Origin of the Difference of the Jovian and Saturnian Satellite Systems

Takanori Sasaki, Shigeru Ida (Tokyo Tech)
Glen R. Stewart (U. Colorado)

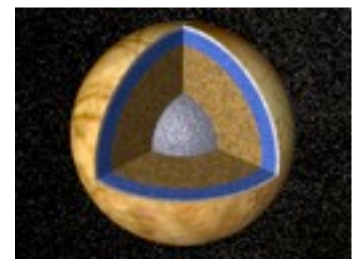
Sasaki, Stewart & Ida (2010) *ApJ* **714,** 1052

Jovian System v.s. Saturnian System

rocky

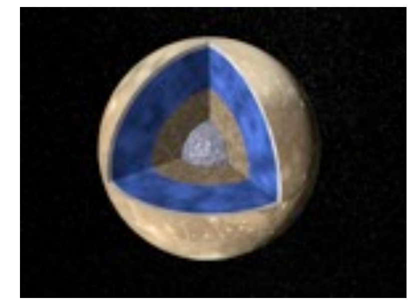
Io

rocky



Europa

icy



Ganymede

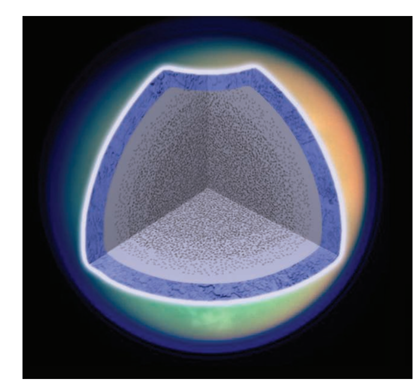
icy, undiff.

Callisto

mutual mean motion resonances (MMR)

only one big body

icy, undiff.



Titan

Satellite Properties

	a/R_p	M/M_p [10^{-5}]	ρ [g/cm^3]	C/MR^2
Io	5.9	4.70	3.53	0.378
Europa	9.4	2.53	2.99	0.346
Ganymede	15.0	7.80	1.94	0.312
Callisto	26.4	5.69	1.83	0.355
Titan	20.3	23.7	1.88	0.34

Callisto and Titan's undifferentiated interiors
→ accretion timescale $> 5\times10^5$ years [Barr & Canup, 2008]

Questions; Motivation of this study

<u>Satellites' size, number, and location</u>

Jovian: 4 similar mass satellites in MMR

Saturnian: only 1 large satellite far from Saturn

What is the origin of the different architecture?

<u>Among Galilean satellites</u>

Io & Europa: rocky satellite

Ganymede & Callisto: icy satellite

Callisto: undifferentiated

What is the origin of the satellites' diversity?

Overview of this study

Circum-Planetary Disk

Canup & Ward, 2002, 2006

Satellites formed in c.-p. disk

Actively-supplied accretion disk

Supplied from circum-stellar disk

→ Analytical solution for T, Σ

Satellite Formation

Ida & Lin, 2004, 2008, 2010

Analytical solution for

- accretion timescale
- type I migration timescale
- trapping condition in MMR

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Adding New Ideas | **Disk boundary conditions**

↓

Difference of Jovian/Saturnian systems is naturally reproduced?

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Adding New Ideas Disk boundary conditions

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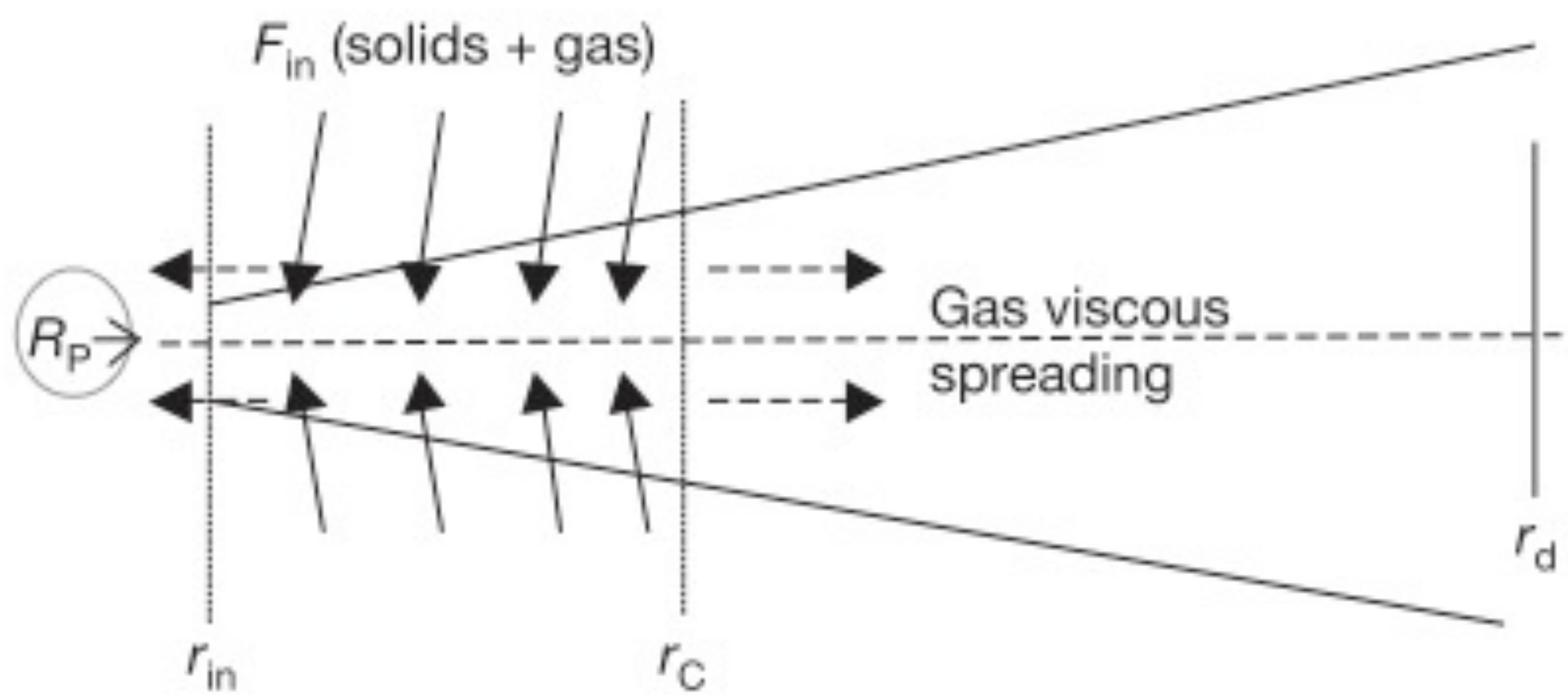
Canup & Ward (2002, 2006)

Actively-Supplied Accretion Disk

Uniform mass infall F_{in} from the circum-stellar disk
Infall regions: $r_{in} < r < r_c$ ($r_c \sim 30R_p$)
Diffuse out at outer edge: $r_d \sim 150R_p$
Infall rate decays exponentially with time
Temperature: balance of viscous heating and blackbody radiation
Viscosity: α model



Canup & Ward (2002, 2006) +α

Inflow flux $F_{in} = F_{in}(t=0)\exp\left(-t/\tau_{in}\right)$ [g/s]

Temperature $T_d \approx 160\left(\frac{M_p}{M_J}\right)^{1/2}\left(\frac{\tau_G}{5\times10^6 yrs}\right)^{-1/4}\left(\frac{r}{20R_J}\right)^{-3/4}$ [K]

Gas density $\Sigma_g \approx 100 f_g\left(\frac{M_p}{M_J}\right)\left(\frac{r}{20R_J}\right)^{-3/4}$ [g/cm²] $f_g \equiv \left(\frac{\alpha}{5\times10^{-3}}\right)^{-1}\left(\frac{\tau_G}{5\times10^6 yrs}\right)^{-3/4}$

Dust density $\Sigma_d = \eta_{ice} f_d\left(\frac{M_p}{M_J}\right)\left(\frac{r}{20R_J}\right)^{-3/4}$ [g/cm²]

Increasing rate of dust density $\frac{df_d}{dt} = 0.029\left(\frac{M_p}{M_J}\right)^{-2/3}\left(\frac{f}{100}\right)^{-1}\left(\frac{\tau_G}{5\times10^6 yrs}\right)^{-1}\left(\frac{r}{20R_J}\right)^{3/4}$ [/years]

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Adding New Ideas | Disk boundary conditions

Difference of Jovian/Saturnian systems is naturally reproduced?

Ida & Lin (2004, 2008, 2010)

Timescales of satellite's accretion & type I migration

$$\tau_{acc} = \frac{M}{\dot{M}} \approx 10^6 f_d^{-1} \eta_{ice}^{-1} \left(\frac{\rho}{\rho_p}\right)^{1/3} \left(\frac{M}{10^{-4} M_p}\right)^{1/3} \left(\frac{M_p}{M_J}\right)^{-5/6} \left(\frac{\beta}{10}\right)^{2} \left(\frac{r}{20 R_J}\right)^{5/4} \quad \text{[years]}$$

$$\tau_{mig} = \frac{r}{\dot{r}} \approx 10^5 \frac{1}{f_g} \left(\frac{M}{10^{-4} M_p}\right)^{-1} \left(\frac{M_p}{M_J}\right)^{-1} \left(\frac{r}{20 R_J}\right)^{1/2} \left(\frac{\tau_G}{5 \times 10^6}\right)^{-1/4} \quad \text{[years]}$$

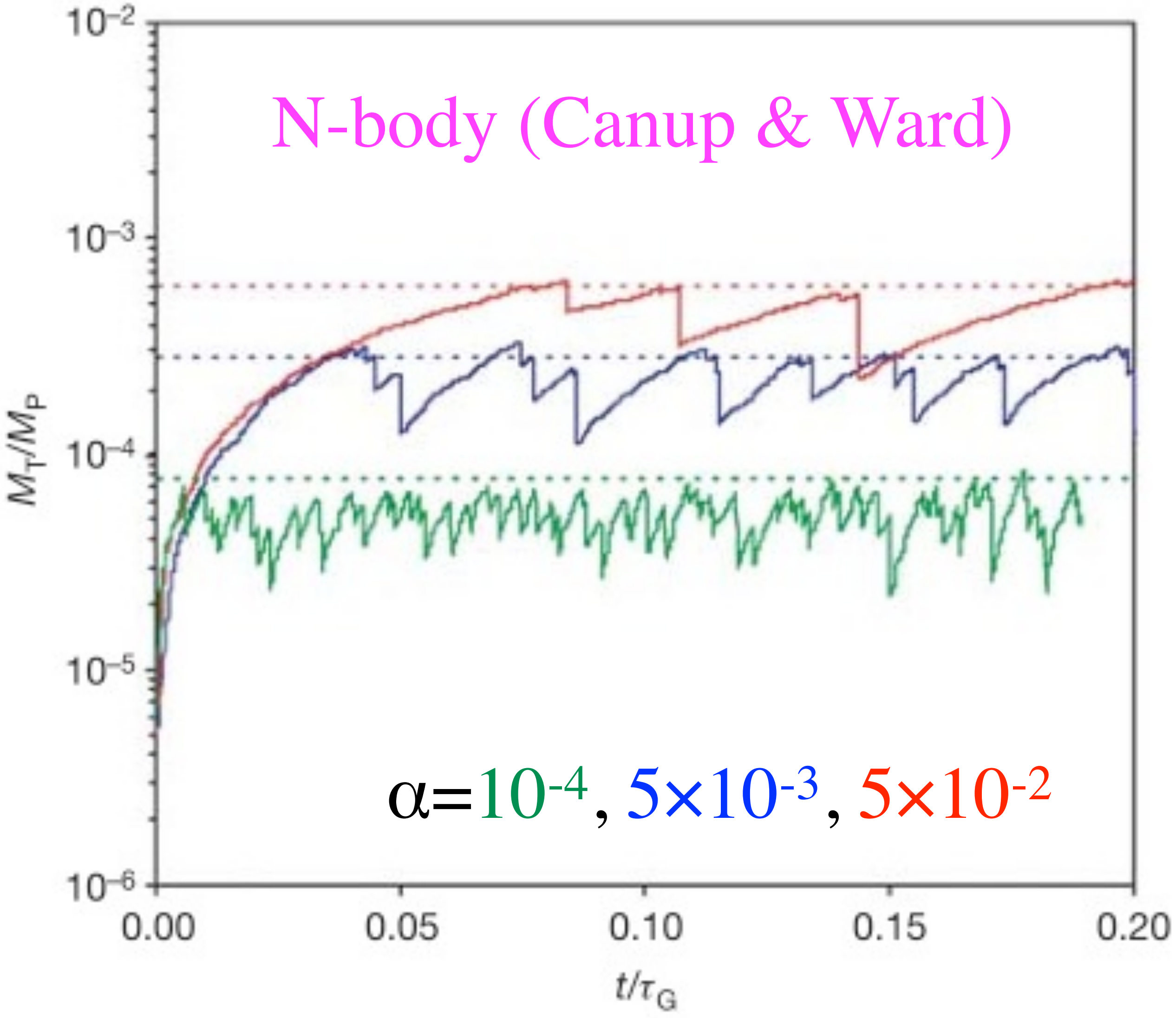
Resonant trapping width of migrating proto-satellites

$$b_{trap} = 0.16 \left(\frac{m_i + m_j}{M_\oplus}\right)^{1/6} \left(\frac{v_{mig}}{v_K}\right)^{-1/4} r_H \quad \text{[m]}$$

These approximate analytical solutions
are based on the results of N-body simulations

Comparison with N-body simulation

Time evolution of total mass of satellites (time-constant inflow)



Comparison with N-body simulation

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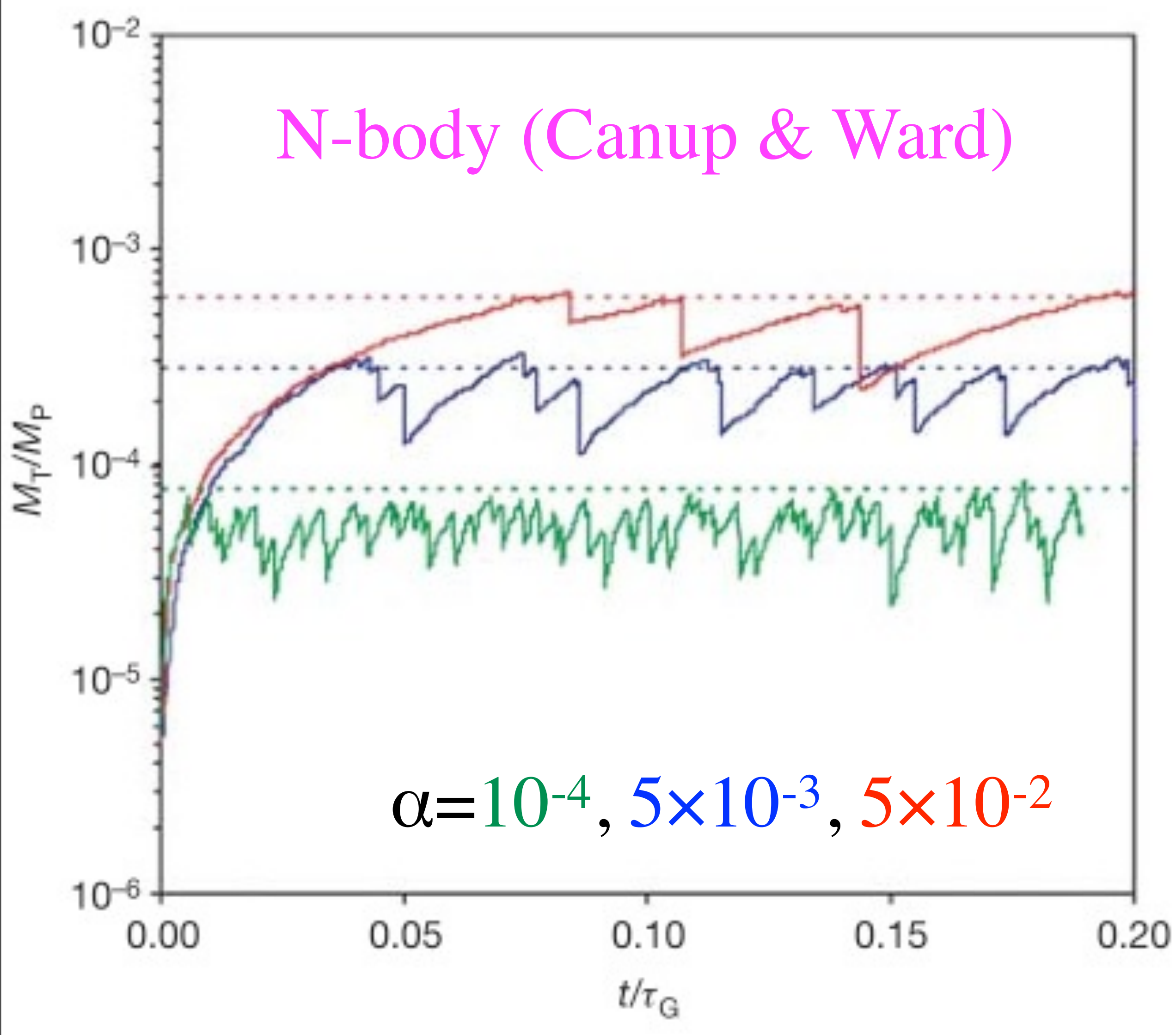

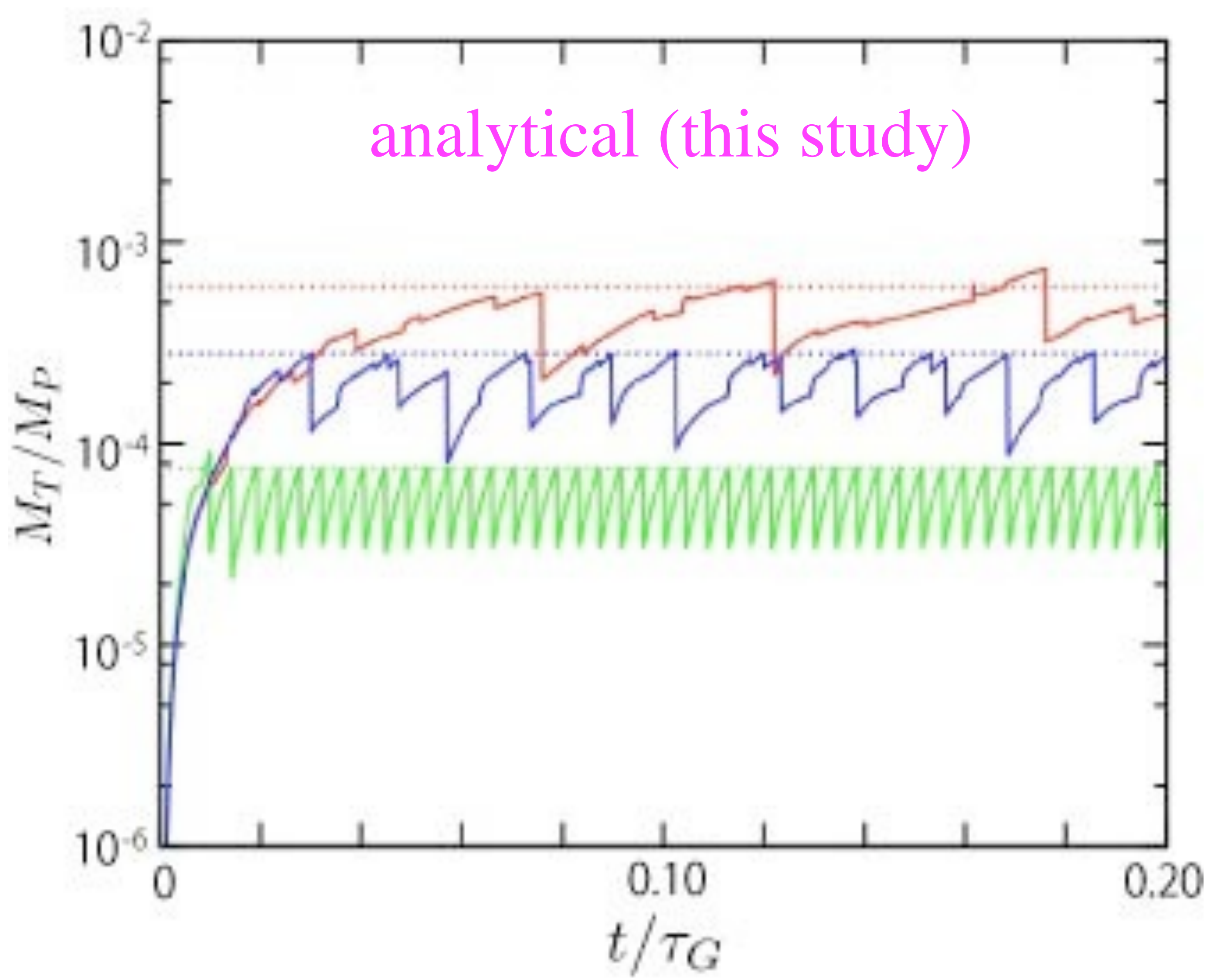

Excellent agreement with N-body simulation!

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Supplied from circum-stellar disk

$\rightarrow$ Analytical solution for T, Σ

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Ida & Lin, 2004, 2008, 2010

Analytical solution for

accretion timescale

type I migration timescale

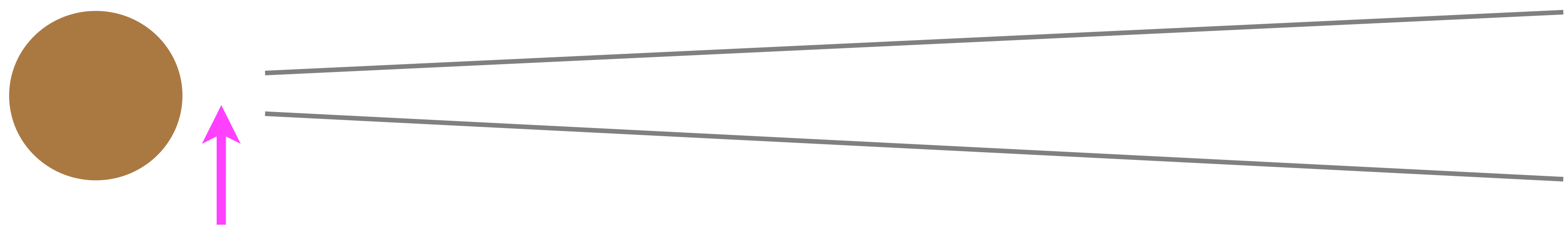
trapping condition in MMR

Adding New Ideas　　Disk boundary conditions

Difference of Jovian/Saturnian systems is naturally reproduced?

The Ideas

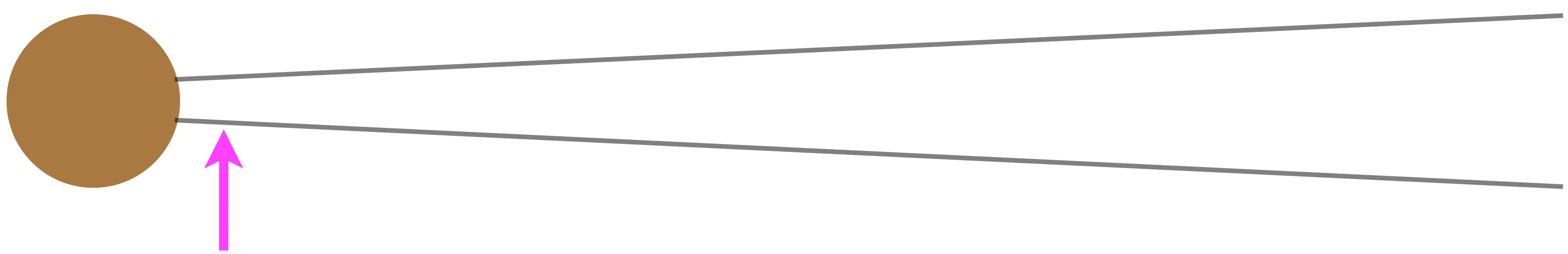
Jupiter



inner cavity

opened up gap in c.-s. disk
→ infall to c.-p. disk stop abruptly

Saturn

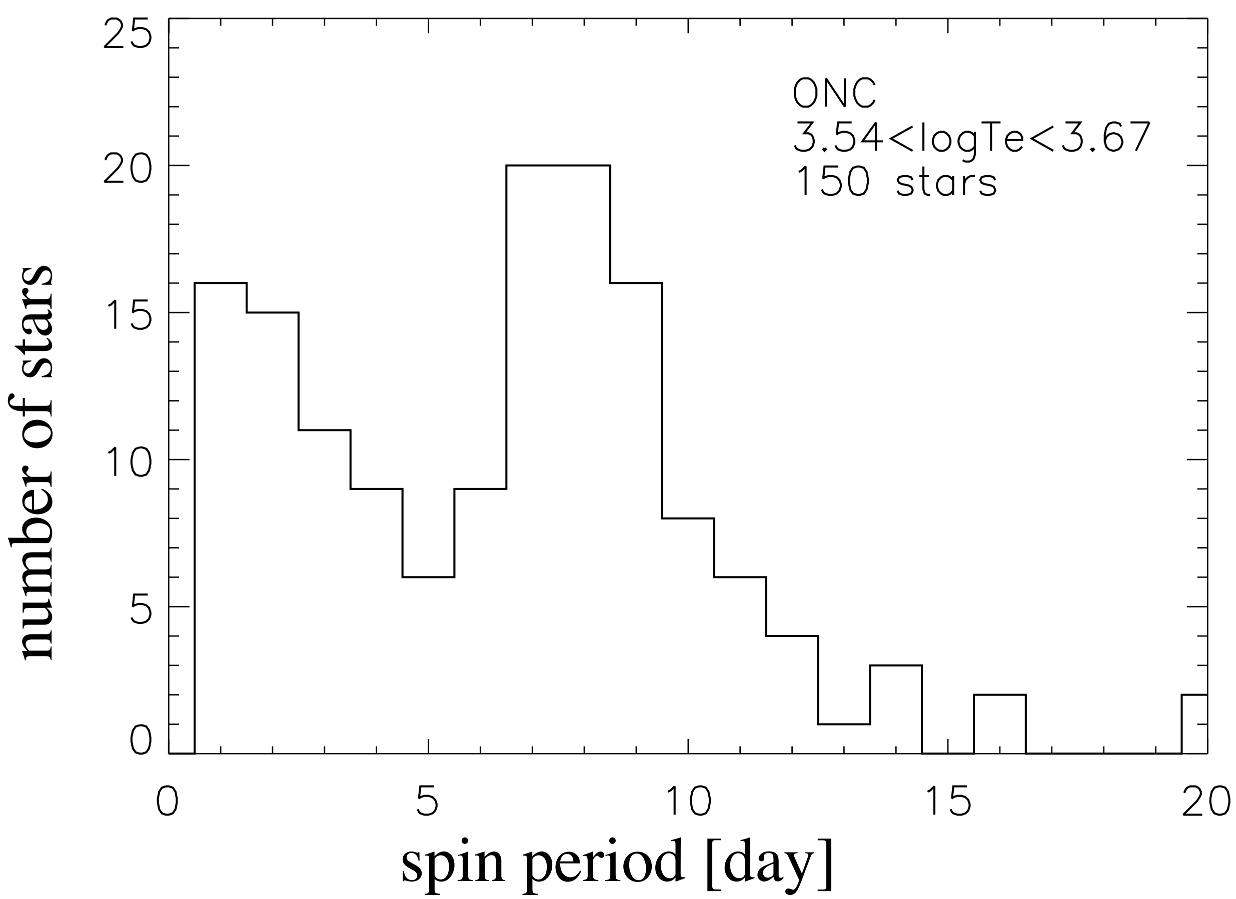


no cavity

did not open up gap in c.-s. disk
→ c.-p. disk decay with c.-s. disk

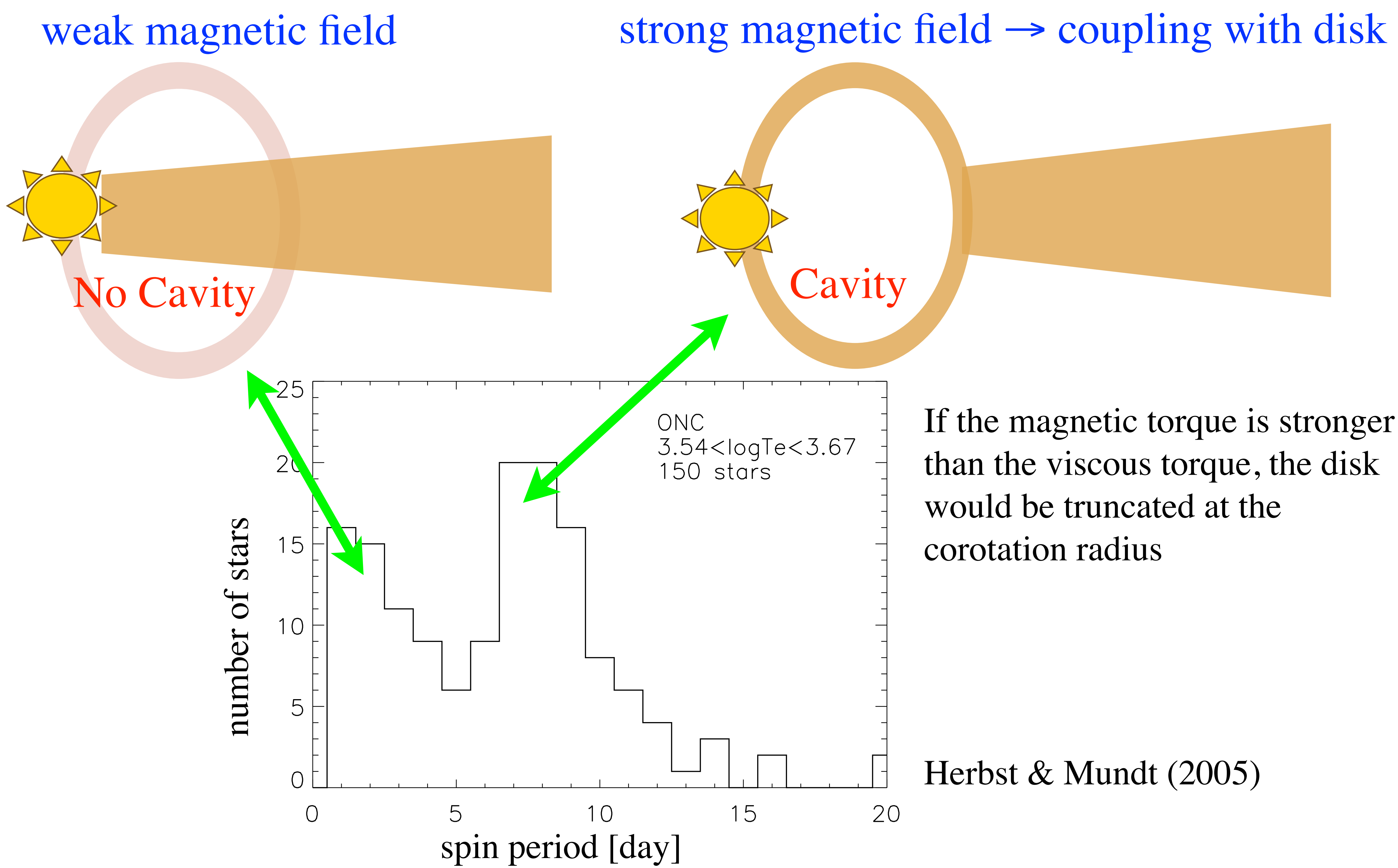
Difference of “inner cavity” is from Königl (1991) and Stevenson (1974)
Difference of gap conditions is from Ida & Lin (2004)

Inner Cavity (Analogy with T-Tauri stars)



Herbst & Mundt (2005)

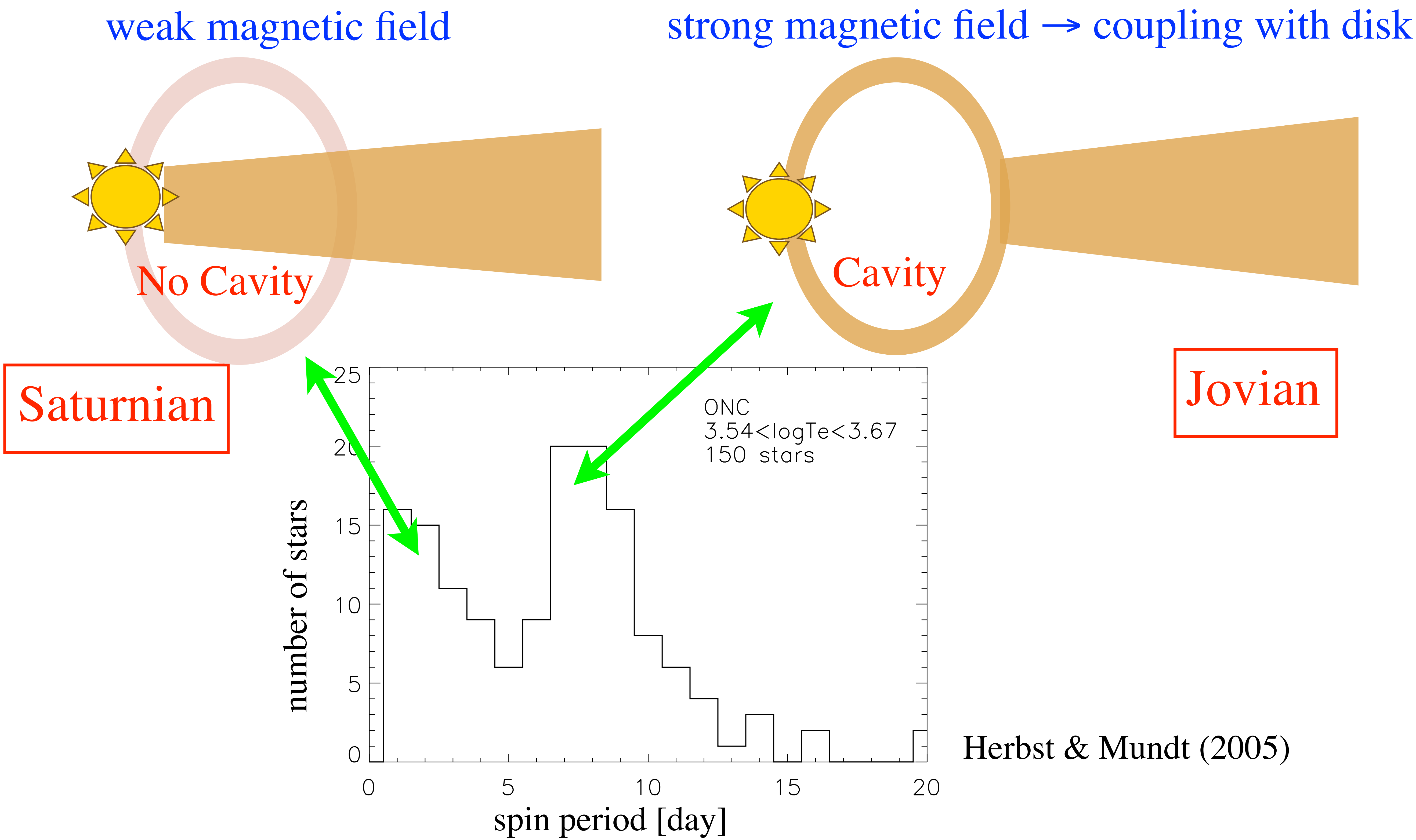
Inner Cavity (Analogy with T-Tauri stars)



If the magnetic torque is stronger than the viscous torque, the disk would be truncated at the corotation radius

Herbst & Mundt (2005)

Inner Cavity (Analogy with T-Tauri stars)



Estimates of Cavity Opening

Stevenson (1974)

proto-Jovian magnetic field ～1000 Gauss

Cavity

(Jovian system should be correspond to the stage)

∨

Königl (1991)

magnetic field for the magnetic coupling

accretion rate $10^{-6} M_J$/yr → ～ a few hundred Gauss

∨

Present Saturnian magnetic field < 1 Gauss

No Cavity

≒ late stage of Saturnian satellite formation

THE IDEAS

Jupiter: open up gap in circum-stellar disk

→ infall to circum-planetary disk stop

→ c.-p. disk quickly depleted

→ frozen satellite system with “inner cavity”

Saturn: did not open up the gap

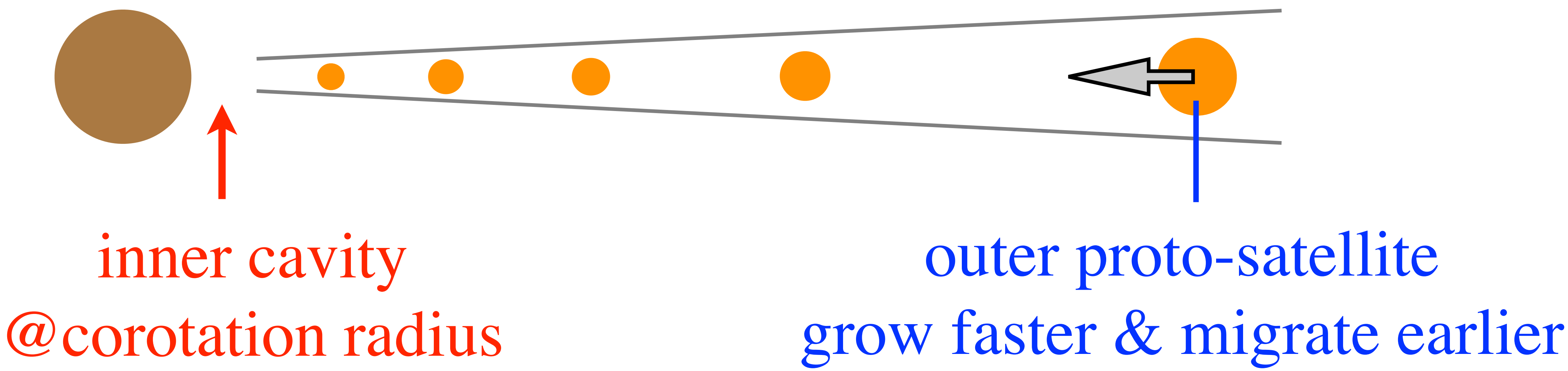
→ c.-p. disk decay with c.-s. disk decay

→ c.-p. disk slowly depleted

→ satellite system without “inner cavity”

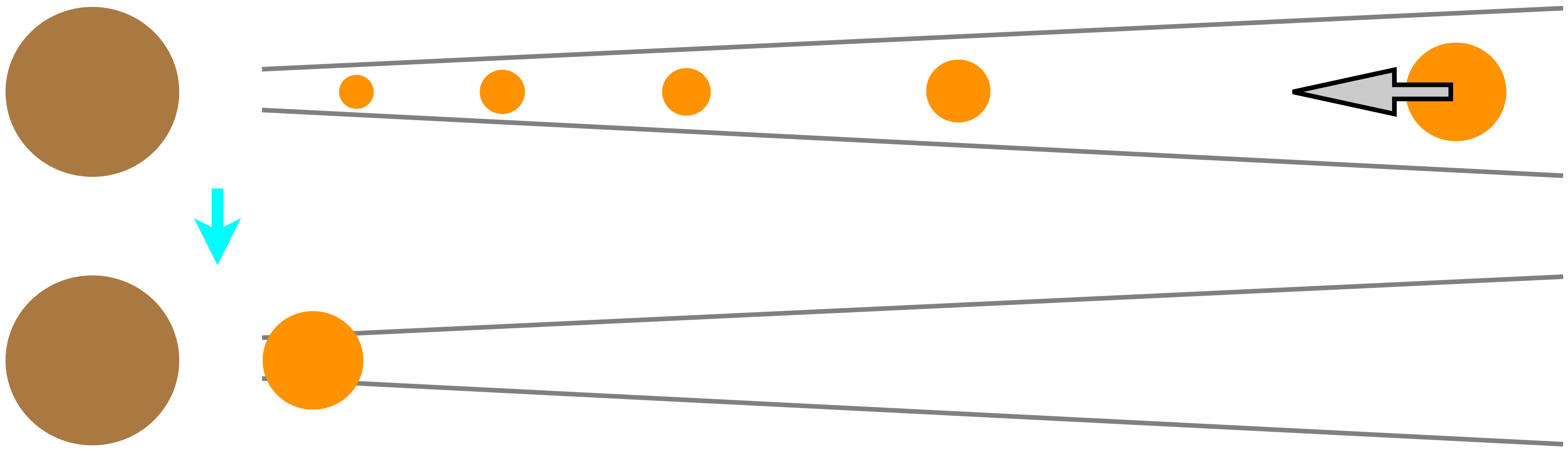
difference of gap conditions are from Ida & Lin (2004)

Jovian System



Because the infall mass flux per unit area is constant,
the total mass flux to satellite feeding zones is larger in outer regions.

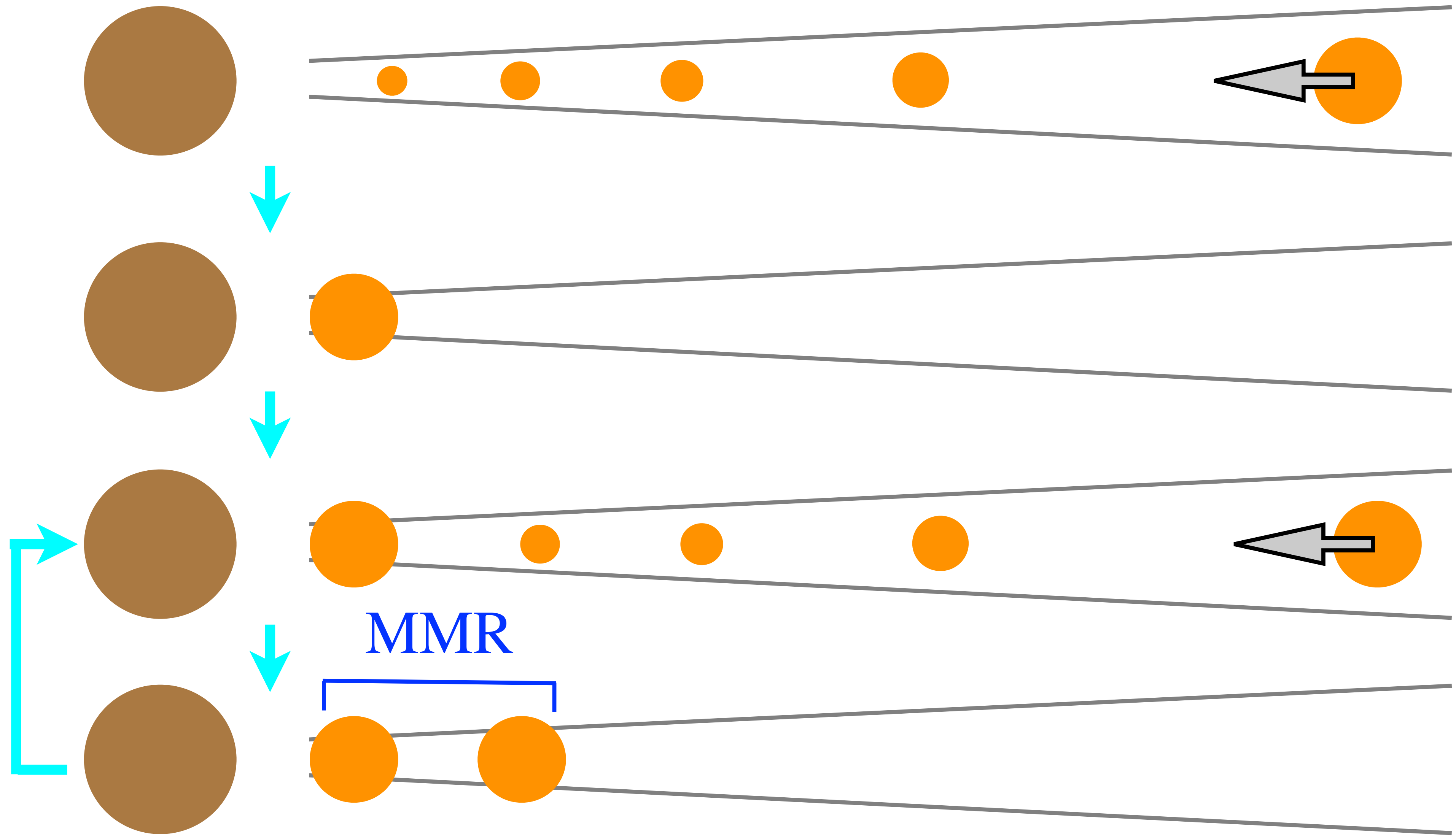
Jovian System



Type I migration is
halted near the inner edge

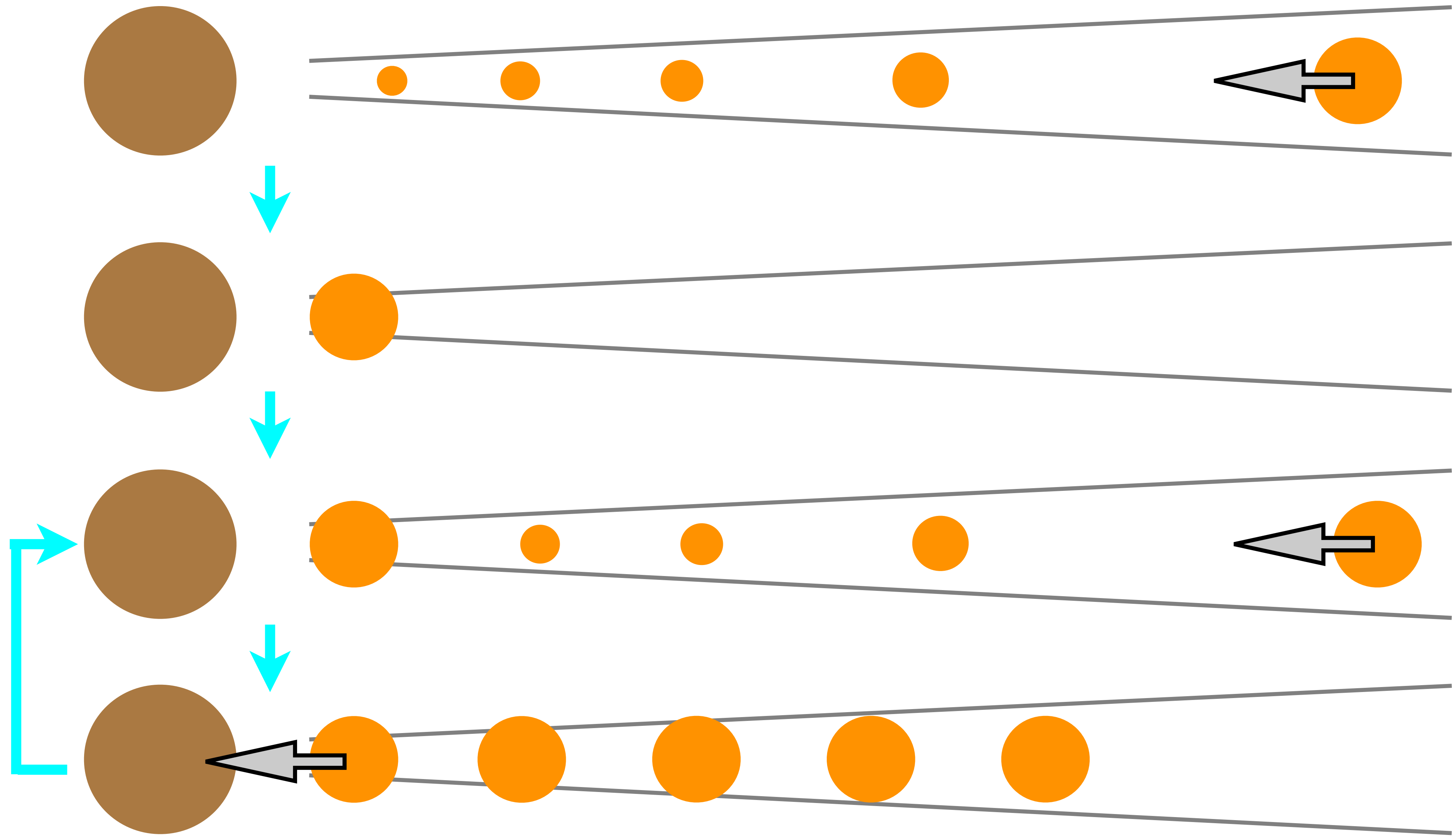
The outer most satellite migrates and sweeps up the inner small satellites.

Jovian System



Proto-satellites grow & migrate repeatedly
They are trapped in MMR with the innermost satellite

Jovian System

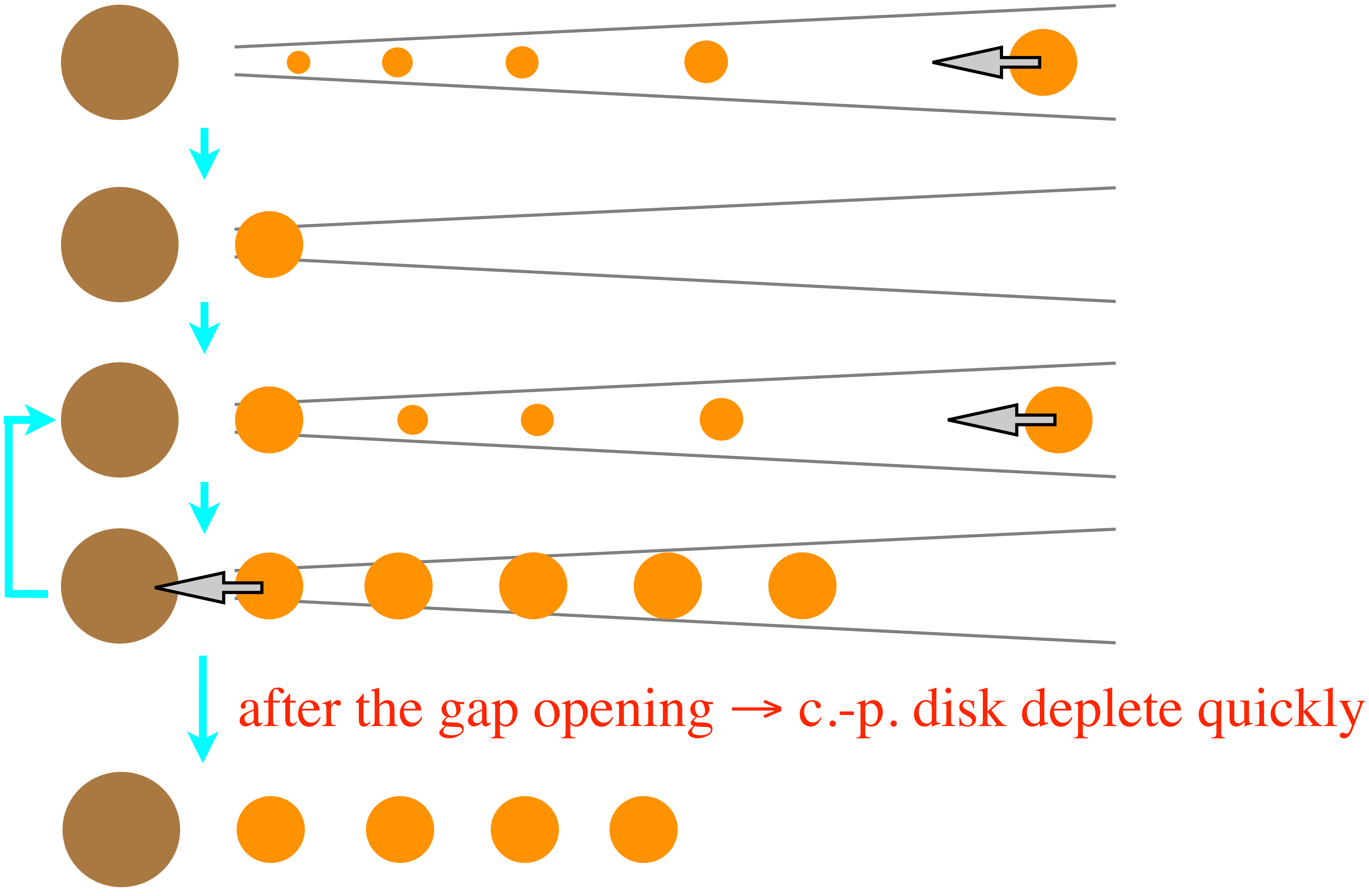


Total mass of the trapped satellites > Disk mass

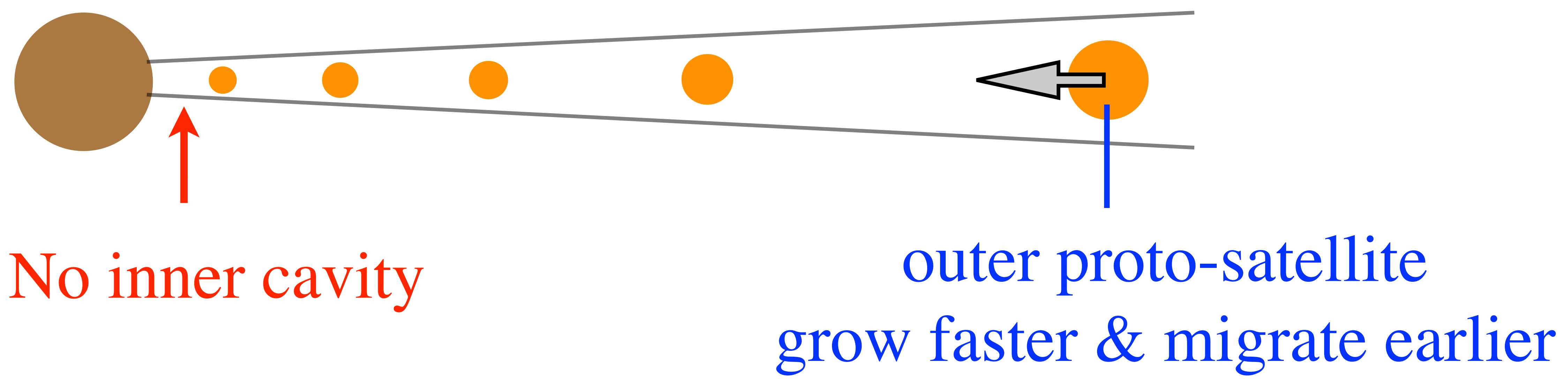
→ the halting mechanism is not effective

→ innermost satellite is released to the host planet

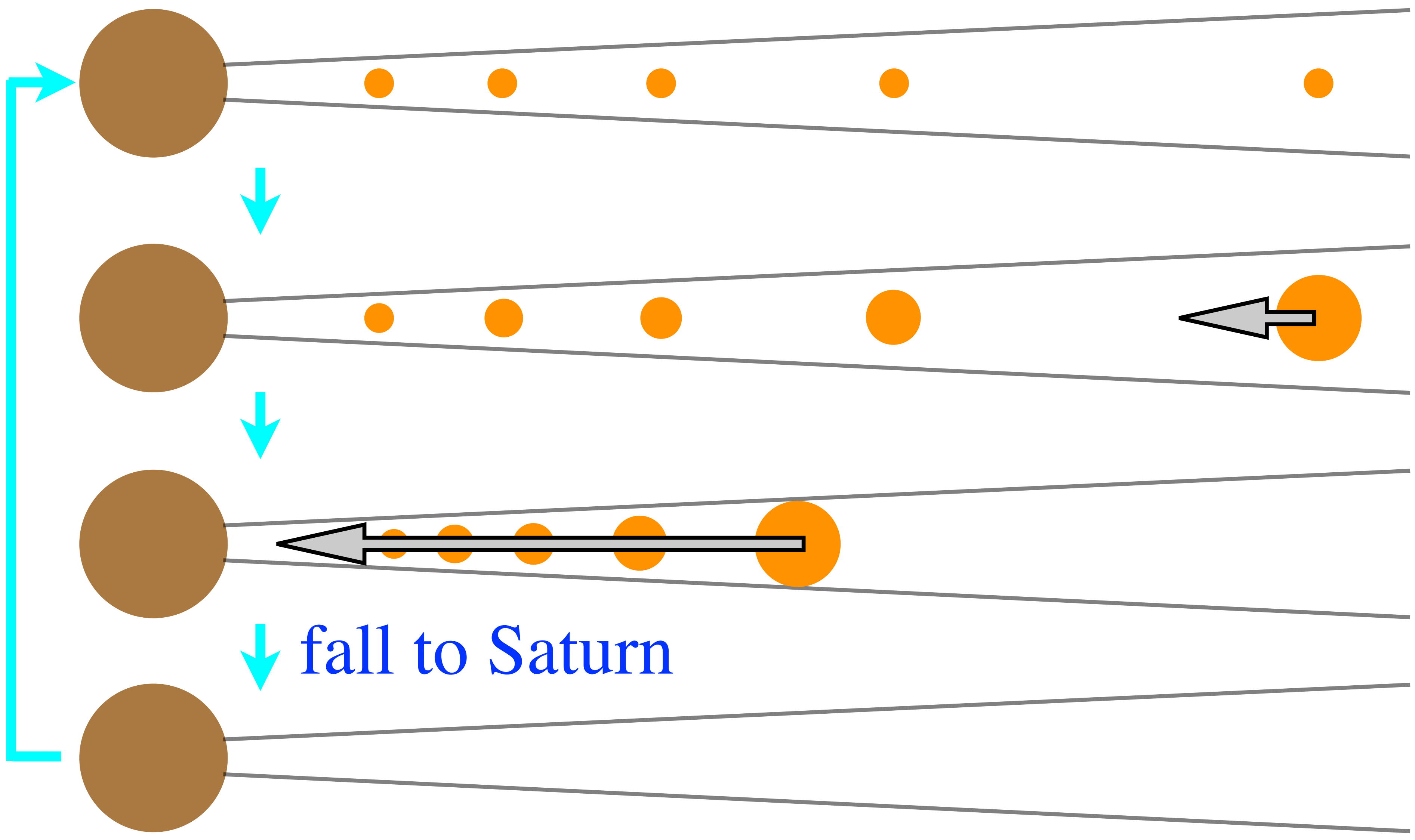
Jovian System



Saturnian System

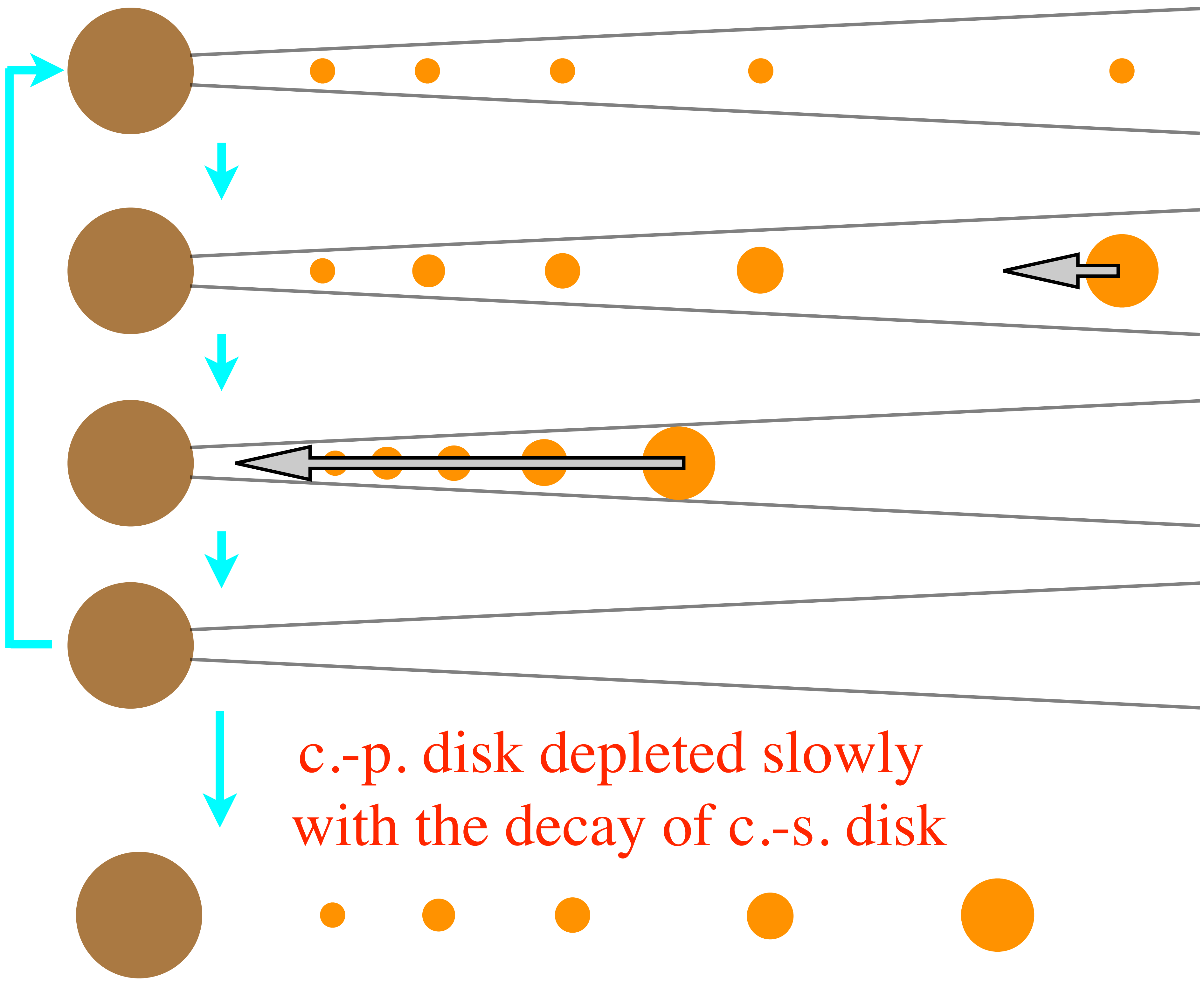


Saturnian System



Large proto-satellites migrate from the outer regions and fall to the host planet with inner smaller satellites

Saturnian System

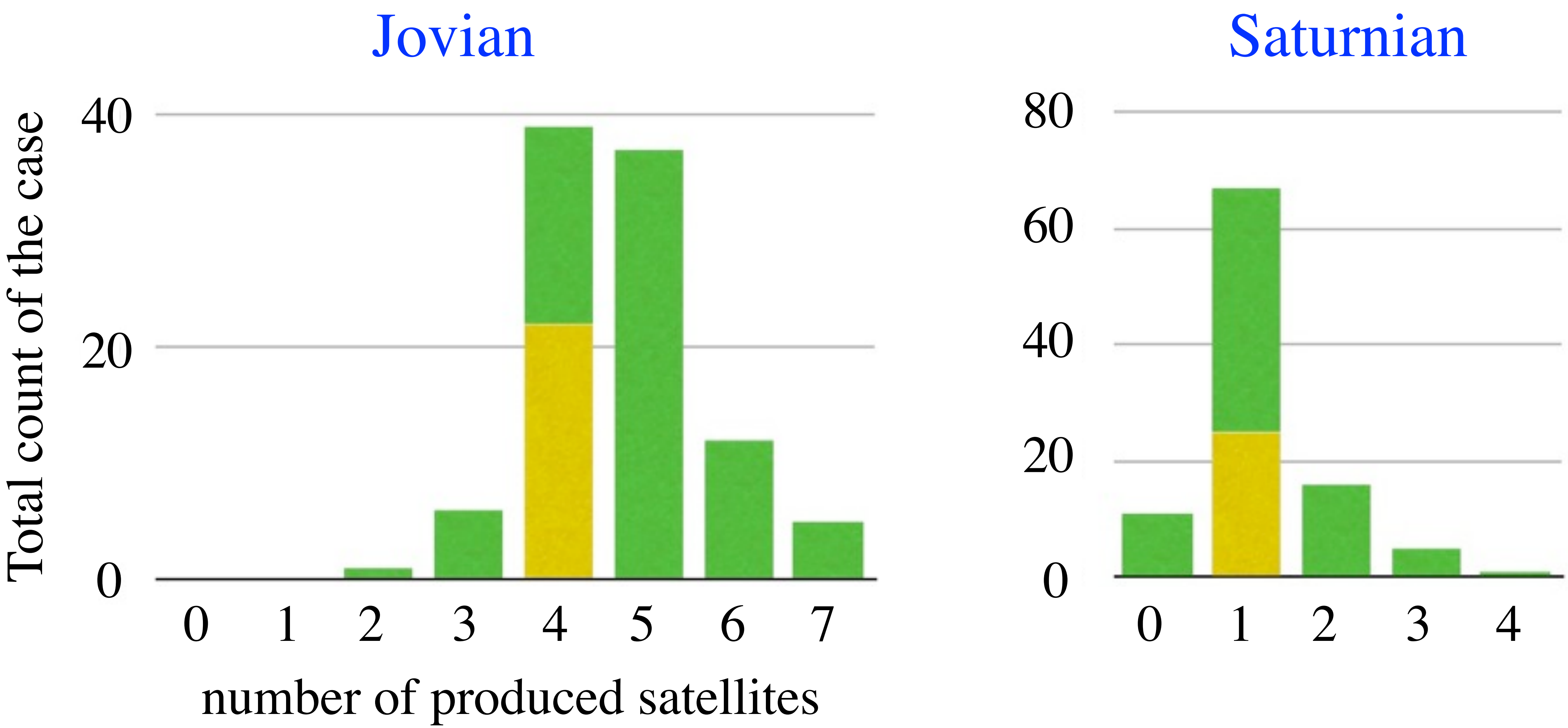


Monte Carlo Simulation (n=100)

Parameters:

Disk viscosity (α model)	$\alpha = 10^{-3} - 10^{-2}$
Disk decay timescale	$\tau_{in} = 3 \times 10^6 - 5 \times 10^6$ yr
Number of “satellite seeds”	$N = 10 - 20$

Results: Distribution of the number of large satellites



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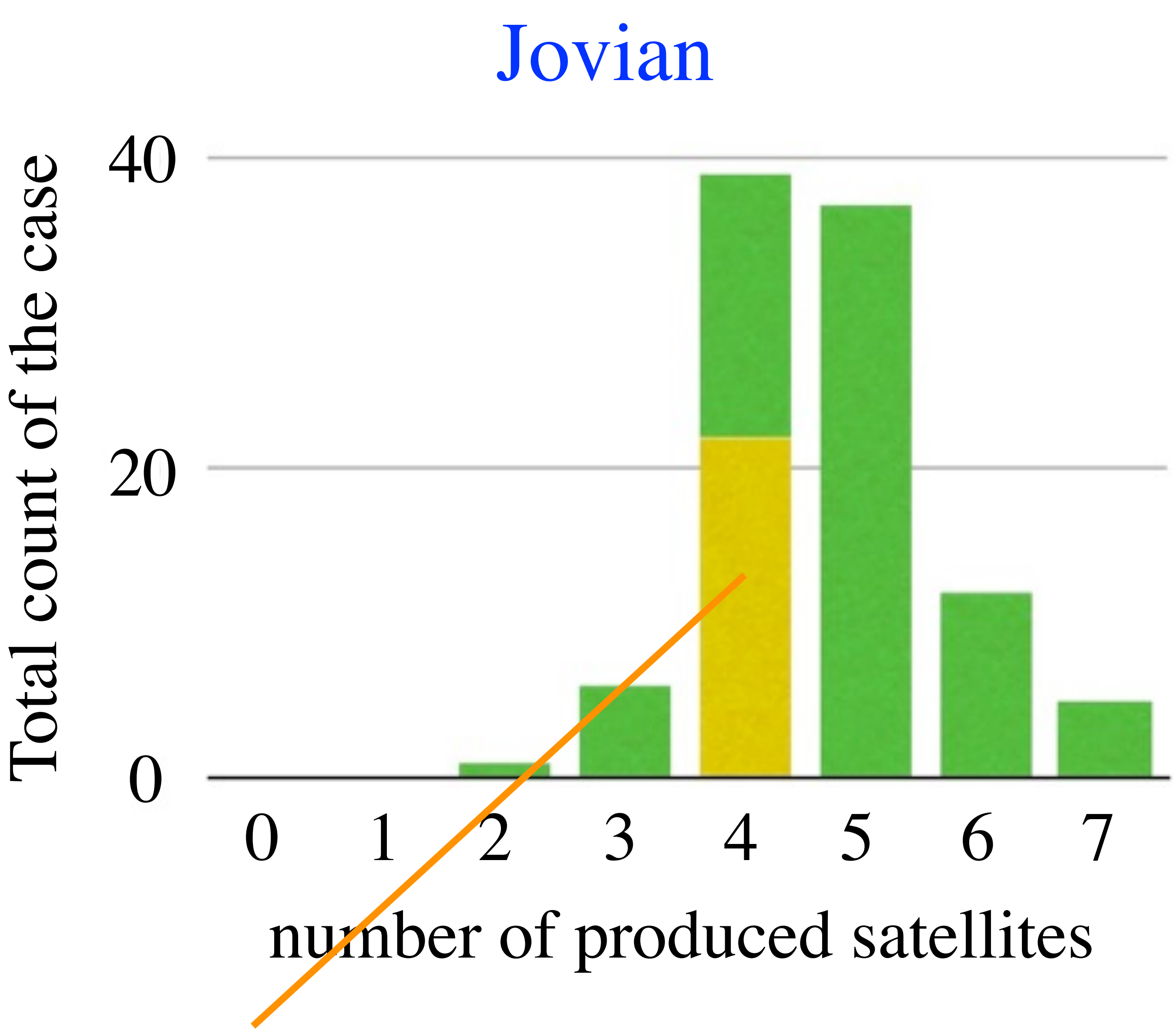
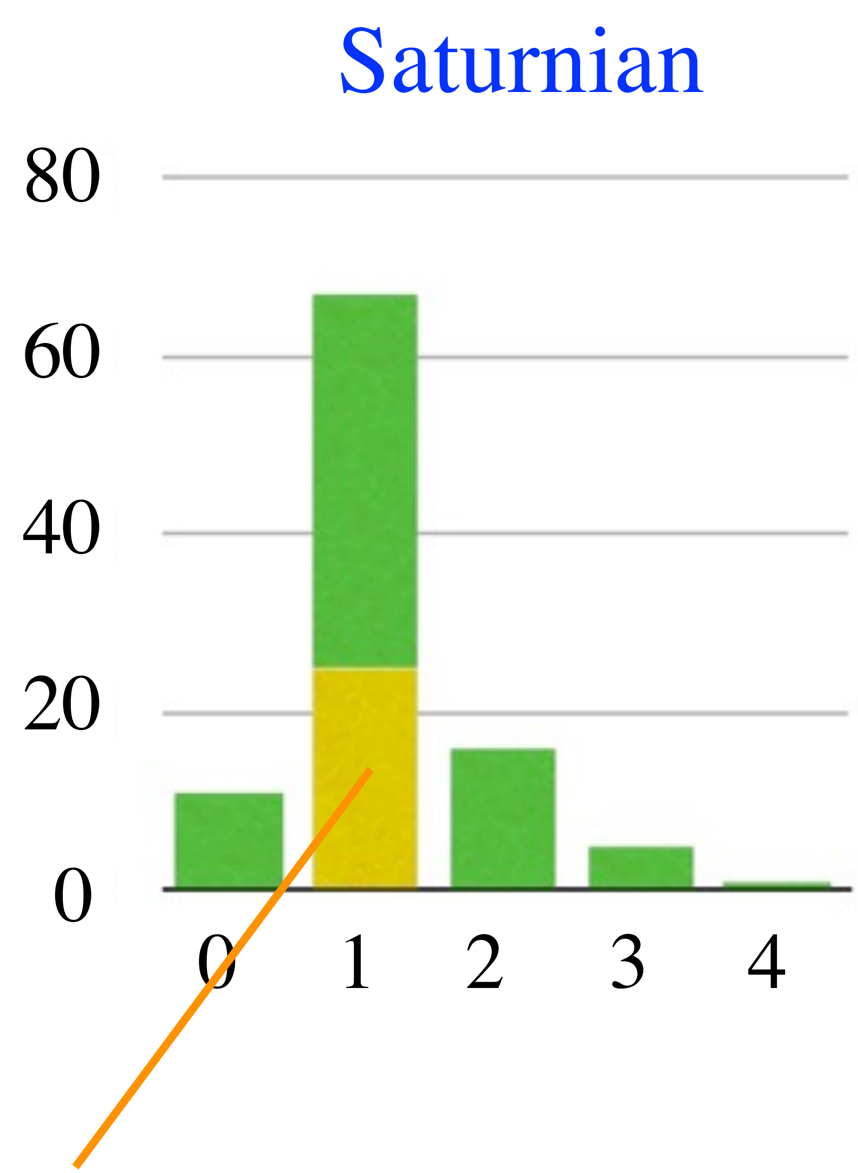
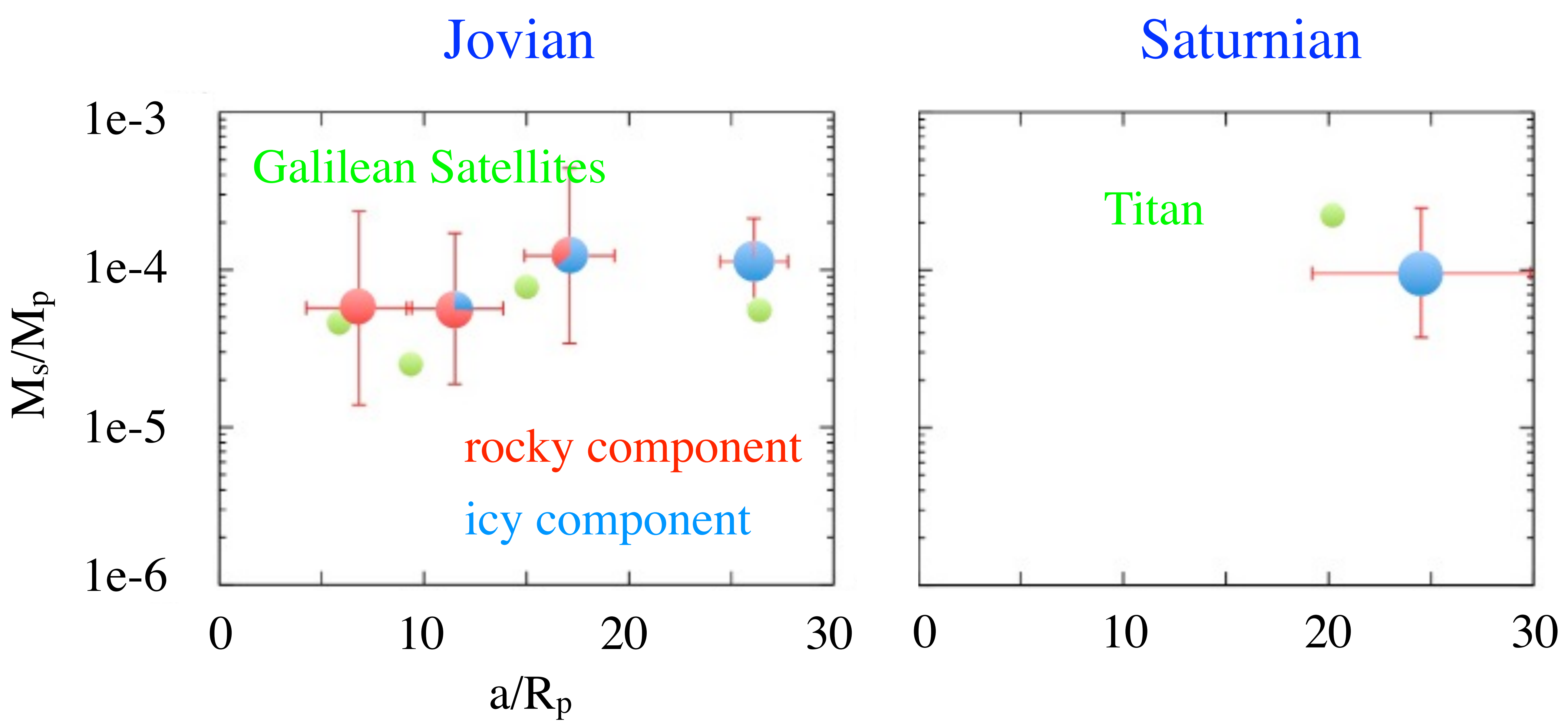




inner two bodies: rocky
& outer two bodies: icy

icy satellite
& large enough (~M_{Titan})

Results: Properties of produced satellite systems



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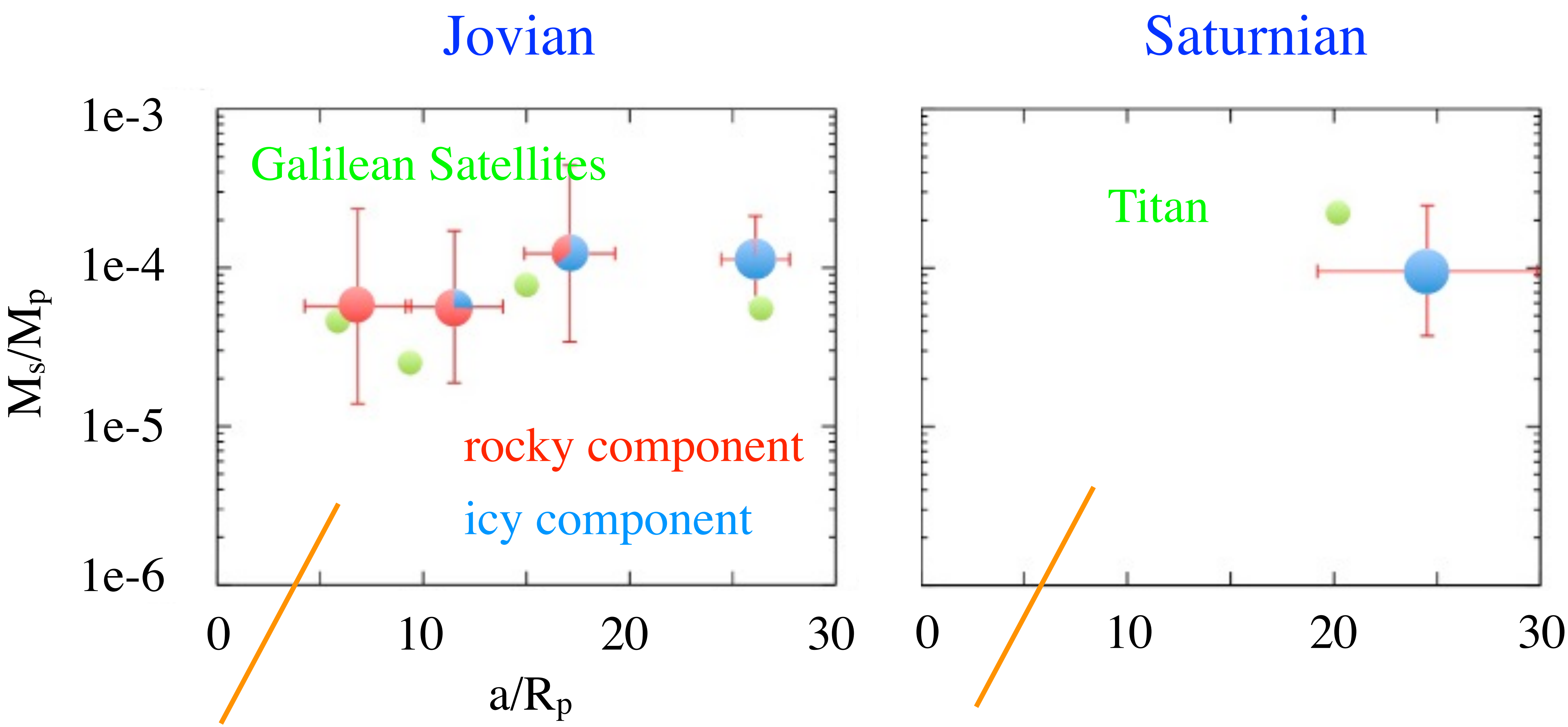


inner three bodies
are trapped in MMR

the largest satellite
has ~90% of total satellite mass

Results: Other features of produced satellite systems

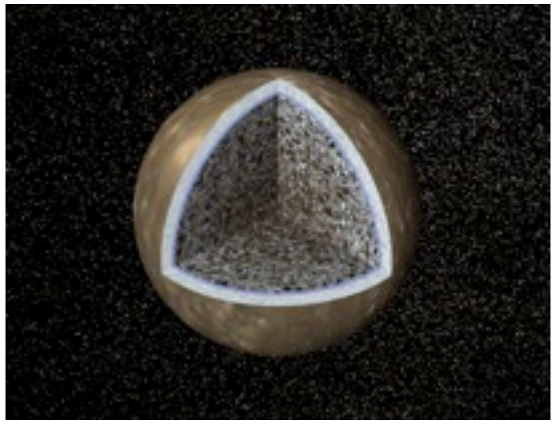
Callisto and Titan's undifferentiated interior

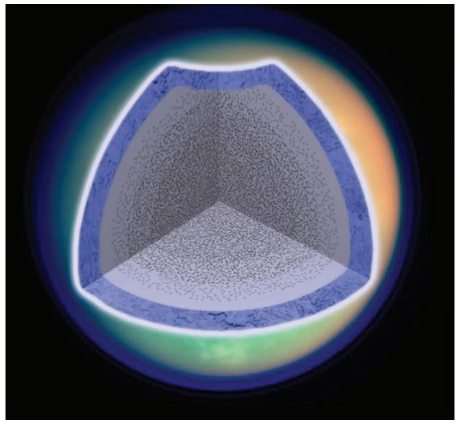
→ accretion timescales $> 5\times10^5$ years [Barr & Canup, 2008]

Accretion timescales in our simulations

Callisto: 10^5-10^6 years

Titan: $\sim10^6$ years





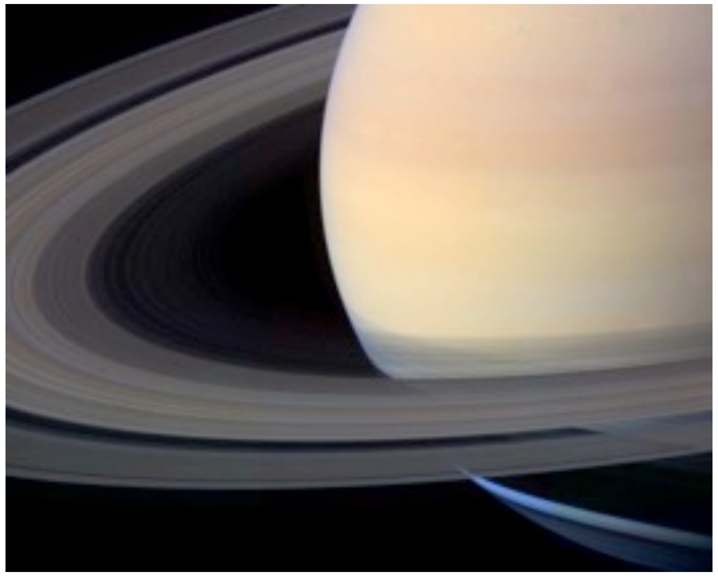
Saturn's ring formed from an ancient satellite at Roche Zone

→ $R_{Roche} > R_{Synch}$ is required [Charnoz et al., 2009]

Jovian: $R_{Roche} < R_{Synch}$

Saturnian: $R_{Roche} > R_{Synch}$

Uranian, Neptunian: $R_{Roche} < R_{Synch}$



Summary

- Jovian Satellite System v.s. Saturnian Satellite System
  Difference of size, number, location, and compositions
- Satellite Accretion/Migration in Circum-Planetary Disk
  Canup & Ward (2002, 2006) + Ida & Lin (2004, 2008, 2010)
- The Ideas of Disk Boundary Conditions
  Difference of inner cavity opening and gap opening conditions
- Monte Carlo Simulations
  Difference of Jovian/Saturnian system are naturally reproduced

[Sasaki, Stewart & Ida (2010) *ApJ* **714,** 1052]