Formation of Dynamically Distinct Satellite Systems of Jupiter and Saturn

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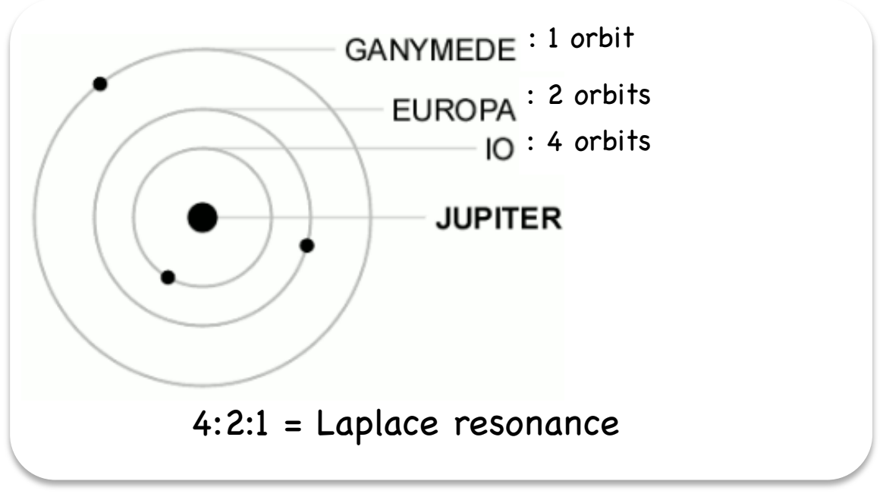
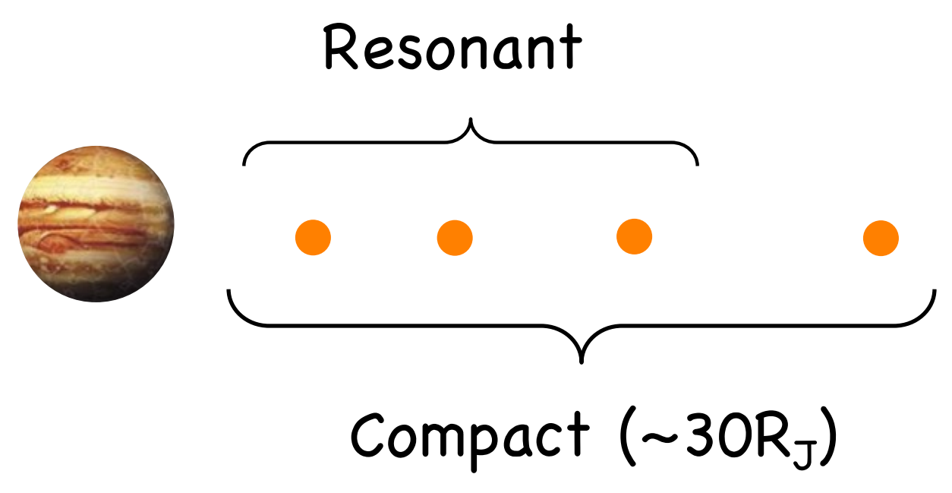
1. What makes difference of two systems?

Jupiter: 4 Galilean moons

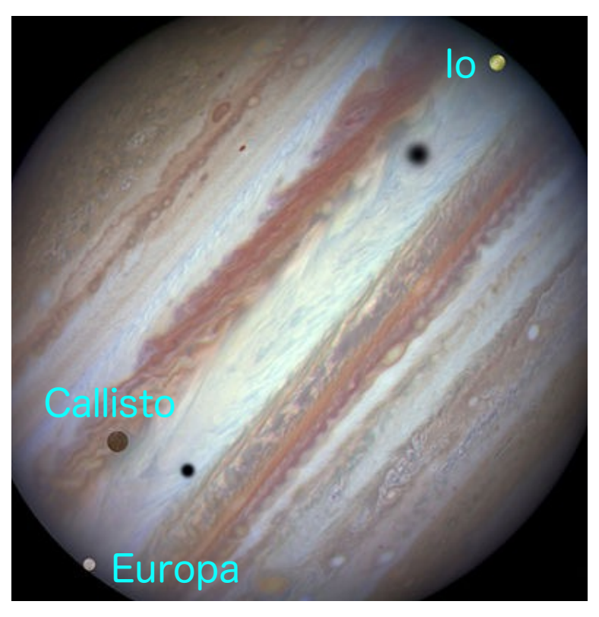
Io, Europa, Ganymede, Callisto

4:2:1 mean motion resonance

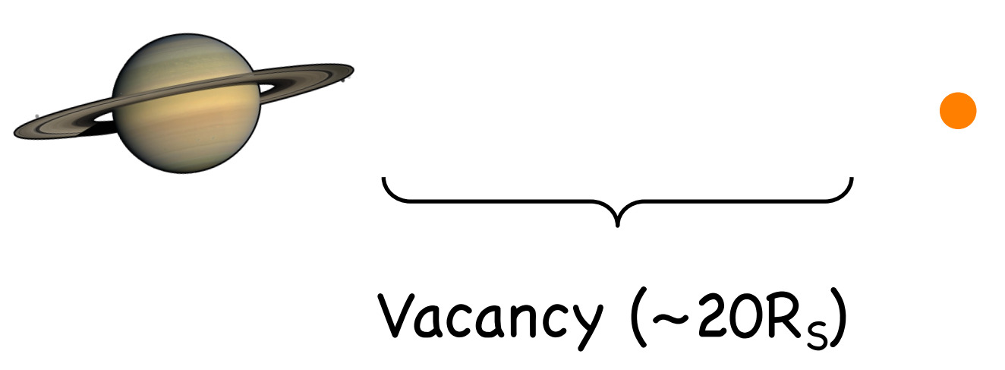


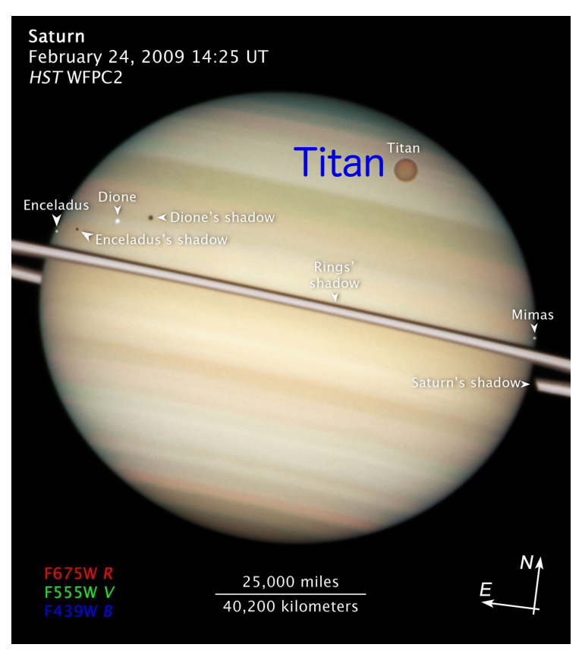


cf. Mercury's orbit: 0.4au
1au = 215R_{sun}



Saturn: Single large moon, Titan





2. What determines final configuration?

- Direction and speed of satellite migration:
  → Depend on radial dependence of disk surface density and temperature
- Timing of disk dissipation

Orbital migration of moons

$$\frac{dr}{dt} = \beta\,(1+0.04K)^{-1}\frac{M_m}{M_p}\frac{\Sigma r^2}{M_p}\left(\frac{r\Omega_K}{c_s}\right)^2 r\Omega_K$$

(e.g., Paardekooper et al. 2011)

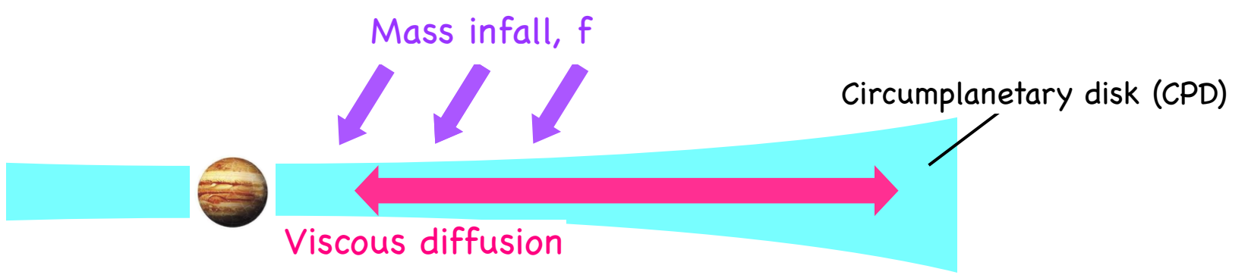
$$\Sigma \propto r^{-p}$$
$$T \propto r^{-q}$$

β: migration parameter (function of p and q)
M_m: mass of moon (Ganymede or Callisto)
M_p: mass of planet
Ω_K: Keplerian frequency
$K=(M_m/M_p)^2(H/r)^{-5}\alpha^{-1}$ (Kanagawa+ 2015, 2018; Ogihara & Hori 2019)

We model dissipating circumplanetary disks (CPDs)

1) First, obtain steady state

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



$f \propto r^{-1}$ (Based on Tanigawa et al. 2012)

$$\frac{\partial T_c}{\partial t} = \frac{2(Q_+ - Q_-)}{c_p\Sigma} - v_r\frac{\partial T_c}{\partial r}$$

$Q_+ = (9/8)\nu\Sigma\Omega^2$: viscous heating
$Q_- = \sigma(3/8\kappa\Sigma)T_c^4$: radiative cooling

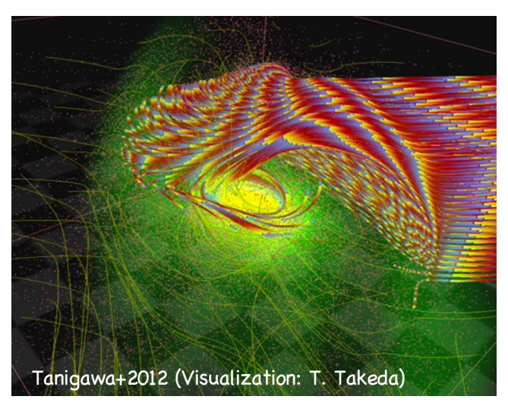
(Cannizzo 1993; Armitage+ 2001)

r : radius	T_c: midplane temperature
Σ: surface density	T_e: effective temperature
c_s: sound speed	C_p: specific heat
H: scale height	v_r: radial velicity
$\nu=\alpha c_s H$: viscous coefficient	κ: opacity (Bell & Lin 1994)
α: viscous parameter	

2) Then, reduce mass infall rate, f

$$f = \exp(-t/t_{\rm dissip})\,f_0\,r^{-1}$$

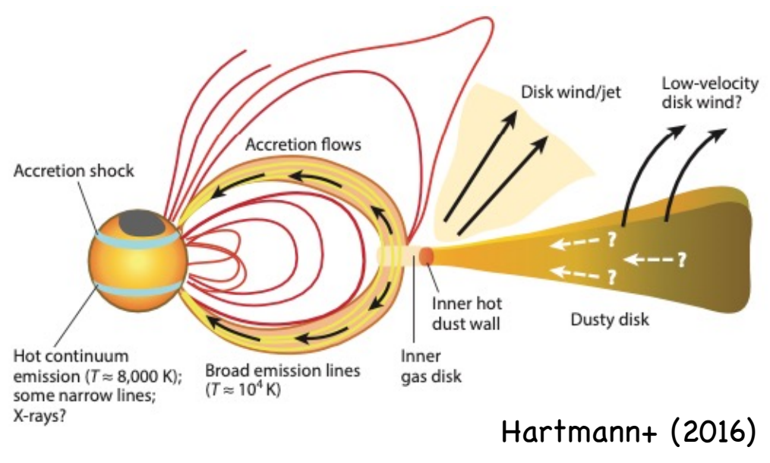
f_0 : infall rate of steady state, $t_{\rm dissip}=10^3$yr



Tanigawa+2012 (Visualization: T. Takeda)

3. Magnetospheric accretion?

Can this happen for circumplanetary disks?



Hartmann+ (2016)

Truncation Radius

$$R_t \sim \left(\frac{\pi^2}{2\mu_0}\frac{\mathcal{M}^4}{\mathcal{G}M\dot{M}^2}\right)^{1/7}$$

μ_0 : permeability
$\mathcal{G}$: grav. const.
M : planet mass
$\dot{M}$: accretion rate
$\mathcal{M} = B_s R^3$
B_s : mag. field
R : planet radius

Batygin (2018), Gosh & Lamb (1979), Ostriker & Shu (1995), Mohanty & Shu (2008)
See also Takasao et al. (2022)

Gas needs to be ionized enough to be coupled with magnetic fields

- Adopt $R_t \sim 4-5\,R_J$ with assuming B~500G. (Batygin 2018)
- Application to exoplanet (PDS70b/c) (Hasegawa+ 2021)

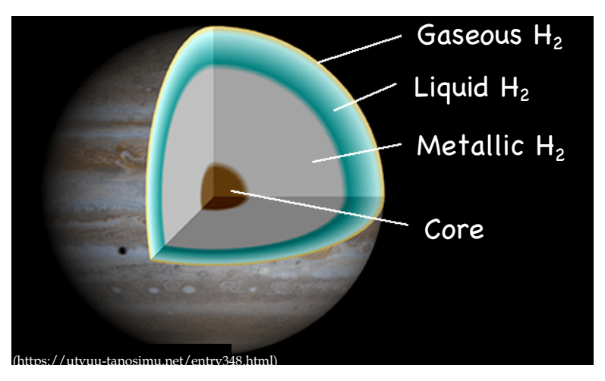
We calculate magnetic-fields strength on surfaces of Jupiter and Saturn

Generation of magnetic field by dynamo in metallic hydrogen region

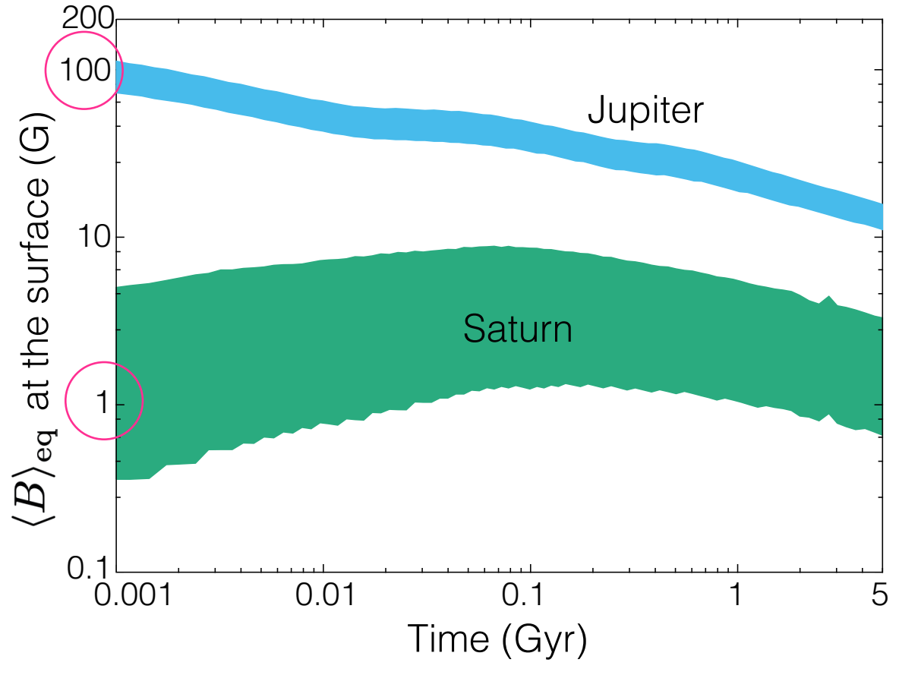
$$B^2/(2\mu_0) \propto f_{\rm ohm}\rho^{1/3}(q_c L/H_T)^{2/3}$$ (Christensen+ 2009)

$f_{\rm ohm}$: efficiency factor of energy conversion
q_0 : convective heat flux
L : length scale of the largest convective structures
H_T : temperature scale height

Inner structure of gas giants



Strength of magnetic field

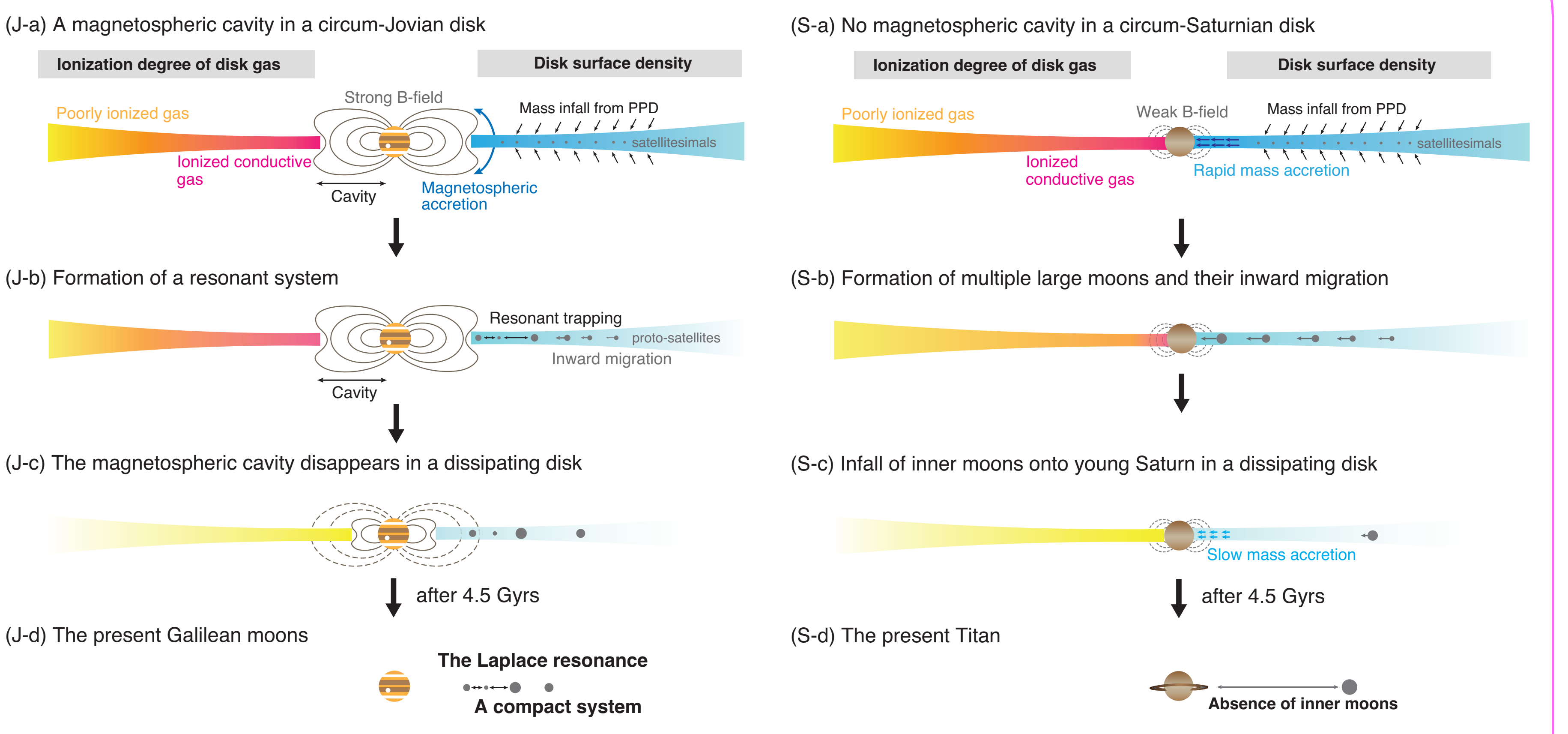


cf. Hori (2021)

Overview of Scenario

Jovian system

Saturnian system



(J-a) A magnetospheric cavity in a circum-Jovian disk

(J-b) Formation of a resonant system

(J-c) The magnetospheric cavity disappears in a dissipating disk

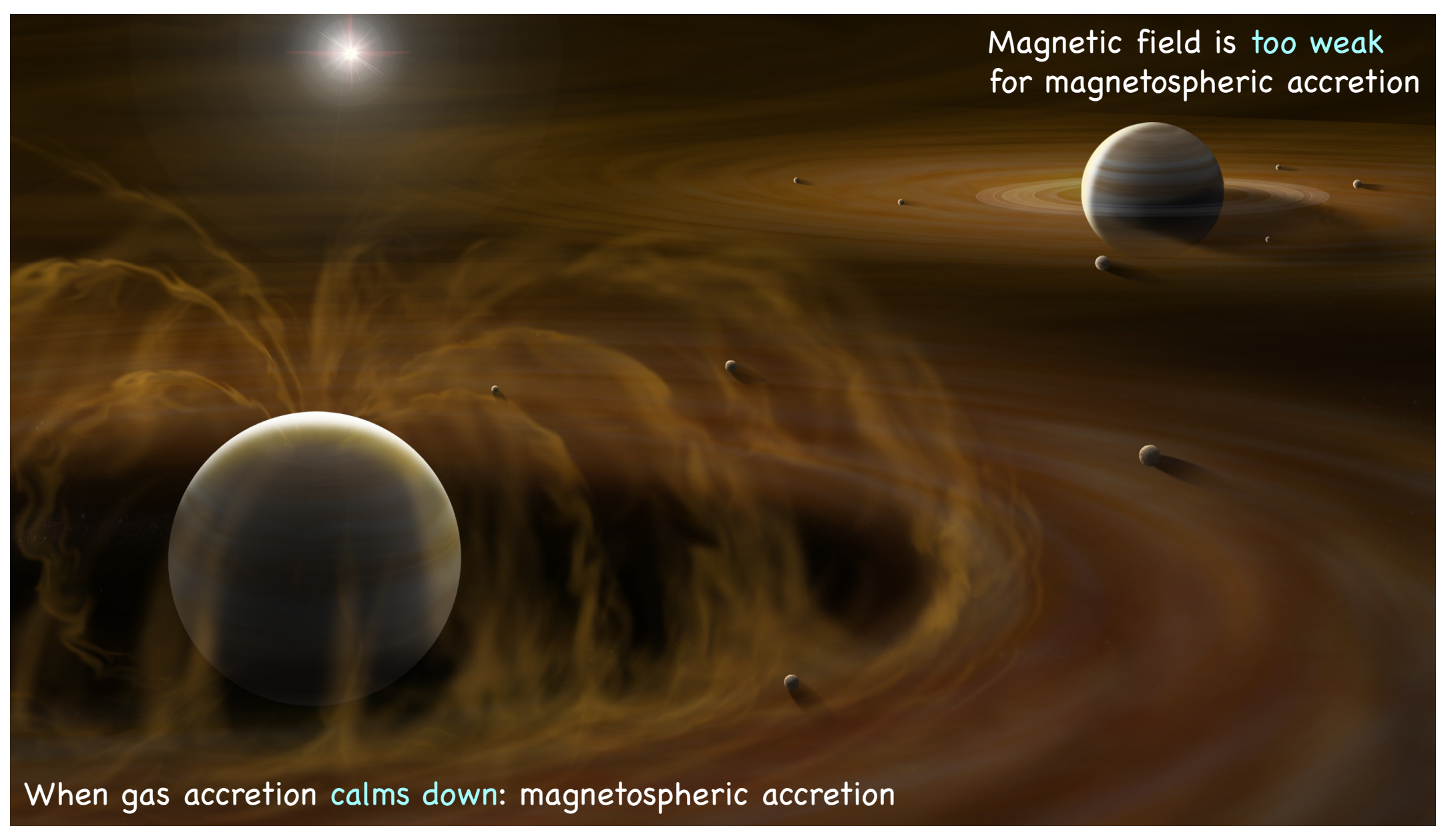
(J-d) The present Galilean moons

(S-a) No magnetospheric cavity in a circum-Saturnian disk

(S-b) Formation of multiple large moons and their inward migration

(S-c) Infall of inner moons onto young Saturn in a dissipating disk

(S-d) The present Titan



4. Evolutions of disk structure & moon orbits

Migrating moon can be stopped at disk structure, such as inner cavity

If one moon is stopped, next migrating one can be captured in resonance

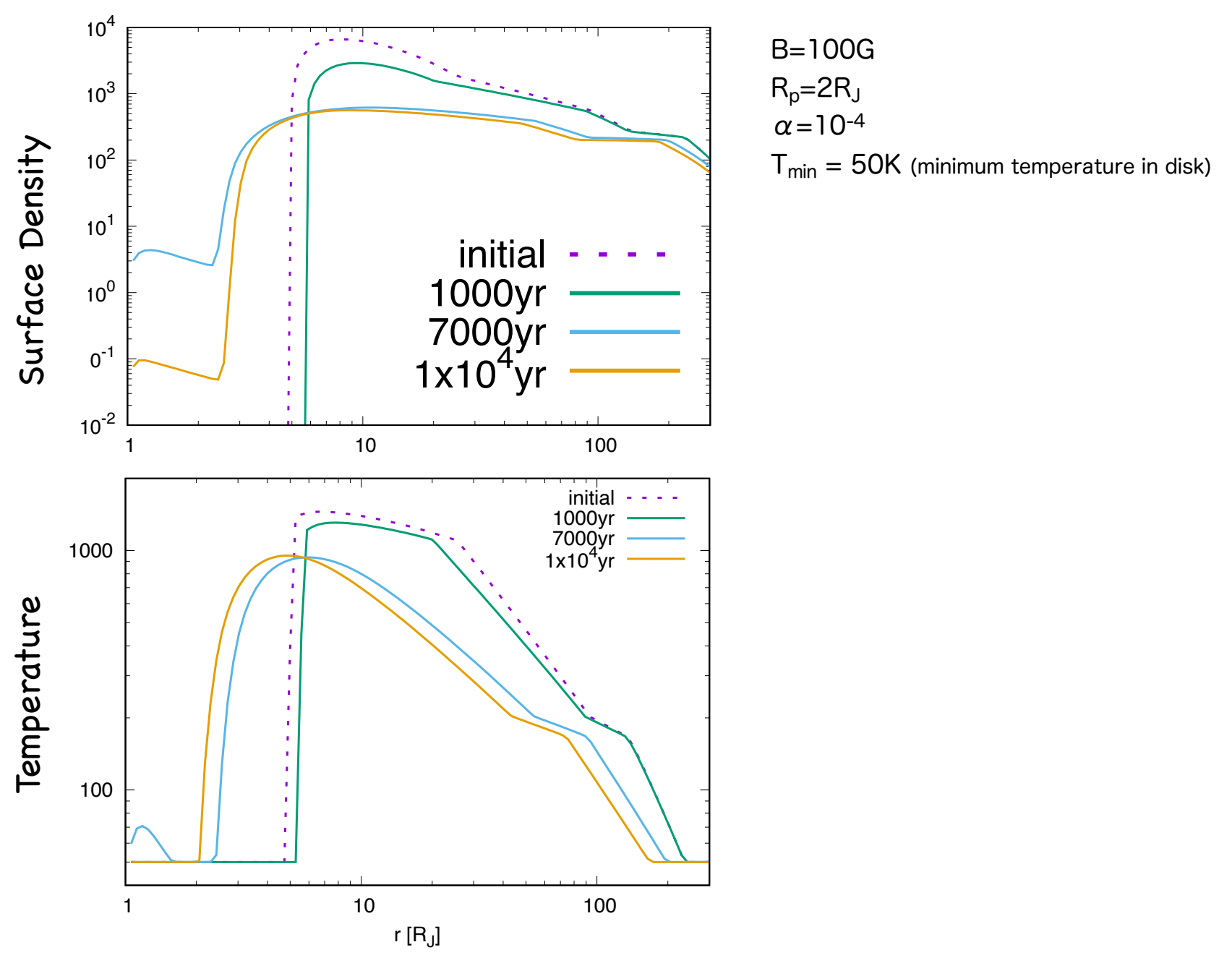
Ogihara & Kobayashi (2013)

➔ Preferable for Jovian system but not for Saturnian one

Jovian system

Formation of inner cavity due to magnetospheric accretion in steady state ("initial" in figure)

Time evolution of disk structure

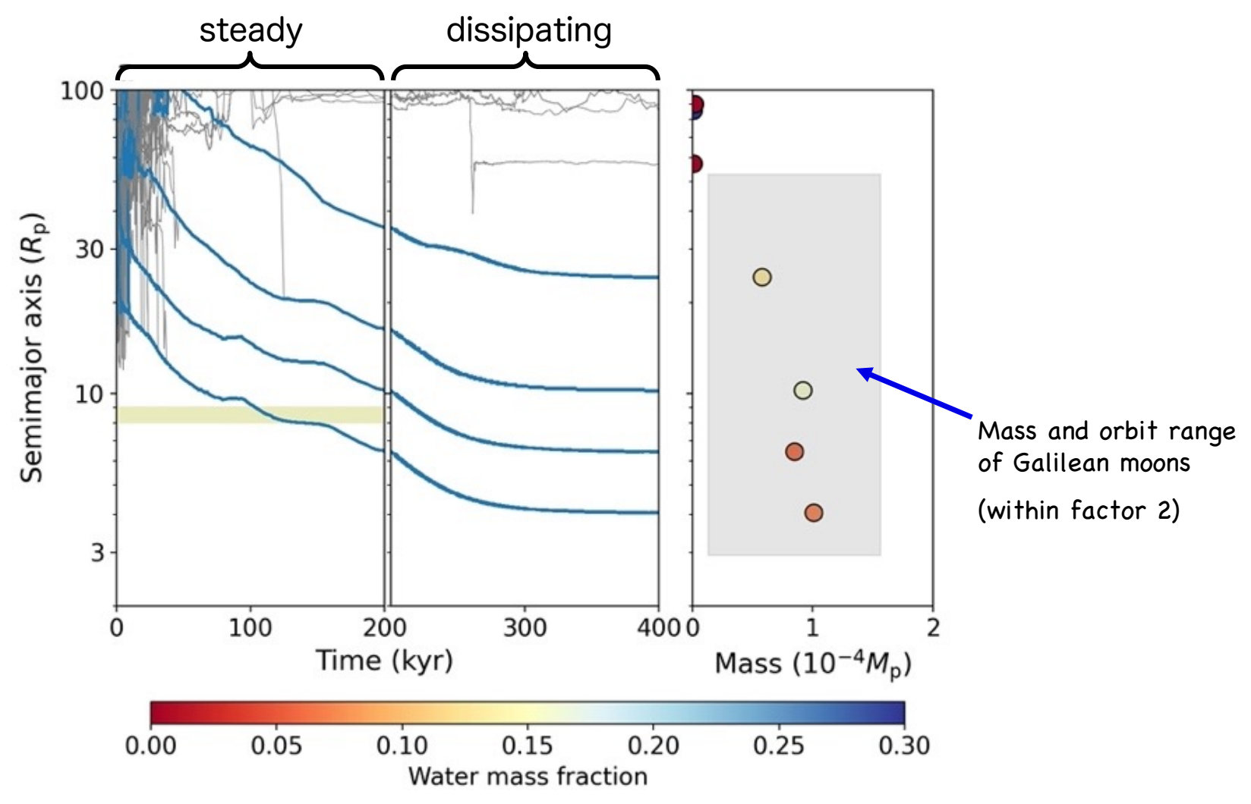


B=100G
$R_p=2R_J$
$\alpha=10^{-4}$
T_{min} = 50K (minimum temperature in disk)

Inner cavity will disappear

➔ Need to configure resonance before disk starts to dissipate

Orbital evolution of moons (*N*-body simulation)



Mass and orbit range of Galilean moons (within factor 2)

- Initial condition: 400-800 bodies of $m=10^{-6}M_J$ randomly placed at 20-80R_J
- Assumption: 50% water content for bodies outer to snowline (65R_J)

We demonstrate the formation of:

- Rock-rich inner two bodies
- Resonant inner three bodies

Saturnian system

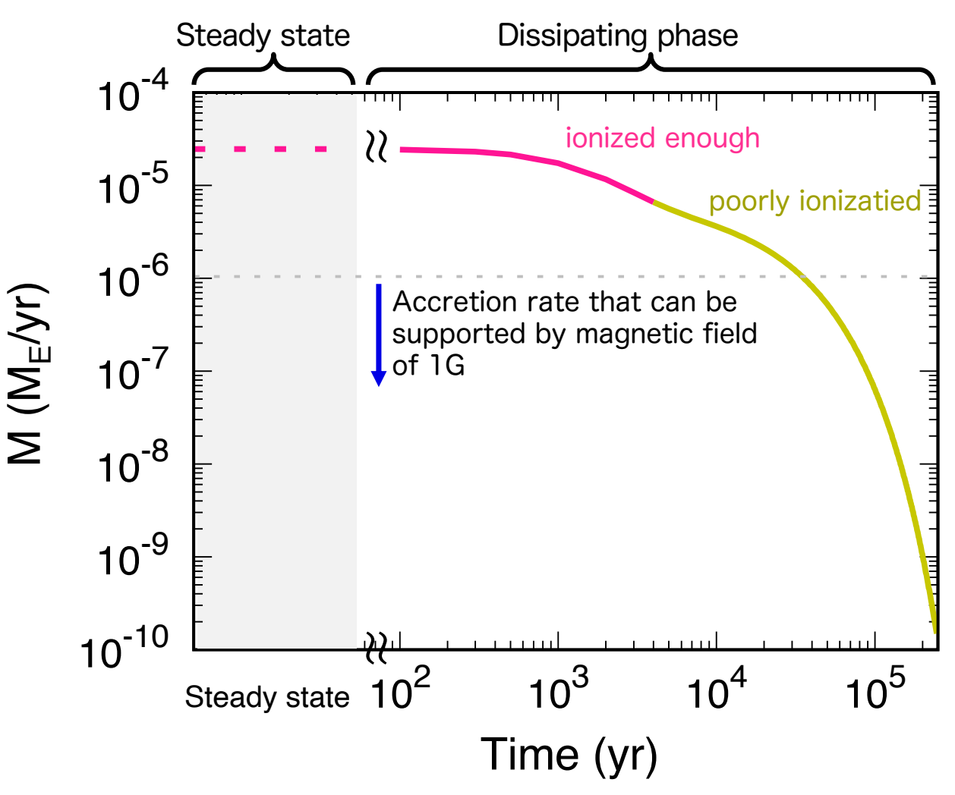
Indicator of ionization degree: magnetic Reynold's number

$$R_{\rm m} = \frac{VH}{\eta}$$

H : disk scale height
η : magnetic diffusivity
V : Kepler velocity
M_E : Earth mass

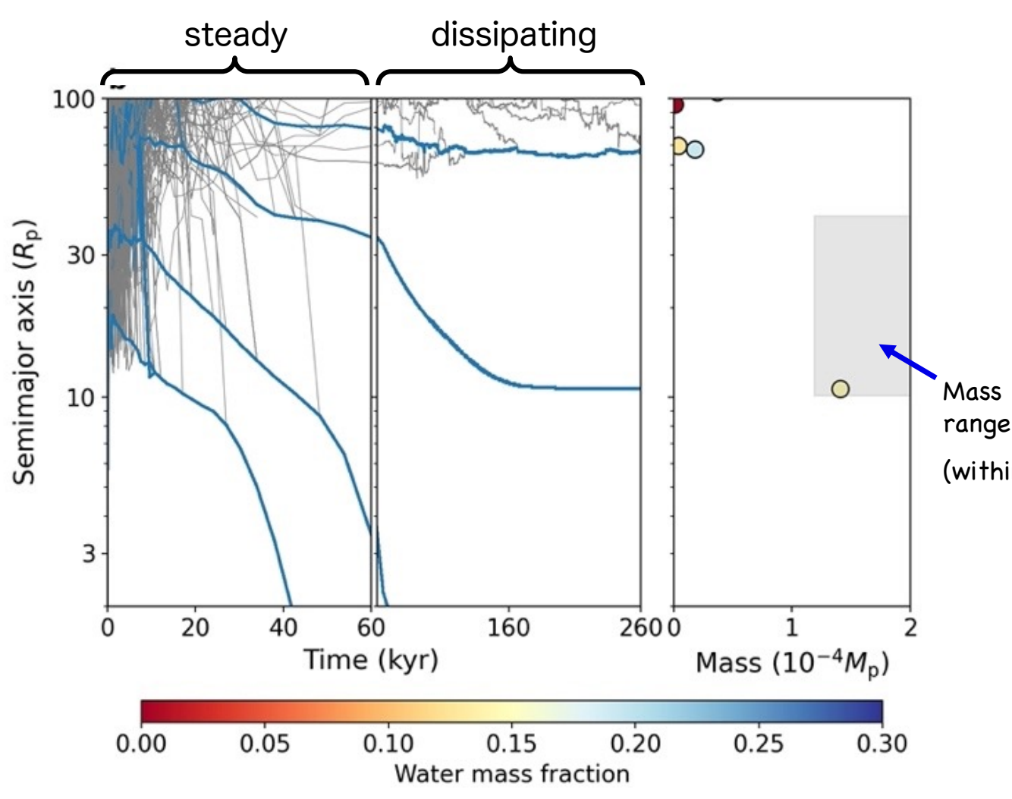
$R_{\rm m} > 1$ & $R_{\rm t} > r$ ➔ Magnetospheric accretion

Time evolution of mass accretion rate



No magnetospheric accretion all time

Orbital evolution of moons (*N*-body simulation)



Mass and orbit range of Titan (within factor 2)

- Initial condition: 400-800 bodies of $m=10^{-6}M_S$ randomly placed at 20-80R_S
- Assumption: 50% water content for bodies outer to snowline

We demonstrate the formation of Titan-like single large moon