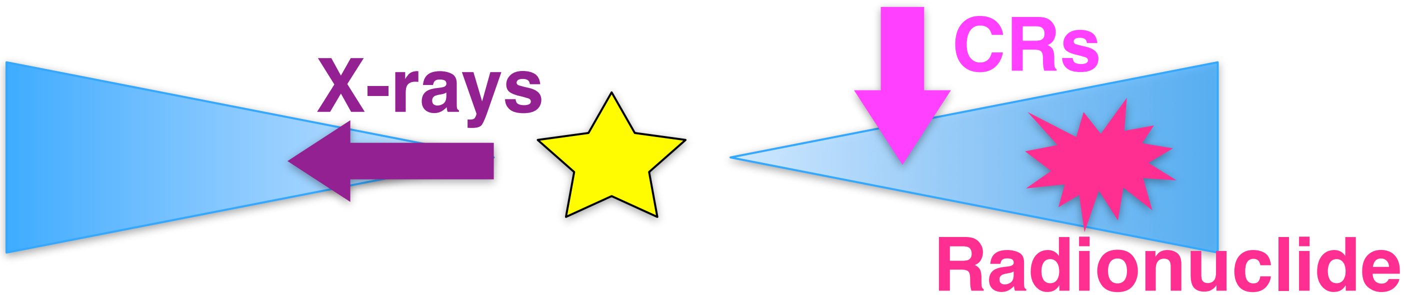


Weakly ionized ⇒ MRI ⇒ Accretion

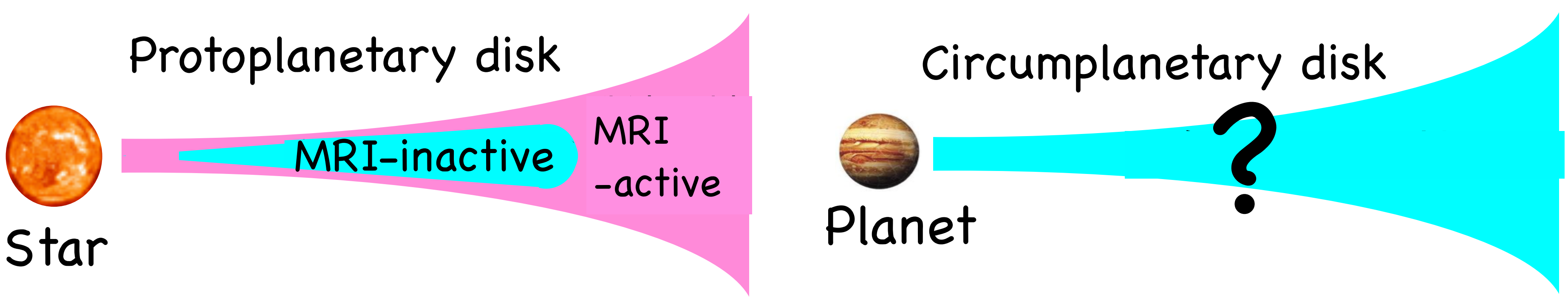


Ionization & MRI

- Protoplanetary disks



Weakly ionized ⇒ MRI ⇒ Accretion



Aim

To understand accretion rate of CPDs...

Investigate accretion rate due to MRI

Accretion mechanism = MRI

⇒ Estimate sizes of MRI-active regions

(Fujii, Okuzumi & Inutsuka, 2011)

⇒ Accretion stress, α, can be derived

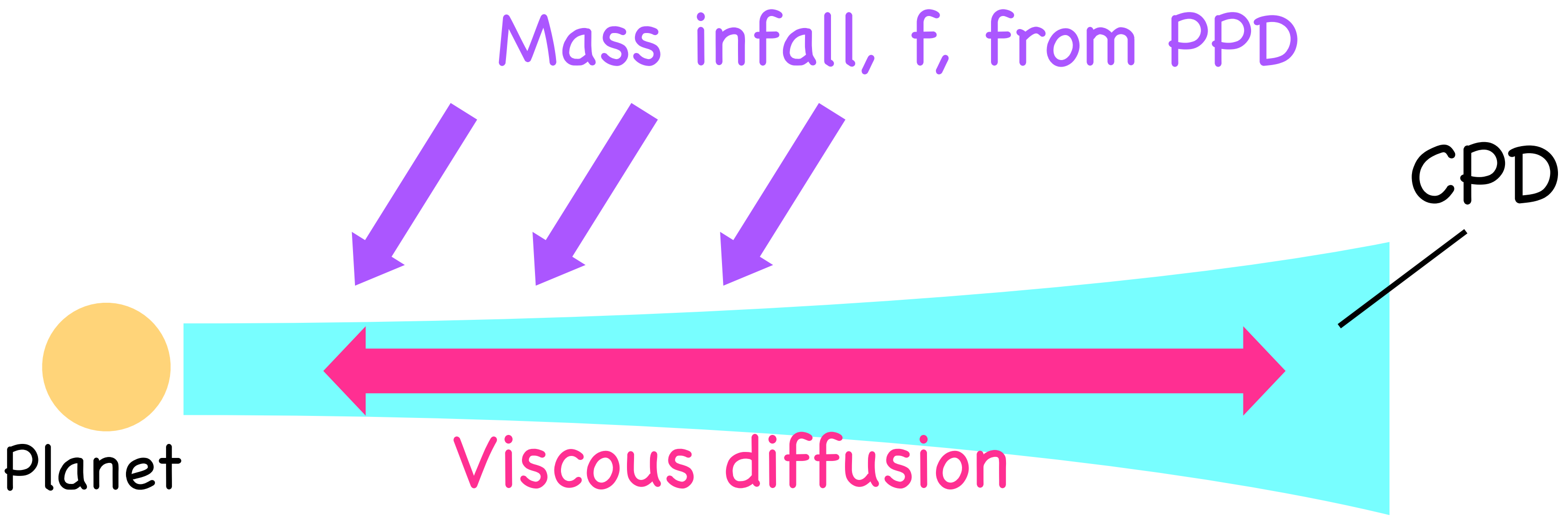
(Okuzumi & Hirose, 2011)

Method

Surface Density

- Diffusion equation of disk with infall

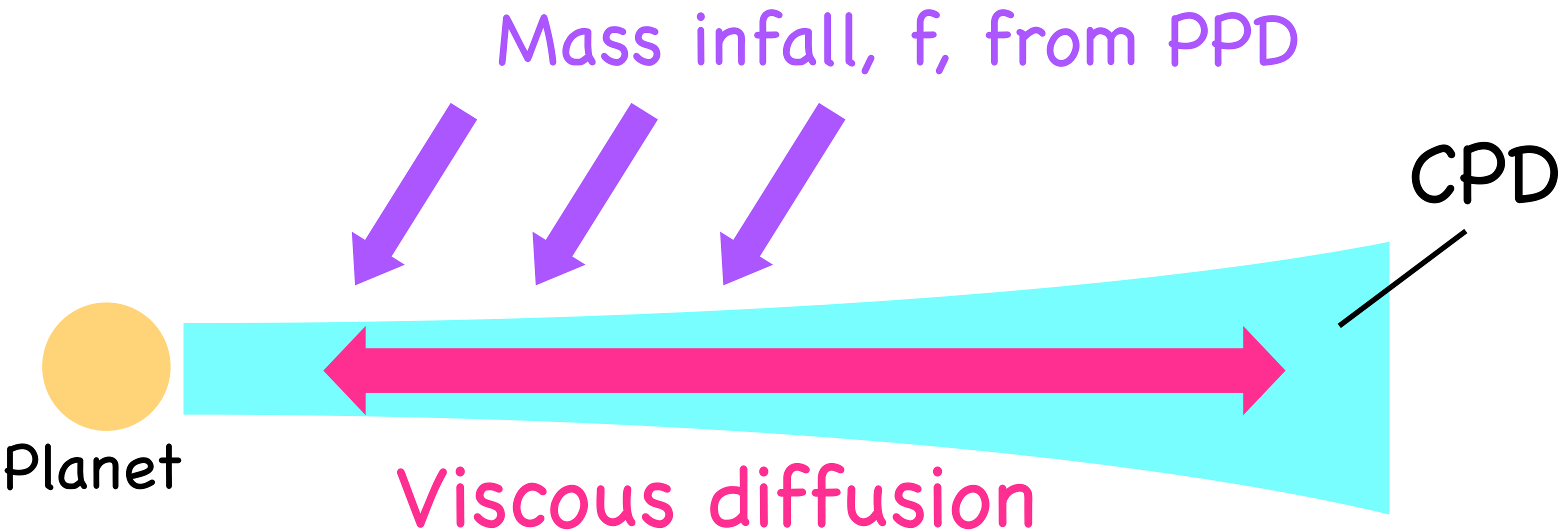
$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(3r^{\frac{1}{2}}\frac{\partial}{\partial r}\left(r^{\frac{1}{2}}\nu\Sigma\right)\right) + f$$



Surface Density

- Diffusion equation of disk with infall

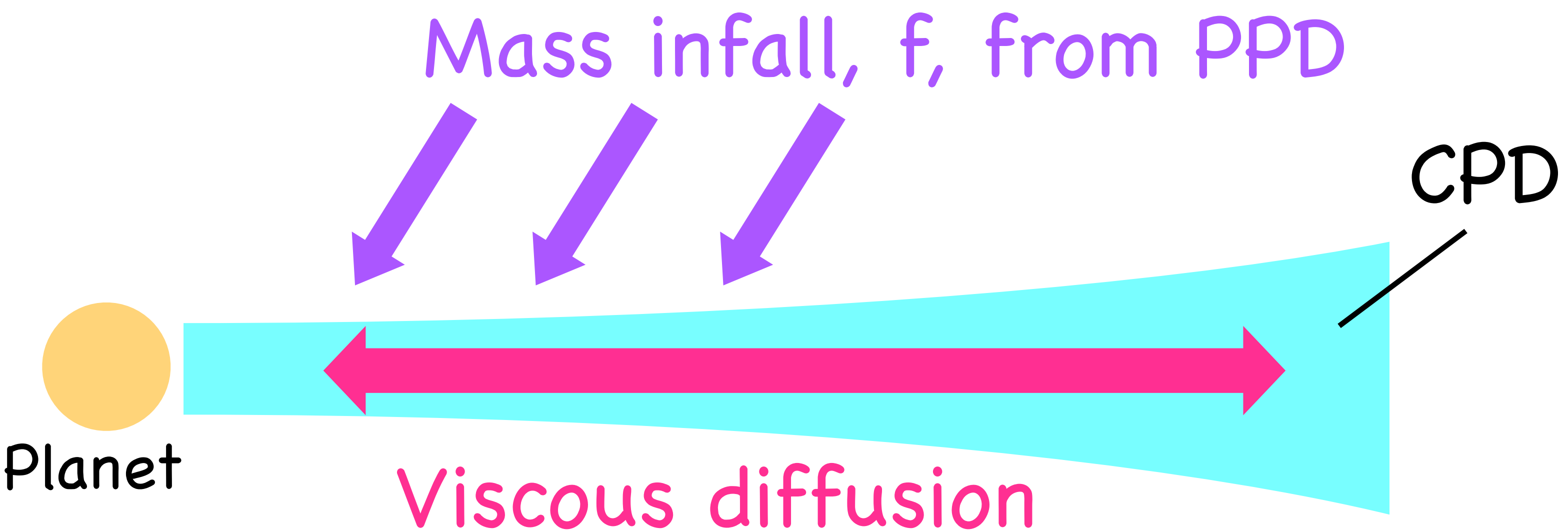
$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(3r^{\frac{1}{2}}\frac{\partial}{\partial r}\left(r^{\frac{1}{2}}\nu\Sigma\right)\right) + f$$



Surface Density

- Diffusion equation of disk with infall

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(3r^{\frac{1}{2}}\frac{\partial}{\partial r}\left(r^{\frac{1}{2}}\nu\Sigma\right)\right) + f$$



Surface Density

H: scale height of disk

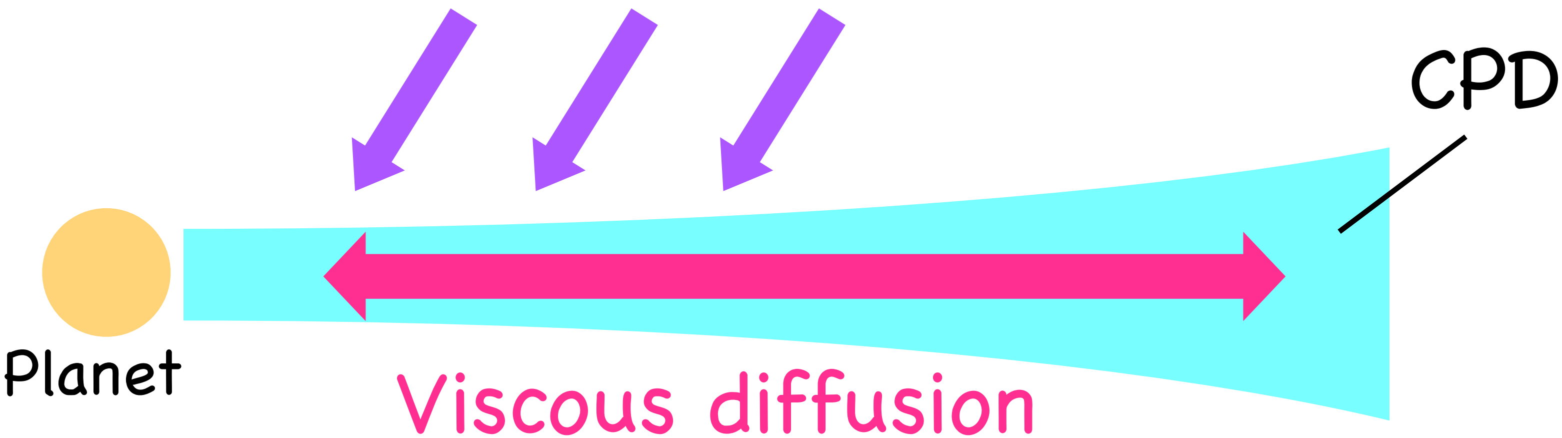
c_s: sound speed

- Diffusion equation of disk with infall

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(3r^{\frac{1}{2}}\frac{\partial}{\partial r}\left(r^{\frac{1}{2}}\nu\Sigma\right)\right) + f$$

$\nu = \alpha c_s H$

Mass infall, f, from PPD



Viscous diffusion

Settings

✦ Mass infall rate onto CPD (Tanigawa et al. 2012)

$$f = 1.3 \times 10^{-3} \left(\frac{\Sigma_{\rm p}}{143 \text{ g cm}^{-2}} \right) \left(\frac{R_{\rm J}}{r} \right) \text{ g cm}^{-2} \text{ s}^{-1}$$

Σ_0: surface density of PPD, r: radius of CPD, R_J: Jupiter radius

for r < $20R_J$ (=0.01AU), f(r>20RJ)=0

✦ Ionization model (Fujii et al. 2011)

- ionization source
  CRs, X-rays, Radionuclide
- dust-to-gas mass ratio: $f_{dg}=10^{-2}$

Condition of MRI Growth

MRI-active region :

$Re_m > 1$ (Re_m: Magnetic Reynolds number)

and

$H > \lambda_{max}$ $(= 2\pi v_{Az}/\Omega)$

H: scale height of disk

λ_{max}:wave length of most unstable mode

v_{Az}: Alfvén velocity (z component)

Ω: Keplerian frequency

Ionization degree & MRI

MRI-active : $Re_m > 1$

$$Re_\mathrm{m} = \frac{v_\mathrm{Az}^2}{\eta\Omega}$$

v_{Az}: Alfvén velocity (z component)
η : Magnetic diffusion coefficient
Ω: Keplerian frequency

$$\eta = 234 \left(\frac{T}{1\ \mathrm{K}}\right)^{1/2} x_\mathrm{e}^{-1}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$

x_e: Ionization degree
T: Temperature

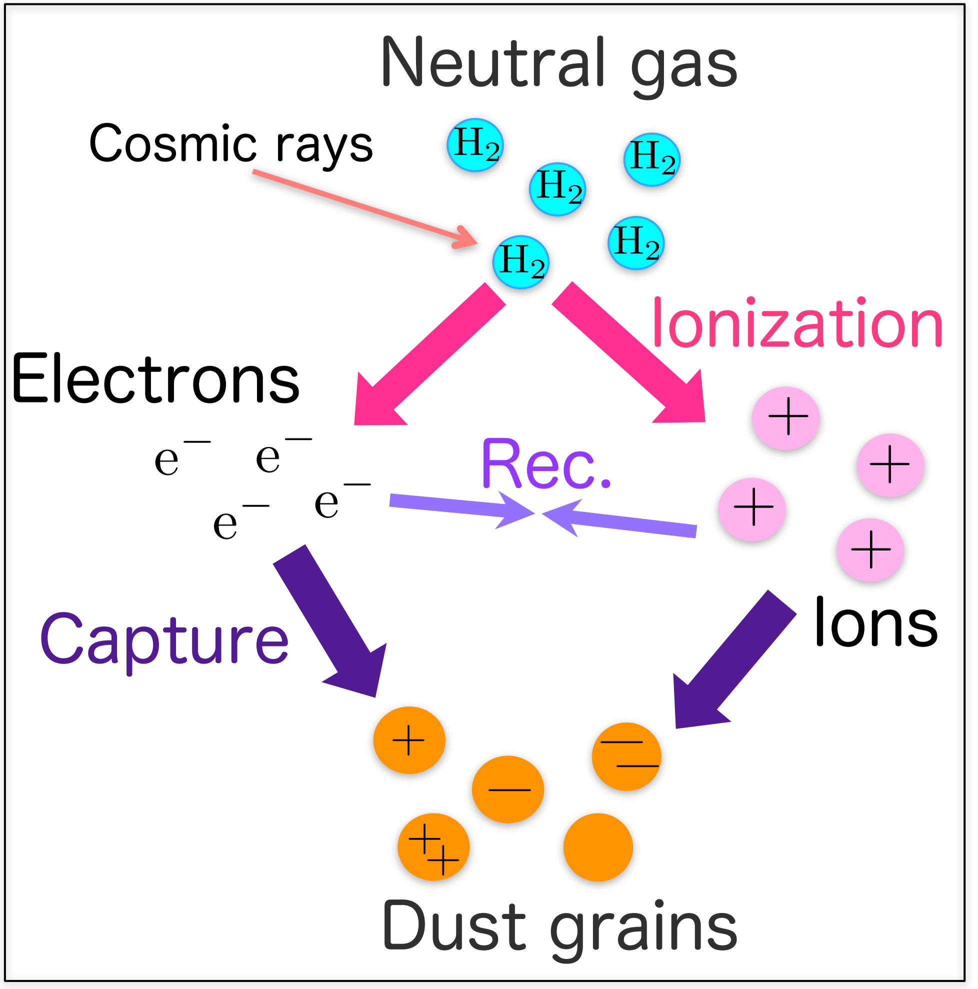
(Blaes & Balbus 1994)

Calculate! (Fujii et al. 2011)

Chemical Reaction Network

- Neutral gas is ionized by ionization source
- Ions and electrons are captured by grains
- Balance of these reactions determines the ionization degree

Complicated
⇒Difficult to calculate



Basic Equations

e : electron
M^+ : metal ion
d : dust grains
Z : charge of grains

$$\frac{dn_{\mathrm{M^+}}}{dt} = \zeta n_{\mathrm{n}} - \alpha_{\mathrm{M^+}} n_{\mathrm{M^+}} n_{\mathrm{e}} - \sum_Z k_{\mathrm{M^+d}}(Z) n_{\mathrm{d}}(Z) n_{\mathrm{M^+}}$$

$$\frac{dn_{\mathrm{e}}}{dt} = \zeta n_{\mathrm{n}} - \alpha_{\mathrm{M^+}} n_{\mathrm{M^+}} n_{\mathrm{e}} - \sum_Z k_{\mathrm{ed}}(Z) n_{\mathrm{d}}(Z) n_{\mathrm{e}}$$

$$\frac{dn_{\mathrm{d}}(Z)}{dt} = -k_{\mathrm{M^+d}}(Z) n_{\mathrm{d}}(Z) n_{\mathrm{M^+}} - k_{\mathrm{ed}}(Z) n_{\mathrm{d}}(Z) n_{\mathrm{e}} + k_{\mathrm{M^+d}}(Z-1) n_{\mathrm{d}}(Z-1) n_{\mathrm{M^+}} + k_{\mathrm{ed}}(Z+1) n_{\mathrm{d}}(Z+1) n_{\mathrm{e}}$$

$\alpha_{\mathrm{M^+}}, k_{\mu\mathrm{d}}(Z)$: Rate coefficients

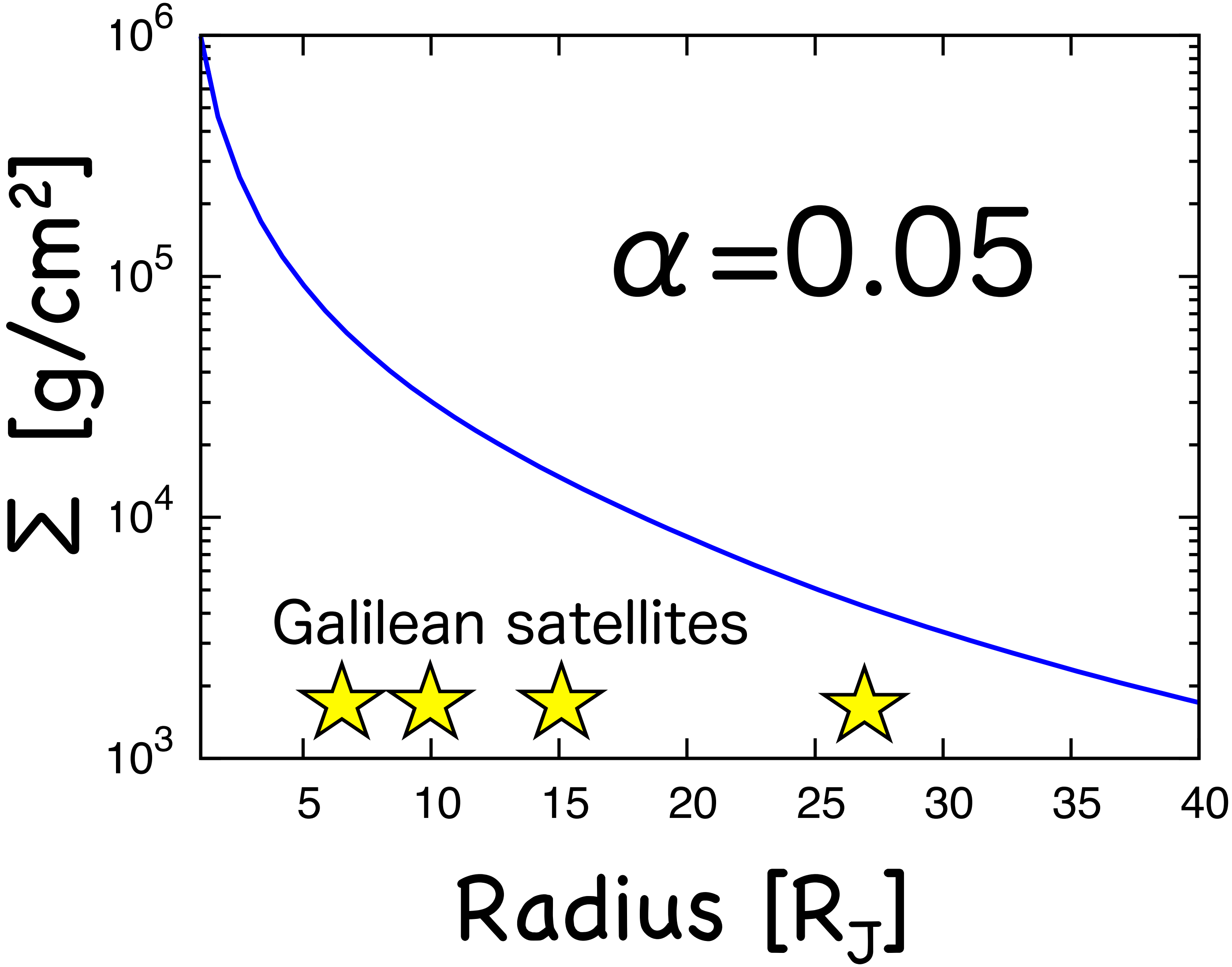
ζ : Ionization rate

|Z| is large ⇒ So many equations !

Solve quickly and accurately ⇒ Fujii + (2011)

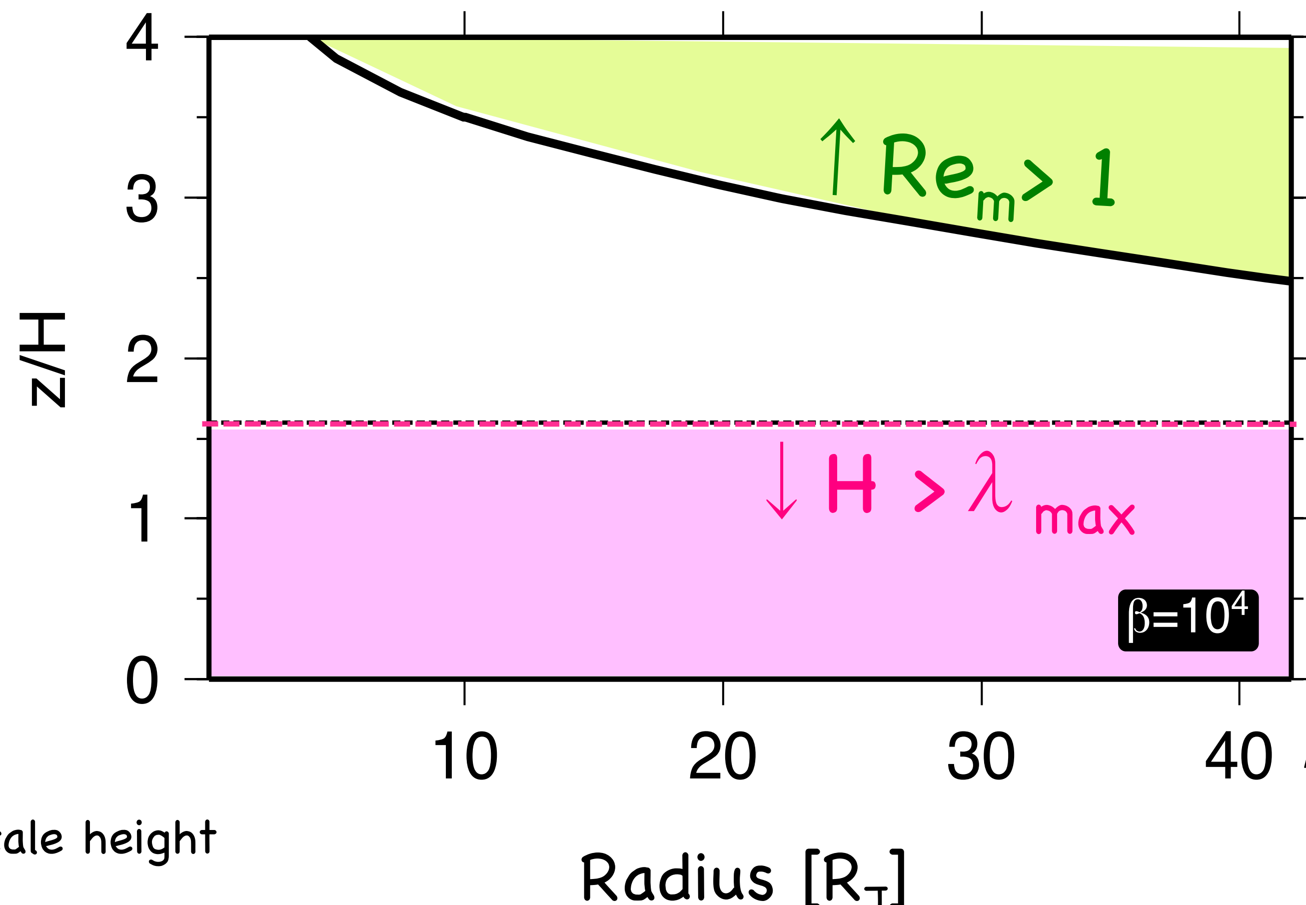
Results

Surface density (f: 100%)



Infall rate f: 100%

$Re_m > 1$ & $H > \lambda_{max}$ ⇒ MRI-active region



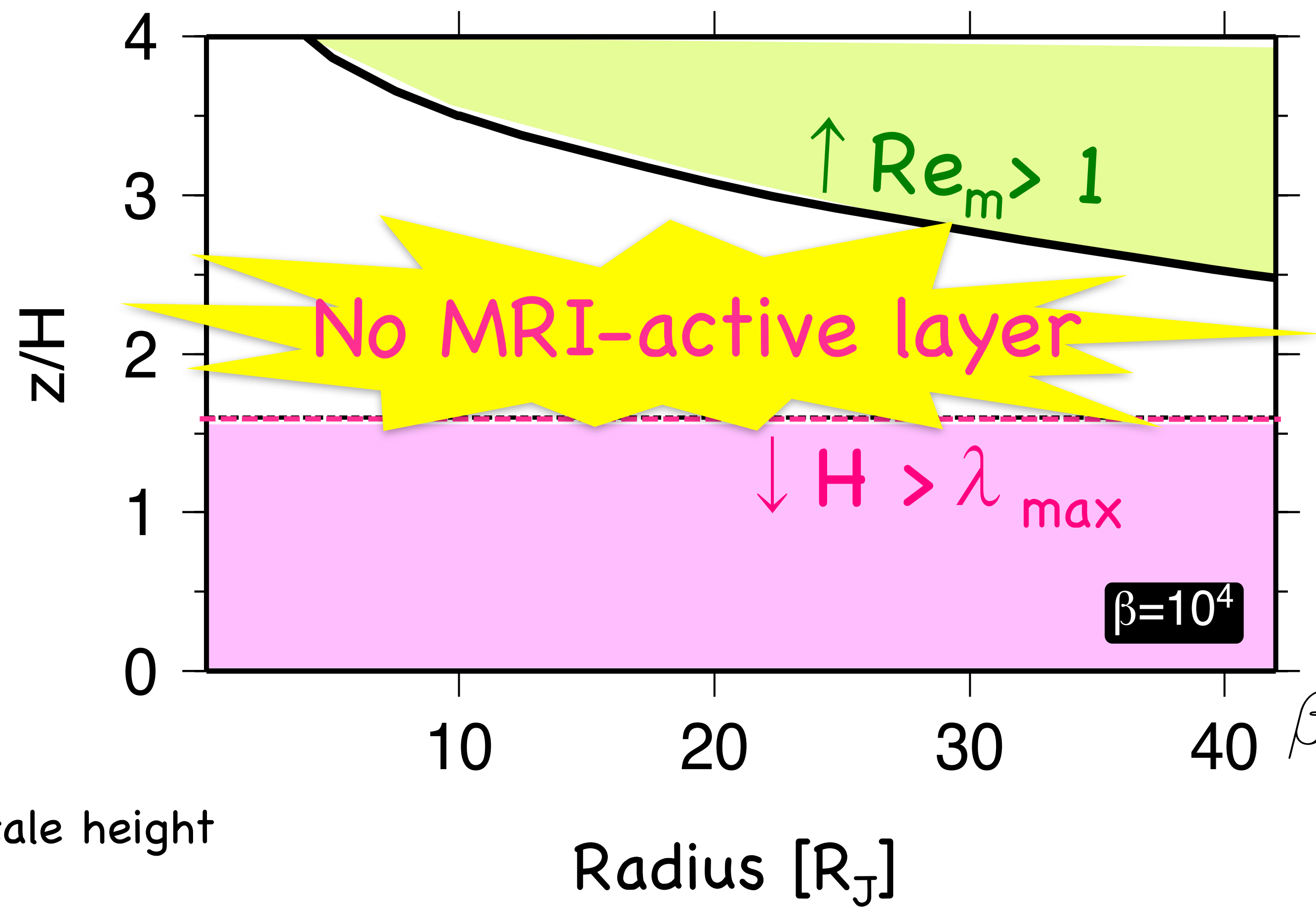
$$\beta = \frac{P_{\rm gas}}{P_{\rm mag}}$$

(Pressure)

H: disk scale height

Infall rate f: 100%

$Re_m > 1$ & $H > \lambda_{max}$ ⇒ MRI-active region



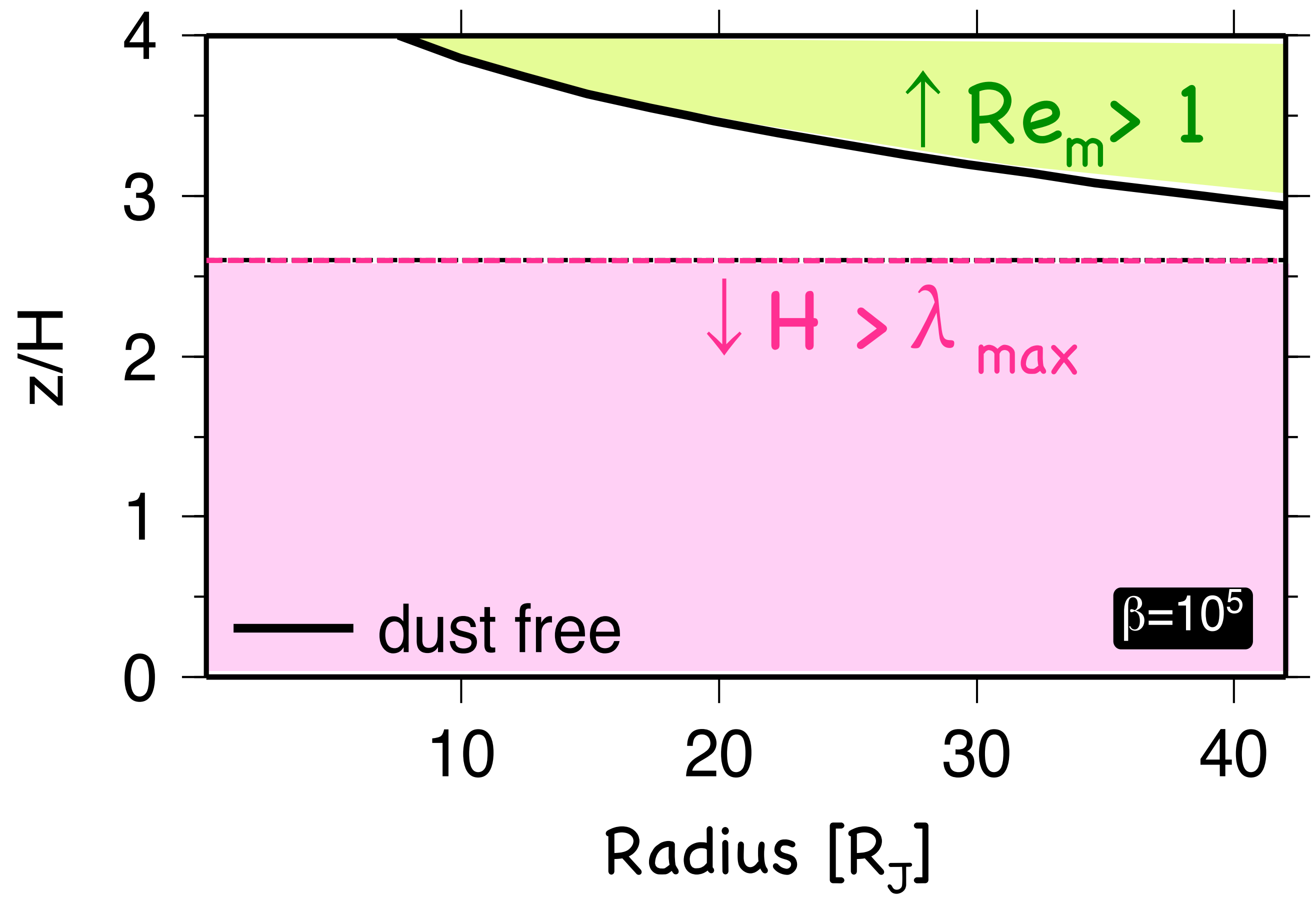
$$\beta = \frac{P_{gas}}{P_{mag}}$$

(Pressure)

H: disk scale height

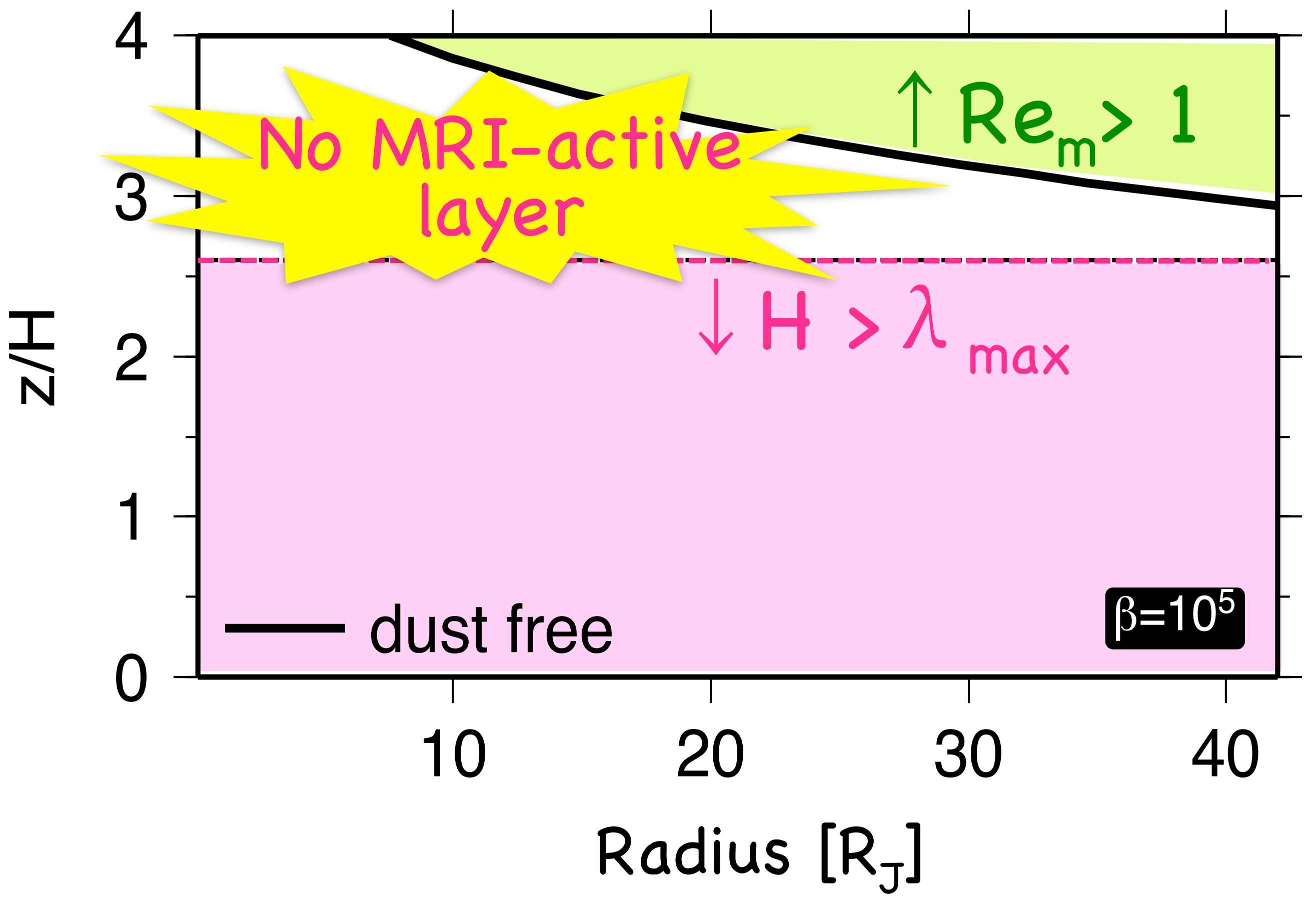
f: 100%, β =10^5

$Re_m > 1$ & $H > \lambda_{max}$ ⇒ MRI-active region

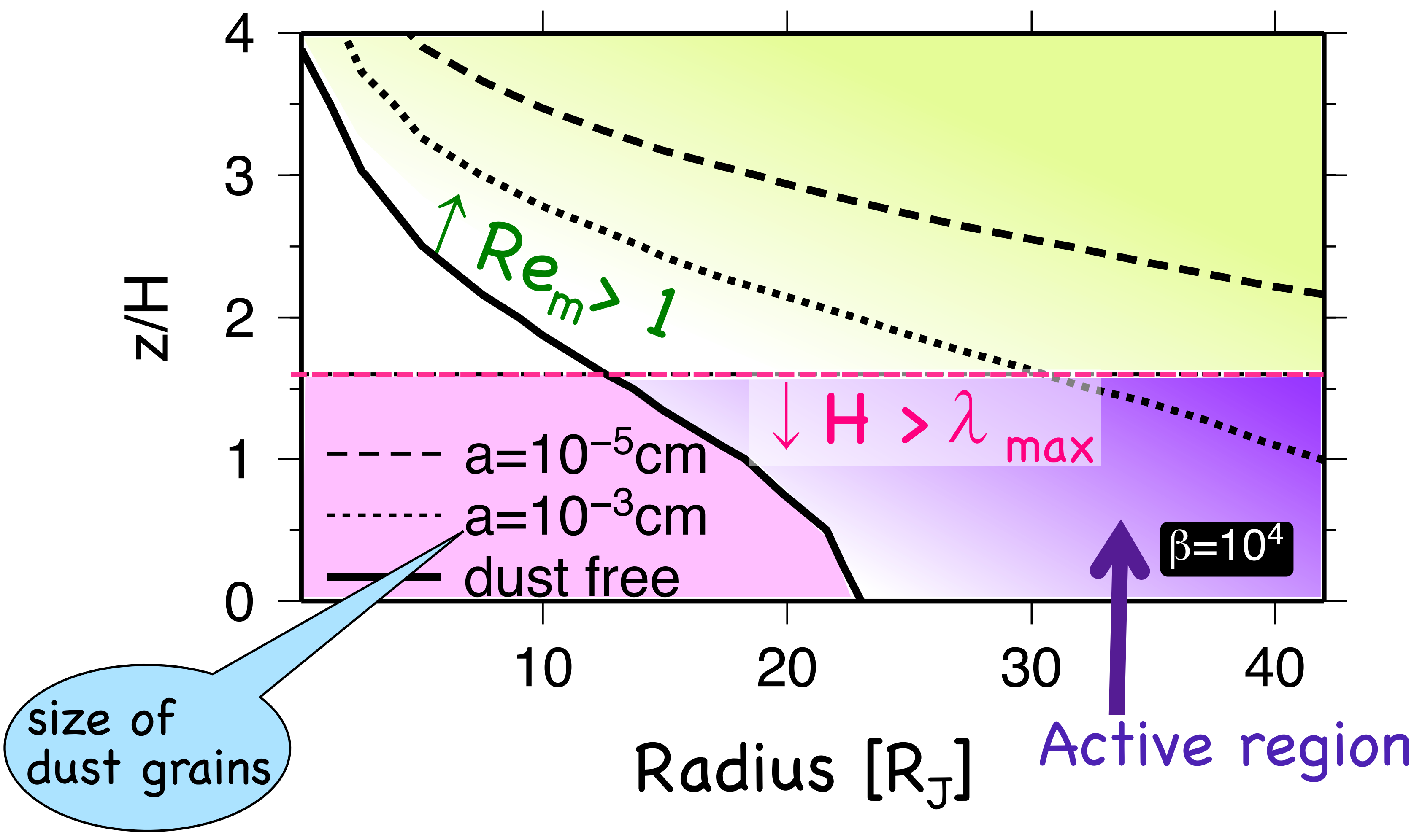


f: 100%, β =10^5

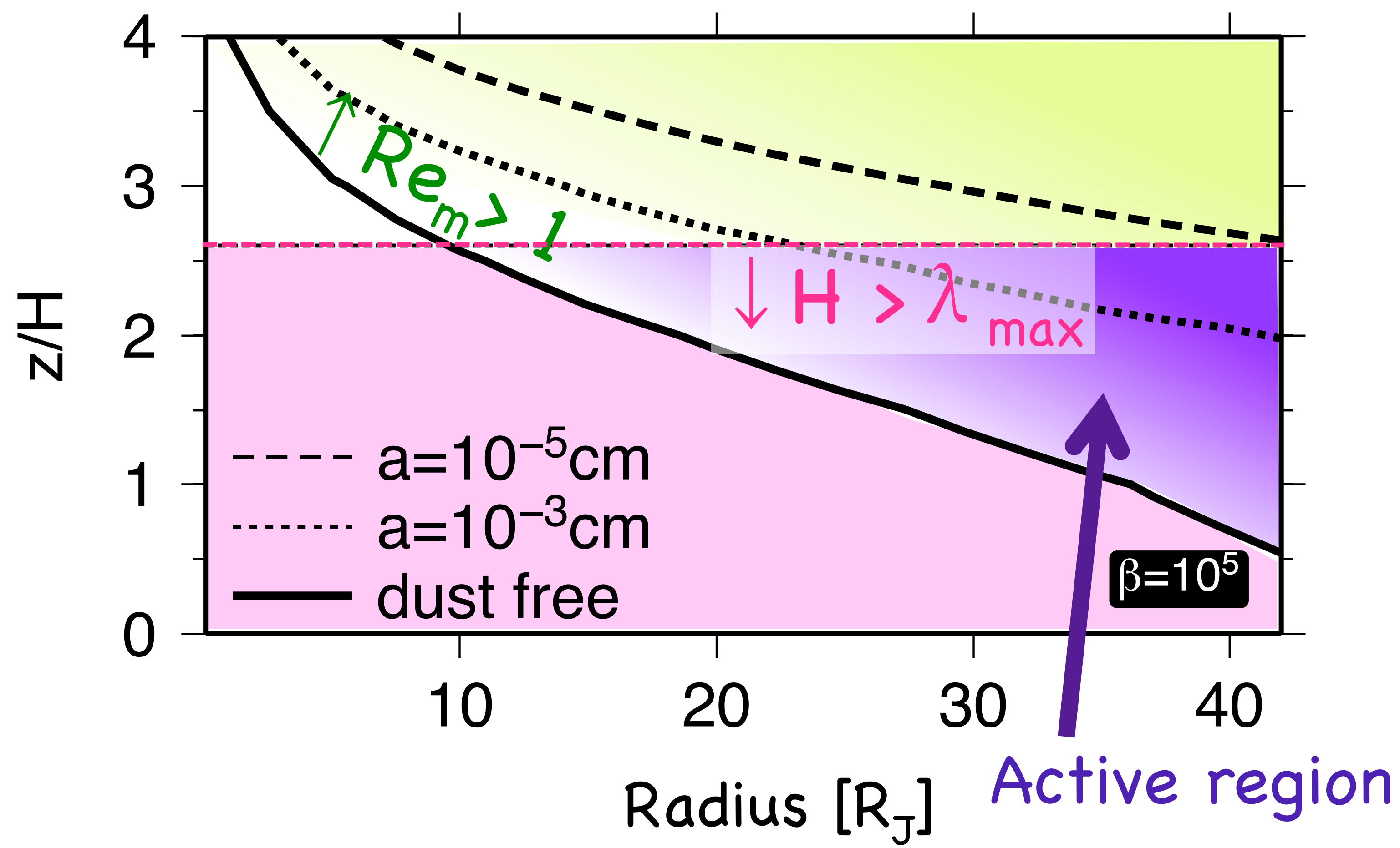
$Re_m > 1$ & $H > \lambda_{max}$ ⇒ MRI-active region



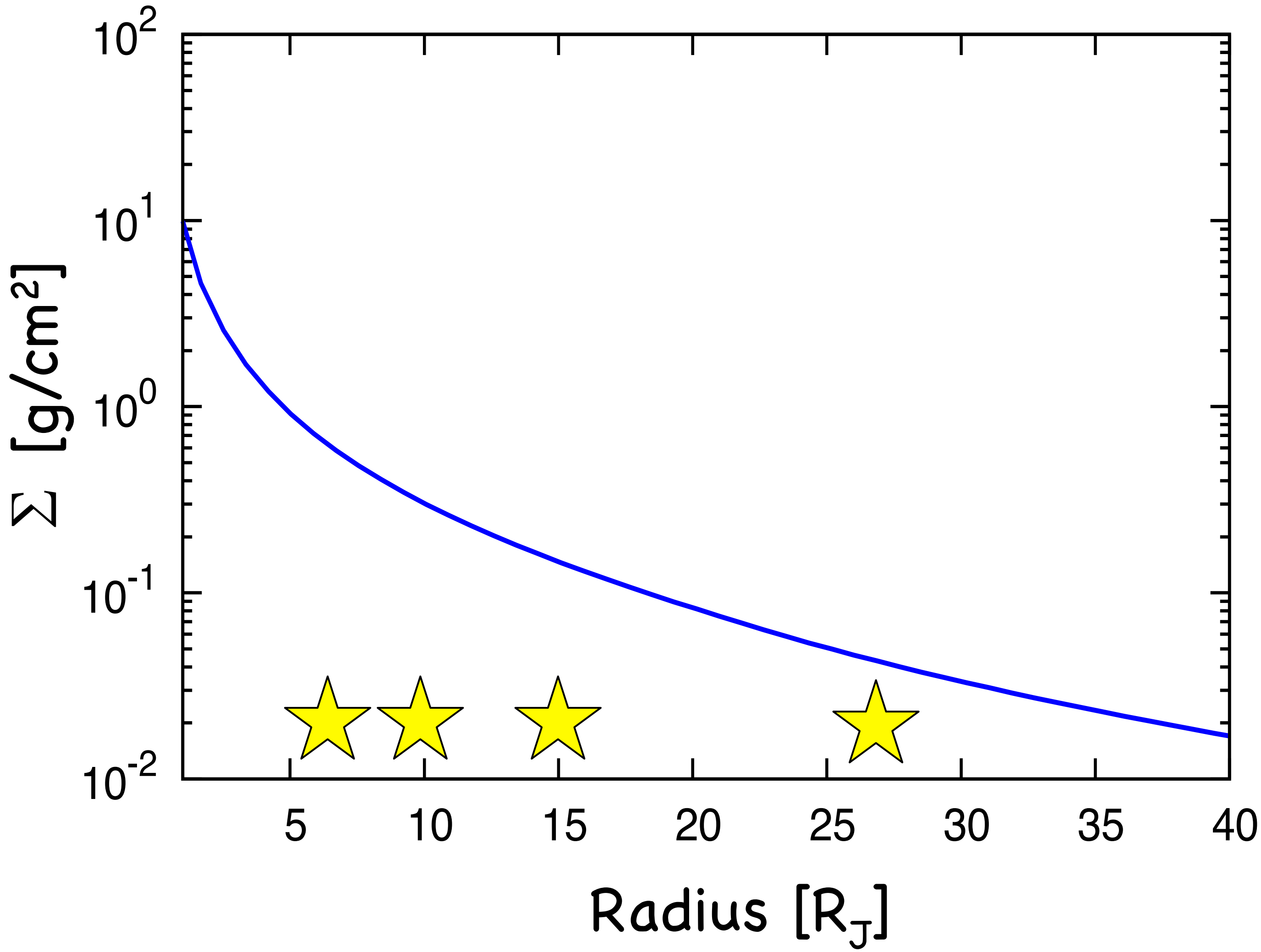
f: ×10^{-5}, $\beta = 10^4$



f: $\times 10^{-5}$, $\beta = 10^5$



Surface density (f: $\times 10^{-5}$)



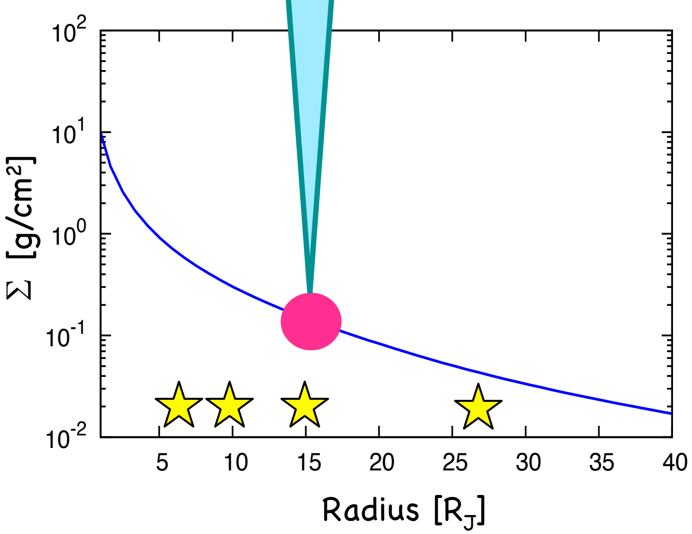
Surface density (f: $\times 10^{-5}$)

Satellite formation timescale (Lissauer & Stewrt 1993; Ward 1996)

$$\tau_A \approx 8\mathrm{yr} \left(\frac{R_s}{2500\ \mathrm{km}} \right) \left(\frac{3 \times 10^5\ \mathrm{g\ cm^{-2}}}{\Sigma} \right) \left(\frac{r}{15 R_J} \right)^{3/2}$$

10^7yr

$$\Sigma \sim 0.1\mathrm{g\ cm}^{-2}$$



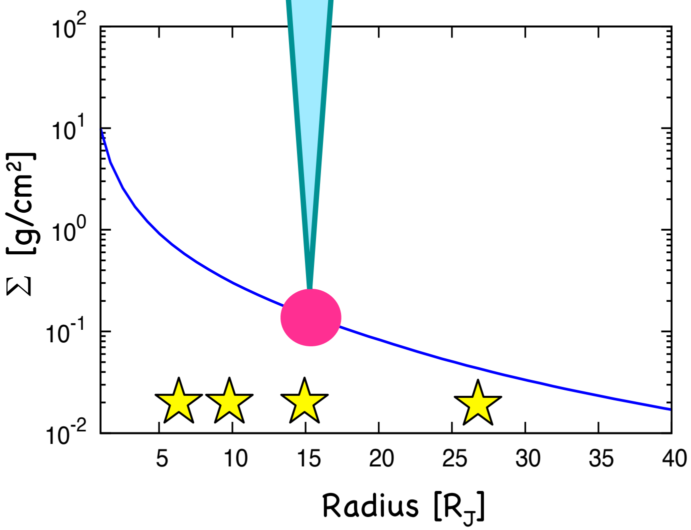
Surface density (f: $\times 10^{-5}$)

Satellite formation timescale (Lissauer & Stewrt 1993; Ward 1996)

$$\tau_{\rm A} \approx 8{\rm yr} \left(\frac{R_{\rm s}}{2500\ {\rm km}}\right)\left(\frac{3\times 10^5\ {\rm g\ cm^{-2}}}{\Sigma}\right)\left(\frac{r}{15 R_{\rm J}}\right)^{3/2}$$

↑ 10^7yr

$\Rightarrow \Sigma \sim 0.1{\rm g\ cm^{-2}}$



Satellite formation not realistic for reduced infall rates

Why so little MRI?

$$Re_{\rm m} = \frac{v_{\rm Az}^2}{\eta\Omega} \sim \frac{2c_s^2}{\eta\beta\Omega}$$

c_s: sound speed

η : magnetic diffusivity

β : plasma beta

Ω: Keplerian frequency

Protoplanetary disk@5AU

Circumplanetary disk@15R_J

Why so little MRI?

$$Re_{\rm m} = \frac{v_{\rm Az}^2}{\eta\Omega} \sim \frac{2c_s^2}{\eta\beta\Omega}$$

c_s: sound speed
η : magnetic diffusivity
β : plasma beta
Ω: Keplerian frequency

Protoplanetary disk@5AU

$x_e \cong 4\times10^{-10}$

Circumplanetary disk@15R_J

$x_e \cong 3\times10^{-10}$

Why so little MRI?

$$Re_{\rm m} = \frac{v_{\rm Az}^2}{\eta\Omega} \sim \frac{2c_s^2}{\eta\beta\Omega}$$

c_s: sound speed
η : magnetic diffusivity
β : plasma beta
Ω: Keplerian frequency

Protoplanetary disk@5AU

$x_e \cong 4\times10^{-10}$

$\Omega \cong 2\times10^{-8}\ s^{-1}$

Circumplanetary disk@15R_J

$x_e \cong 3\times10^{-10}$

$\Omega \cong 1\times10^{-5}\ s^{-1}$

Why so little MRI?

$$Re_{\rm m} = \frac{v_{\rm Az}^2}{\eta\Omega} \sim \frac{2c_s^2}{\eta\beta\Omega}$$

c_s: sound speed
η : magnetic diffusivity
β : plasma beta
Ω: Keplerian frequency

Protoplanetary disk@5AU

$x_e \cong 4\times10^{-10}$

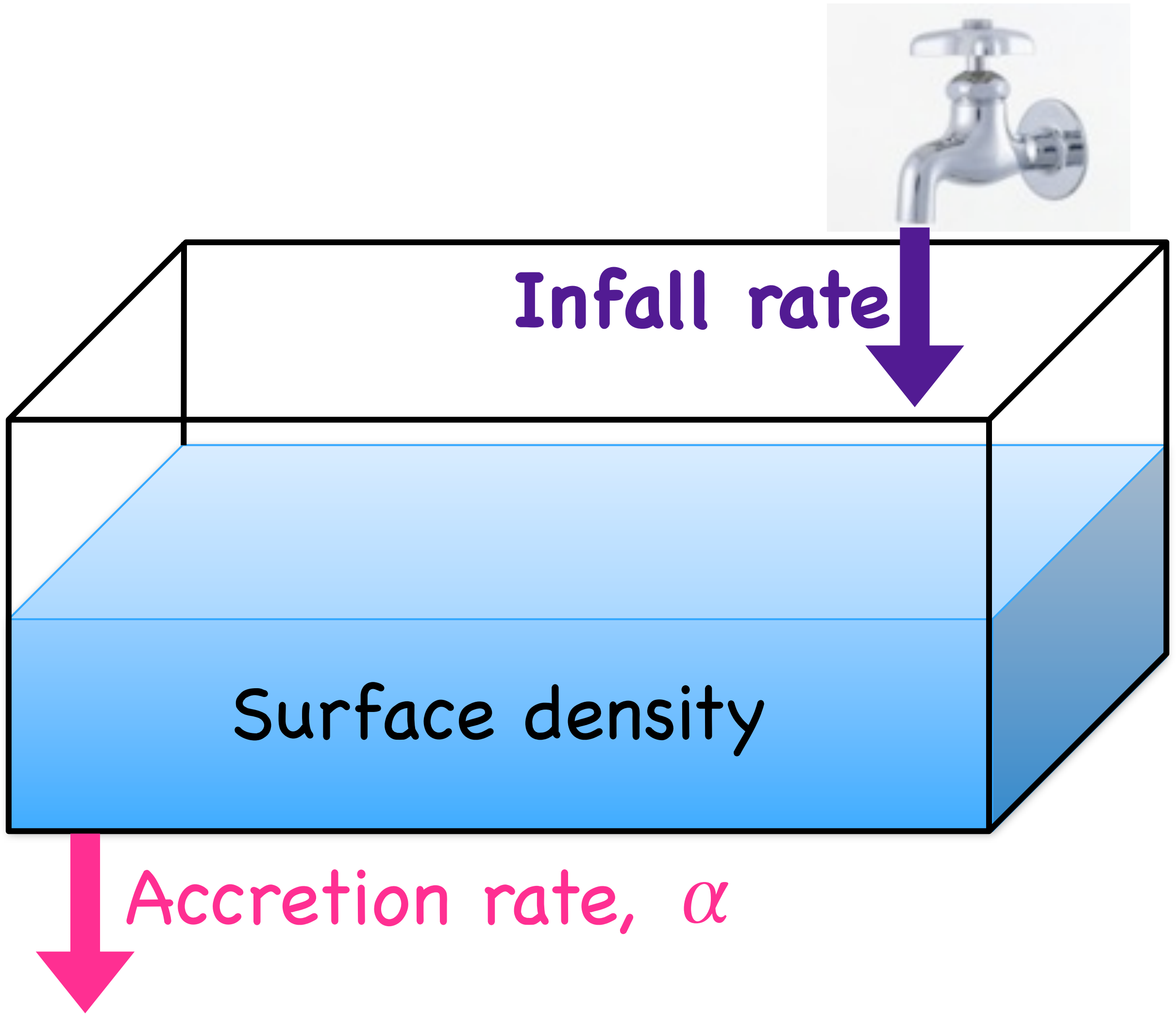
$\Omega \cong 2\times10^{-8}\ s^{-1}$

Circumplanetary disk@15R_J

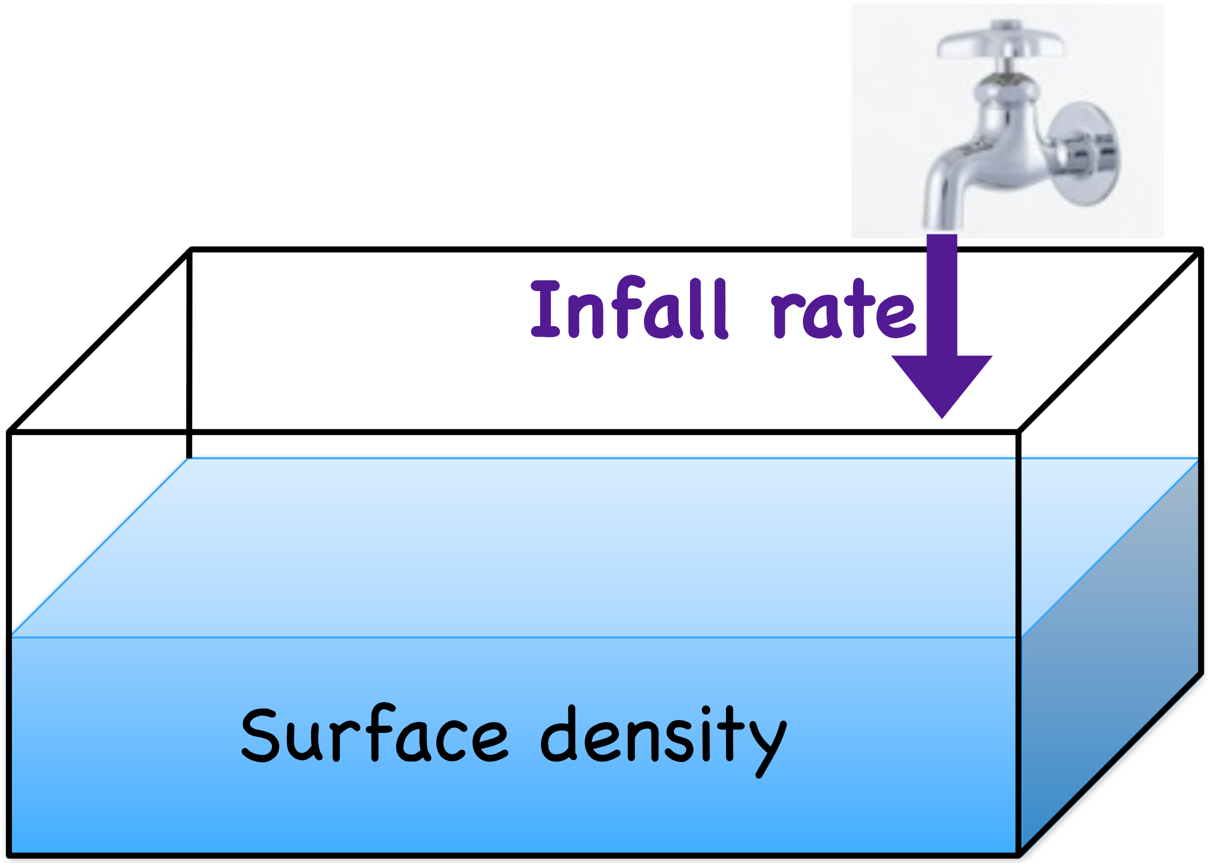
$x_e \cong 3\times10^{-10}$

$\Omega \cong 1\times10^{-5}\ s^{-1}$

3 orders of magnitude!



Infall rate
Surface density
Accretion rate, α


Infall rate
Surface density

Gravitational Instability

Toomre parameter

$$Q = \frac{c_s \Omega}{\pi G \Sigma}$$

Pressure
Rotation

Gravity

c_s : Sound speed

G : Gravitational constant

Σ : Surface density

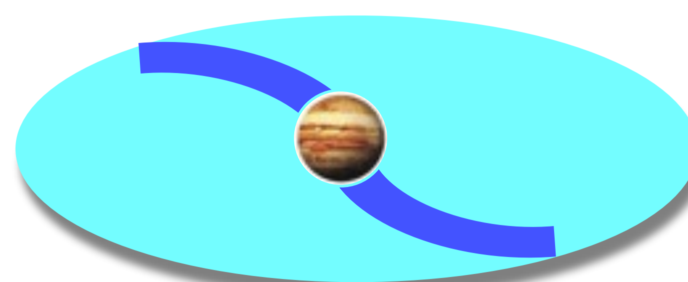
$1 < Q < 2$

⇒ spiral arms

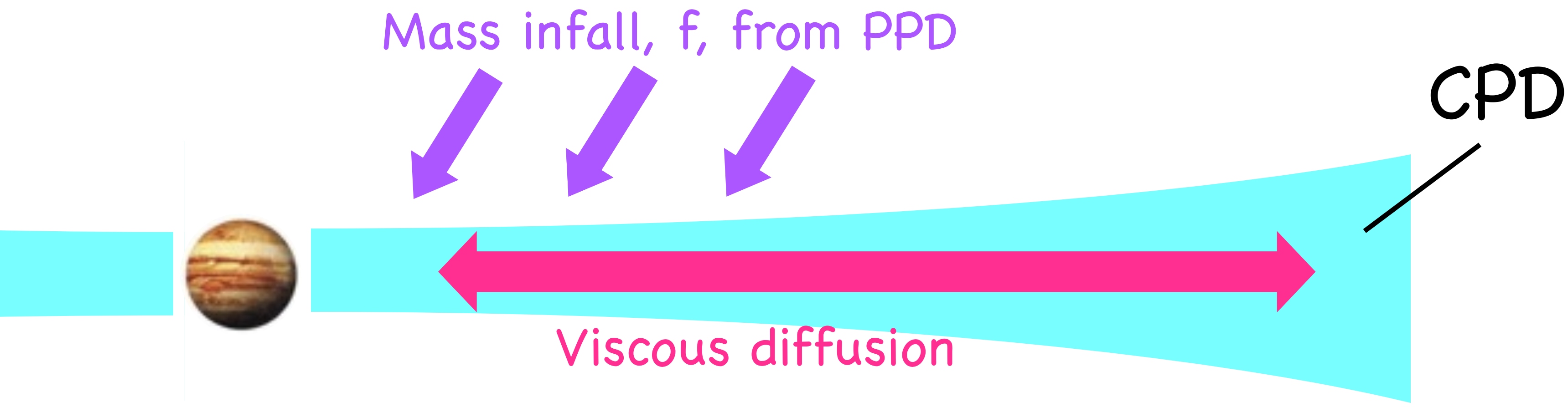
⇒ effective viscosity

$$\alpha_{\mathrm{eff}} = \exp\left(Q^{-4}\right)$$

Takahashi et al. (2013)



重力不安定を考慮して再計算



mass infall rate

$$f = 1.3 \times 10^{-3} \left(\frac{\Sigma_{\rm p}}{143 \ {\rm g \ cm^{-2}}} \right) \left(\frac{R_{\rm J}}{r} \right) \ {\rm g \ cm^{-2} \ s^{-1}}$$

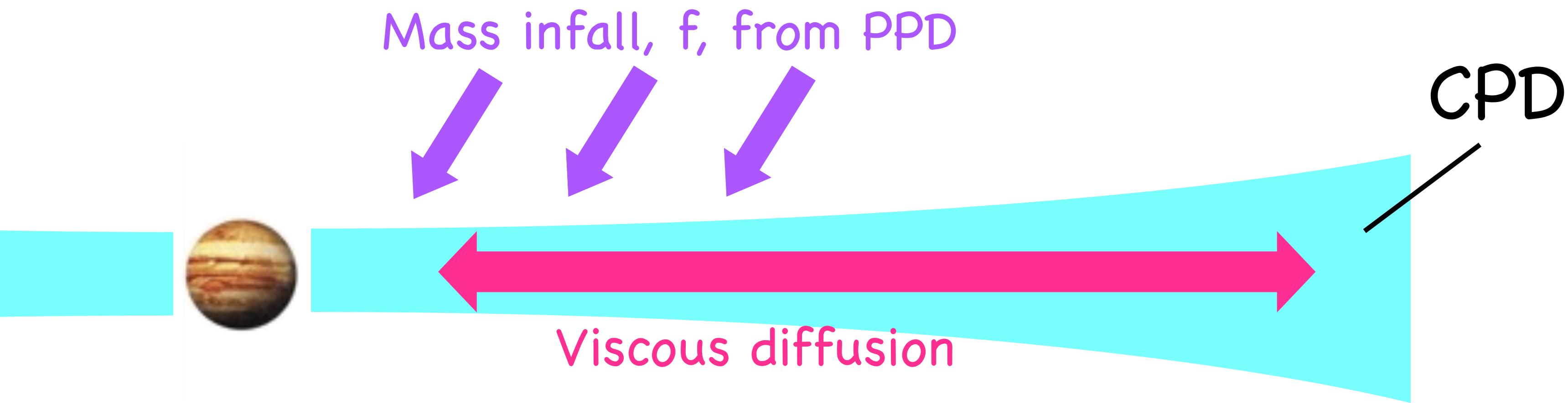
(Tanigawa et al. 2012)

Σ_0: surface density of PPD, R_J: Jupiter radius

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(3 r^{\frac{1}{2}} \frac{\partial}{\partial r} \left(r^{\frac{1}{2}} \nu \Sigma \right) \right) + f$$

calculate surface density

重力不安定を考慮して再計算



mass infall rate

$$f = 1.3 \times 10^{-3} \left(\frac{\Sigma_{\rm p}}{143 \ {\rm g} \ {\rm cm}^{-2}} \right) \left(\frac{R_{\rm J}}{r} \right) \ {\rm g} \ {\rm cm}^{-2} \ {\rm s}^{-1}$$

(Tanigawa et al. 2012)

Σ_0: surface density of PPD, R_J: Jupiter radius

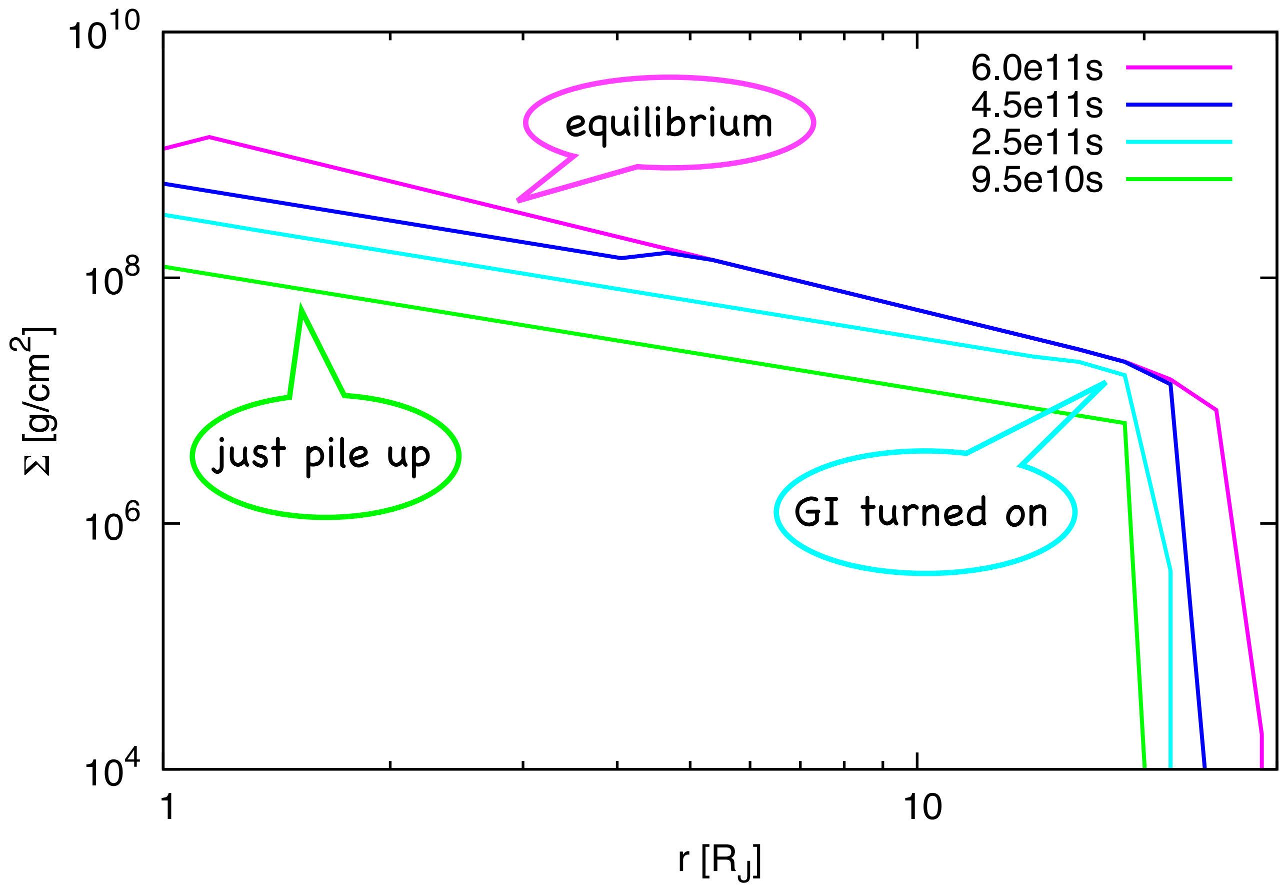
$\nu = \alpha c_s H$

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(3 r^{\frac{1}{2}} \frac{\partial}{\partial r} \left(r^{\frac{1}{2}} \nu \Sigma \right) \right) + f$$

calculate surface density

面密度分布

Surface density evolution of CPD
with Gravitational Instability (GI)

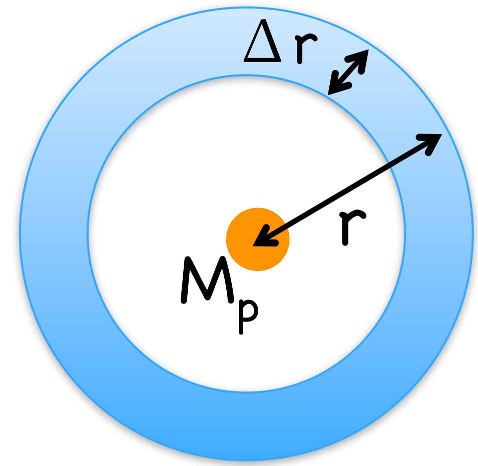


Viscous Heating

Gravitational energy ⇒ Heating

$$\frac{GM_p\dot{M}}{r^2}\Delta r = 2\sigma T^4(2\pi r\Delta r)$$

σ : Stefan-Boltzmann constant



$$T_{\rm vis} = \left(\frac{GM_p\dot{M}}{4\pi\sigma r^3}\right)^{1/4}$$

mid-plane temperature

$$T_c = \left(1 + \frac{3\tau}{8}\right)^{1/4} T_{\rm vis}$$

If mid-plane temperature exceed 1000K, thermal ionization kicked on MRI

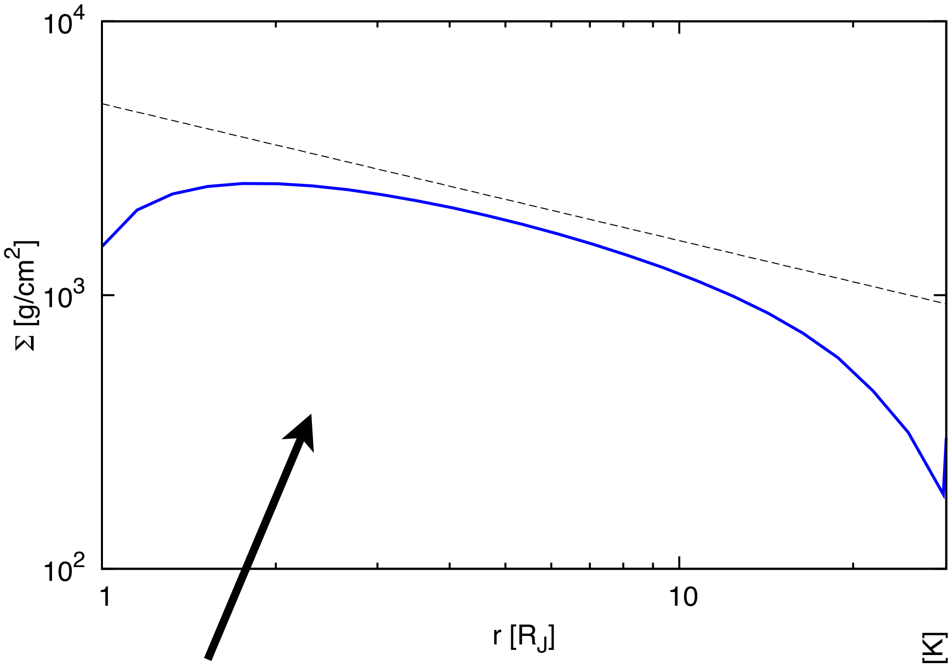
τ : optical depth
κ : opasity

$$\tau \sim \kappa\Sigma$$

κ = 5cm^2/g   160 < T < 1350
κ = 10^{-4}cm^2/g   T > 1350K   (Pollack et al. 1994)

熱電離も考慮

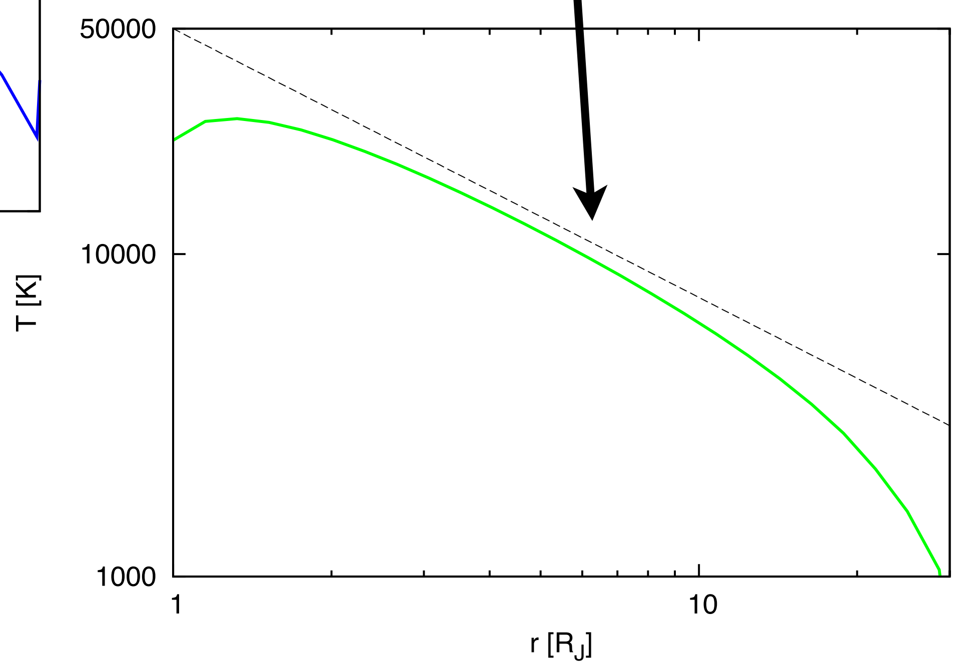
Surface density evolution with thermal ionization



mid-plane temperature
easily exceed 1000K

N.B. opacity at 1000K (ϰ=5cm^2/g) is used

$$T \propto (\dot{M}/r^3)^{1/4}\Sigma^{1/4} \propto r^{-5/6}$$



thermal ionization: α_{MRI}=0.01

$$\dot{M} = 3\pi\nu\Sigma \propto T\Sigma/\Omega$$

steady state:

$$\Sigma \propto \Omega/T \propto r^{-1/2}$$

まとめ

- 角運動量輸送の有力候補であるMRIが周惑星円盤で起こるかどうか調べた
- 非熱的電離ではMRIは期待できない
- 他に降着メカニズムがないと重力不安定によるスパイラル波で角運動が輸送される
- 粘性加熱で熱電離によるMRIが駆動される
- 加熱源は必ずしも重力不安定に限られない

e.g. 恒星からのトルク Rivier et al. (2013) $\dot{M}_p \approx 2 \times 10^{-7}\ M_{\rm Jup}/{\rm yr}$