巨大天体衝突による
天王星衛星形成

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佐々木貴教

CPSセミナー@Zoom 2022/10/07

本日の内容

起：太陽の周りを横倒しで回る天王星系

Slattery et al., *Icarus* (1992), Kegerreis et al., *ApJ* (2018)

承：巨大天体衝突で天王星の衛星は作れるか？

Ishizawa, Sasaki & Hosono, *ApJ* (2019)

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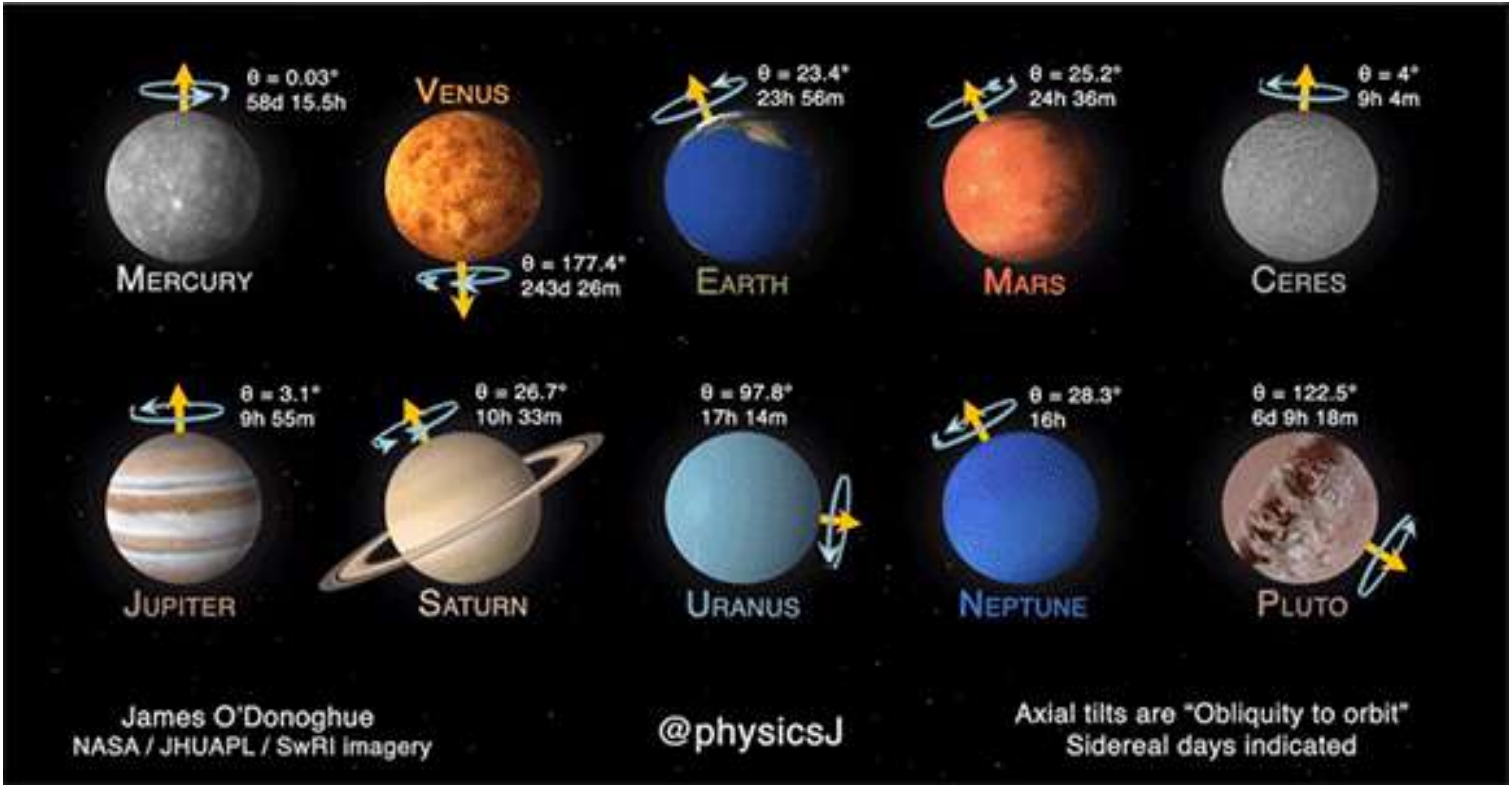
結：新しい天王星衛星形成シナリオの完成（？）

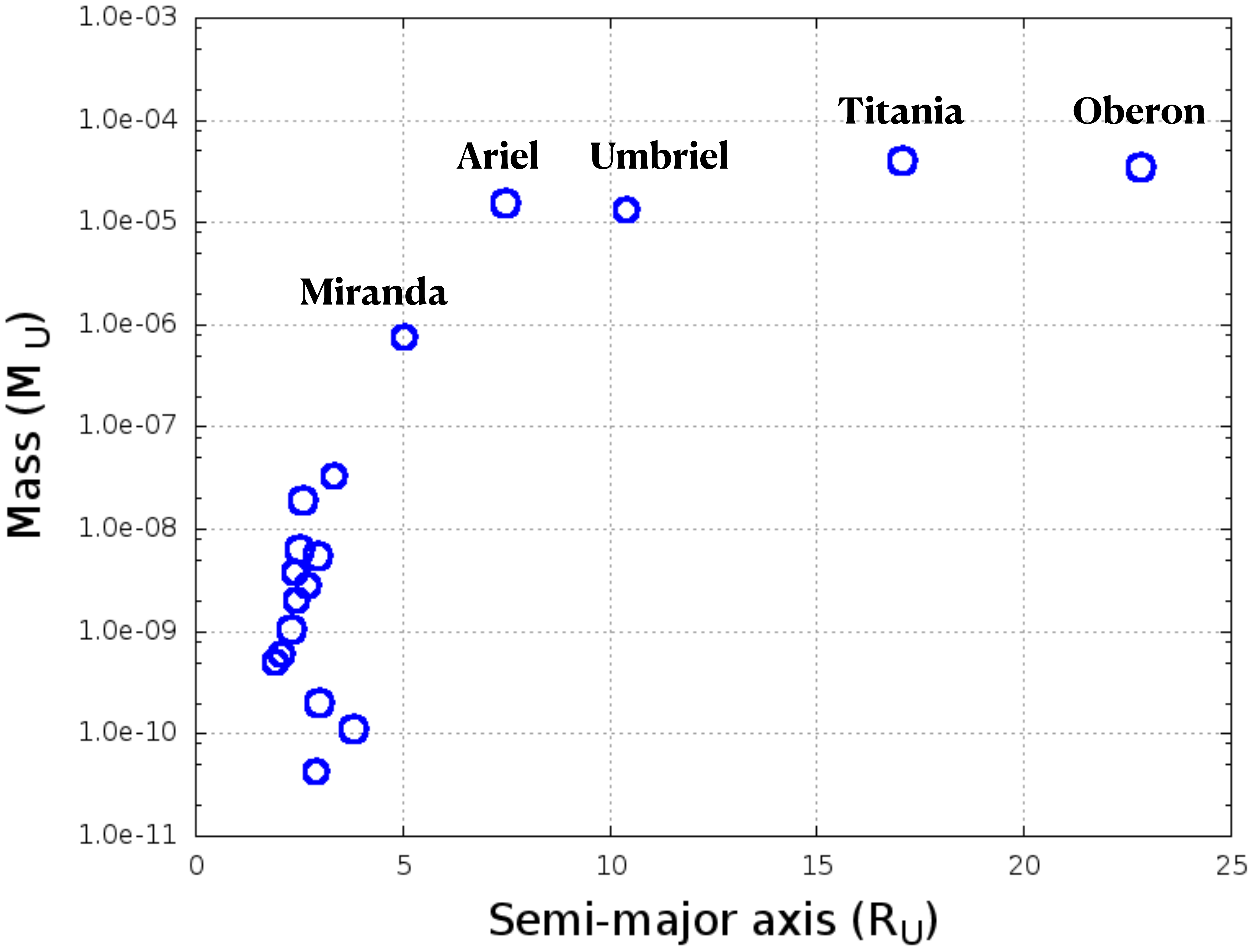
Kihara, Sasaki & Ida, *to be submitted*

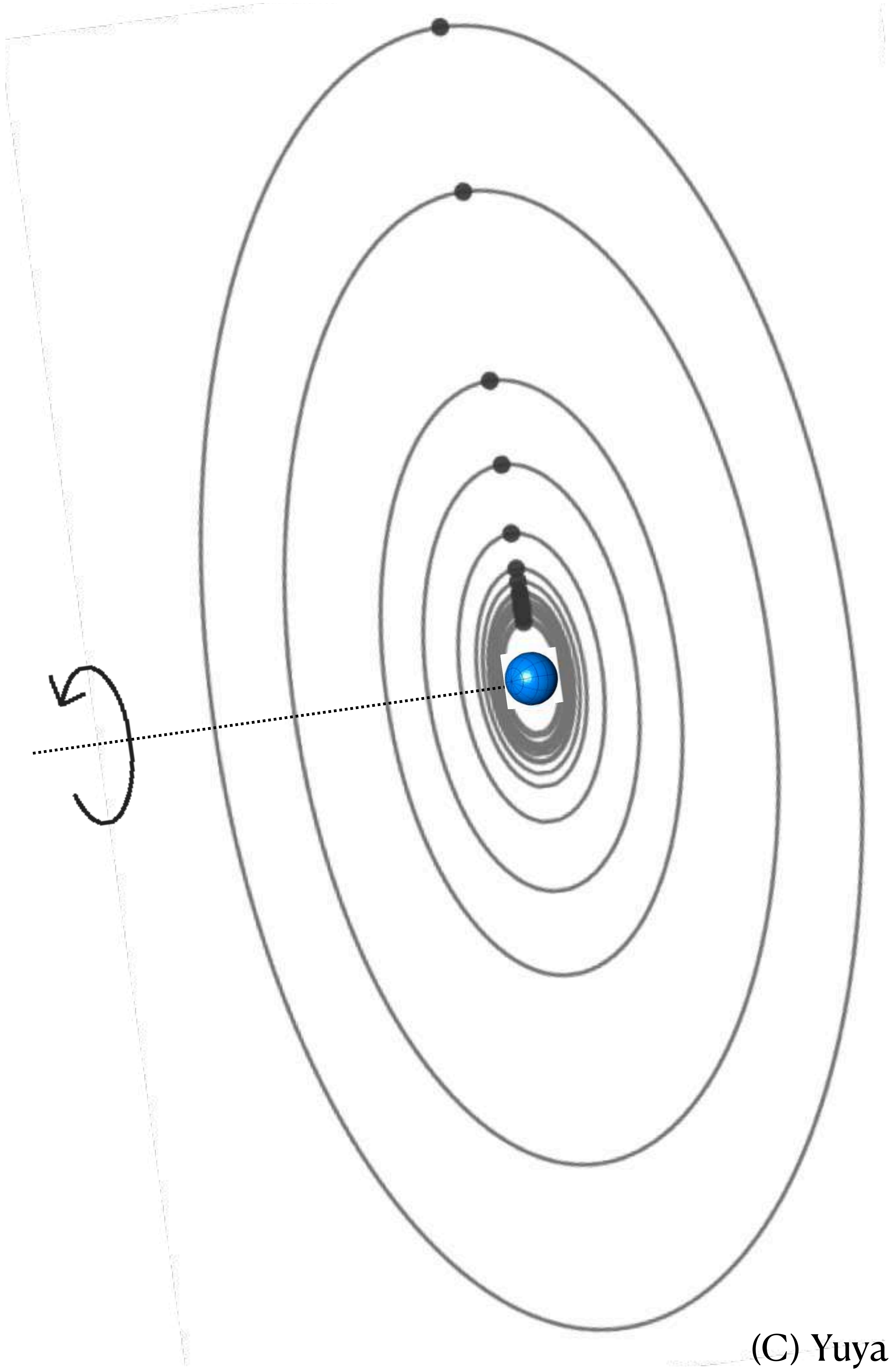
太陽系の惑星の自転



θ = 0.03°
58d 15.5h
MERCURY
VENUS
θ = 177.4°
243d 26m
θ = 23.4°
23h 56m
EARTH
θ = 25.2°
24h 36m
MARS
θ = 4°
9h 4m
CERES
θ = 3.1°
9h 55m
JUPITER
θ = 26.7°
10h 33m
SATURN
θ = 97.8°
17h 14m
URANUS
θ = 28.3°
16h
NEPTUNE
θ = 122.5°
6d 9h 18m
PLUTO
James O'Donoghue
NASA / JHUAPL / SwRI imagery
@physicsJ
Axial tilts are "Obliquity to orbit"
Sidereal days indicated

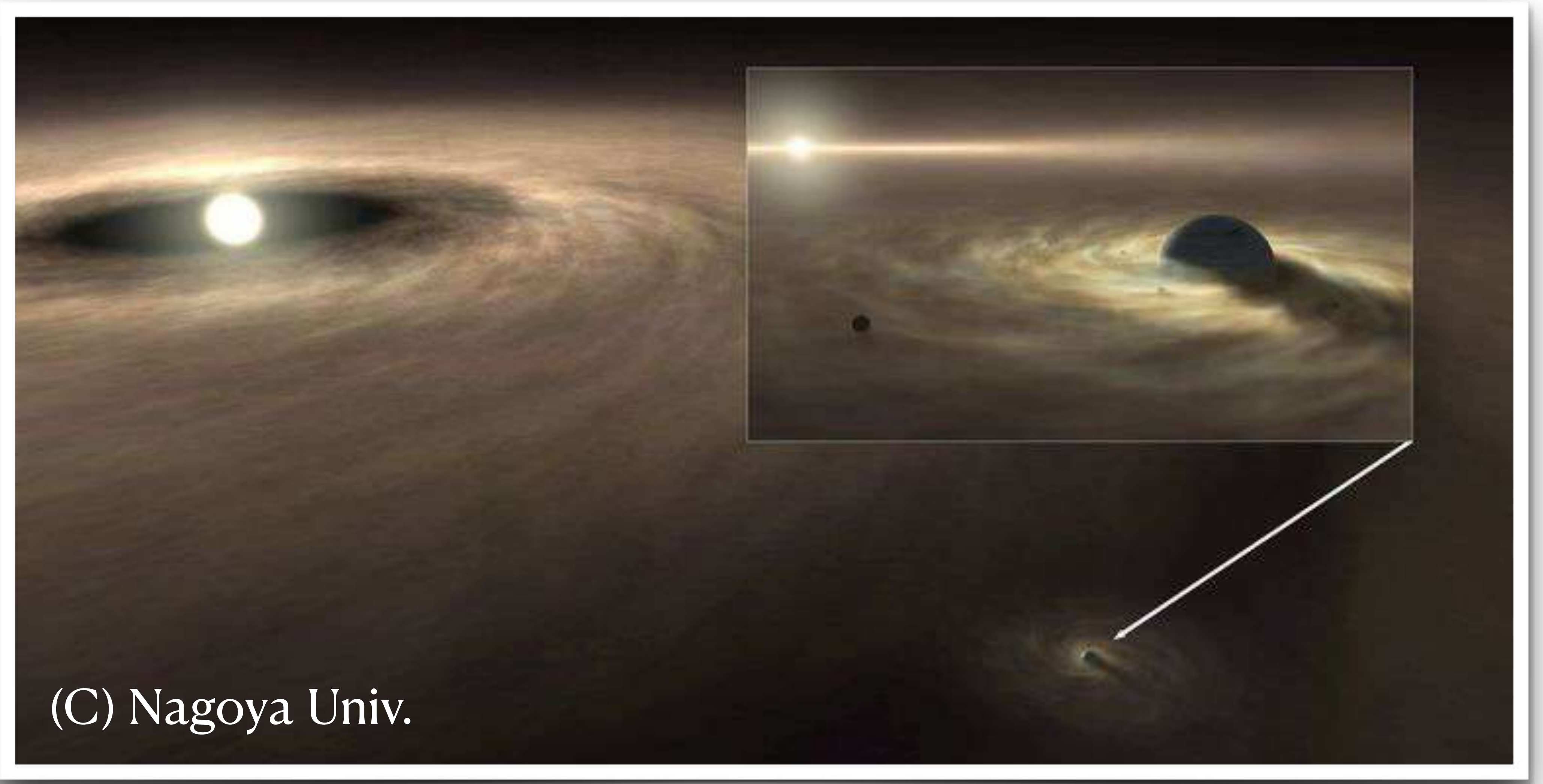
天王星衛星系の特徴

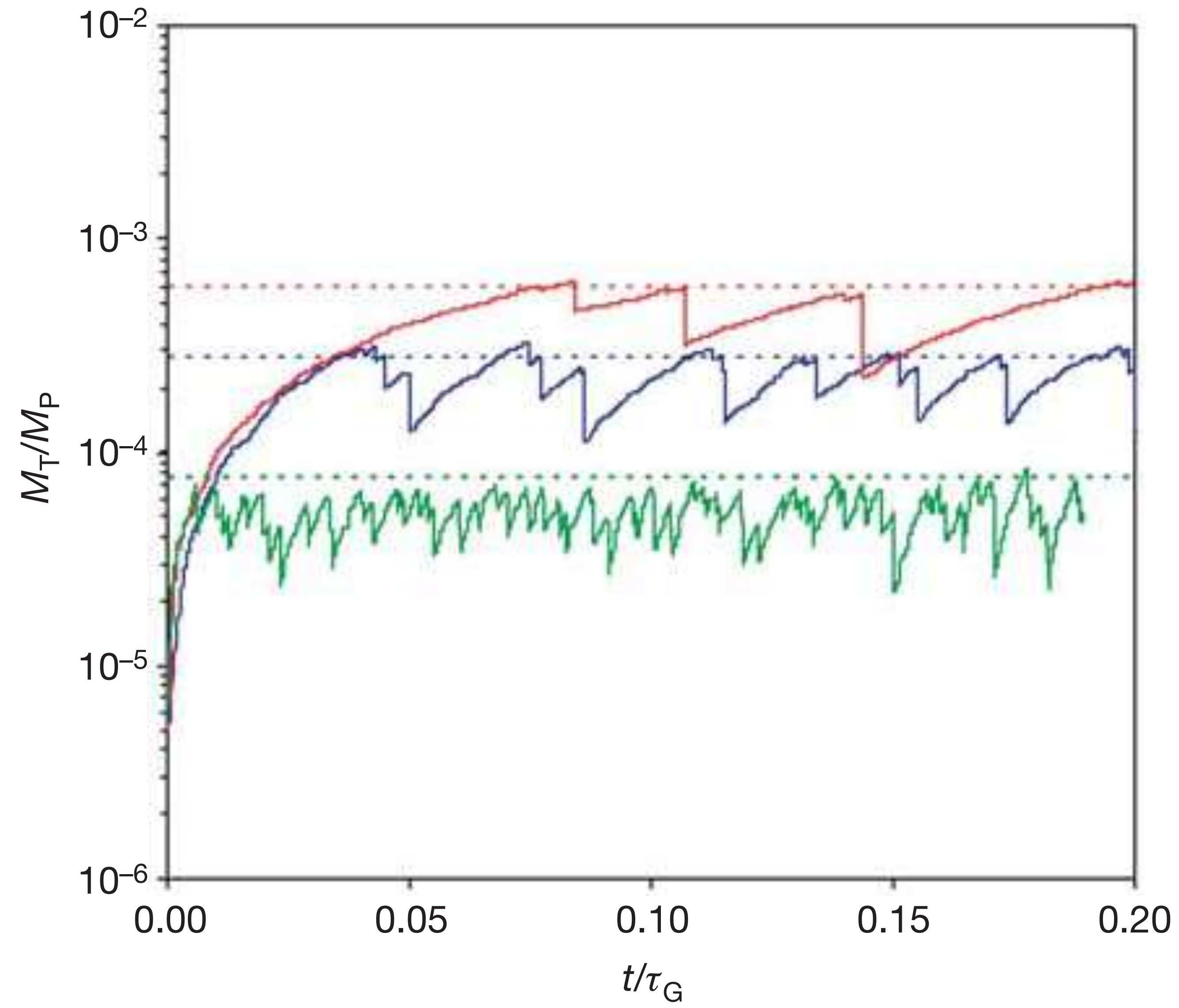


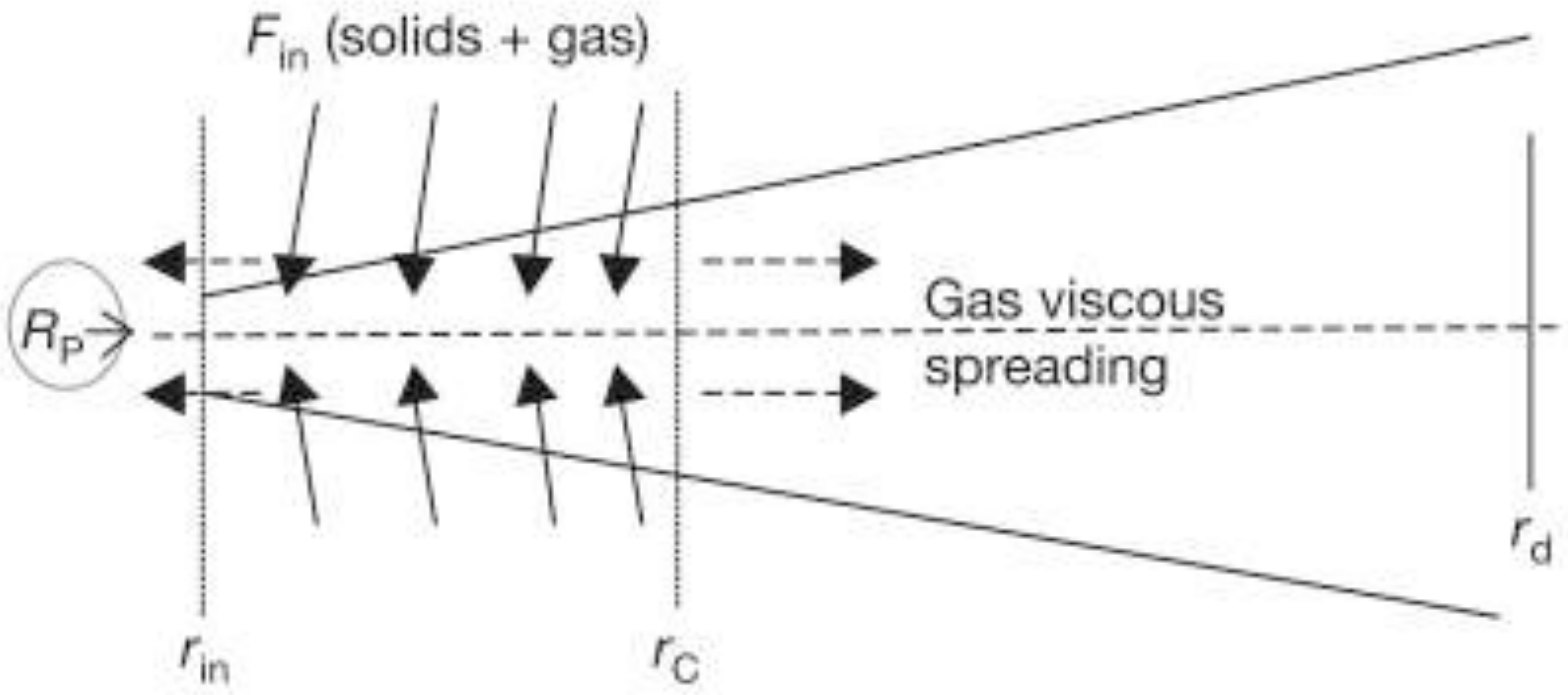


(C) Yuya Ishizawa

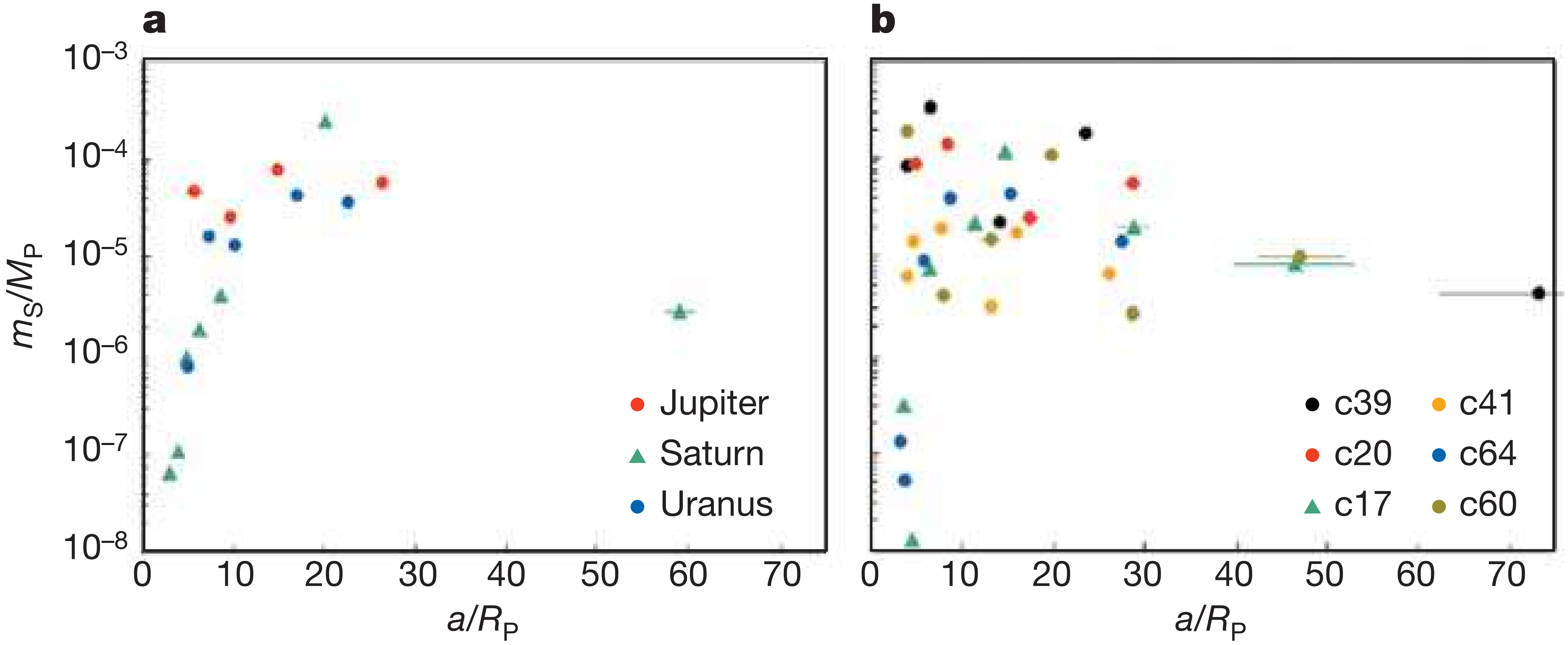
天王星衛星系の形成メカニズム（１）



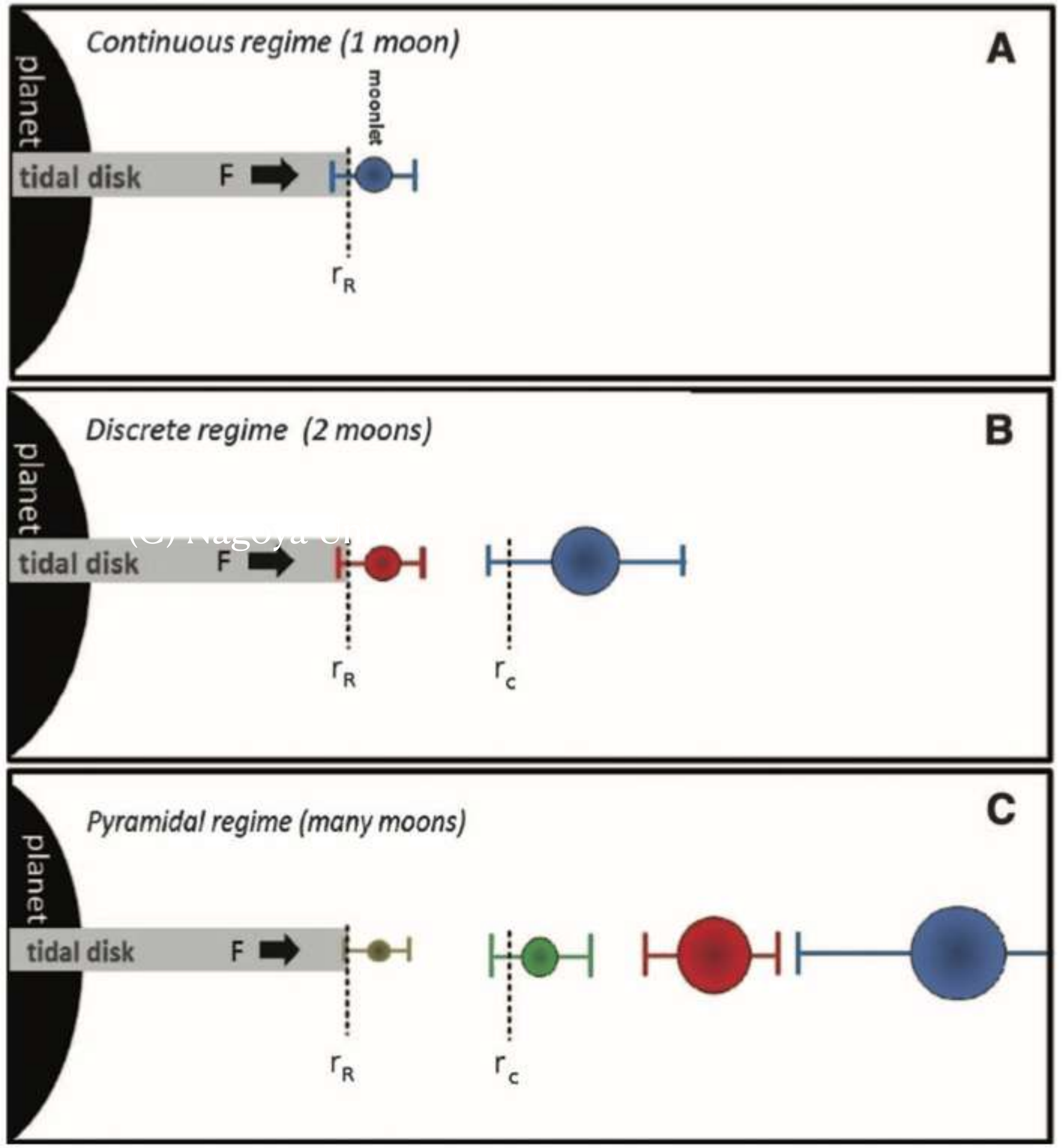


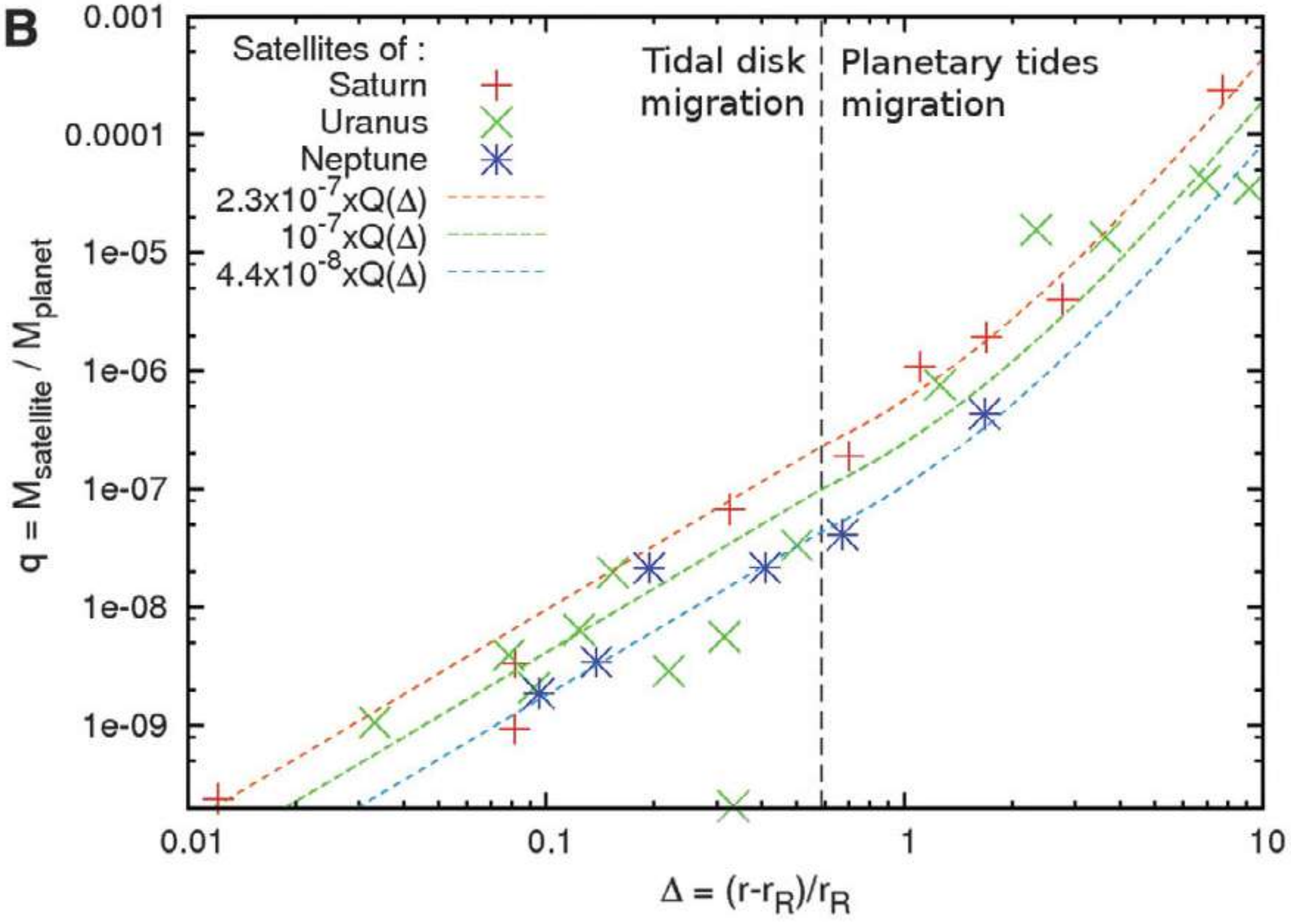


Canup & Ward (2006)



天王星衛星系の形成メカニズム（2）

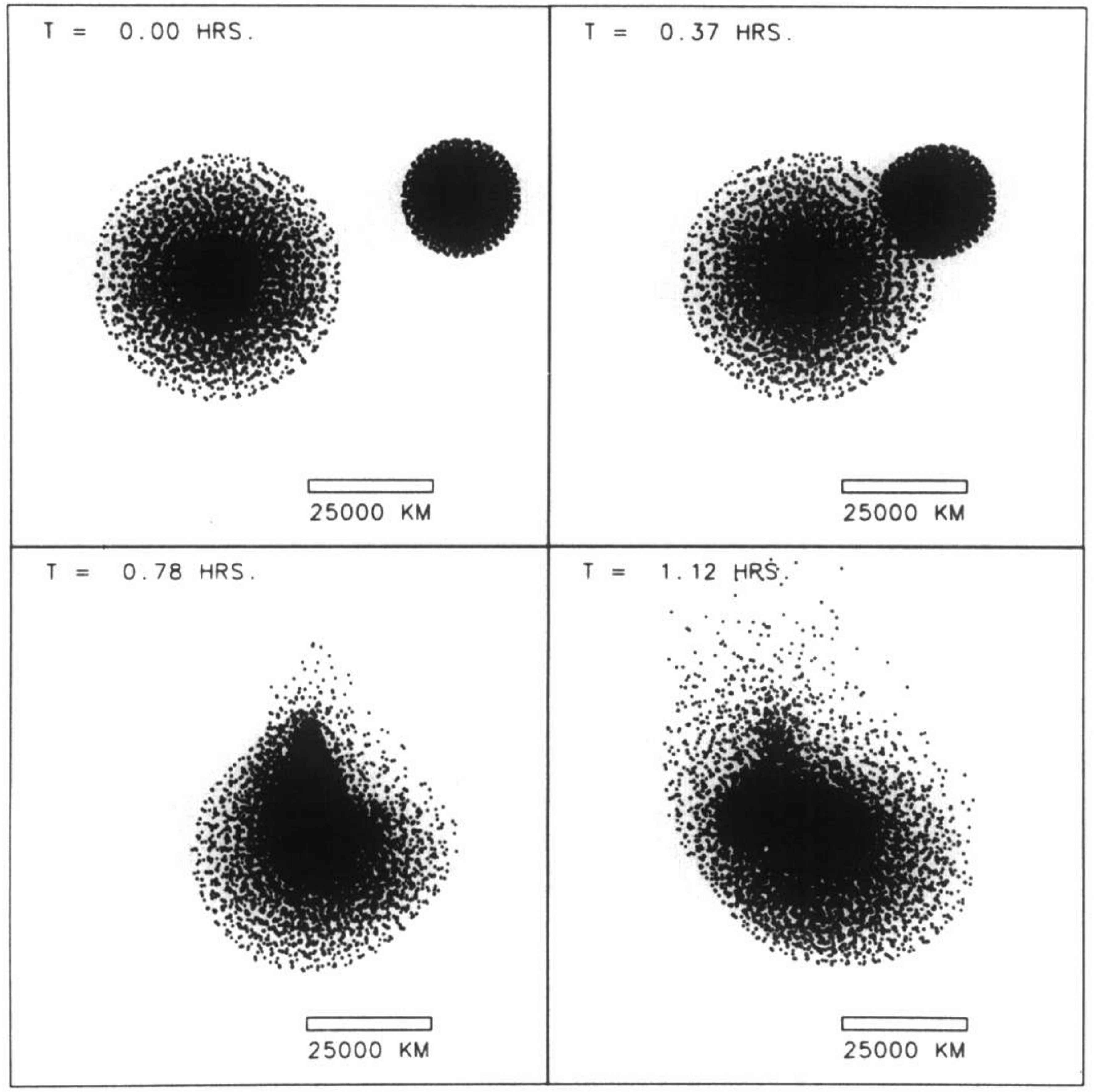




Crida & Charnoz (2012)

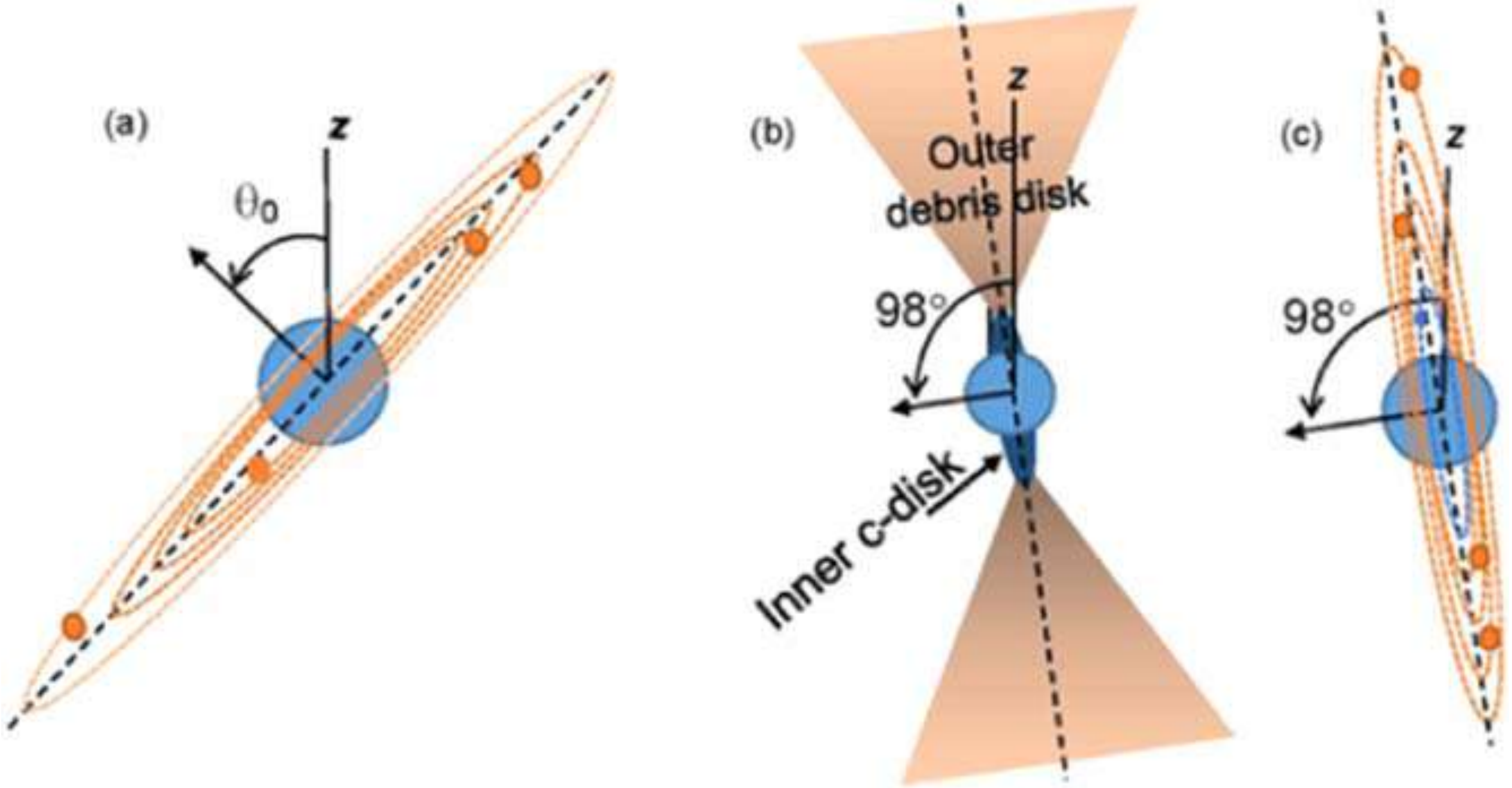
巨大天体衝突で天王星系を傾ける

Giant impact simulation (SPH; N=8,000)



Slattery et al. (1992)

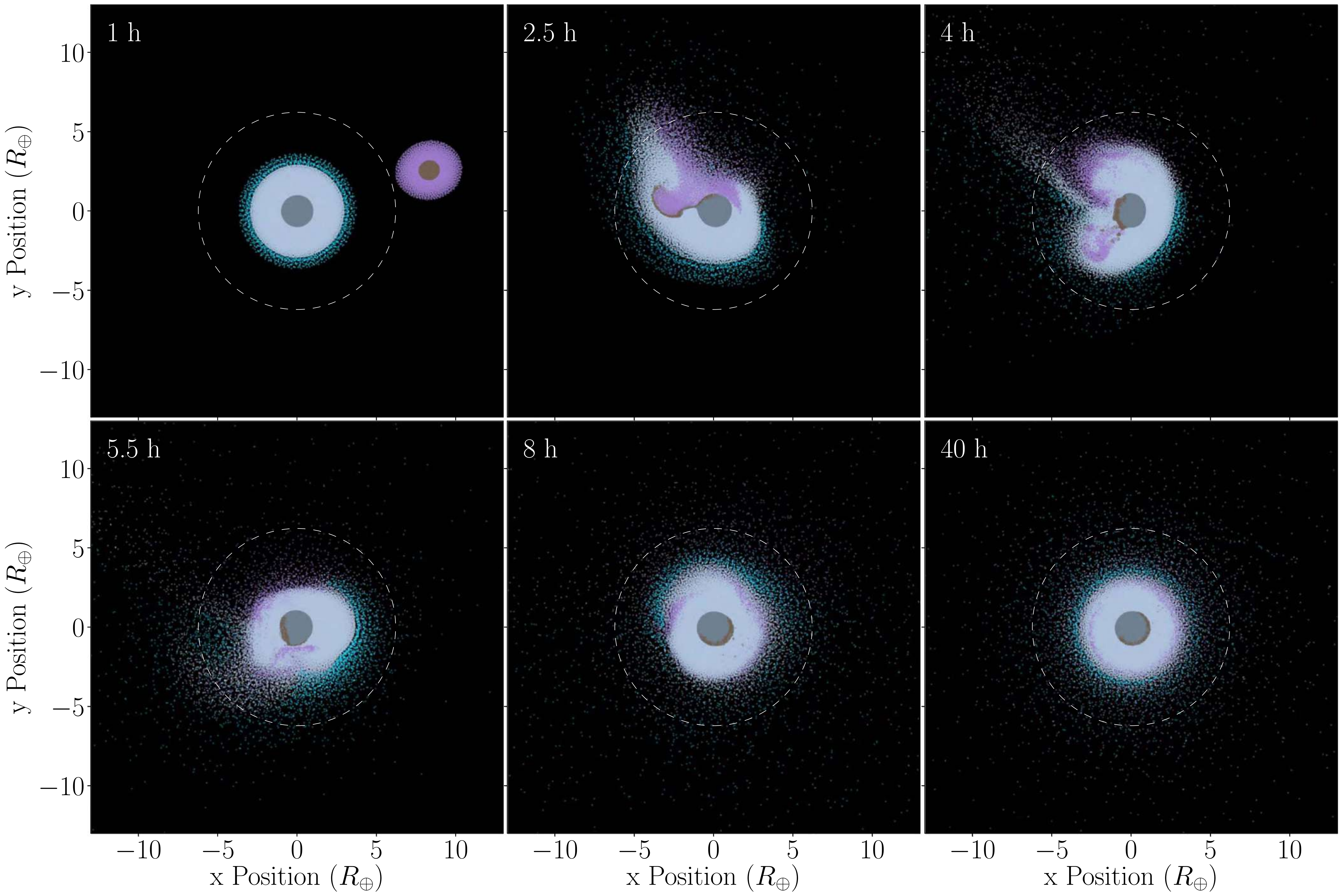
Co-accretion + giant impact concept
Morbidelli et al. (2012)

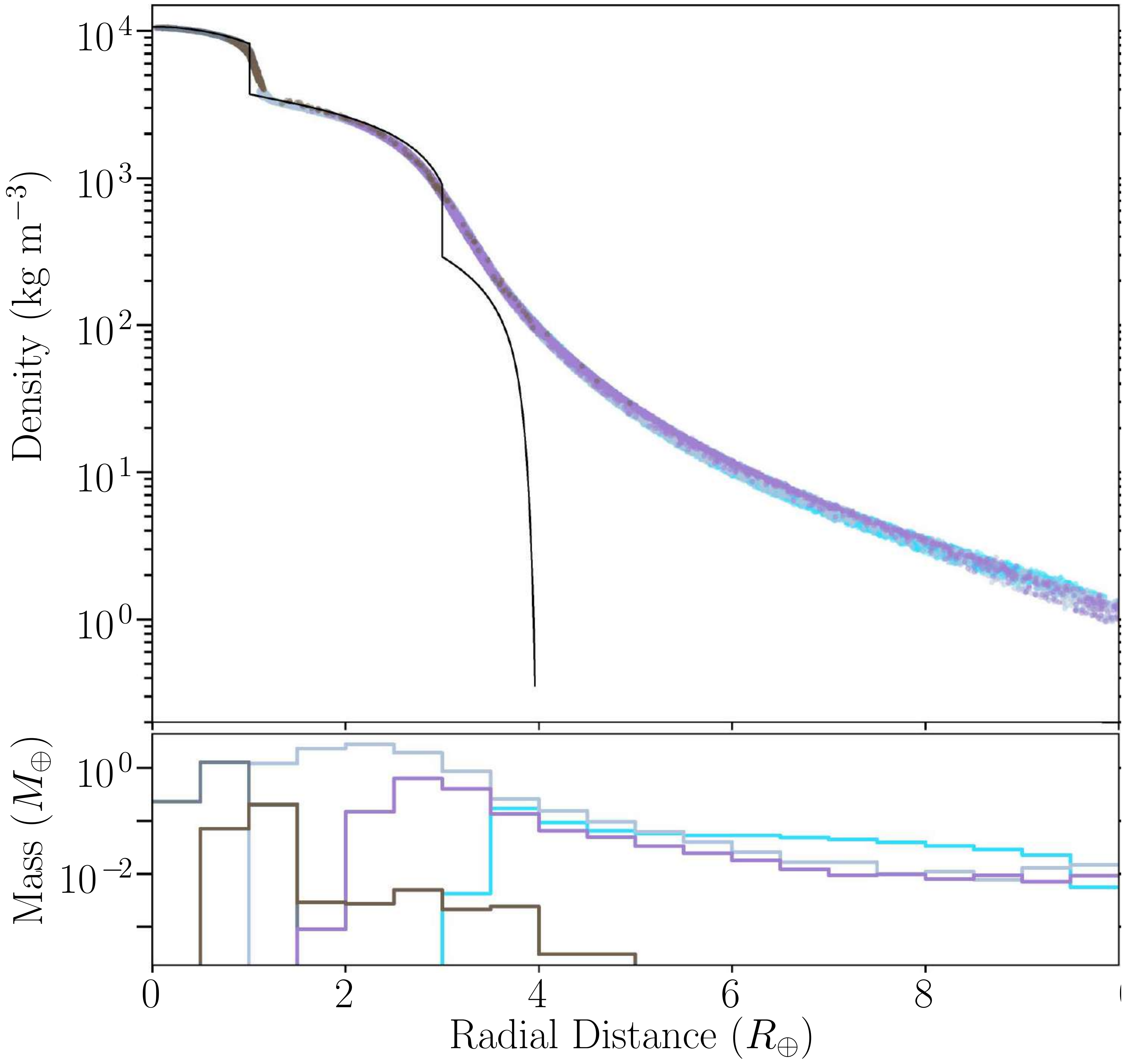


Salmon & Canup (2022)

巨大天体衝突計算（高解像度）

N = 100,000-1,000,000





Kegerreis et al. (2018)

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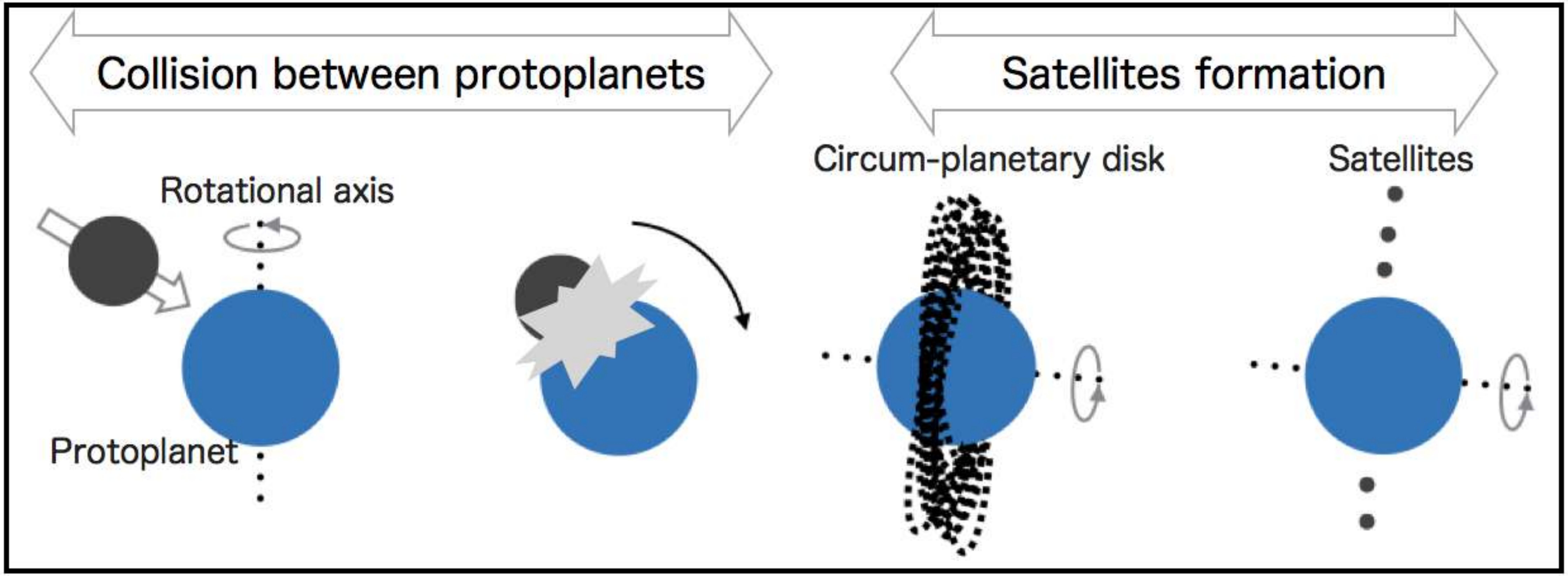


Ishizawa et al. (2019)

天王星衛星形成のN体シミュレーション

Method (N-body simulation)

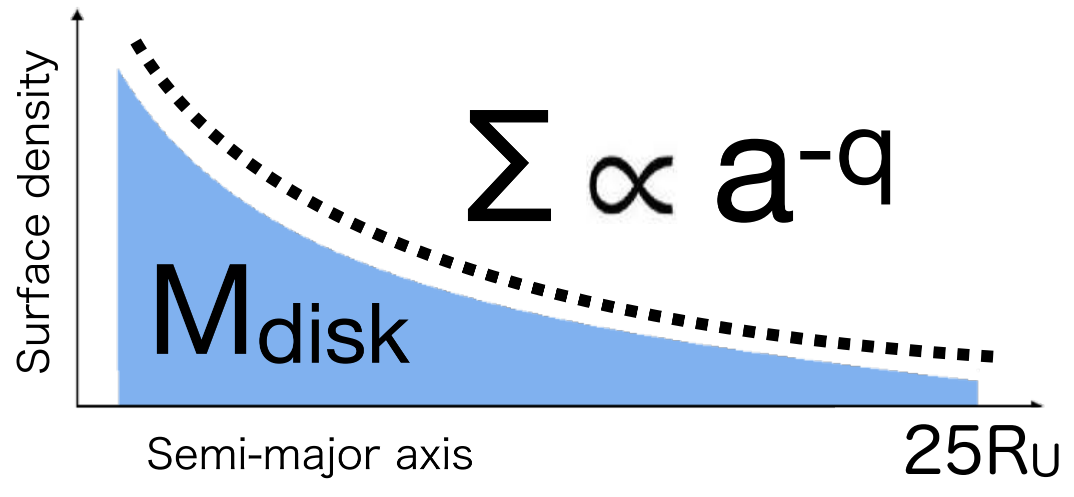
- Equation of motion : $$\frac{d^2\boldsymbol{r}_i}{dt^2} = -\sum_{j\neq i} Gm_j \frac{\boldsymbol{r}_i - \boldsymbol{r}_j}{|\boldsymbol{r}_i - \boldsymbol{r}_j|^3}$$
- **Number of disk particles : N_{disk} = 10,000**
- **Collisions** are moderately inelastic, and **mergers** occur if the Jacobi energy after the collision is negative (e.g., Kokubo et al., 2000)
- Using 4th Hermite scheme and Leap Frog method for the numerical time integration
- Using FDPS for speeding up calculations

  (Framework for Developing Particle Simulator ; Iwasawa et al., 2016)

Disk models with negative gradient

Surface density of a circumplanetary disk generated by a GI is assumed to have a power-low distribution

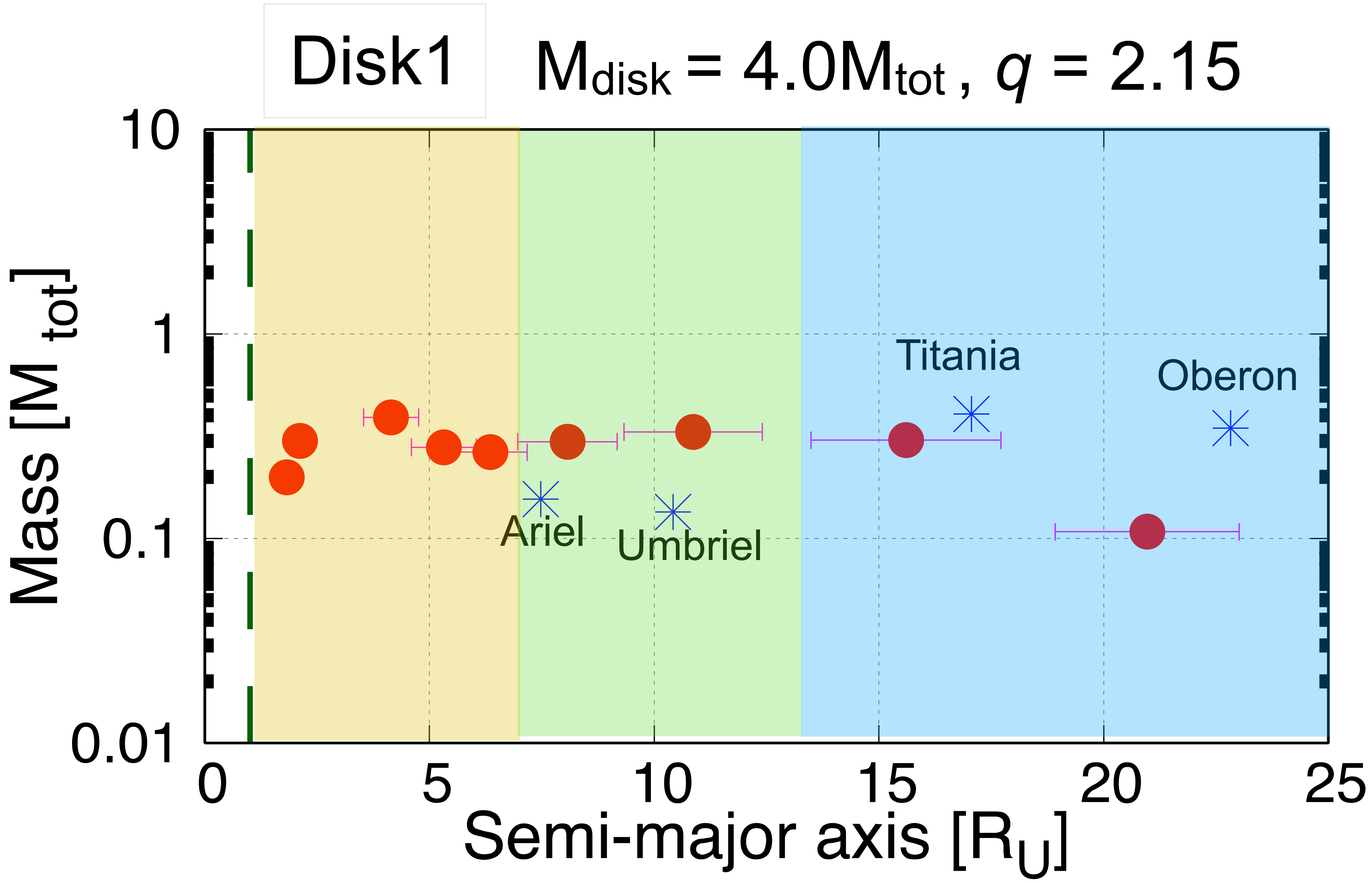
- Disk size a → R_U < a < 25R_U
- Disk mass M_{disk} → Several times M_{tot} (the total satellite mass)
- Surface density Σ(a) ∝ a^{-q} → The power-index -*q* is varied as a parameter



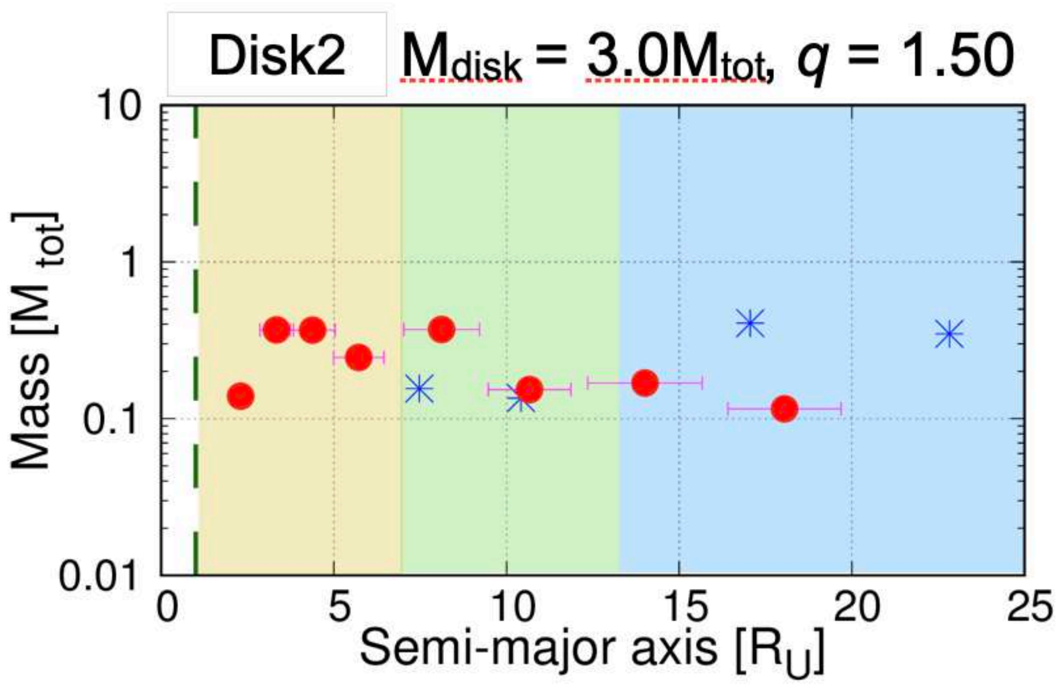
	Disk1	Disk2	Disk3	Disk4	Disk5	Disk6
M_{disk}	4M_{tot}	3M_{tot}	3M_{tot}	4M_{tot}	3M_{tot}	10M_{tot}
q	2.15	1.50	1.95	1.95	3.0	2.15

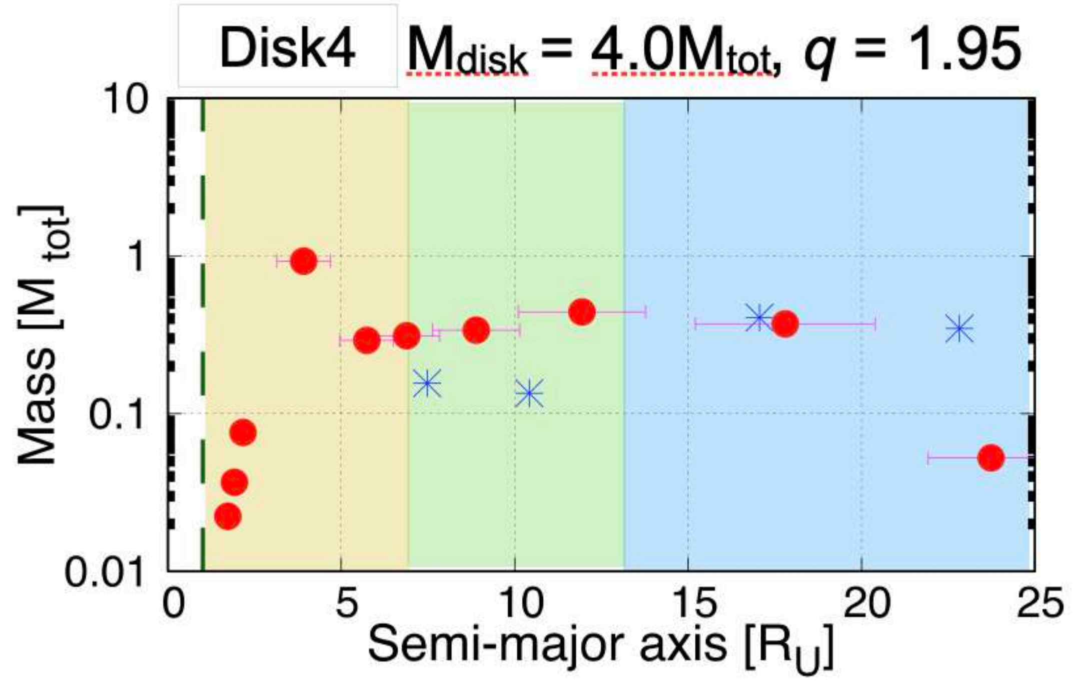
These disk models have **negative gradients** directly inferred from the results of the SPH simulations (Kegerreis et al., 2018)

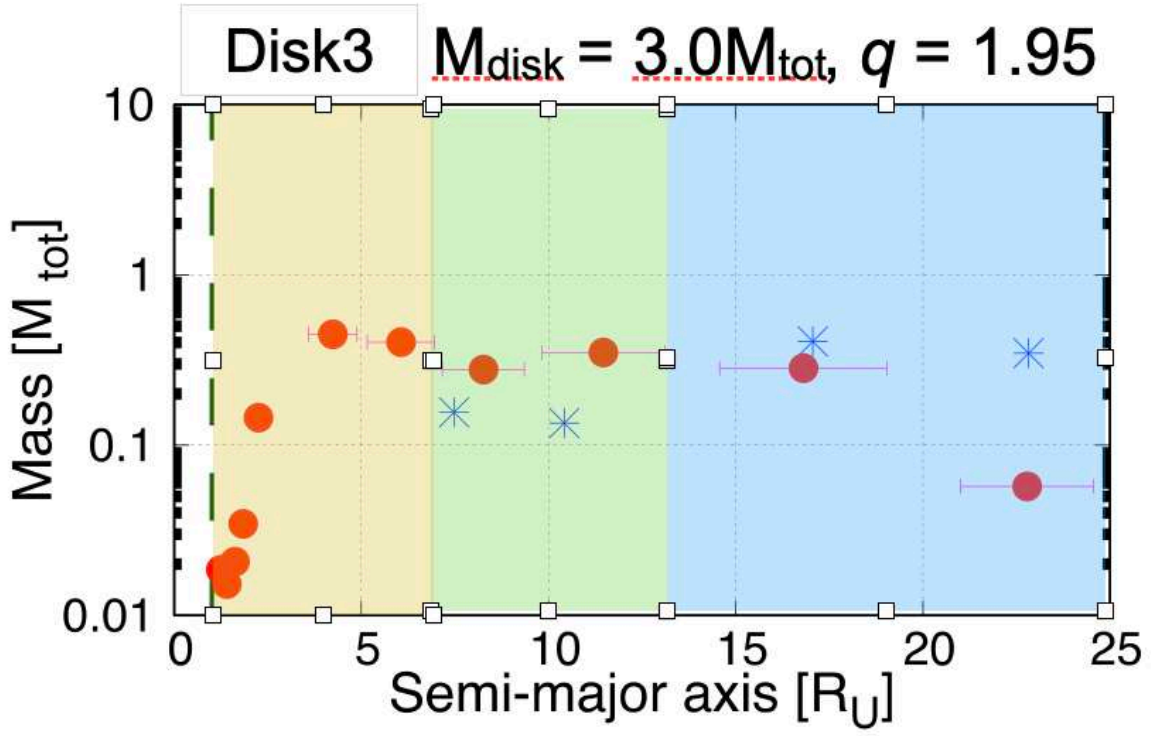
結果：形成された天王星衛星系の特徴



$R_U < a < 7R_U$	extra massive satellites
$7R_U < a < 13R_U$	too large satellites
$13R_U < a$	too small satellites





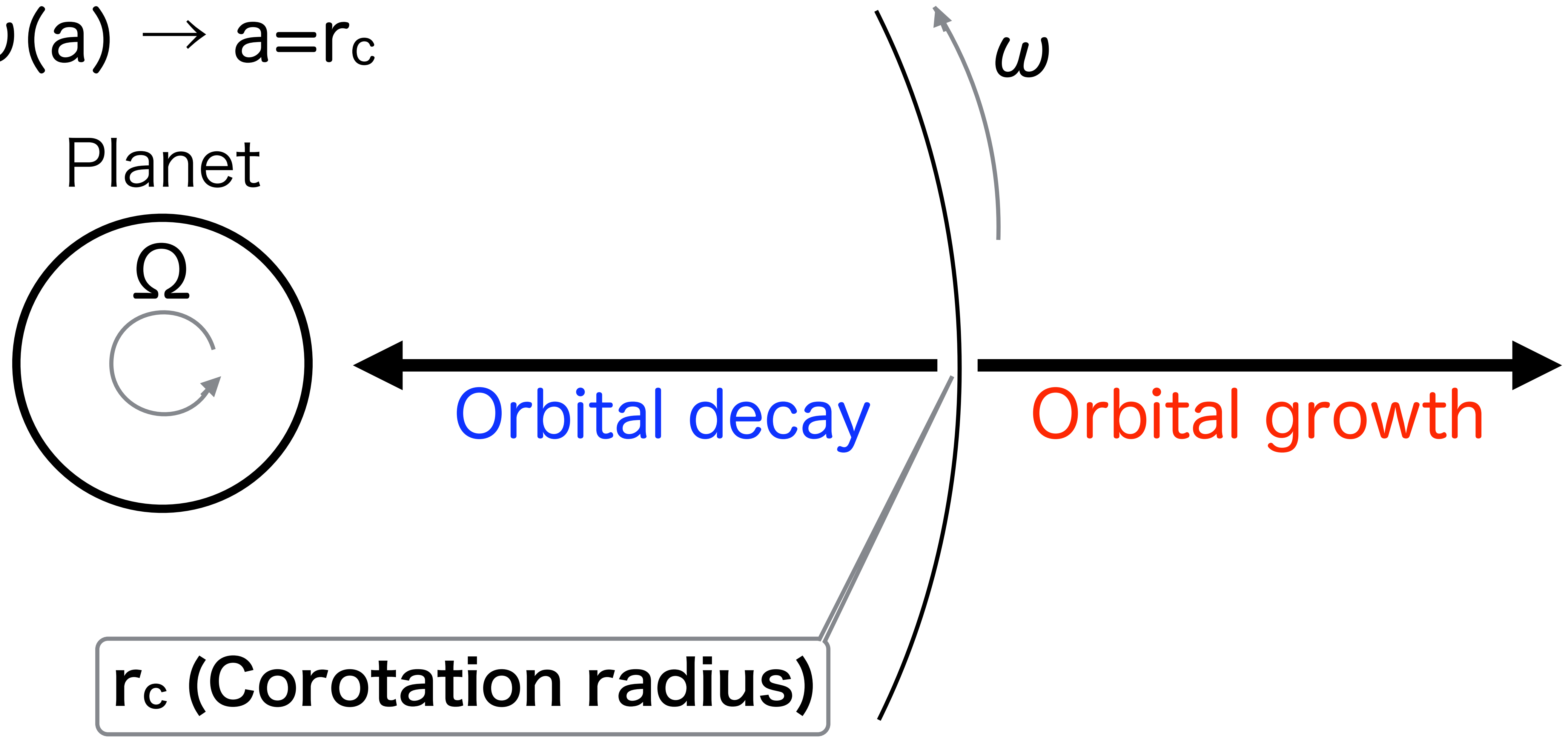


Ishizawa et al. (2019)

潮汐による軌道進化

Corotation radius : the orbital radius where a satellite has an angular velocity equal to a spin angular velocity of a planet

$\Omega = \omega(a) \rightarrow a = r_c$



(Charnoz et al., 2011)

- Inside ：$\Omega < \omega$, recieving negative torque ⇒ Orbital decay
- Outside：$\Omega > \omega$, recieving positive torque ⇒ Orbital growth

The corotation radius of Uranus $r_c \sim 3.3 R_U$

議論：衛星の潮汐軌道進化を考慮する

A satellite's semi-major axis evolves according to

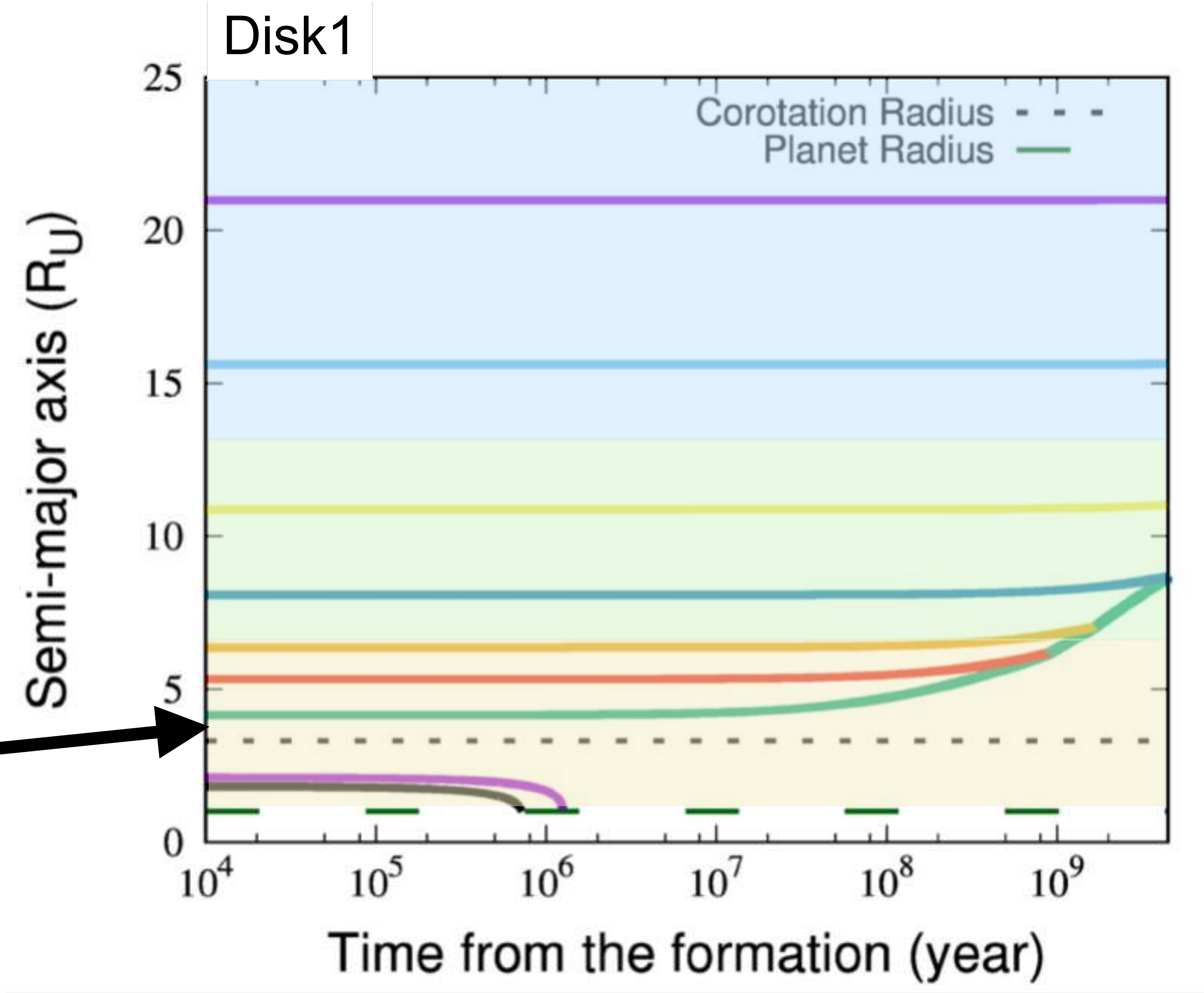
$$\frac{\mathrm{d}a_{\mathrm{s}}}{\mathrm{d}t} = \mathrm{sgn}(a_{\mathrm{s}} - r_{\mathrm{c}}) \frac{3k_{2\mathrm{p}} M_{\mathrm{s}} G^{1/2} R_{\mathrm{p}}^5}{Q_{\mathrm{p}} M_{\mathrm{p}}^{1/2} a_{\mathrm{s}}^{11/2}}$$

(Charnoz et al. 2011)

$k_{2p} = 0.104$ **(Gavrilov and Zharkov 1977)**

$Q_p = 11{,}000$ **(Tittemore and Wisdom 1989)**

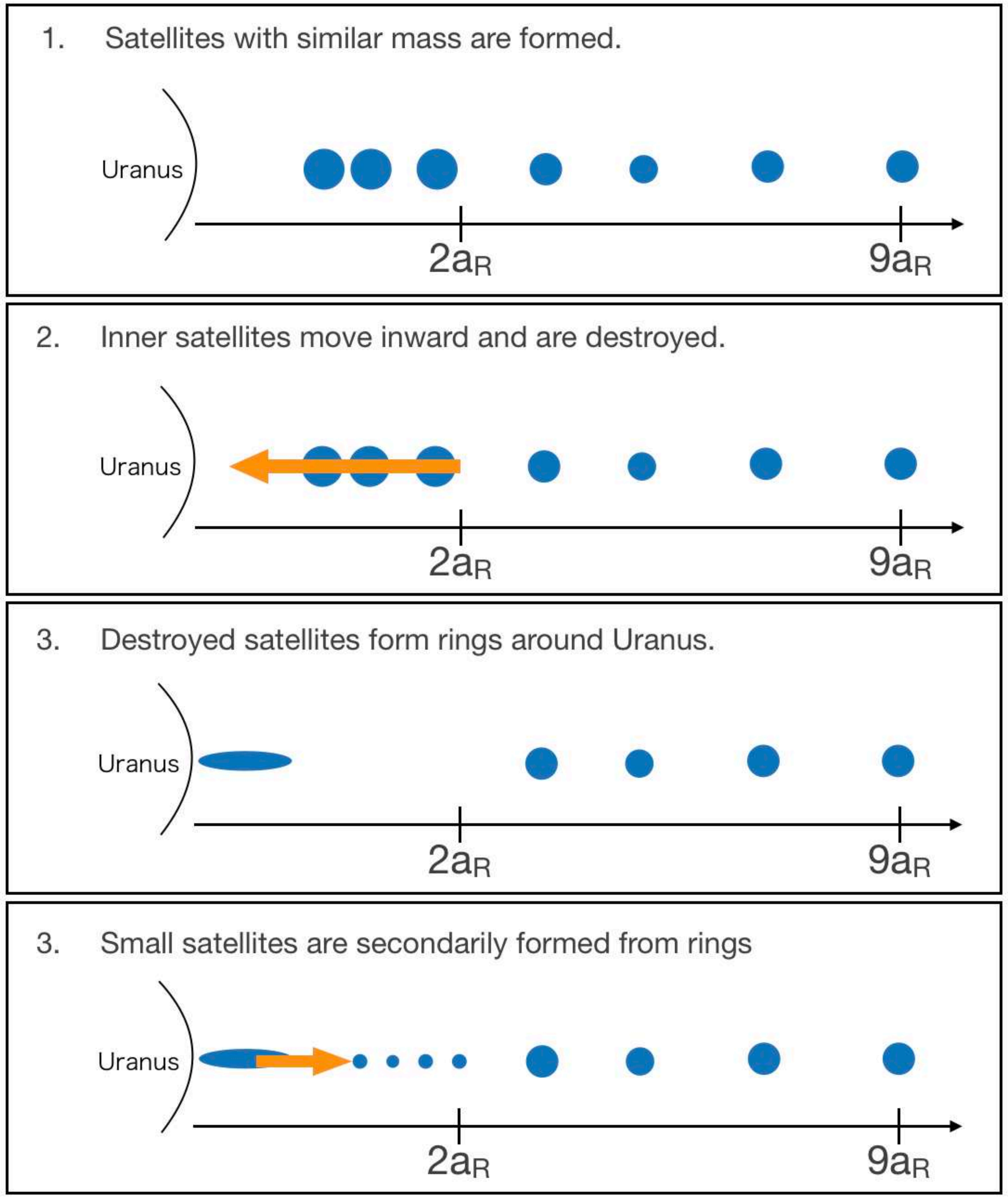
The corotation radius of Uranus $r_c \sim 3.3R_U$



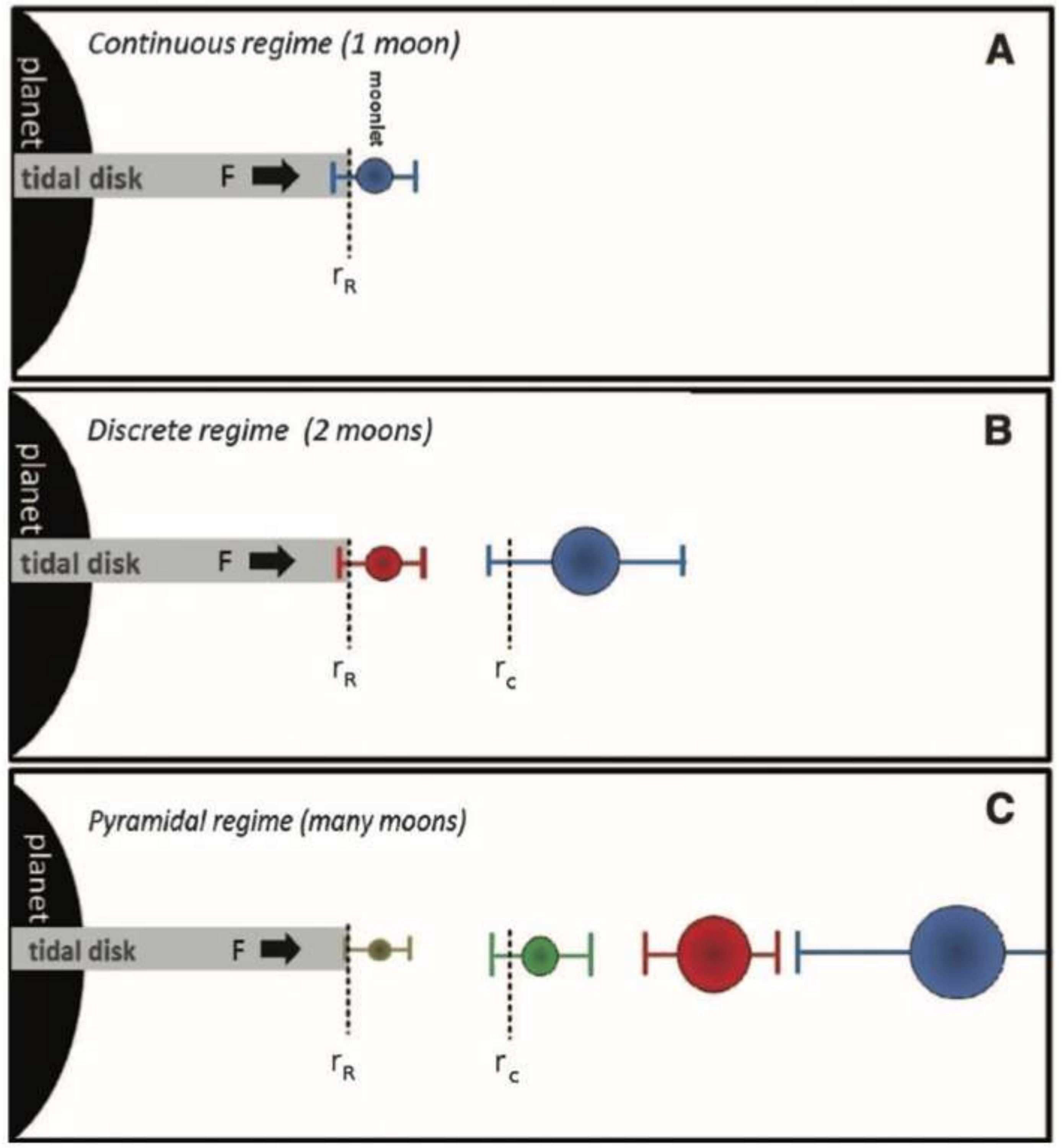
- Inner satellites fall into Uranus or move outward
- Satellites in the middle merge each other
- Outer satellites (>10RU) remain in the almost same orbits

Ishizawa et al. (2019)

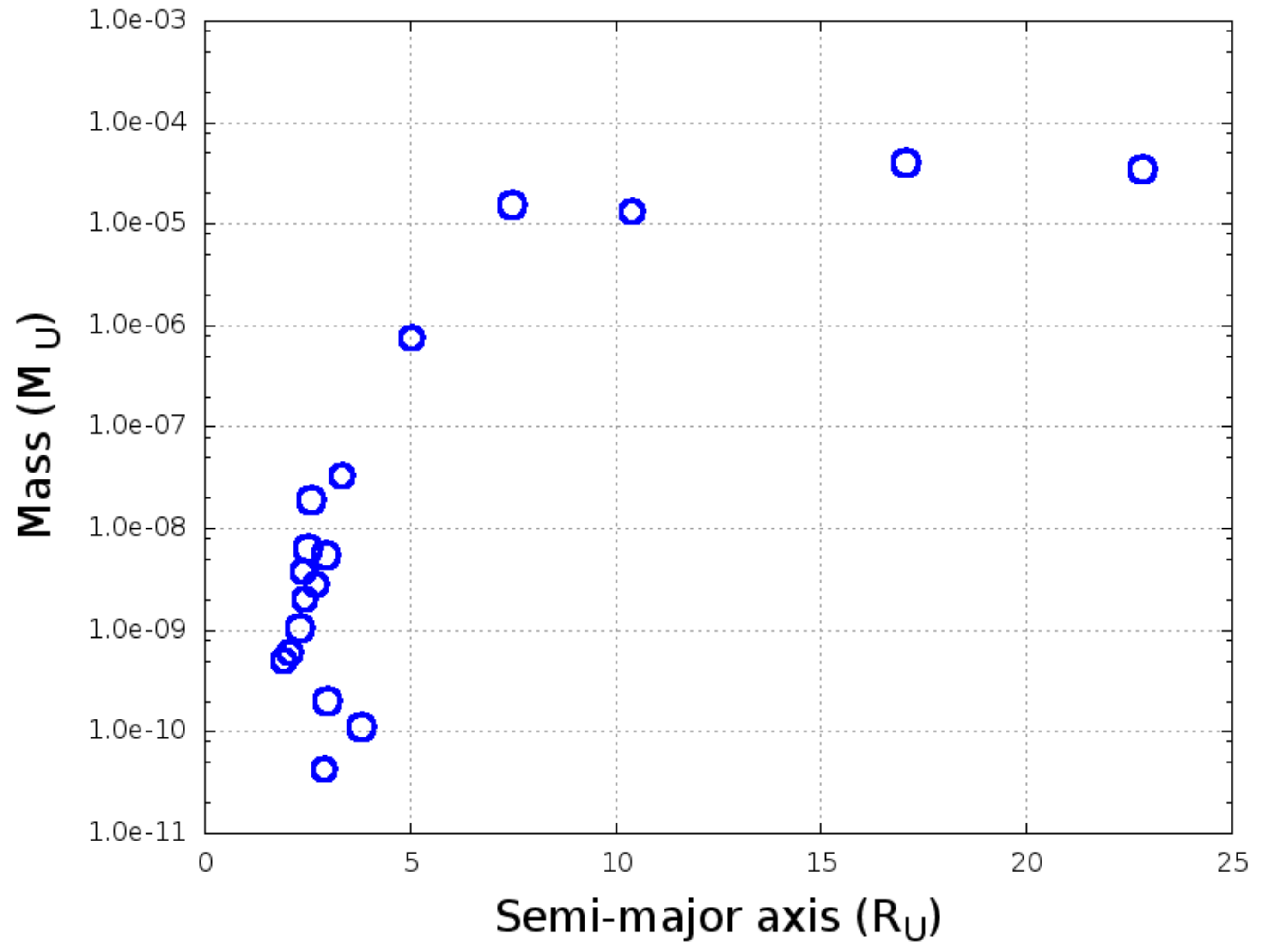
リングからの内側衛星の形成可能性



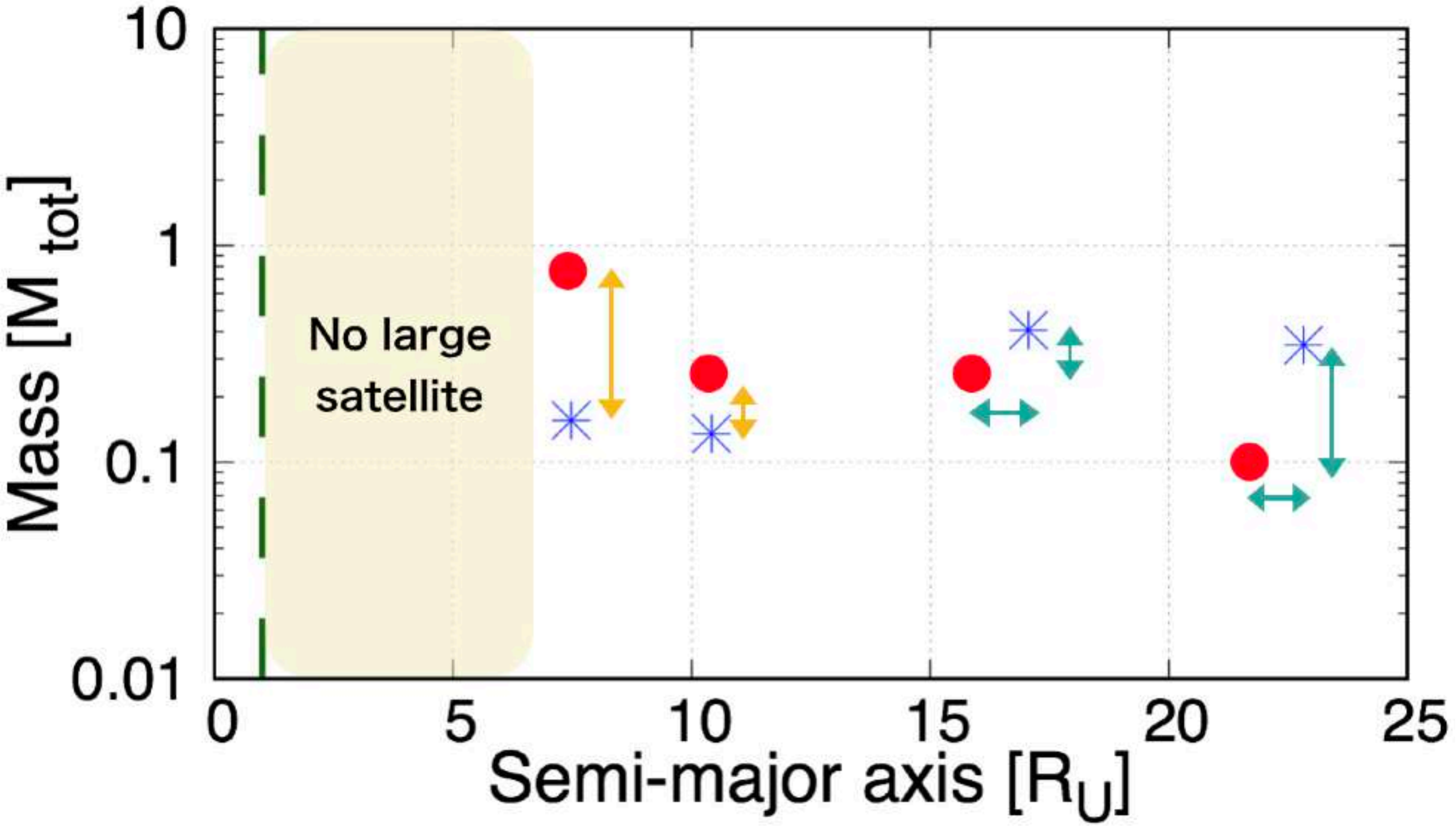
(C) Yuya Ishizawa



Crida & Charnoz (2012)



結論：天王星衛星系を再現できなかった



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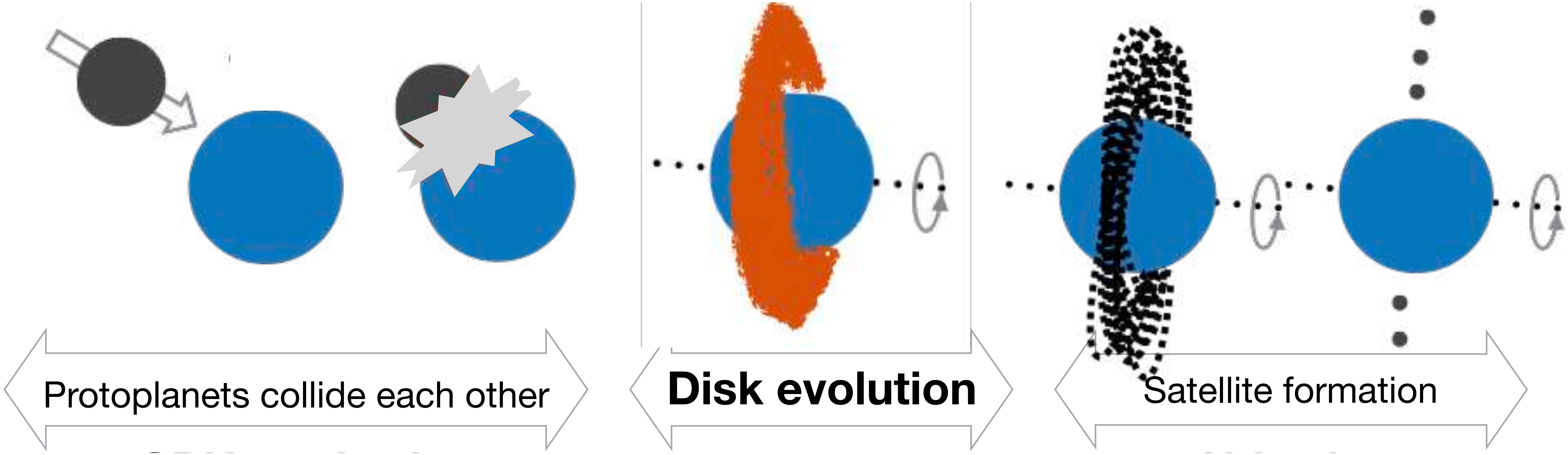
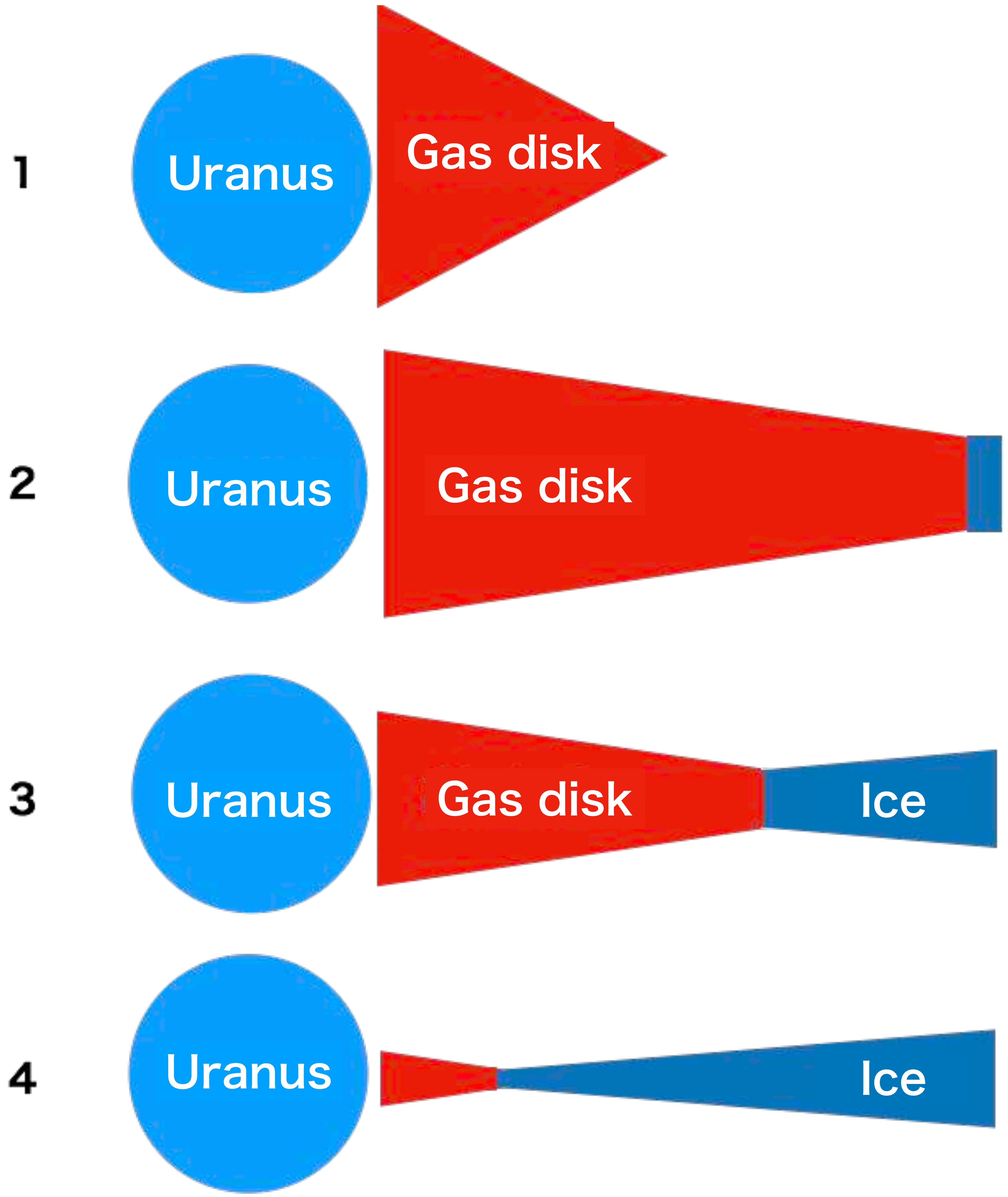
周天王星円盤の進化を考える必要がある



(C) Yuya Ishizawa

周天王星円盤の進化の概念図



An impact generates a gas disk of H/He and vaporized H_2O and rock

Viscous diffusion and radiative cooling of the gas disk

Ice condensates when T_{disk} falls bellow the freezing point of H_2O

A disk of ice has more mass on the outer side

円盤進化モデル

- **Viscosity *ν*** (Shakura & Sunyaev 1973)

  α is a constant parameter to represent the turbulence strength

$$\nu \sim \alpha c_s^2 \Omega^{-1}$$

- **Local disk temperature *T***

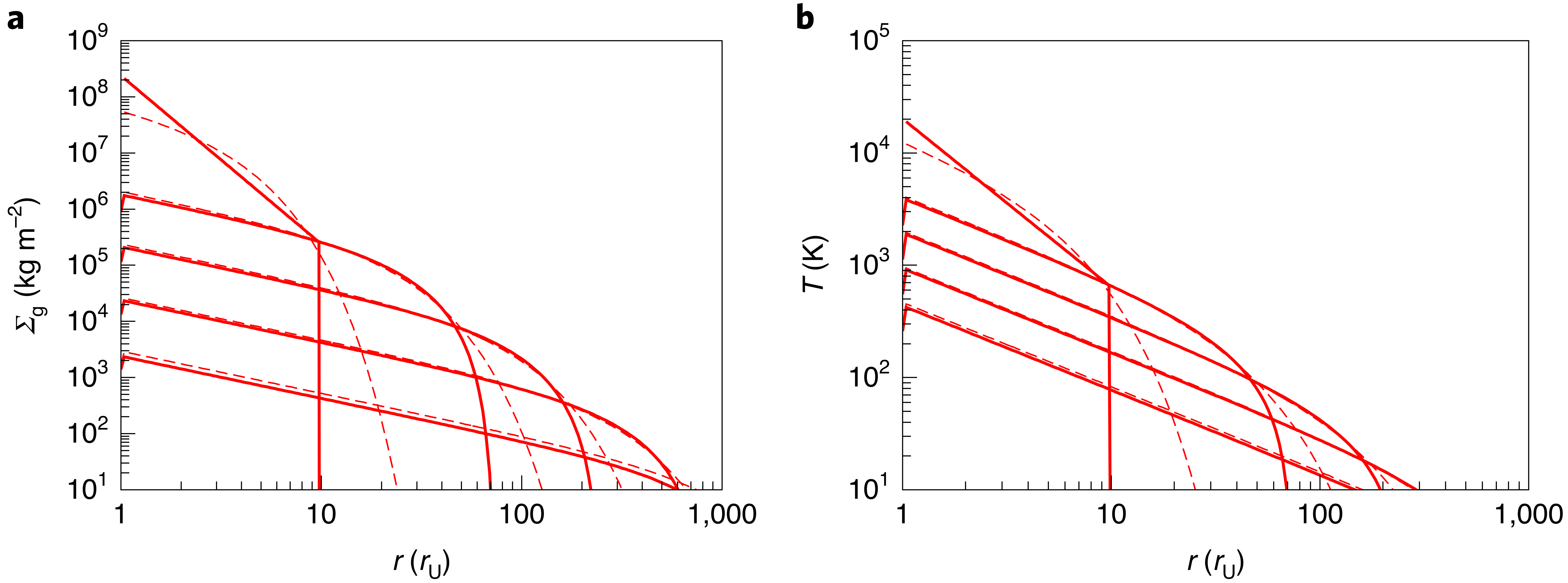
  Equilibrium between viscous heating and radiative cooling

$$T \simeq \left(\frac{9\, G M_{\mathrm{U}} \Sigma_{\mathrm{g}} \nu}{8\, \sigma r^3} \right)^{1/4}$$

- **Surface density of gas (H/He/H_2O) Σ_g**

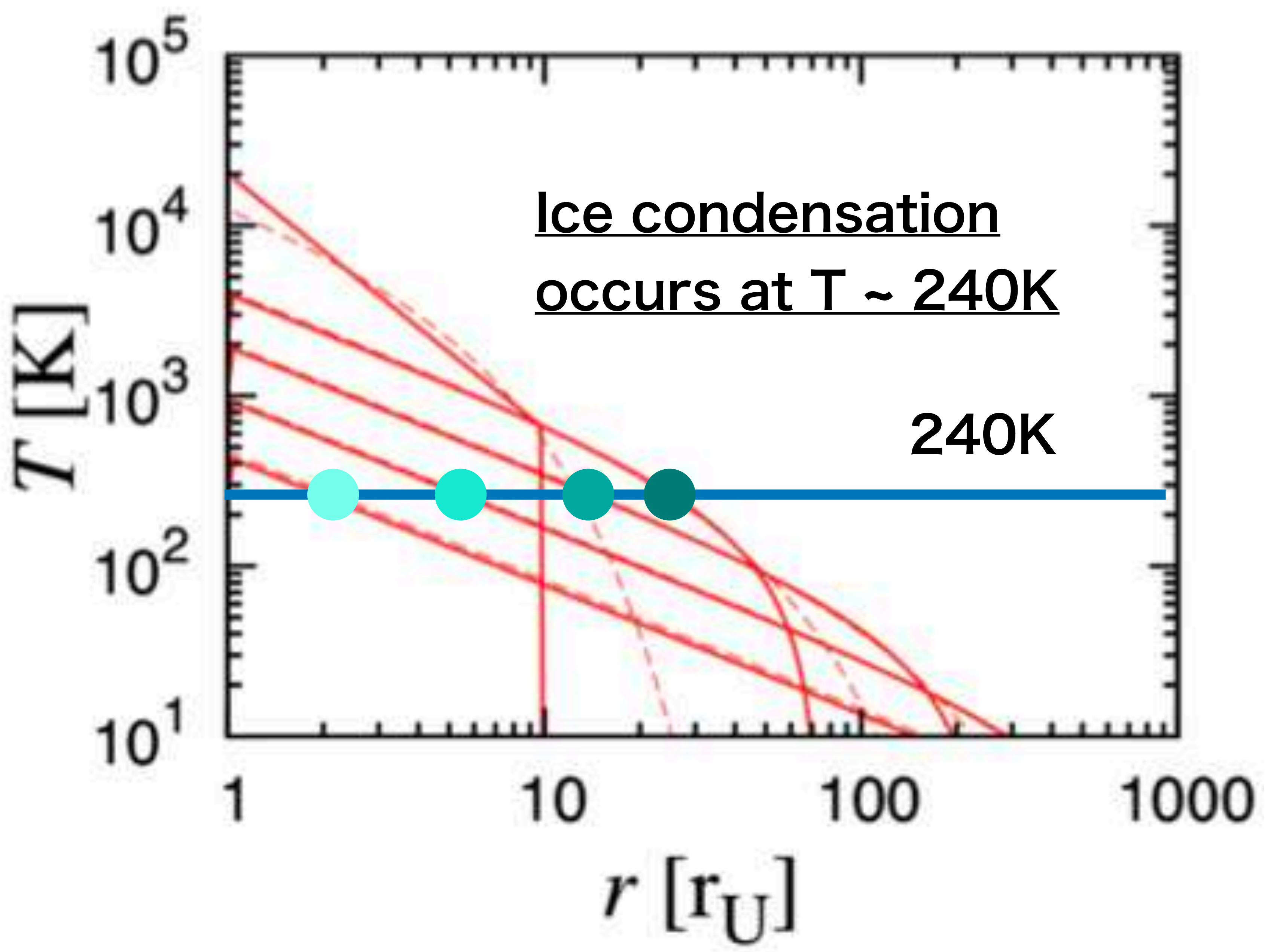
  Surface density evolves according to the viscous diffusion equation

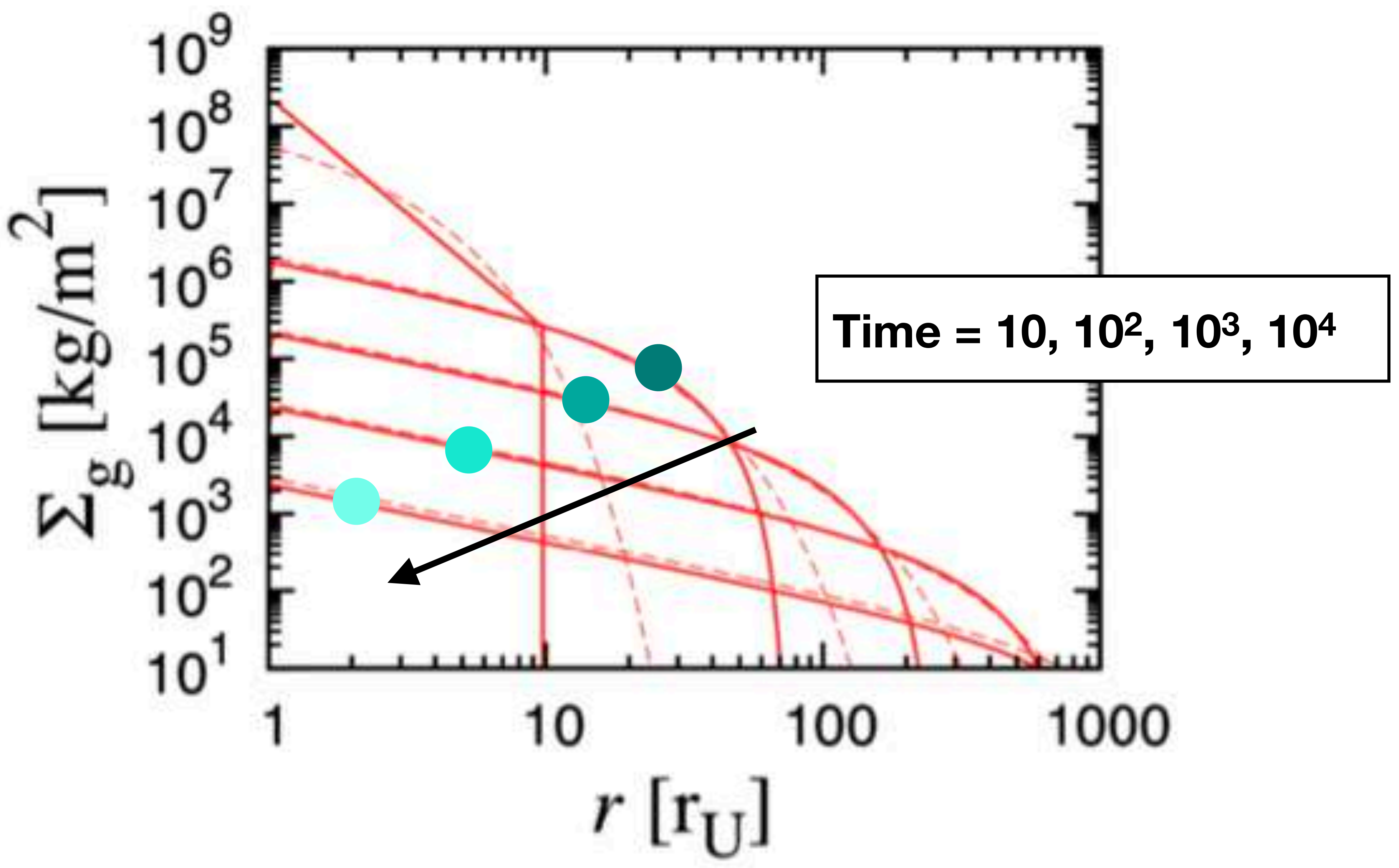
$$\frac{\partial \Sigma_{\mathrm{g}}}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left[3 r^{1/2} \frac{\partial}{\partial r} (\Sigma_{\mathrm{g}} \nu r^{1/2}) \right] = 0$$

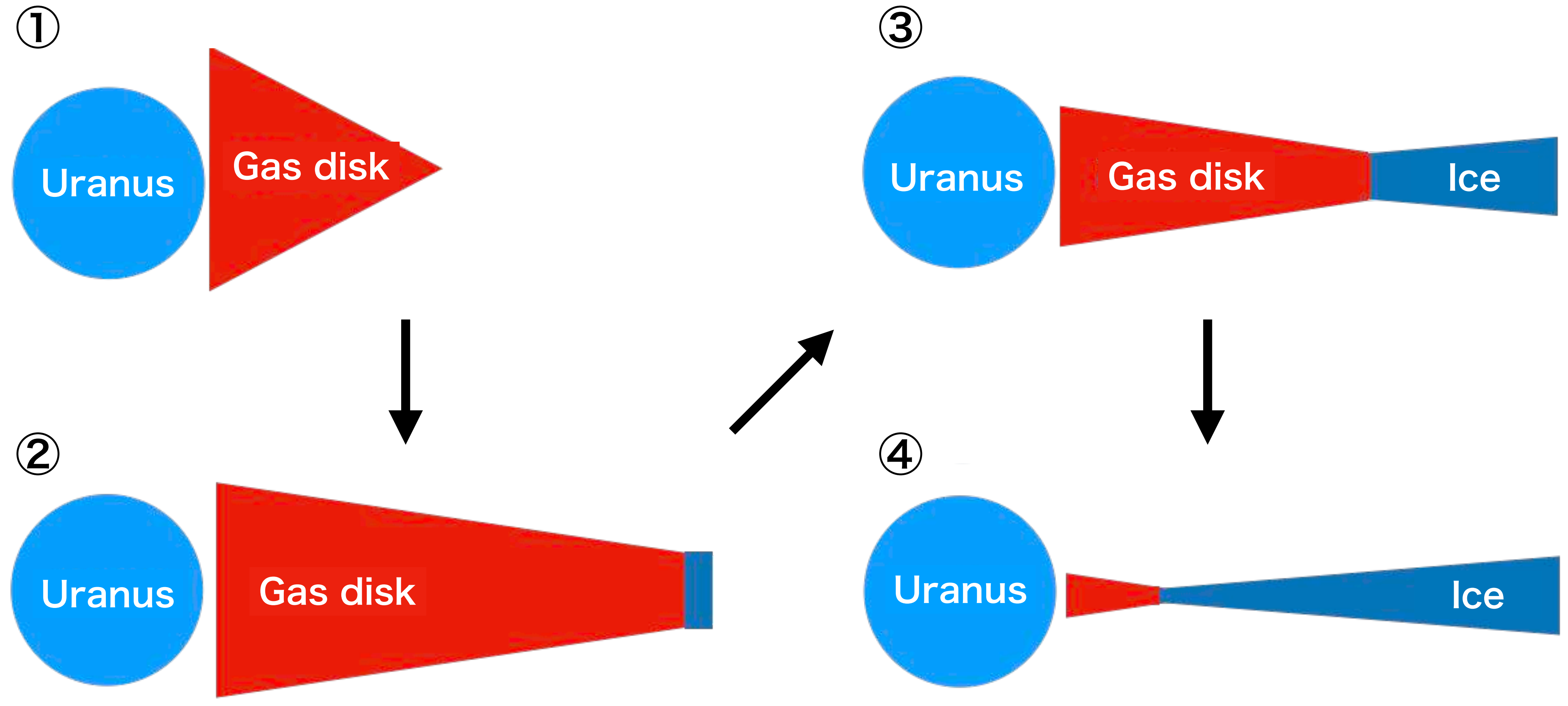


Ida et al. (2020)

円盤内での氷の凝縮

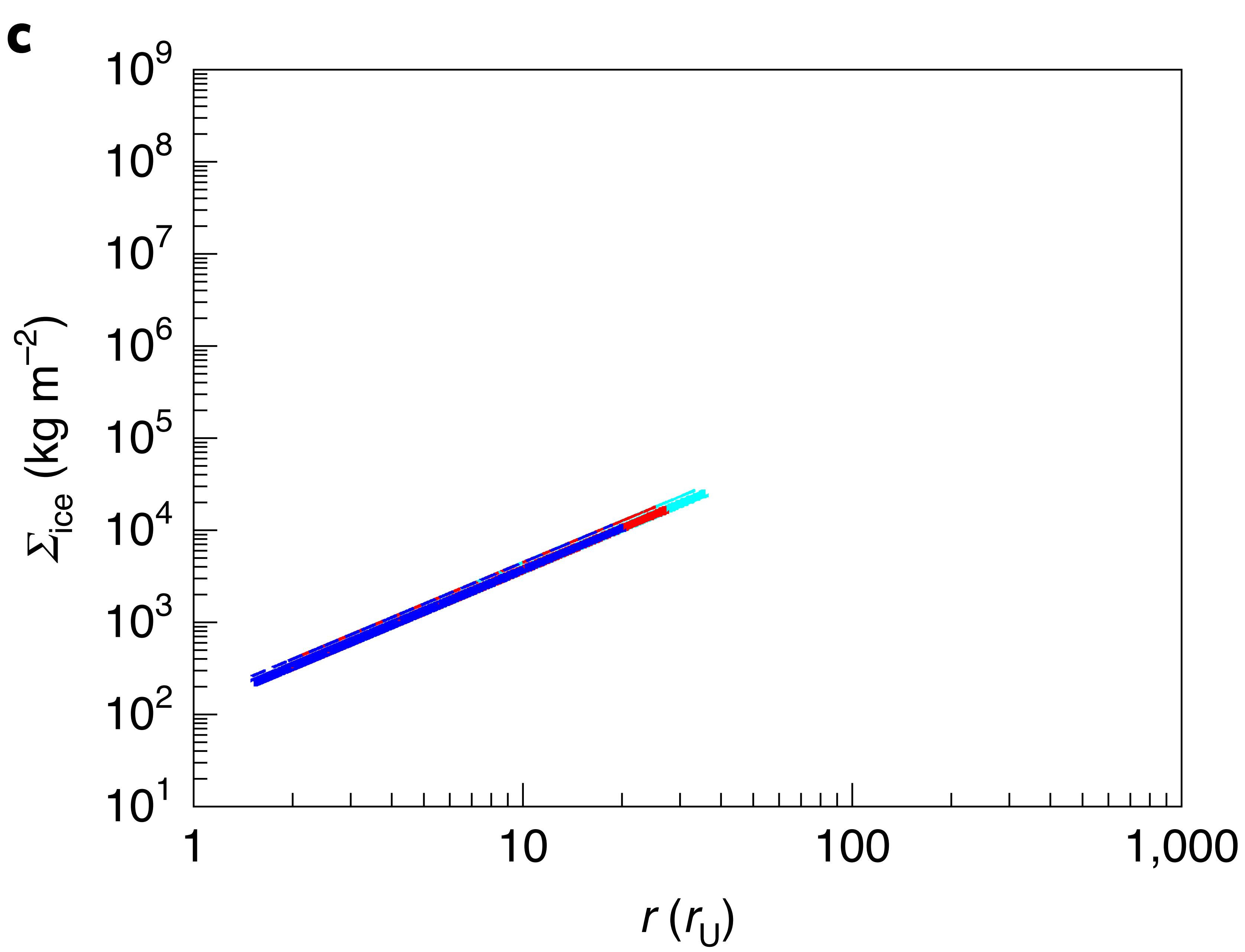


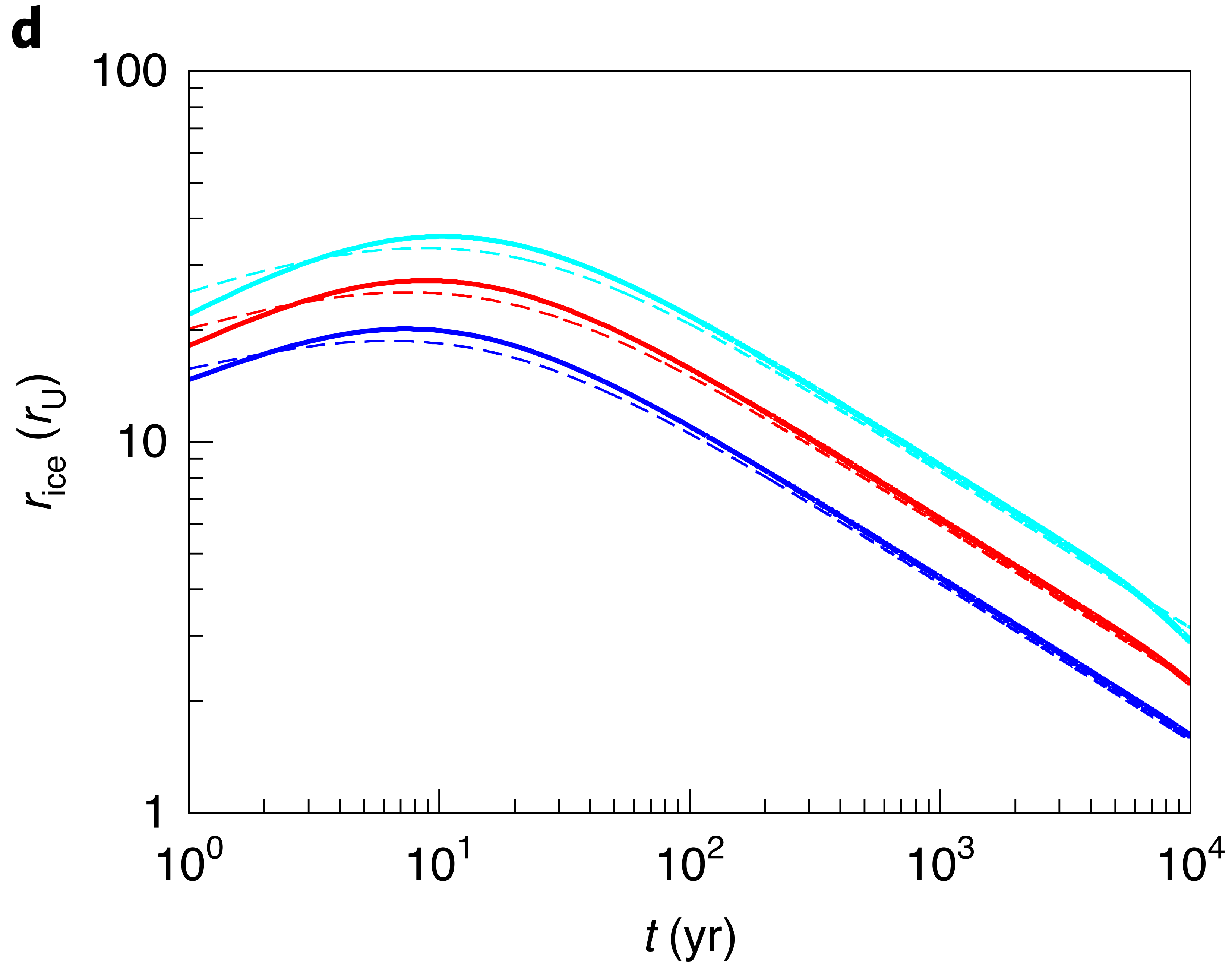




Ida et al. (2020)

最終的に形成される氷円盤の解析解





$$\Sigma_{\rm ice} \simeq \gamma\Sigma_{\rm g} \simeq 1.2\times10^2\beta^{-1}\gamma_{03}\left(\frac{r}{r_{\rm U}}\right)^{3/2}\ {\rm kg\ m^{-2}}$$

$$r_{\rm max} \simeq 20\ \left[\beta\left(\frac{\langle r_{\rm d,imp}\rangle}{2r_{\rm U}}\right)^{-5/4}\left(\frac{M_{\rm d,imp}}{10^{-2}M_{\rm U}}\right)\right]^{1/4} r_{\rm U}$$

$$M_{\rm ice} \simeq \int_{r_{\rm U}}^{r_{\rm max}} 2\pi r\Sigma_{\rm ice}{\rm d}r \simeq 0.58\times10^{-4}\ \beta^{1/8}\gamma_{03}\left(\frac{\langle r_{\rm d,imp}\rangle}{2r_{\rm U}}\right)^{-5/4}\left(\frac{M_{\rm d,imp}}{10^{-2}M_{\rm U}}\right)^{7/8} M_{\rm U}$$

Ida et al. (2020)

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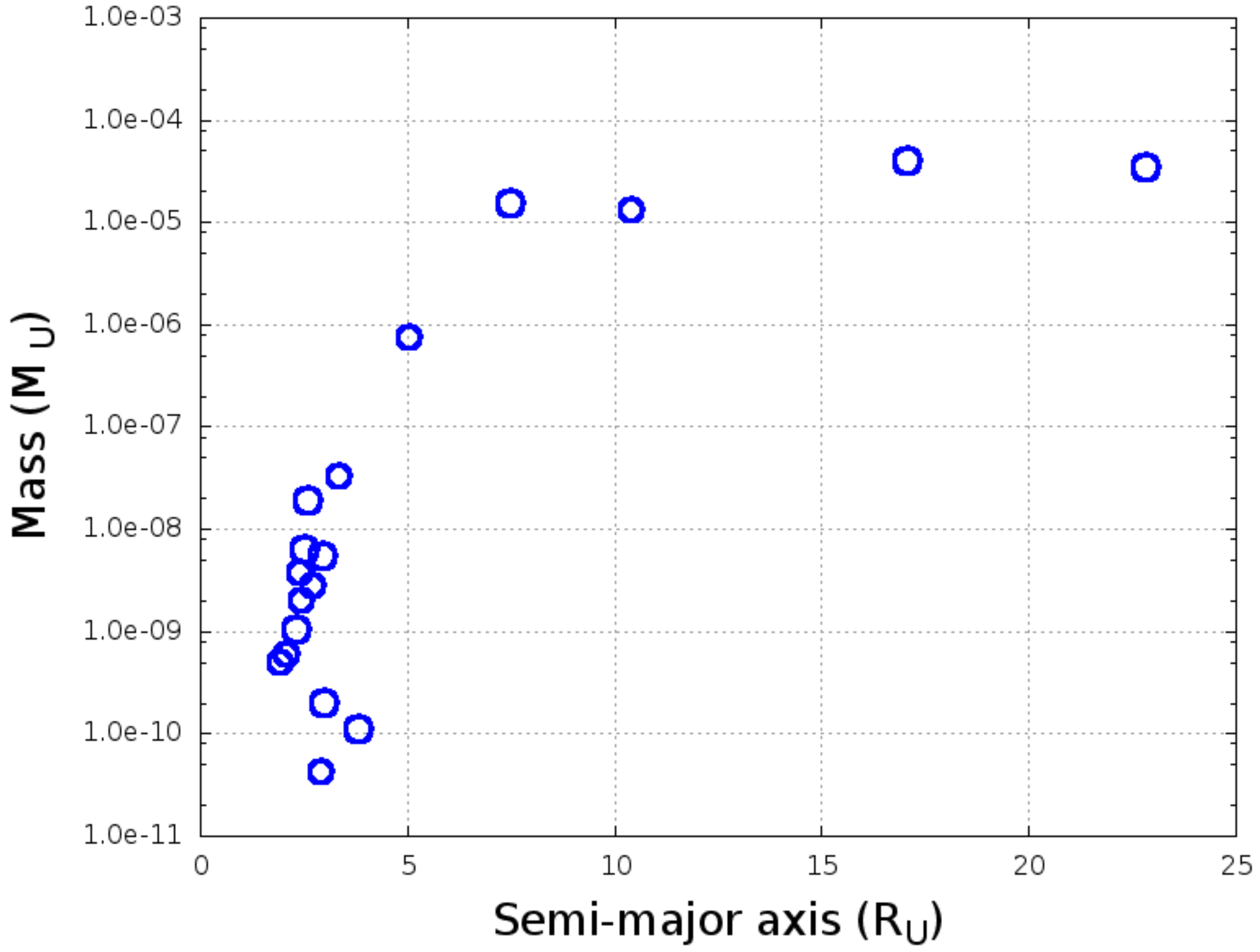
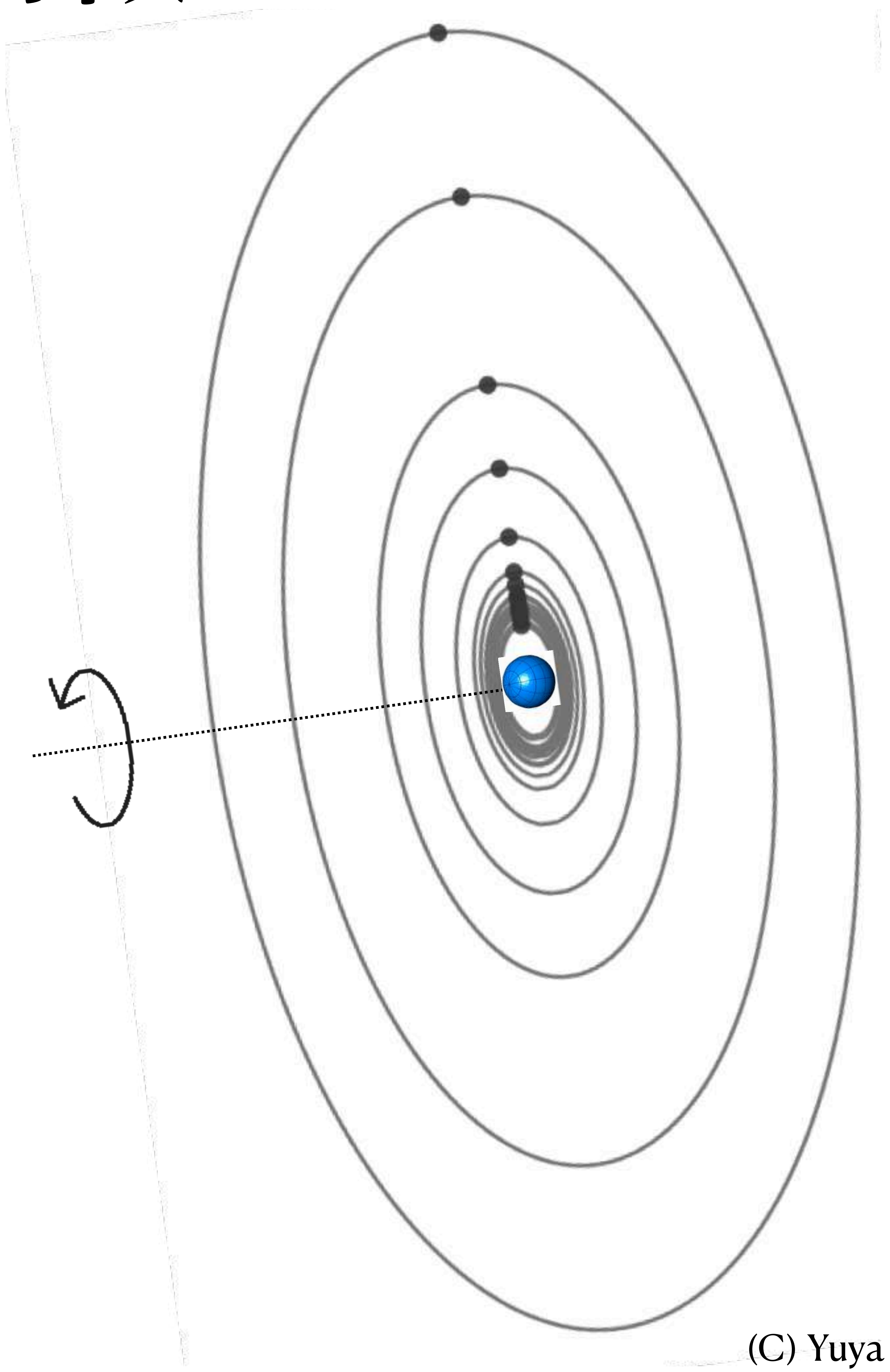
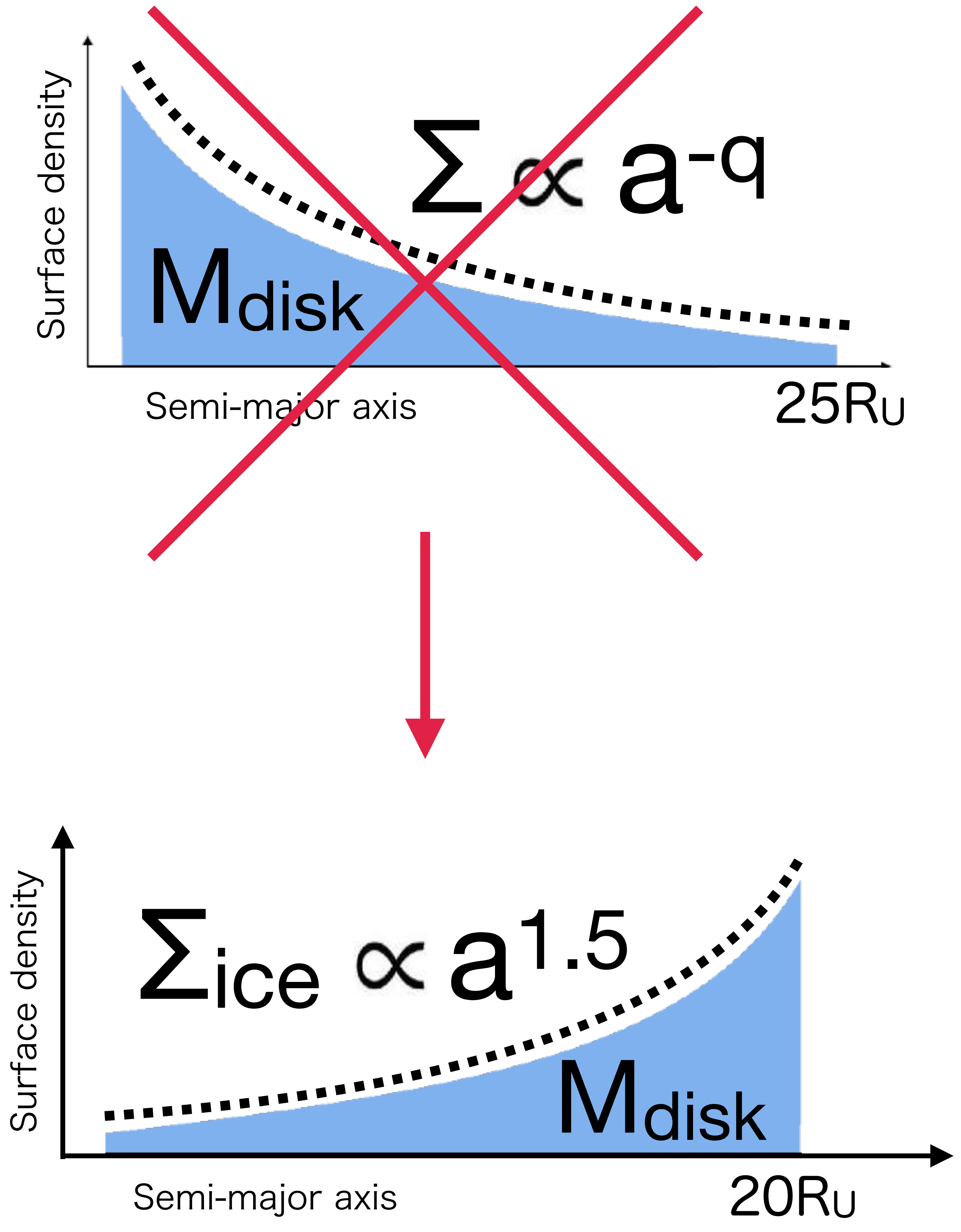
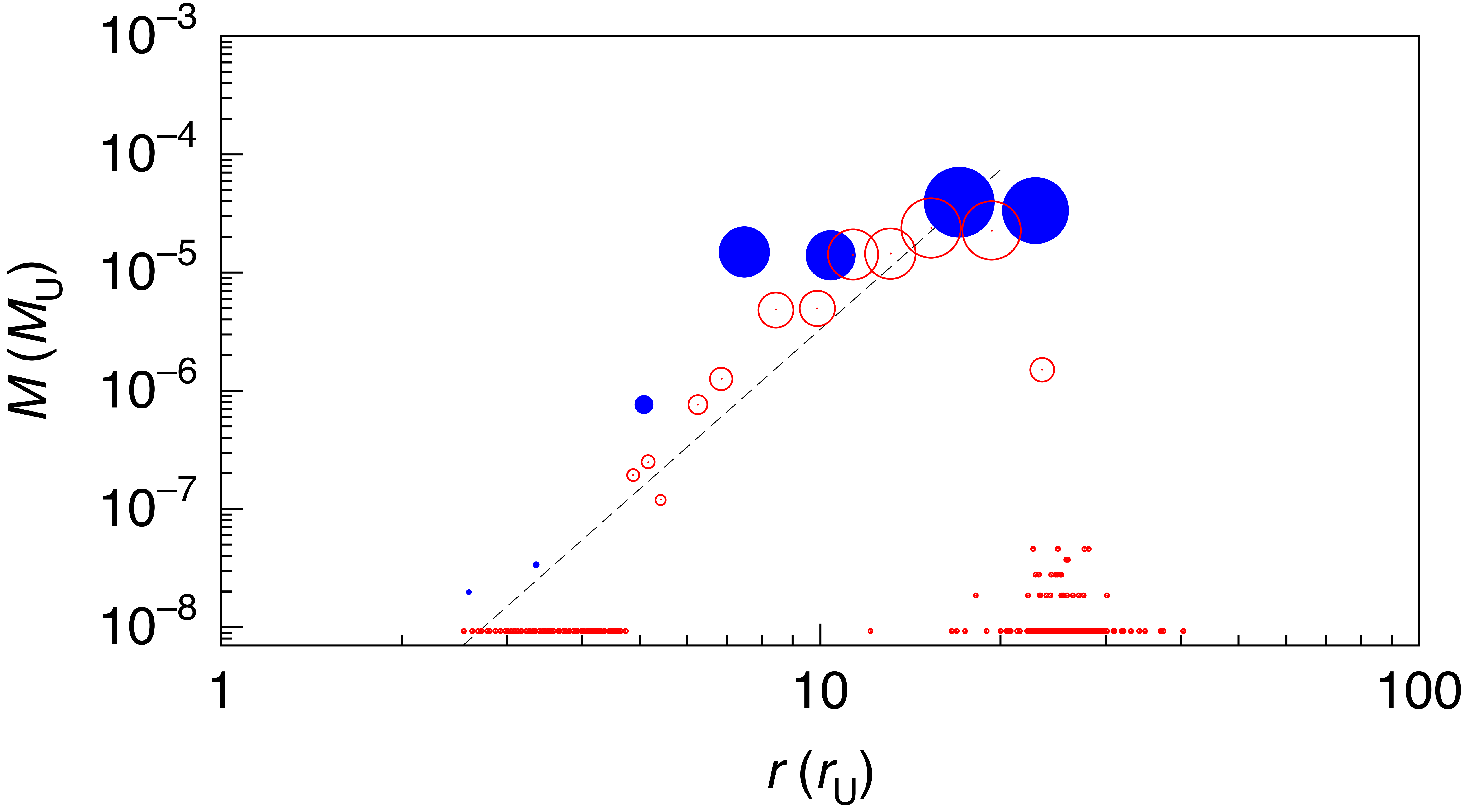




(C) Yuya Ishizawa

天王星衛星形成のN体シミュレーション（改）





Ida et al. (2020)

議論：各種タイムスケールの比較

Disk diffusion timescale: $t_{\rm diff} \simeq t \simeq 9.2\times 10^5 \left[\beta\left(\frac{\langle r_{\rm d,imp}\rangle}{2r_{\rm U}}\right)^{-5/4}\left(\frac{M_{\rm d,imp}}{10^{-2}M_{\rm U}}\right)\right]^{22/21}\left(\frac{\alpha}{10^{-3}}\right)^{-1}\Omega^{-1}$

Drift timescale of icy particles due to gas drag: $t_{\rm drift} \simeq \frac{r}{v_{\rm r}} \simeq \frac{r}{2\eta\ v_{\rm K}}\frac{1+{\rm St}^2}{\rm St} \simeq 0.5\left(\frac{c_{\rm s}}{v_{\rm K}}\right)^{-2}\frac{1+{\rm St}^2}{\rm St}\Omega^{-1}$

Growth timescale of icy particles: $t_{\rm grow} \simeq 1\left(\frac{{\rm St}+\alpha}{10^{-4}}\right)^{-1/2}\left(\frac{\gamma}{0.3}\right)^{-1}\left(\frac{\alpha}{10^{-3}}\right)\left(\frac{T_{\rm ice}}{240\ {\rm K}}\right)^{-11/4}\left(\frac{r}{r_{\rm U}}\right)^{-3/4}\Omega^{-1}$

Type-I migration timescale of a satellite: $t_{\rm mig} \simeq \frac{1}{2.7+1.1\times(3/4)}\left(\frac{M_{\rm U}}{m}\right)\left(\frac{M_{\rm U}}{\Sigma_{\rm g}r^2}\right)\left(\frac{c_{\rm s}}{v_{\rm K}}\right)^2\Omega^{-1}$

$c_{\rm s} < v_{\rm K},\ \ \alpha \ll 1,\ \ {\rm St} \simeq 1 \longrightarrow t_{\rm grow} \ll t_{\rm drift} \ll t_{\rm diff} \ll t_{\rm mig}$

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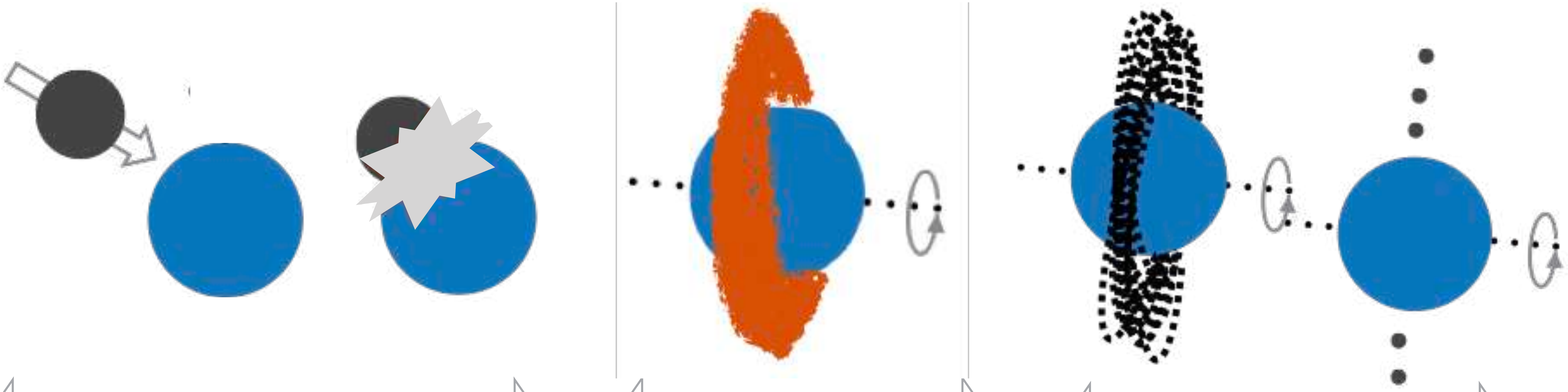
天王星衛星形成シナリオの完成に向けて



Protoplanets collide each other

SPH method

Disk evolution

Satellite formation

N-body

Slattery et al. (1992)
Kegerreis et al. (2018)
Kurosaki & Inutsuka (2019)
Reinhardt et al. (2020)
Woo et al. (2022)

Ida et al. (2020)

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大量のN体計算による統計的検証

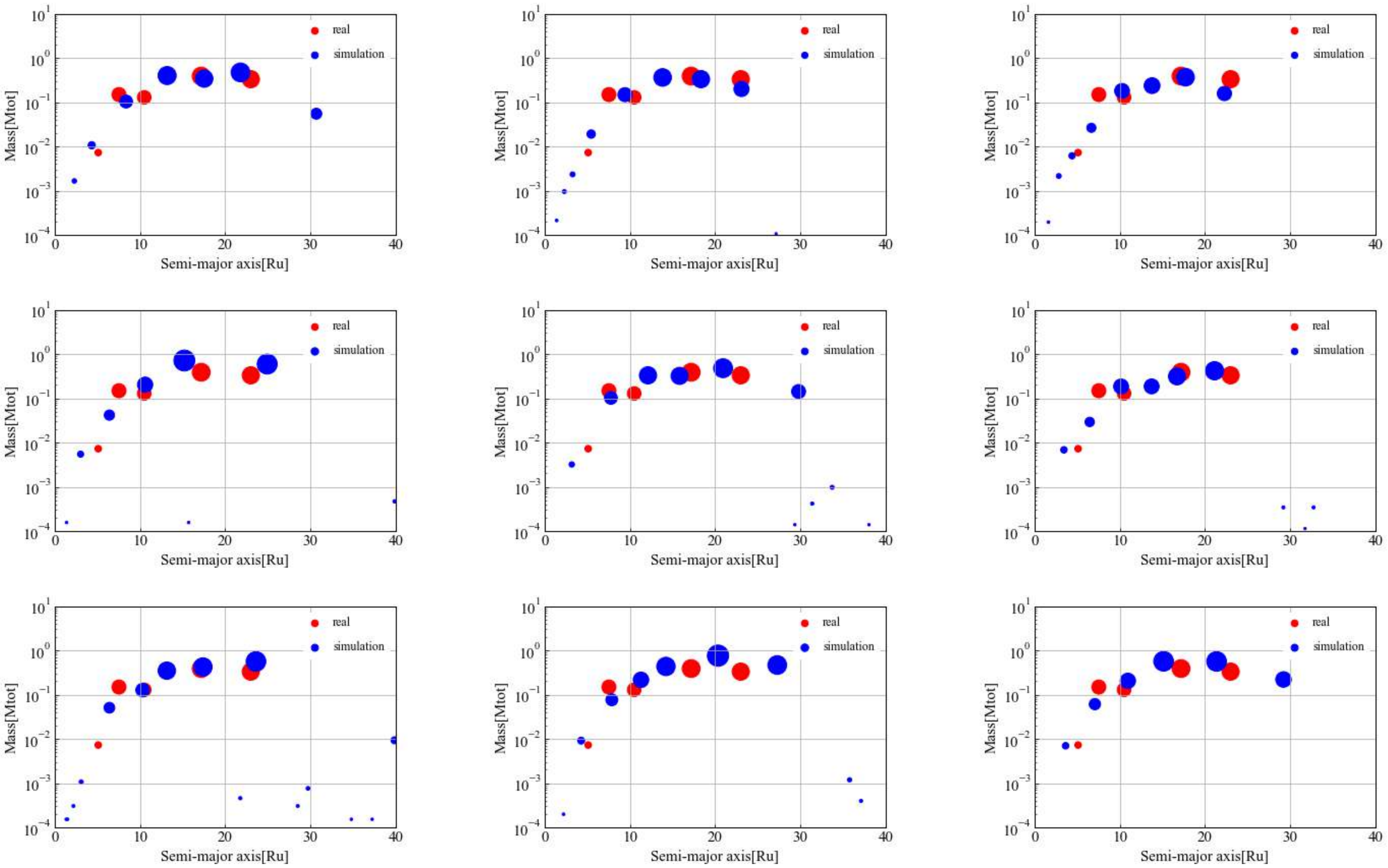

Table 1. Model sets of initial condition

Run	$M_{\mathrm{disk}}(M_{\mathrm{U}})$	$r_{\max}(r_{\mathrm{U}})$
1	1.02×10^{-4}	20
2	8.92×10^{-5}	19.3
3	7.95×10^{-5}	18.7
4	7.16×10^{-5}	18.1
5	6.51×10^{-5}	17.6
6	1.44×10^{-4}	22.1
7	1.27×10^{-4}	21.3
8	1.13×10^{-4}	20.6
9	1.02×10^{-4}	20.0
10	9.29×10^{-5}	19.5
11	1.86×10^{-4}	23.8
12	1.64×10^{-4}	22.9
13	1.46×10^{-4}	22.2
14	1.31×10^{-4}	21.5
15	1.19×10^{-4}	21.0
16	2.26×10^{-4}	25.1
17	1.99×10^{-4}	24.2
18	1.77×10^{-4}	23.5
19	1.60×10^{-4}	22.8
20	1.45×10^{-4}	22.2
21	2.65×10^{-4}	26.3
22	2.33×10^{-4}	25.4
23	2.08×10^{-4}	24.5
24	1.87×10^{-4}	23.8
25	1.70×10^{-4}	23.2

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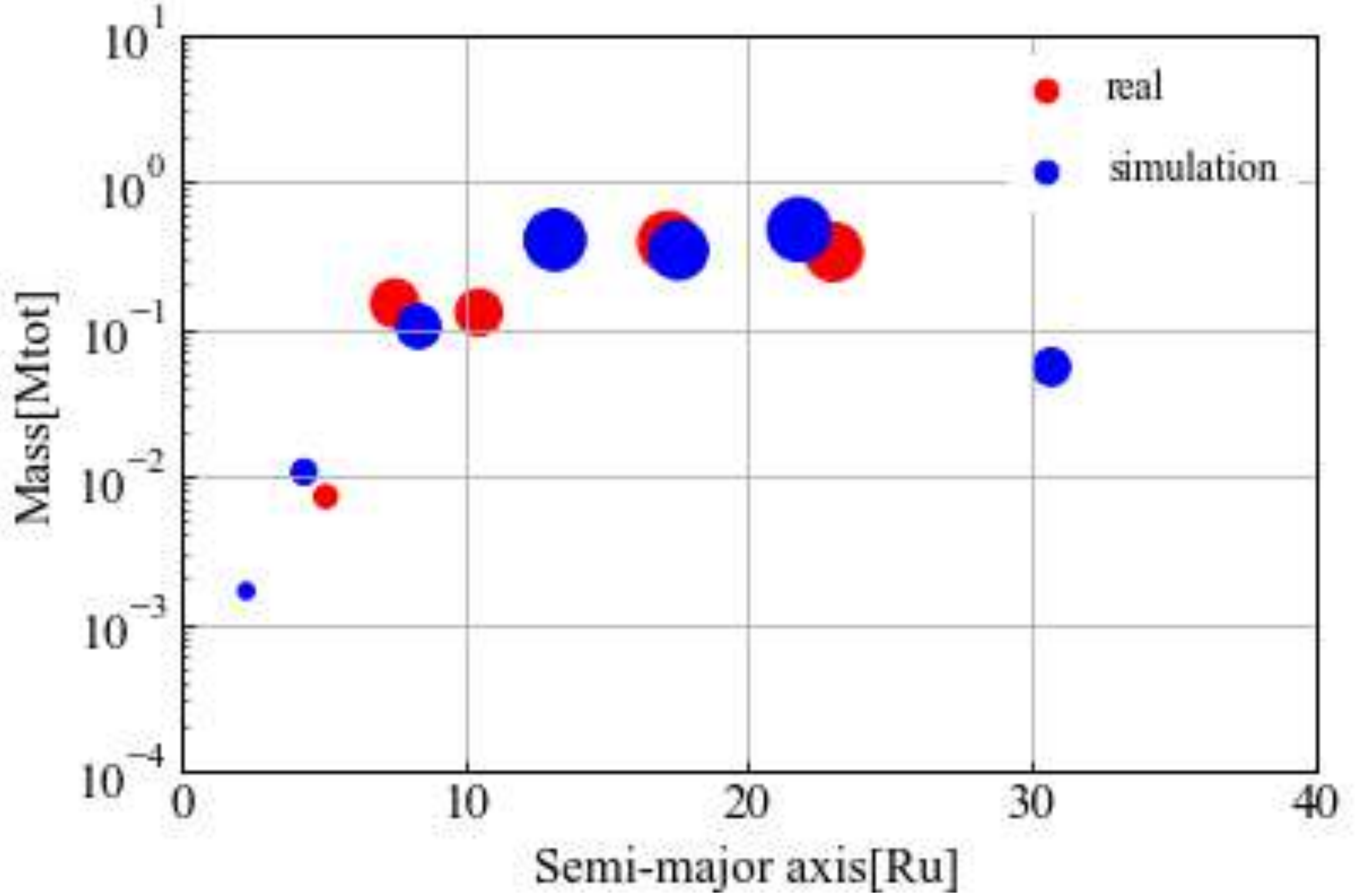
典型的な計算結果の１例



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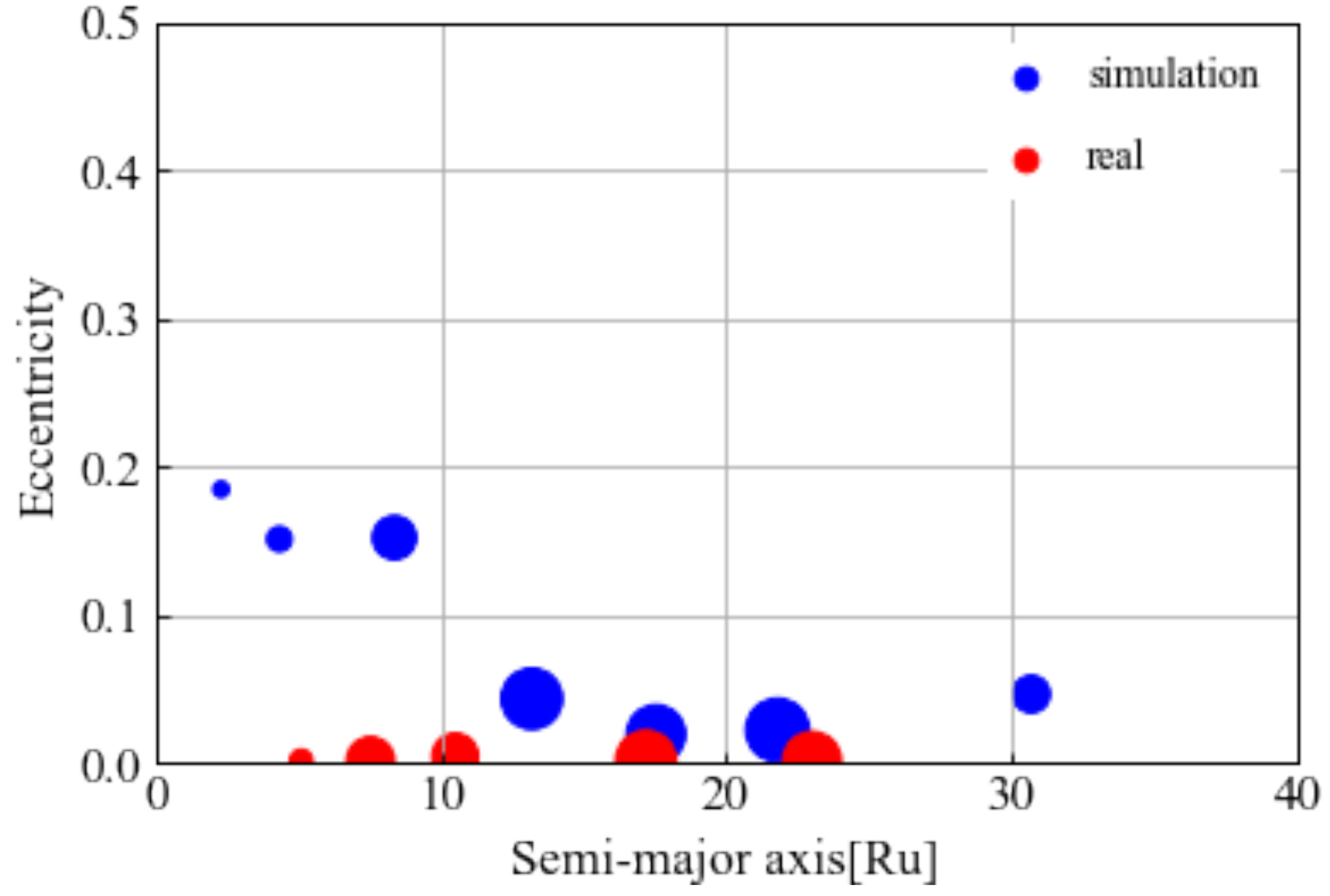
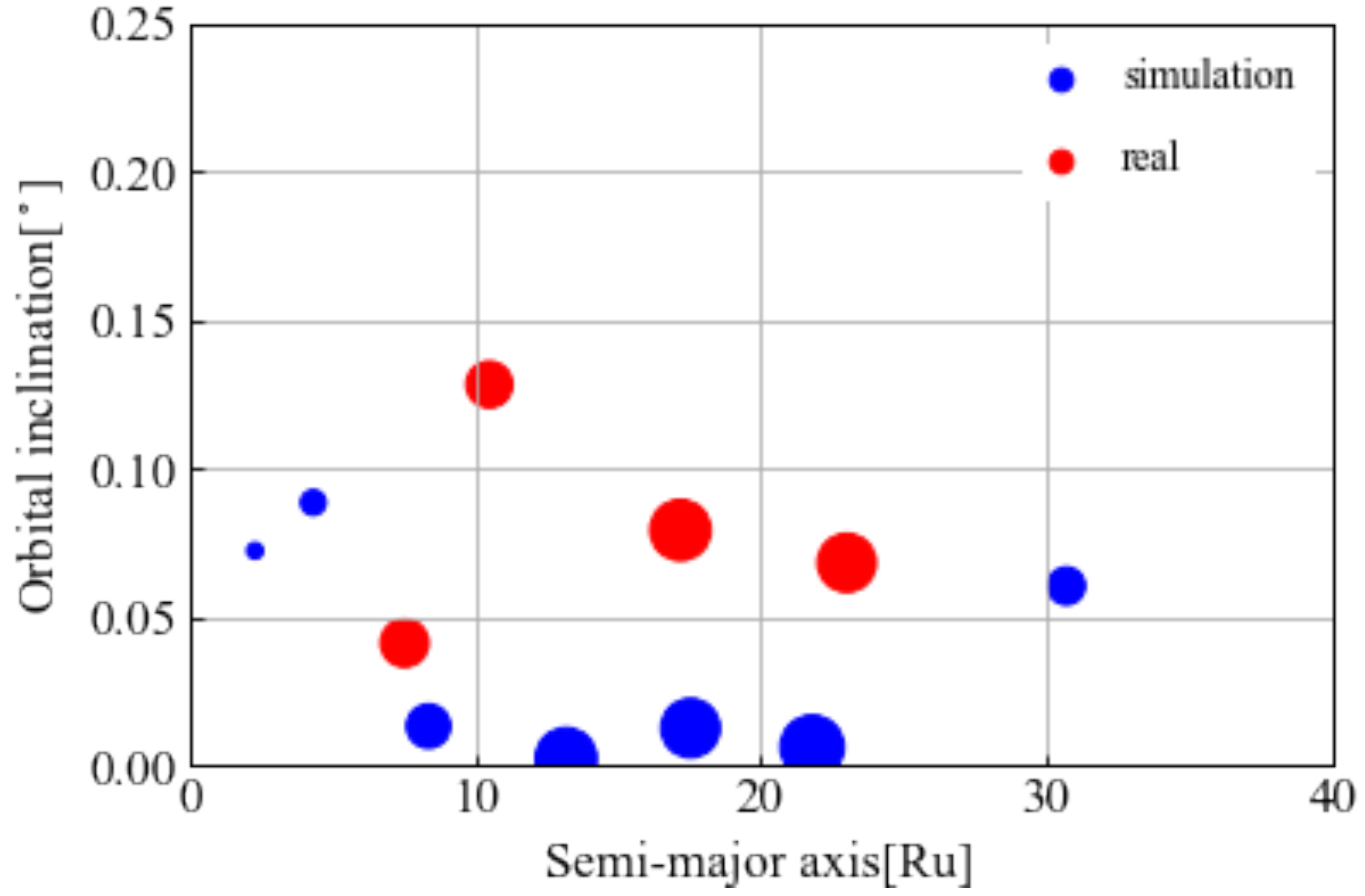


(a) The eccentricity of each satellite

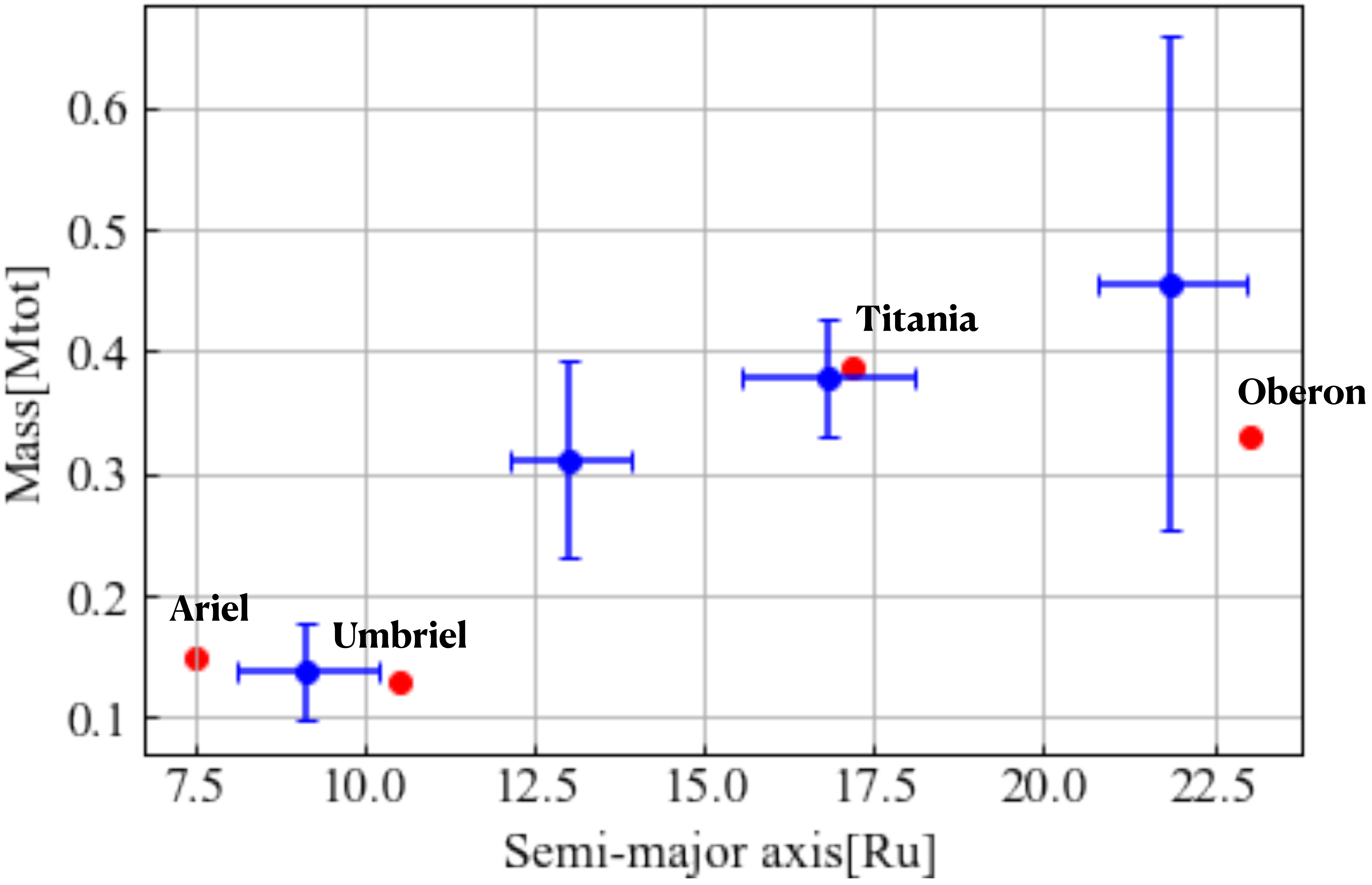


(b) The orbital inclination of each satellite

N体計算結果のまとめ

- Averagely four large satellites are formed and the smaller satellites locate in the inner area and the larger ones in the outer area.

- Only one satellite is formed around Ariel and Umbriel's orbits.
- A large satellite is robustly formed around 13 Ru where between Umbriel and Titania's location.
- Several satellites are formed outside of Oberon where no satellites have been discovered.



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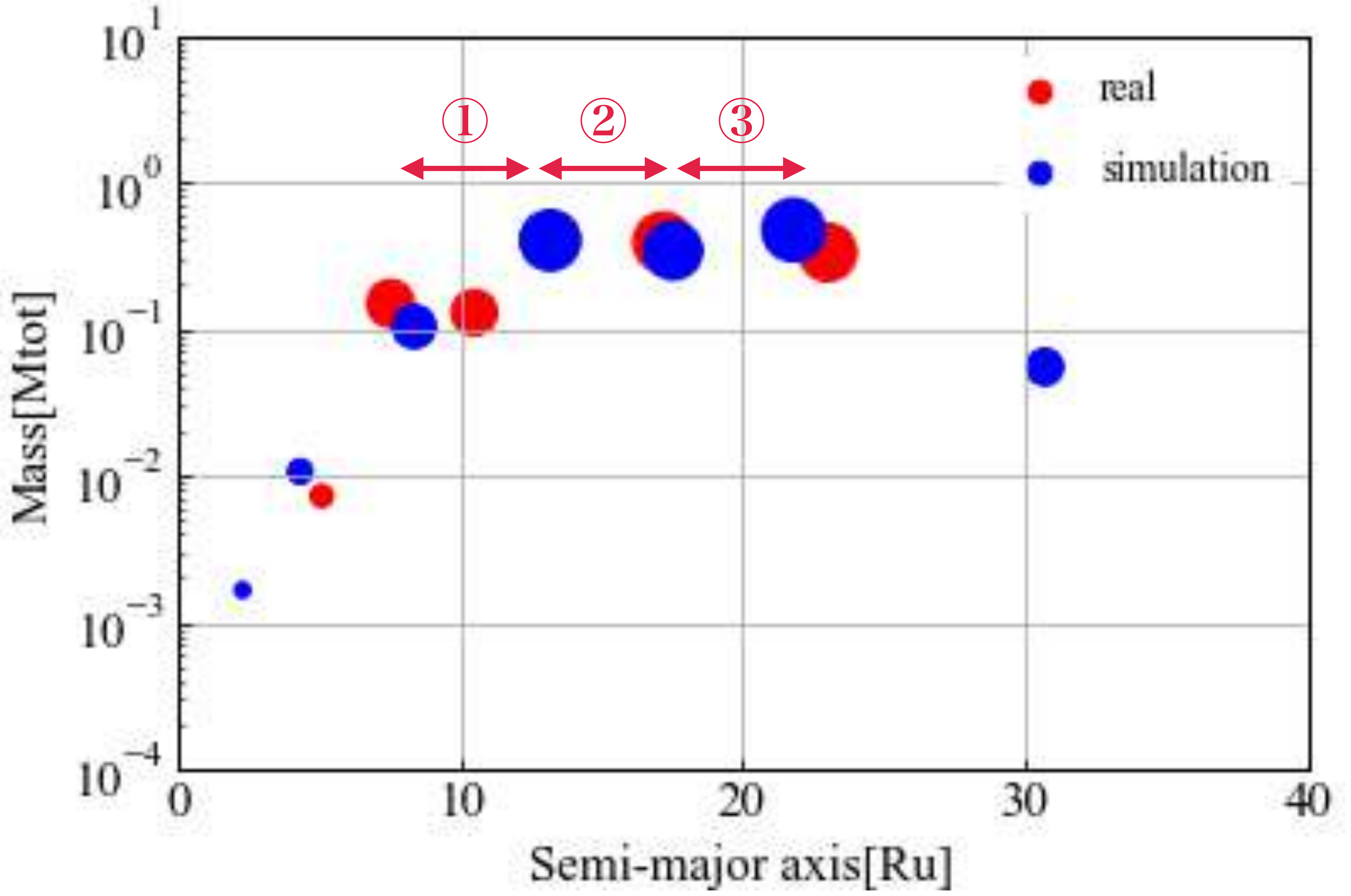
議論：形成された衛星系の軌道安定性

<u>The orbit-crossing time</u> Zhou et al. (2007)

$$\log\left(\frac{T_c}{1\mathrm{yr}}\right) = A + B\log\left(\frac{k_0}{2.3}\right)$$

$$A = -2 + \frac{e}{h} - 0.27\log\frac{m}{M_U}$$

$$B = 18.7 + 1.1\log\frac{m}{M_U} - \left(16.8 + 1.2\log\frac{m}{M_U}\right)\frac{e}{h}$$



① $k_0 = 12.0,\quad T_c = 3.3\times10^7$ [yr]

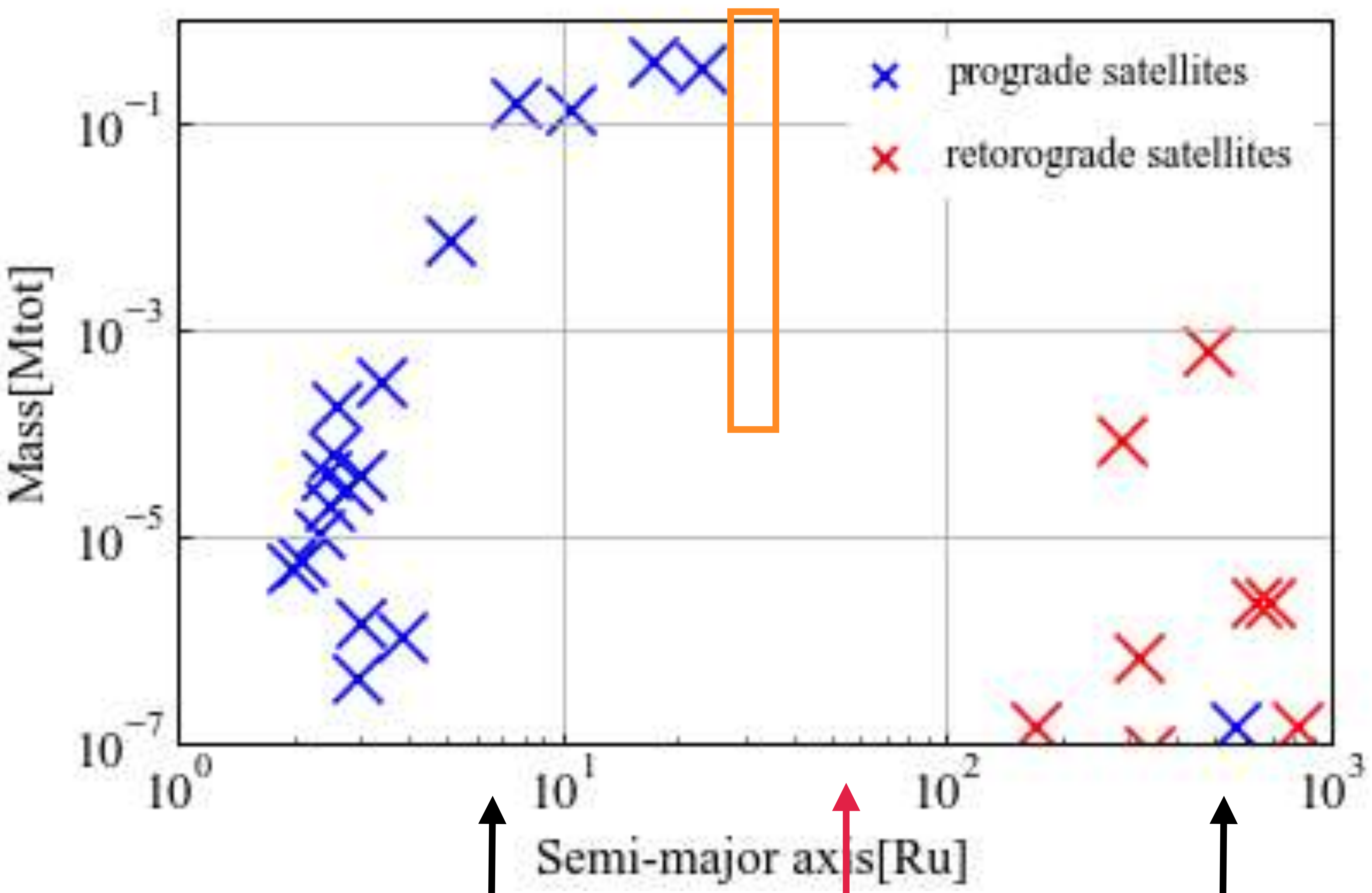
② $k_0 = 9.0,\quad T_c = 1.7\times10^6$ [yr]

③ $k_0 = 8.7,\quad T_c = 7.5\times10^5$ [yr]

The produced satellites will be scattered with each other by gravitational interactions via orbital crossing on a timescale about 10^6 years, then move into the current orbits.

Kihara et al., to be submitted

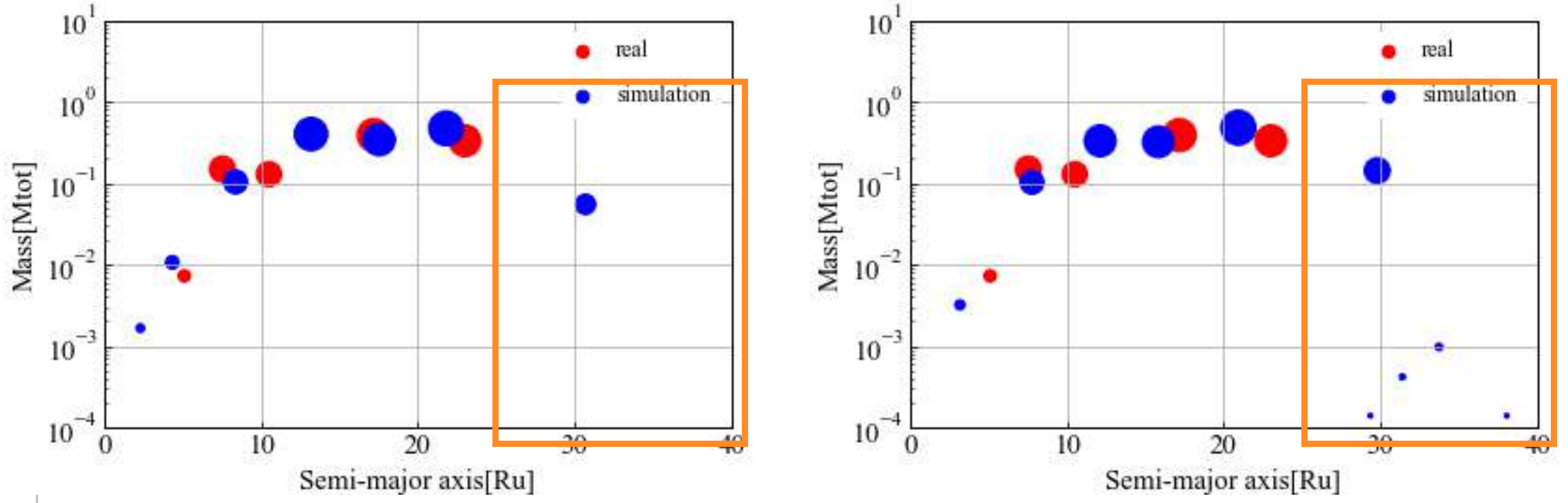
議論：遠方に形成された存在しない衛星たち



Produced via accretion

Capture ?

No satellites between 25-150Ru



1. The outer satellites will collide with Oberon ?
 —> No; they have larger perigee distances than the Oberon's orbit.

2. Protoplanets' encounters to the Uranian system ?
 —> Possibly; we need to estimate the probability of such encounter events.

Kihara et al., to be submitted

本日の内容

起：太陽の周りを横倒しで回る天王星系

Slattery et al., *Icarus* (1992), Kegerreis et al., *ApJ* (2018)

承：巨大天体衝突で天王星の衛星は作れるか？

Ishizawa, Sasaki & Hosono, *ApJ* (2019)

転：天王星周囲に形成された円盤は進化する！

Ida, Ueta, Sasaki & Ishizawa, *Nature Astronomy* (2020)

結：新しい天王星衛星形成シナリオの完成（？）

Kihara, Sasaki & Ida, *to be submitted*