Planet Formation III

Masahiro Ogihara

T.D.Lee Fellow/Associate professor

李政道研究所

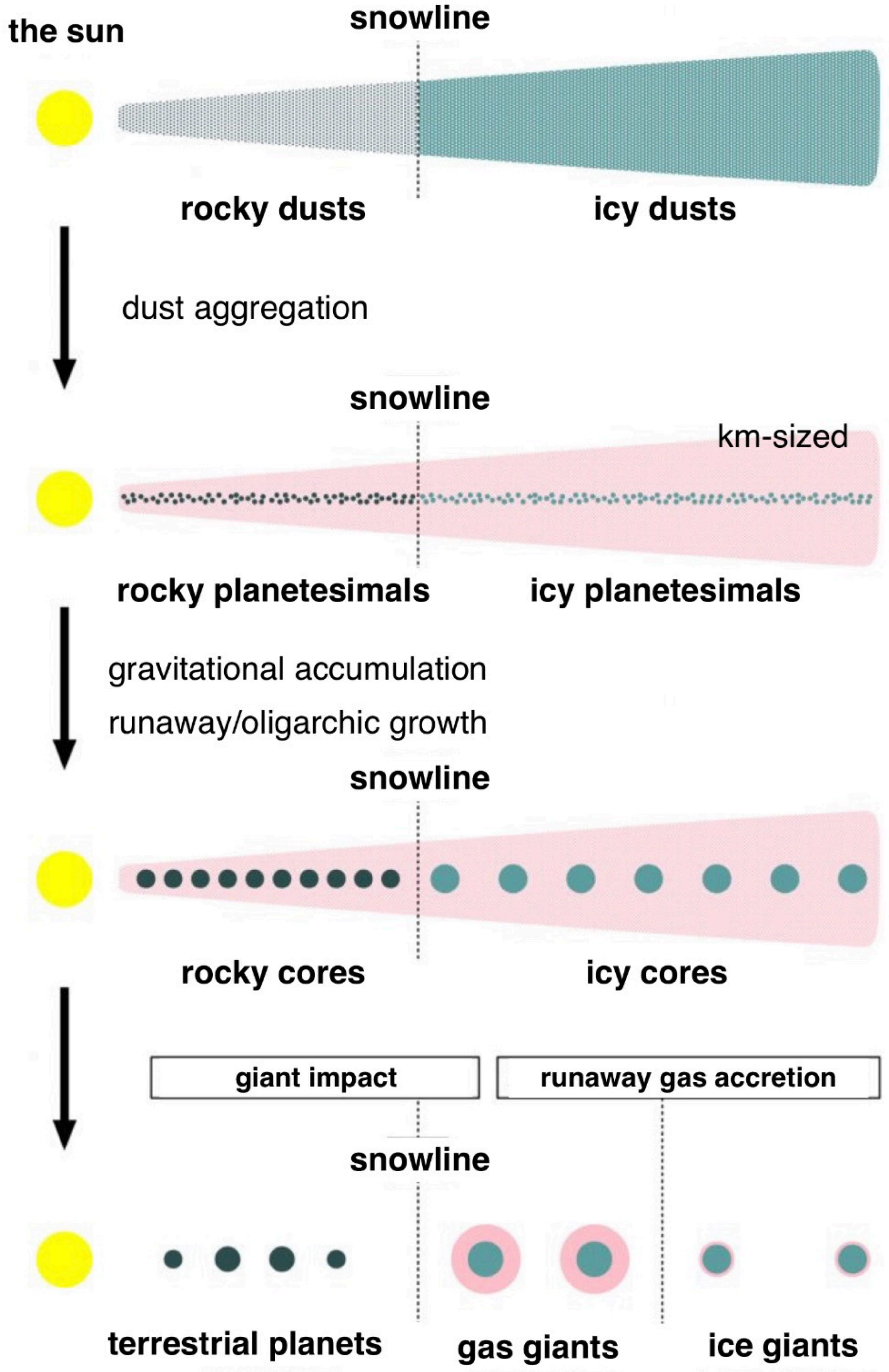
TSUNG-DAO LEE INSTITUTE

Overview of topics on PLANET FORMATION

- Dust coagulation and dynamics
- Accretion of planetesimals/pebbles

- Formation of planets
  - Terrestrial planet formation
  - Giant planet formation
- Solar system formation
- Exoplanet formation (population synthesis)

- Disk-planet interactions



Final stage of terrestrial (giant) planet formation

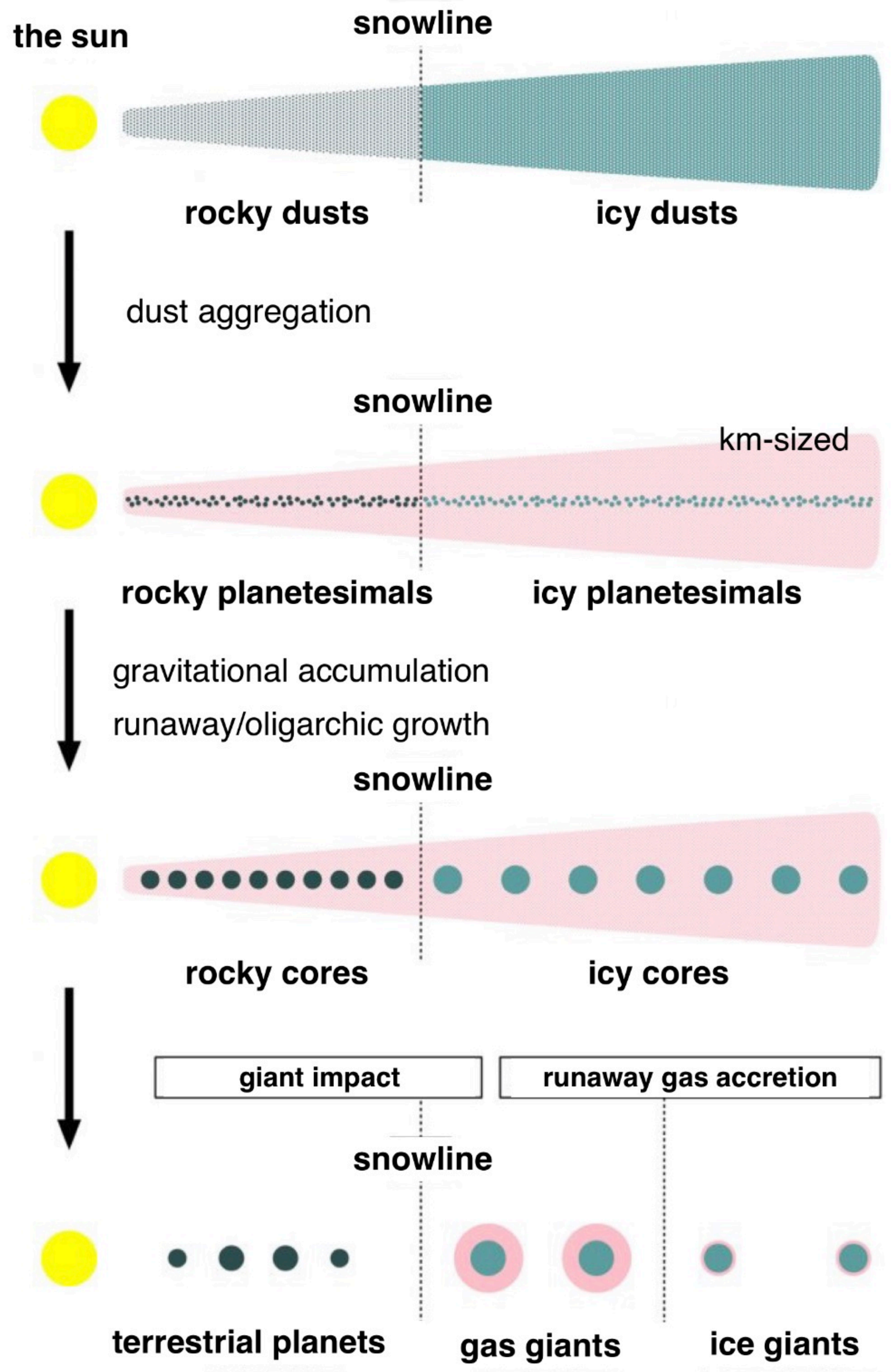
- After planetesimal growth, protoplanets form with adequate orbital separation (eg, 10 r_H)

$$M_{\mathrm{iso,pl}} = 0.16 \left(\frac{a}{1\,\mathrm{au}}\right)^{3/4} \left(\frac{\Delta a}{10\,r_{\mathrm{H}}}\right)^{3/2} \left(\frac{M_*}{M_\odot}\right)^{-1/2} M_\oplus$$

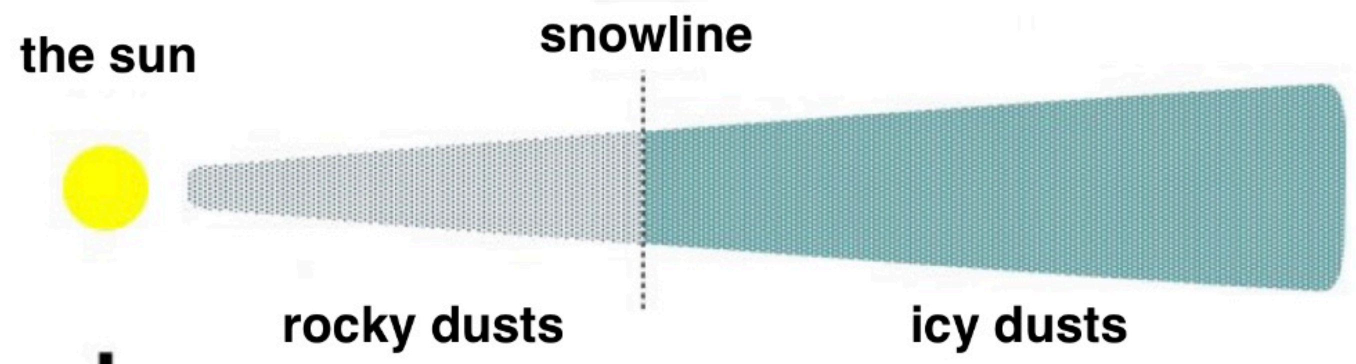
$$r_{\mathrm{H}} = \left(\frac{M_1 + M_2}{3M_*}\right)^{1/3} \frac{a_1 + a_2}{2}$$

$$M_{\mathrm{iso,pb}} = 20 \left(\frac{H/r}{0.05}\right)^{3} \left(\frac{M_*}{M_\odot}\right) M_\oplus$$

- Stable orbits tend to be maintained in the presence of gas (ie, eccentricity damping)
- Gas dissipation causes orbital instability: orbits are perturbed, leading to orbital crossings
  → collisions and scatterings (movie)
- Collision between protoplanets are called “**giant impacts**”
- Eventually, the planets settles on stable orbits



Final stage of terrestrial (giant) planet formation

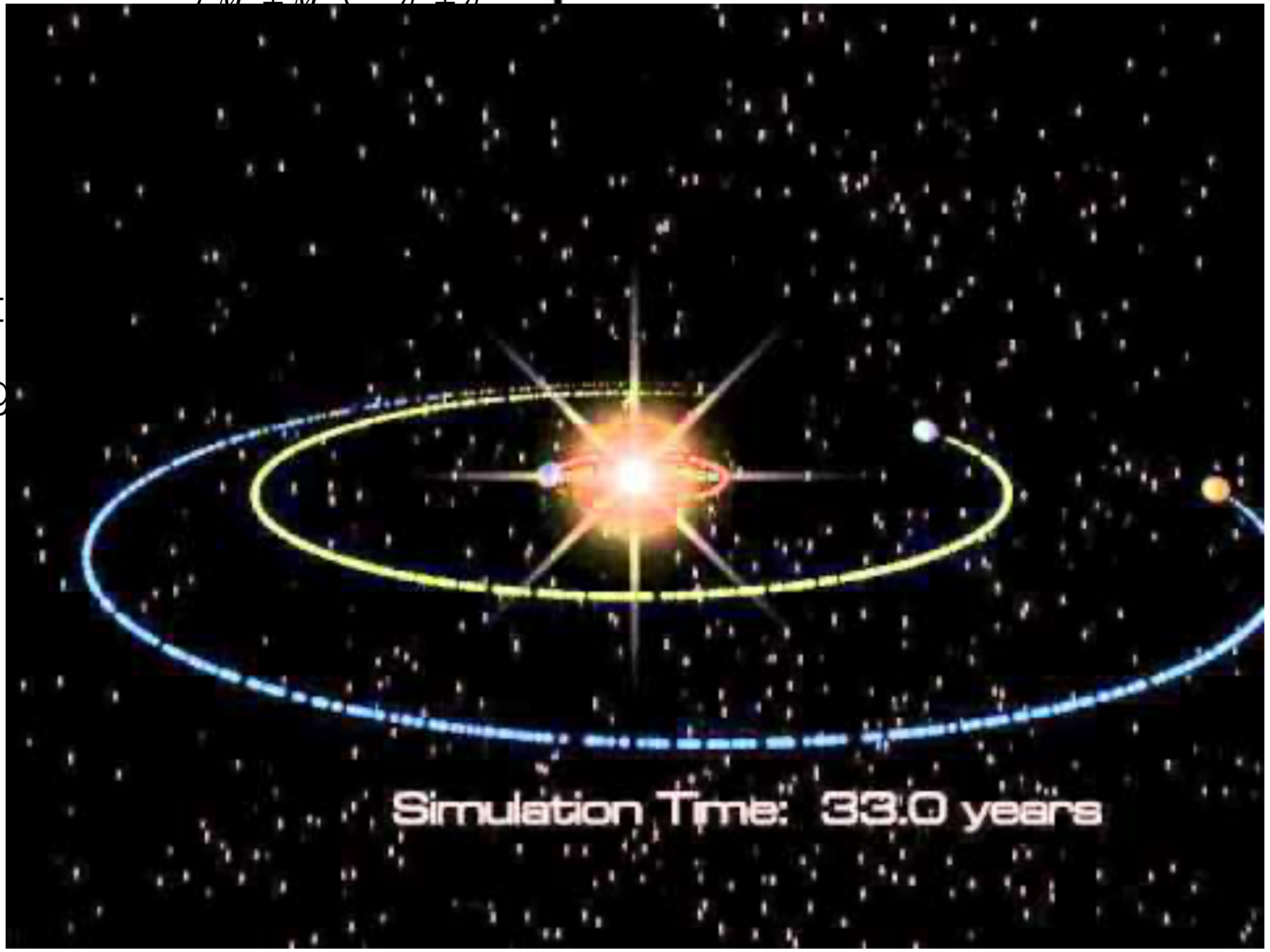


- After planetesimal growth, protoplanets form with adequate orbital separation (eg, 10 r_H)

$$M_{\rm iso,pl} = 0.16 \left(\frac{a}{1\,{\rm au}}\right)^{3/4} \left(\frac{\Delta a}{10\, r_{\rm H}}\right)^{3/2} \left(\frac{M_*}{M_\odot}\right)^{-1/2} M_\oplus$$

$$M_{\rm iso,pb} = 20 \left(\frac{H/r}{0.05}\right)^{3} \left(\frac{M_*}{M_\odot}\right) M_\oplus$$

- Stable orbits tend to be maintained in the presence of gas (ie, eccent
- Gas dissipation causes orbital instability: orbits are perturbed, leading
  → collisions and scatterings (movie)
- Collision between protoplanets are called "**giant impacts**"
- Eventually, the planets settles on stable orbits

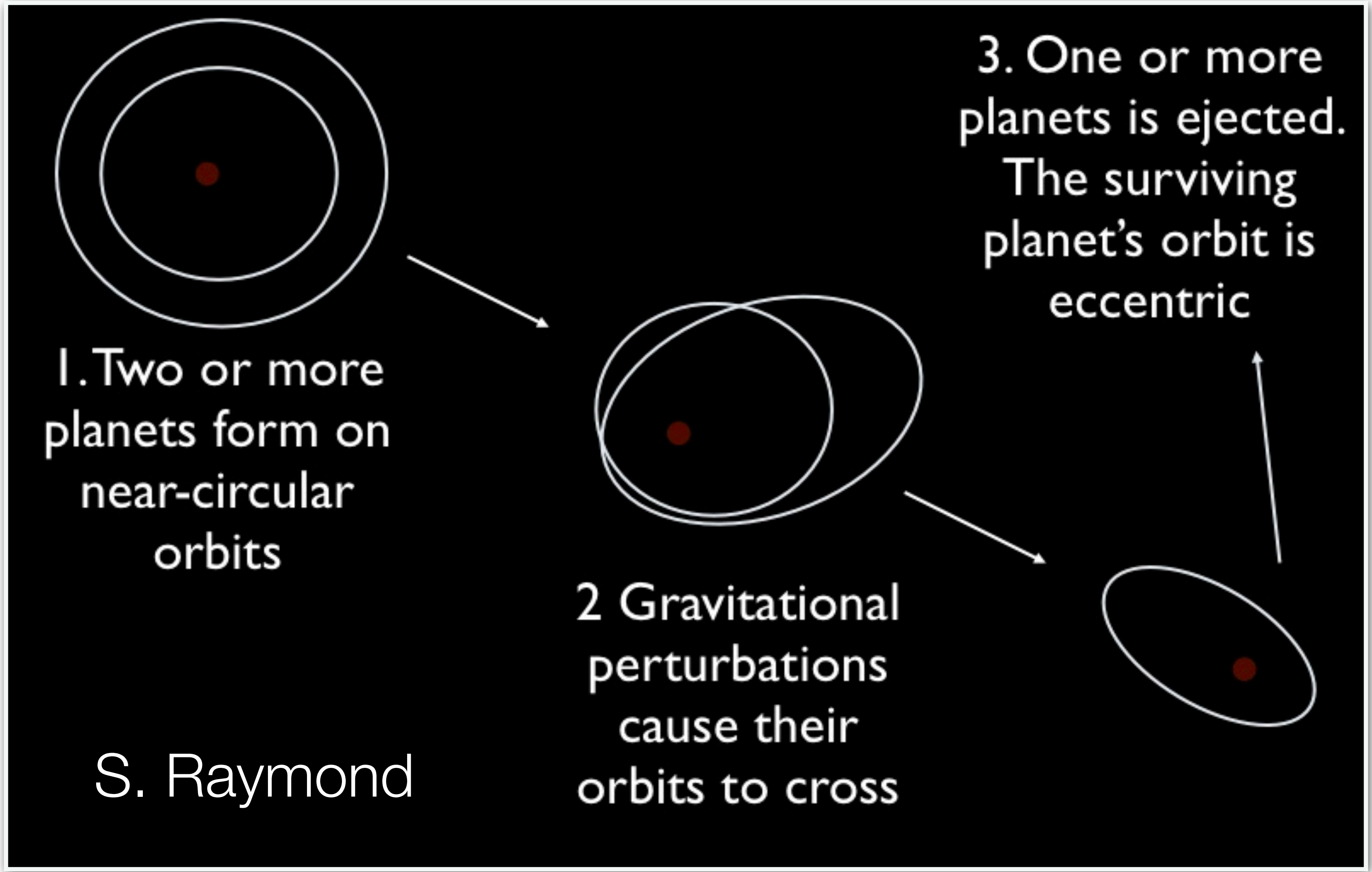


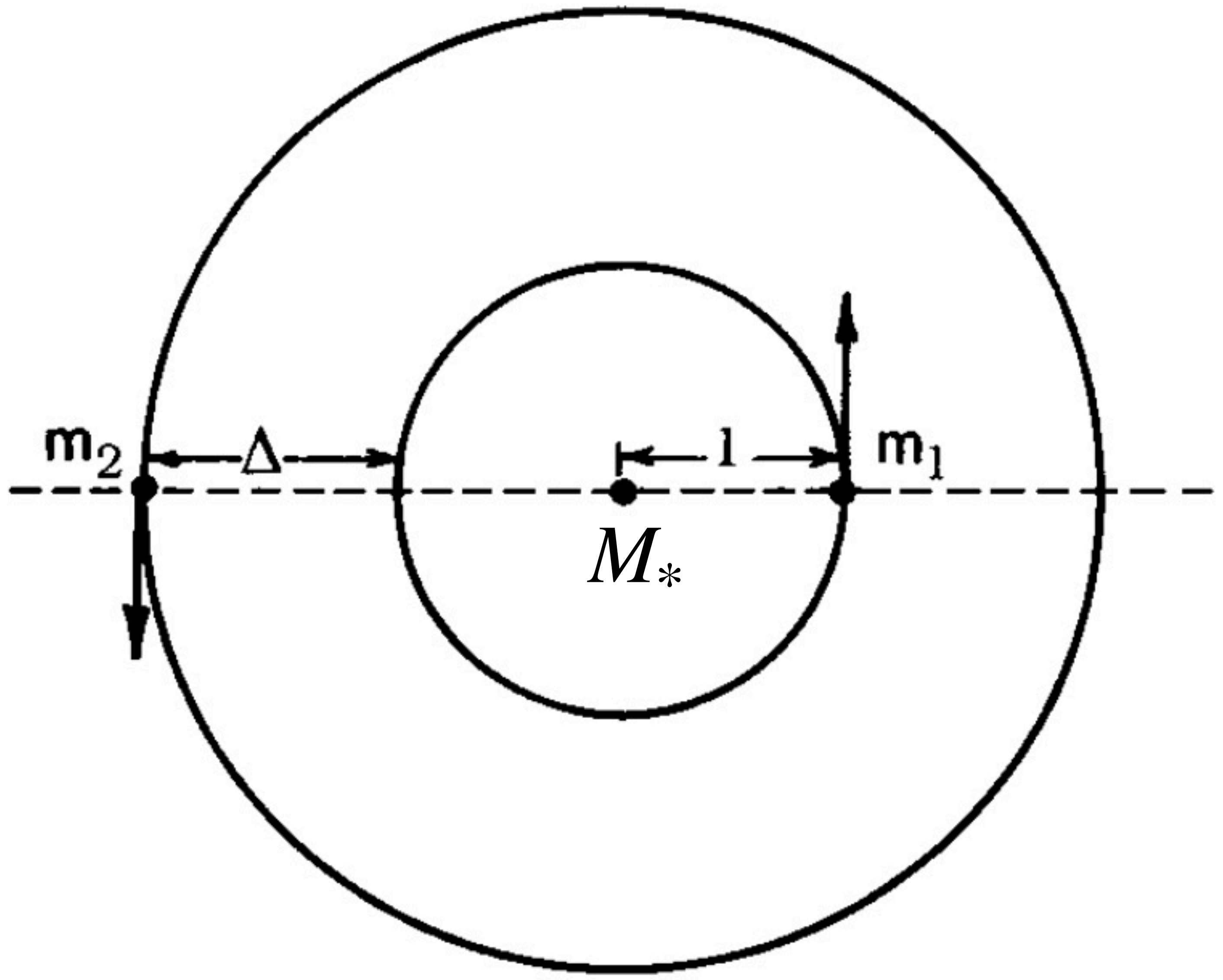
Stability of planetary system: Hill stability

- A system with multiple planets becomes orbitally unstable (orbit crossing → collision, scattering) in a finite time
- If two planets have e~i~0 and small M_p/M_{star}, they will not have a close encounter if their orbits are far enough apart

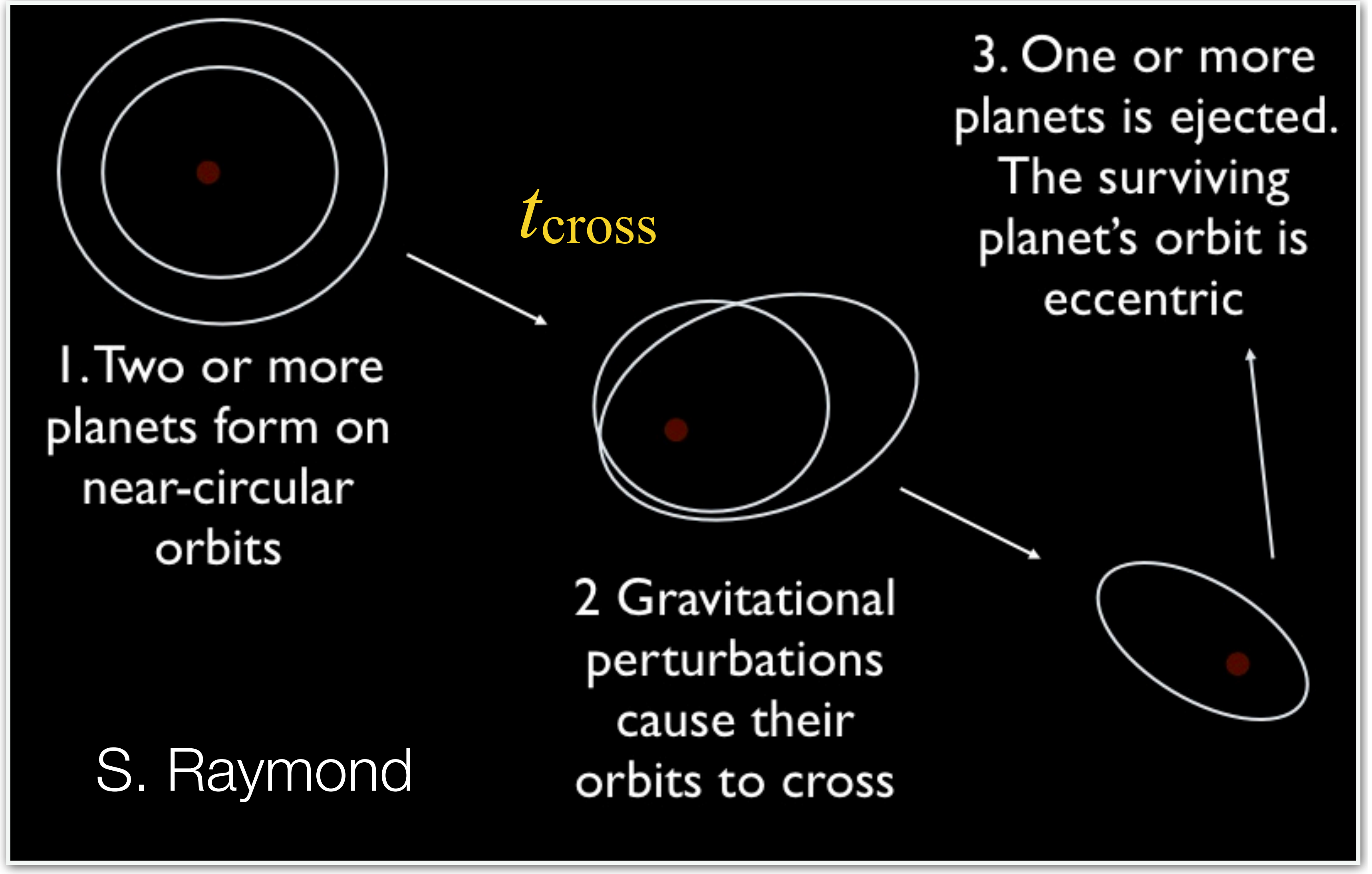
(Hill stability, Gladman 1993)

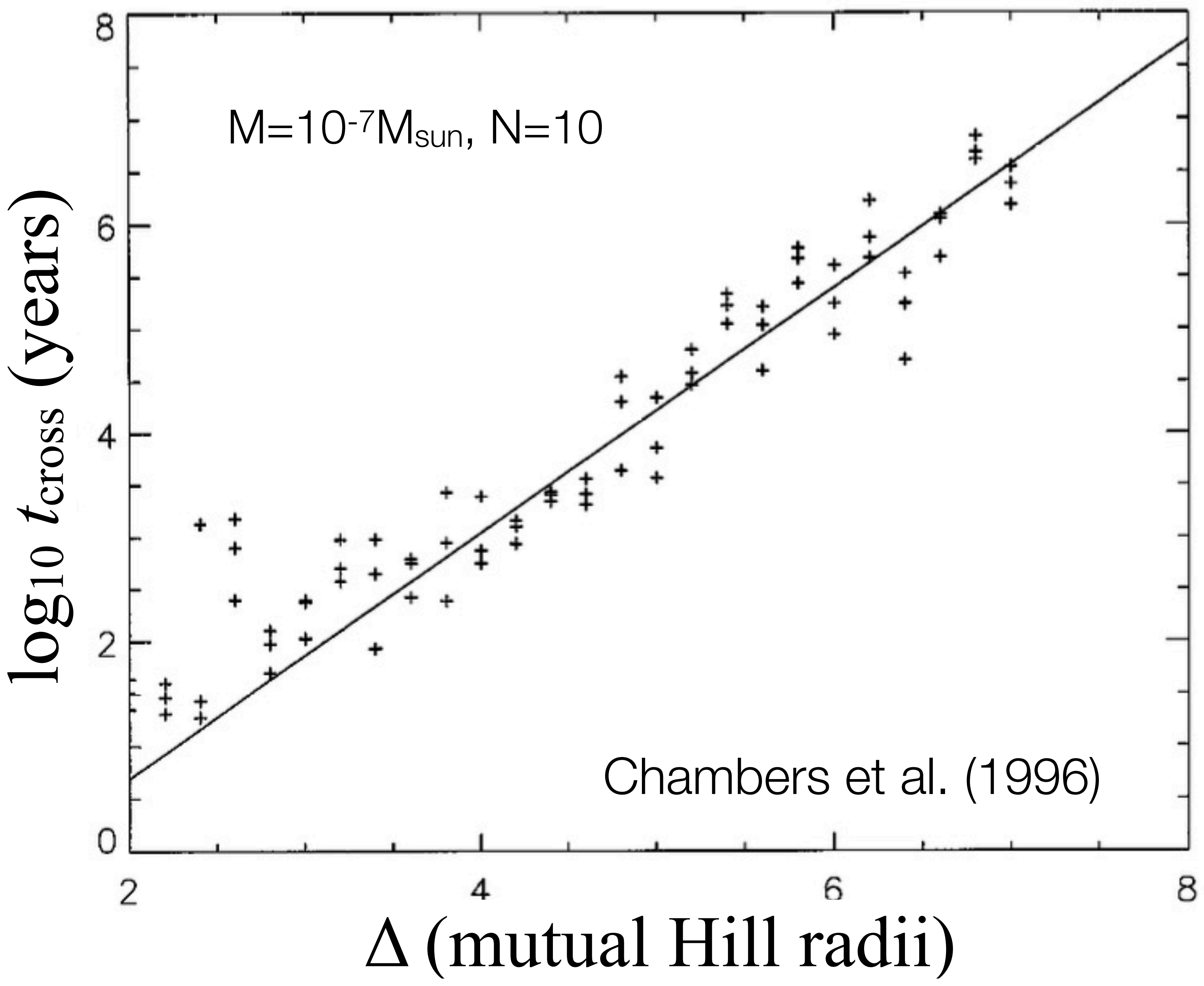
$$\Delta > 2.4\left(\frac{M_1+M_2}{M_*}\right)^{1/3}\left(\frac{a_1+a_2}{2}\right) = 3.46 r_H \qquad r_H = \left(\frac{M_1+M_2}{3M_*}\right)^{1/3}\frac{a_1+a_2}{2}$$

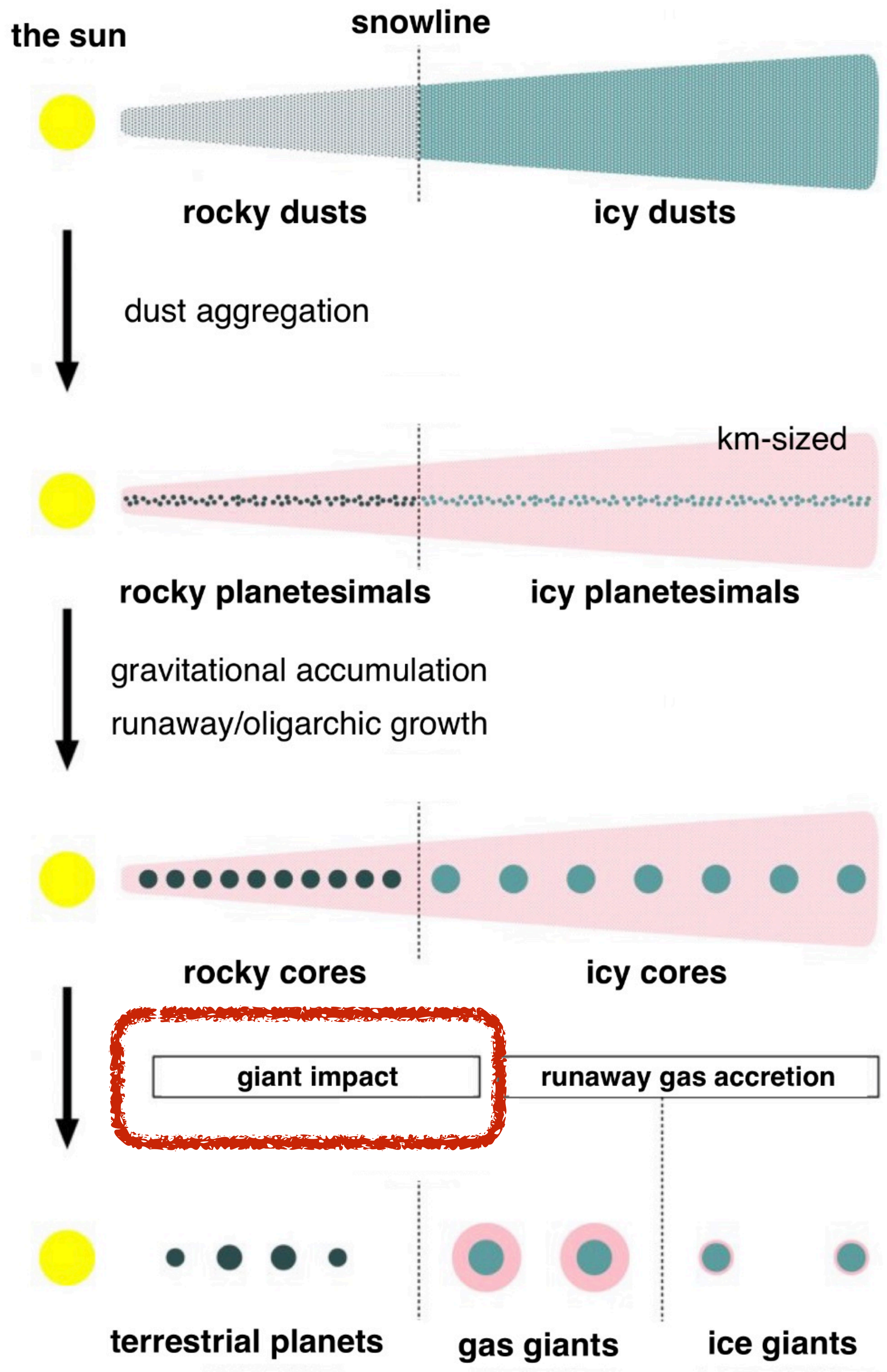




Stability of planetary system: Orbit crossing time







- Dynamical instability ←measured by the orbit crossing time, t_{cross}
- The degree of system instability depends on the properties of the system (eg, N, M, Δa, e) (e.g., Chambers et al. 1996, Yoshinaga et al. 1999, Zhou et al. 2007)

Stability of planetary system: Effects of gas damping

- Another condition of orbital instability: orbit crossing time < eccentricity damping time by gas (Iwasaki et al. 2002)

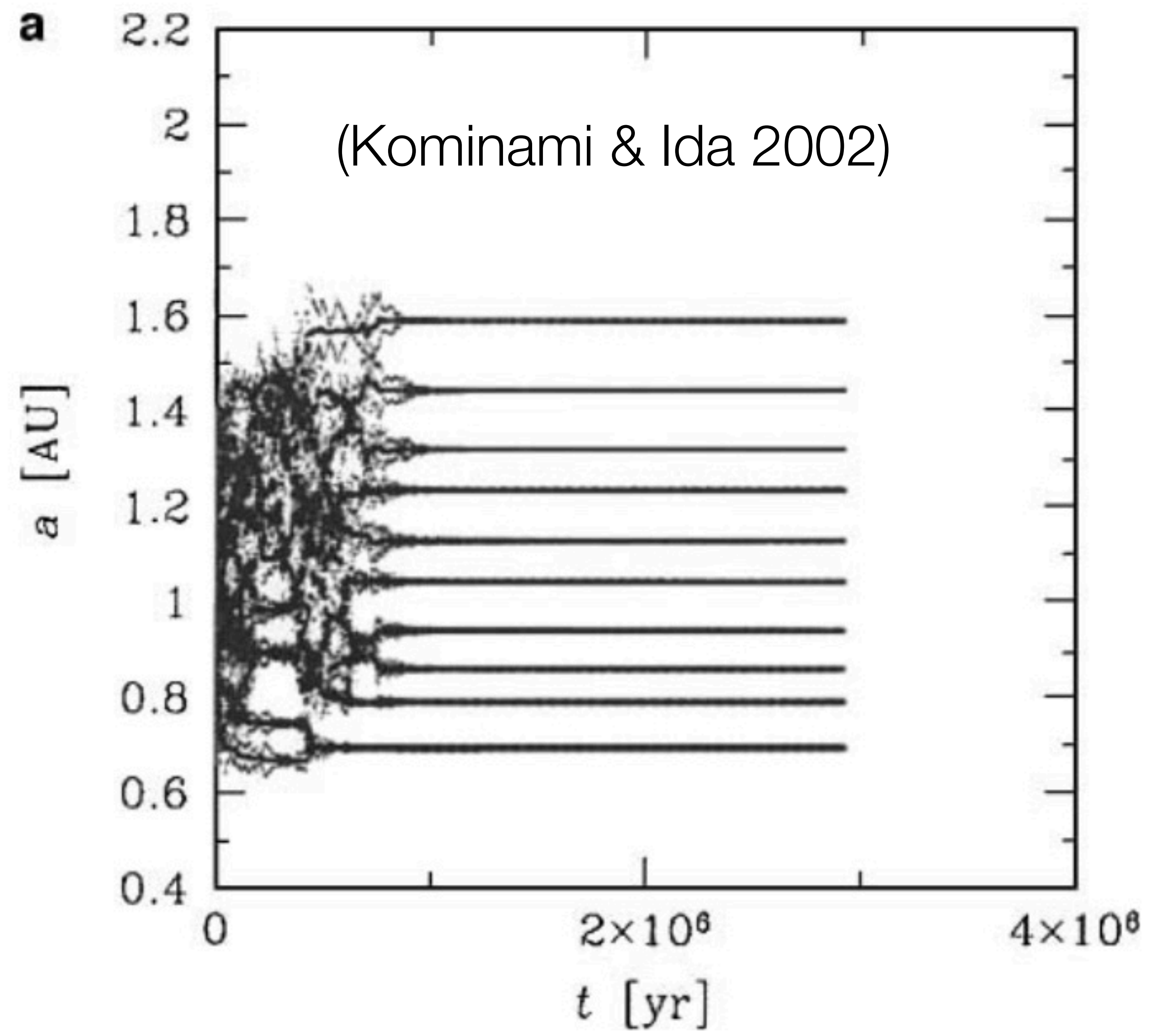
$t_{\rm cross}$

$$t_{\rm wave} = \left(\frac{M}{M_*}\right)^{-1}\left(\frac{\Sigma_g r^2}{M_*}\right)^{-1}\left(\frac{H}{r}\right)^{4}\Omega^{-1} = 240 f_g \left(\frac{M}{M_\oplus}\right)^{-1}\left(\frac{r}{1\,\mathrm{au}}\right)^{2}\,\mathrm{yr}$$

$$\Sigma_g = 2400 f_g \left(\frac{r}{1\,\mathrm{au}}\right)^{-3/2}\,\mathrm{g\,cm^{-2}}$$

$$f_g < 10^{-3}\left(\frac{t_{\rm cross}}{1\,\mathrm{Myr}}\right)^{-1}\left(\frac{M}{0.1 M_\oplus}\right)^{-1}\left(\frac{r}{1\,\mathrm{au}}\right)^{2}\,\mathrm{yr}$$

$M \sim 0.5 M_\oplus$, N=10, Δ=8 Hill radii → $t_{\rm cross}$ ~ 0.1 Myr ~ $t_{\rm wave}$ ~ 0.1 Myr

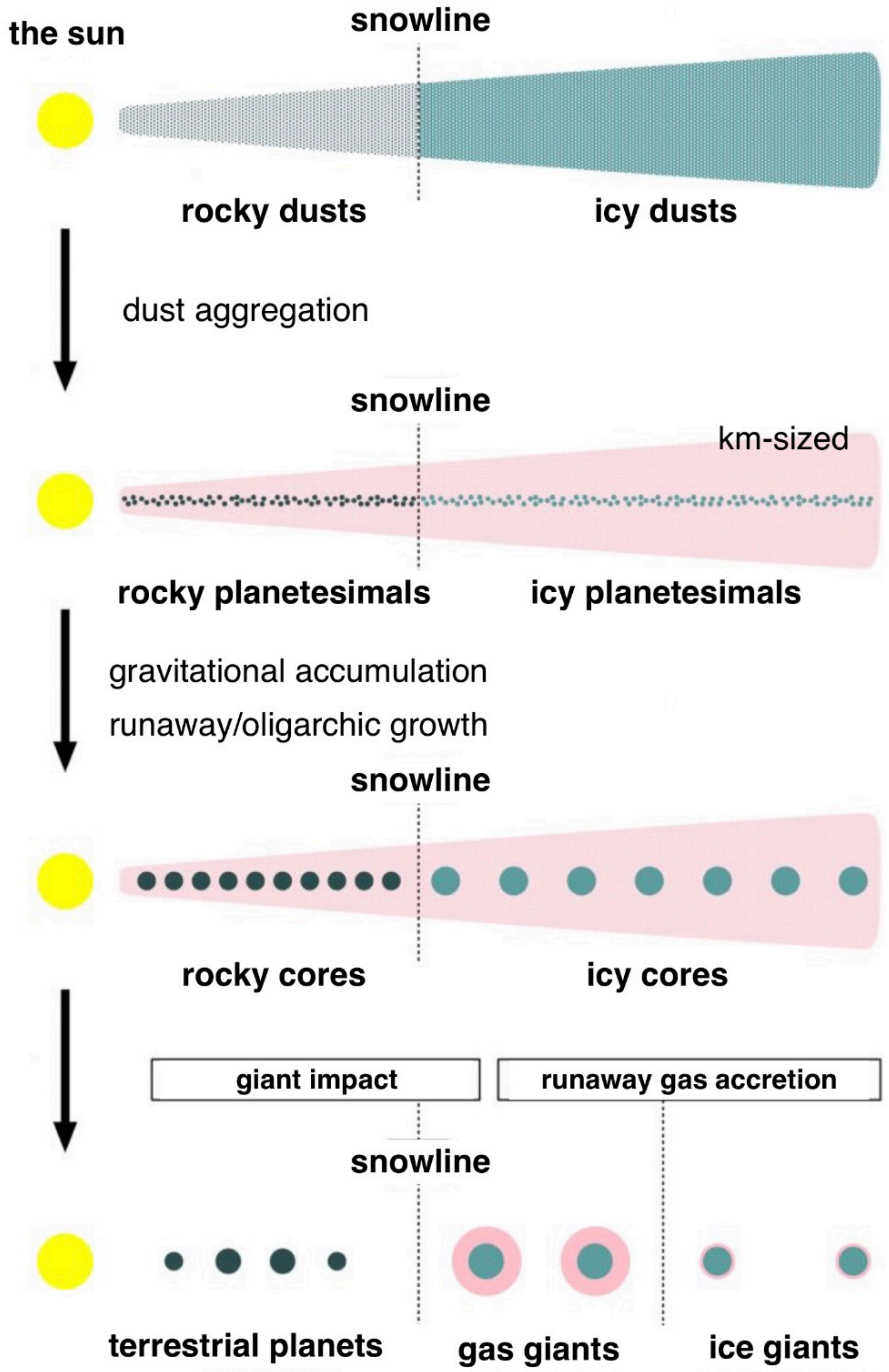


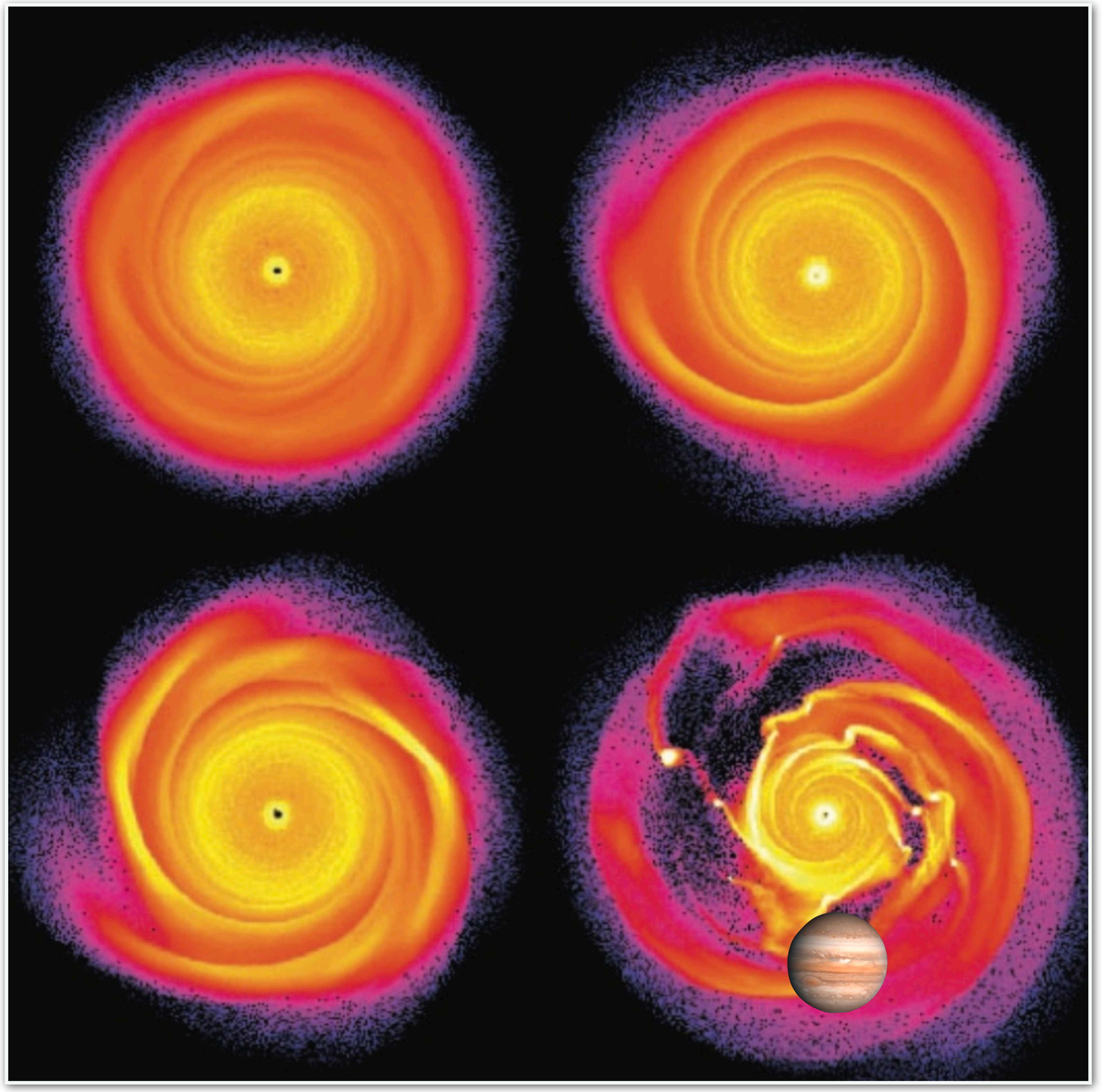
- Dynamical instability requires gas dissipation (not necessarily complete)

Giant planets

- Next we see formation of giant planets
- Two models
- Core accretion (eg, Mizuno 1980)
- Disk instability

  (eg, Cameron 1978; Boss 2003)

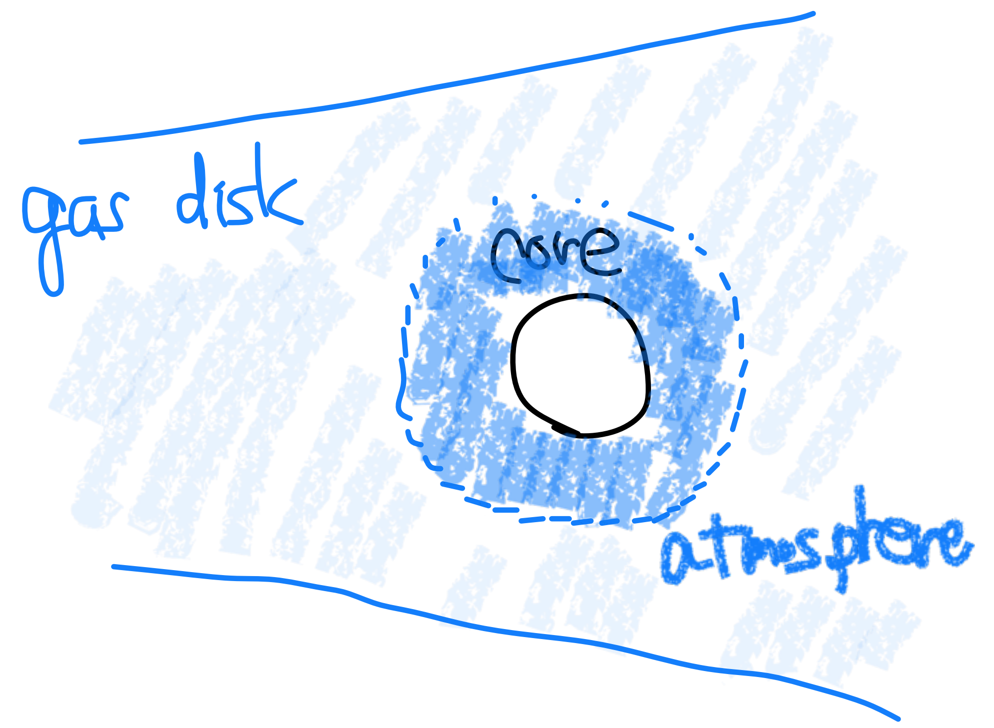




(Mayer et al. 2002)

Giant planets: Core accretion

- Large planets in the disk can gravitationally accrete an atmosphere



- A planet can have an atmosphere:

  the kinetic energy of atmosphere < the gravitational potential of planet

  $c_s^2/2$ GM/R

- **Bondi radius**: Radius at which the two are balanced

$$R_\mathrm{B} = \frac{GM}{c_s^2} \simeq 3.3 \times 10^5 \left(\frac{M}{M_\oplus}\right)\left(\frac{T}{300\,\mathrm{K}}\right)^{-1} \mathrm{km}$$

- Minimum planetary mass that can have the atmosphere:

  Bondi radius R_B > planetary radius R

$$R = 7.8 \times 10^3 \left(\frac{M}{M_\oplus}\right)^{1/3} \left(\frac{\rho}{3\,\mathrm{g/cm^3}}\right)^{-1/3} \mathrm{km}$$

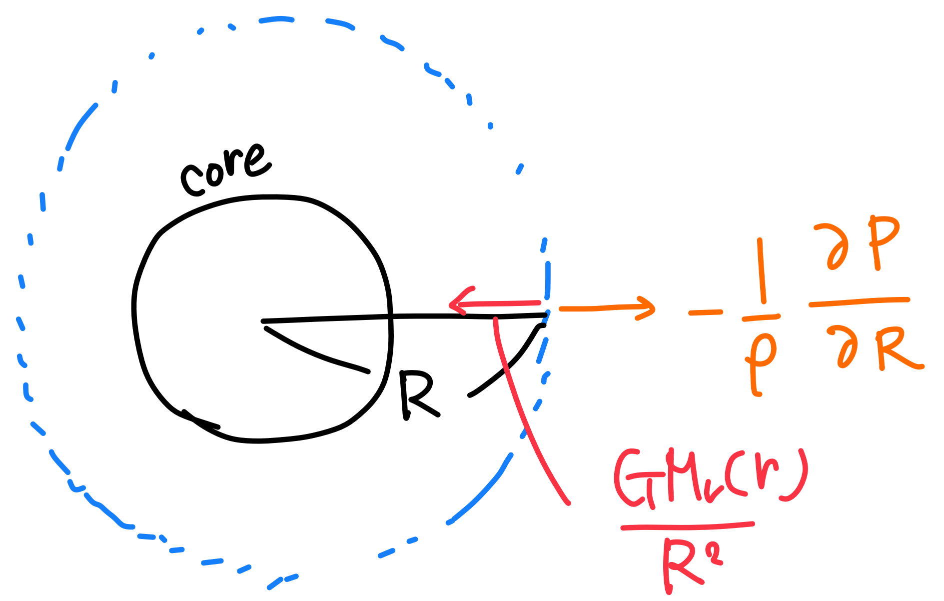
- For T=300K, planets with masses of about 0.01$M_\oplus$~Moon can have atmospheres

Giant planets: Core accretion

- Condition to maintain stable equilibrium atmospheric structure:

  the expansion due to pressure gradient = the gravity

  $(1/\rho)\partial P/\partial r$ $\qquad$ GM_r/R^2



$$P = \frac{\rho k_B T}{m}$$

- If the core is too massive, there is no equilibrium solution
- **Critical core mass**: Upper limit mass with equilibrium atmosphere
- The pressure gradient is affected by the accretion heating

$$M_{\rm crit} \sim 10 \left(\frac{\dot{M}}{1\, M_\oplus/{\rm Myr}} \right)^{(0.2\sim0.3)} \left(\frac{\kappa}{1\ {\rm cm^2/g}} \right)^{(0.2\sim0.3)} M_\oplus$$

- Gas accretion rate (quasi-static):
- Gas inflow rate to the planet beyond the critical core mass is determined by the gravitational contraction of the atmosphere
- **Kelvin-Helmholtz time**: Total energy / energy radiation rate

$$t_{\rm KH} \sim 10^7 \left(\frac{M}{10\, M_\oplus} \right)^{-(2.3\sim4)} \left(\frac{\kappa}{1\ {\rm cm^2/g}} \right) {\rm yr}$$

- The accretion ends when the gas supply ends (disk dissipation)

Giant planets: Disk instability

- The disk can gravitationally collapse when the disk's self gravity overcomes tidal forces
- Condition: an object is stable against tidal forces tidal force < self gravity

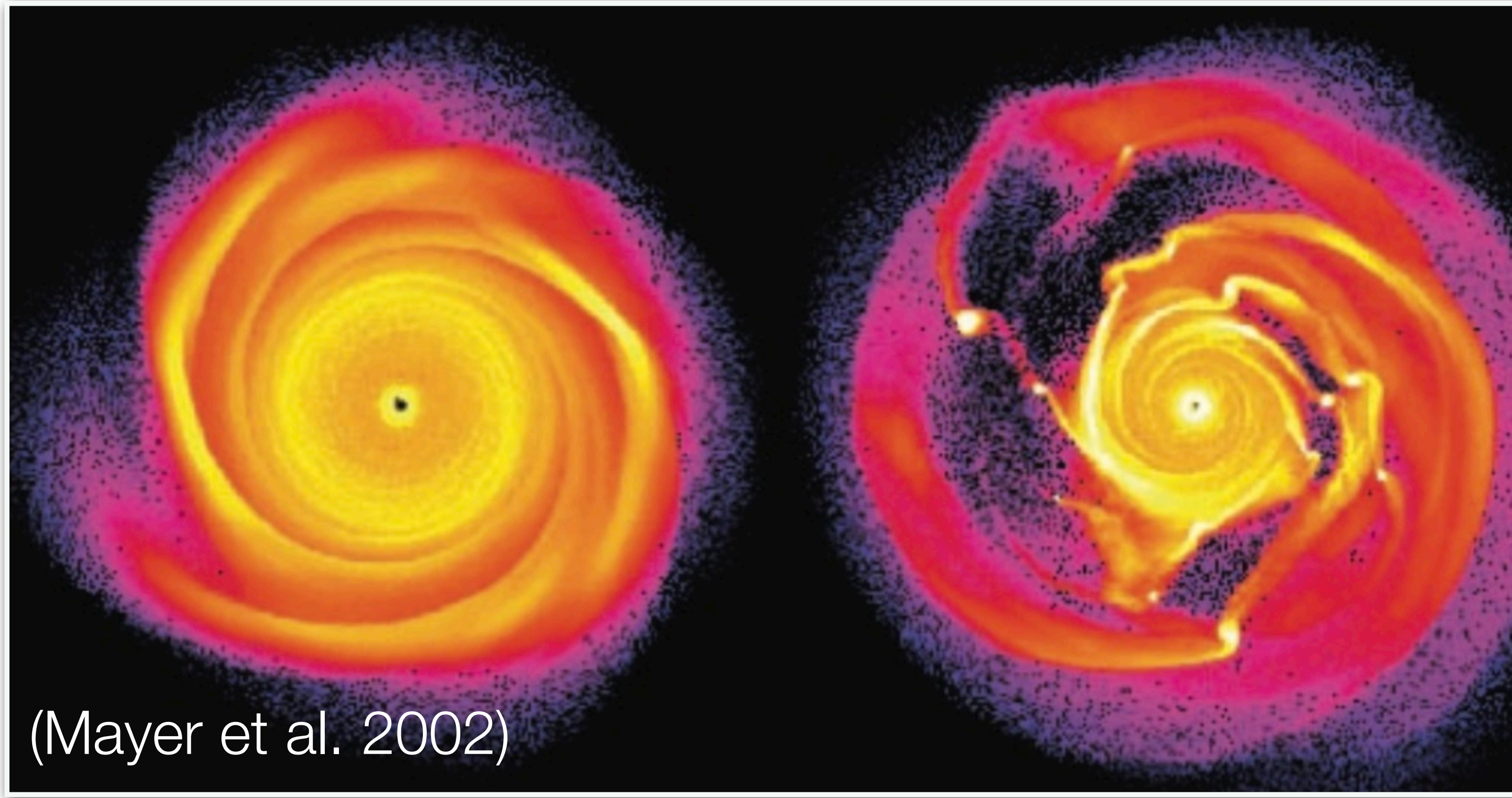
$$f_{\rm tide}(a+R) \simeq \frac{3GM_cR}{a^3} \qquad \frac{GM}{R^2} \qquad \left(M = \frac{4\pi\rho R^3}{3}\right)$$

$$\Leftrightarrow \quad \rho > \frac{9}{4\pi}\frac{M_c}{a^3} \quad \Leftrightarrow \quad 1 > \frac{c_s\Omega_K}{\Sigma G} \equiv Q \quad \left(\rho \sim \frac{\Sigma}{H} \sim \frac{\Sigma}{c_s/\Omega_K},\ \Omega_K = \left(\frac{GM_c}{a^3}\right)^{1/2}\right) \quad \Leftrightarrow \quad Q \sim 10\left(\frac{a}{1\,{\rm au}}\right)^{-1/4} f_g^{-1}\left(\frac{M_*}{M_\odot}\right)$$

Toomre's Q parameter <1-2 (Toomre 1964)

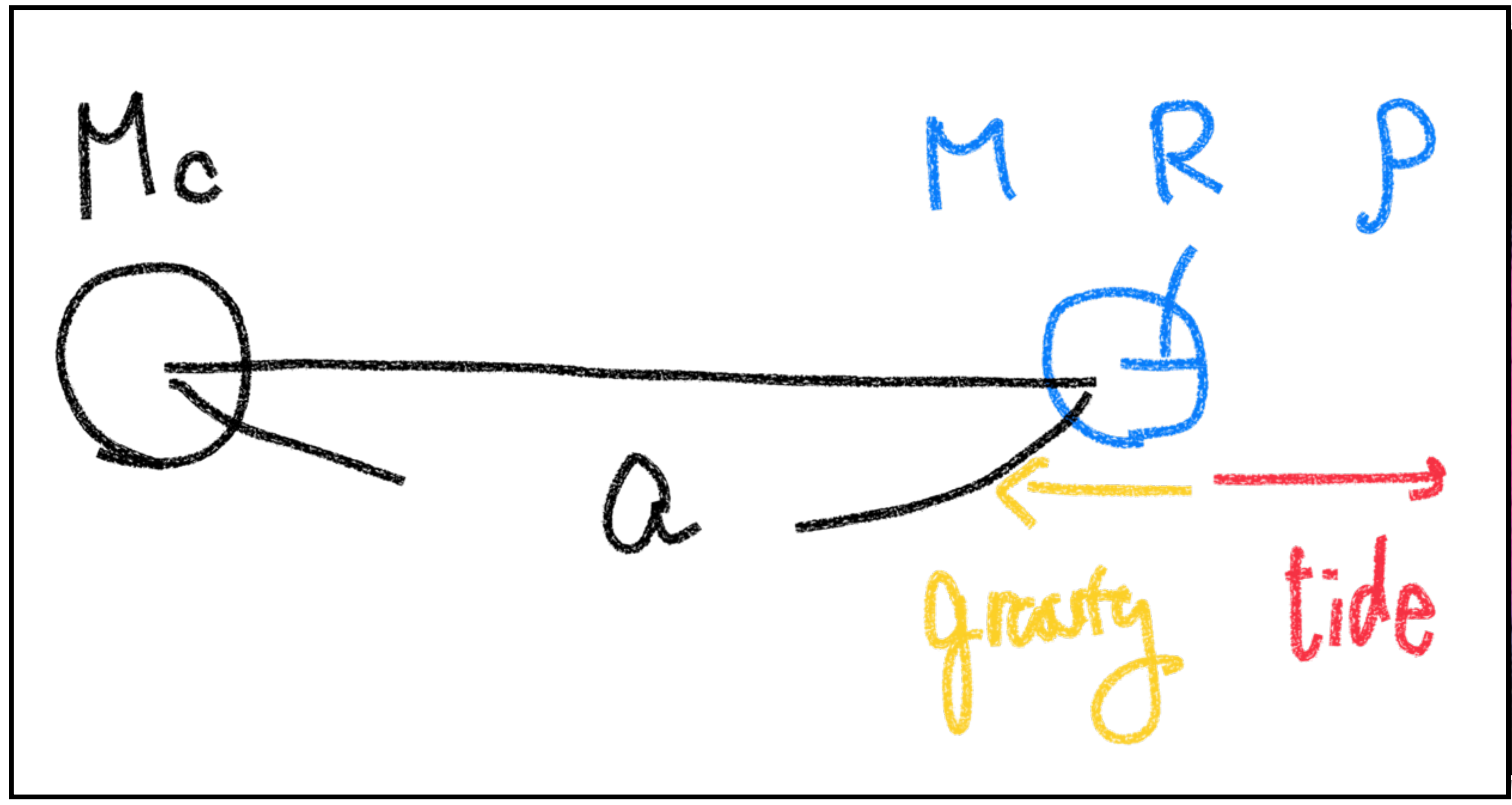
$$\Sigma_g = 1700 f_g \left(\frac{r}{1\,{\rm au}}\right)^{-3/2} {\rm g\,cm^{-2}}$$

$$T = 280\left(\frac{r}{1\,{\rm au}}\right)^{-1/2}\left(\frac{L}{L_\odot}\right)^{1/4} {\rm K}$$


(Mayer et al. 2002)

- In a disk more massive than MMSN, planets can form in wide orbits.
- Linear analysis is used to obtain (eg, Binney & Tremain 1987)
- Note that migration is problematic (e.g., Zhu et al. 2012)

Giant planets: Disk instability



- The disk can gravitationally collapse when the disk's self gravity overcomes tidal forces
- Condition: an object is stable against tidal forces tidal force < self gravity

$$f_{\rm tide}(a+R) \simeq \frac{3GM_cR}{a^3} \qquad \frac{GM}{R^2} \qquad \left(M = \frac{4\pi\rho R^3}{3}\right)$$

$$\Leftrightarrow \quad \rho > \frac{9}{4\pi}\frac{M_{\rm c}}{a^3} \quad \Leftrightarrow \quad 1 > \frac{c_s\Omega_{\rm K}}{\Sigma G} \equiv Q \qquad \left(\rho \sim \frac{\Sigma}{H} \sim \frac{\Sigma}{c_s/\Omega_{\rm K}},\ \Omega_{\rm K} = \left(\frac{GM_c}{a^3}\right)^{1/2}\right) \qquad \Leftrightarrow \quad Q \sim 10\left(\frac{a}{1\ {\rm au}}\right)^{-1/4} f_g^{-1}\left(\frac{M_*}{M_\odot}\right)$$

Toomre's Q parameter <1-2 (Toomre 1964)

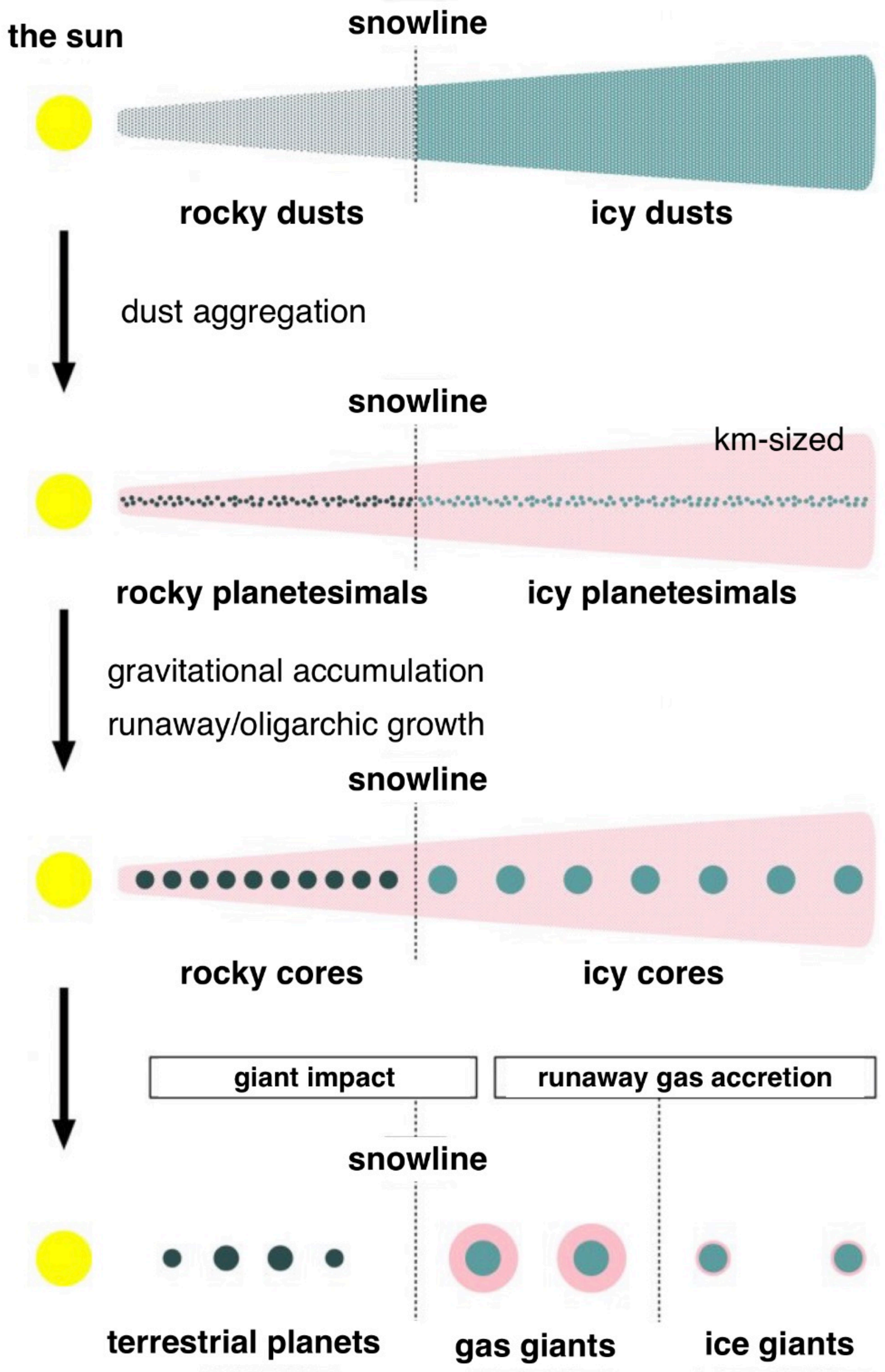
$$\Sigma_{\rm g} = 1700 f_g \left(\frac{r}{1\ {\rm au}}\right)^{-3/2} {\rm g\ cm^{-2}}$$

$$T = 280\left(\frac{r}{1\ {\rm au}}\right)^{-1/2}\left(\frac{L}{L_\odot}\right)^{1/4} {\rm K}$$

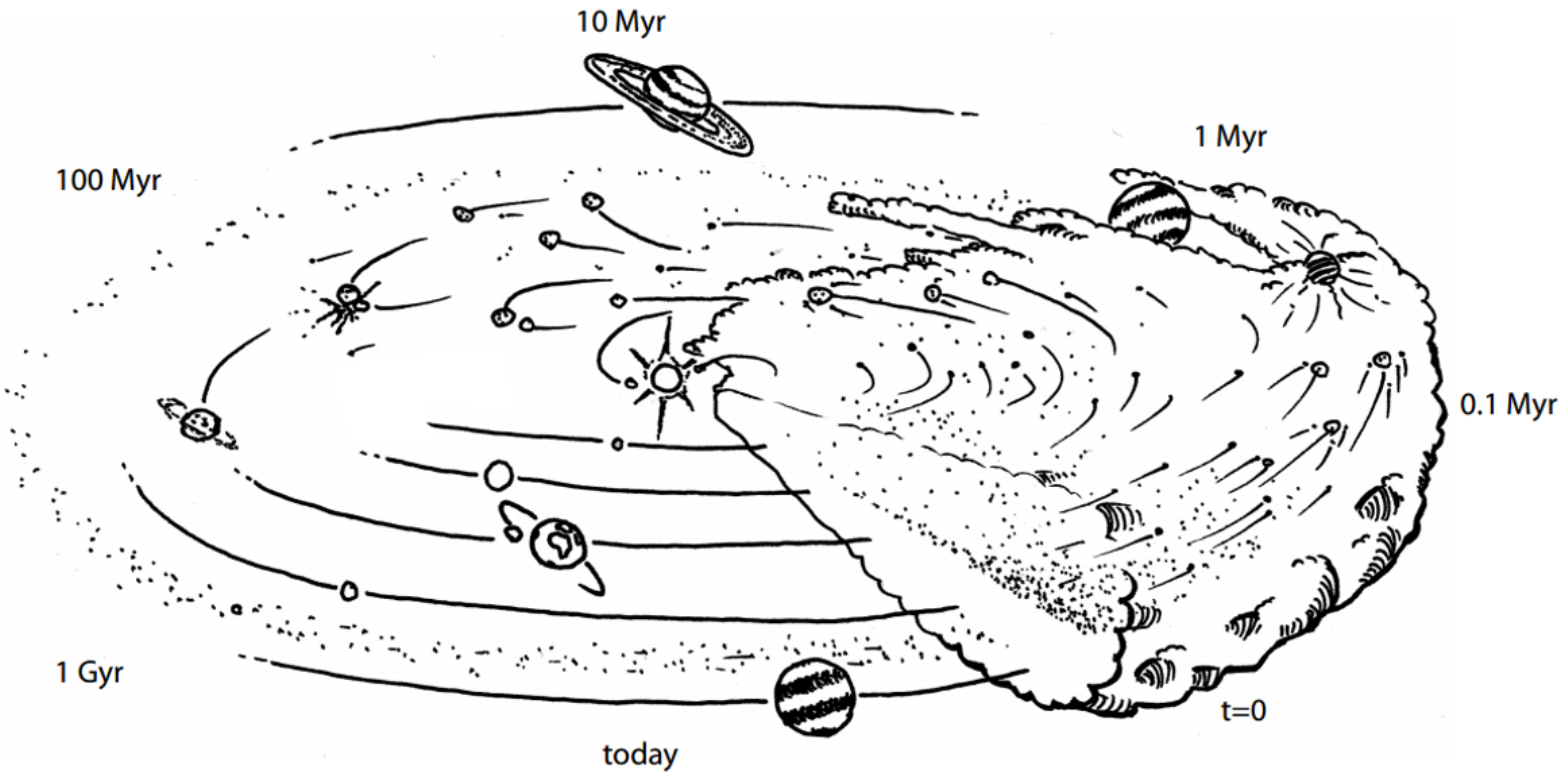
- In a disk more massive than MMSN, planets can form in wide orbits.
- Linear analysis is used to obtain (eg, Binney & Tremain 1987)

- Note that migration is problematic (e.g., Zhu et al. 2012)

Summary

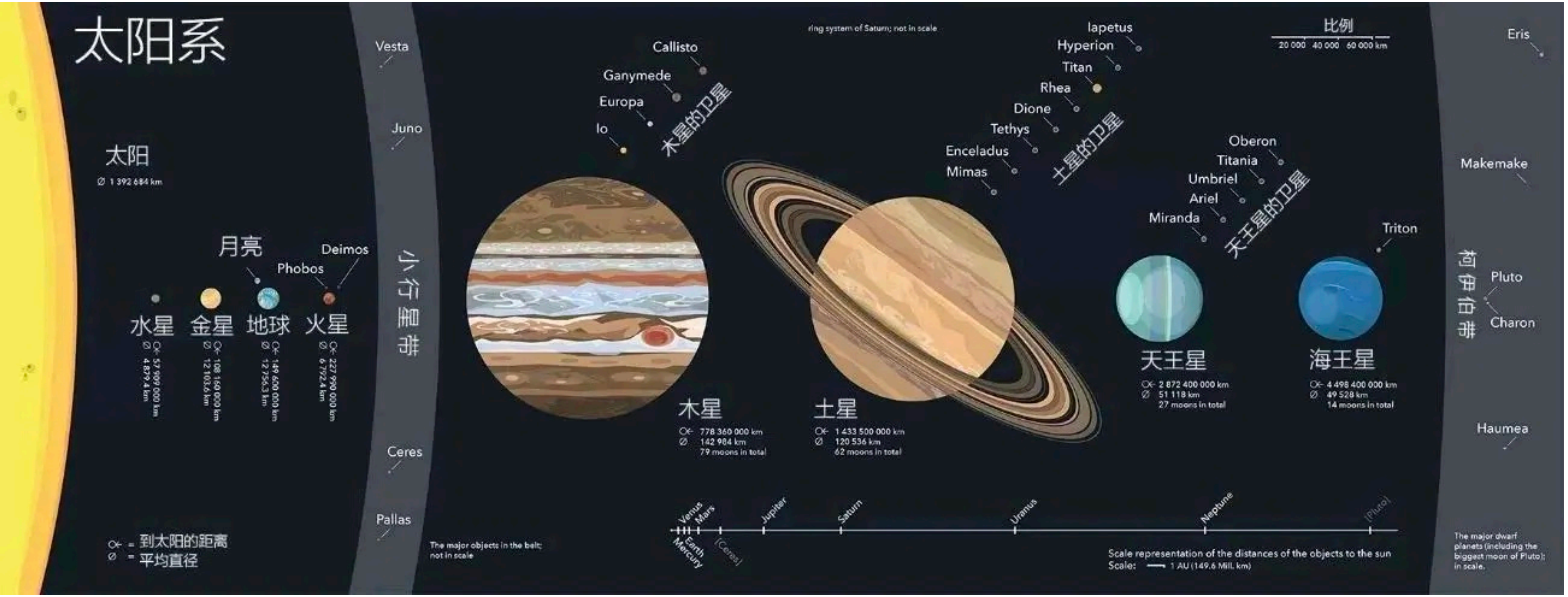


the sun
snowline
rocky dusts
icy dusts
dust aggregation
snowline
km-sized
rocky planetesimals
icy planetesimals
gravitational accumulation
runaway/oligarchic growth
snowline
rocky cores
icy cores
giant impact
runaway gas accretion
snowline
terrestrial planets
gas giants
ice giants



10 Myr
1 Myr
100 Myr
0.1 Myr
1 Gyr
t=0
today

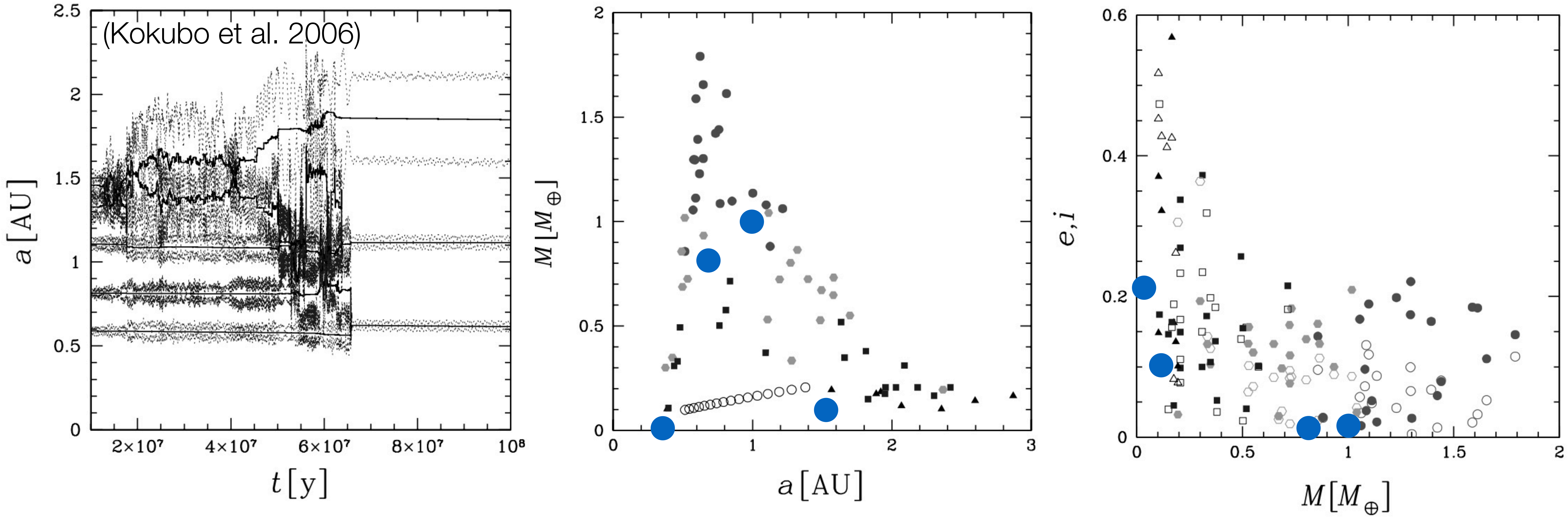
Solar system formation models and simulations

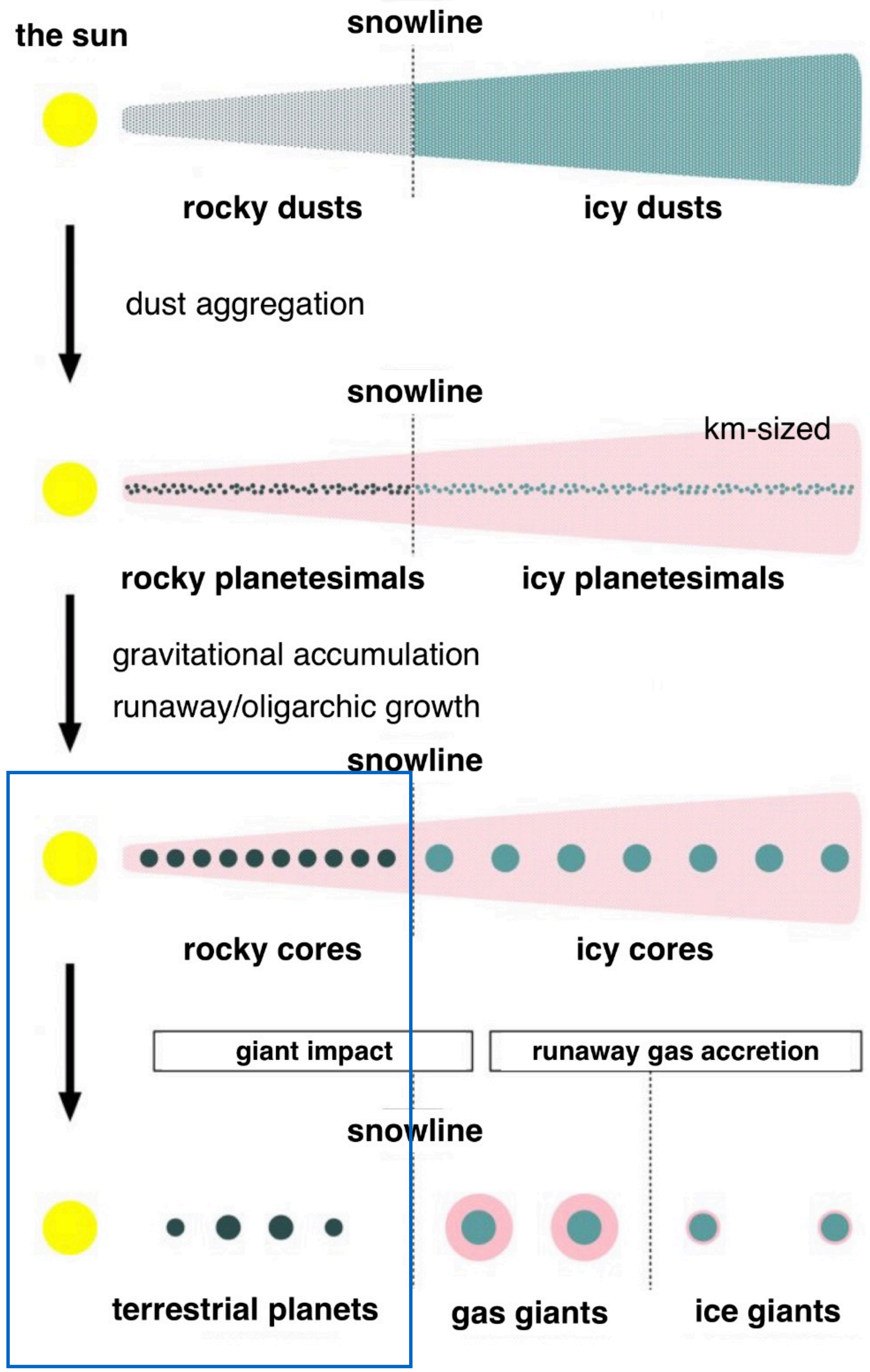


I will introduce some theoretical models that explain features in the solar system

Orbital characteristics of terrestrial planets

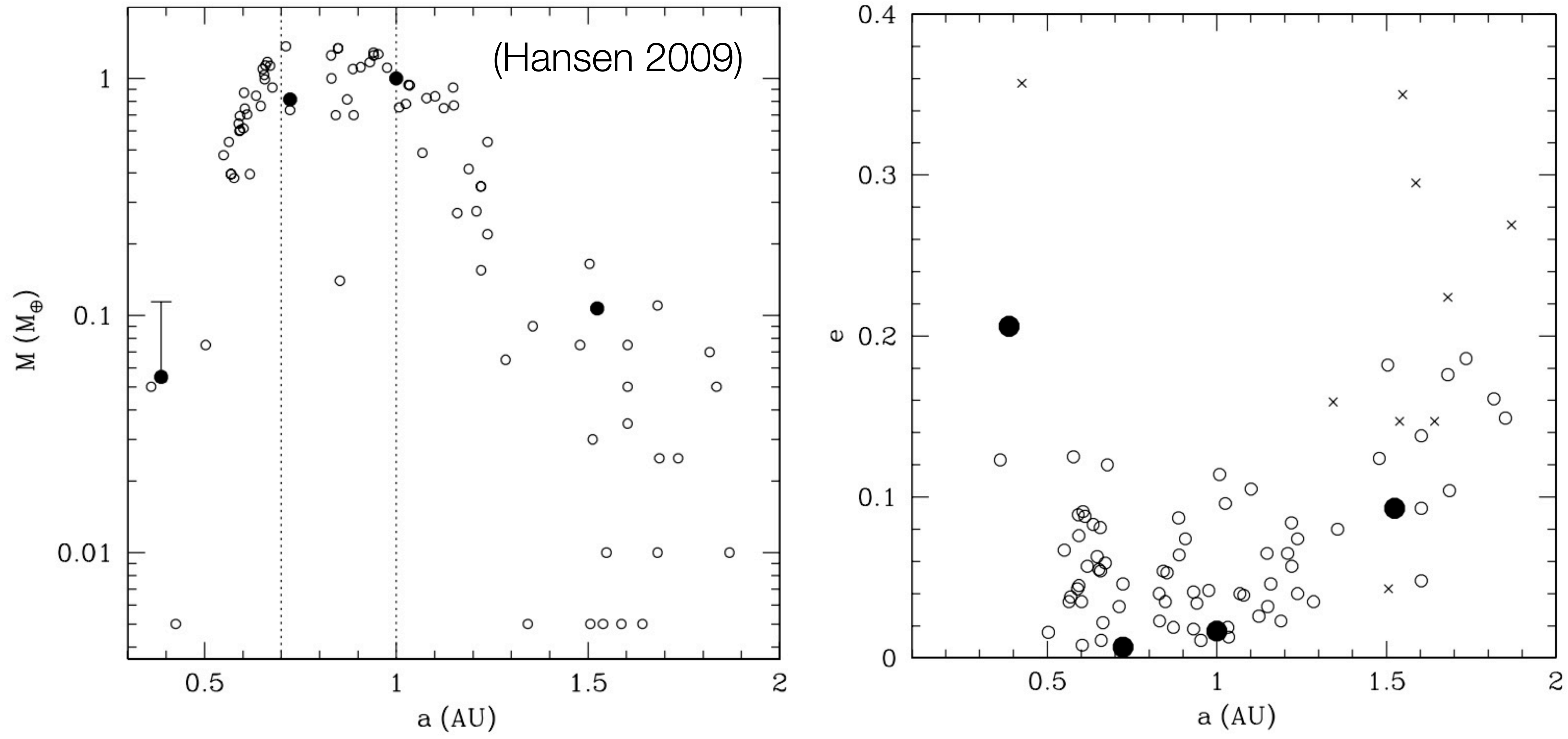
- Giant impact phase (Kokubo et al. 2006): larger eccentricity
- Higher resolution (Hansen 2009): better results but requires a narrow ring (0.7-1 au)

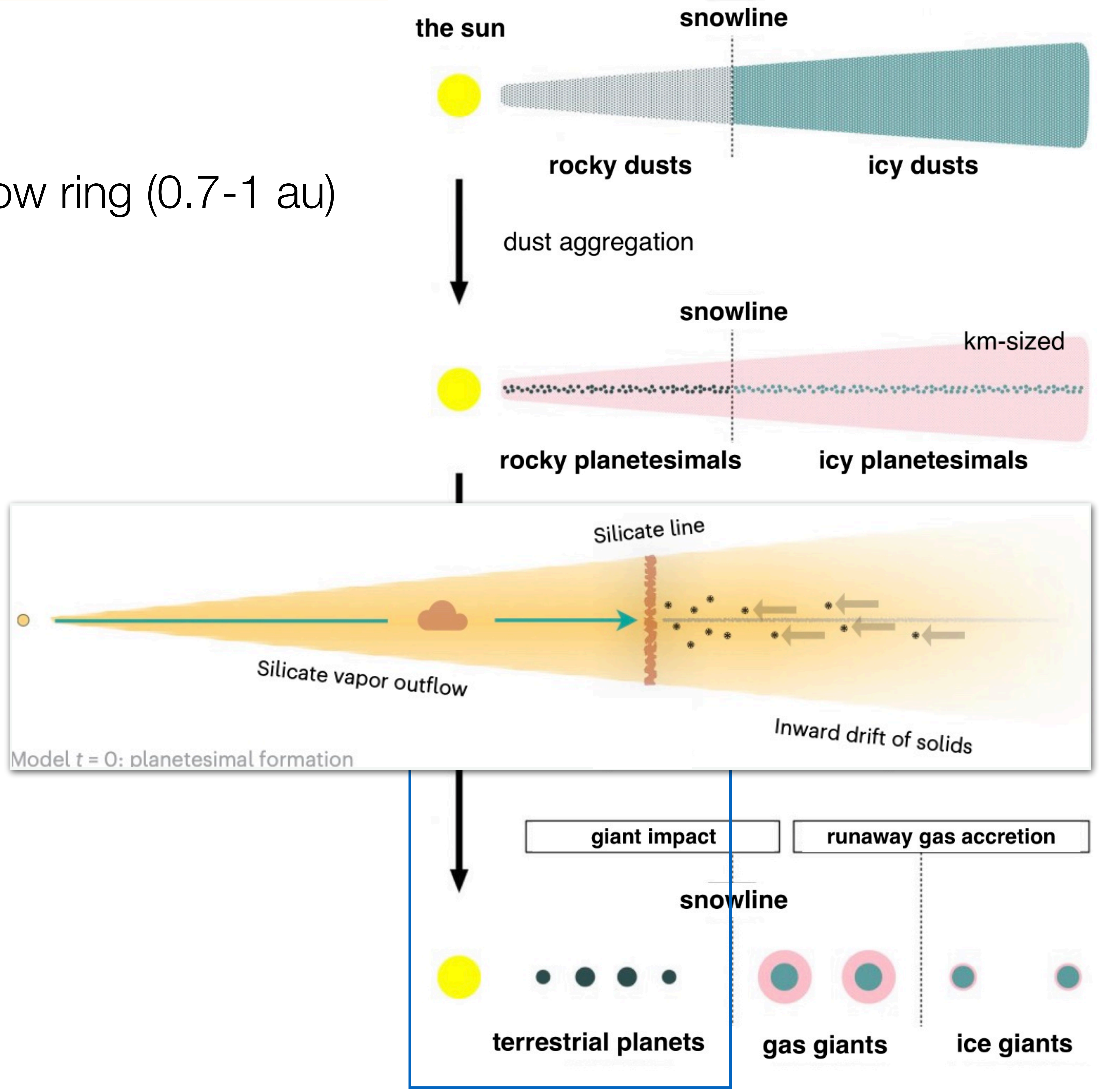




Orbital characteristics of terrestrial planets

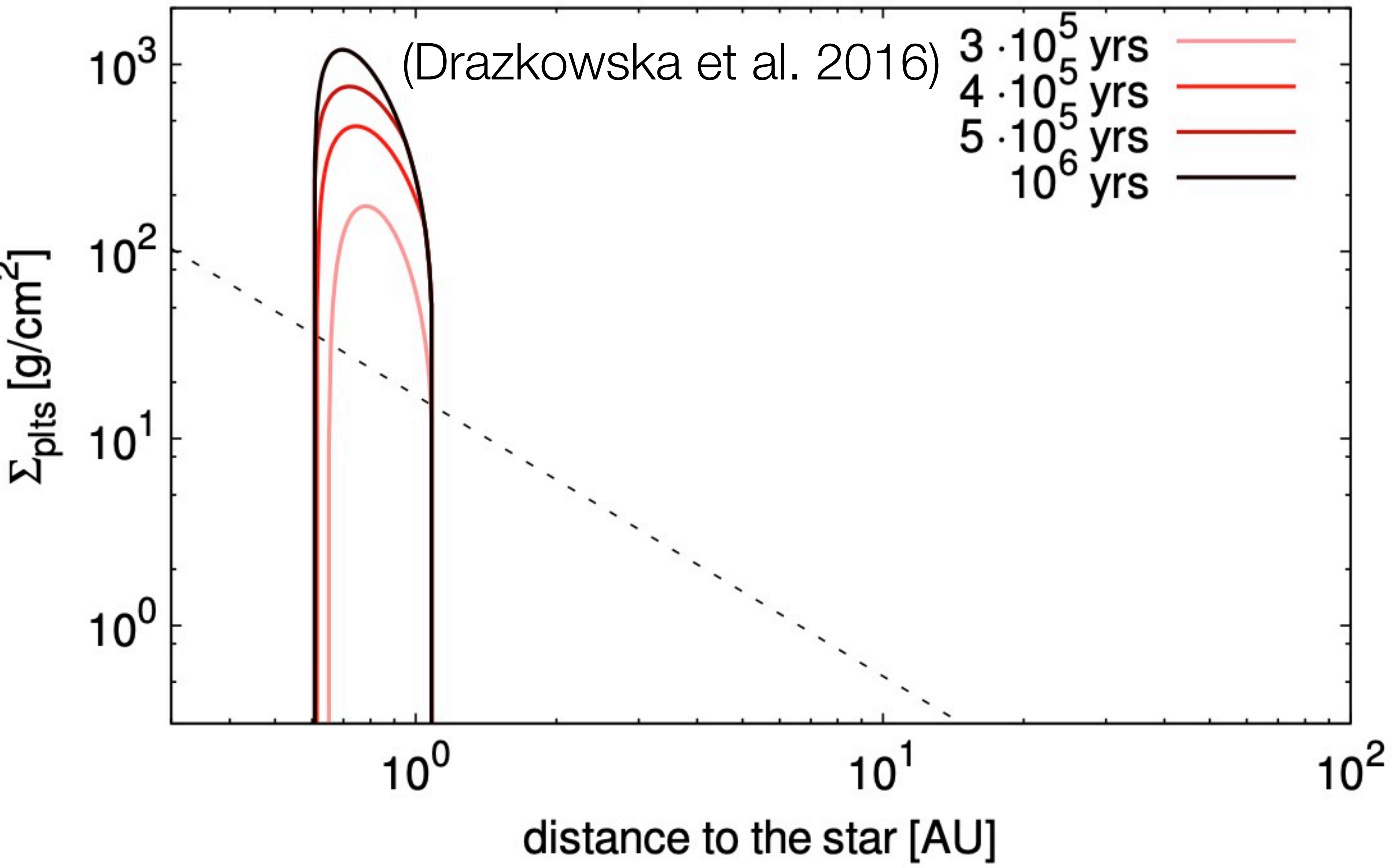
- Giant impact phase (Kokubo et al. 2006): larger eccentricity
- Higher resolution (Hansen 2009): better results but requires a narrow ring (0.7-1 au)

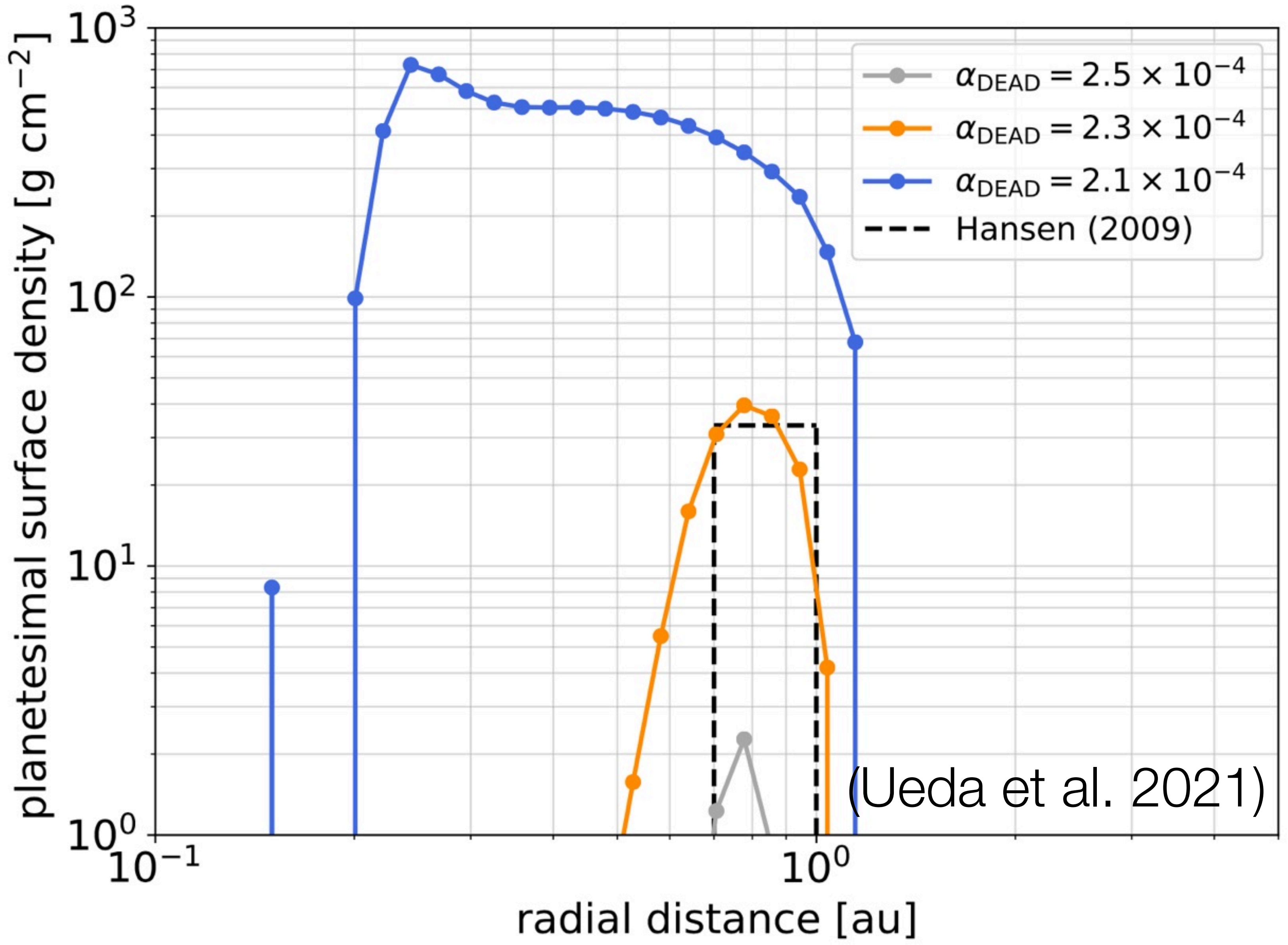


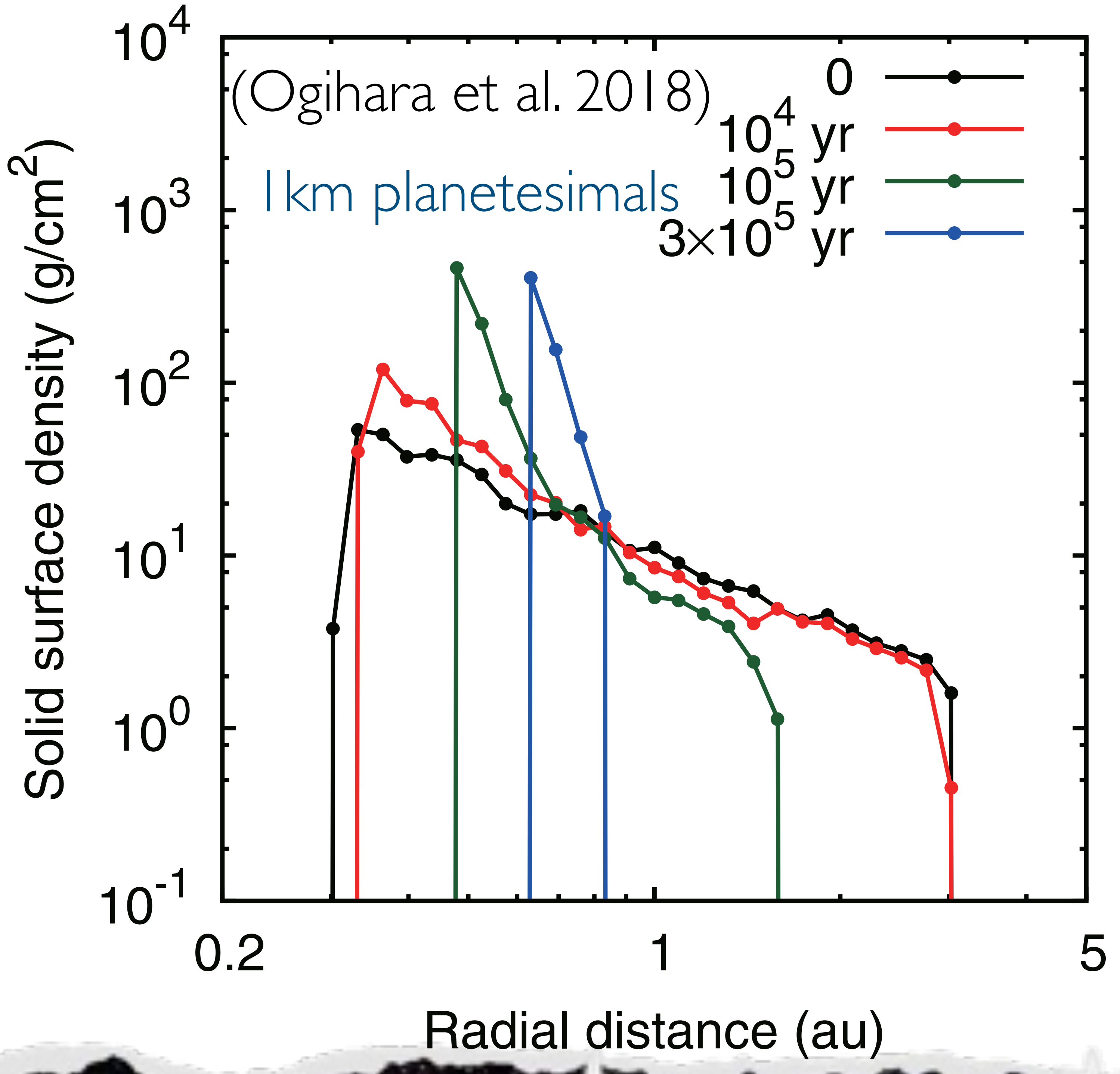


Ideas to create a narrow ring near 1 au

- Planetesimal formation by pebble pileup (Drazkowska et al. 2016), silicate sublimation line (Morbidelli et al. 2022), dead zone inner boundary (Ueda et al. 2019), convergent radial drift (Suzuki et al. 2016)
- Embryo formation by convergent radial drift (Ogihara et al. 2018)

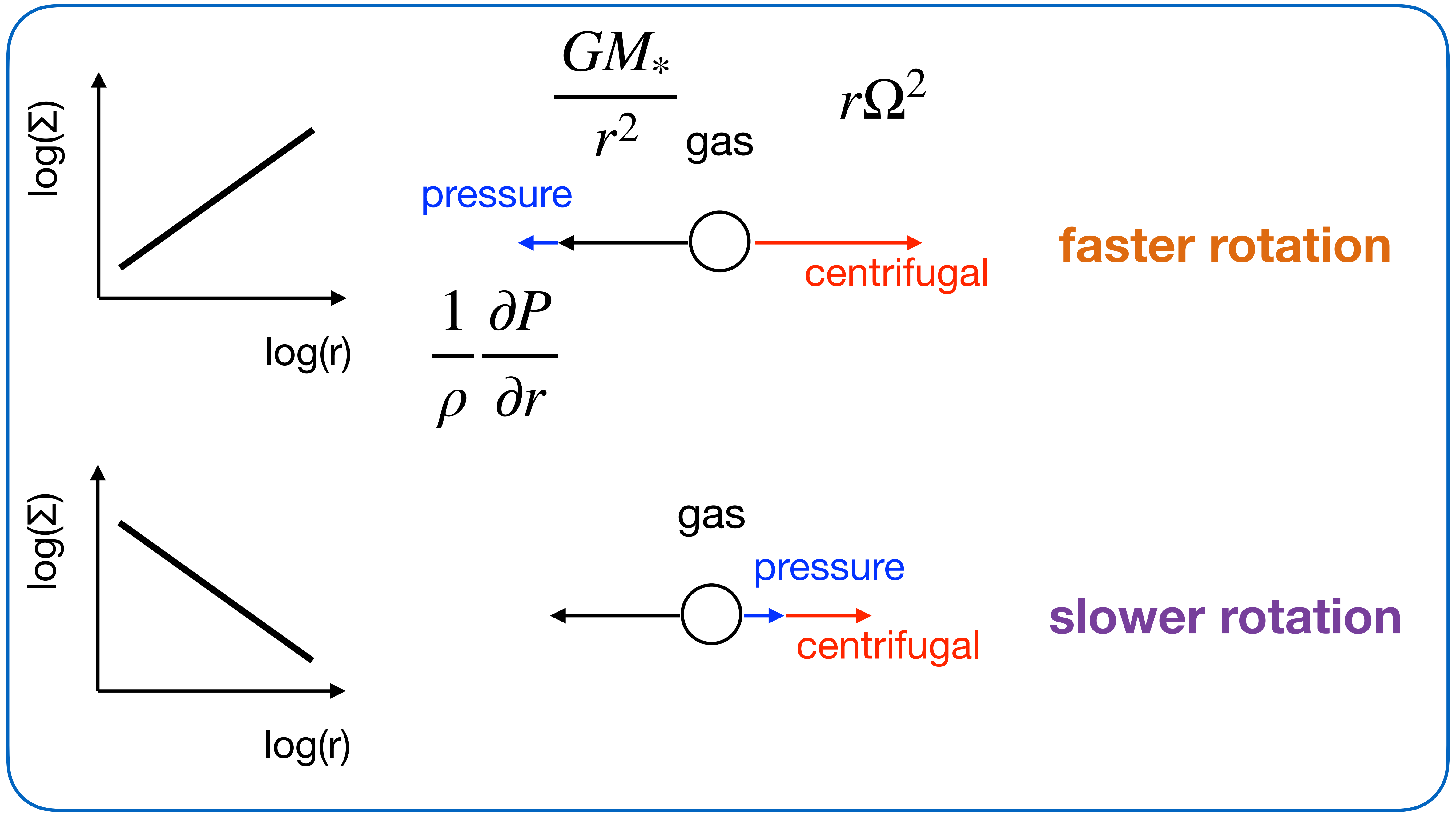


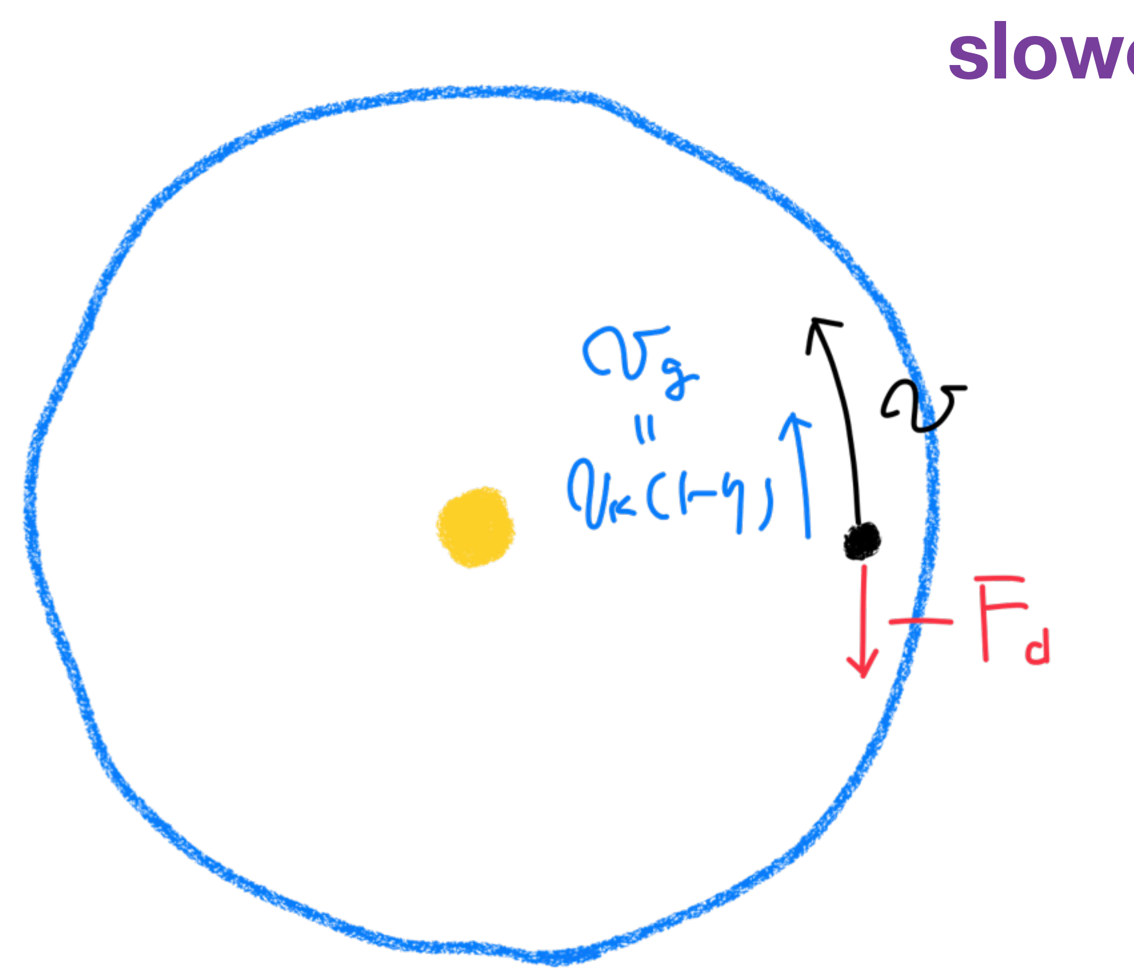




Aerodynamical drag

- Gas rotates different speeds depending on the density distribution
- Gas rotates faster/slower than solid →tail/head wind →outward/inward drift



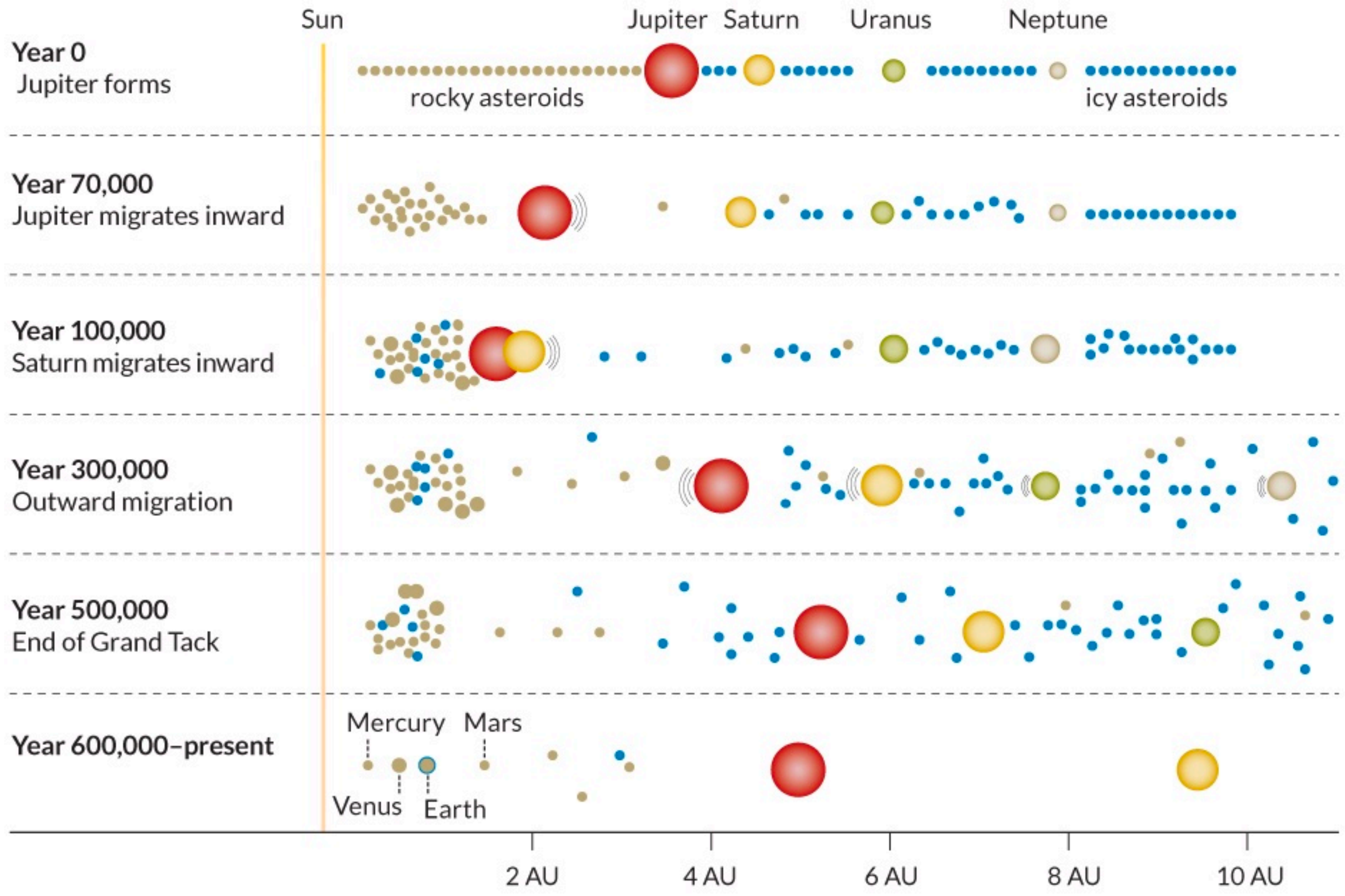


$$F_d = -m\frac{v - v_g}{t_{\rm stop}}$$

Ideas to create a narrow ring near 1 au

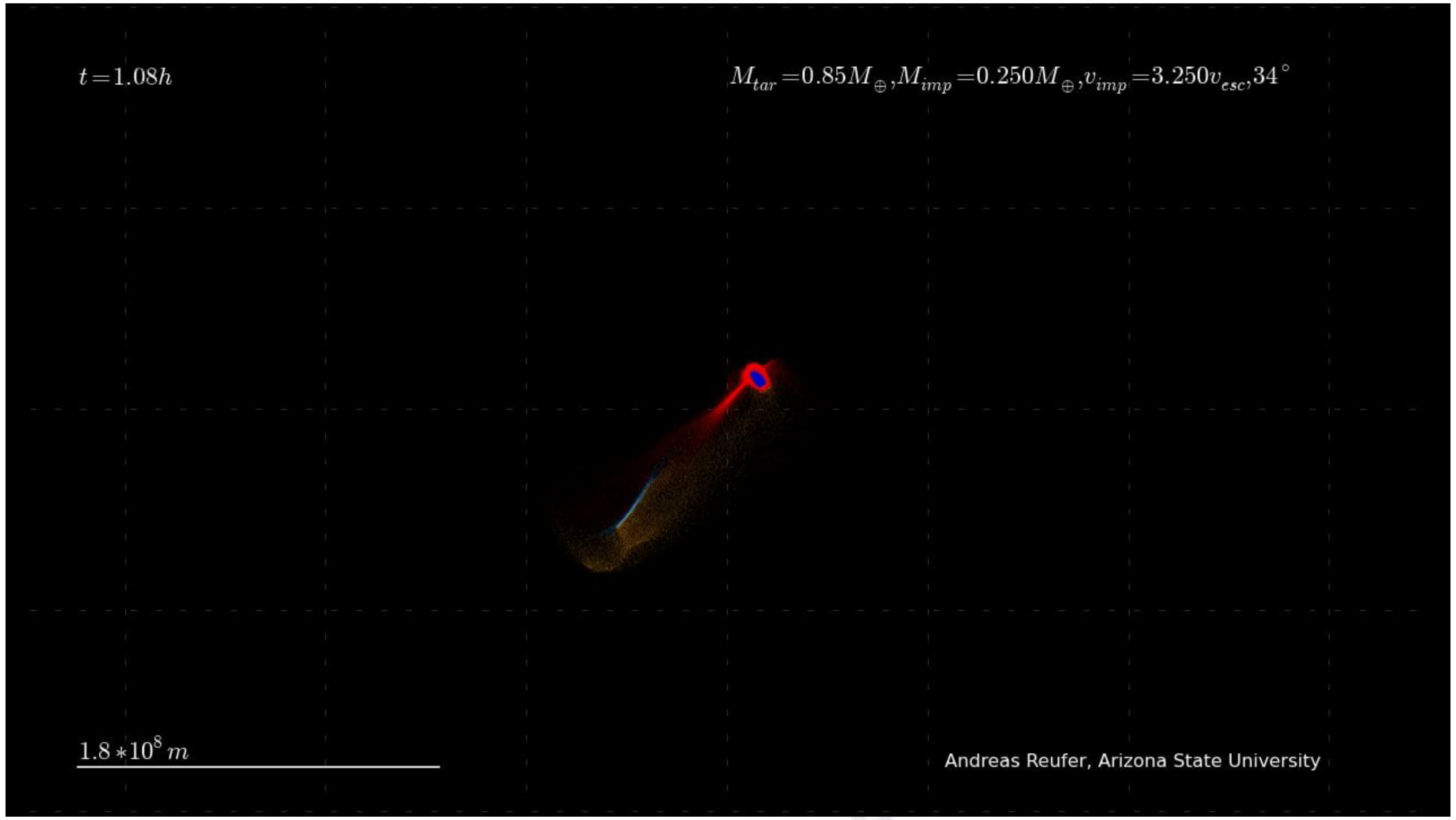
- Grand Tack model (Walsh et al. 2011)
- Migration of Jupiter and Saturn
- Also explains mass deficit in solid surface density
- Connected to the initial condition of Nice model

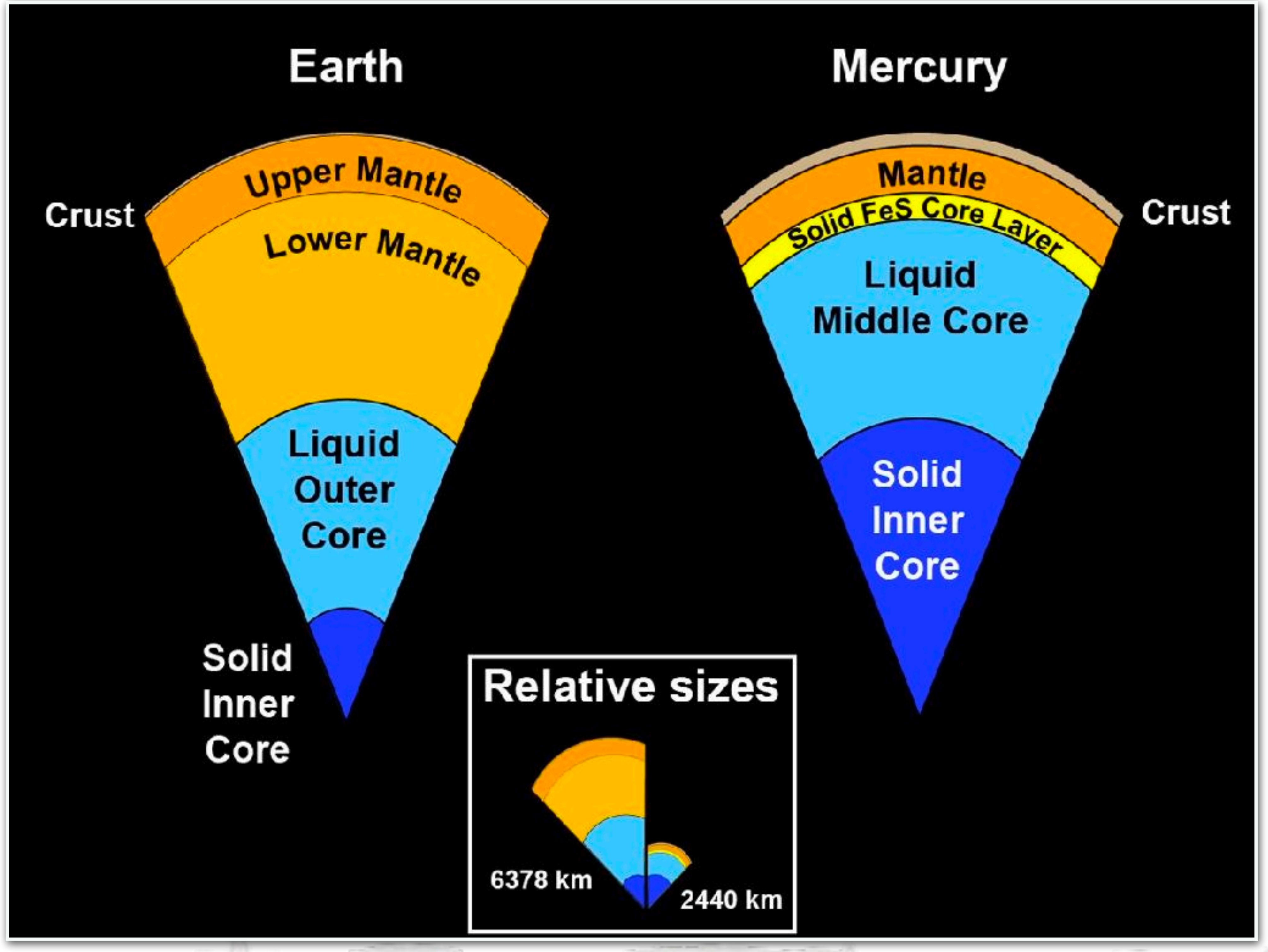
- If gas accretion during migration is considered, giant planets exceed the current Jupiter and Saturn masses (D'Angelo & Marzari 2012, Tanaka et al. 2020)
- Fine-tuning is required so that giant planets are captured in a 3:2 MMR (eg, Pierens et al. 2014)



Giant impacts as origin of Mercury

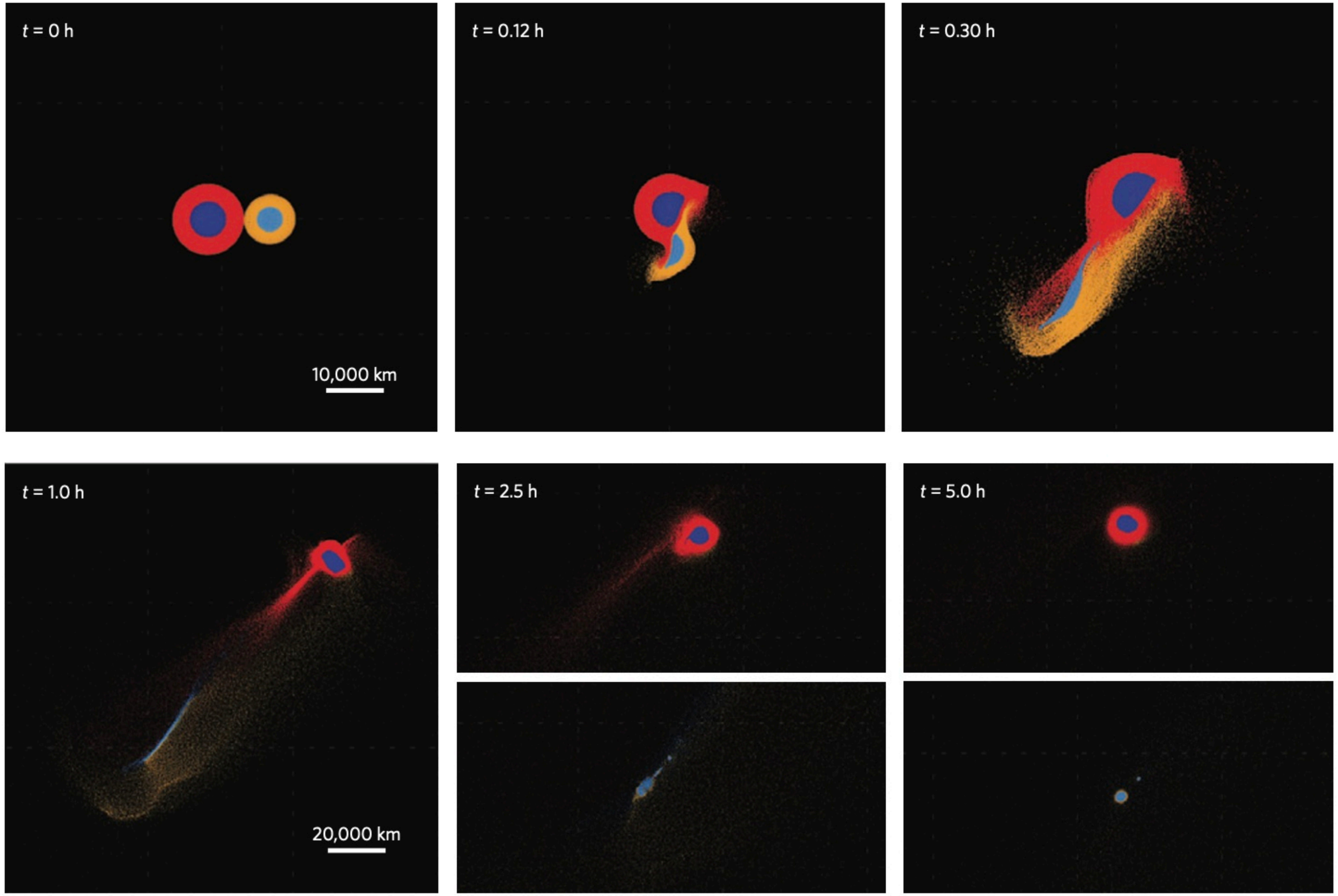
- High density, 70% of mass is core
- Hit-and-run collision of giant impacts (eg, Asphaug & Reufer 2014)
- However, high-speed (>2v_{esc}) and grazing (~30°) impacts are rare (~1%, Franco et al. 2022)
- Another idea (Deng 2020)





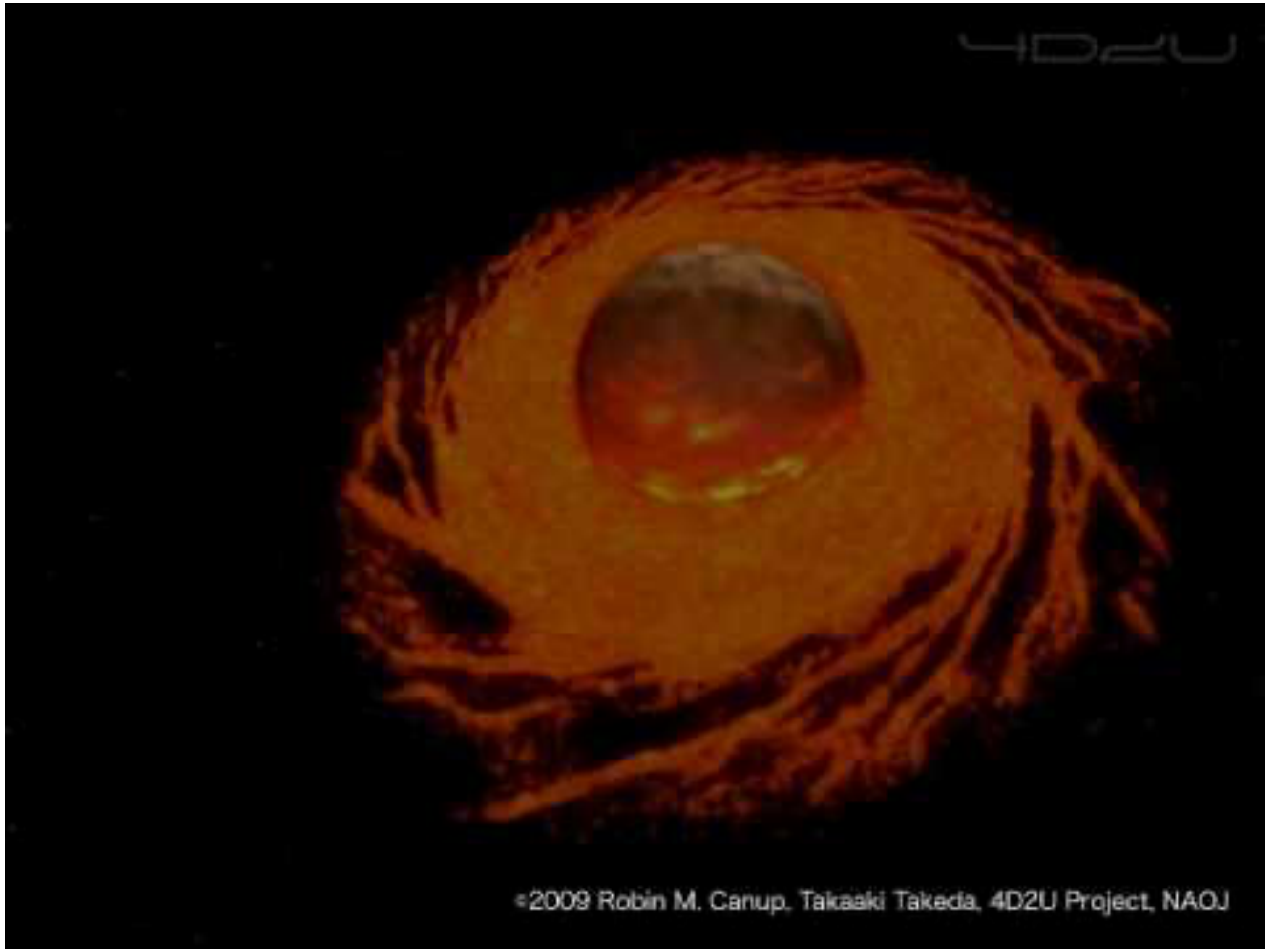
Giant impacts as origin of Mercury

- High density, 70% of mass is core
- Hit-and-run collision of giant impacts (eg, Asp
- However, high-speed (>2v_{esc}) and grazing (~3(
- Another idea (Deng 2020)



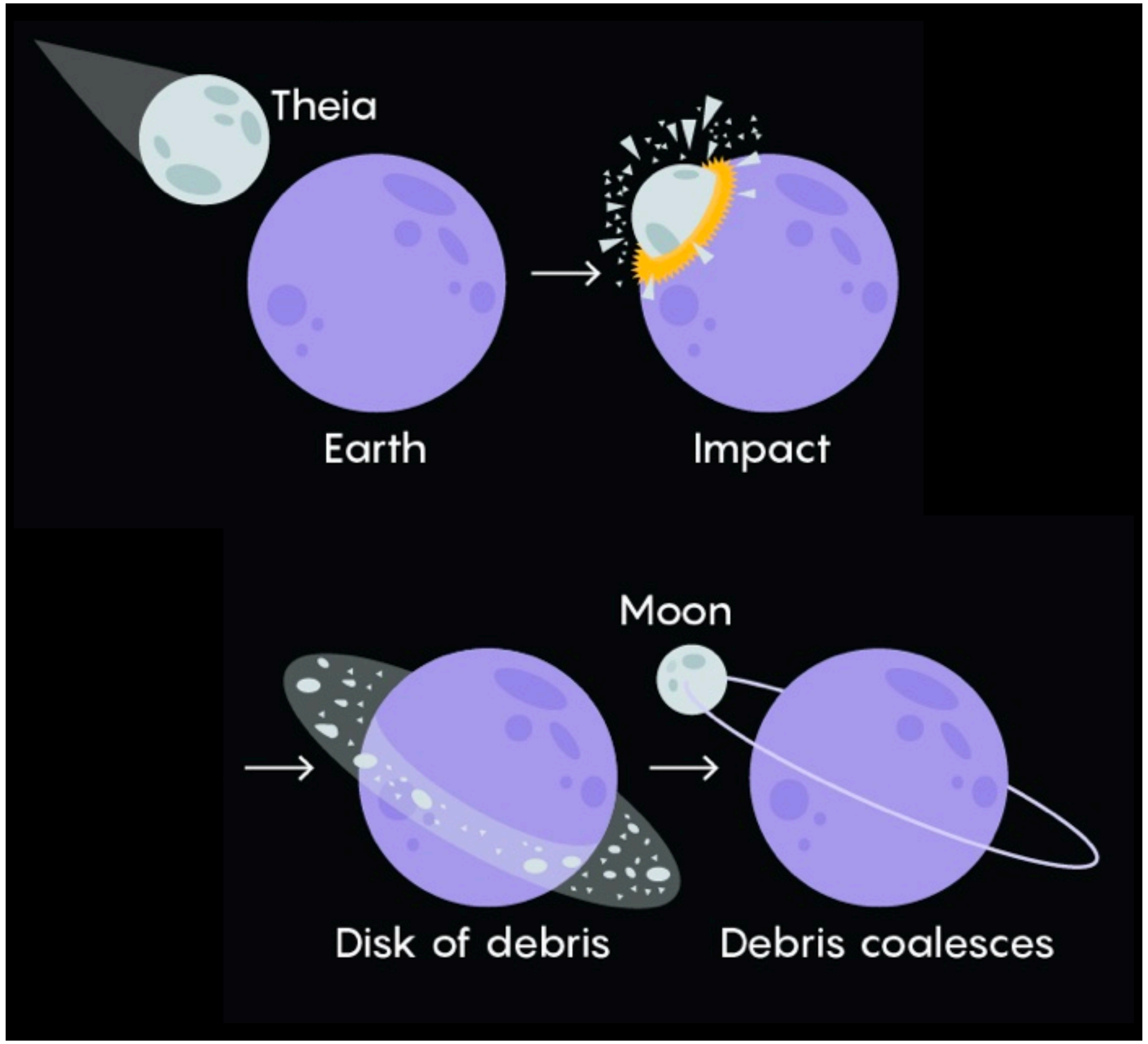
Giant impacts as origin of Moon

- A debris disk forms after giant impacts (eg, Hartmann & Davis 1975, Canup & Asphaug 2001)
- Moon forms from the disk (eg, Takeda & Ida 2001)
  →The Moon would be of Theia composition
- But the lunar rock shows that the Moon has a near-identical isotopic composition to Earth (Melosh 2014): Isotopic crisis
- One possible idea: Immediate formation (Kegerreis et al. 2022), another idea (Hosono et al. 2019)



Giant impacts as origin of Moon

- A debris disk forms after giant impacts (eg, Hartmann & Davis 1975, Canup & Asphaug 2001)
- Moon forms from the disk (eg, Takeda & Ida 2001)
  →The Moon would be of Theia composition
- But the lunar rock shows that the Moon has a near-identical isotopic composition to Earth (Melosh 2014): Isotopic crisis
- One possible idea: Immediate formation (Kegerreis et al. 2022), another idea (Hosono et al. 2019)



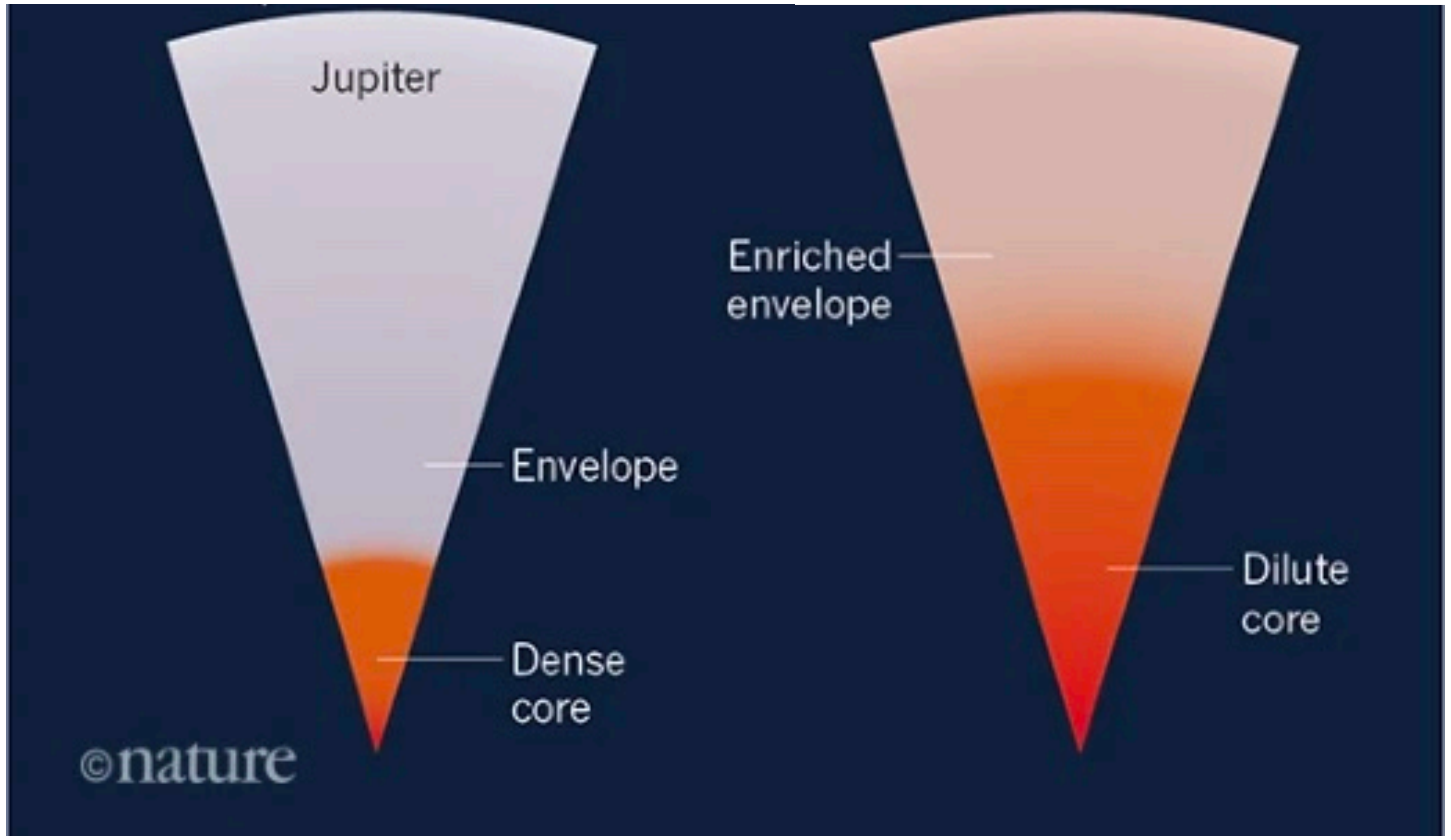
Giant impacts as origin of Moon

- A debris disk forms after giant imp
  Hartmann & Davis 1975, Canup &
- Moon forms from the disk (eg, Take
  →The Moon would be of Theia co
- But the lunar rock shows that the M
  identical isotopic composition to Ea
  2014): Isotopic crisis
- One possible idea: Immediate form
  al. 2022), another idea (Hosono et

Giant impacts as origin of Jupiter

- Jupiter has a diluted core (eg, Wahl et al. 2017)
- Juno's observation

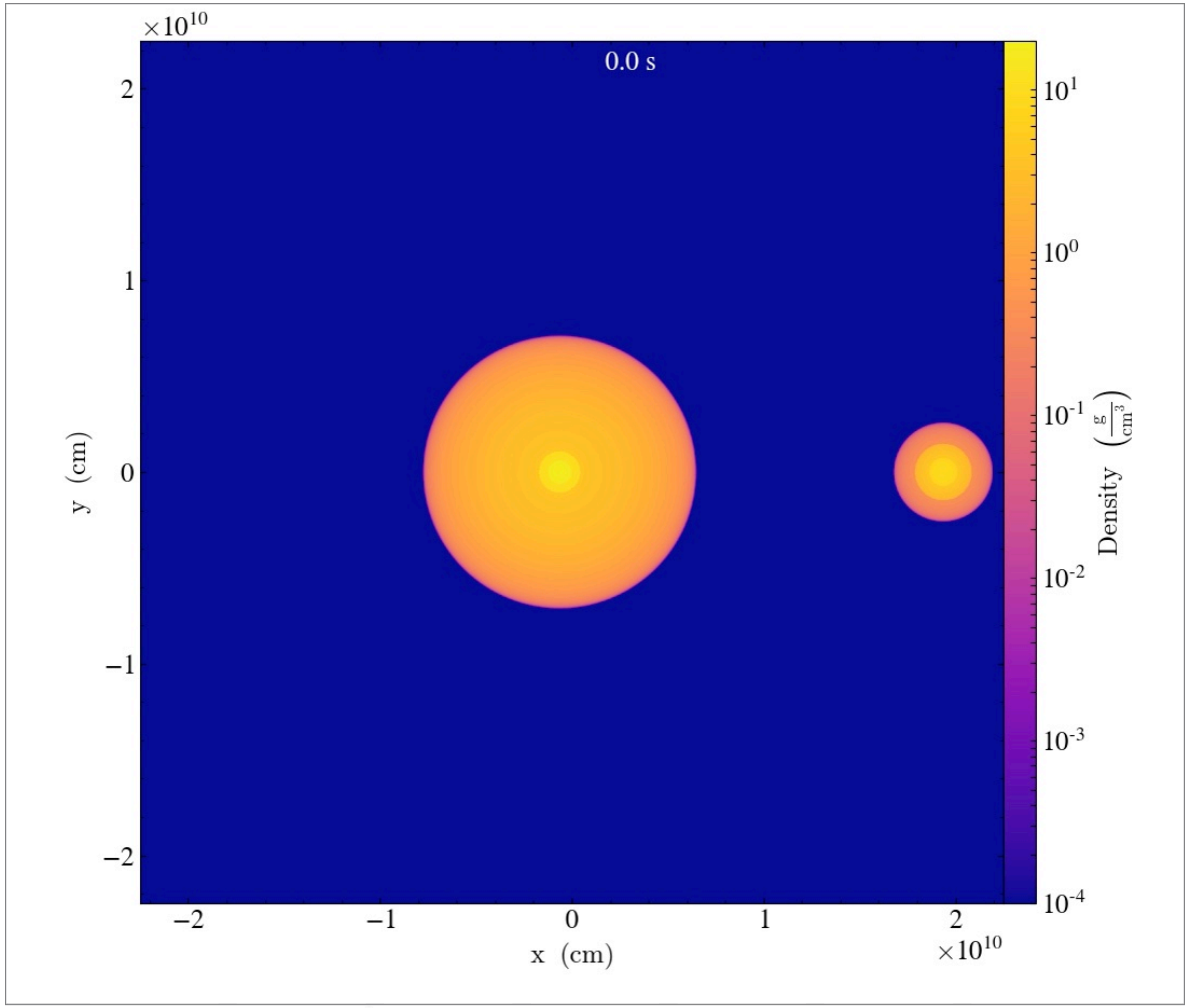
- One possible idea: energetic head-on collision mixes the heavy elements with the envelope (Liu et al. 2019). The assumed impact velocity is 46 km/s.
- Another idea (e.g., Ormel et al. 2021: pebble sublimation)



Giant impacts as origin of Jupiter

- Jupiter has a diluted core (eg, Wahl et al. 2017)
- Juno's observation

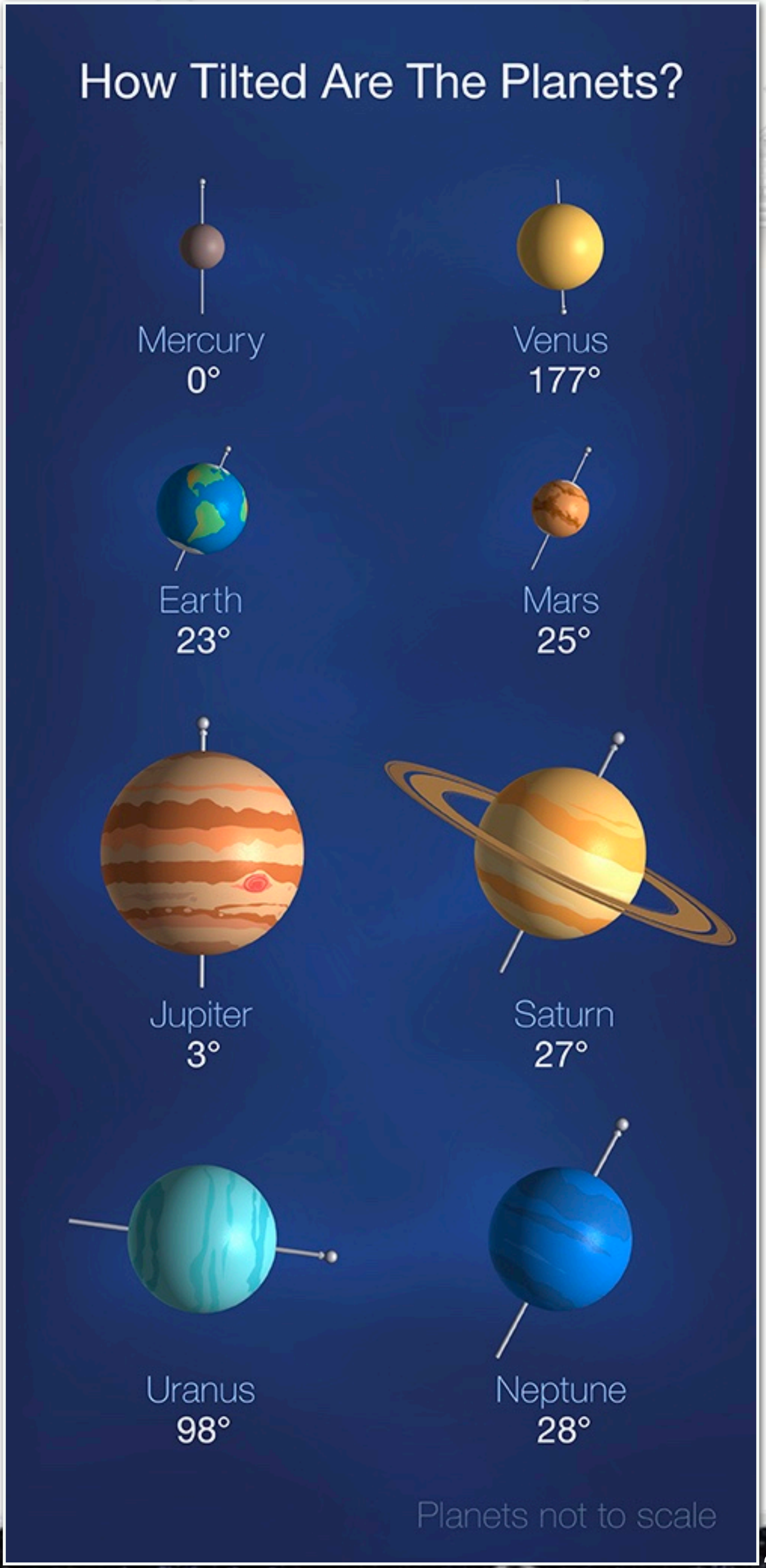
- One possible idea: energetic head-on collision mixes the heavy elements with the envelope (Liu et al. 2019). The assumed impact velocity is 46 km/s.
- Another idea (e.g., Ormel et al. 2021: pebble sublimation)



Giant impacts as origin of Uranus

- Spin axis is tilted 98° from the orbital plane
- Giant impacts can explain the tilted Uranus (eg, Slattery et al. 1992, Kegerreis et al. 2018, Reinhardt et al. 2020)

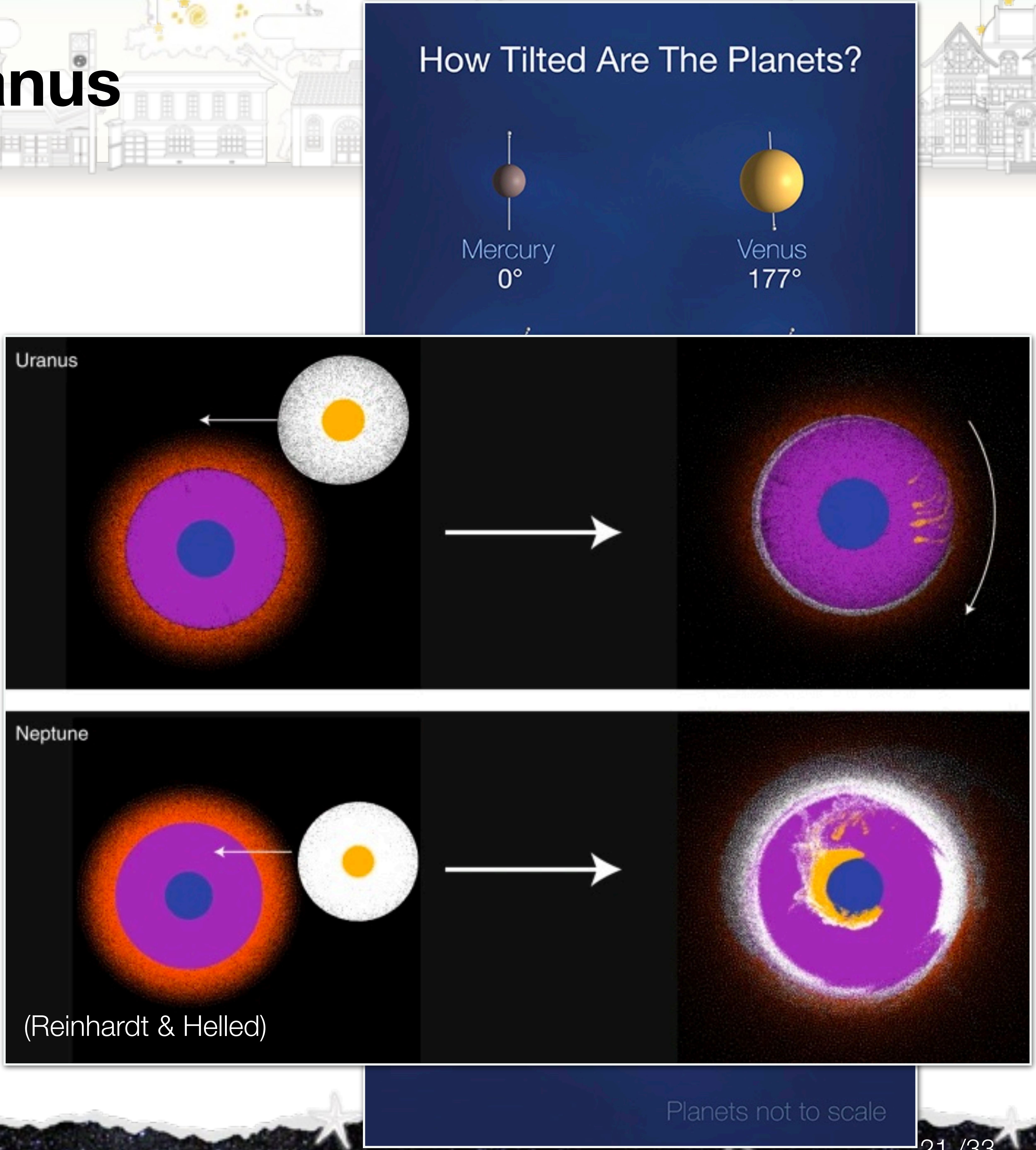
- Heat flux from interior is significantly small (0.06 x energy received from the Sun; 1.6 x for Neptune)
- The small hear flux from interior is also explained (?)
- But it is unclear if such collisions occur



Giant impacts as origin of Uranus

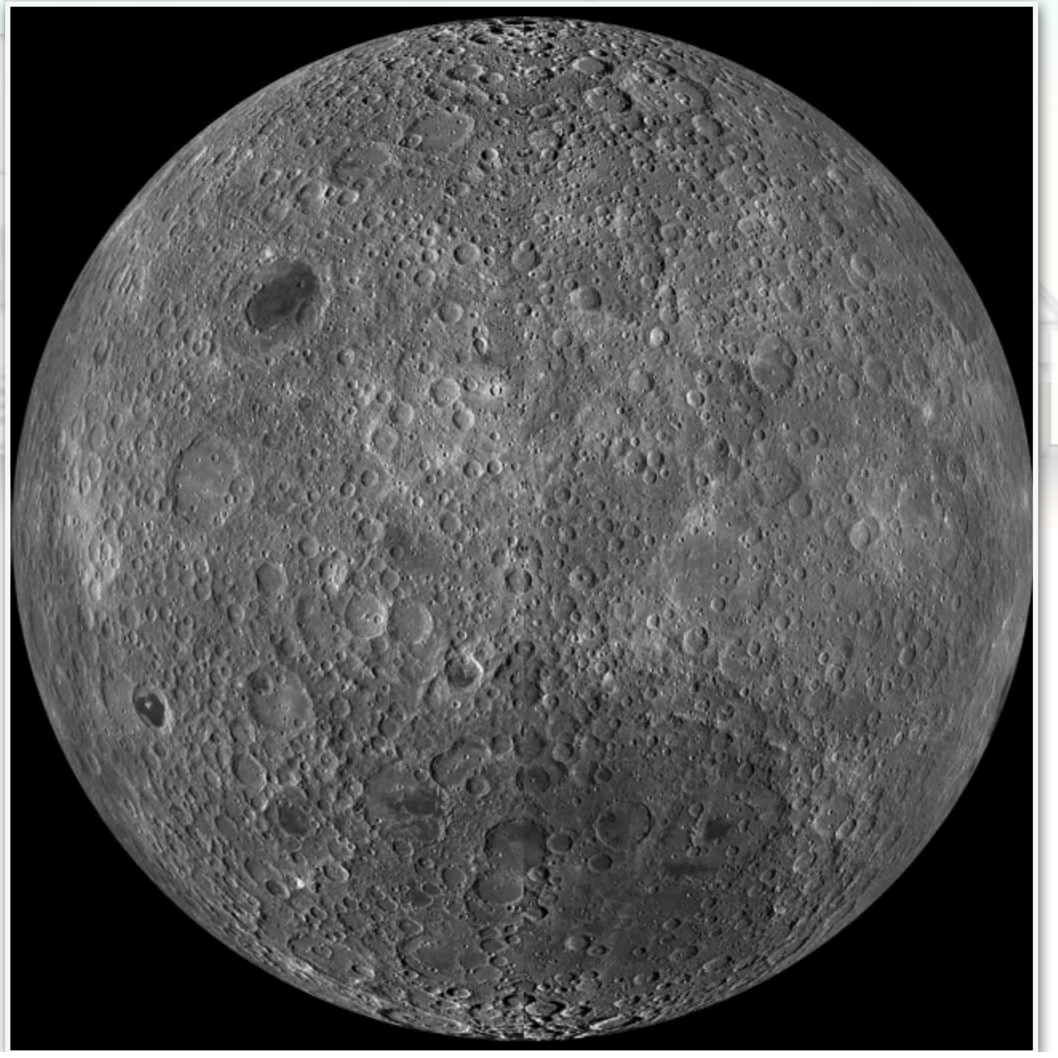
- Spin axis is tilted 98° from the orbital plane
- Giant impacts can explain the tilted Uranus (eg, Slattery et al. 1992, Kegerreis et al. 2018, Reinhardt et al. 2020)

- Heat flux from interior is significantly small (0.06 x energy received from the Sun; 1.6 x for Neptune)
- The small hear flux from interior is also explained (?)
- But it is unclear if such collisions occur

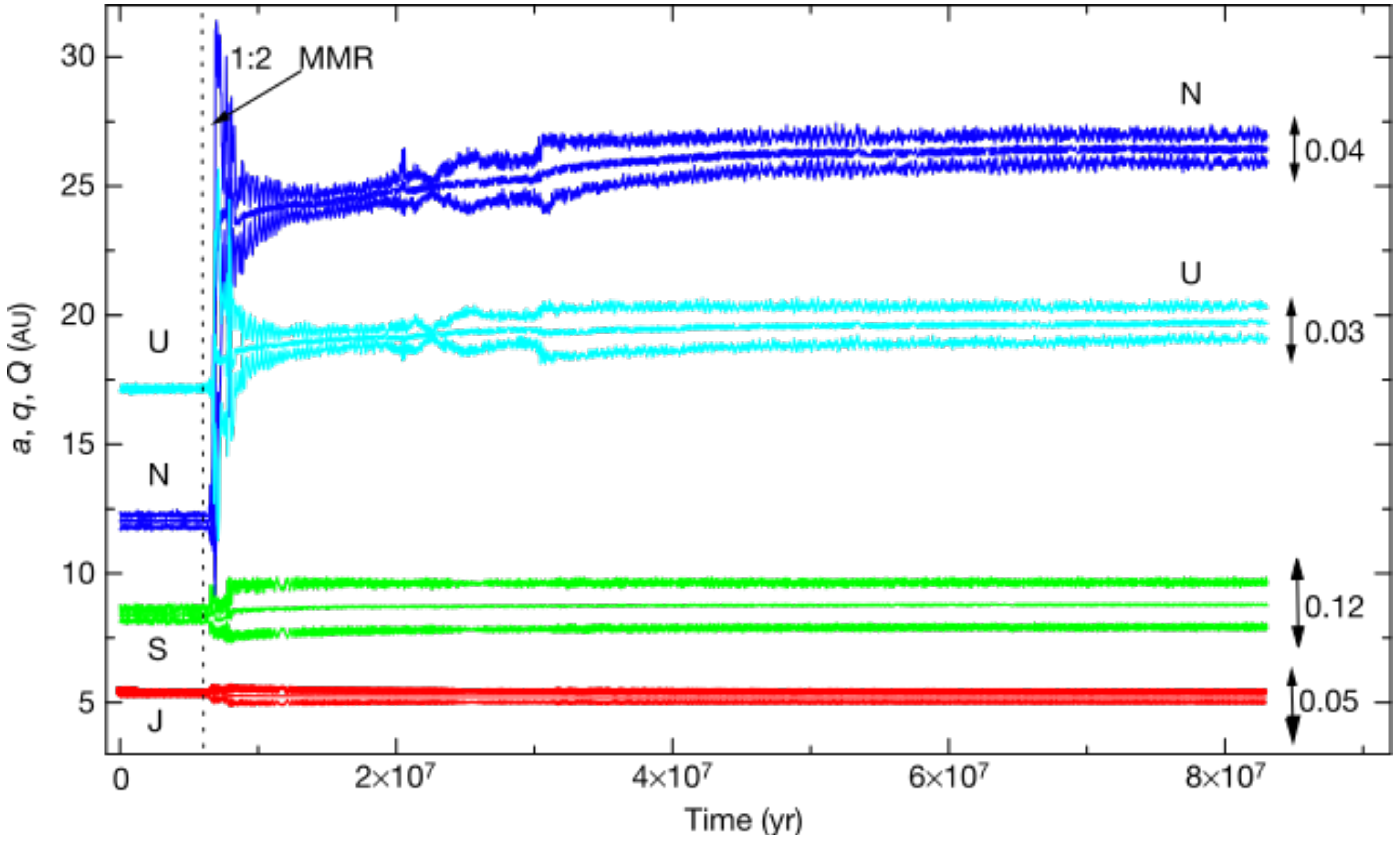


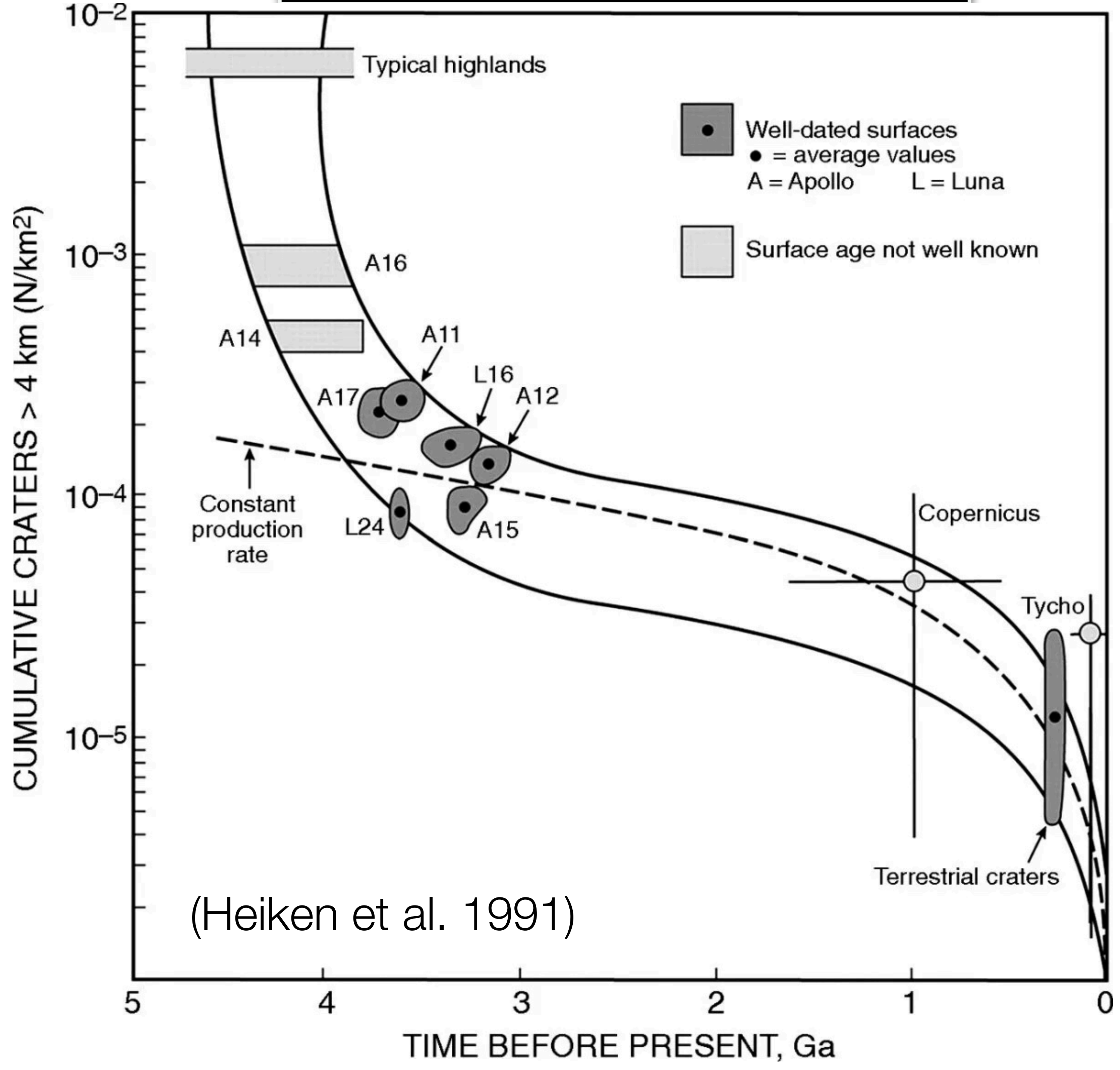
Late Heavy Bombardment

- Late Heavy Bombardment (a large amount of asteroids and comets collided objects in the inner solar system during 3.8-4.1 Gyr ago)
- Nice model (Gomes et al. 2005): a dynamical instability of giant planets that occurred 0.5-0.7 Gyr after the solar system formation



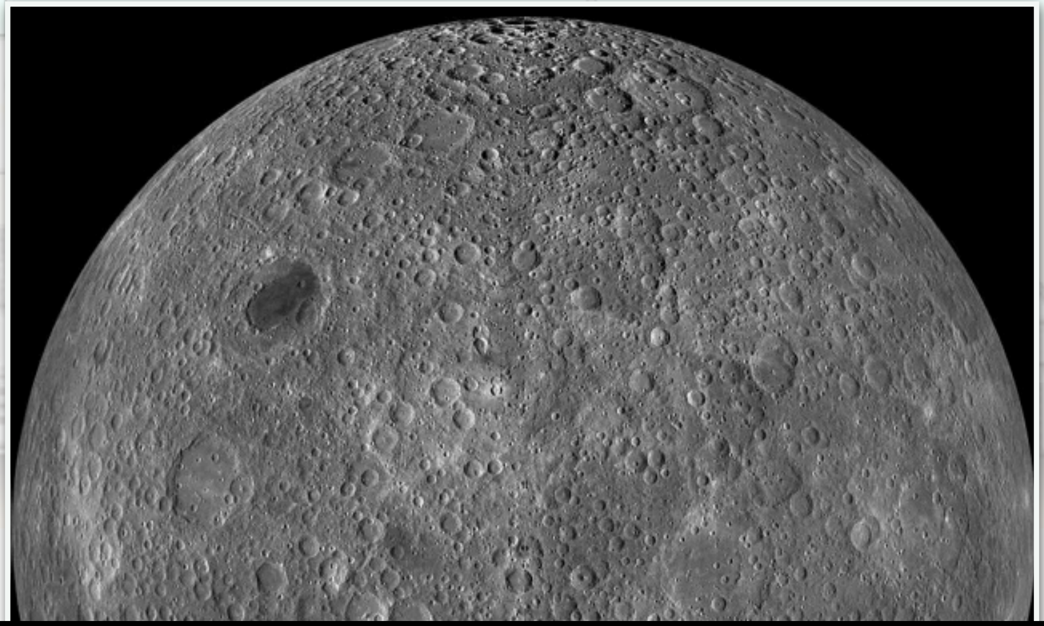
(Tsiganis et al. 2005)





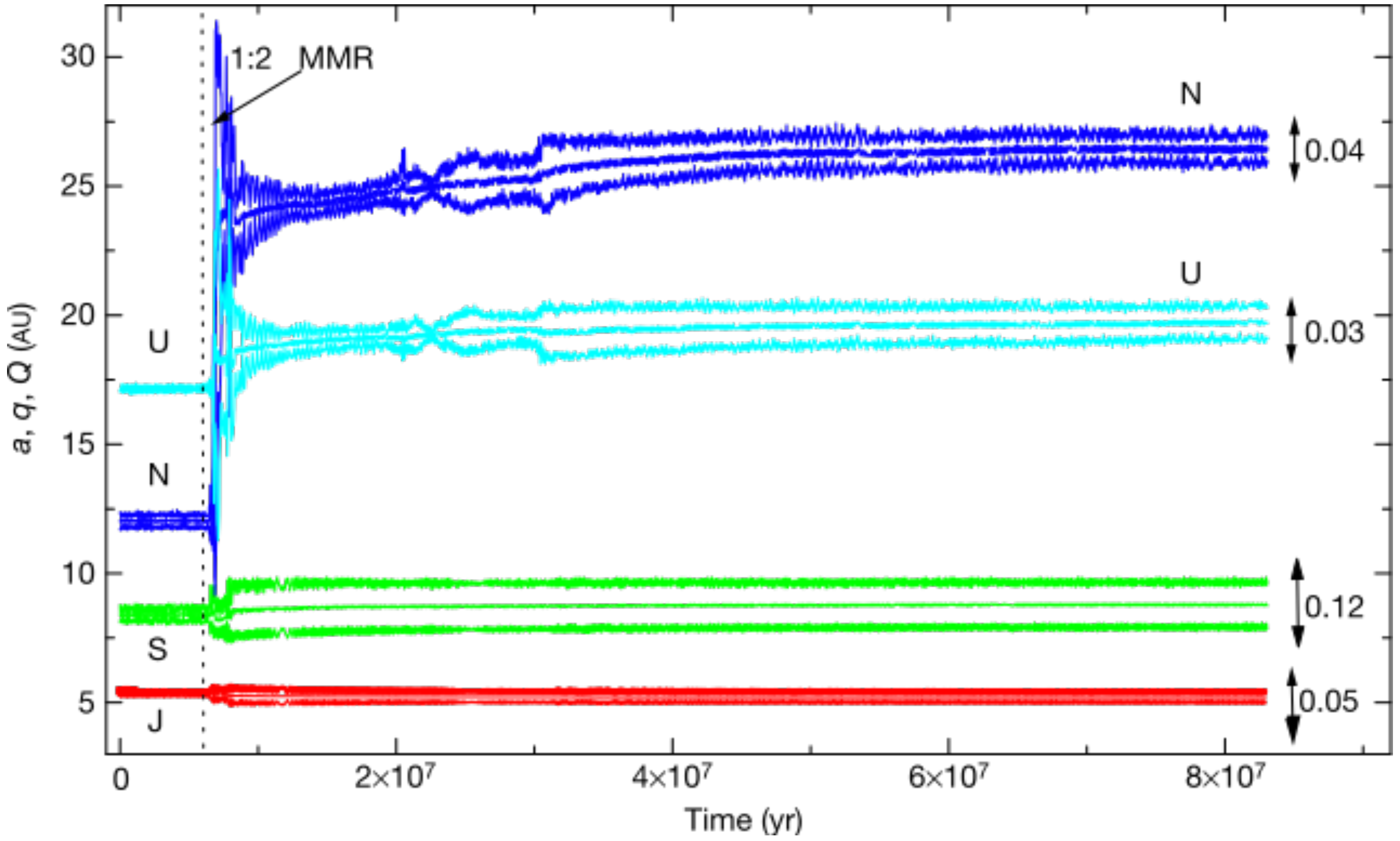
(Heiken et al. 1991)

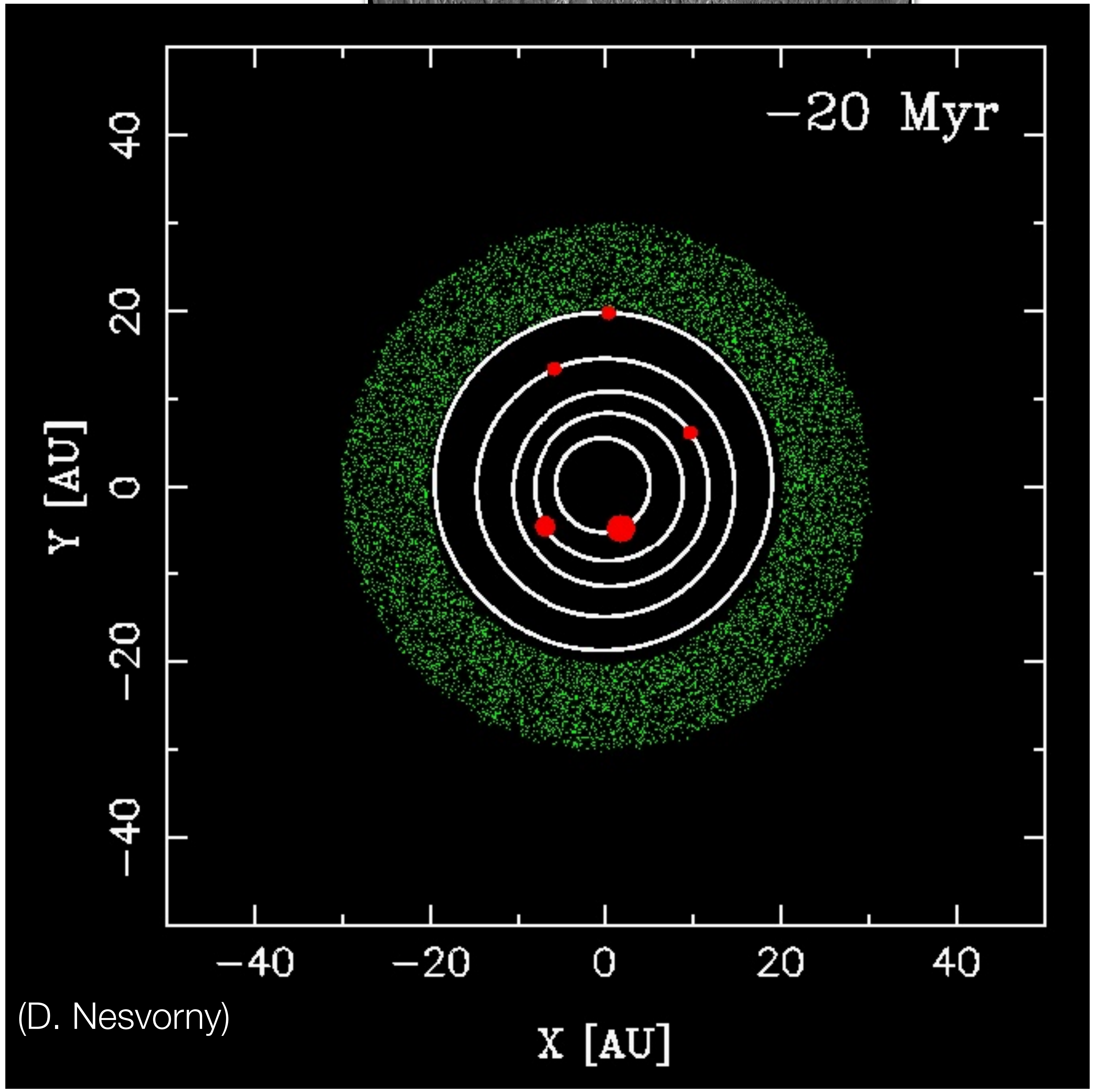
Late Heavy Bombardment



- Late Heavy Bombardment (a large amount of asteroids and comets collided objects in the inner solar system during 3.8-4.1 Gyr ago)
- Nice model (Gomes et al. 2005): a dynamical instability of giant planets that occurred 0.5-0.7 Gyr after the solar system formation

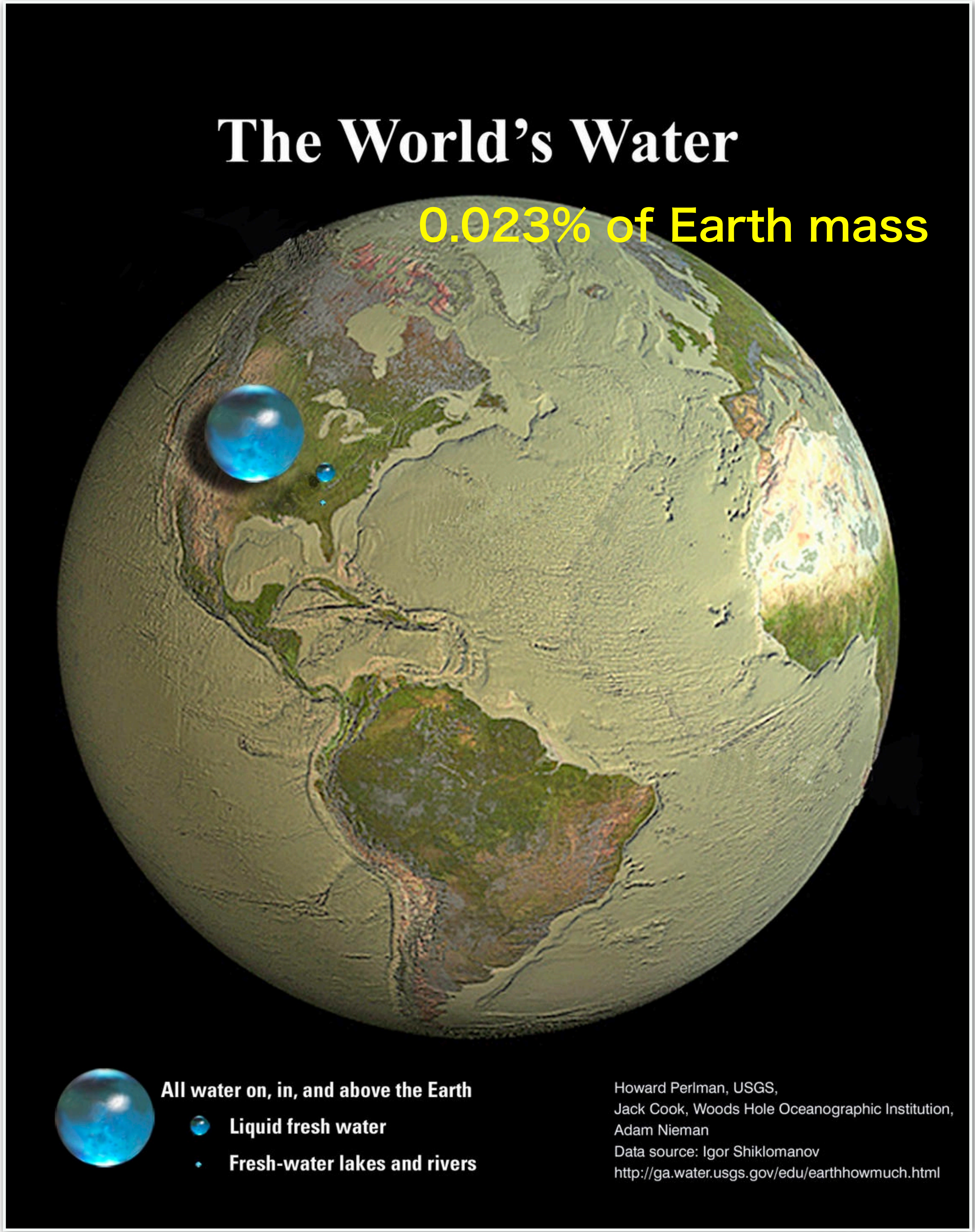
(Tsiganis et al. 2005)

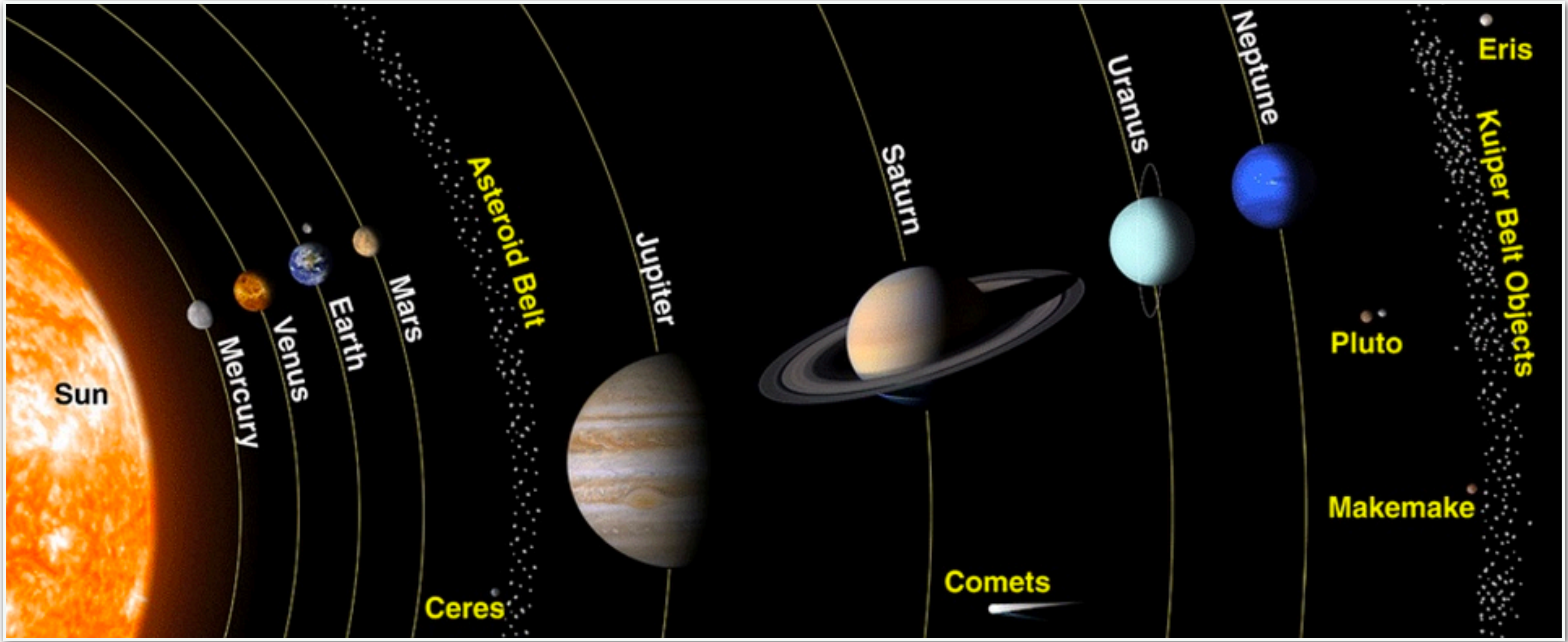




(D. Nesvorny)

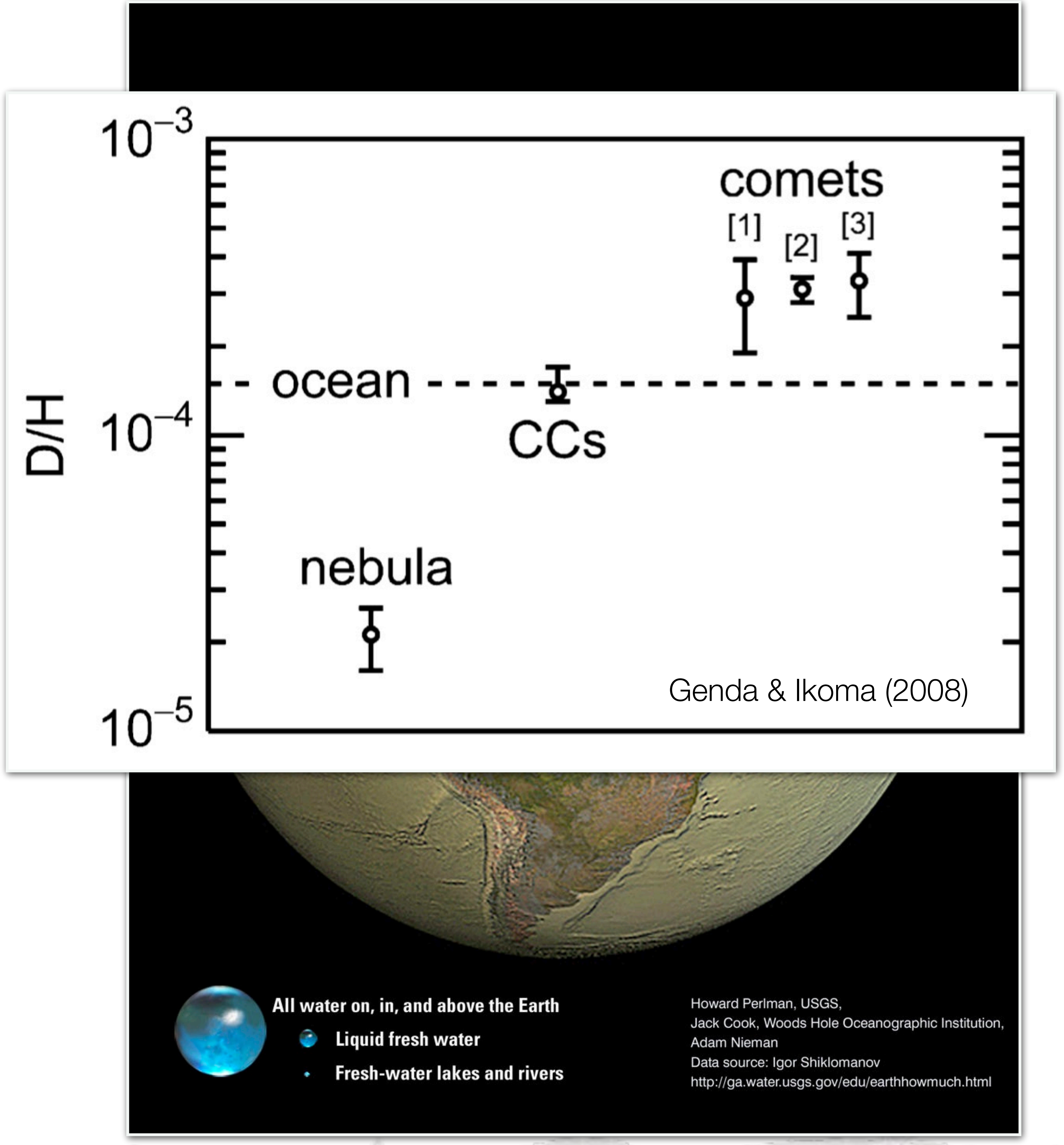
Origin of water on Earth

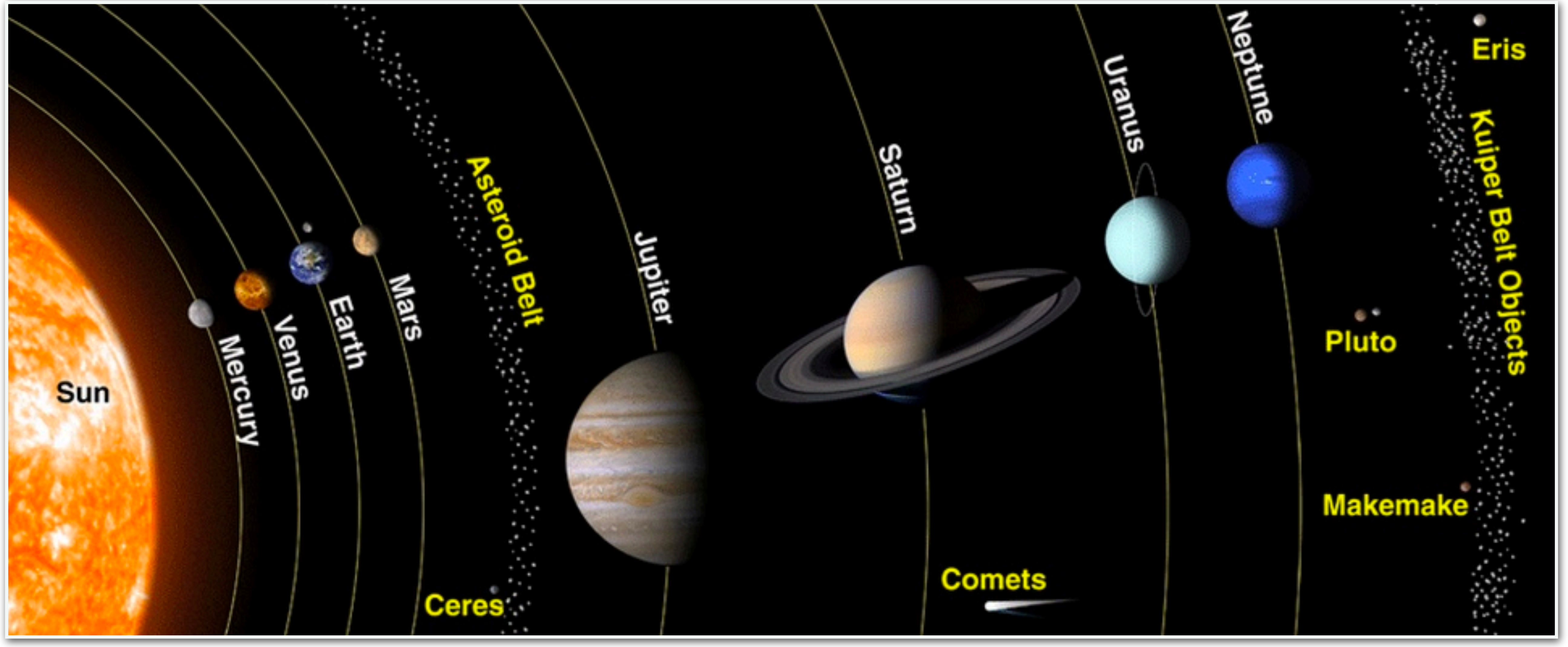




- Origins
  - nebula: H_2 + FeO (magma ocean) → H_2O + Fe
  - CCs: wmf ~ 3-10wt%
  - comets: wmf ~ 50wt%
- Carbonaceous Chondrites in the asteroid belt are thought to be responsible for water on Earth

Origin of water on Earth

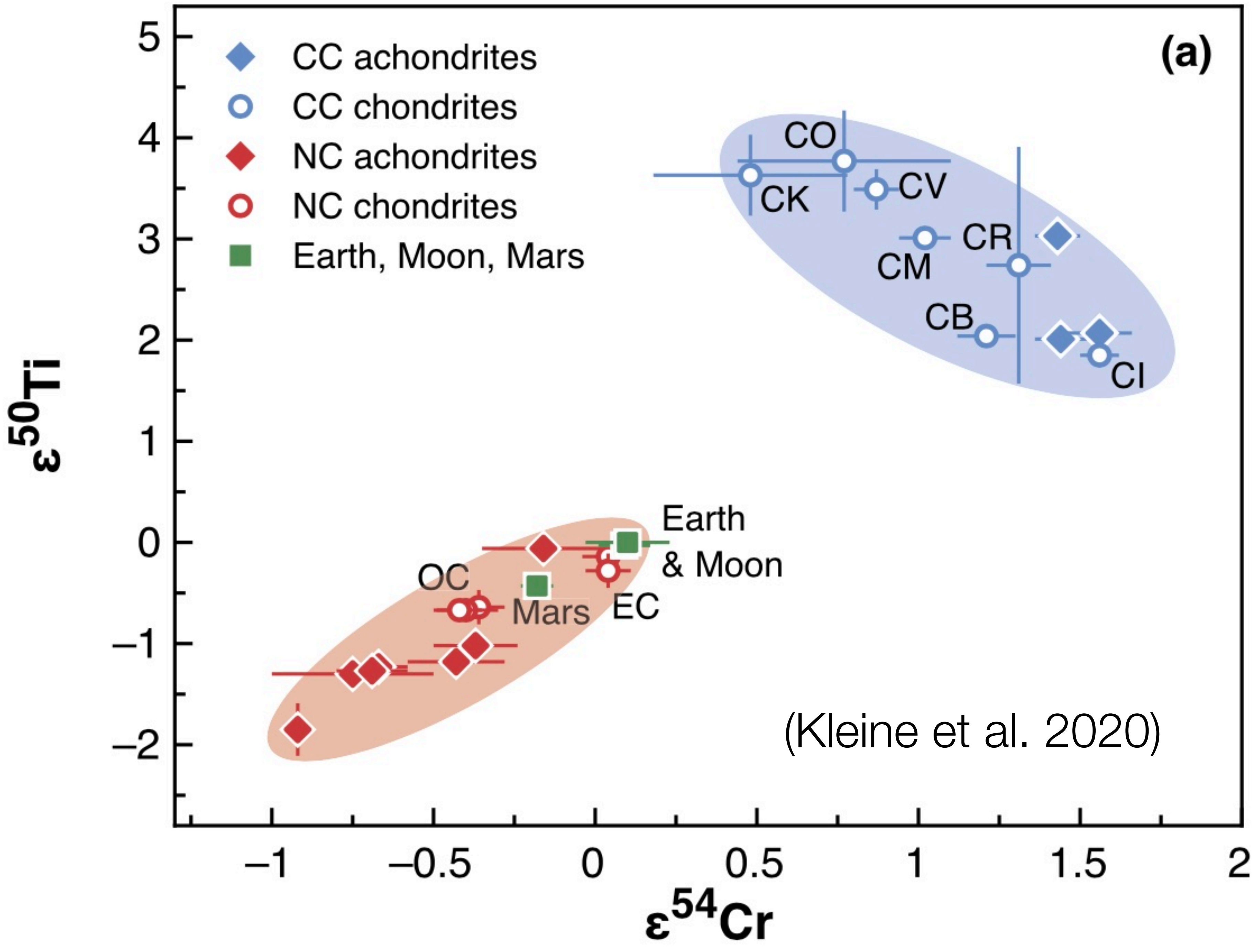


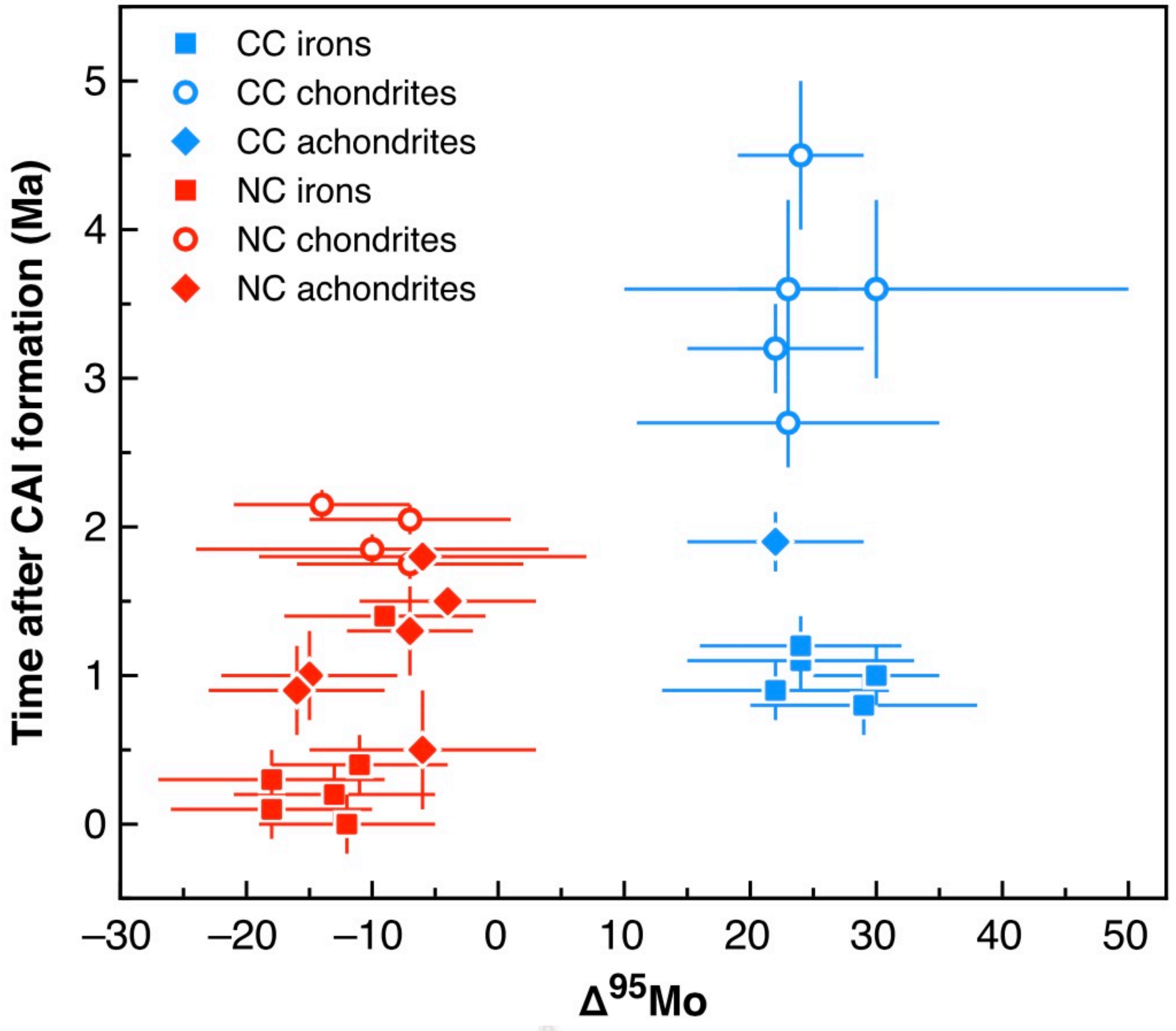


- Origins
  - nebula: H2 + FeO (magma ocean) → H2O + Fe
  - CCs: wmf ~ 3-10wt%
  - comets: wmf ~ 50wt%
- Carbonaceous Chondrites in the asteroid belt are thought to be responsible for water on Earth

Meteorites: NC-CC dichotomy

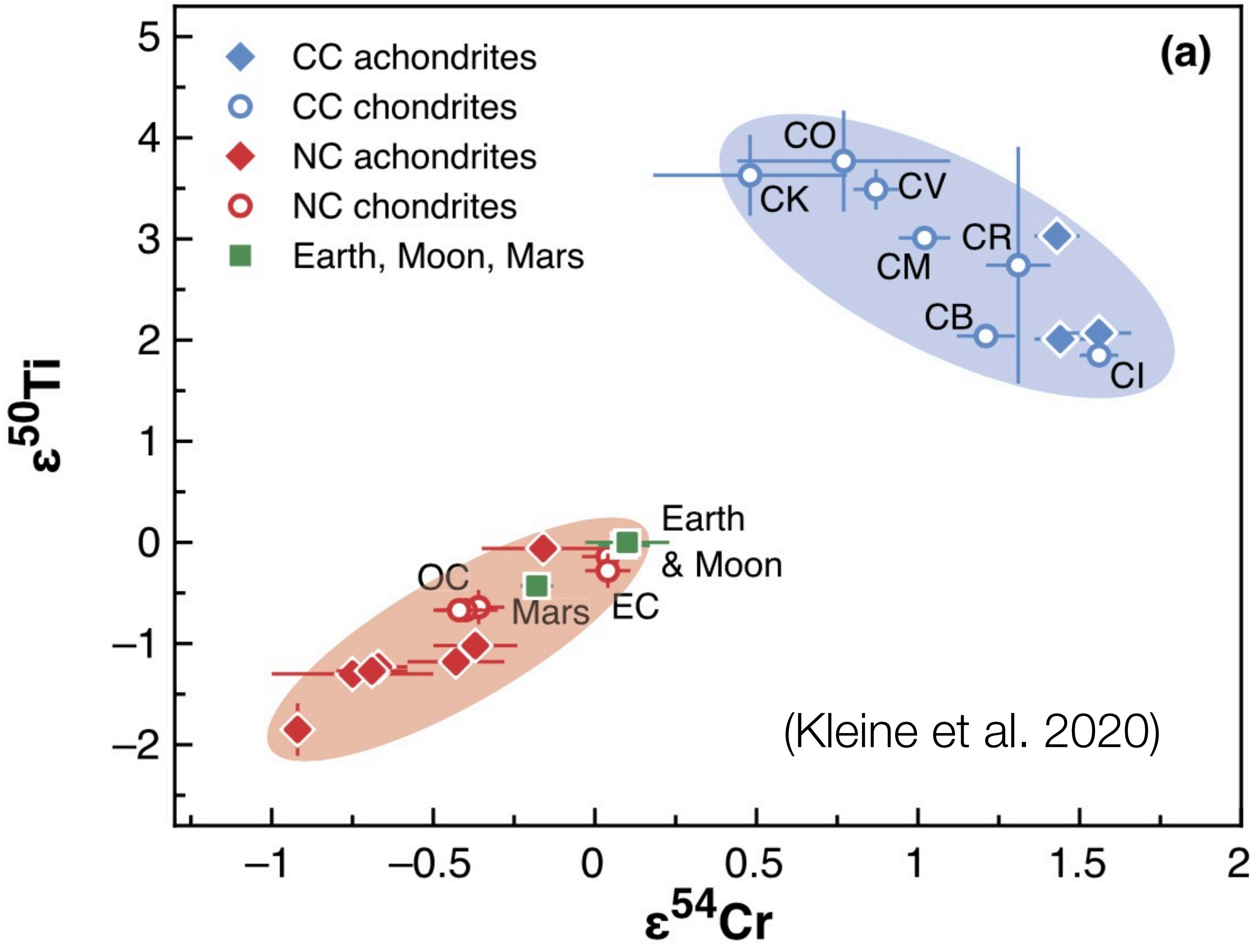
- TIMS: extremely precise analysis of isotope ratios (precision has improved by 10 times in the last 15 years)
- Isotopic composition of meteorites can be divided into two groups! → CC/NC groups → they formed in different places
- Formation times overlap among NC/CC groups ← If each group is mixed and collides with each other, materials with intermediate composition should form!
- Jupiter played the role of a barrier that prevented the material transport at 1-2 Myr

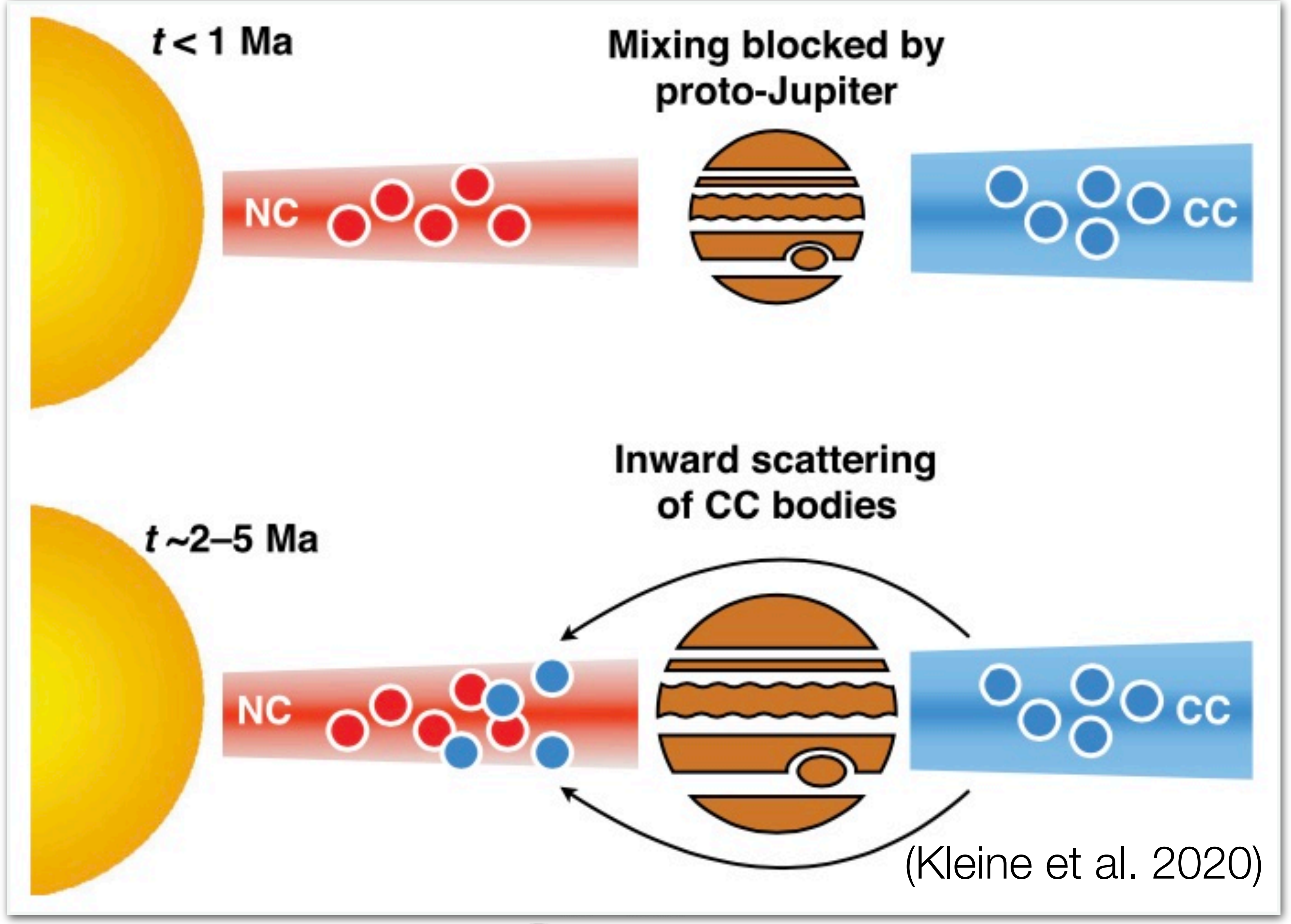




Meteorites: NC-CC dichotomy

- TIMS: extremely precise analysis of isotope ratios (precision has improved by 10 times in the last 15 years)
- Isotopic composition of meteorites can be divided into two groups! → CC/NC groups → they formed in different places
- Formation times overlap among NC/CC groups ← If each group is mixed and collides with each other, materials with intermediate composition should form!
- Jupiter played the role of a barrier that prevented the material transport at 1-2 Myr



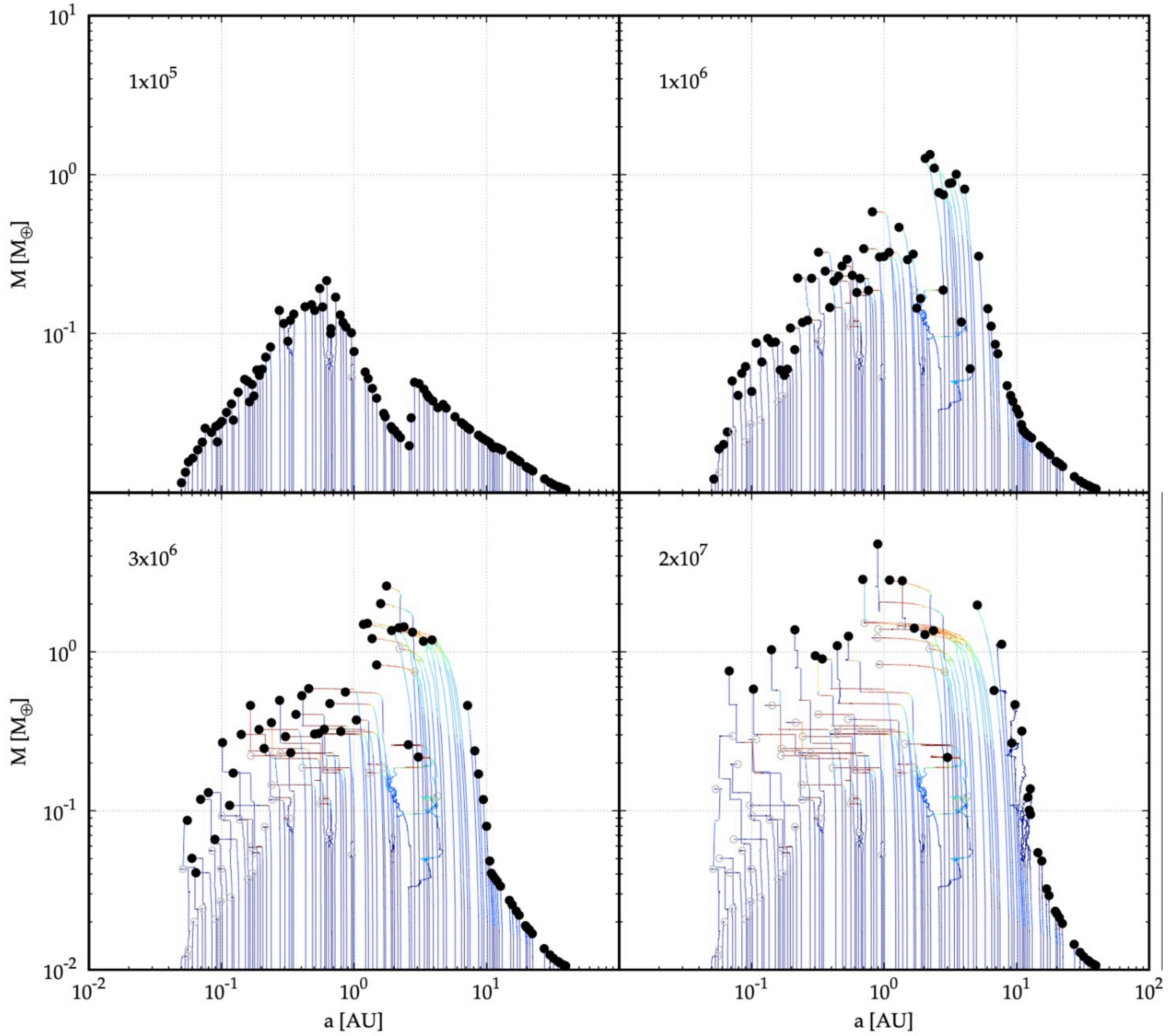


Planet formation models and simulations

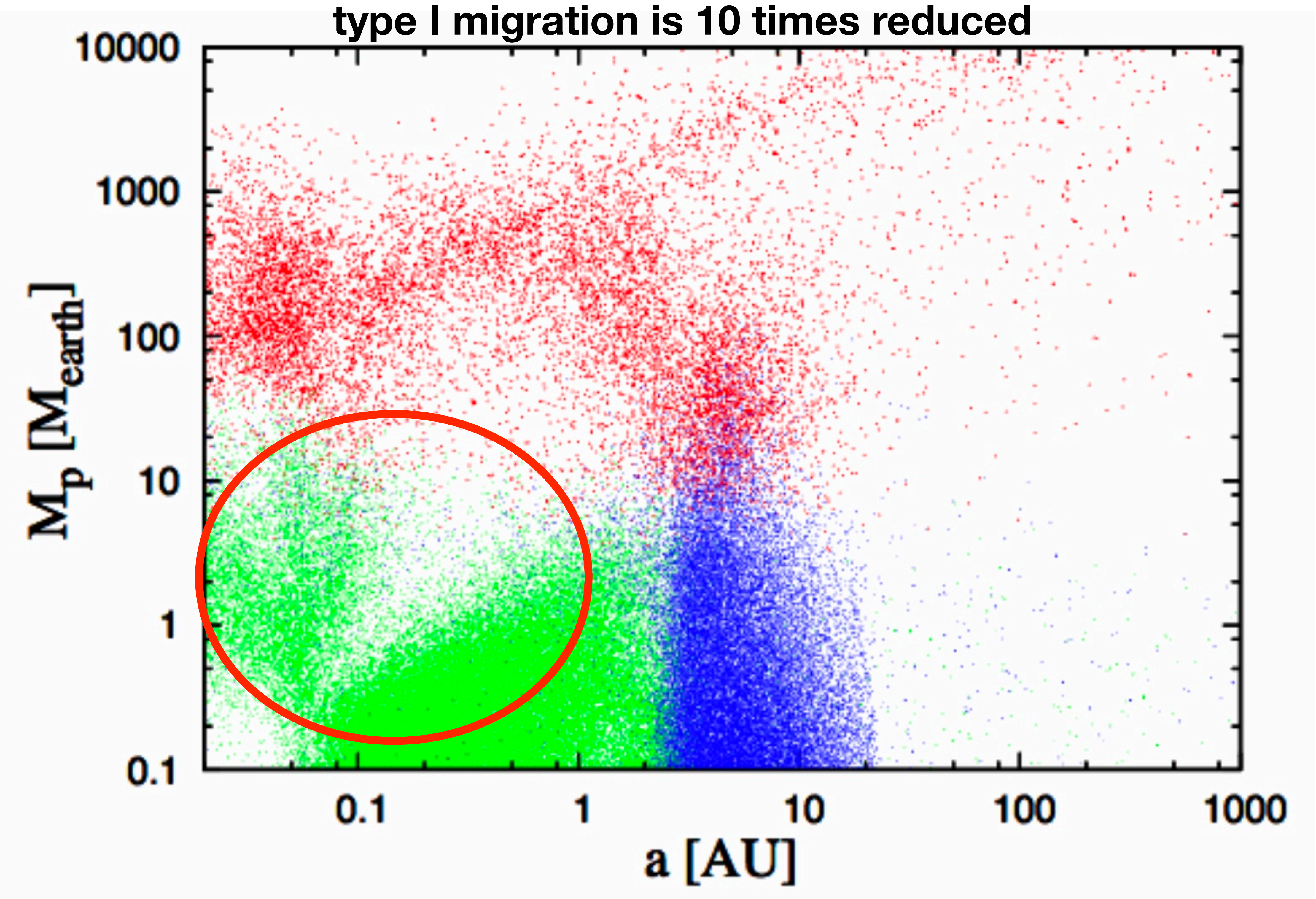
Population synthesis

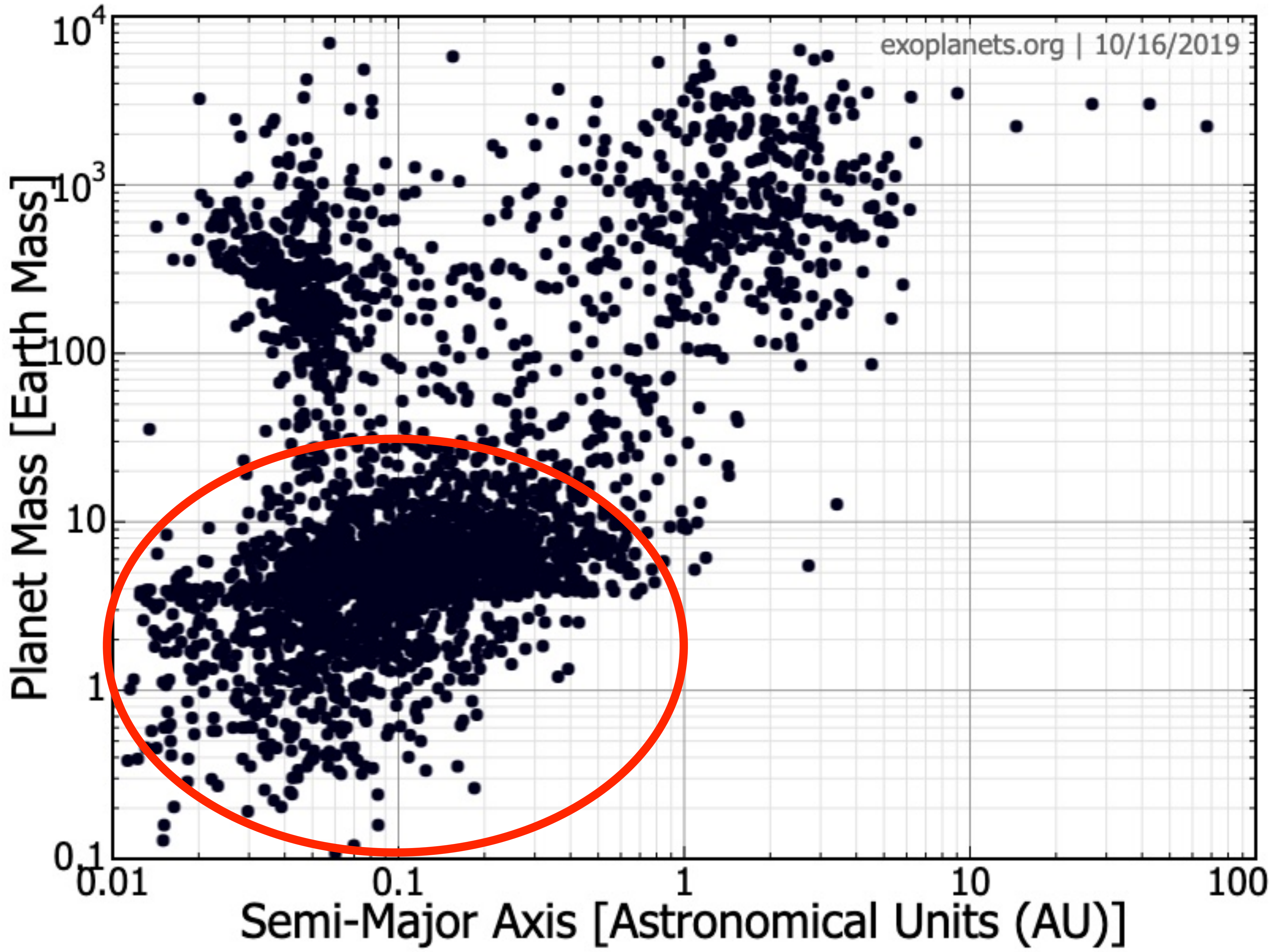
- **Planet population synthesis**: There are many uncertainties in planet formation models (eg, disk mass, gas distribution). We can treat these uncertainties as parameters, and perform a large number of simulations with various values of the parameters.
- The results of the simulations are compared with observations (eg, occurrence rate, orbital distribution), which can lead to constrain the parameters.
- Famous models:
  - **Ida & Lin model** (2004ab, 2005, 2008ab, 2010, 2013)
  - **Bern model** (2009ab, 2011, 2012, 2013, etc.)→NGPPS (2020, 2021abc, etc.)
- Some physics (eg, pebble accretion, disk instability) not included.

(Emsenhuber et al. 2020)



Hot super-Earths and sub-Neptunes



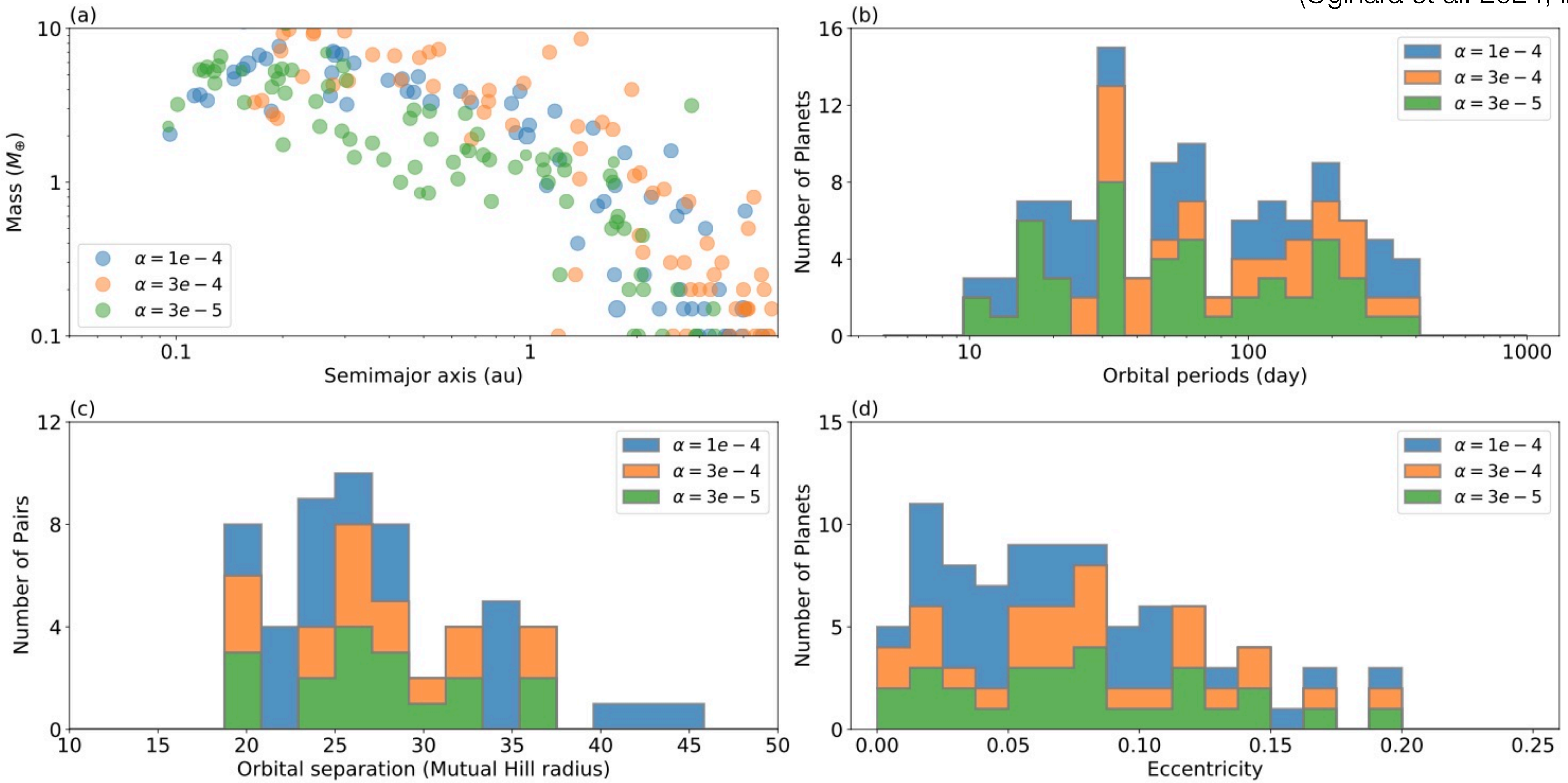


(Ida et al. 2013; see also Mordasini et al. 2014)

- There are several critical problems in small planet formation
- One problem is **rapid type I migration problem**
- Even if type I migration is artificially reduced by a factor of 10, we see a pileup of SENs at < 0.1 au

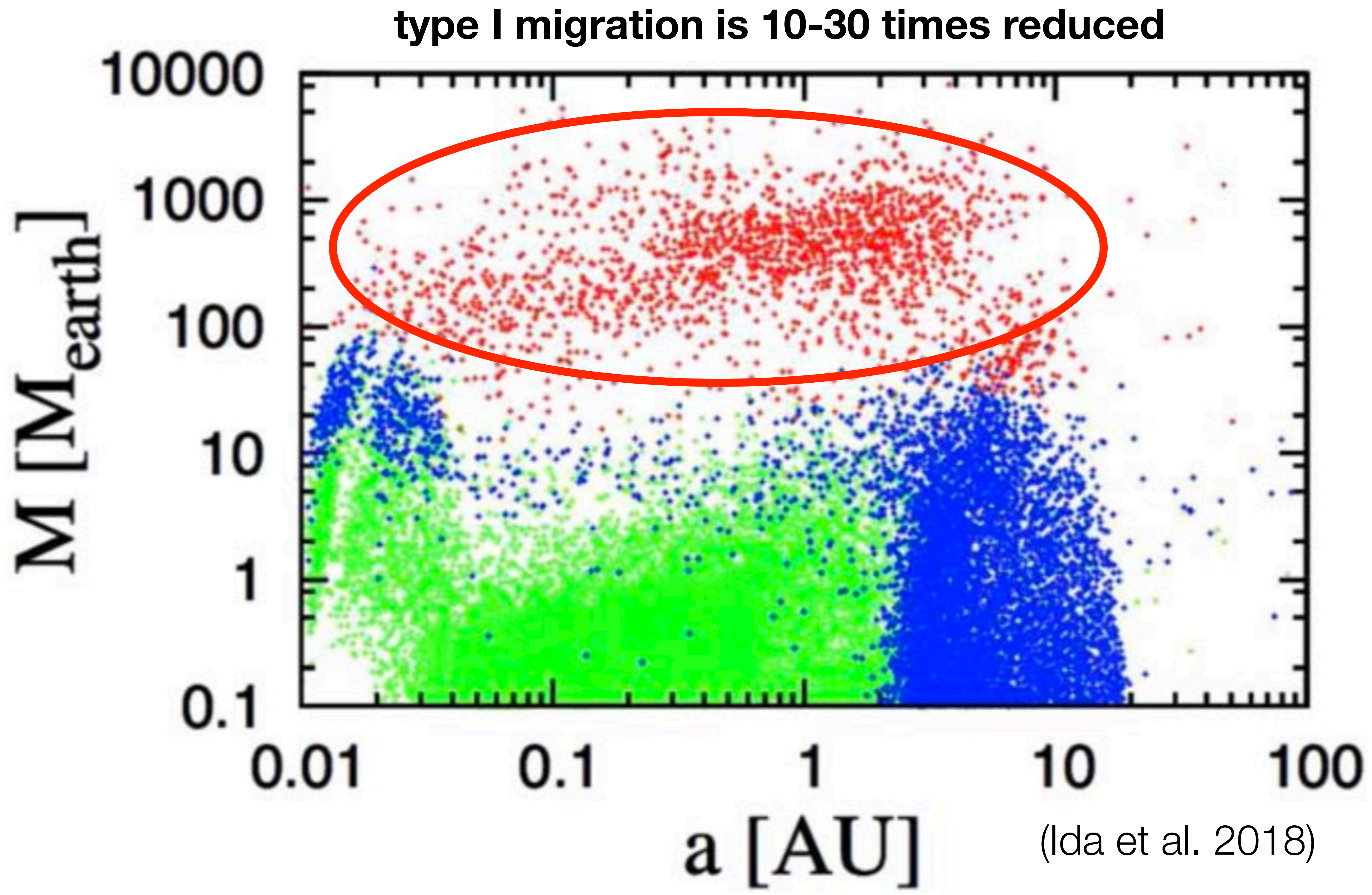
Hot super-Earths and sub-Neptunes (advertisement)

(Ogihara et al. 2024, in press)

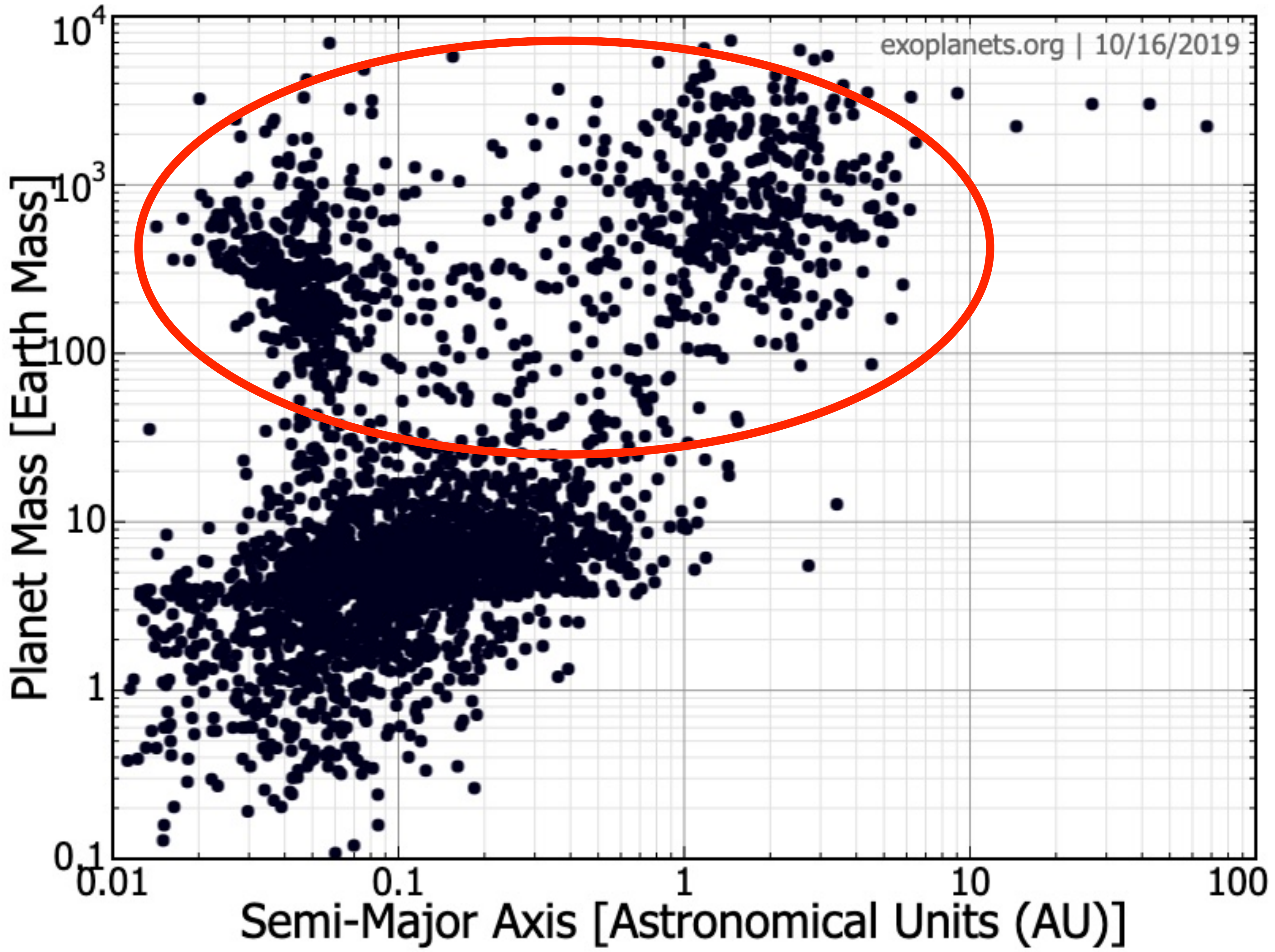


- Some recent studies by N-body simulation have successfully reproduce the characteristics of SENs

Giant planets



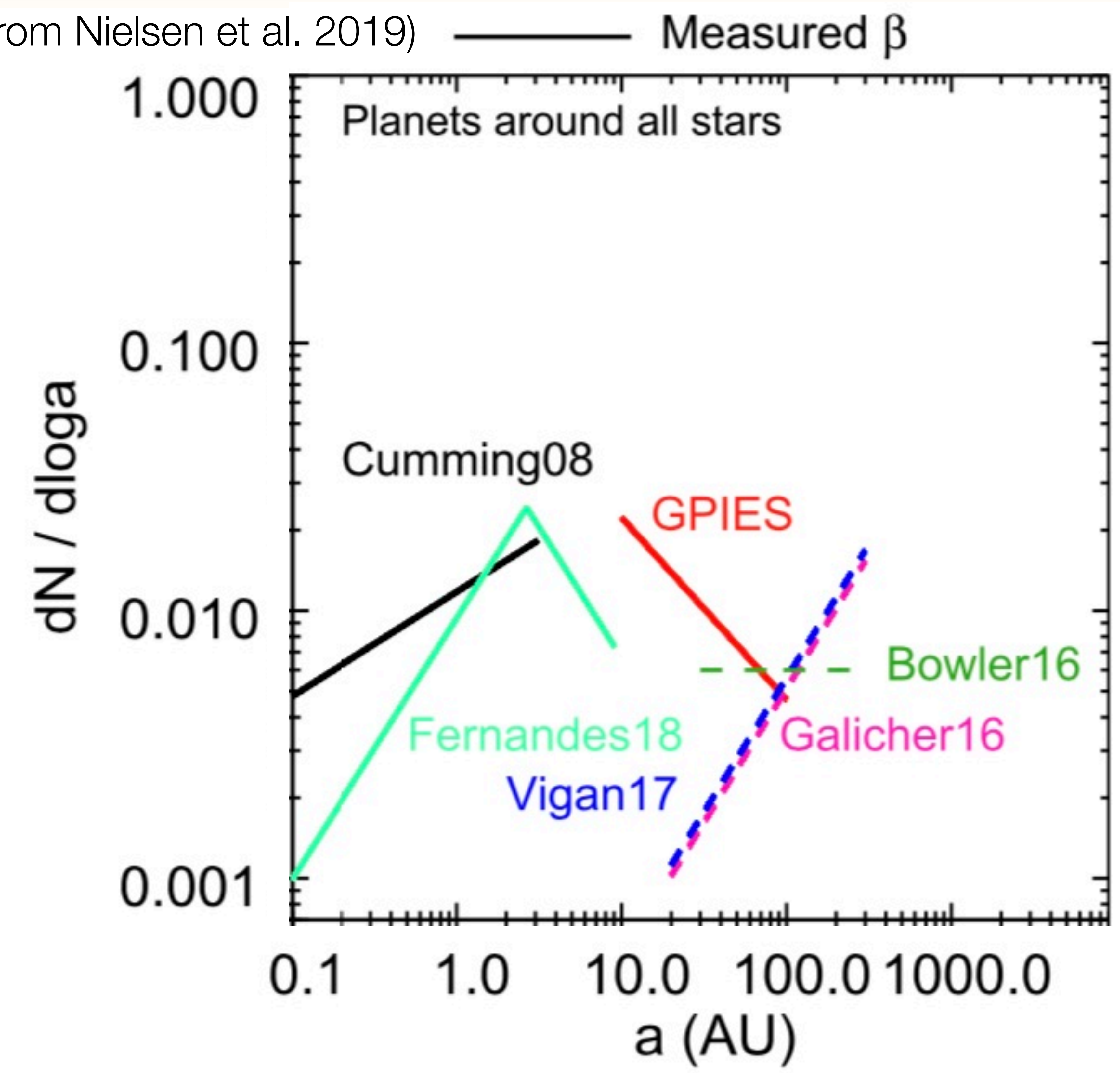
(Ida et al. 2018)

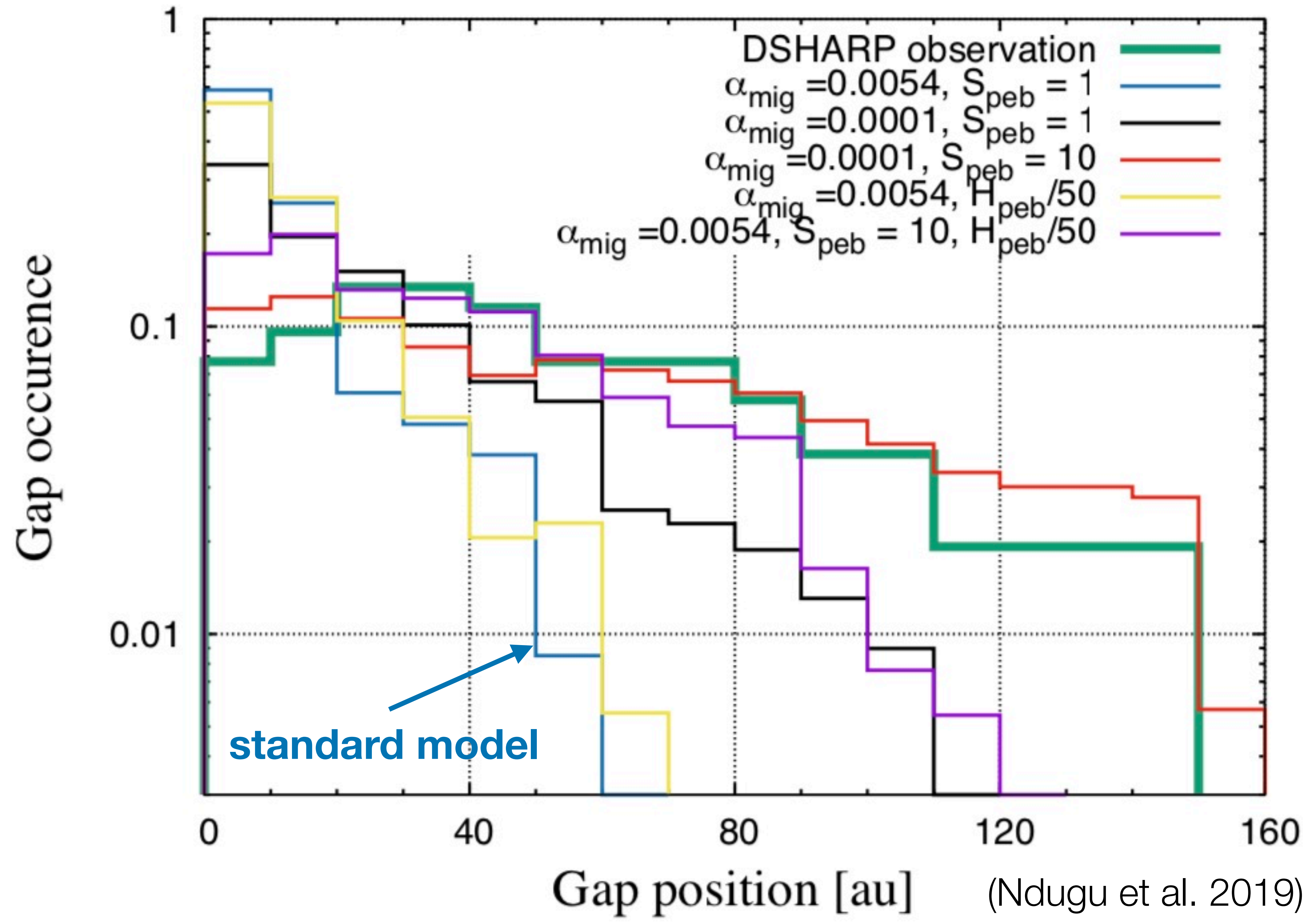


- There are also several critical problems in giant planet formation
- The problems include the **core growth problem** and the **orbital migration problem**
- Although there have been some updates to the type II migration model (Kanagawa et al. 2018), the orbital distribution of giant planets differs from observations

Occurrence rate

(from Nielsen et al. 2019)



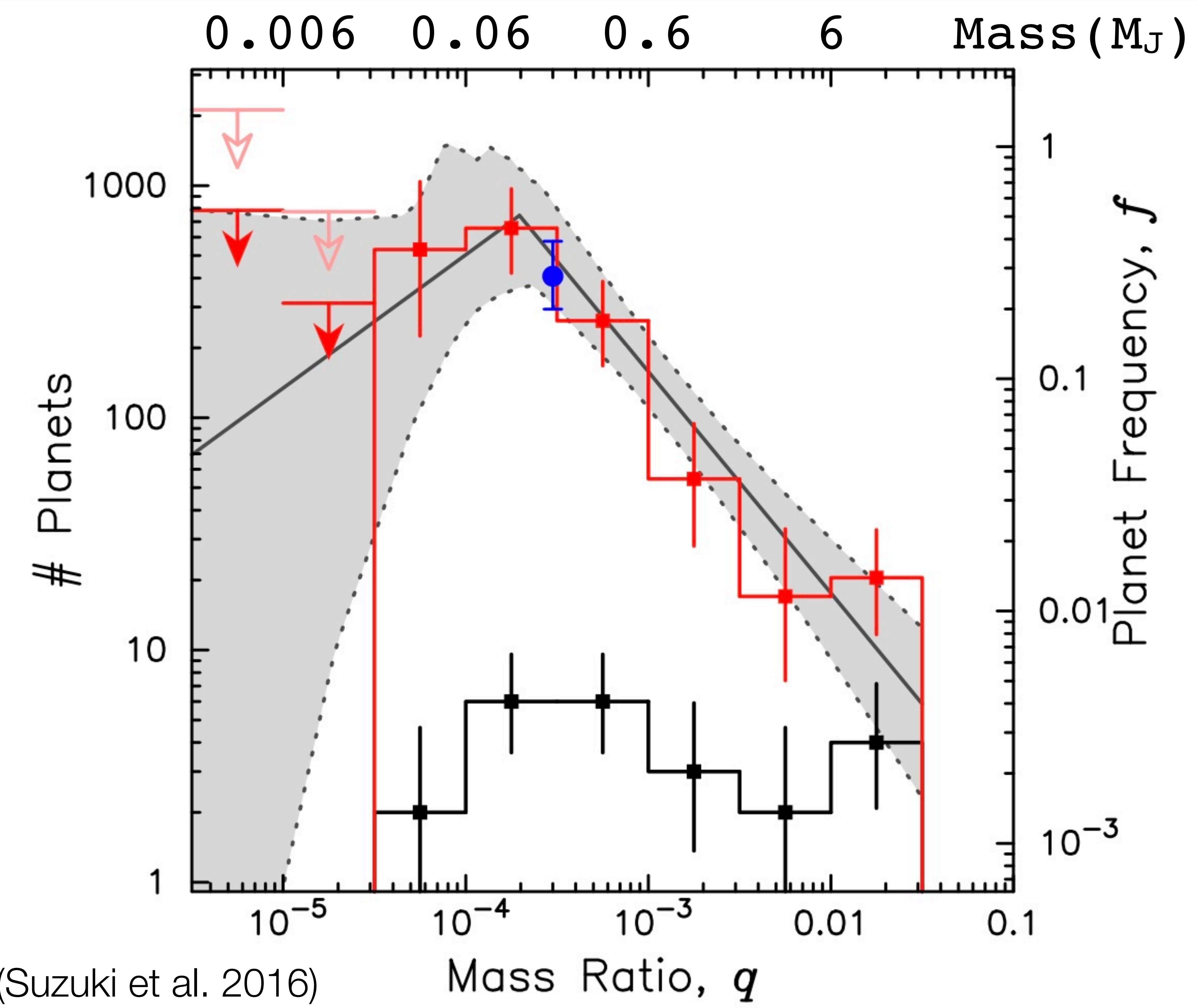


(Ndugu et al. 2019)

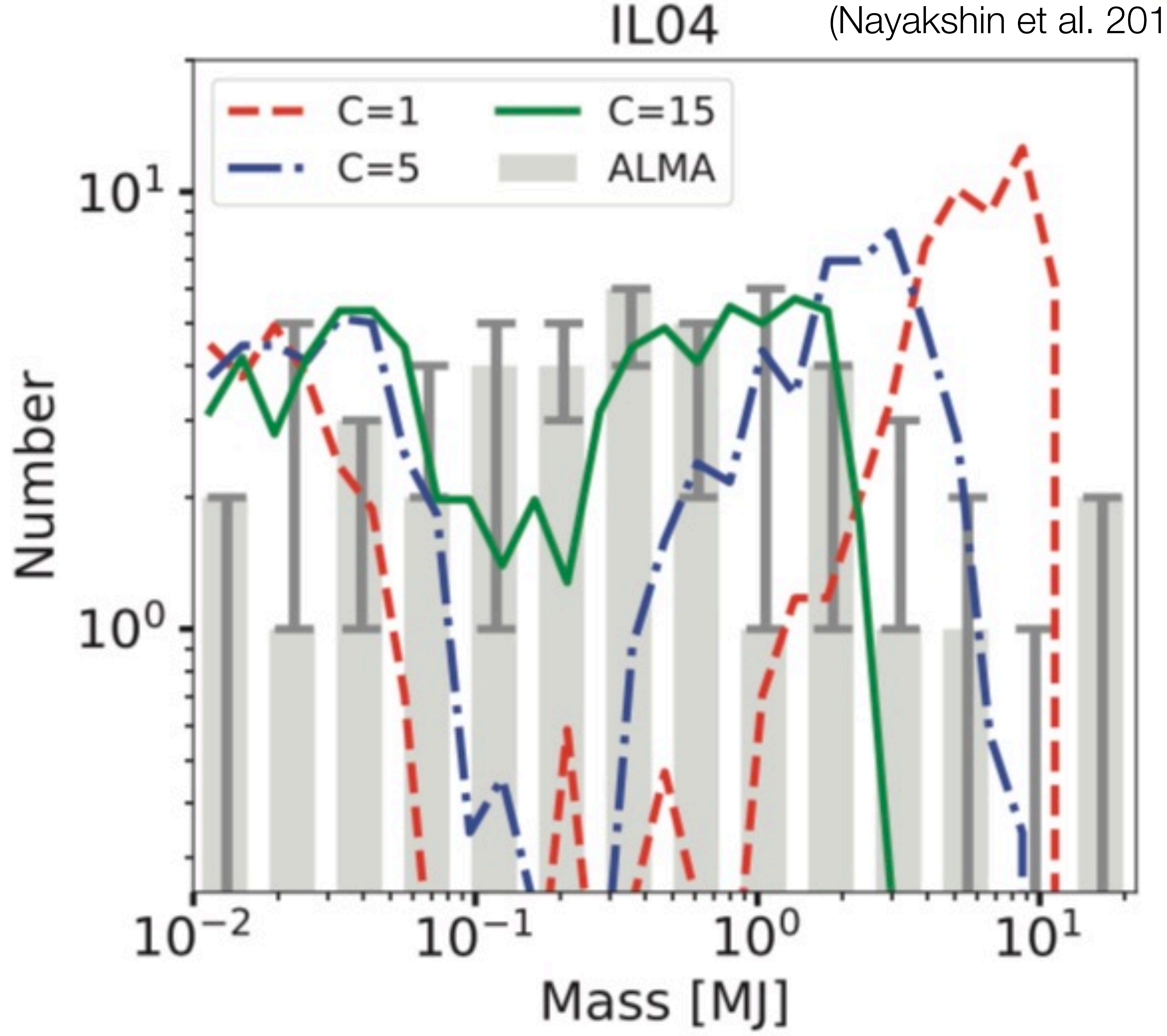
- Occurrence rates would be useful for development of planet formation theory
- Not much statistical theoretical studies yet

- The occurrence rate of CJs estimated by DSHARP (Huang+2018) cannot be reproduced by current simulations
  → further investigation is required (eg, Lodato et al. 2019)

Mass distribution



(Suzuki et al. 2016)

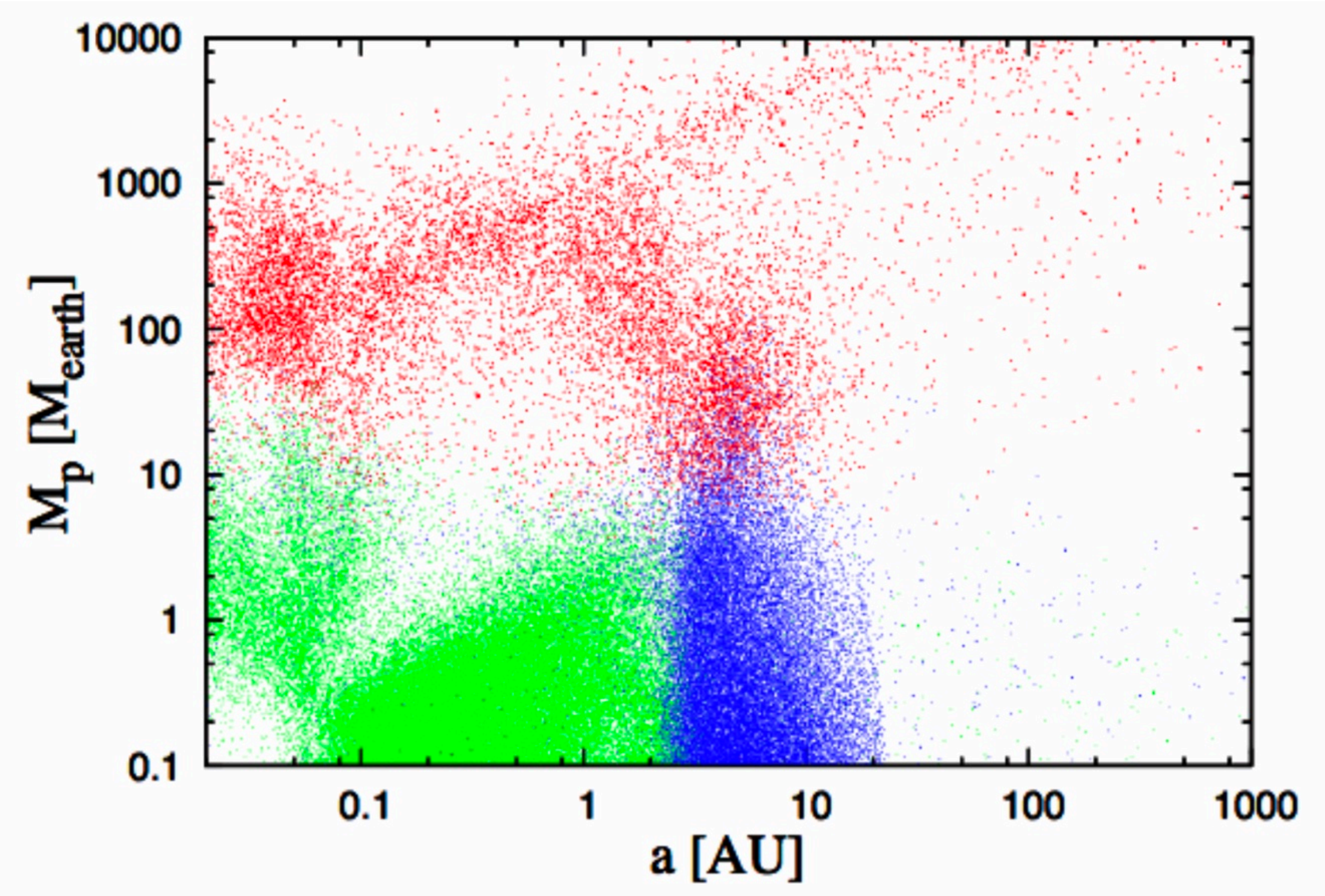


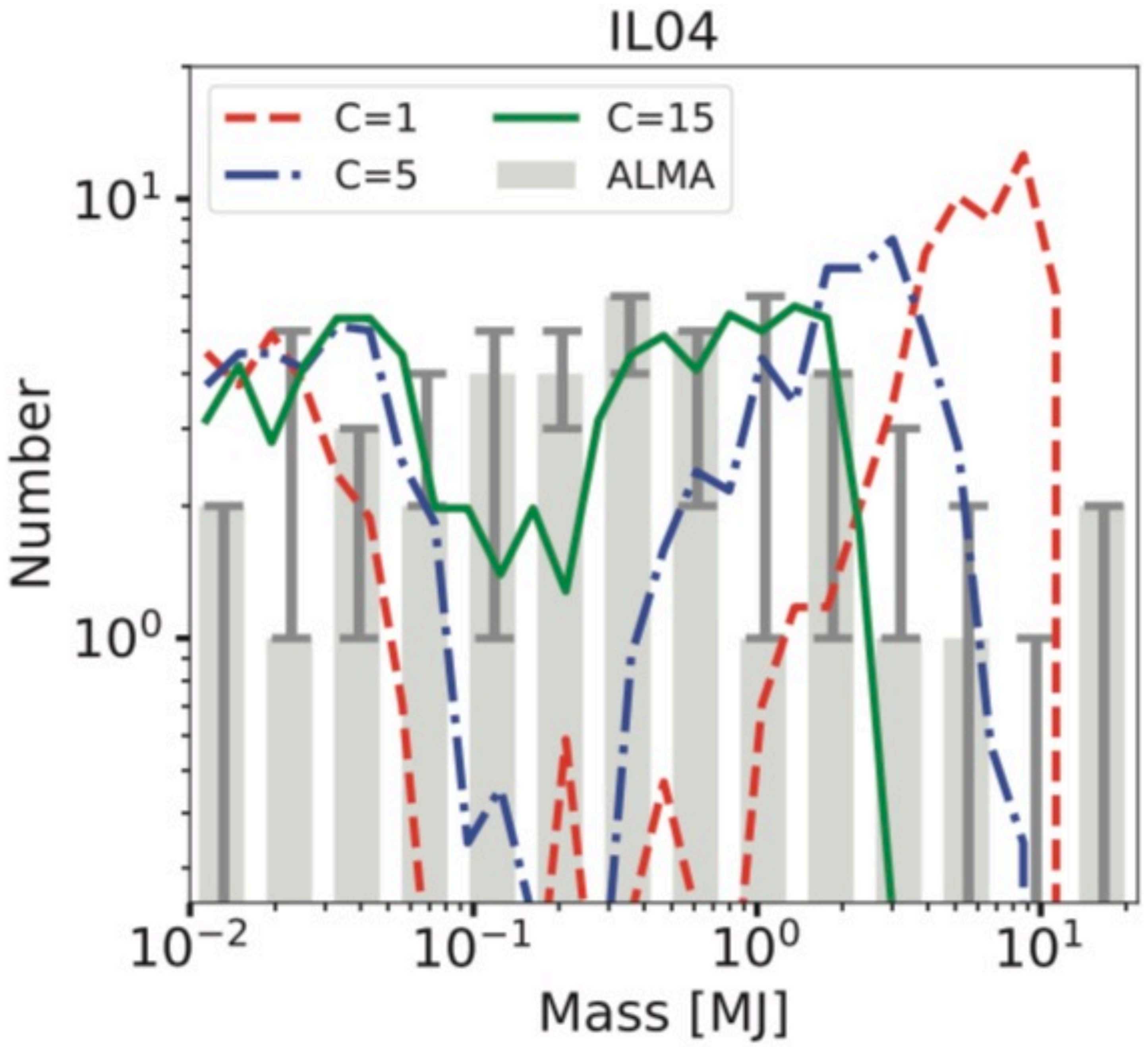
(Nayakshin et al. 2019)

- Mass distribution of cold planets is estimated by microlensing observations (→ new observations!?)
- A similar mass distribution is estimated by ALMA observations
- Population synthesis simulations predict a bimodal distribution (e.g., Ida et al. 2018)

Population synthesis

- The current planet population synthesis models can only roughly explain the observed properties of exoplanets
- This means that some physical processes included in the current model are probably incorrect
- Therefore, it is also important to perform detailed study of each physical process to identify important physical processes of planet formation and to gain a deeper understanding of such processes





Conclusions

- Further reading
  - Textbooks: e.g., Astrophysics of Planet Formation (P. Armitage)
  - Reviews: e.g., Protostars and Planets VII (PP7)
  - But the textbooks are 10 years behind. You need to read the latest papers by yourself. Discuss the contents with various people.

- When doing planet research
  - It would be helpful to think about the situation in the next 5-10 years
  - You can do research that will get a lot of attention in the next 5-10 years
  - You can also do something niche (on purpose)