Moon formation of rocky/icy planets by a giant impact

Shigeru Ida

(ELSI, Tokyo Tech)

Ida, Ueta, Sasaki, Ishizawa (2020, Nature Astron.)

Nakajima, Genda, Asphaug, Ida (2022, Nature Comm.)

EARTH - LIFE SCIENCE INSTITUTE

Back-ground: How common are large moons around rocky or icy exoplanets?

- Earth's Moon → control Earth's climate → **one possible factor of habitability?**
  - control Earth's obliquity and spin period evolution; mix deep ocean water
- Standard Moon formation model: **giant impact model**
  - Final phase of rocky planet accretion is "giant impacts" : energetic collisions between protoplanets formed by "oligarchic growth" (Kokubo & Ida 1998)
  - In many cases, a "large" moon is formed as a by-product such as Earth's Moon?

$M_{Moon} \sim 0.01\ M_{Earth}$

- Other planets in Solar system?
  - **Venus:** retrograde impact → planet spin & moon: retrograde
    → the moon falls onto the planet by tidal orbital evolution (Atobe & Ida 1997)
  - **Mercury & Mars**: left-over protoplanets that avoided giant impacts? (Hansen 2009)
  - **Uranus**: tiled by 98 degree ← giant impact

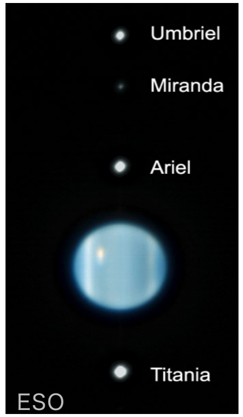
→ **Large exo-moons: common around exoplanets?**
But, transit timing/duration variation observation (e.g., HEK): no detection

Back-ground: Mysteries of Uranian moon system

- Earth:
  - impact by protoplanet with ~ 0.1 M_{planet} (consistent with oligarchic growth model)
    → ~ 0.02 M_{planet} debris disk (e.g., Canup & Asphaug 2001, Nature)
    → ~ 0.01 M_{planet} single moon (Ida, Canup & Stewart 1997, Nature)
    succeeded to reproduce Earth's Moon
    (except the identical isotope ratios)
- Uranus:
  - spin axis is tilted by 98 degrees ← giant impact: likely
  - 17 hour spin period → ~ 0.1 M_{planet} impact
    → ~ O(0.01) M_{planet} debris disk → **~ 0.01 M_{planet} single moon?**
    NO: four small major moons ~ 10^{-4} – 10^{-5} M_{planet}

→ moons were formed in a different way?

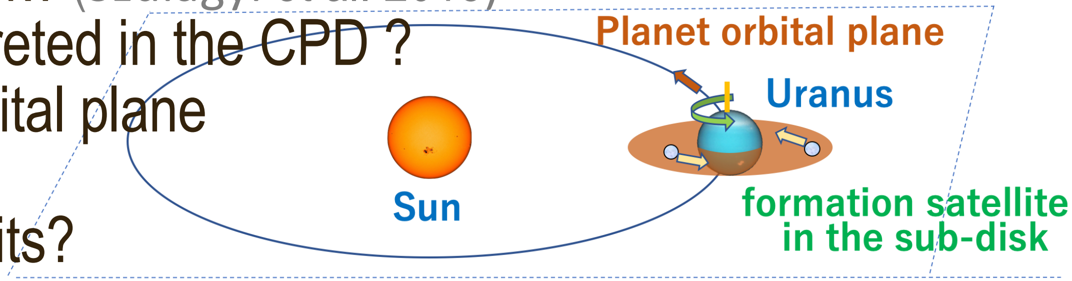
Back-ground: Mysteries of Uranian moon system

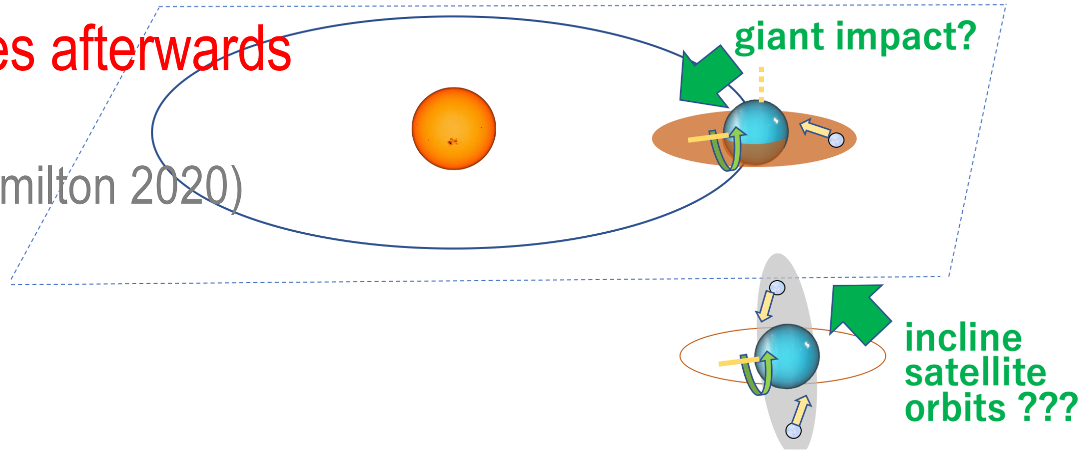


- Uranus
  - **both spin axis & moons' orbits: tilted by 98 degrees**

- moon accretion in CircumPlanetary gas Disk? (Szulágyi et al. 2018)
  - ~10 wt.% gas envelope → moons: accreted in the CPD ?
    → moons' orbital plane ~ planetary orbital plane

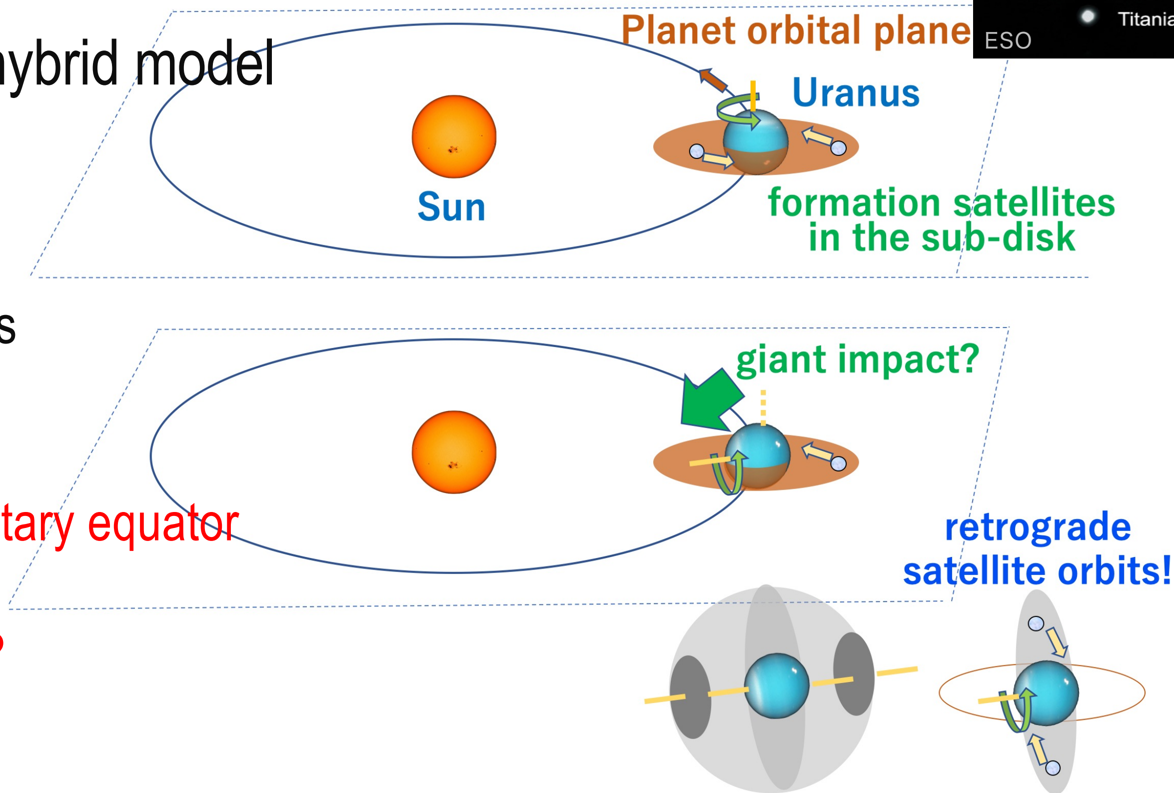
  - How to tilt the spin axis and moons' orbits?
    - ✓ A giant impact (instantaneously)
      hard to incline the moon orbital planes afterwards
    - ✓ Spin-orbit resonance (secular)
      (Boue & Laskar 2010, Rogoszinski & Hamilton 2020)
      hard to incline by > 90 degrees



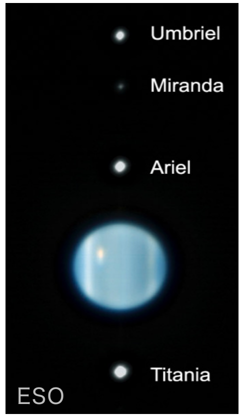


Back-ground: Mysteries of Uranian moon system

- Morbidelli et al. (2012)
  -- clever, complicated, multi-step hybrid model
  1. Protomoons form in a CPD
  2. Giant impact tilts the spin
     - Protomoon orbits are not inclined
  3. Nodal precession of protomoon orbits along tilted spin axis→ thick torus
  4. Collisional damping
     → Debris orbits: align the tilted planetary equator
  5. Re-accreted moons – Retrograde!
     → Multiple giant impacts??

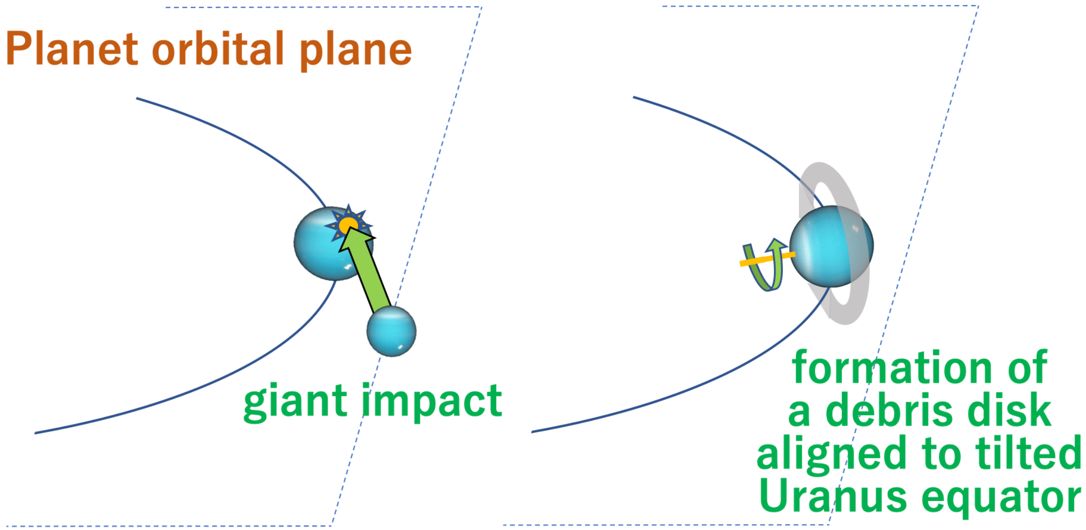


Back-ground: Mysteries of Uranian moon system



- A single-impact model: accretion of moos from an impact debris disk?
  - The giant impact onto slowly spinning Uranus: naturally forms the tilted spin and a similarly inclined prograde satellite system.

Much more simple



Problems in the single impact model

- impact: constrained by the current spin period
  - oblique, $M \sim 0.1\ M_U$ (consistent with oligarchic growth model)

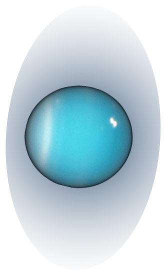
- **Disks predicted by giant impact simulated by SPH**

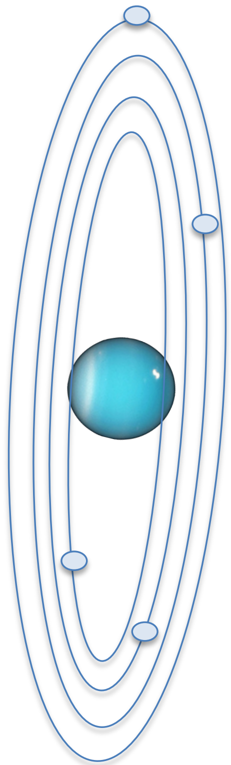
  Slattery et al. (1992), Kegerreis et al. (2018),

  Kurosaki et al. (2019), Reinhardt et al. (2020)

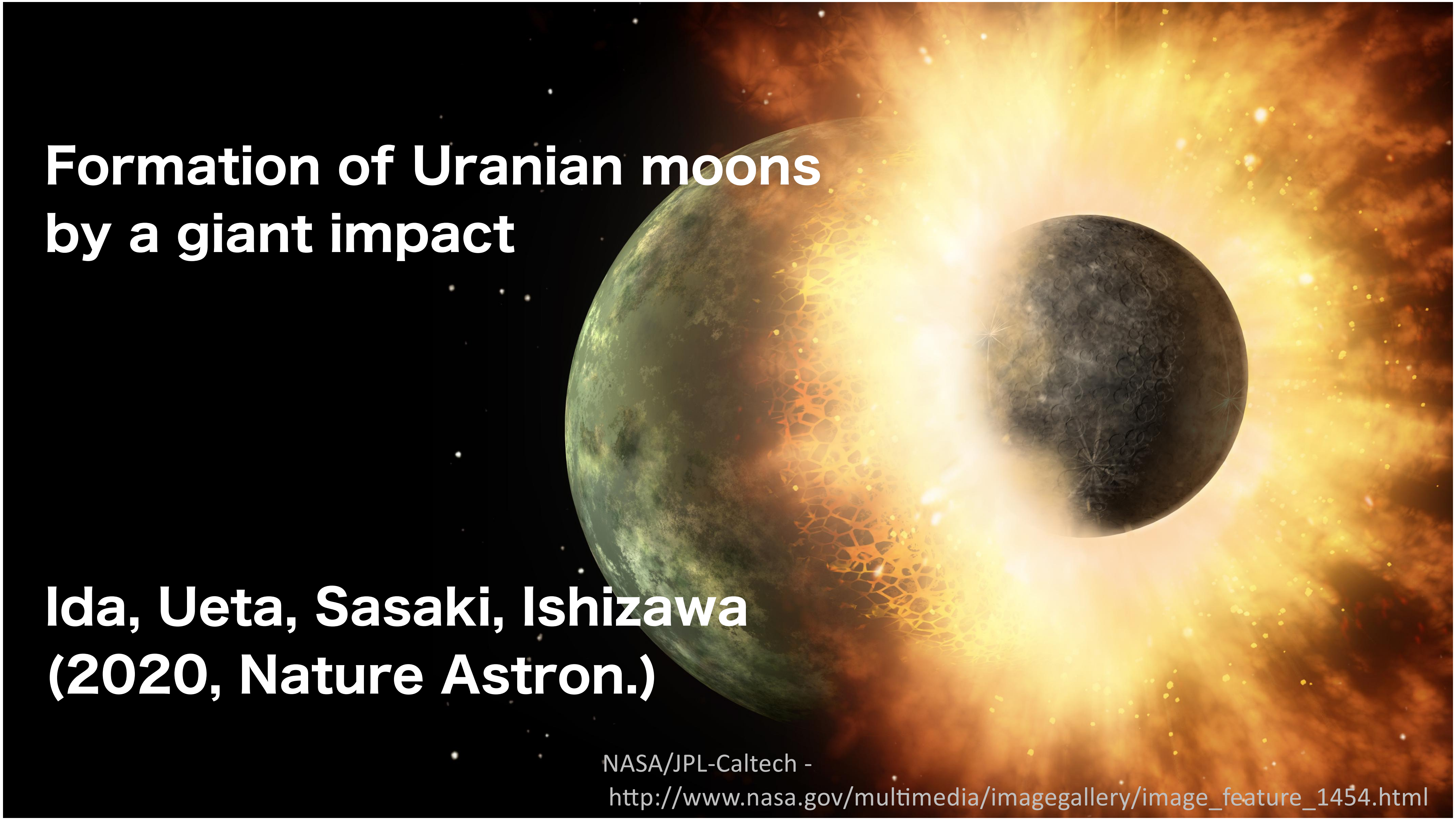
  - 10 x more compact ($\sim 2r_U$), 100 x heavier disk ($\sim 10^{-2} M_U$) than the current moon systems
    - ✓ Tidal orbital expansion afterward: not effective Dermott et al. (1988)
  - almost no rock component:
    - ✓ rocks : central part as a core ← oblique impact

    → inconsistent with current moons (half rock + half ice) !





The single impact model: inconsistent?


Formation of Uranian moons
by a giant impact
Ida, Ueta, Sasaki, Ishizawa
(2020, Nature Astron.)
NASA/JPL-Caltech -
http://www.nasa.gov/multimedia/imagegallery/image_feature_1454.html

Conclusion in advance

Giant impact -- debris disk: too massive (x100), too compact (x10), too low rock/ice

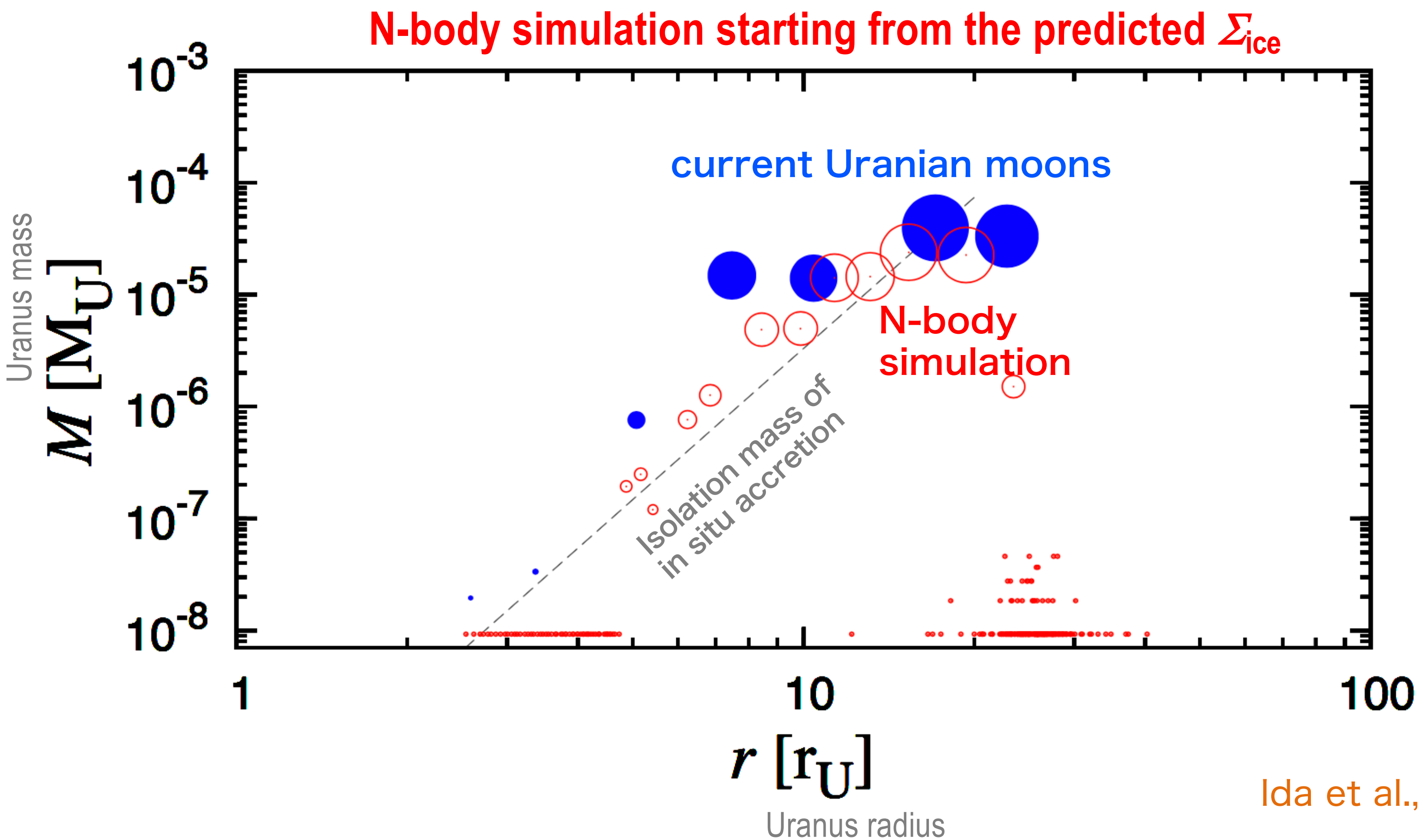
- Debris disk: water vapor ＋ H/He gas
  - **vaporized**: low vaporization temperature of H_2O, high impact velocity to Uranus
  - **substantial viscous disk evolution until re-condensation of H_2O**
    - **only 1% of initial $M_{disk,vapor}$ remains**
    - **size spreading by x10** **~ the current satellites**

- $\Sigma_{ice} \propto r^{3/2}$ ← viscous heating: inefficient in outer region
  - In situ moon accretion ← low density of H/He gas

  → **larger moons in outer region** **~ the current satellites**

- **rock/ice ratio: enhanced** (← high condensation temperature of silicates)

Reproduction of the current satellites

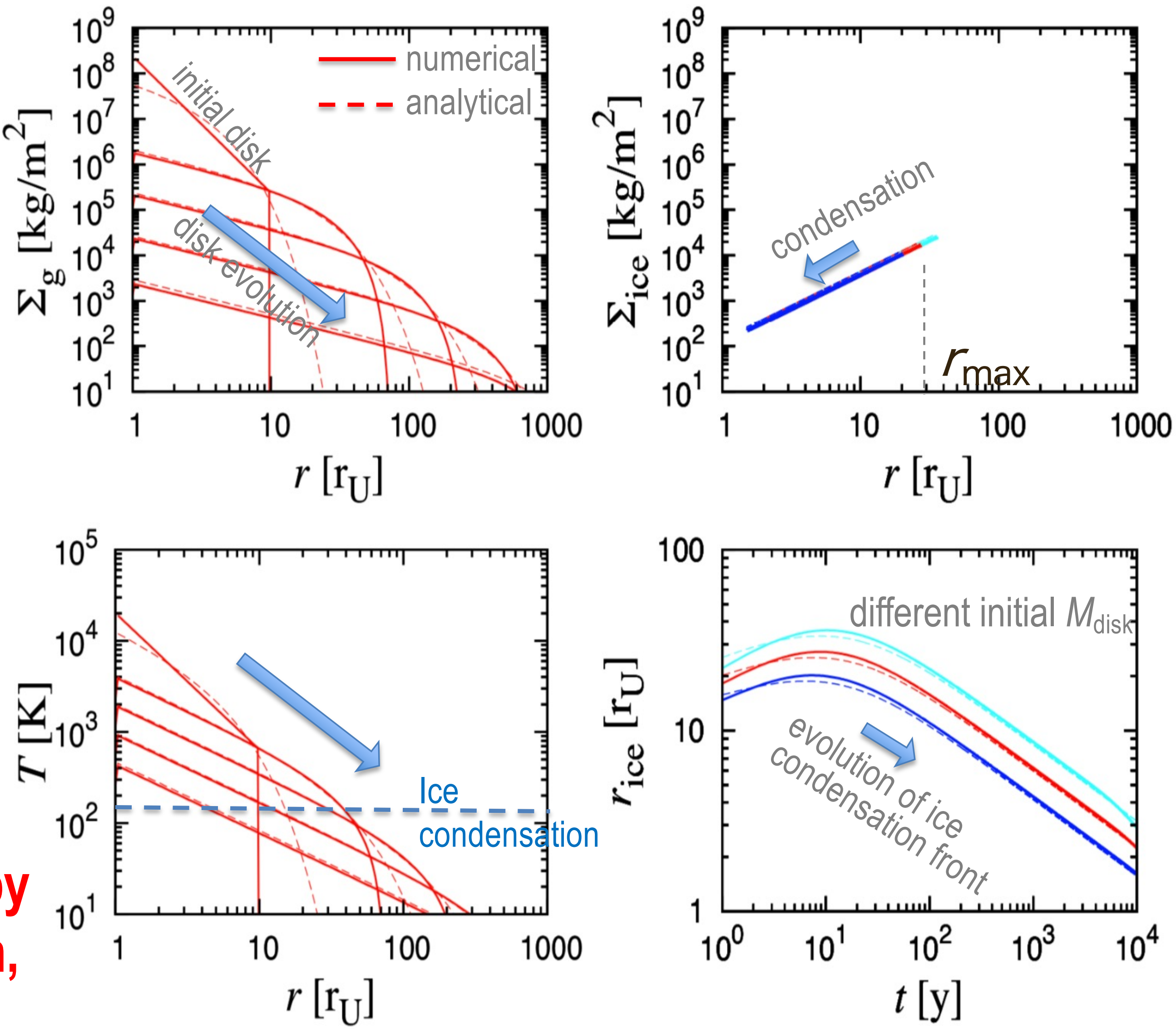


Ida et al., 2020

Disk evolution

We performed 1D diffusion calc. with constant α & viscous heating ($T \propto \Sigma_{disk}^{1/3}\, r^{-1/2}$)

- ice condensation:
  - ✓ T ~ 240K
    - → threshold $\Sigma_{disk} \propto r^{3/2}$
    - → $\Sigma_{ice} \propto r^{3/2}$
    - **indep. of the initial disk**
  - ✓ outside-in manner



Final moon mass is determined by disk evolution until condensation, not by initial disk mass.

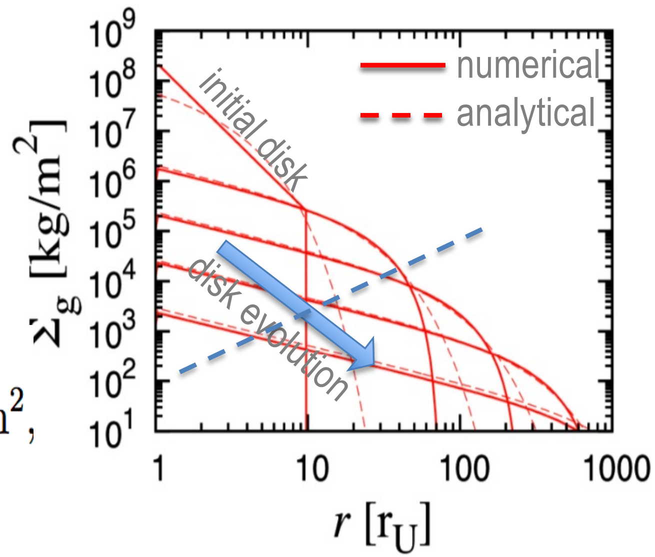
Ice condensation

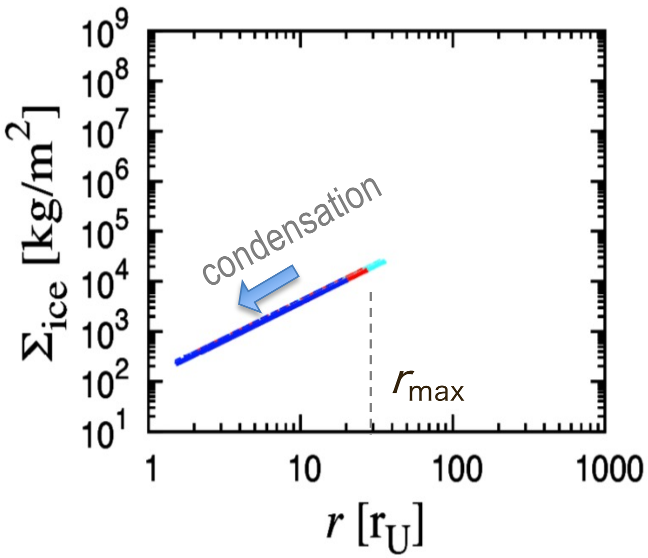
-- condensed ice surface density

$$\Sigma_{\rm ice} \simeq \gamma \Sigma_{\rm g} \simeq 1.2 \times 10^2 \beta^{-1} \gamma_{03} \left(\frac{r}{r_{\rm U}}\right)^{3/2} \ {\rm kg/m^2},$$

$$\beta = (\alpha/10^{-3})$$

γ_{03} = (water vapor fraction)/0.3





-- ice distribution extent ← initial *M,L* of the impact-generated disk

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

← intersection of envelope of Σ_{disk} and ice condensation Σ_{ice}

$M_{\rm d,imp}$: initial debris disk mass

$\langle r_{\rm d,imp}\rangle = ((J_{\rm d,imp}/M_{\rm d,imp})/r_{\rm U}^2\Omega_{\rm U})^2\, r_{\rm U}$: initial disk radius

$2\ r_U$ – viscous spreading → $20\ r_U$

←→ current satellites $a < 22.8\ r_U$

x 10 expansion weak dependence on initial disk

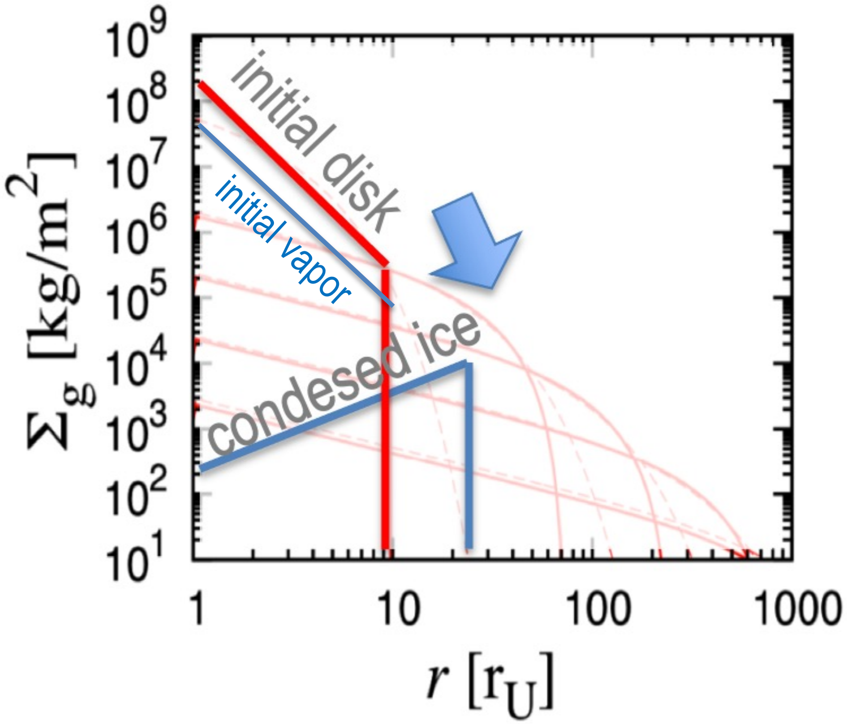
Ice condensation

-- total mass of condensed ice

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

$\beta = (\alpha/10^{-3})$

$M_{\rm d,imp}$: initial debris disk mass,
$r_{\rm d,imp}$: initial debris disk radius



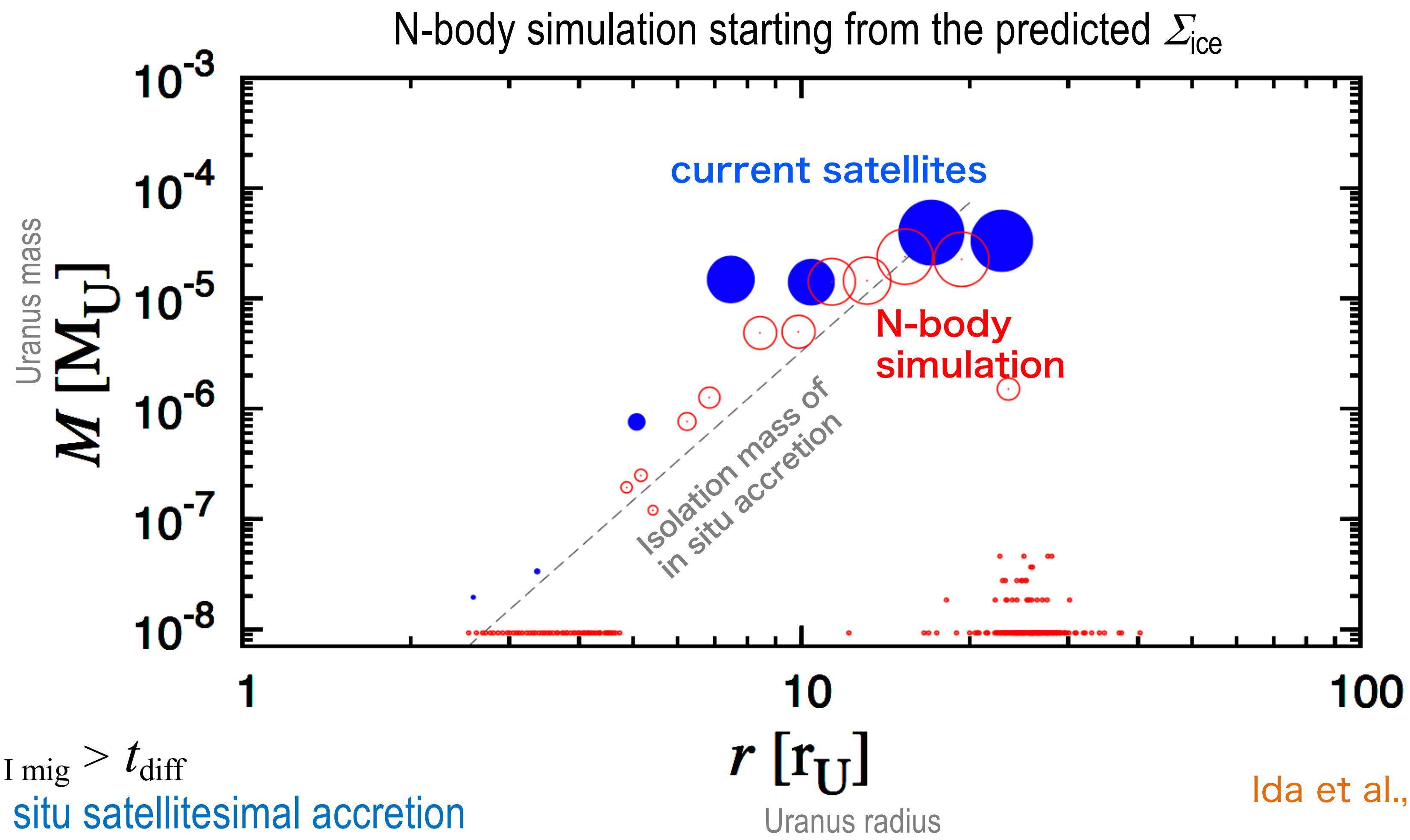
$10^{-2} M_{\rm U}$ – viscous diffusion → $10^{-4} M_{\rm U}$ **x 1/100**

←→ current moons $M_{\rm tot}$ ~ $10^{-4} M_{\rm U}$

-- in situ moon accretion

$$t_{\rm grow} \ll t_{\rm drift} \ll t_{\rm diff}.$$

Reproduction of the current satellites



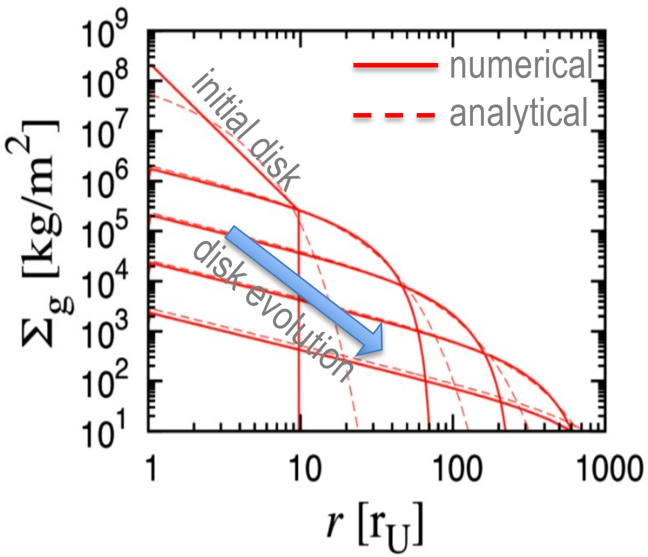
$t_{\text{type I mig}} > t_{\text{diff}}$

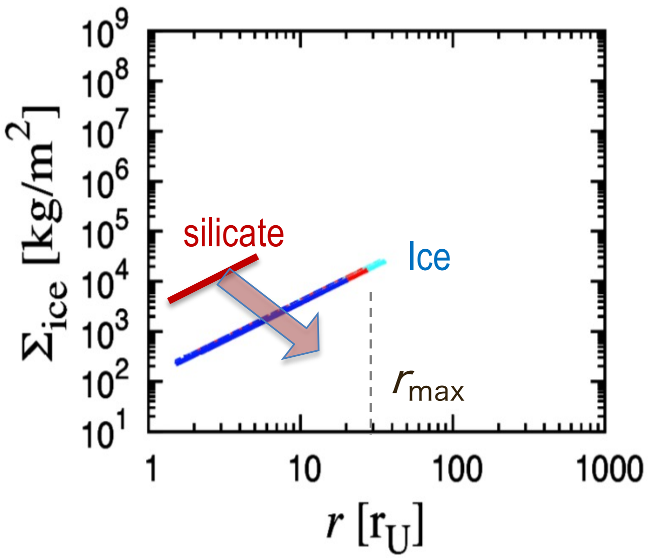
→ in situ satellitesimal accretion

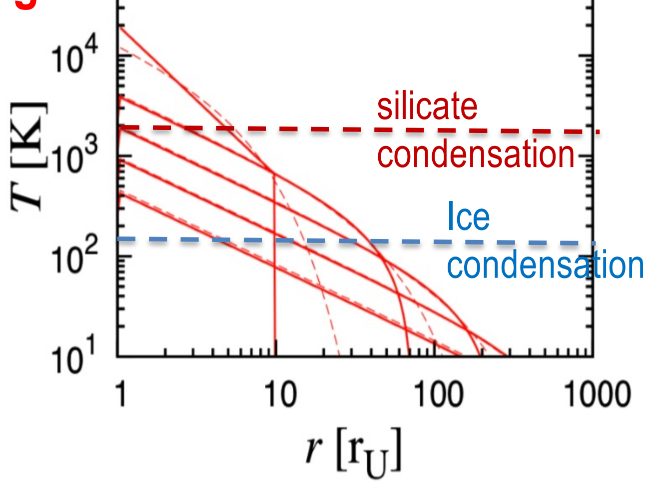
Ida et al., 2020

Enhancement of rock/ice ratio

- **silicates**
  - higher condensation T
    → **earlier condensation than ice**
  - do not grow (less sticky)
    → viscous spreading with gas
  → **after ice condensation,**
  stick to the icy particles in outer region



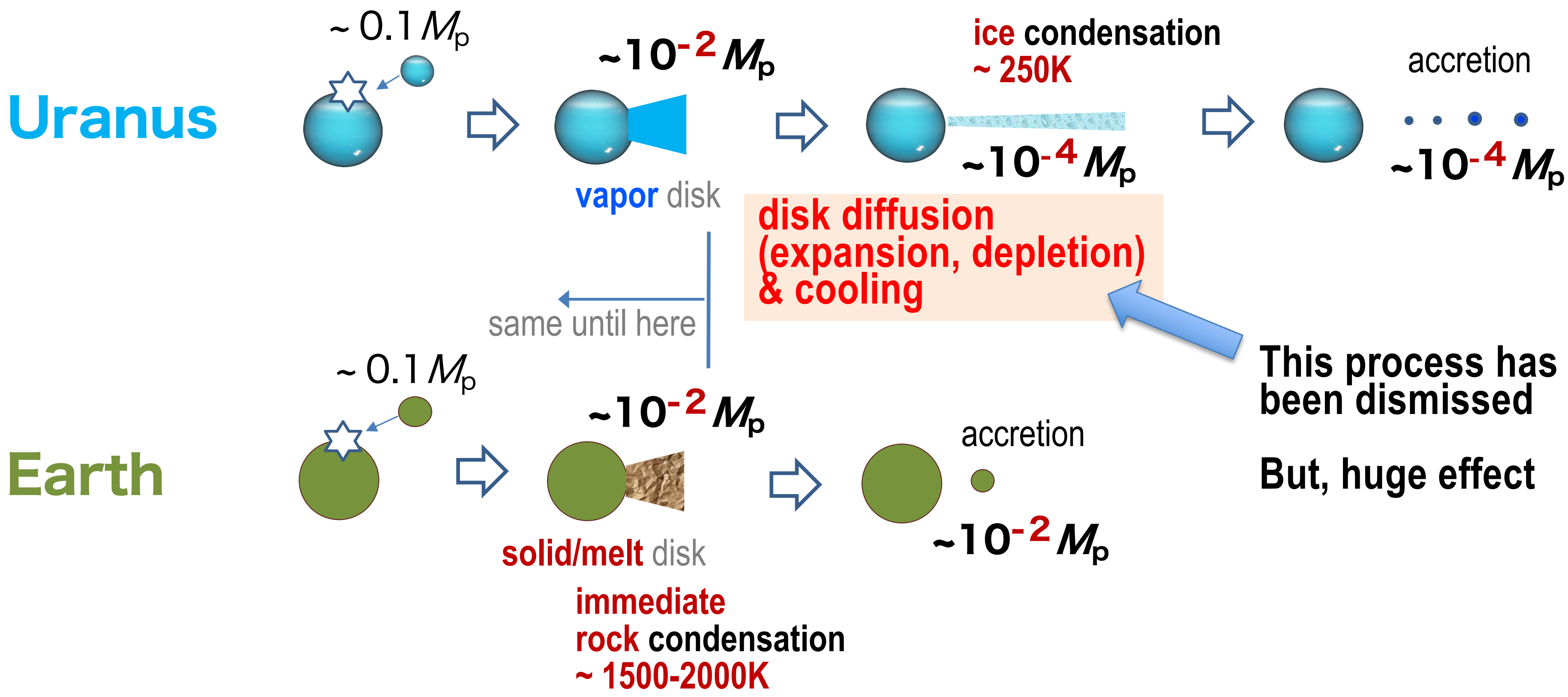




→ $\Sigma_{silicate} / \Sigma_{ice}$ [condense] >> $\Sigma_{silicate} / \Sigma_{ice}$ [initial]

potentially explains $\Sigma_{silicate}/\Sigma_{ice}$~ O(1) of the current moons, produced from ice-rich body impact

Summary of Ida et al.(2020)

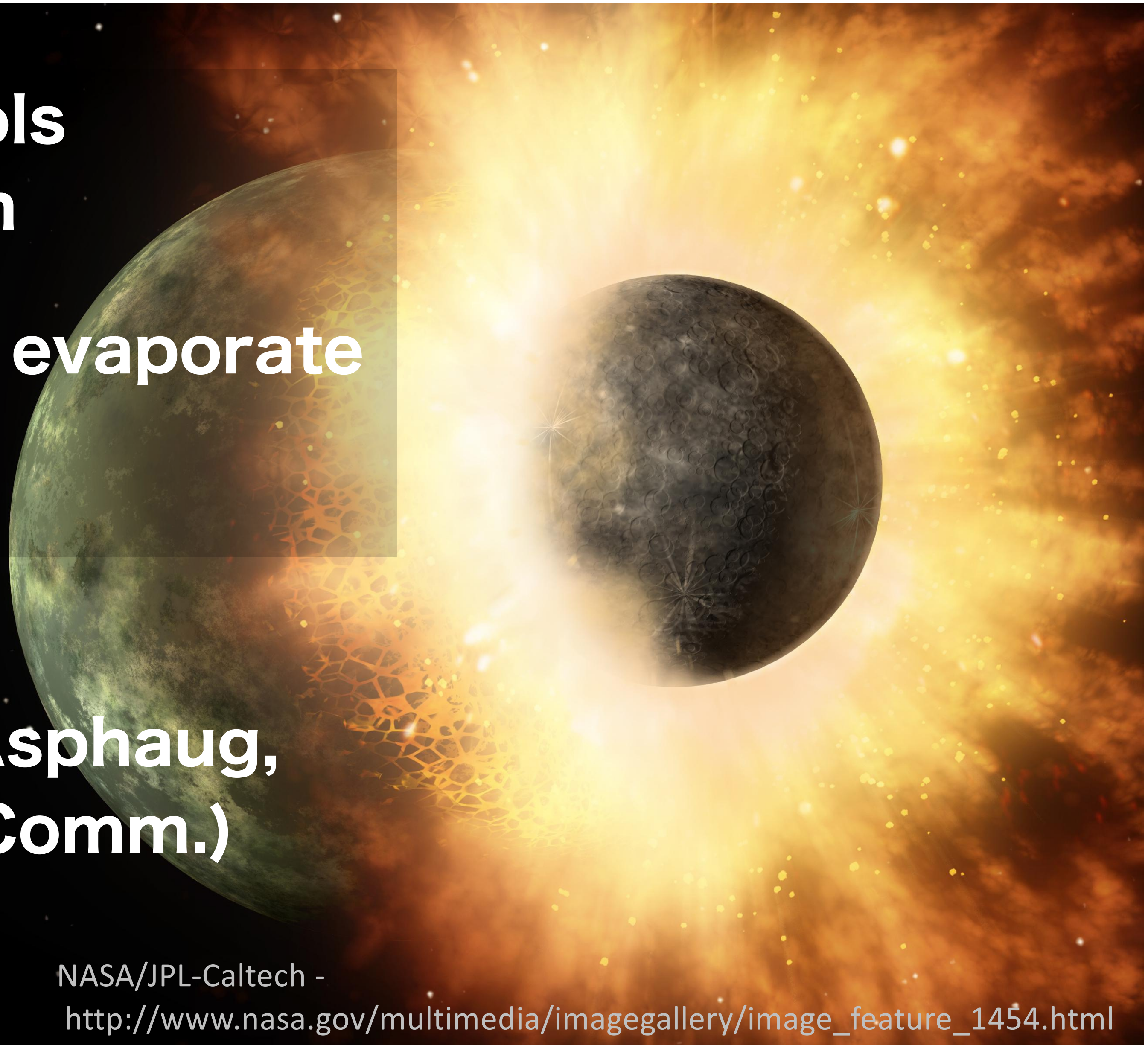


Evaporation controls icy moon formation

Rocky planets also evaporate for M_p > 5-6 M_{earth} !

--> No large moon

Nakajima, Genda, Asphaug, Ida (2022, Nature Comm.)

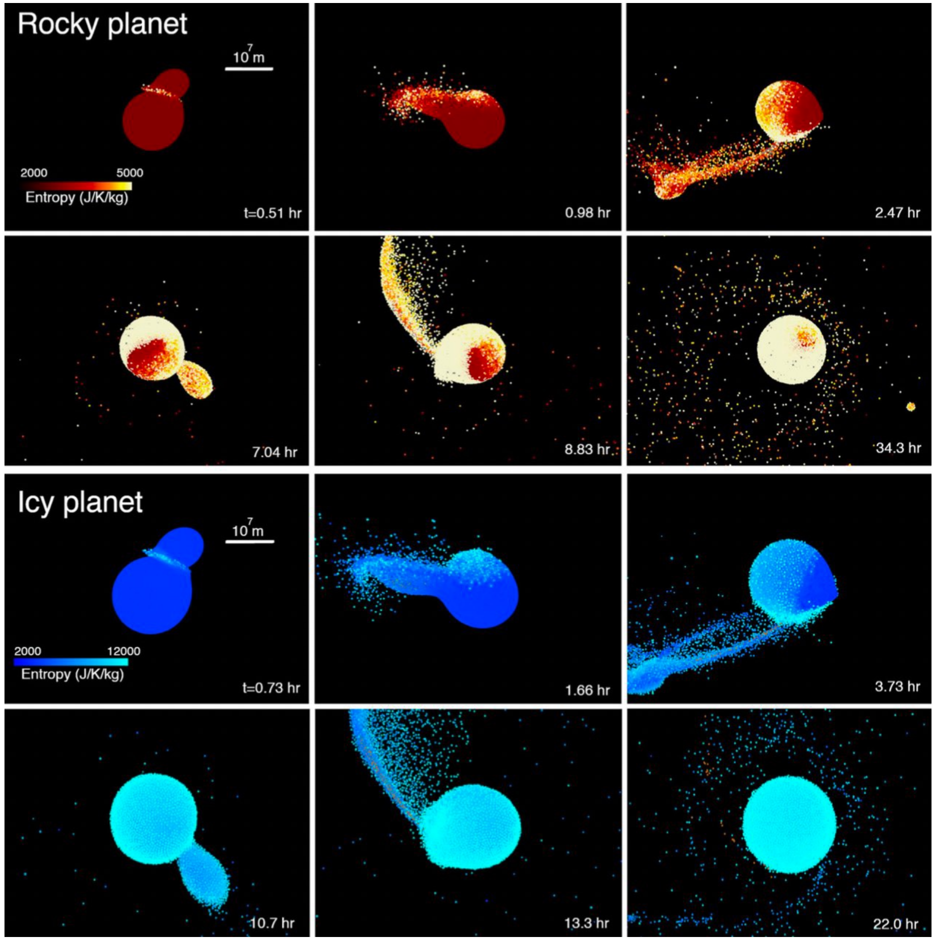


NASA/JPL-Caltech - http://www.nasa.gov/multimedia/imagegallery/image_feature_1454.html

SPH impact simulation

- latent heat
  - rock(silicate) : ~ 1 x 10^7 J/kg
  - water ice: ~ 2 x 10^6 J/kg

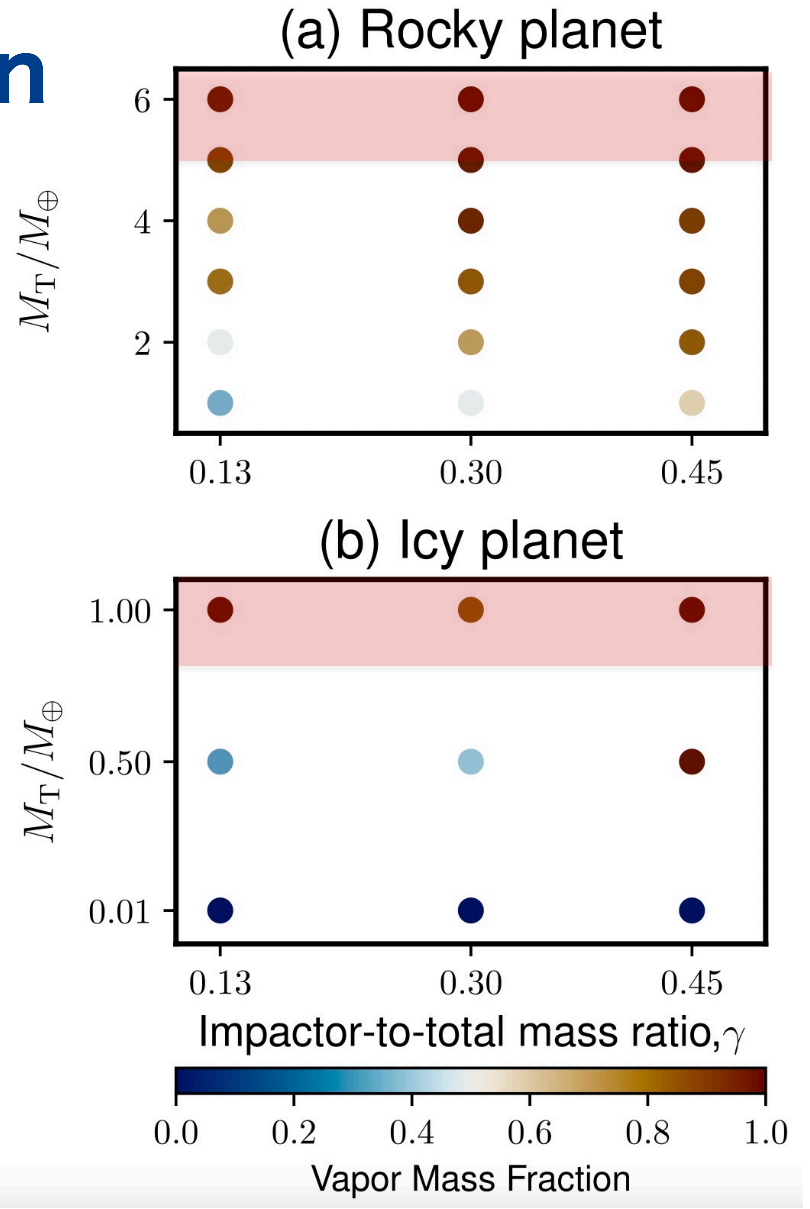
- SPH
  - N = 50K or 100K
  - rocky/icy planets: M-ANEOS + SESAME



Results: Vapor Mass Fraction

- latent heat
  - rock(silicate) : ~ 1 x 10^7 J/kg
  - water ice: ~ 2 x 10^6 J/kg

- VFM ~ 1 → would not have large moons
  - rock : >~ 5-6 M_{earth}
  - ice : >~ 1 M_{Earth}

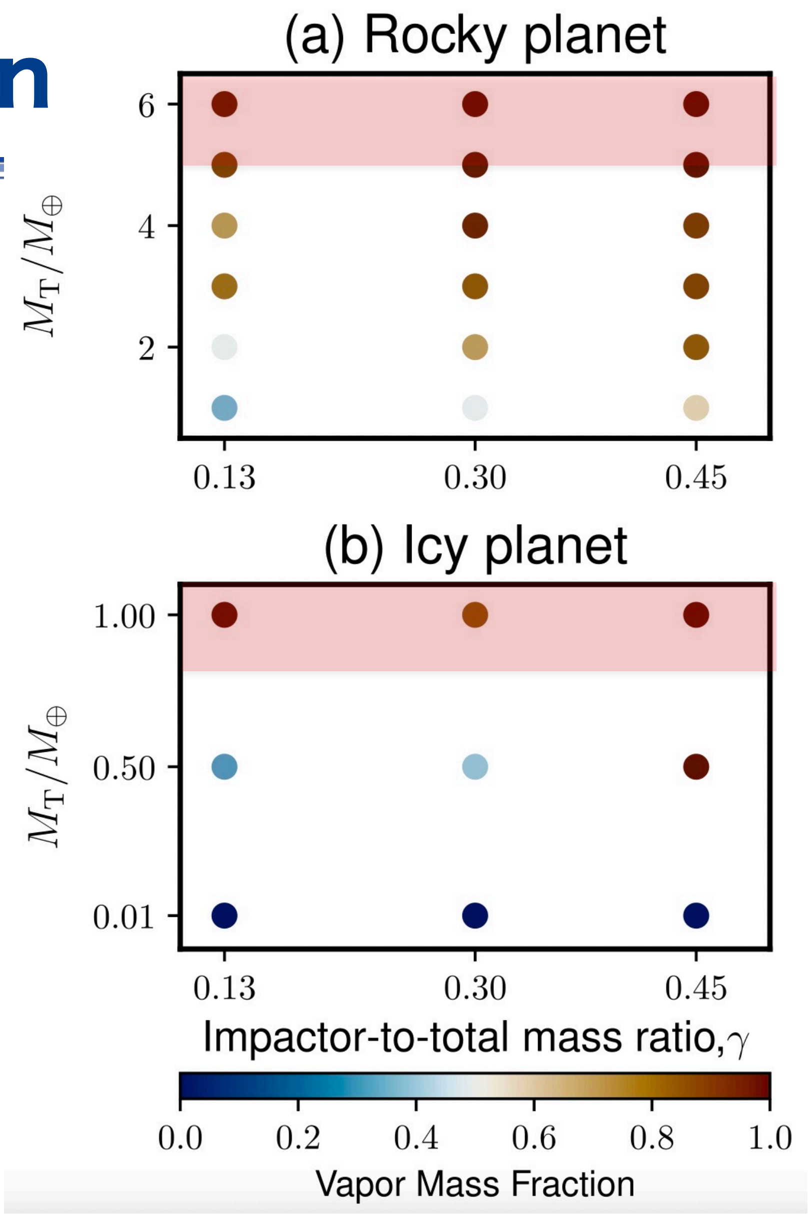


Results: Vapor Mass Fraction

- latent heat
  - rock(silicate) : ~ 1×10^{7} J/kg
  - water ice: ~ 2×10^{6} J/kg

- impact energy :
  ~ $6 \times 10^{7} (M/M_{Earth})^{2/3} (\rho/\rho_{Earth})^{1/3}$ J/kg
  heating energy :
  ~ $3 \times 10^{6} (\varepsilon/0.05) (M/M_{Earth})^{2/3} (\rho/\rho_{Earth})^{1/3}$ J/kg
  efficiency factor
  ↑ determined by SPH impact simulations

- Exomoons : should be searched around
  - rock planets: <~ 5-6 M_{Earth}
  - icy planets : <~ 1 M_{Earth}



Summary

- Uranian moons formation by an giant impact
  - disk evolution until ice condensation controls the moon mass & orbit configuration
    → The big difference between Earth's Moon & Uranian moons is explained [fractionally similar impactor mass, but 100 times different moon mass]

- Exomoons formed by giant impacts
  - "totally vaporized or not" is the most important
  - survey should target
    - rock planets: <~ 5-6 M_{Earth}
    - icy planets : <~ 1 M_{Earth}