Explaining the Solar System

Andre Izidoro

in collaboration with ***Sean N. Raymond,*** *Alessandro Morbidelli, Arnaud Pierens, Nathan Kaib, Othon Winter, and David Nesvorny*

UNESP
Guaratinguetá


How did Earth get its water? Where did C-type asteroids come from?


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Where did Planet 9 come from?
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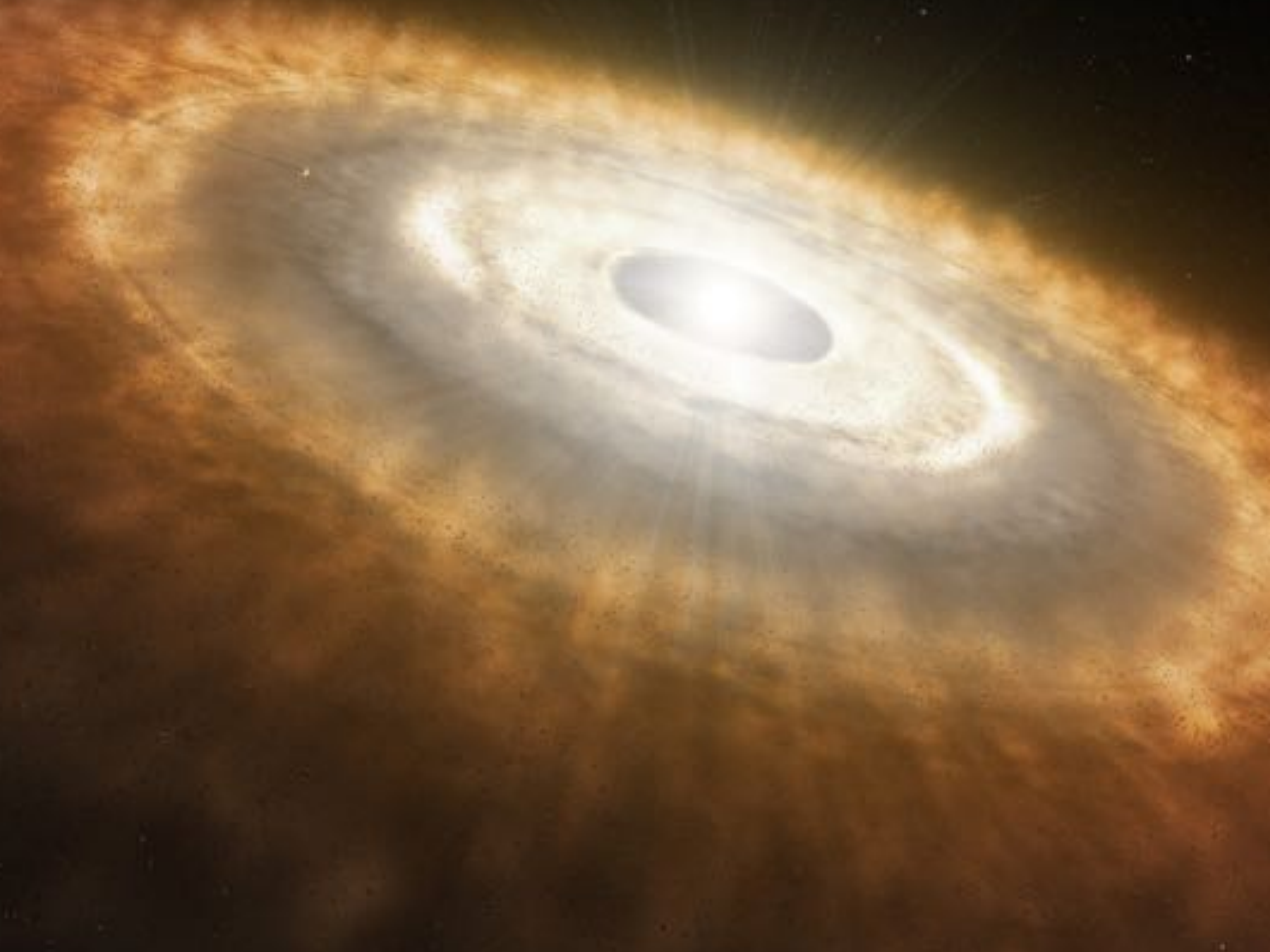
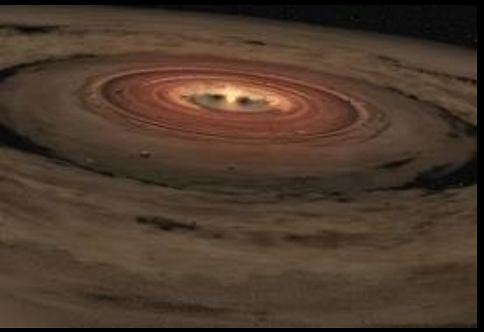
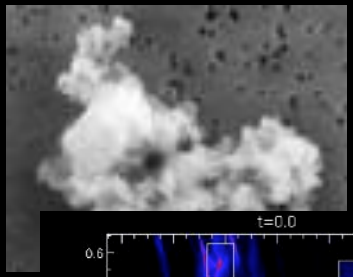
Planet 9





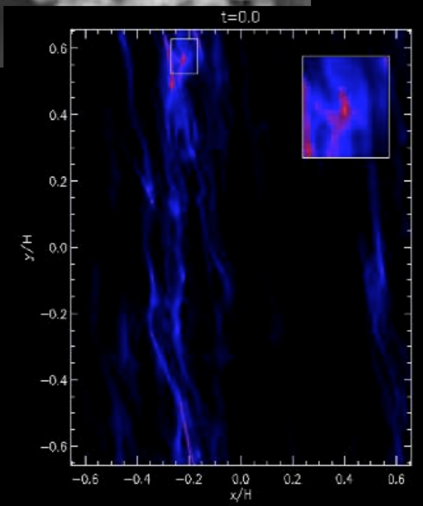
Stages of Planet Formation

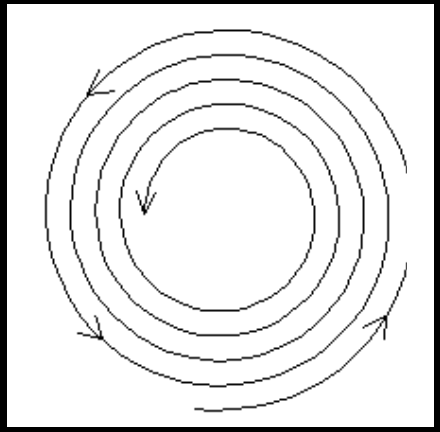


Aerodynamic drift

Grain

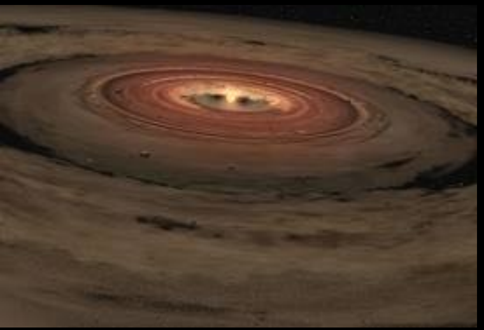
Pebbles





Planetesimals

Planetary Embryos



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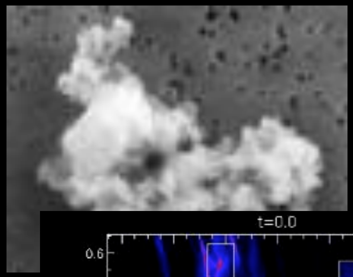

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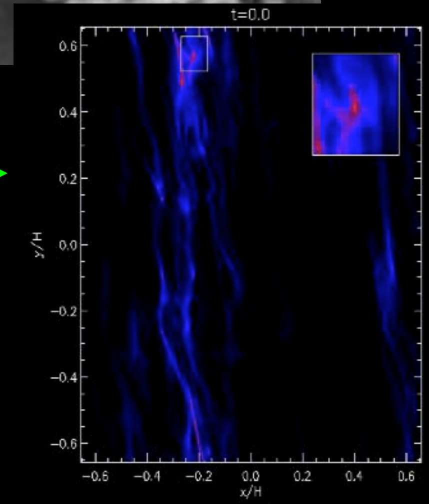
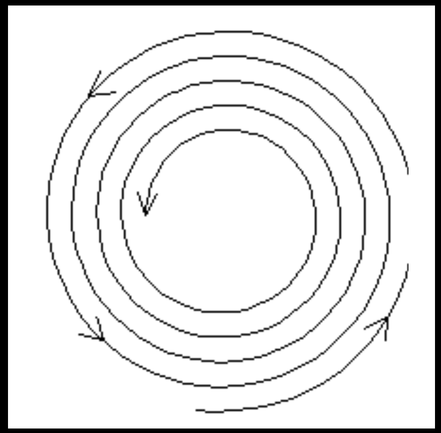
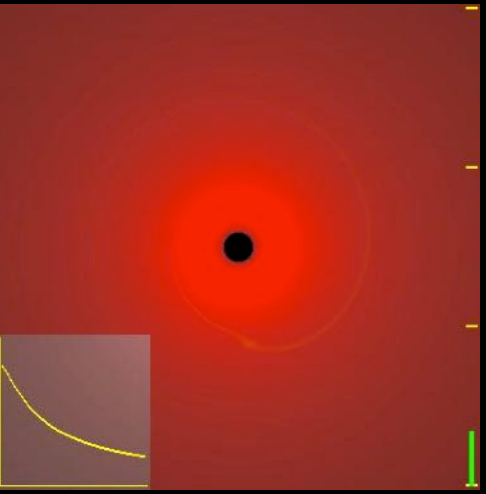




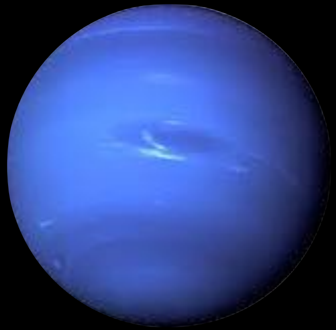
Type-I migration

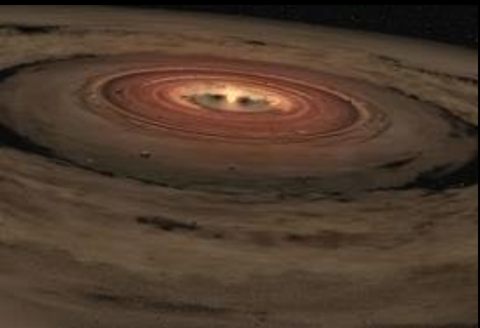


Planetesimals

Planetary Embryos

while gas remains in disk





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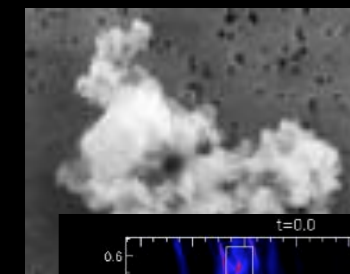
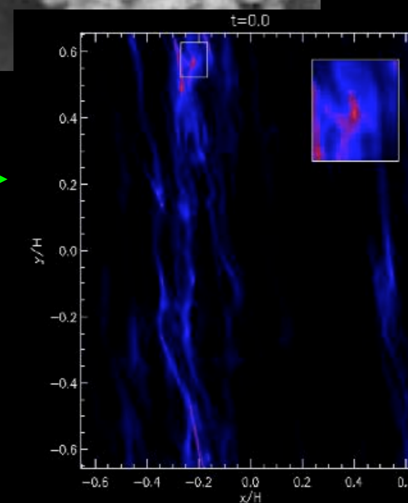
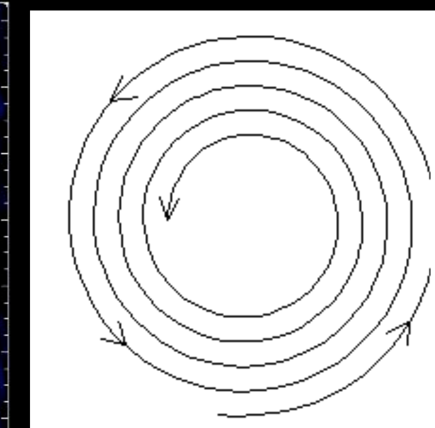


Aerodynamic drift





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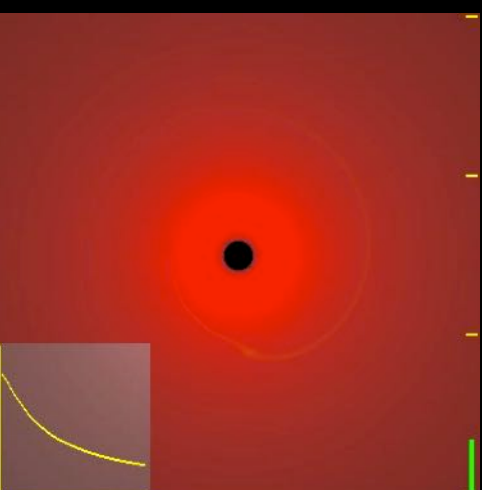
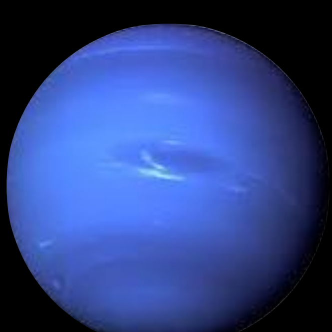
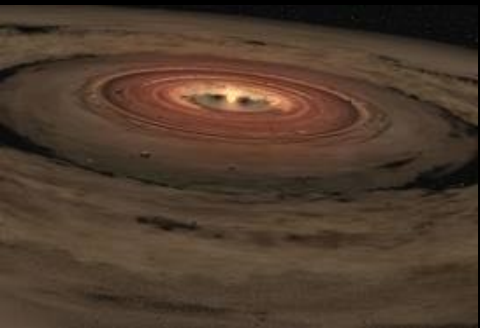


while gas remains in disk

Gaseous Planets





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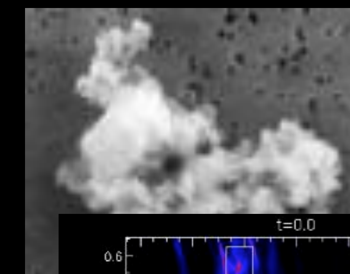
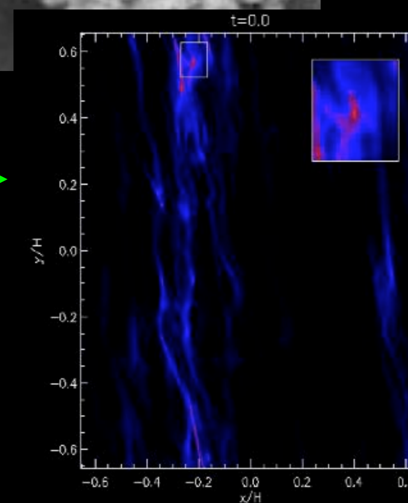
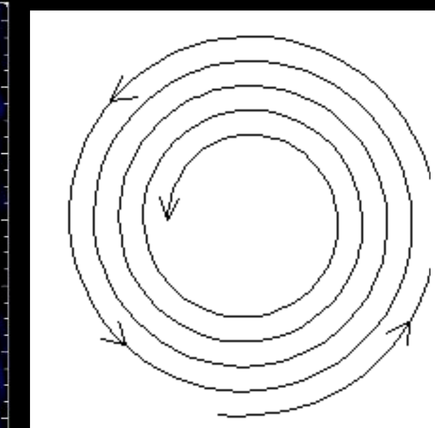


Aerodynamic drift





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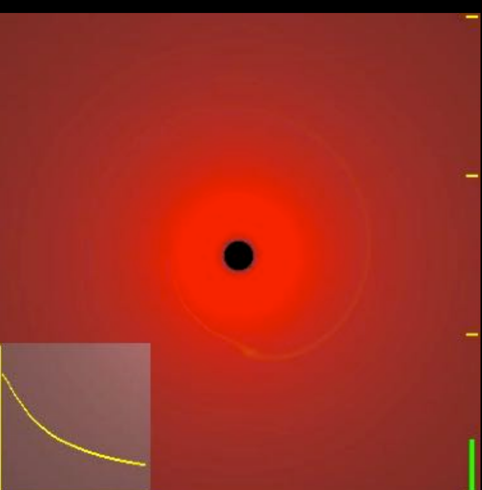

while gas remains in disk

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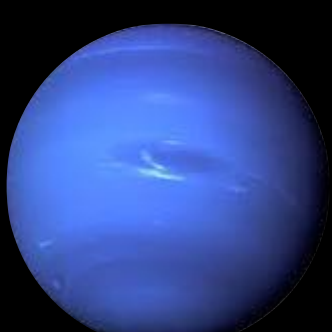
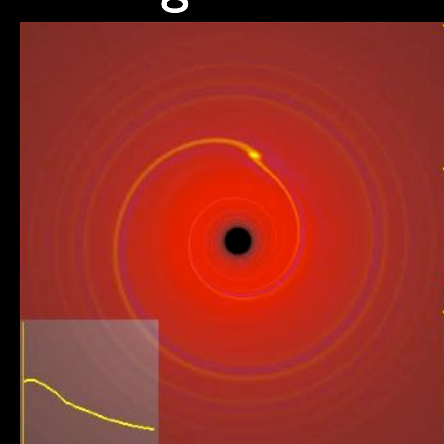
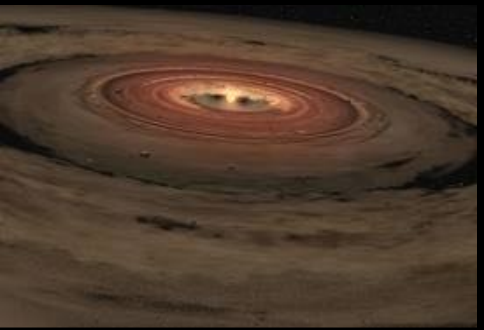


Type 2 migration



Stages of Planet Formation



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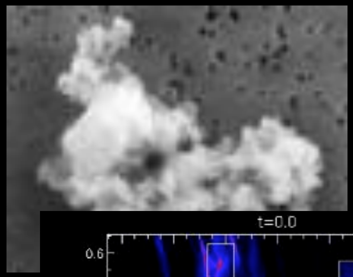

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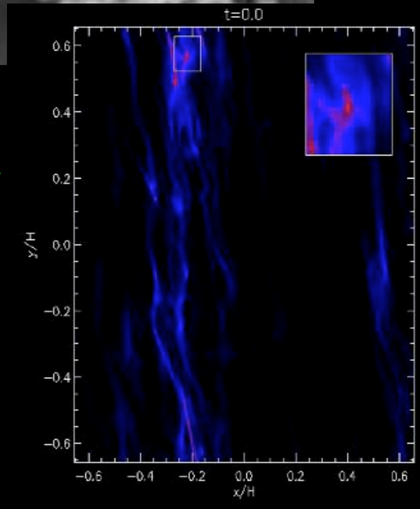

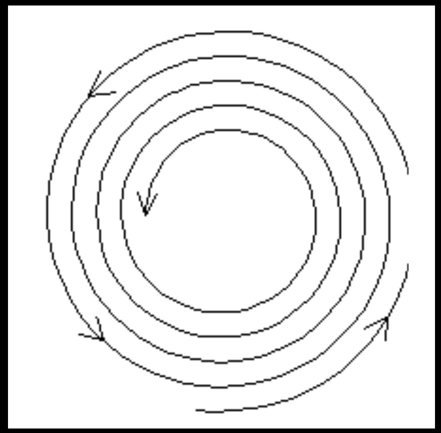

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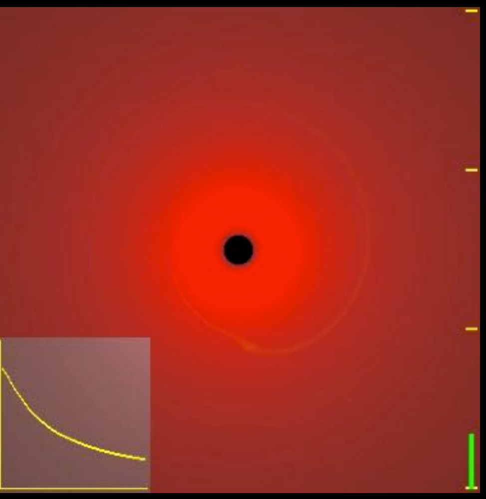


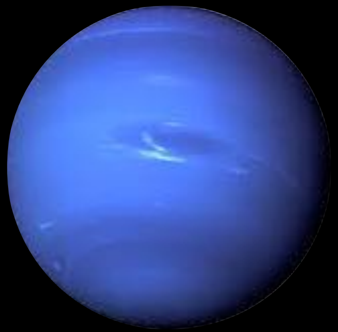
Planetesimals

No more gas

Planetary Embryos

while gas remains in disk

Gaseous Planets



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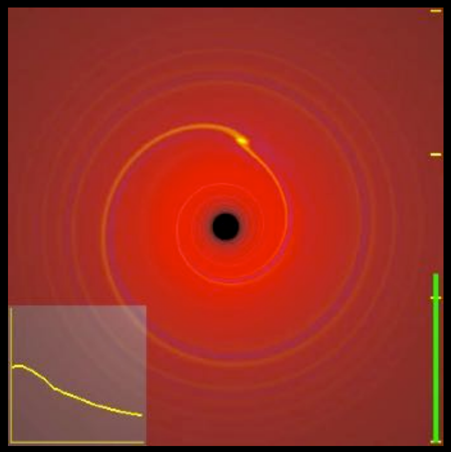

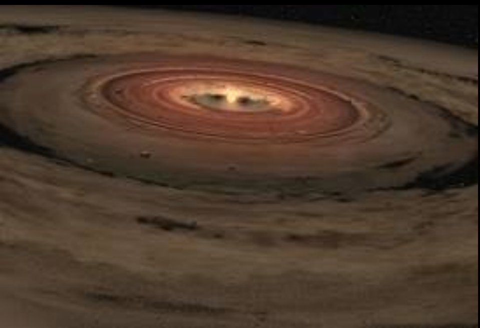

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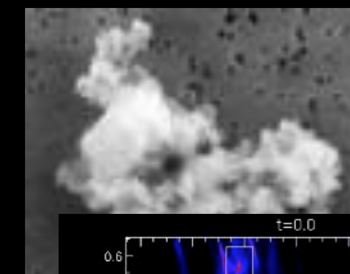
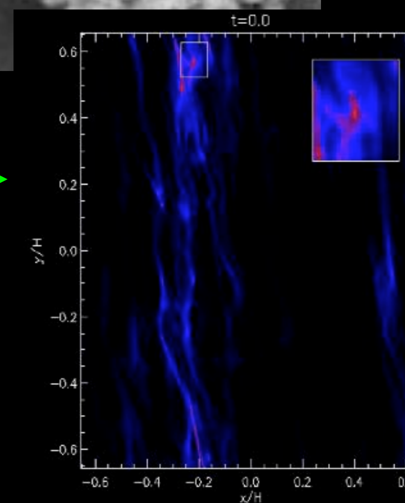
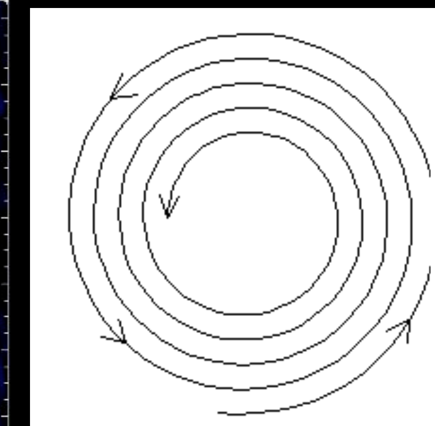
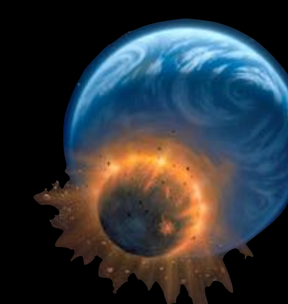


Aerodynamic drift





No more gas



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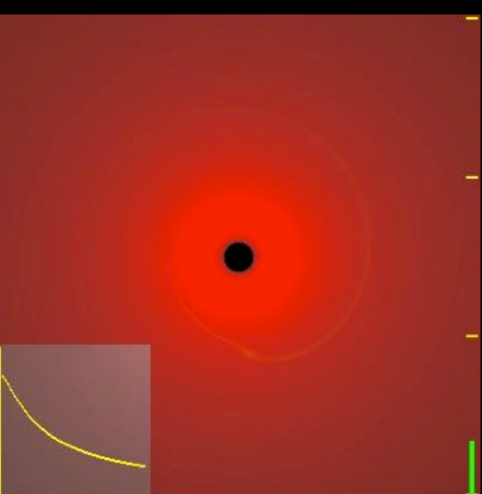

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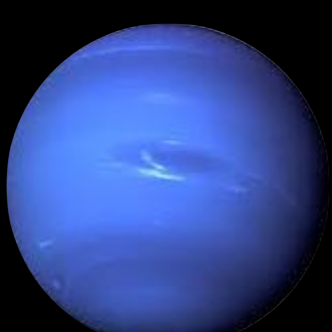
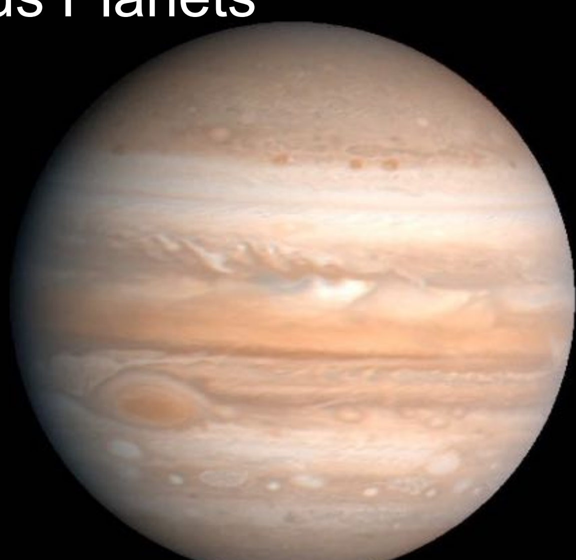
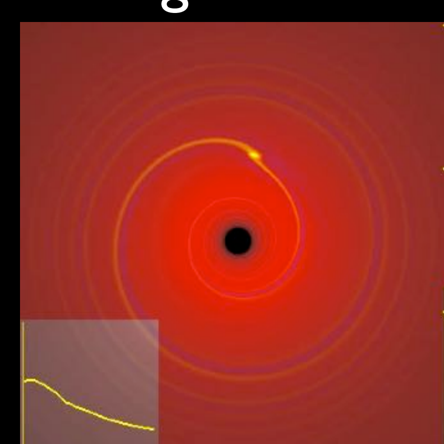
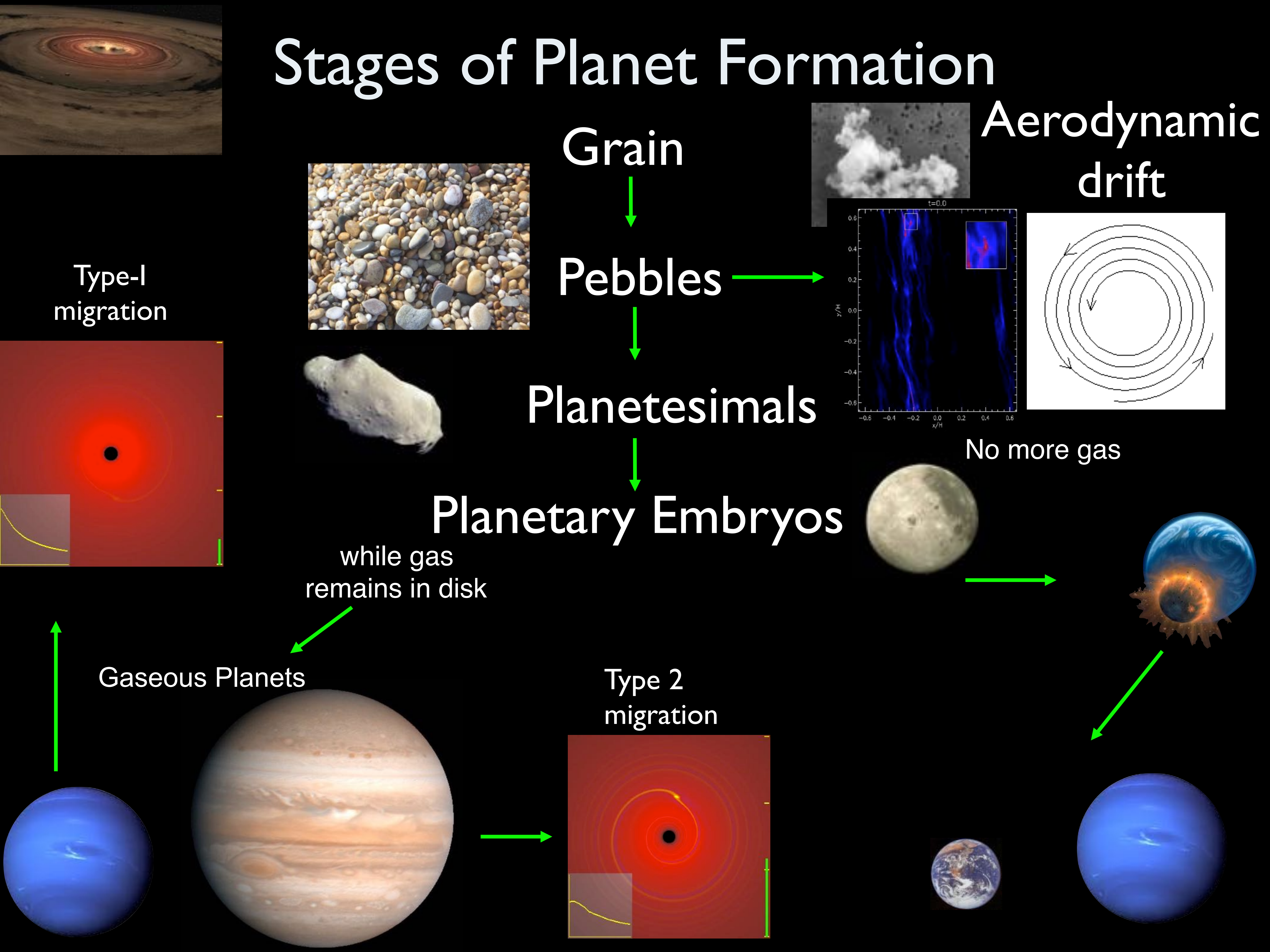




Type 2 migration




Stages of Planet Formation
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Pebbles
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Planetary Embryos
Aerodynamic drift
No more gas
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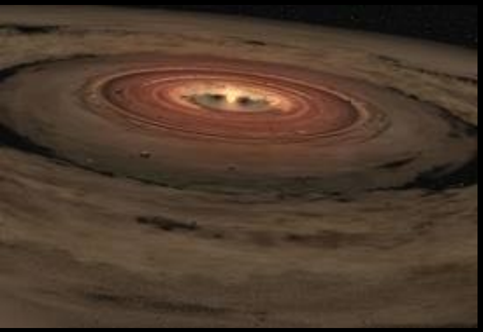
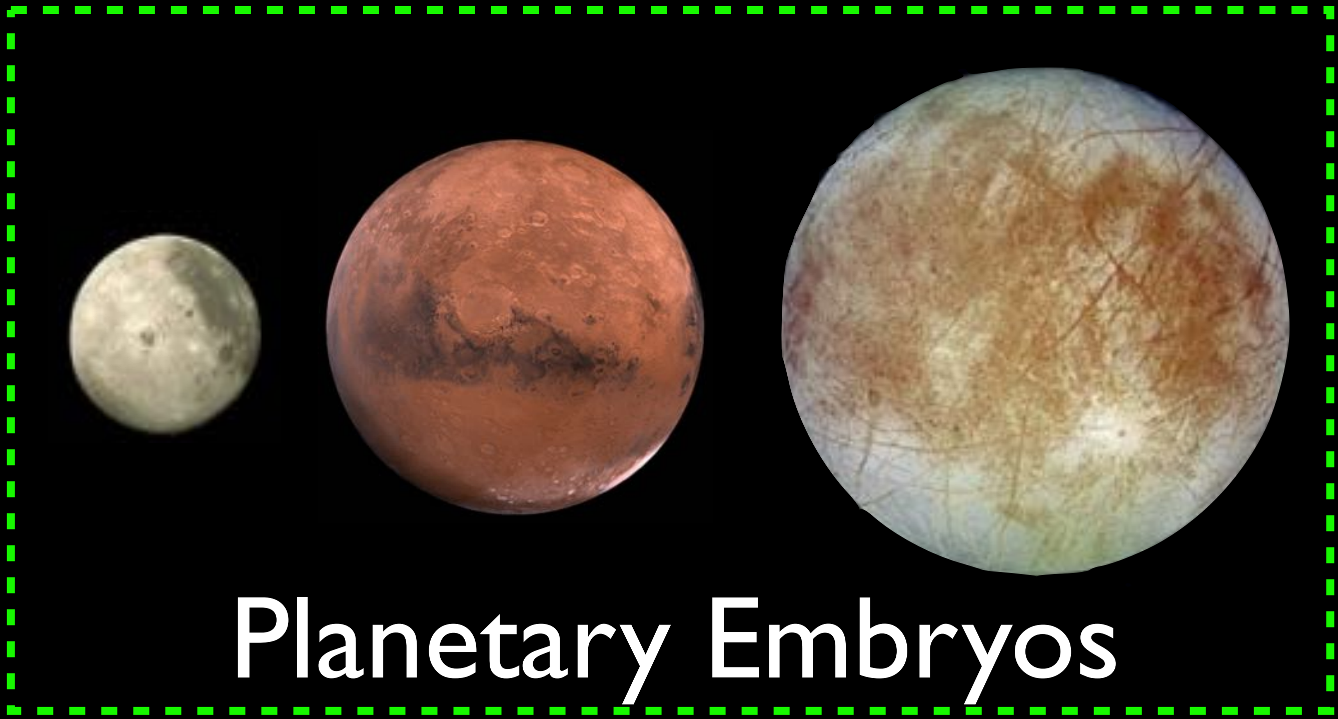
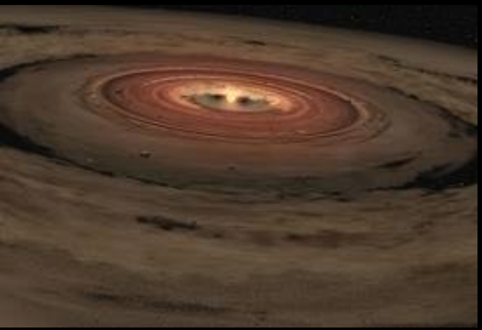
Type 2 migration

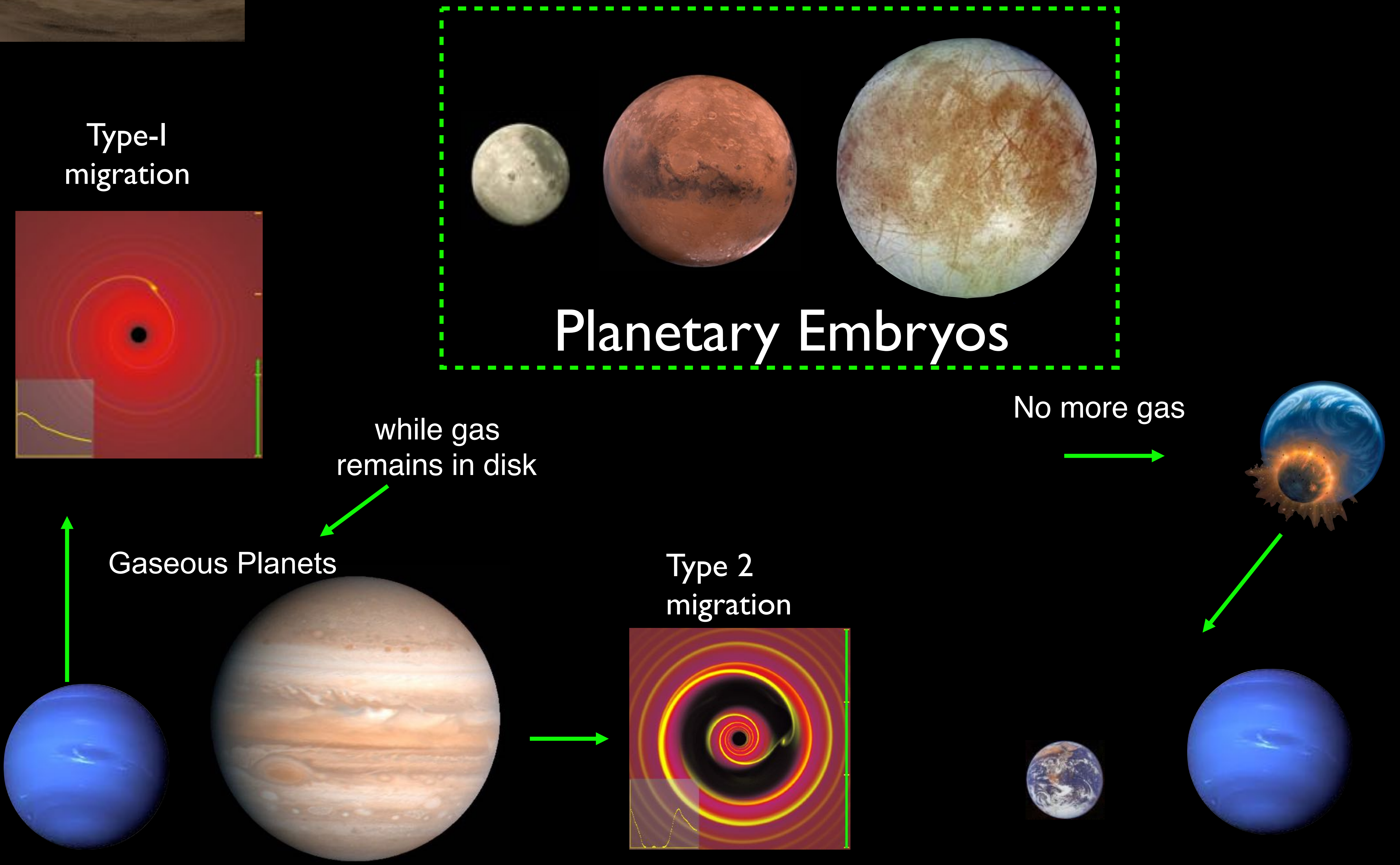
Late Stage of Planet Formation

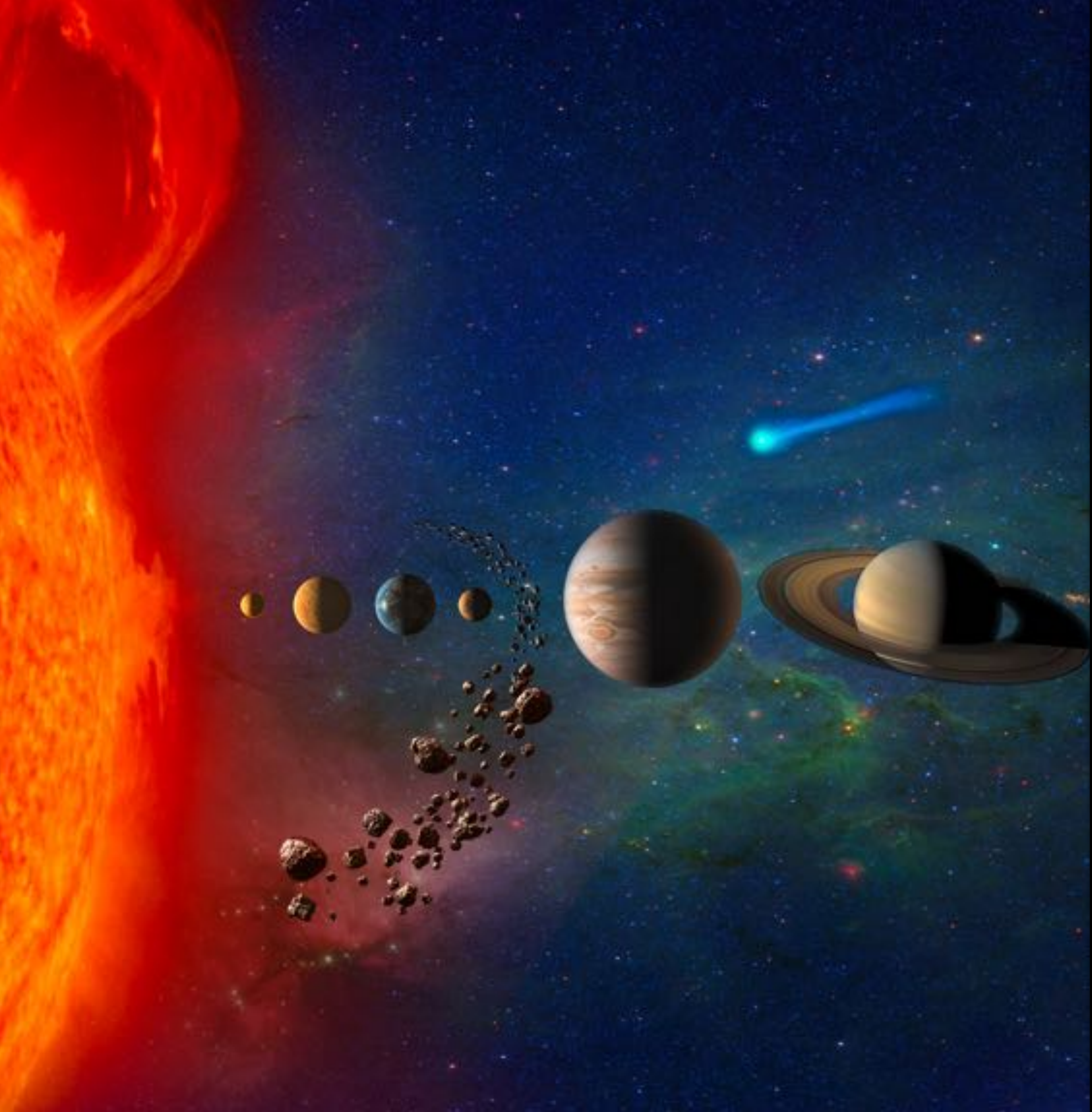


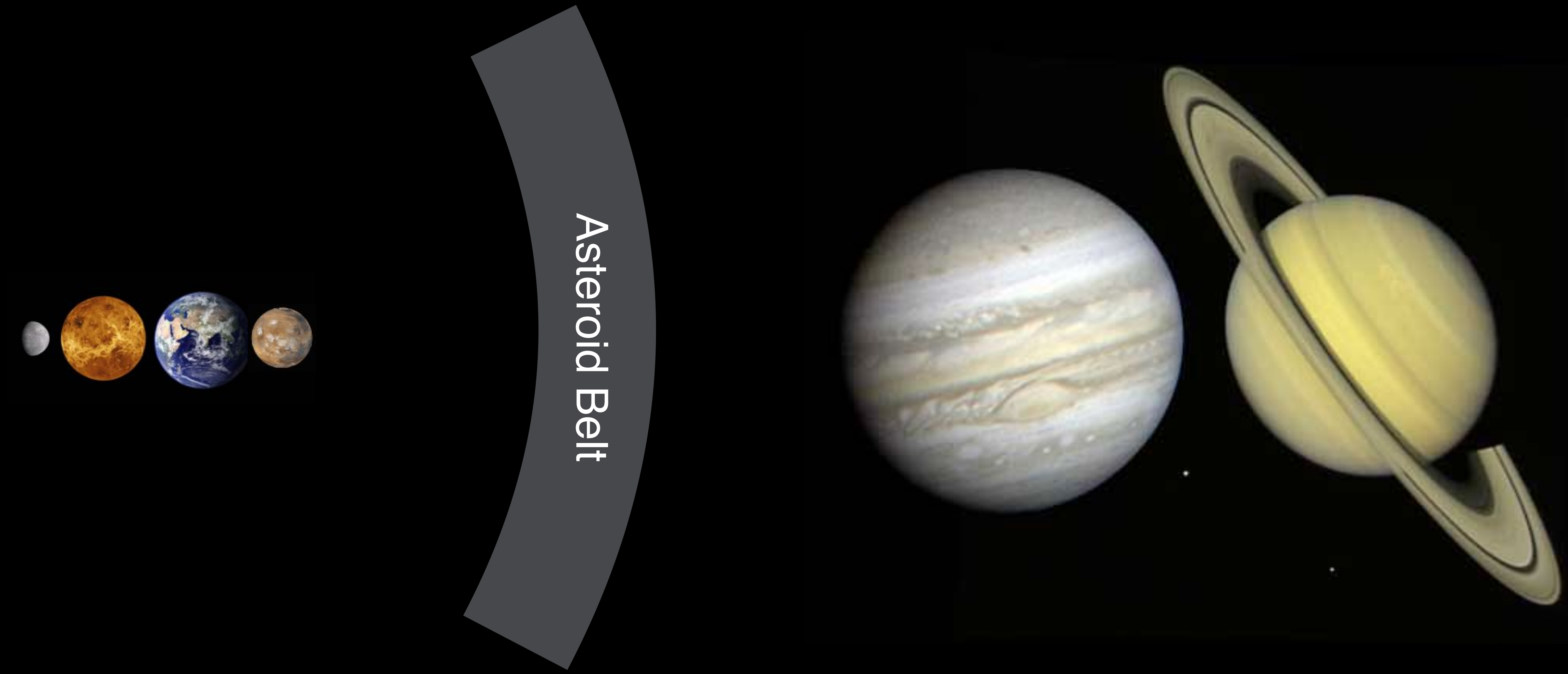


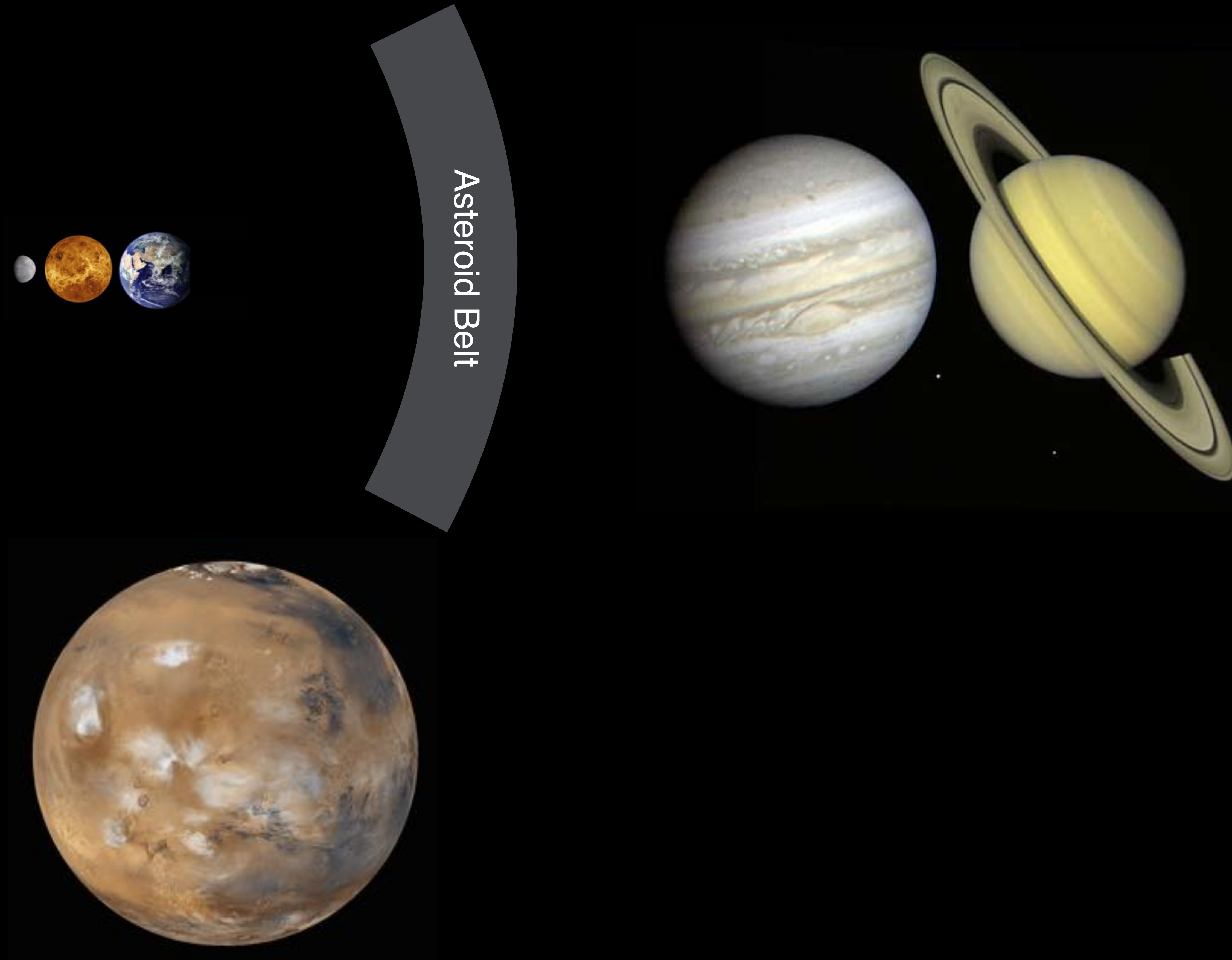
Late Stage of Planet Formation








Asteroid Belt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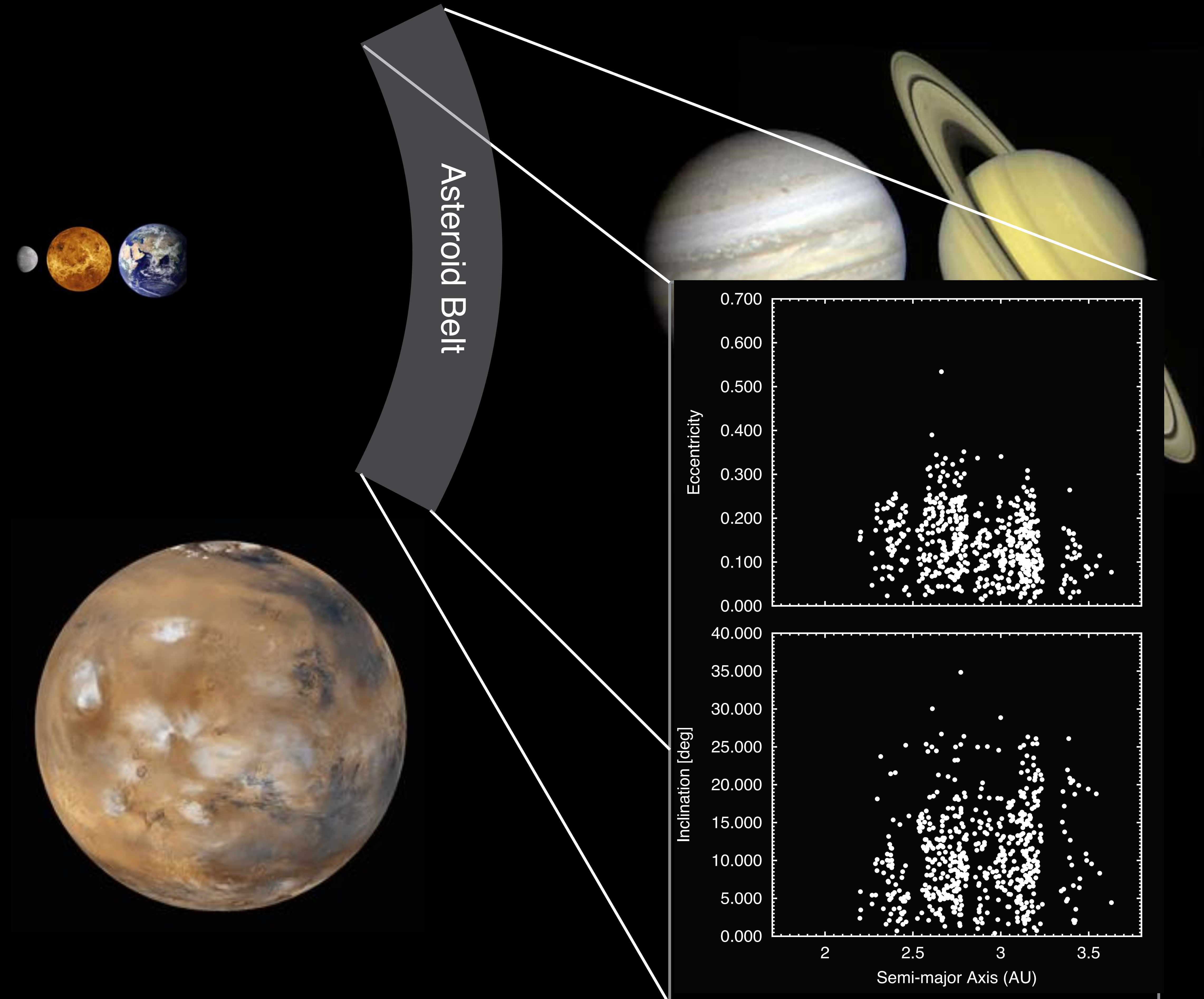
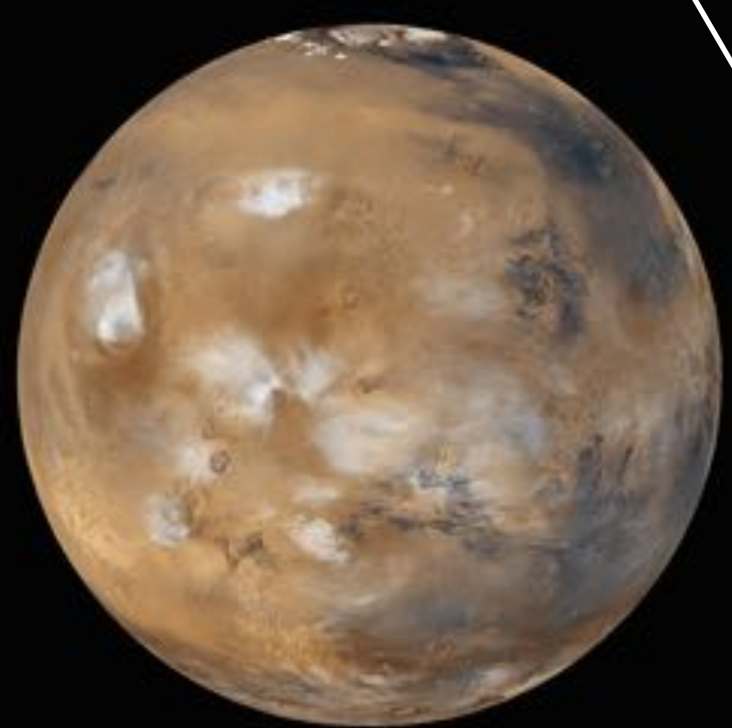
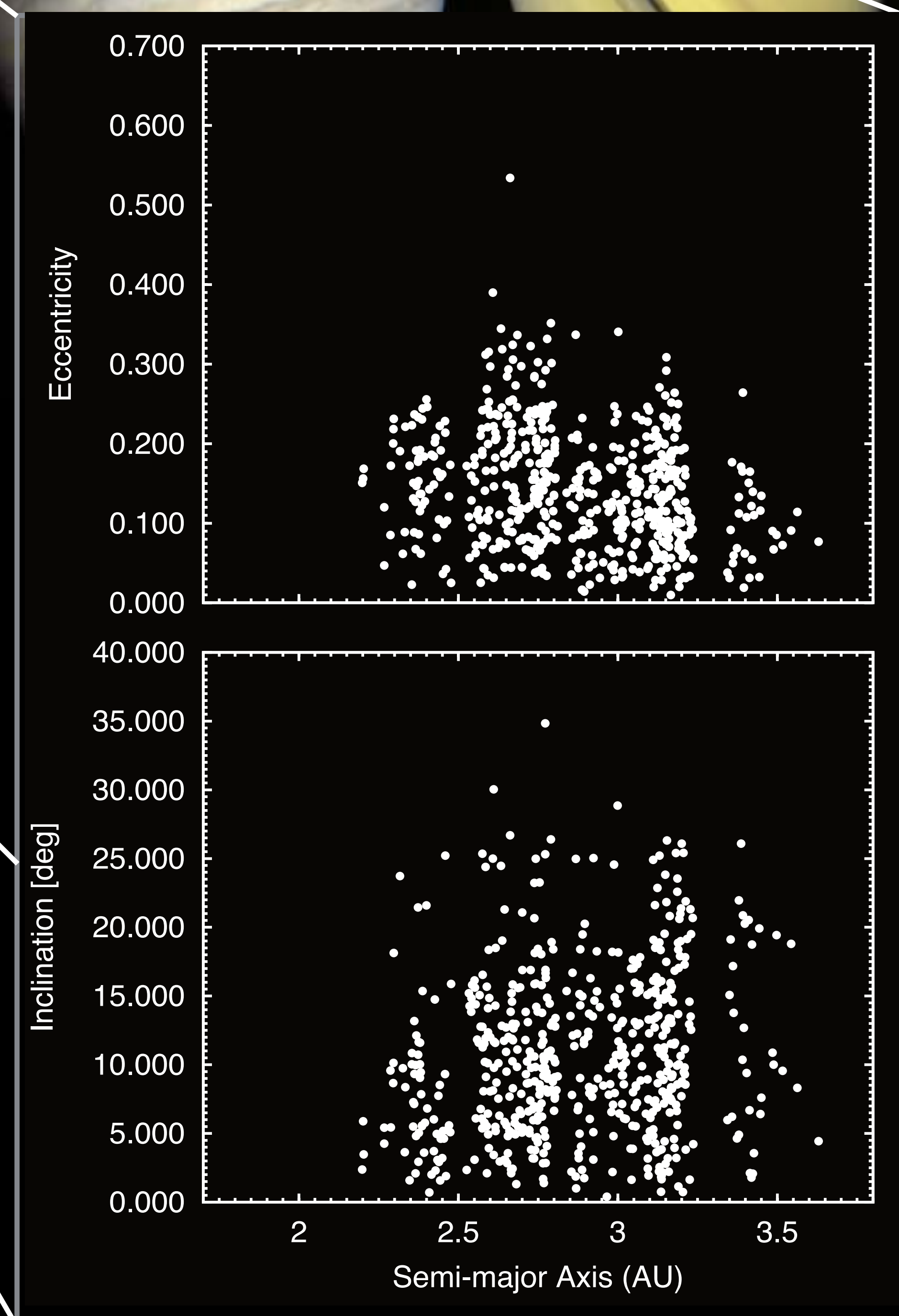


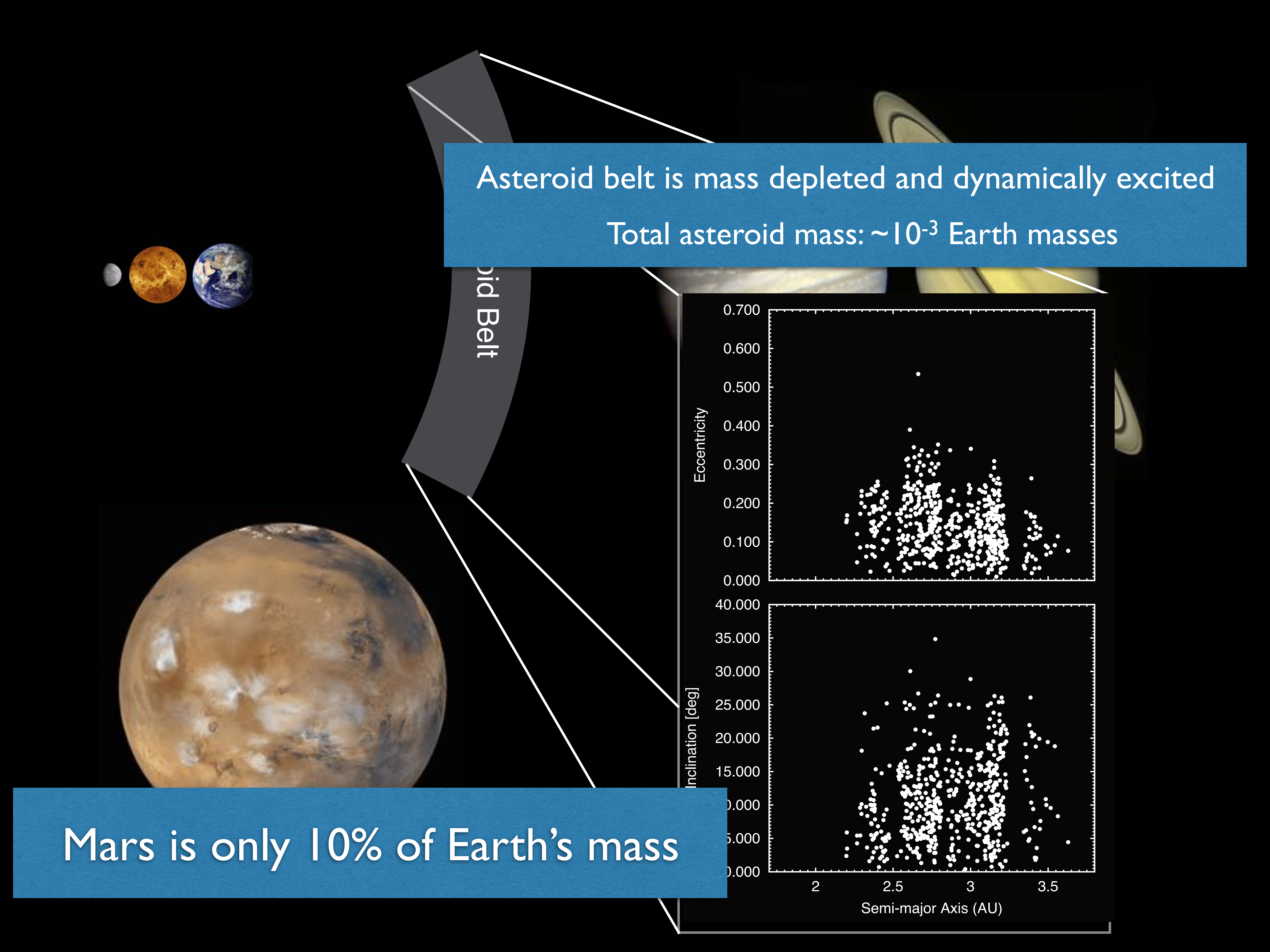
Asteroid Belt
Eccentricity
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Inclination [deg]
40.000
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0.000
2
2.5
3
3.5
Semi-major Axis (AU)

Asteroid belt is mass depleted and dynamically excited

Total asteroid mass: ~10^{-3} Earth masses



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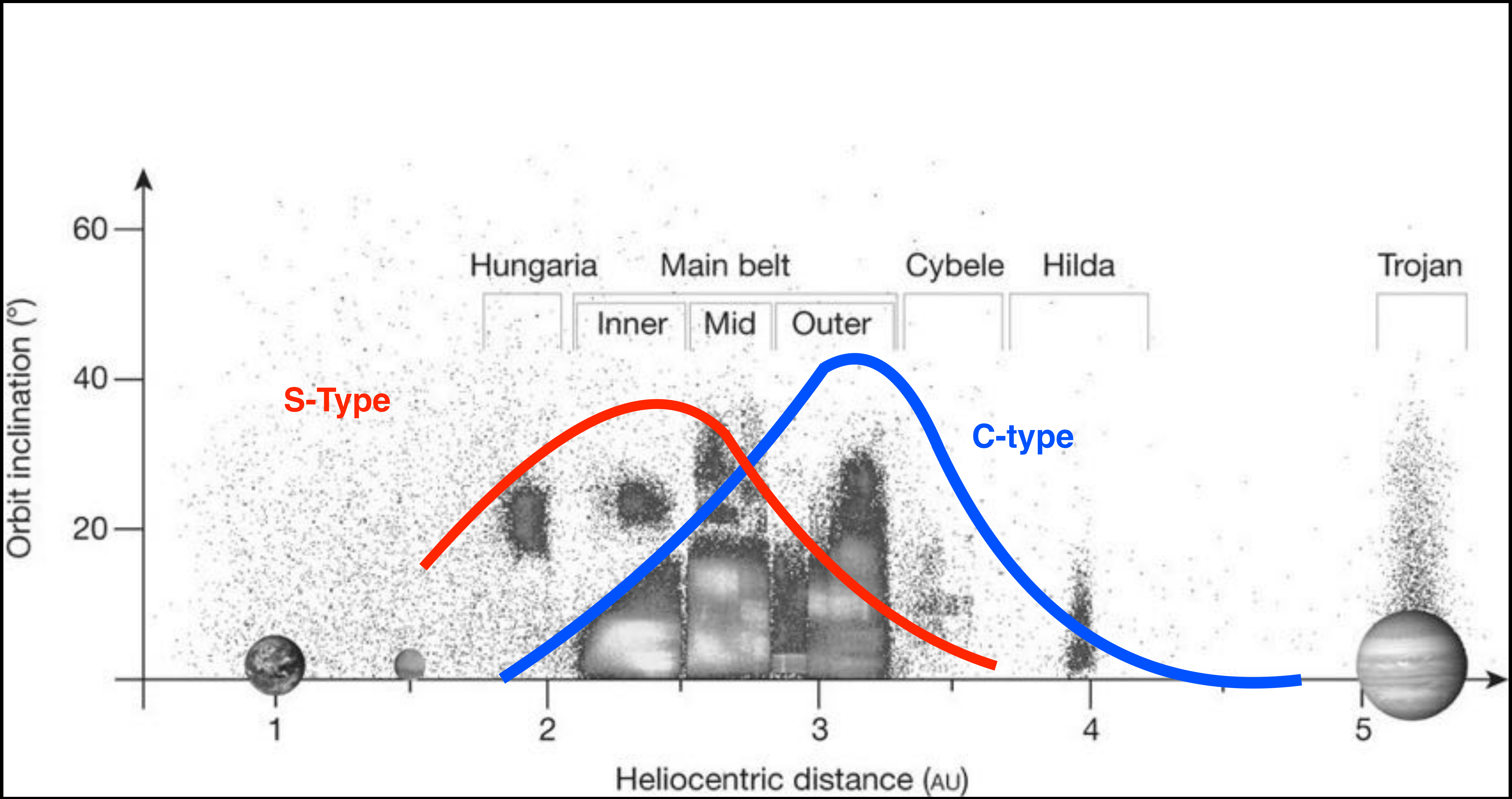
40.000
35.000
30.000
25.000
20.000
15.000
2
2.5
3
3.5
Semi-major Axis (AU)
Mars is only 10% of Earth's mass

The asteroid belt composition

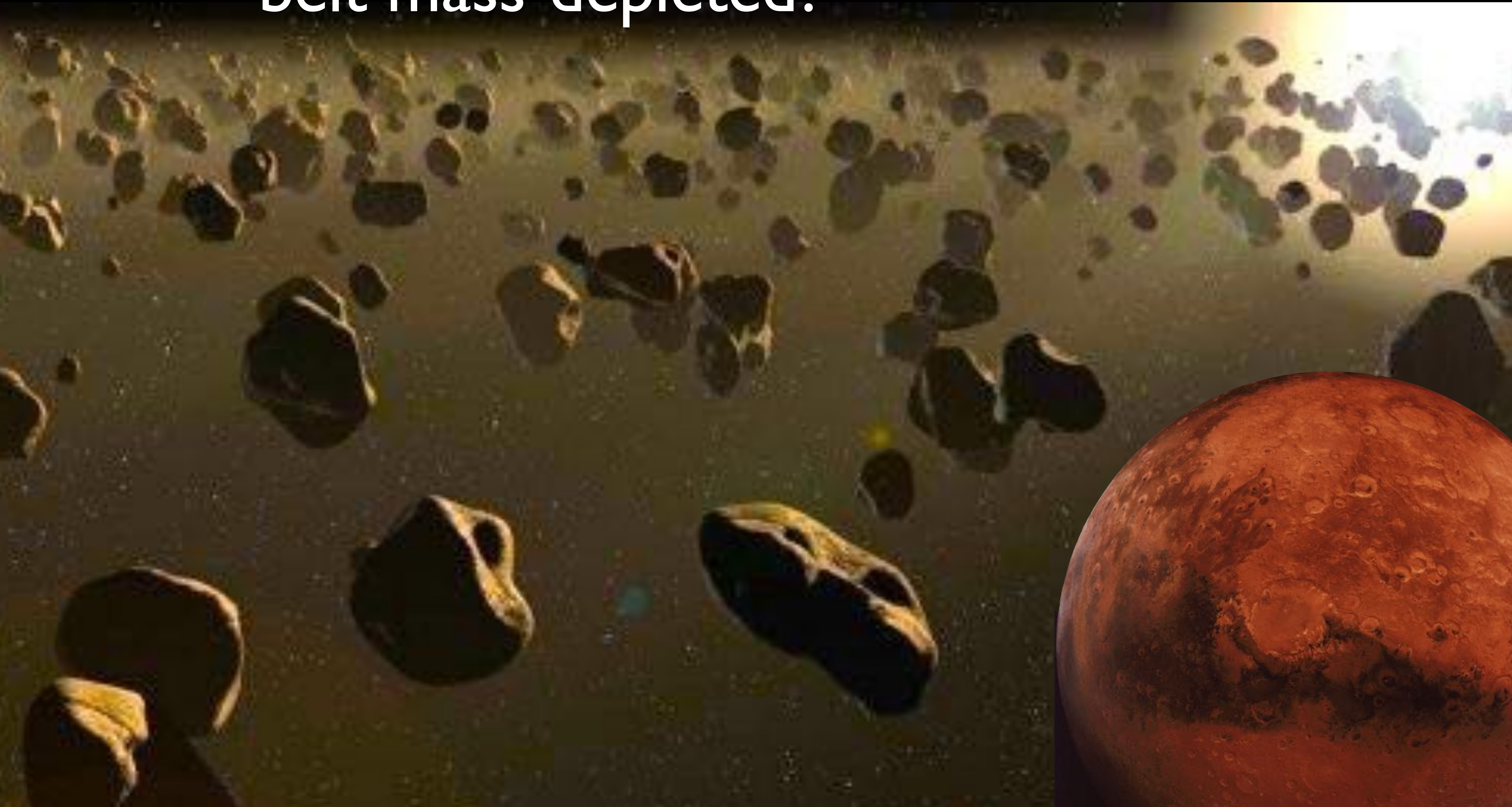


Inner Solar System Constraints

- Masses, orbits of terrestrial planets
  - Low mass of Mars
  - Almost circular and coplanar orbits
- Structure of asteroid belt
  - Mass depleted
  - Dynamically excited
  - Mix of S and C-type objects
- Water delivery to Earth

Stronger Constraints

Why is Mars so small? And why are the asteroids' orbits excited and the belt mass-depleted?

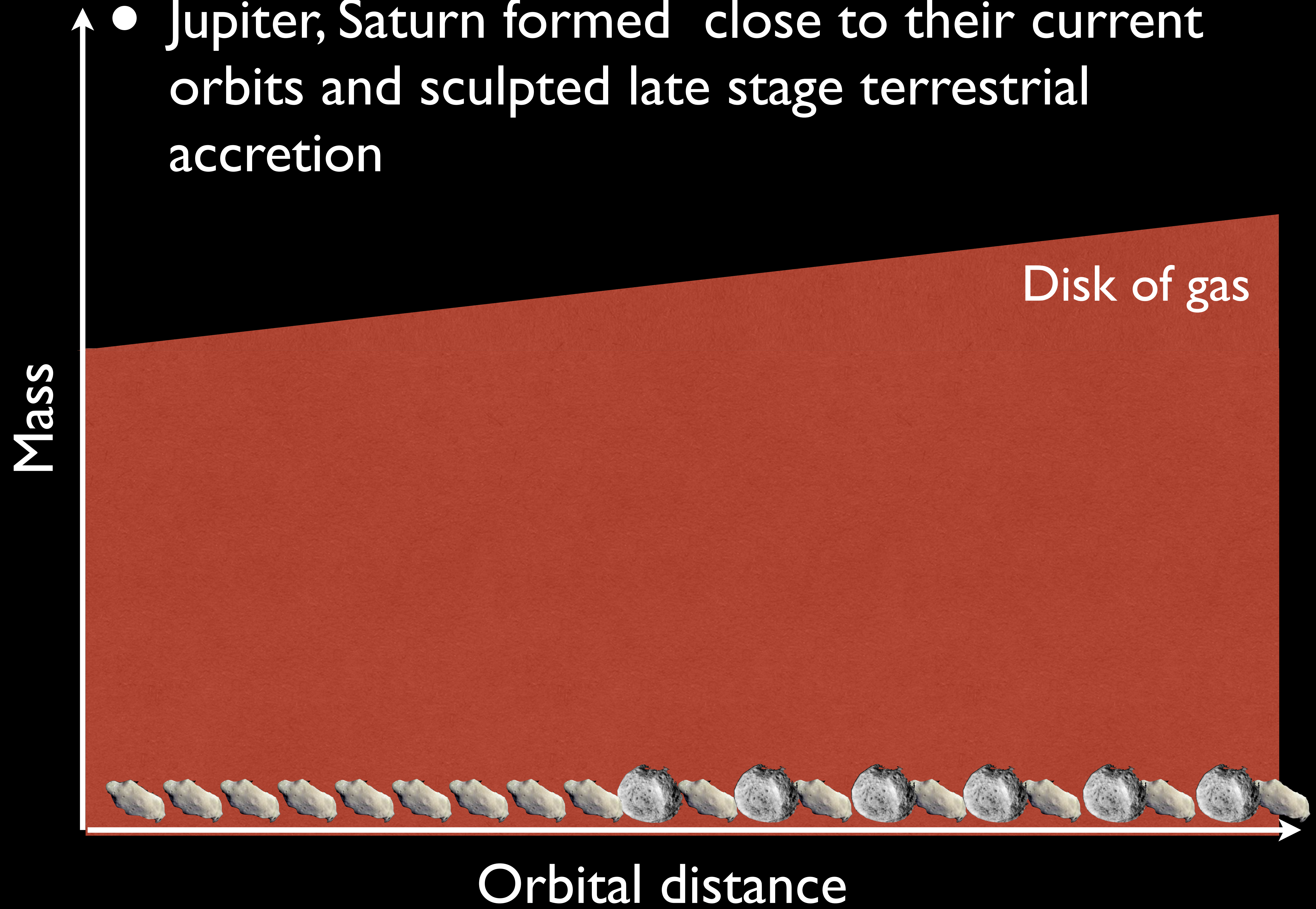


Key ingredients to build the inner solar system

- Rocky-mass distribution in the terrestrial region
- Giant planets' orbits

The classical scenario of terrestrial planet formation

- Jupiter, Saturn formed close to their current orbits and sculpted late stage terrestrial accretion



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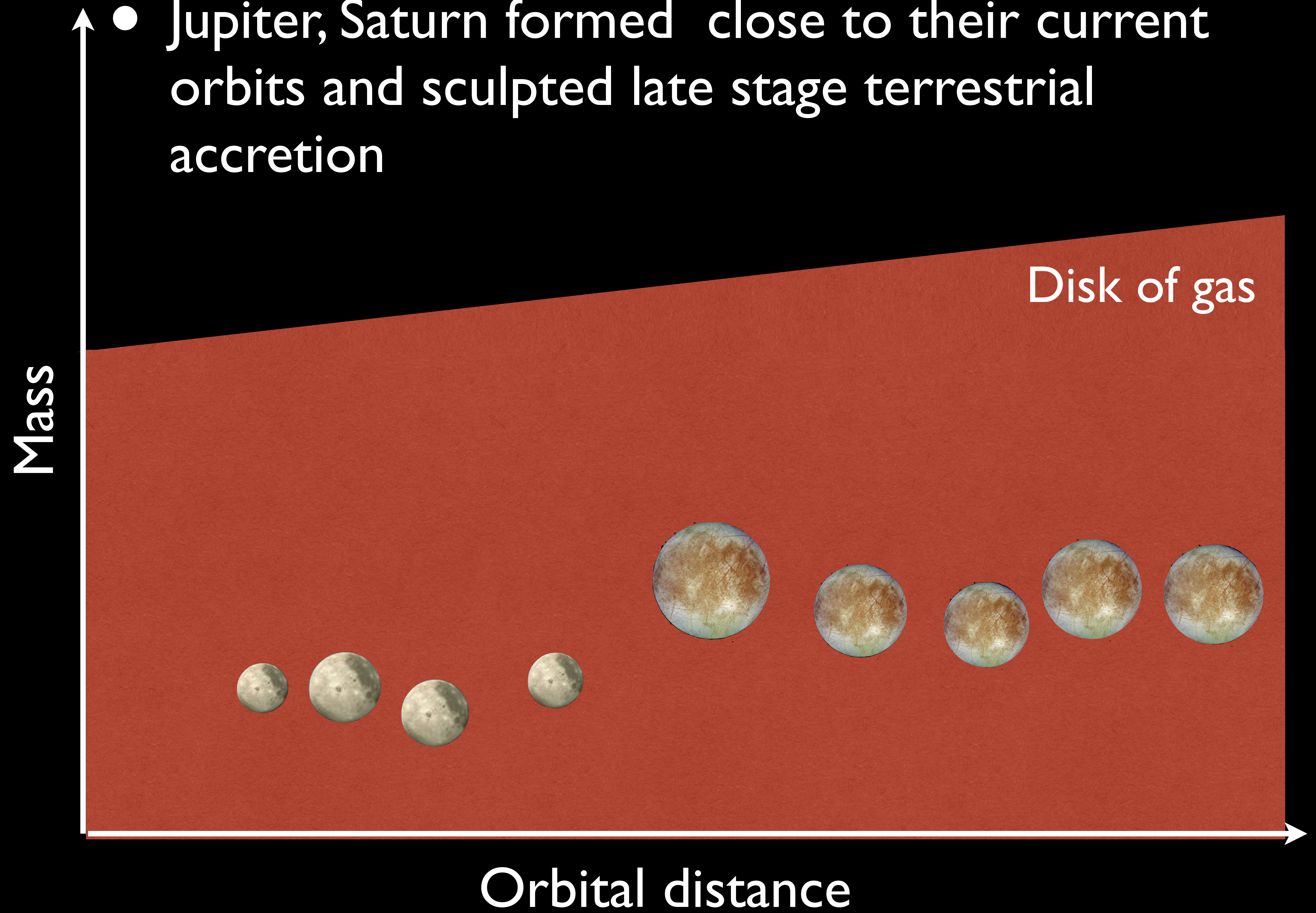

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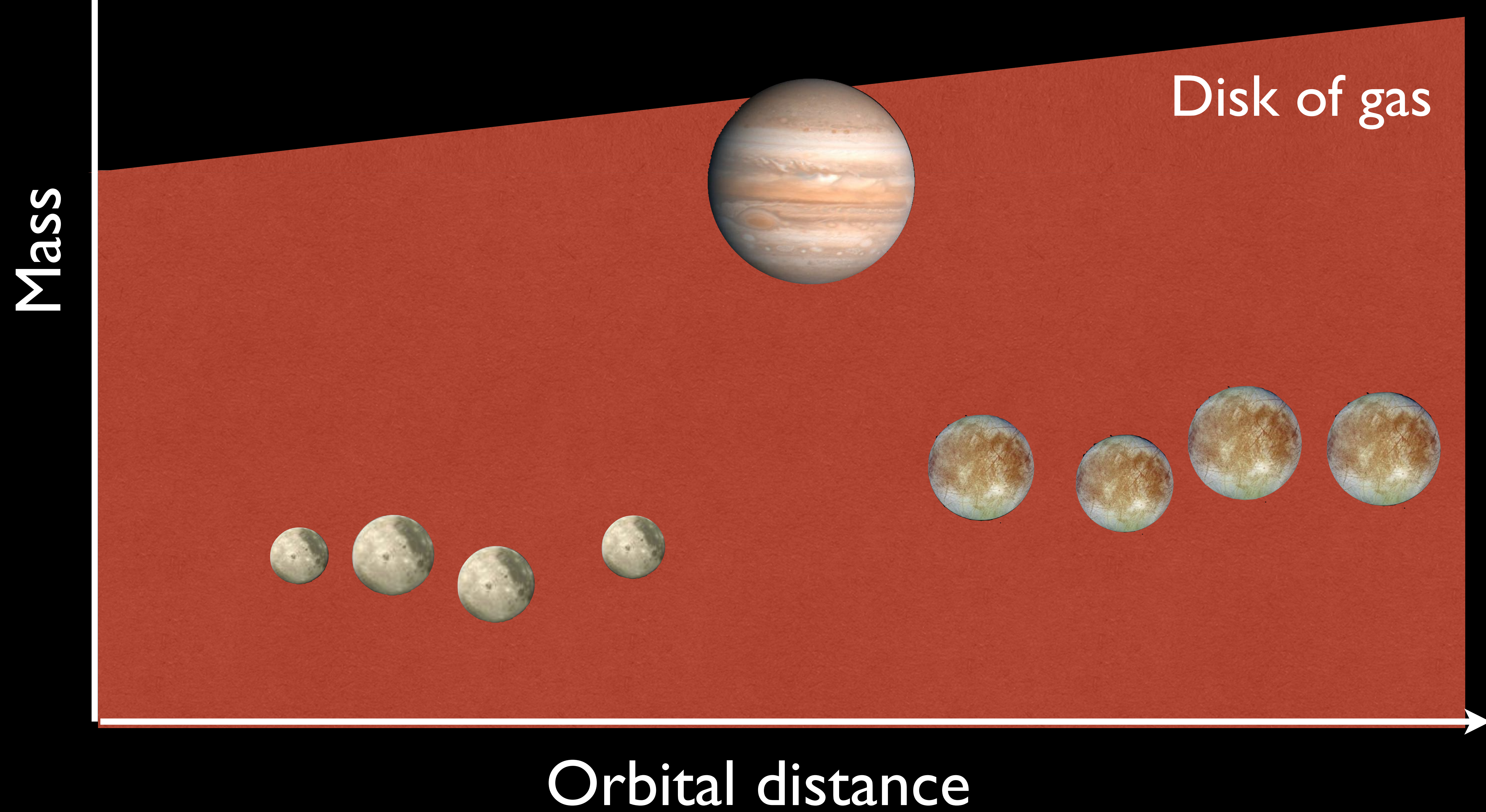

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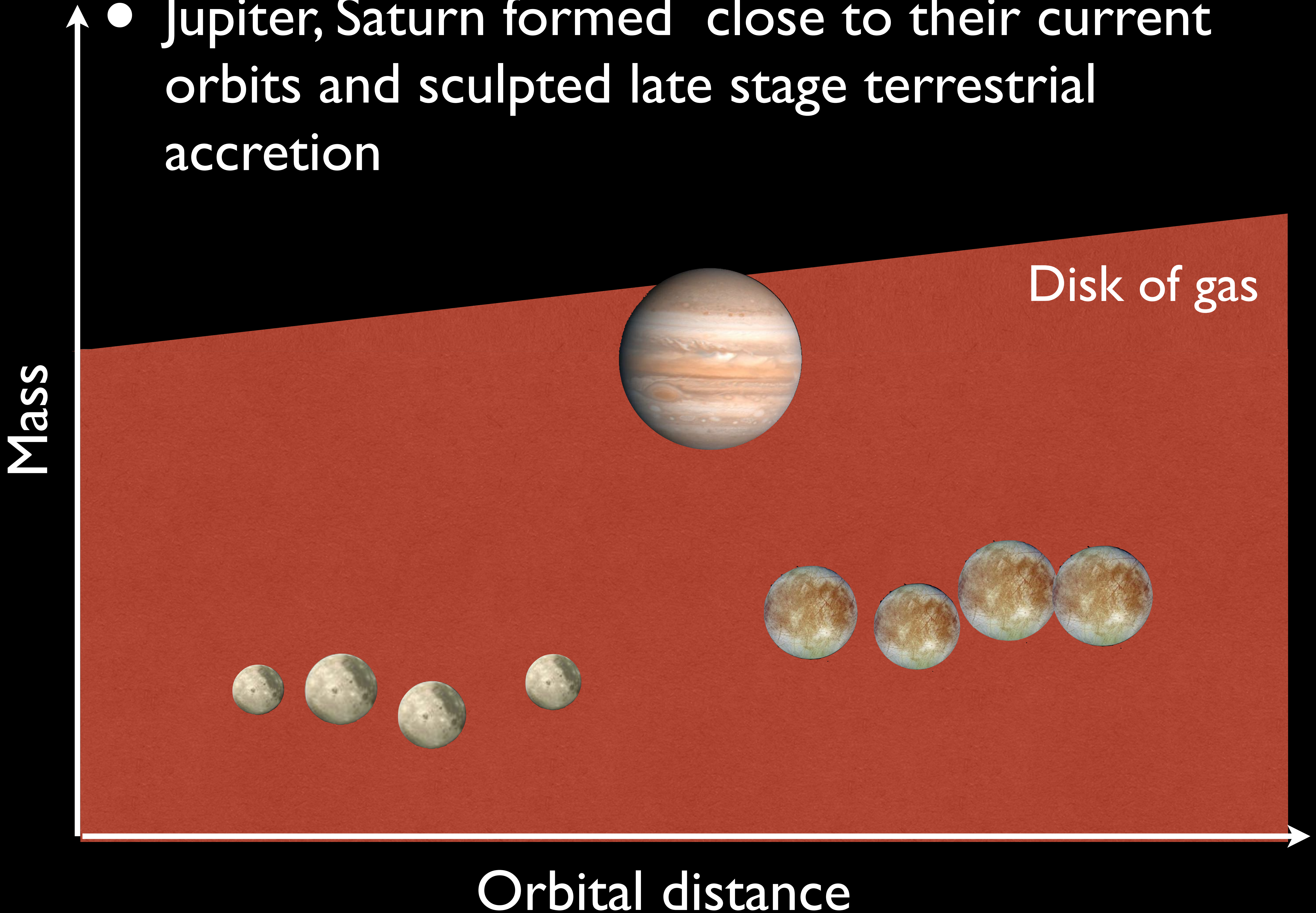

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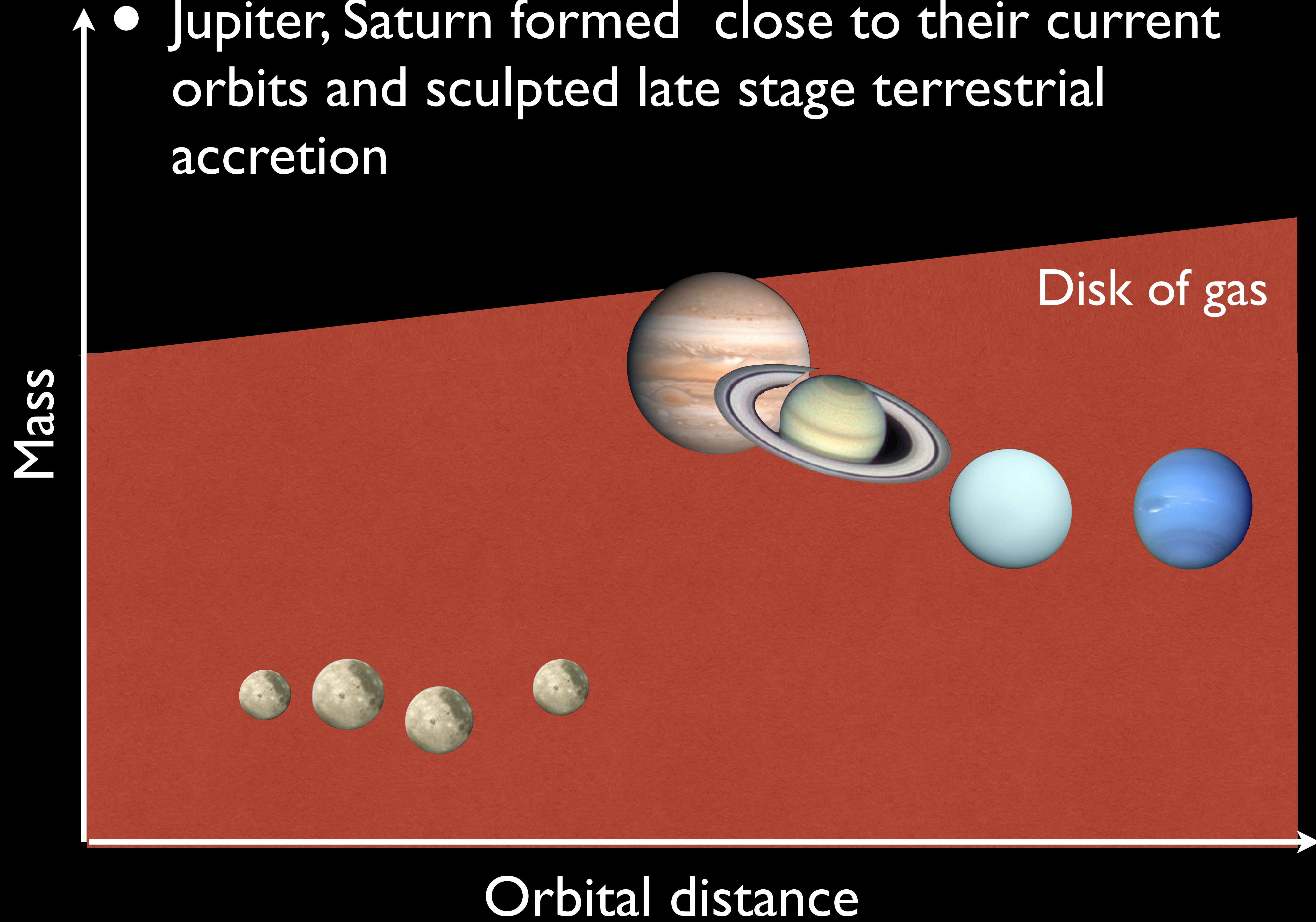

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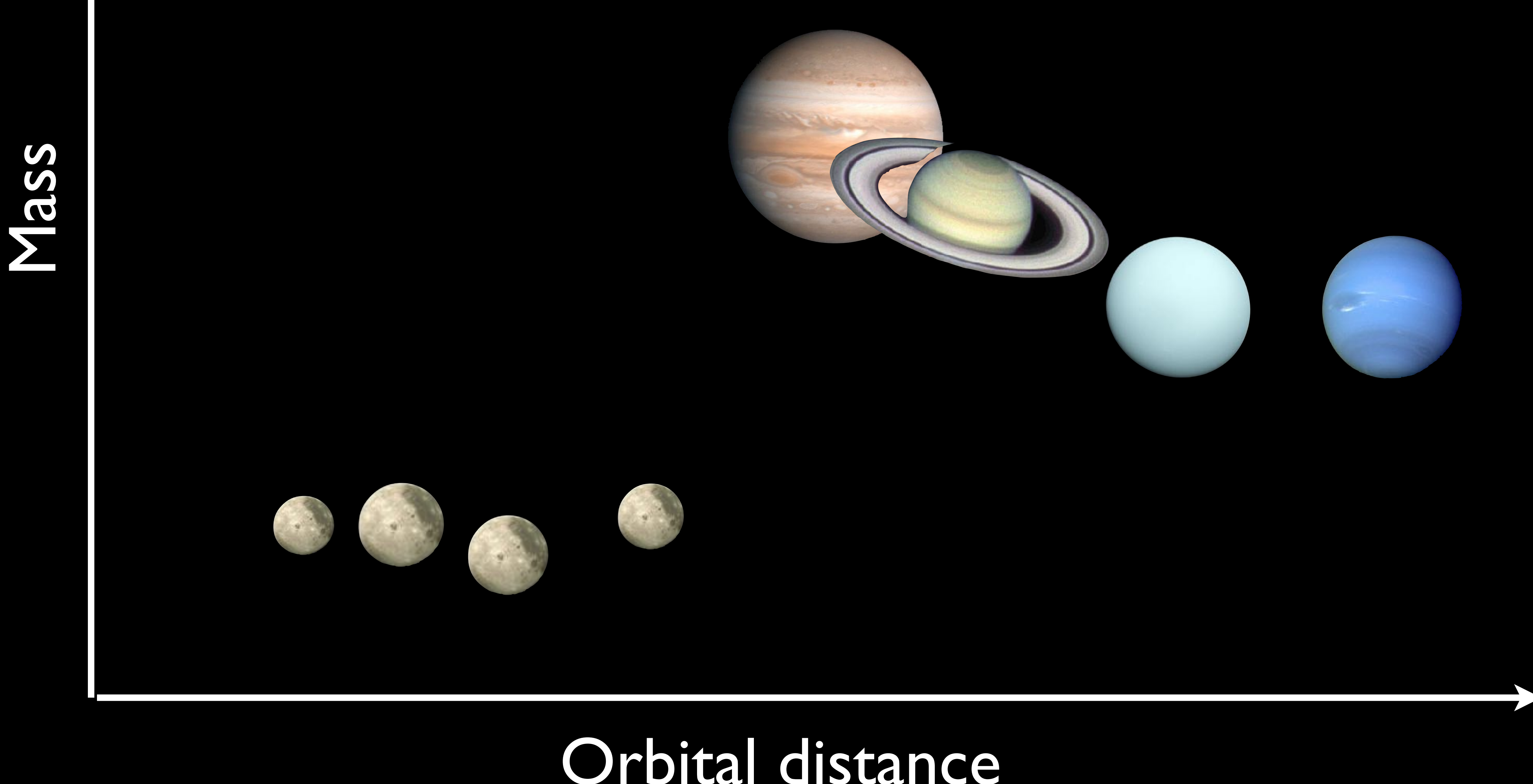

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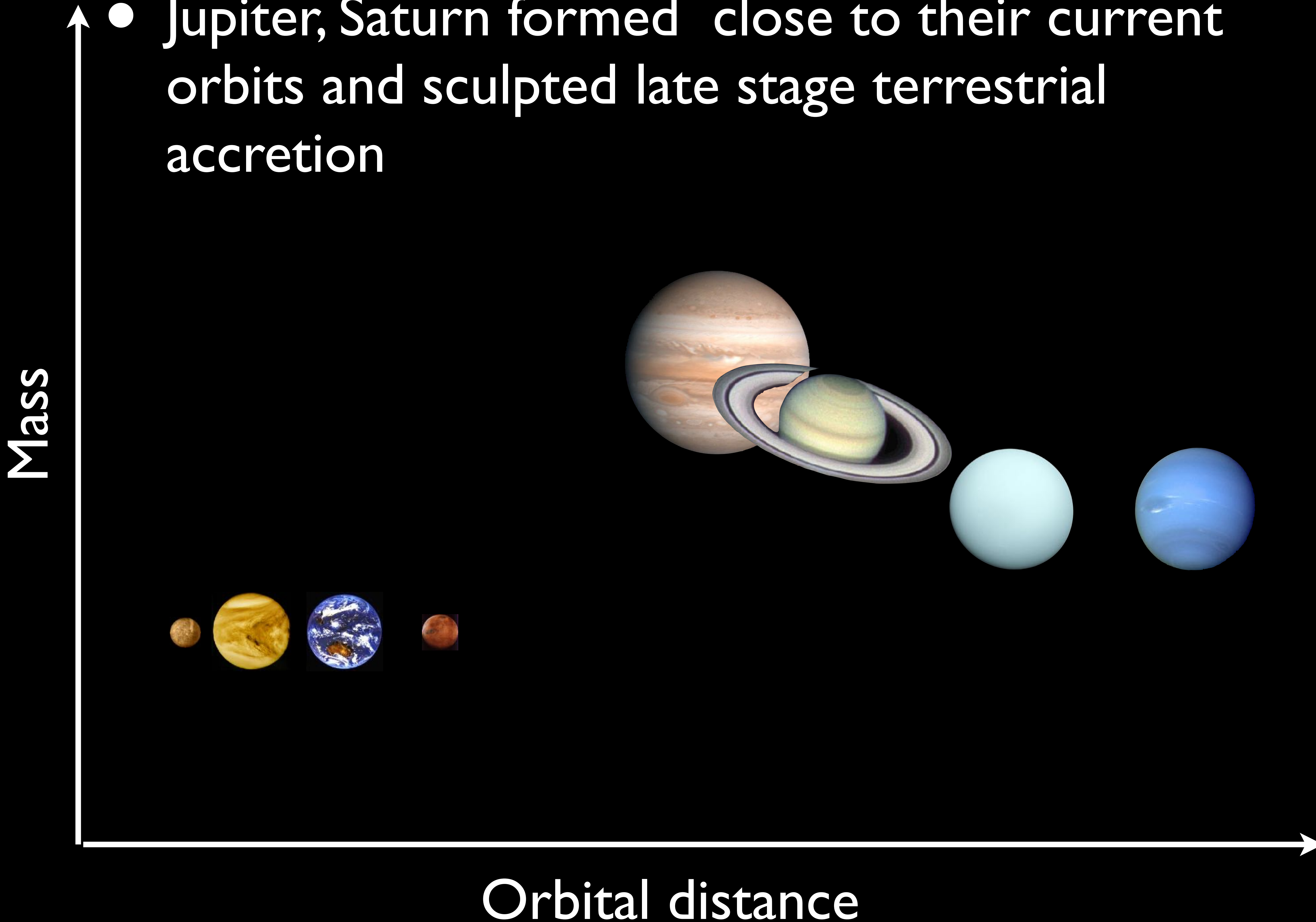
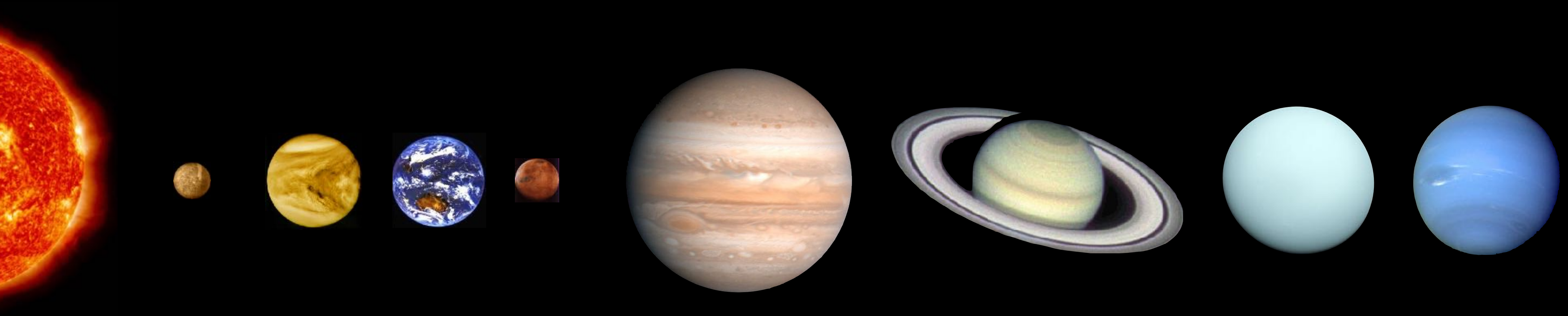
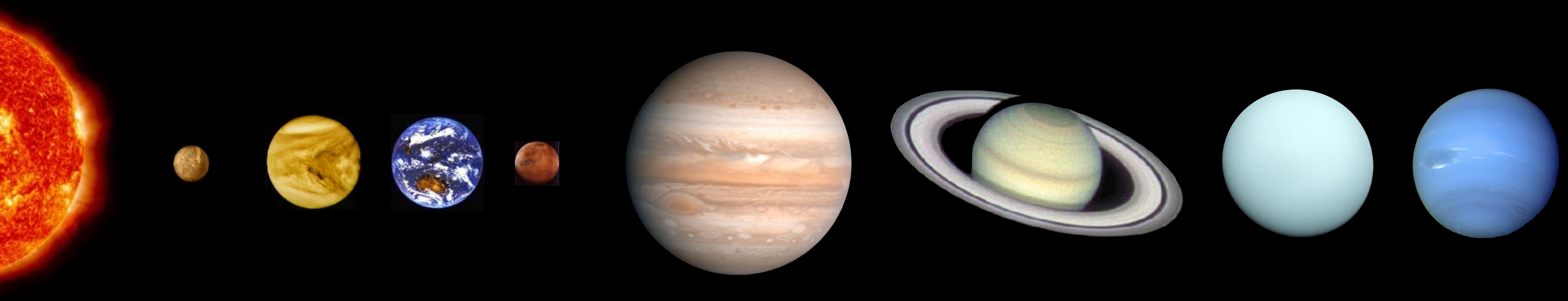
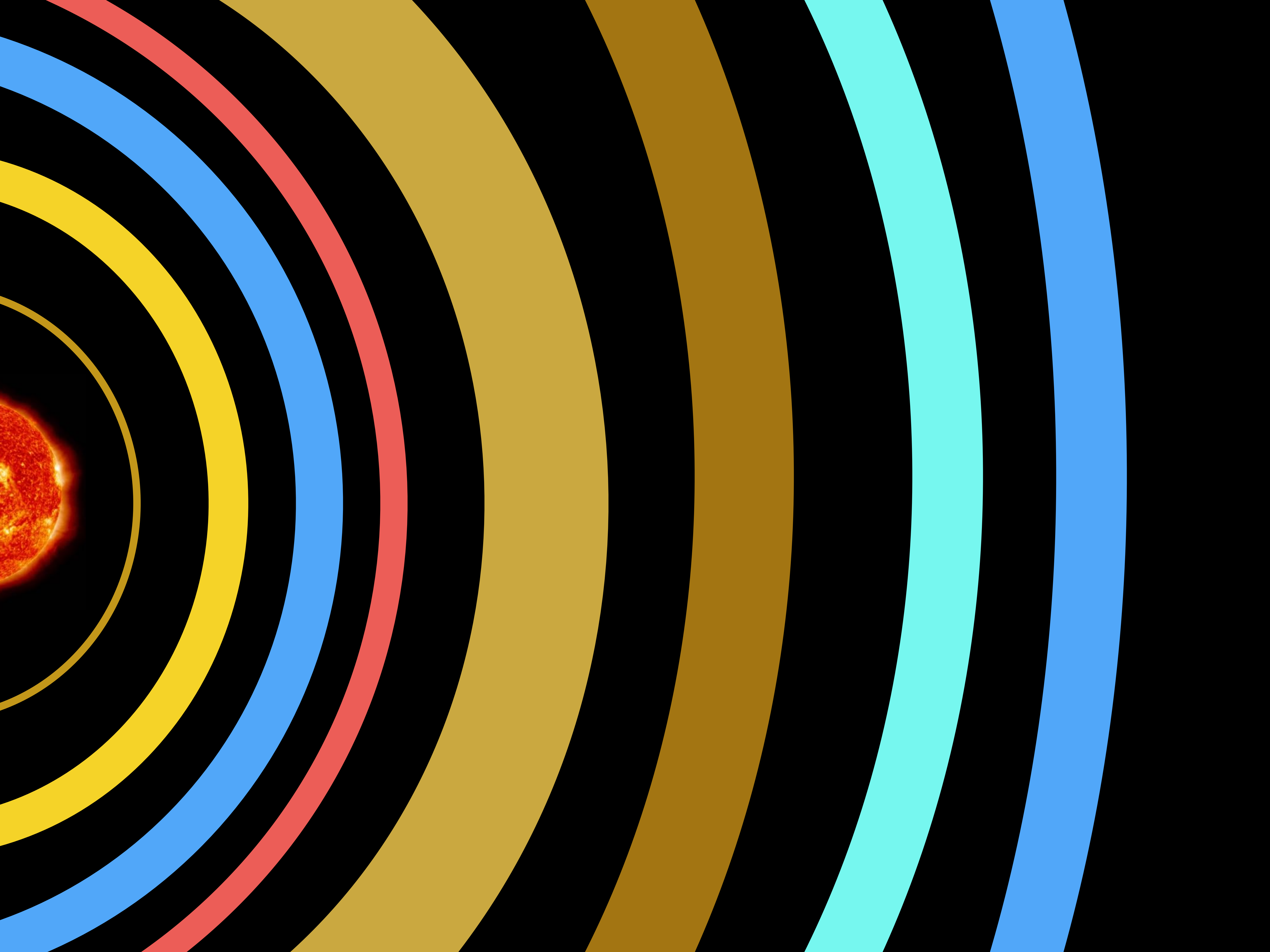


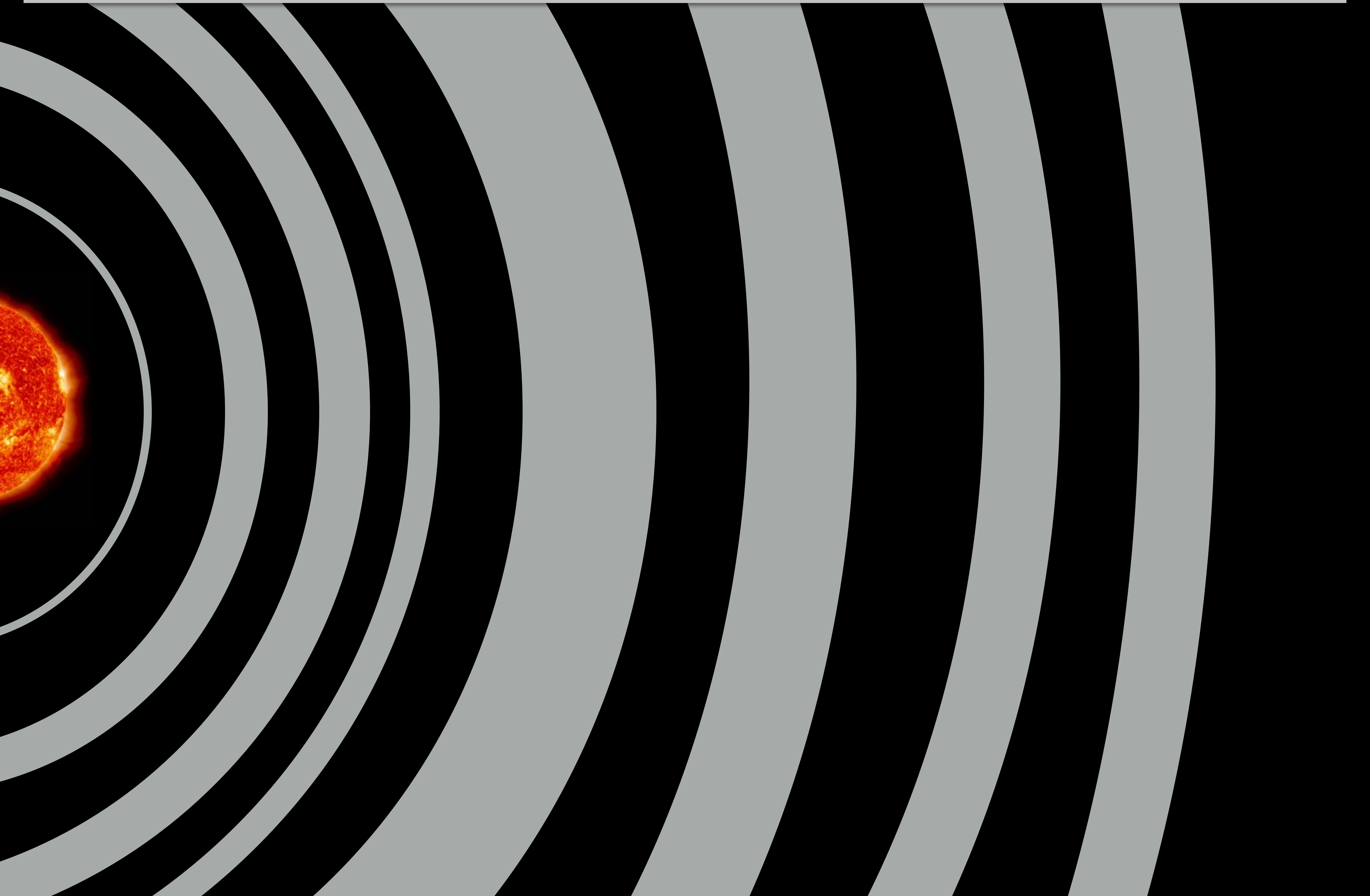
- The rocky-mass distribution in the classical model is based on the minimum mass solar nebula and disk dust observations (Weidenschilling, 1977; Hayashi et al 1981)







Replenish the planet’s (observed) composition until they reflect solar abundance.



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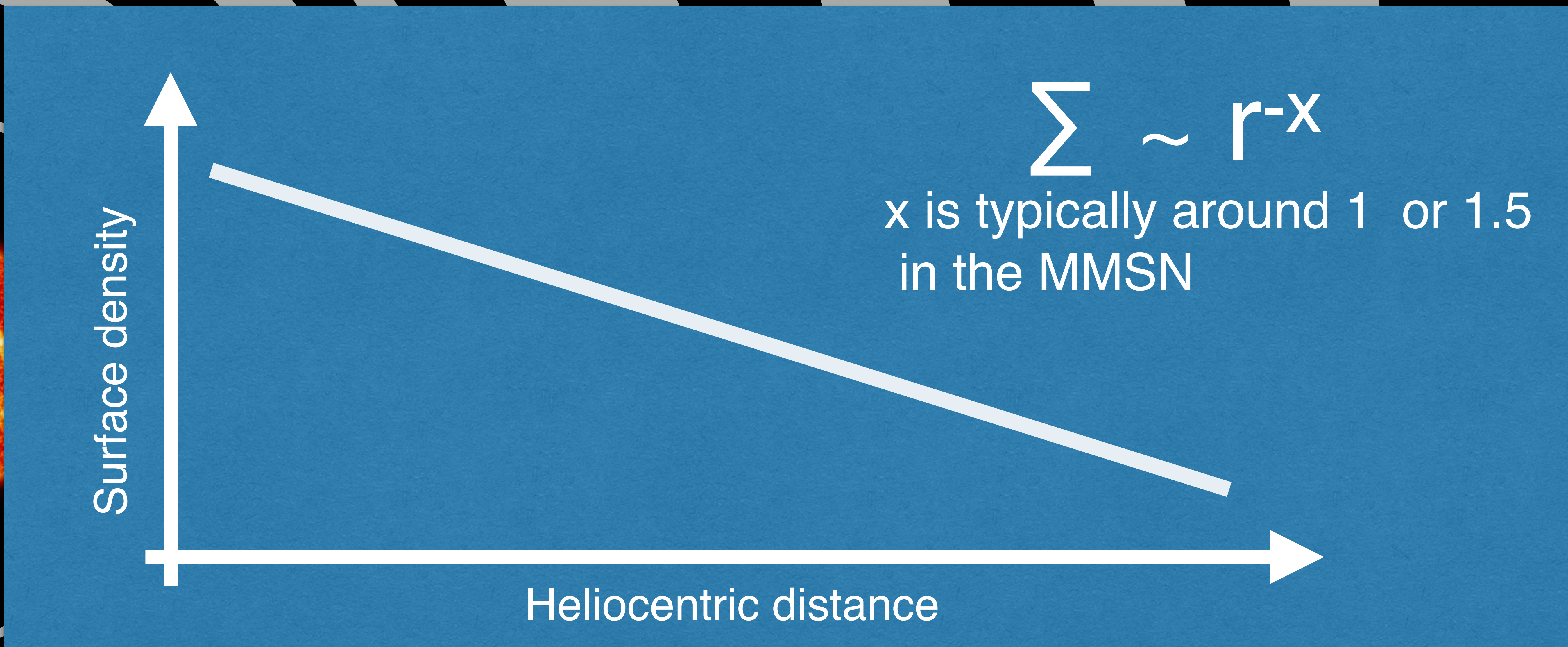
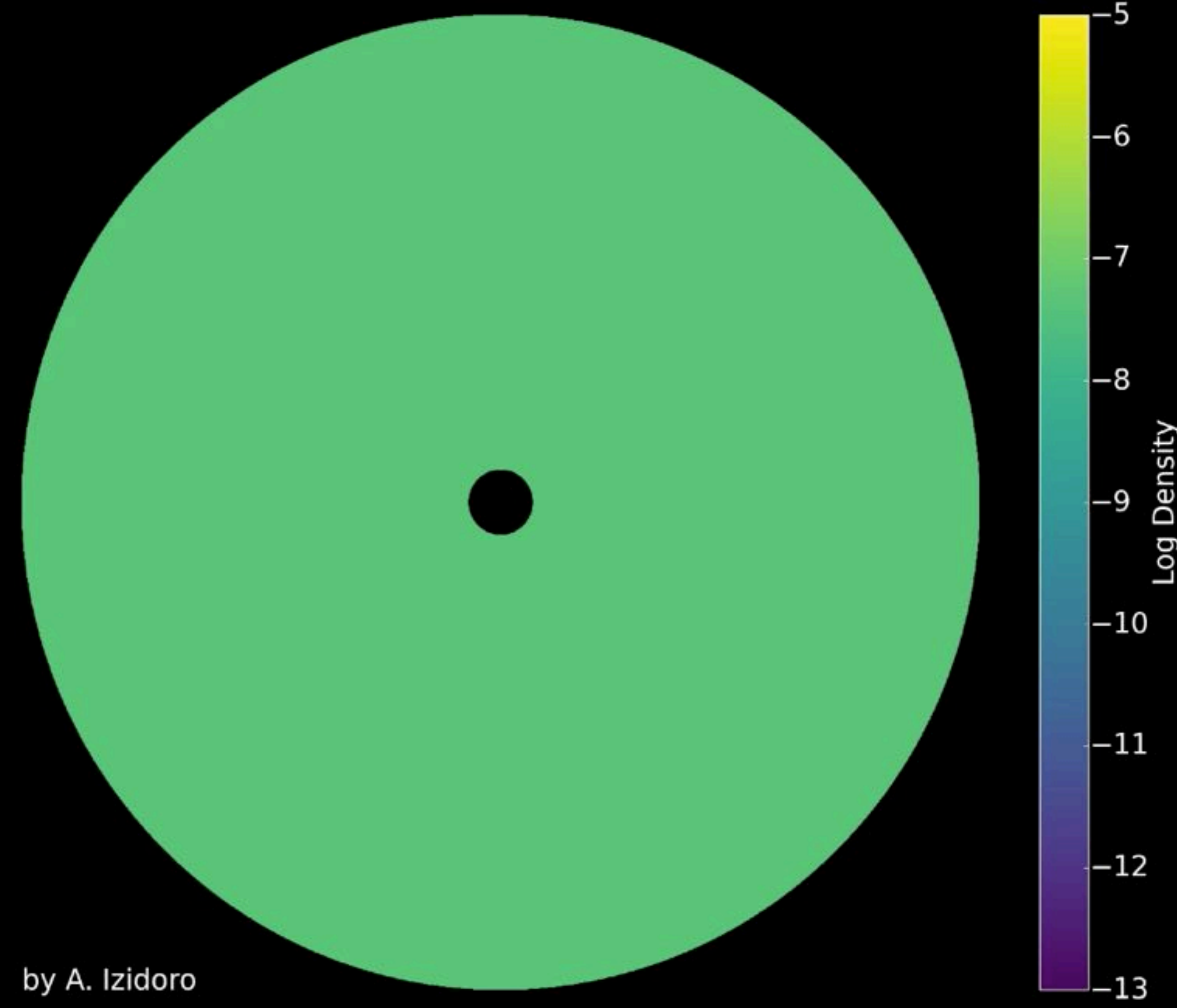


Giant Planet Orbits



Jupiter and Saturn gas disk phase evolution
(typically capture in 3:2 or 2:1 MMR)

e.g. Pierens et al. 2014

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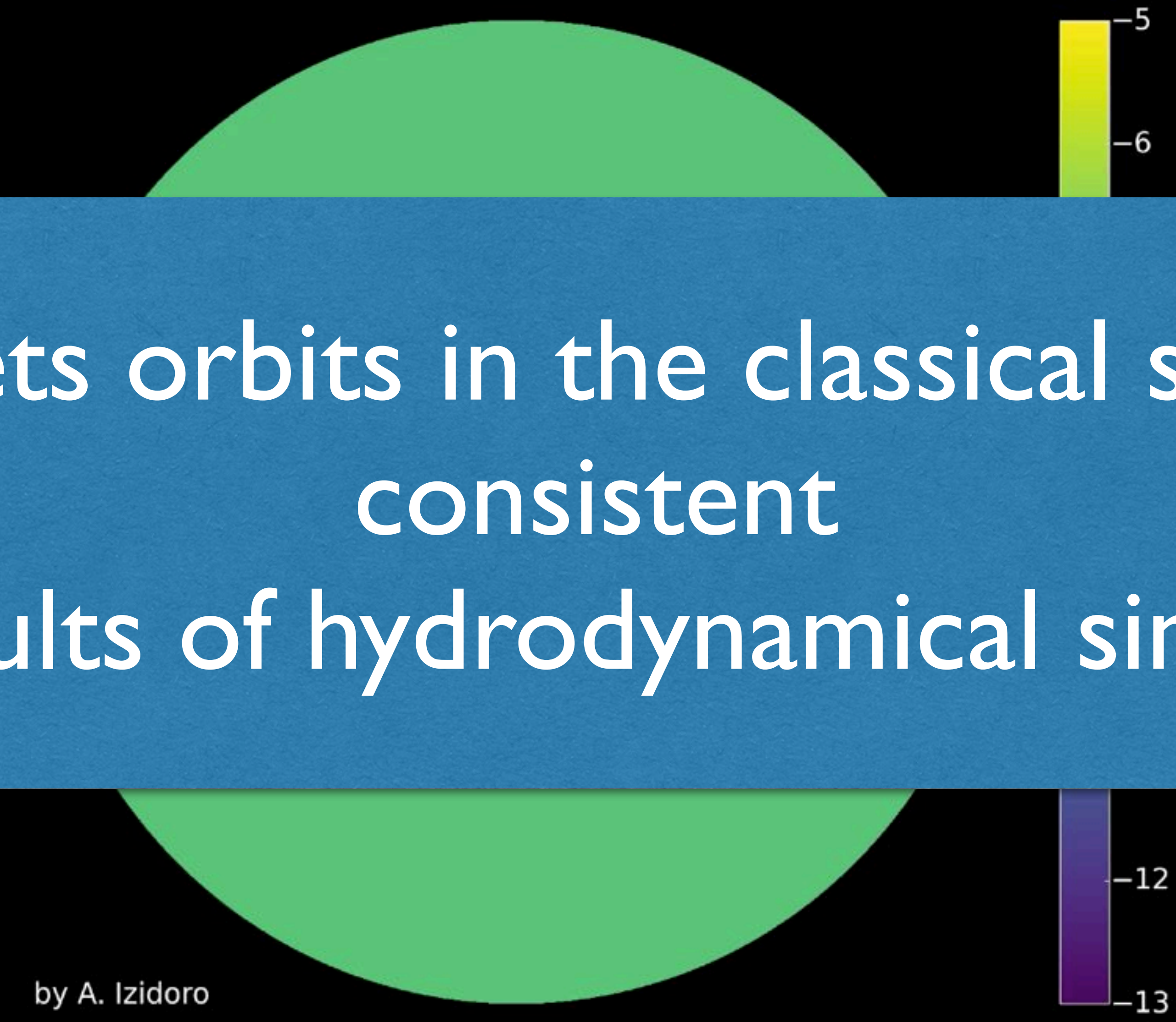

Giant planets orbits in the classical scenario are consistent
with results of hydrodynamical simulations

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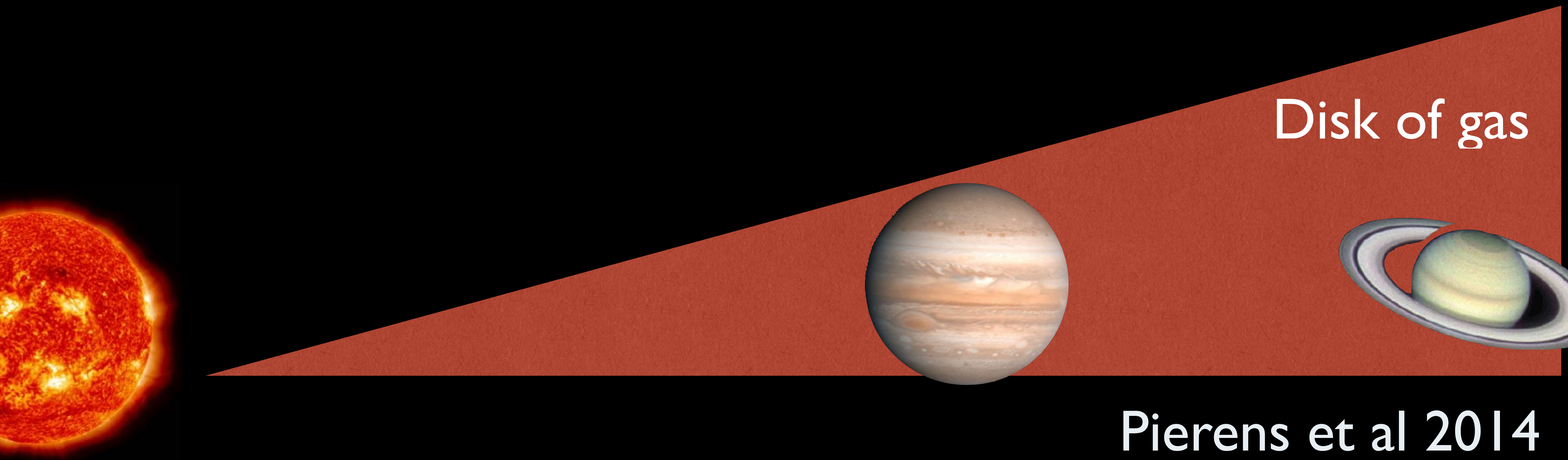
Jup. & Sat. migration during the disk-phase



Pierens et al 2014

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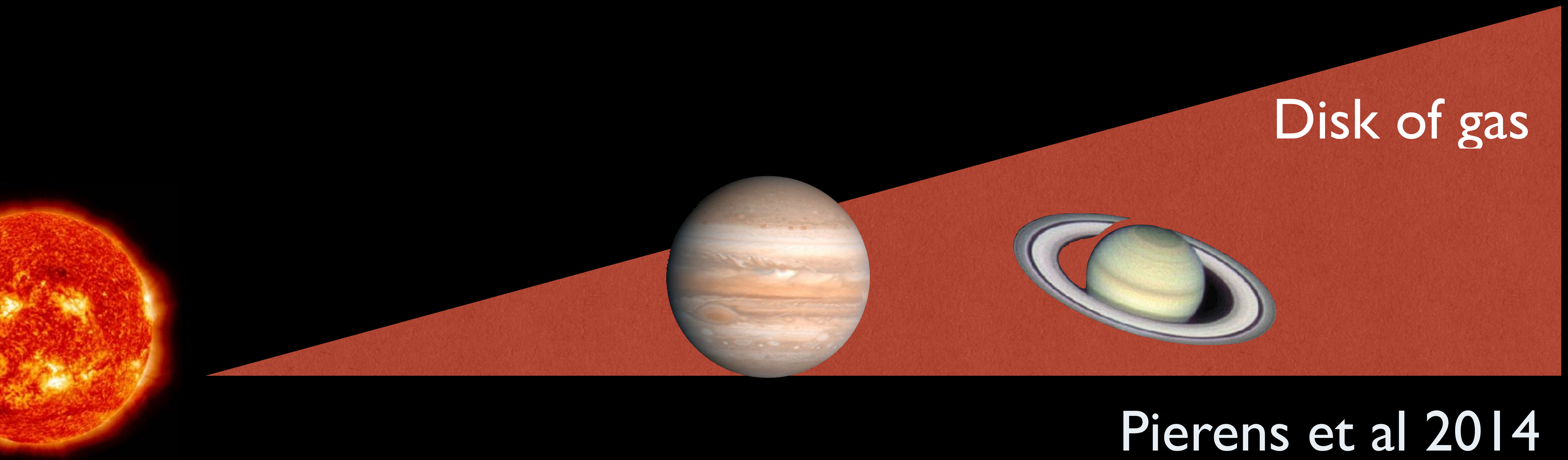

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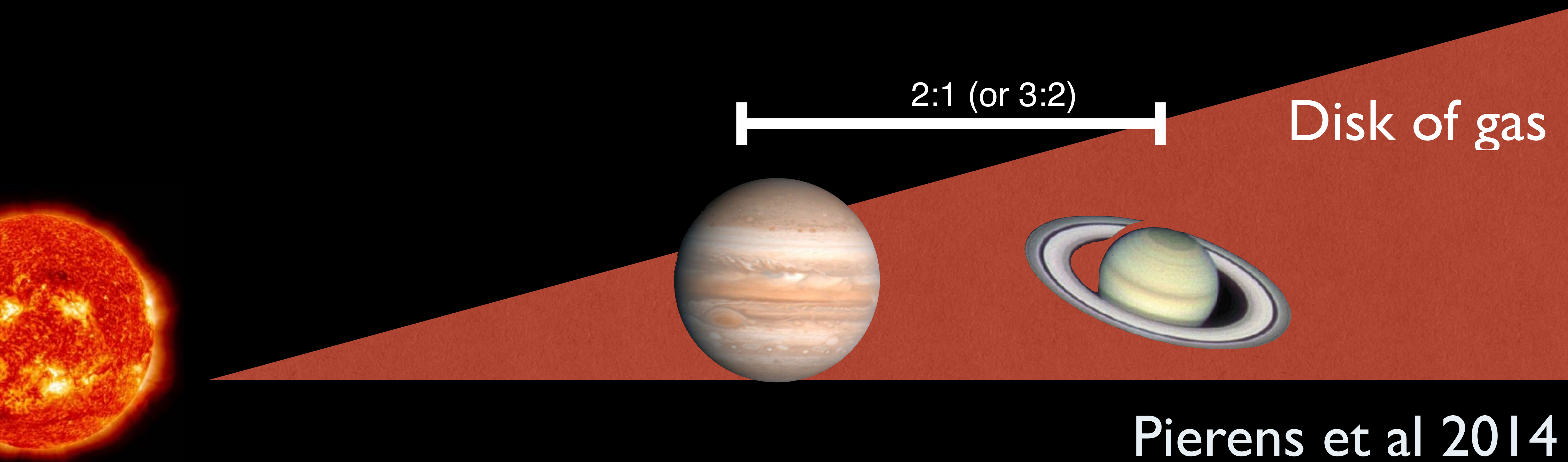

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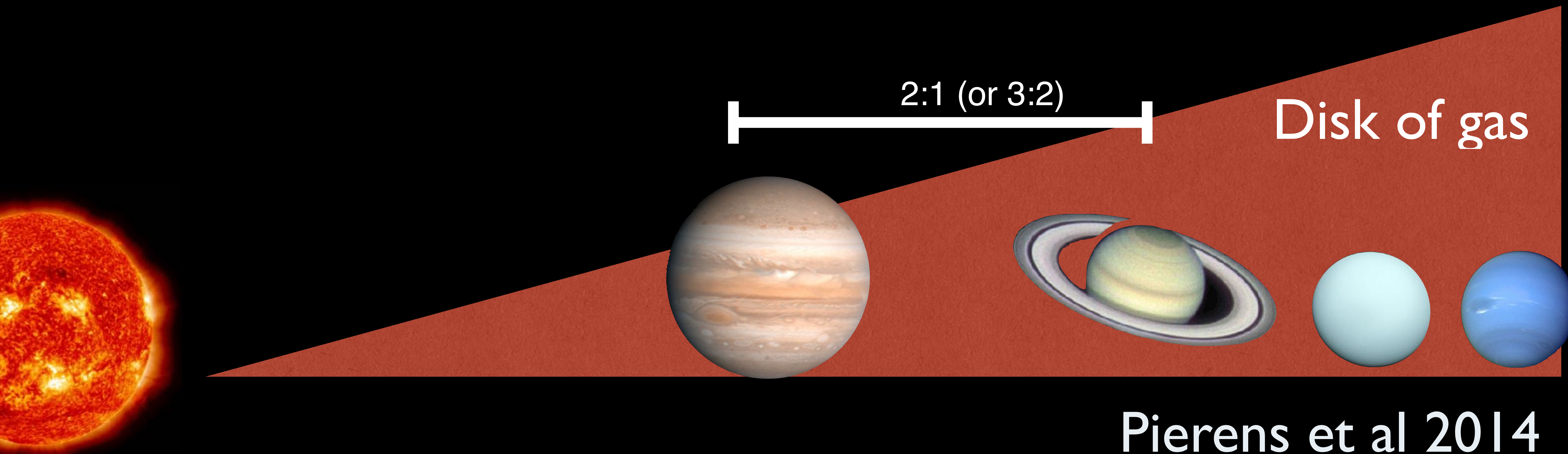

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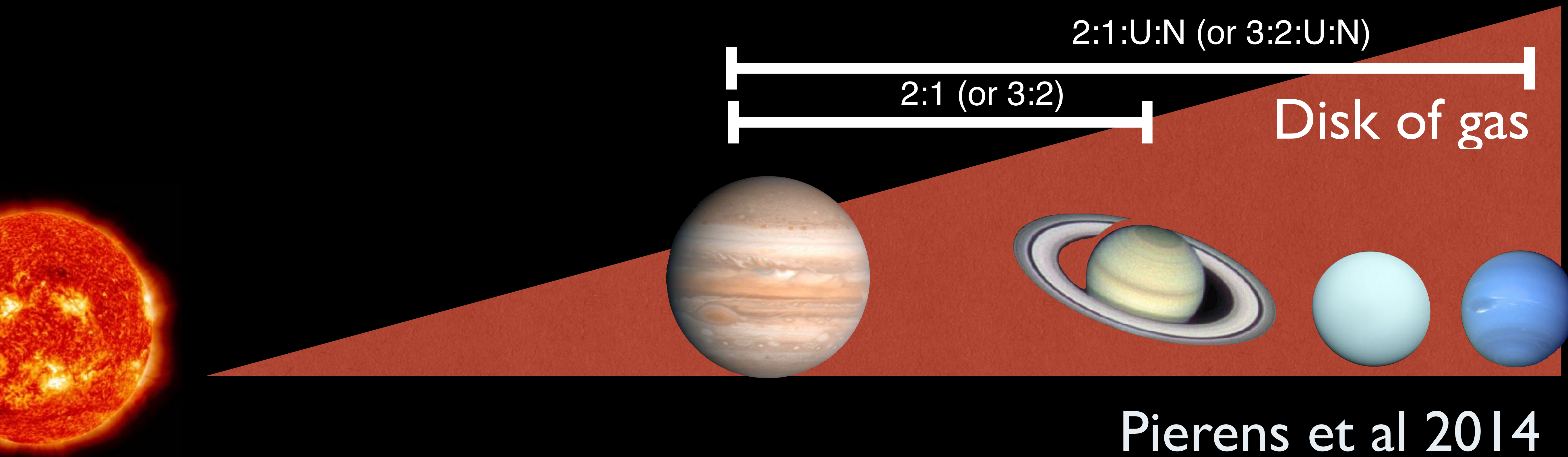

Pierens et al 2014

How did Jupiter and Saturn reach their current orbits?

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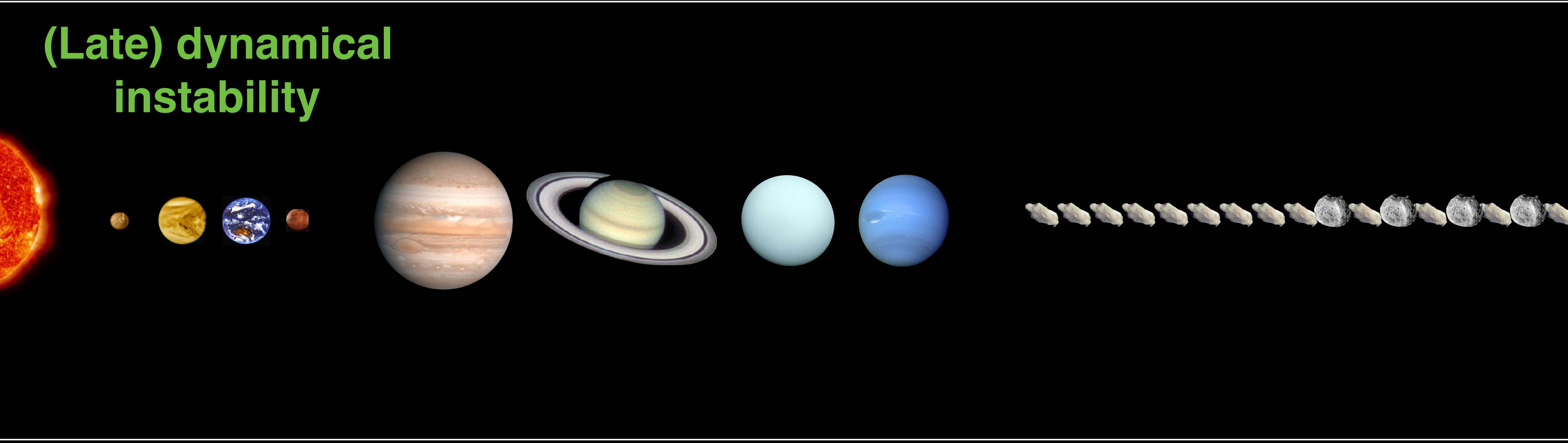
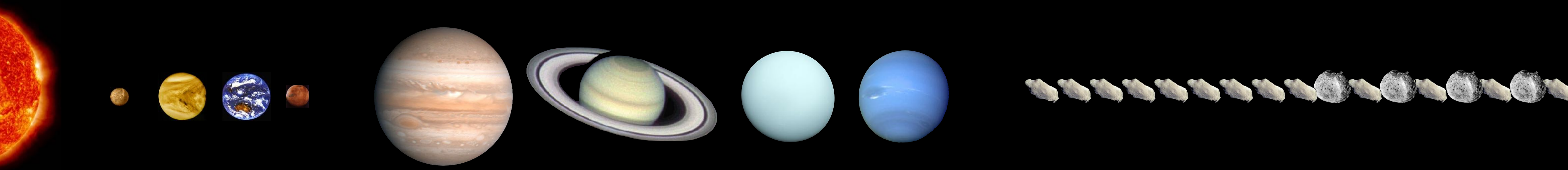


How did Jupiter and Saturn reach their current orbits?

After gas dispersal

(Late) dynamical instability



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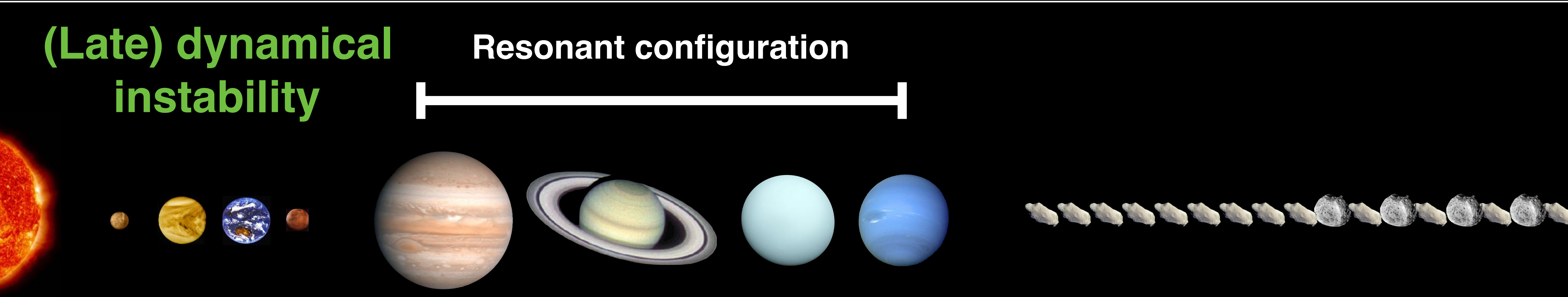

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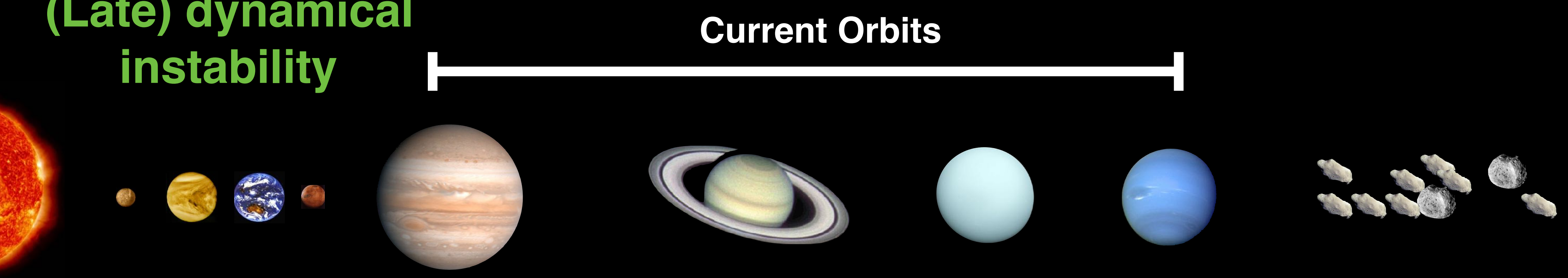
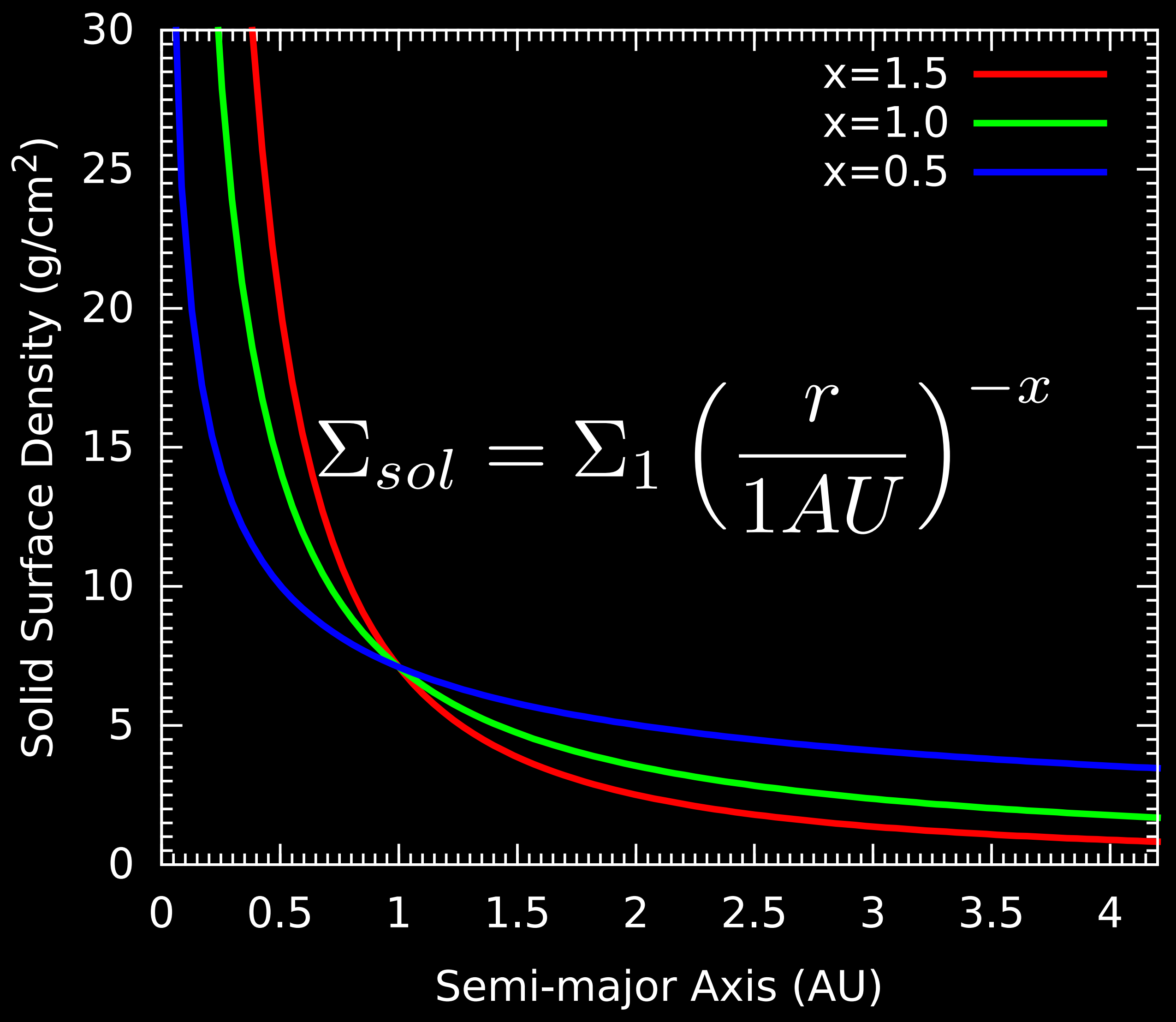


Gomes et al. 2005; Nesvorny 2011

Giant Planets dynamical instability

Gomes et al., 2005; Levison et al. 2011

The classical model setup



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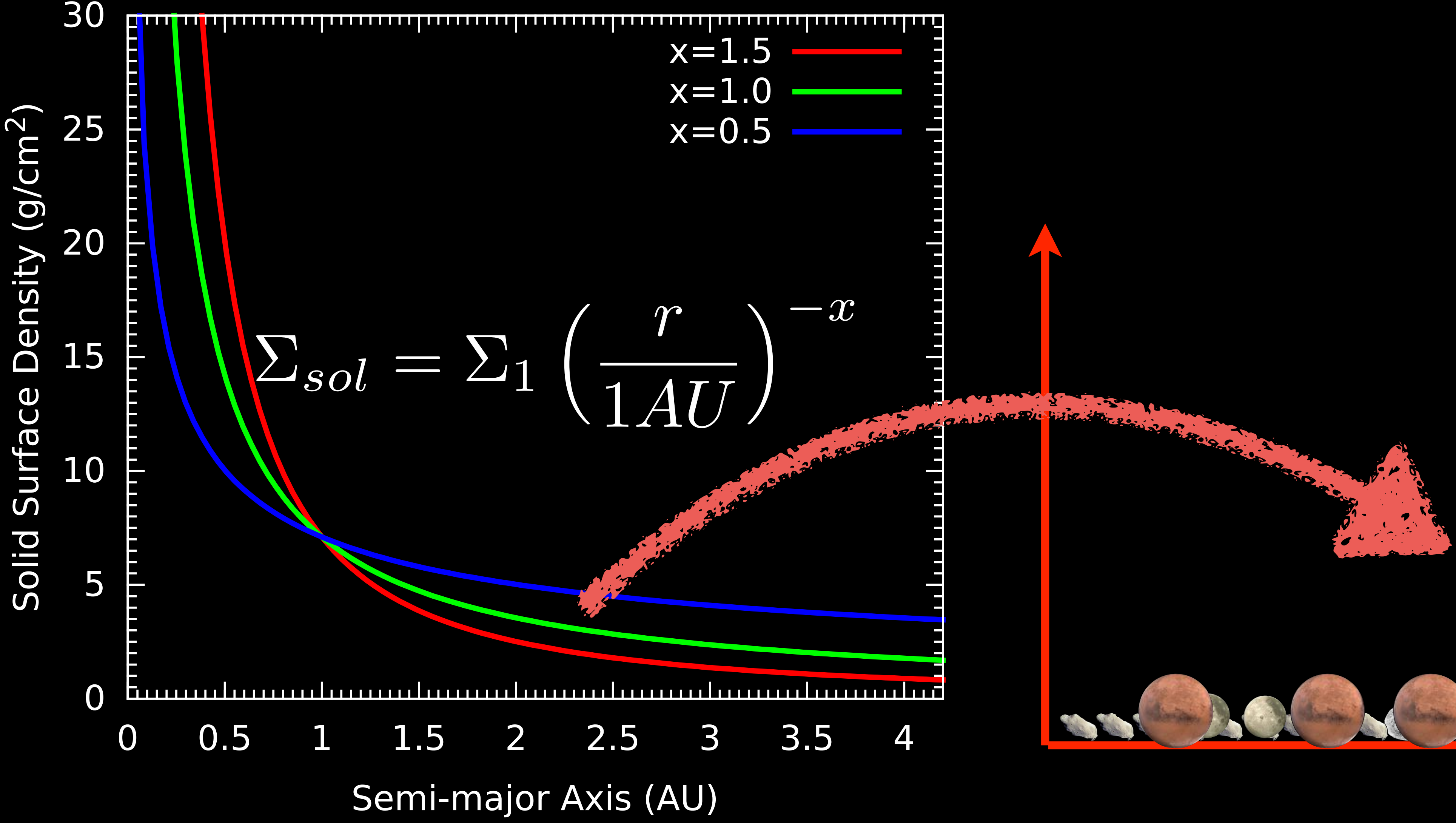

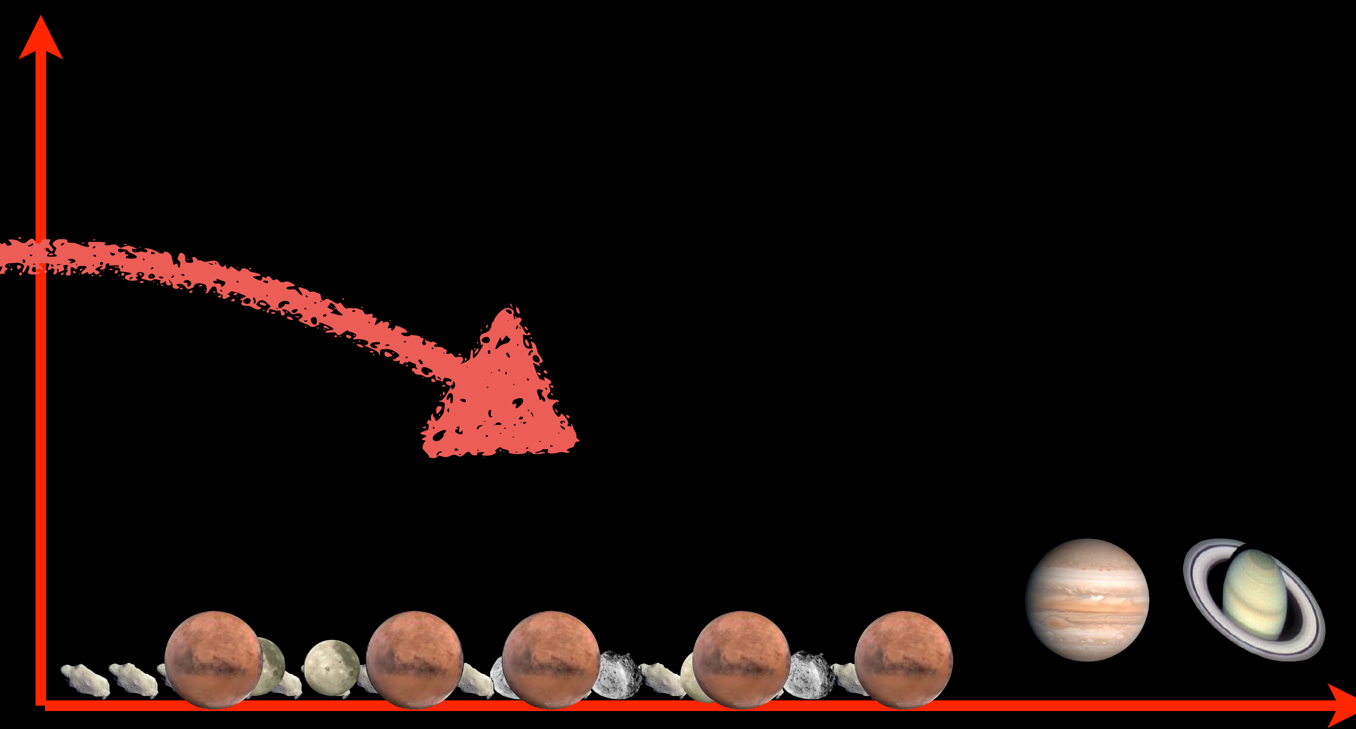

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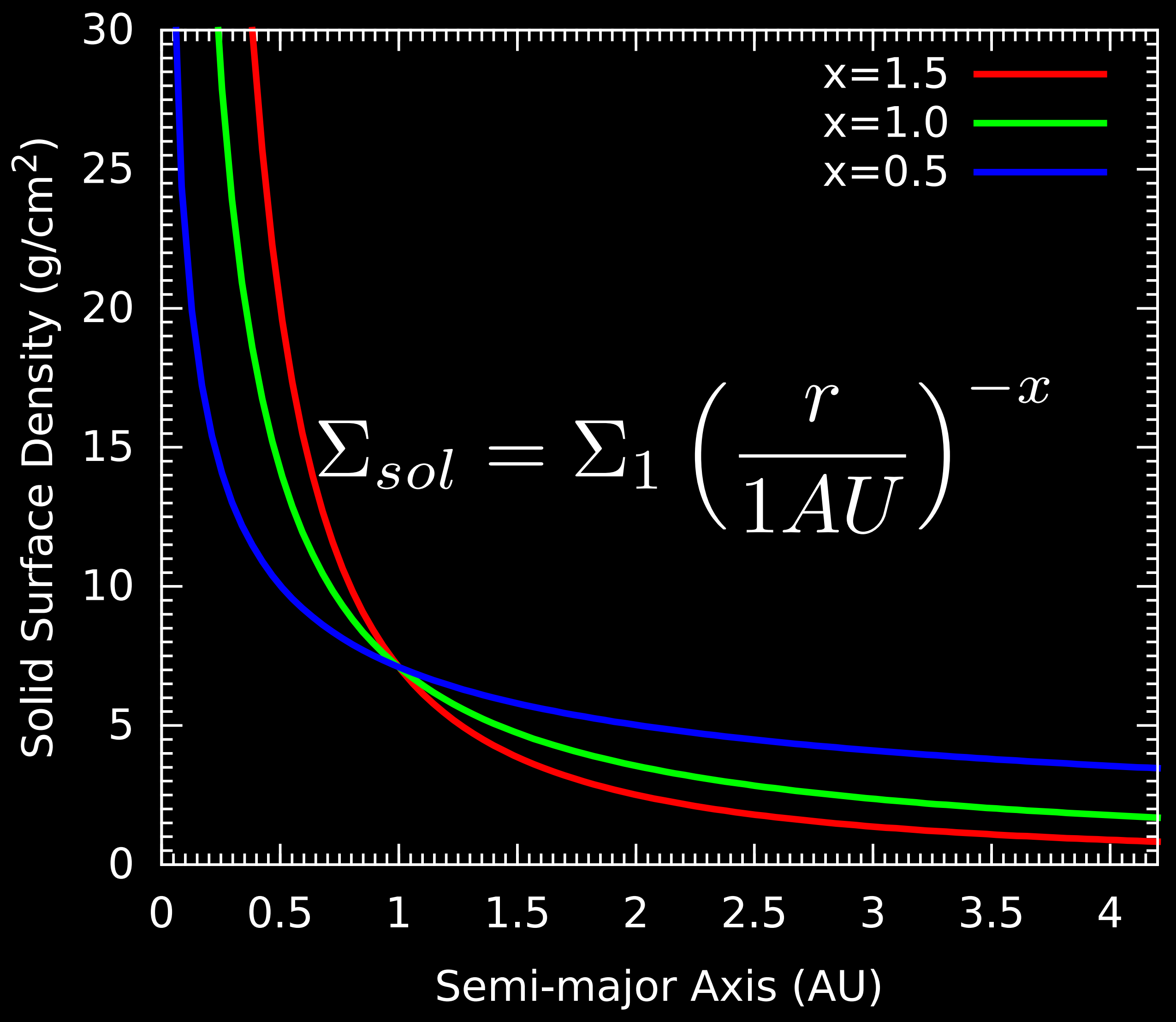
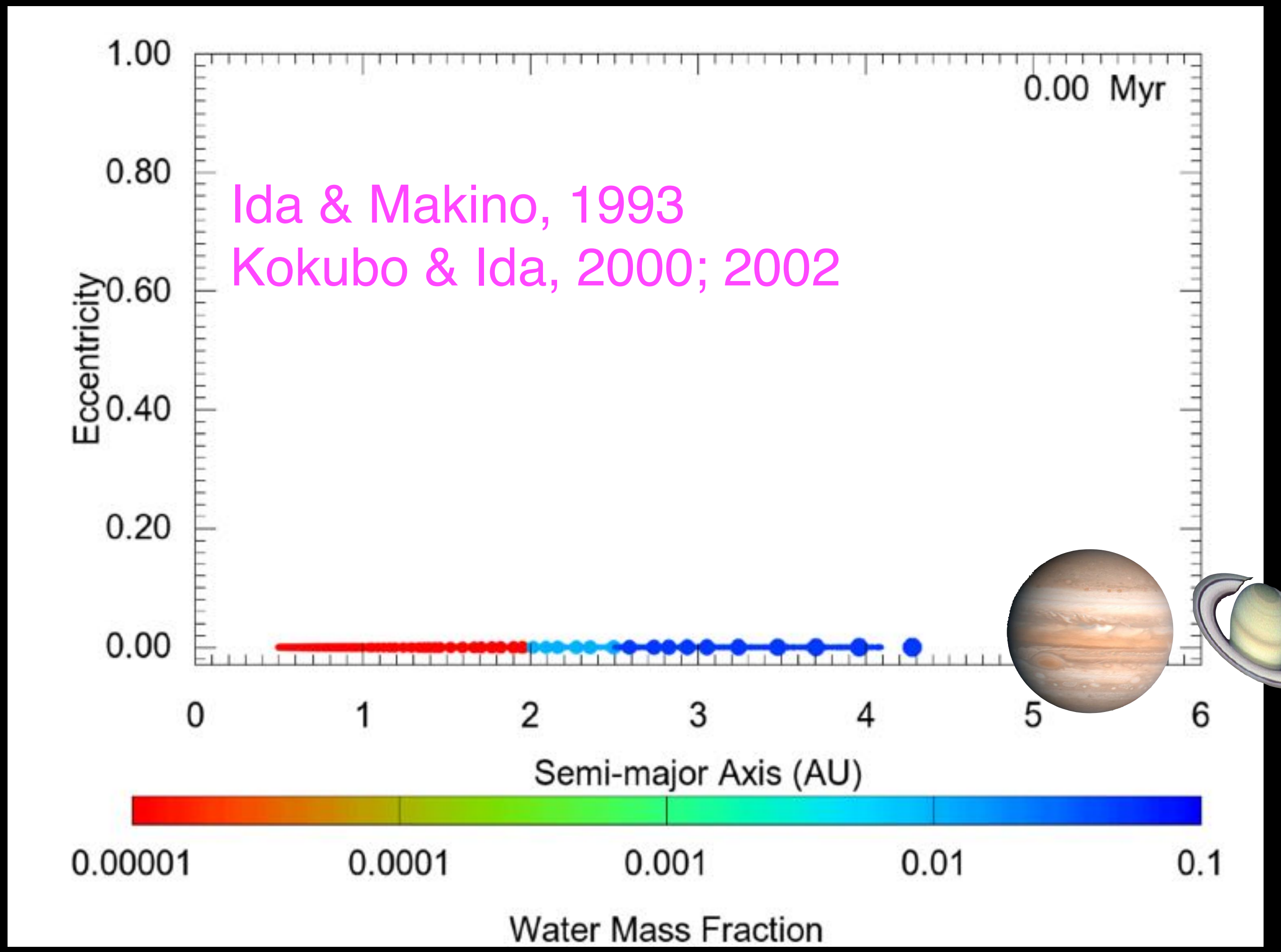
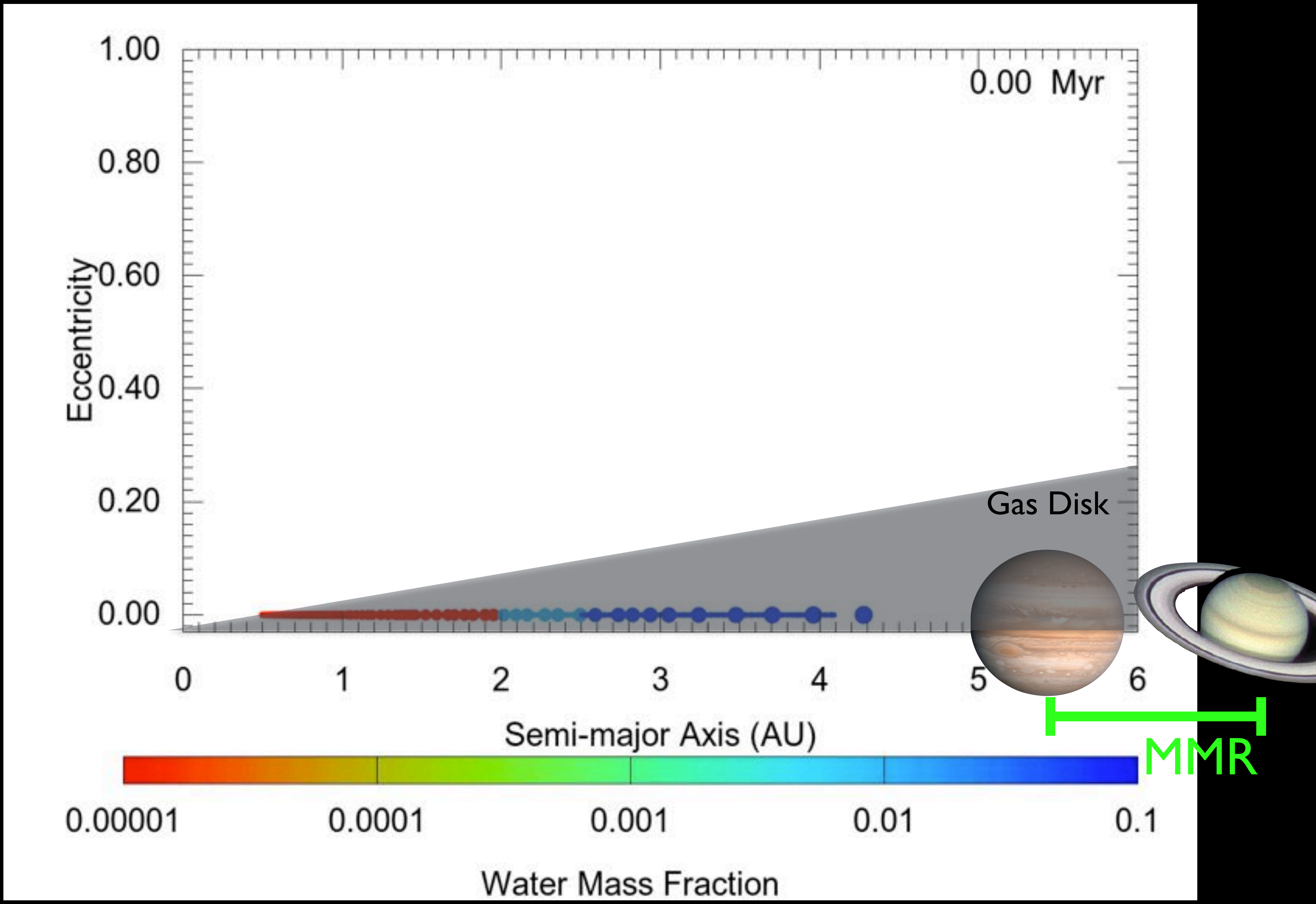




The "classical" Model (J&S resonant)



Izidoro et al. 2014, ApJ

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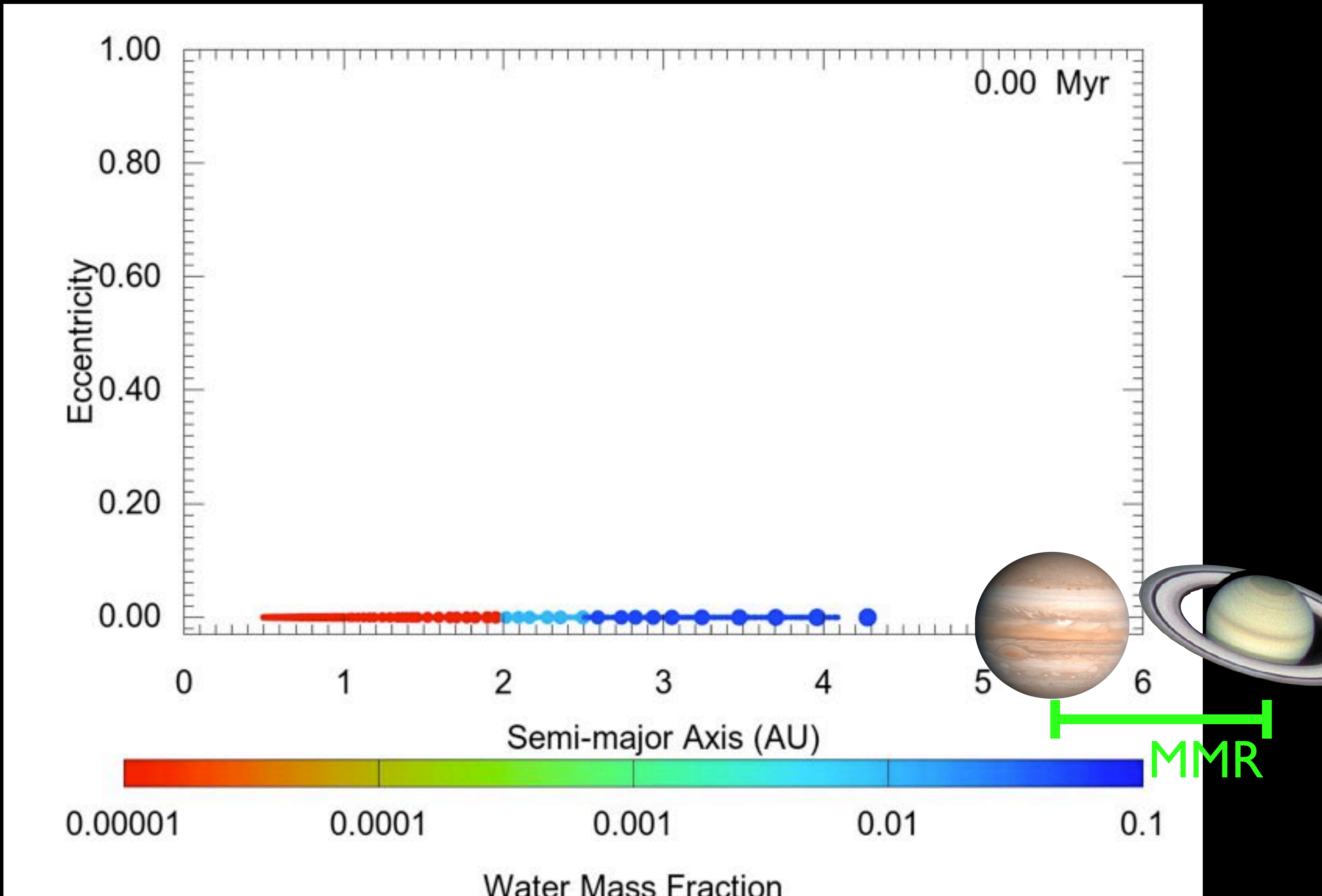

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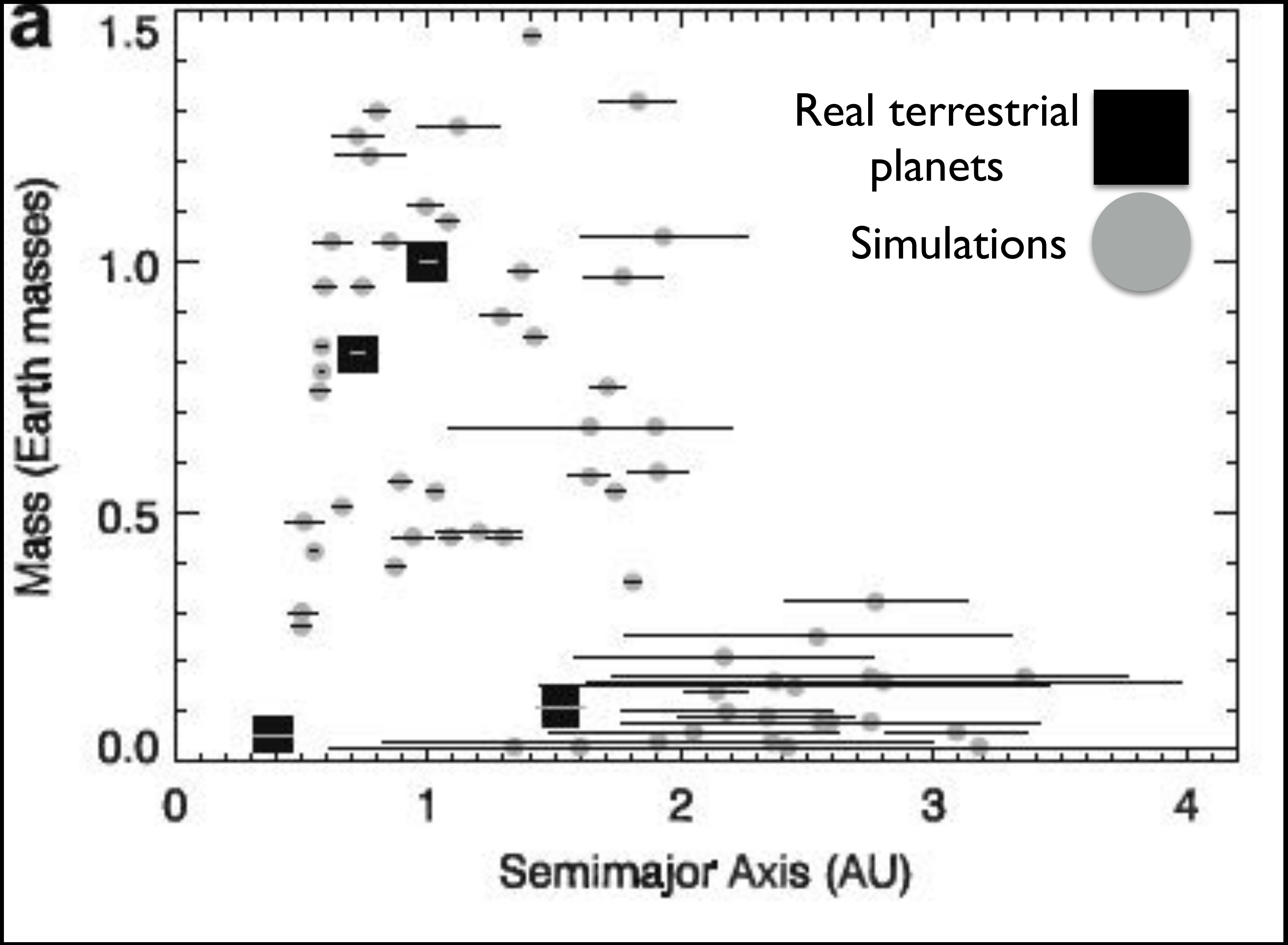
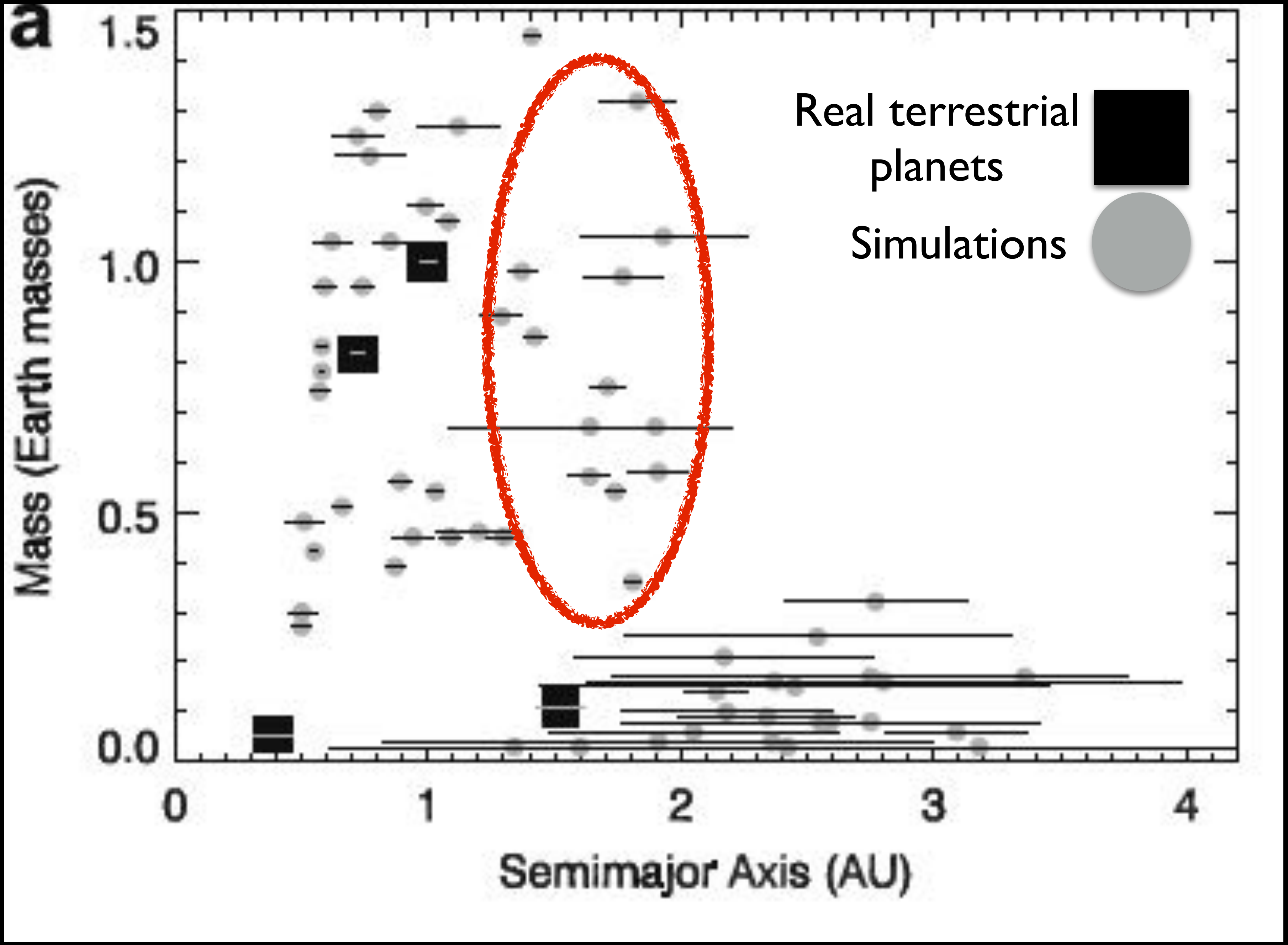


Raymond et al 2009

Wetherill 1991; Chambers 2001; O'Brien et al 2006; Raymond et al 2006, 2009, Morishima et al 2008, 2010; Nagasawa et al 2005, 2007; Thommes et al 2008; Fischer & Ciesla 2014; Izidoro et al 2014, 2015

The "small Mars" Problem



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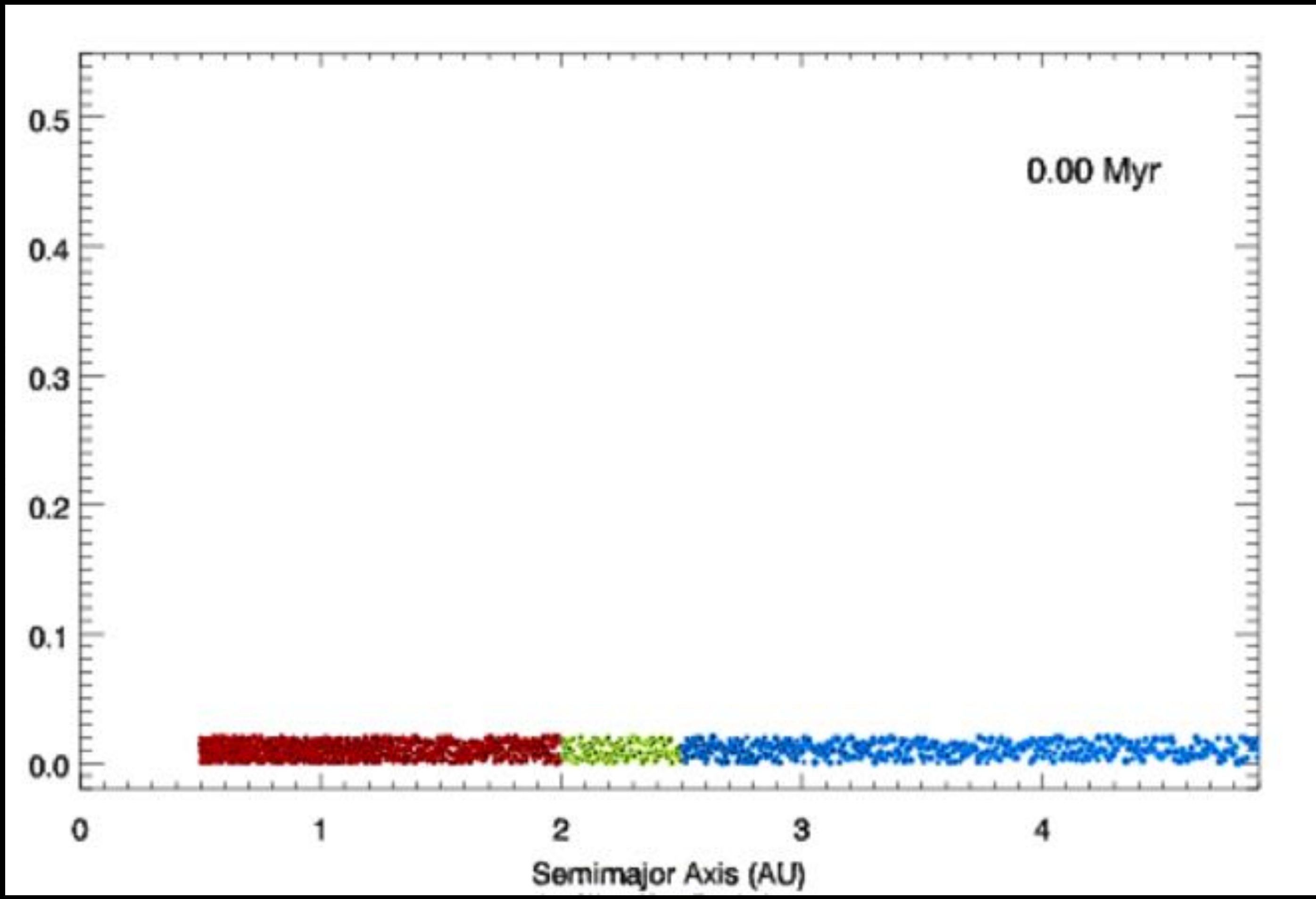
A solution to the Mars problem

(Hansen 2009; also Wetherill 1978; Chambers 2001)



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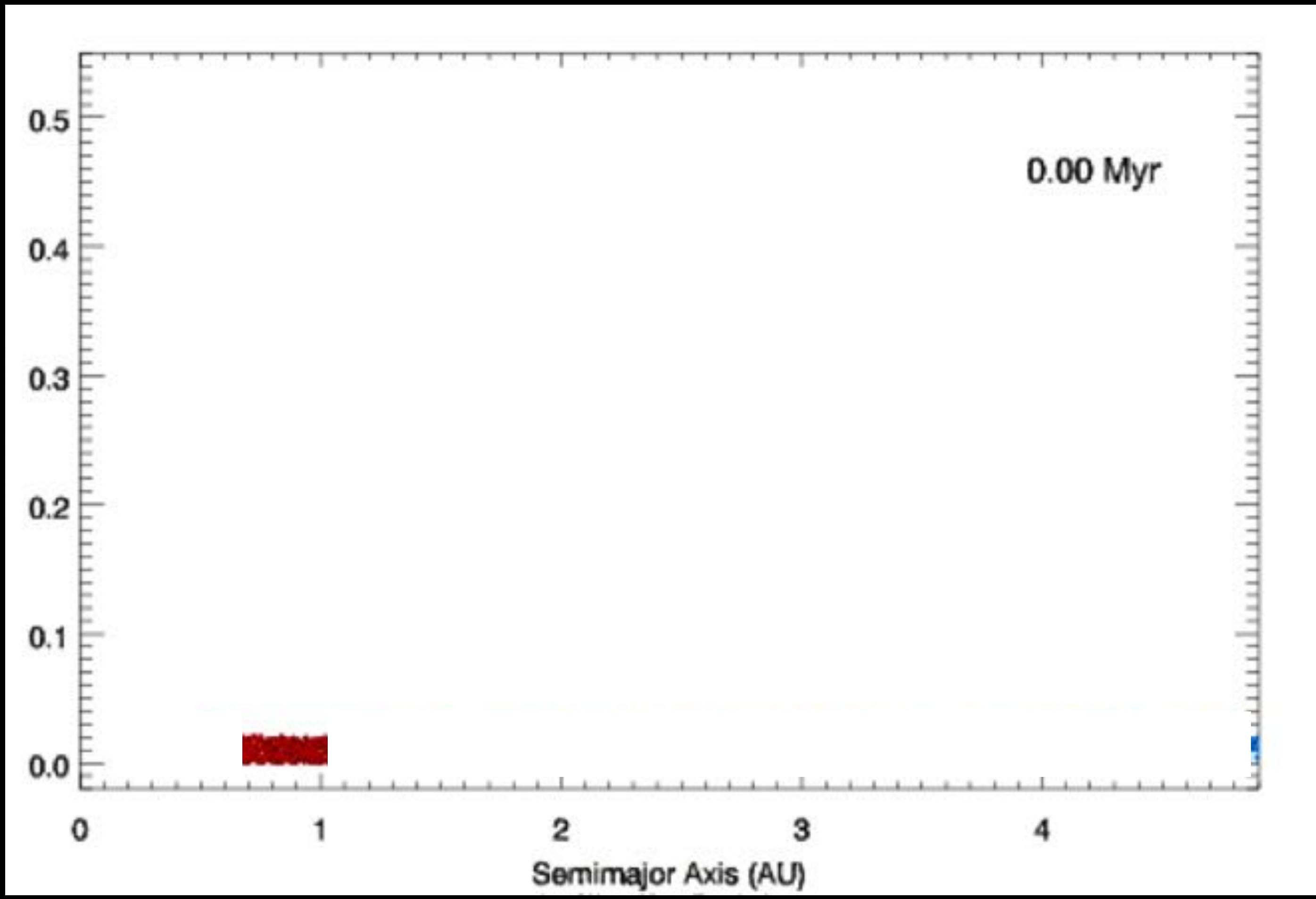

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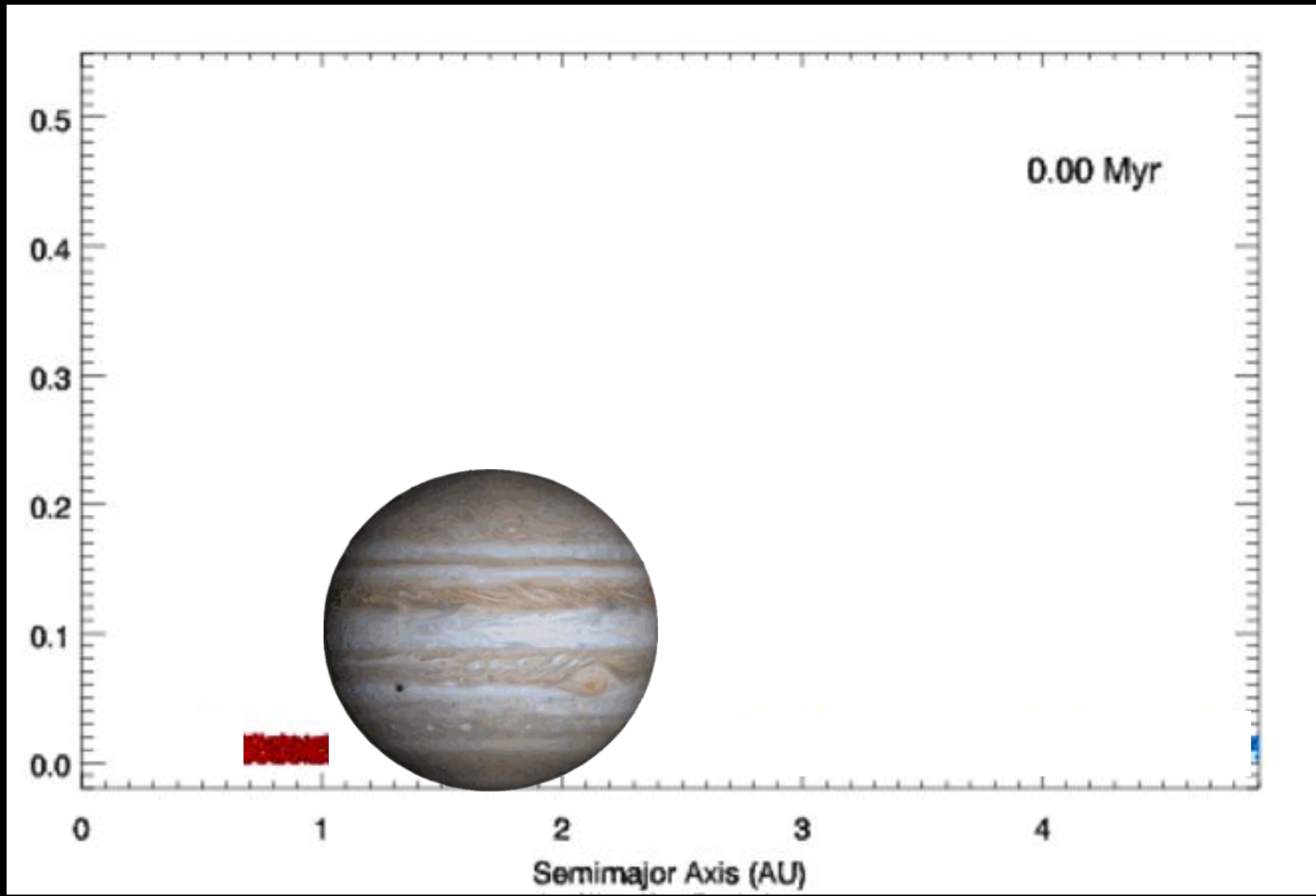

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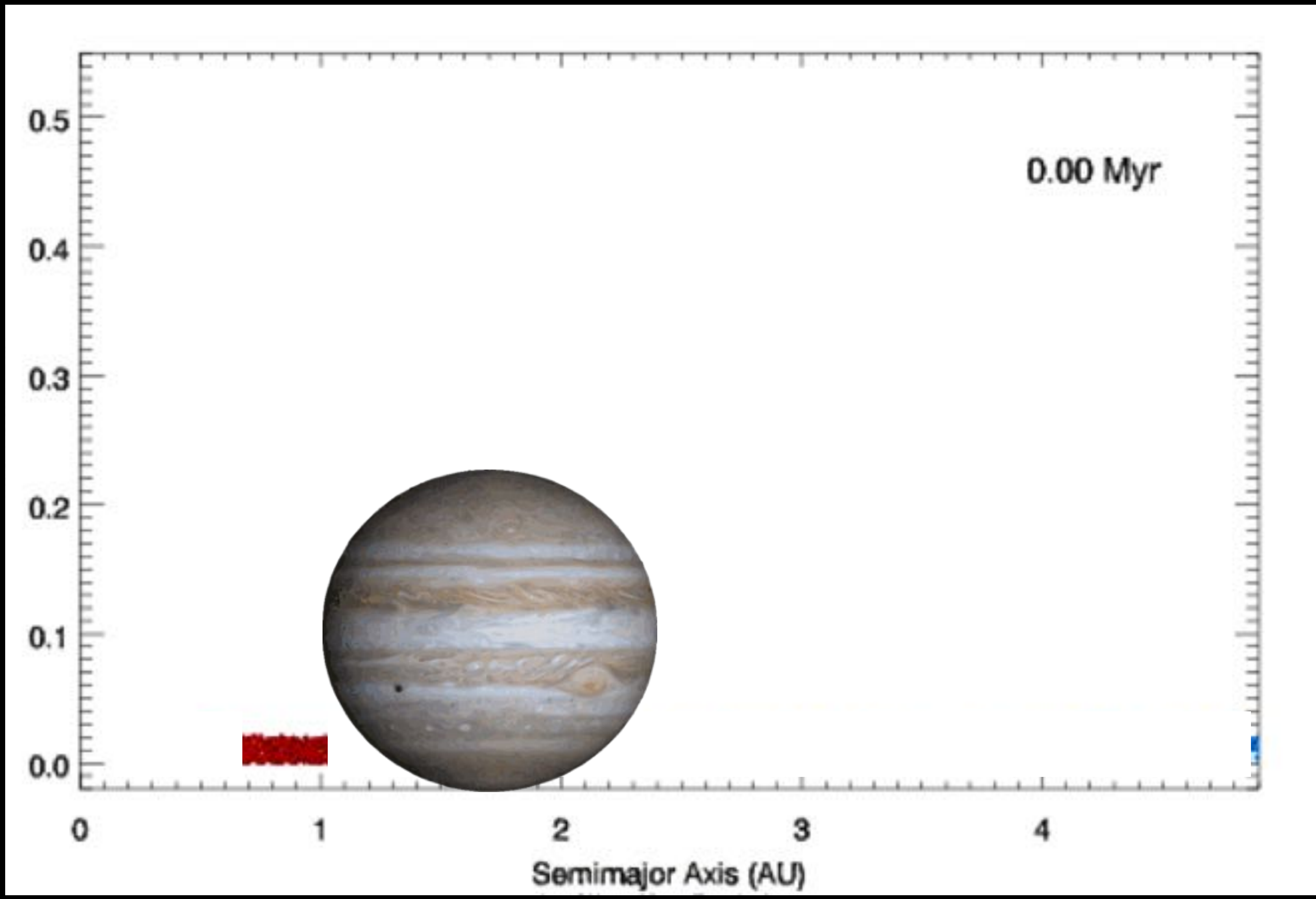
(Hansen 2009; also Wetherill 1978; Chambers 2001)

- A small Mars forms naturally if inner disk is only from 0.7-1 AU
  - An edge effect



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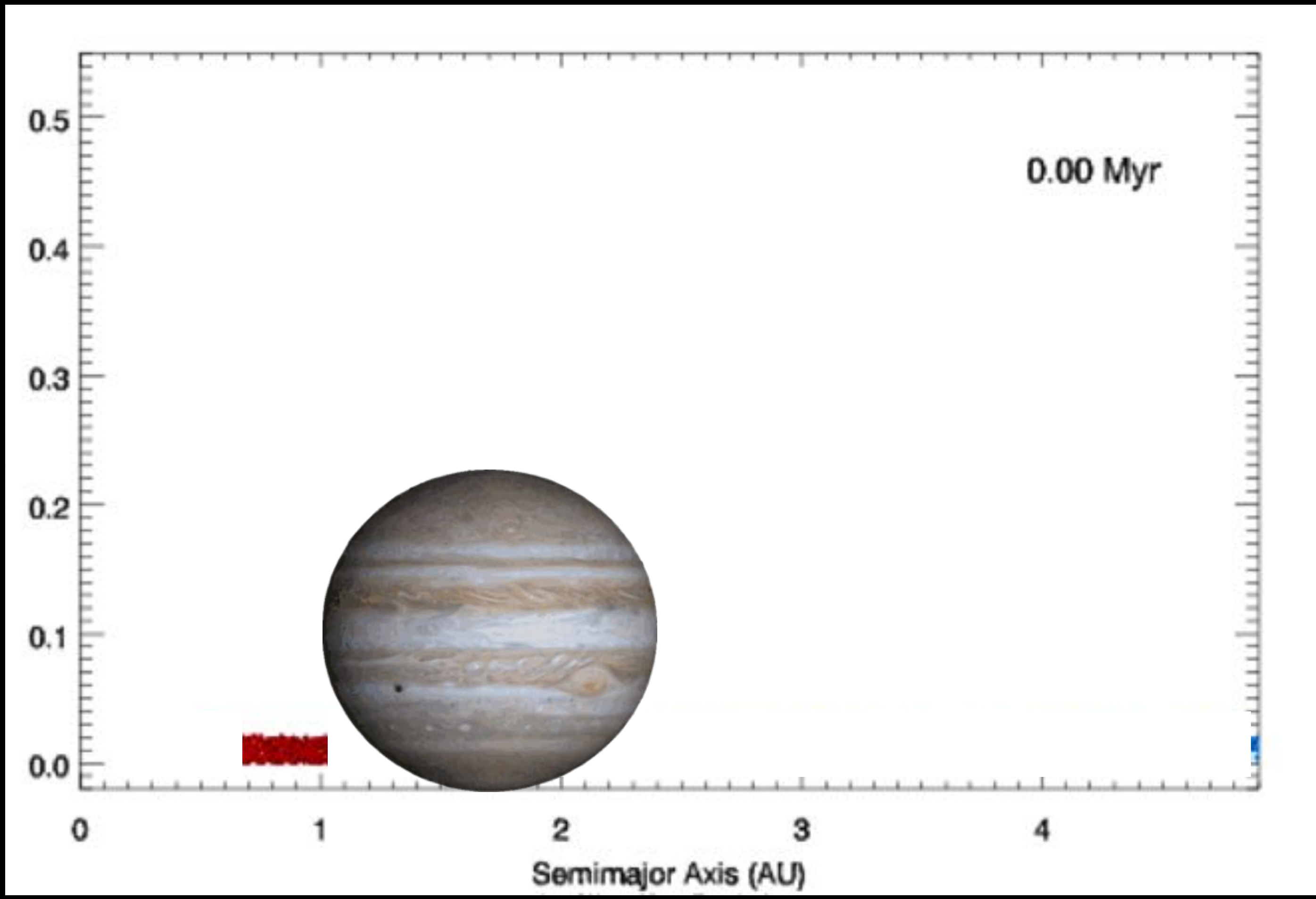
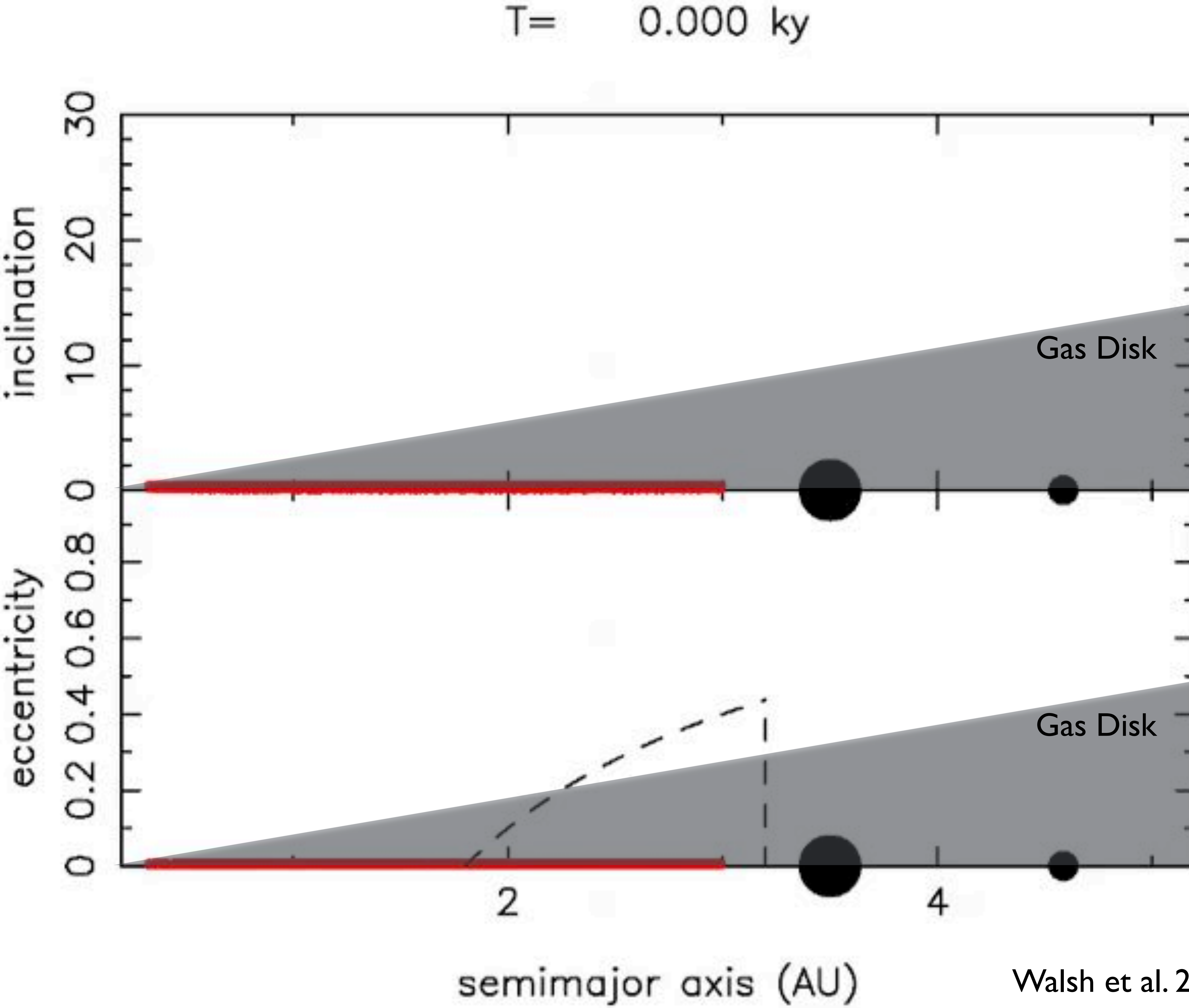
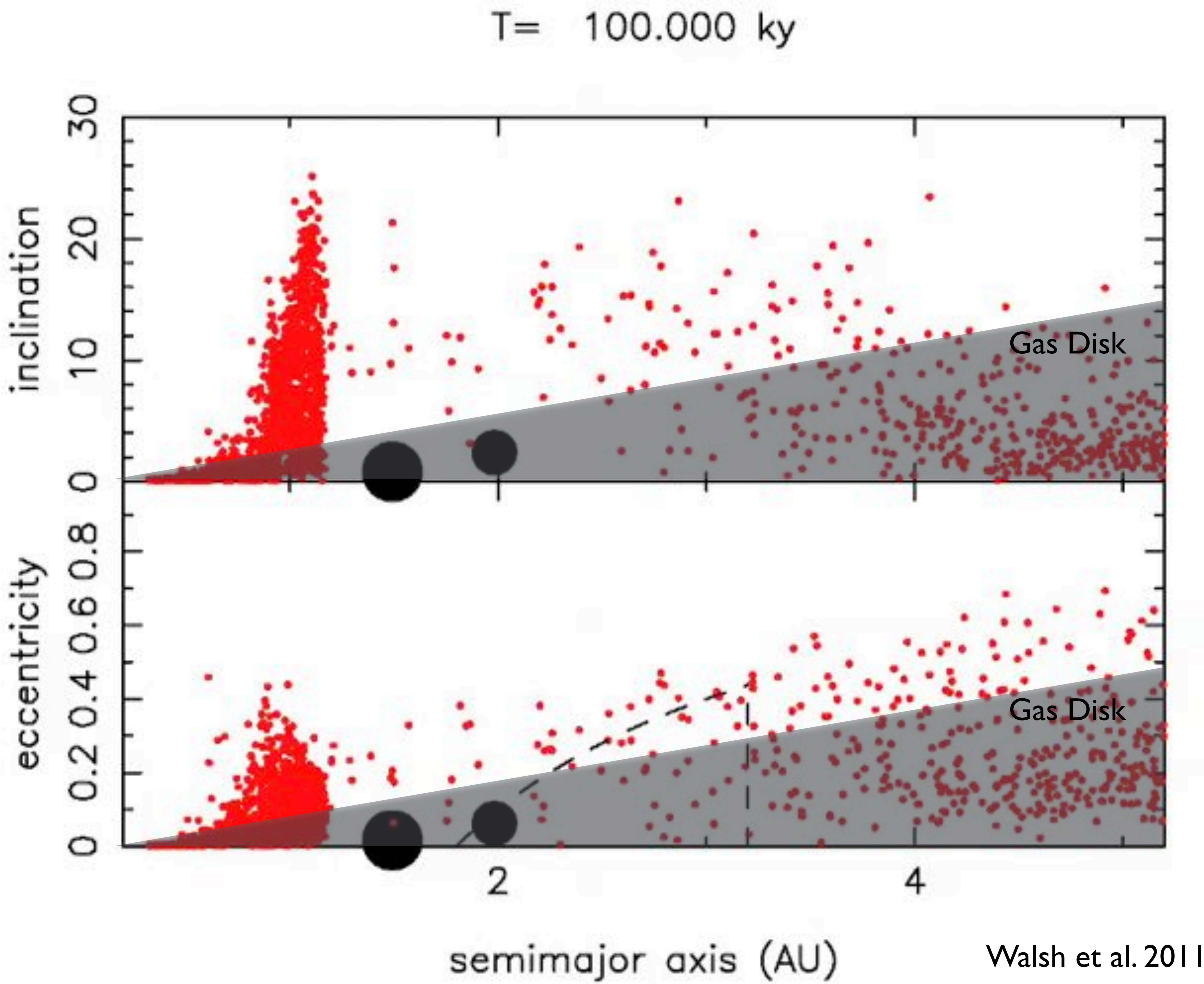
- The formation of the asteroid belt is not addressed in Hansen's work

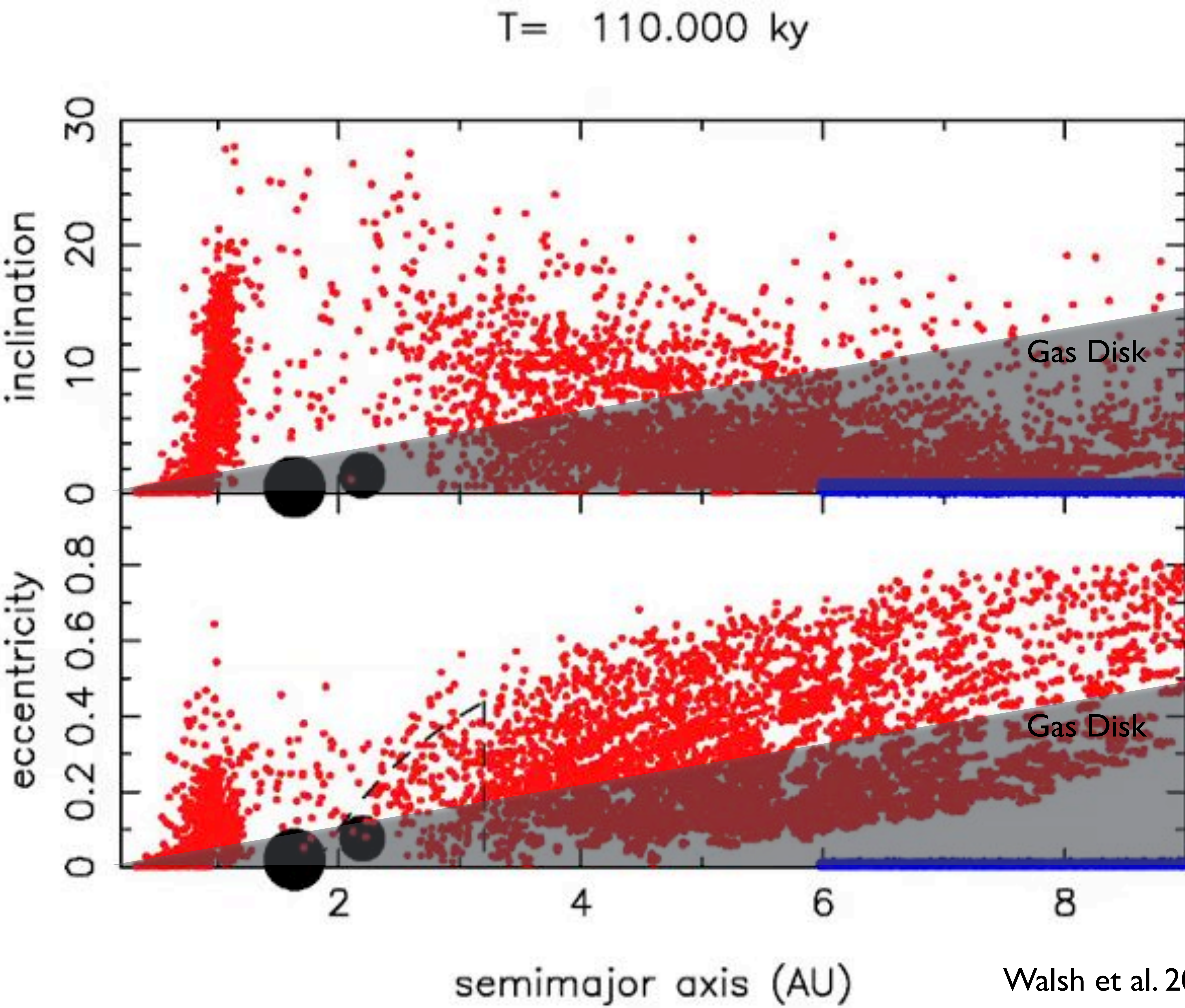




Walsh et al. 2011



T= 100.000 ky
inclination
30
20
10
0
Gas Disk
eccentricity
0.8
0.6
0.4
0.2
0
Gas Disk
2
4
semimajor axis (AU)
Walsh et al. 2011



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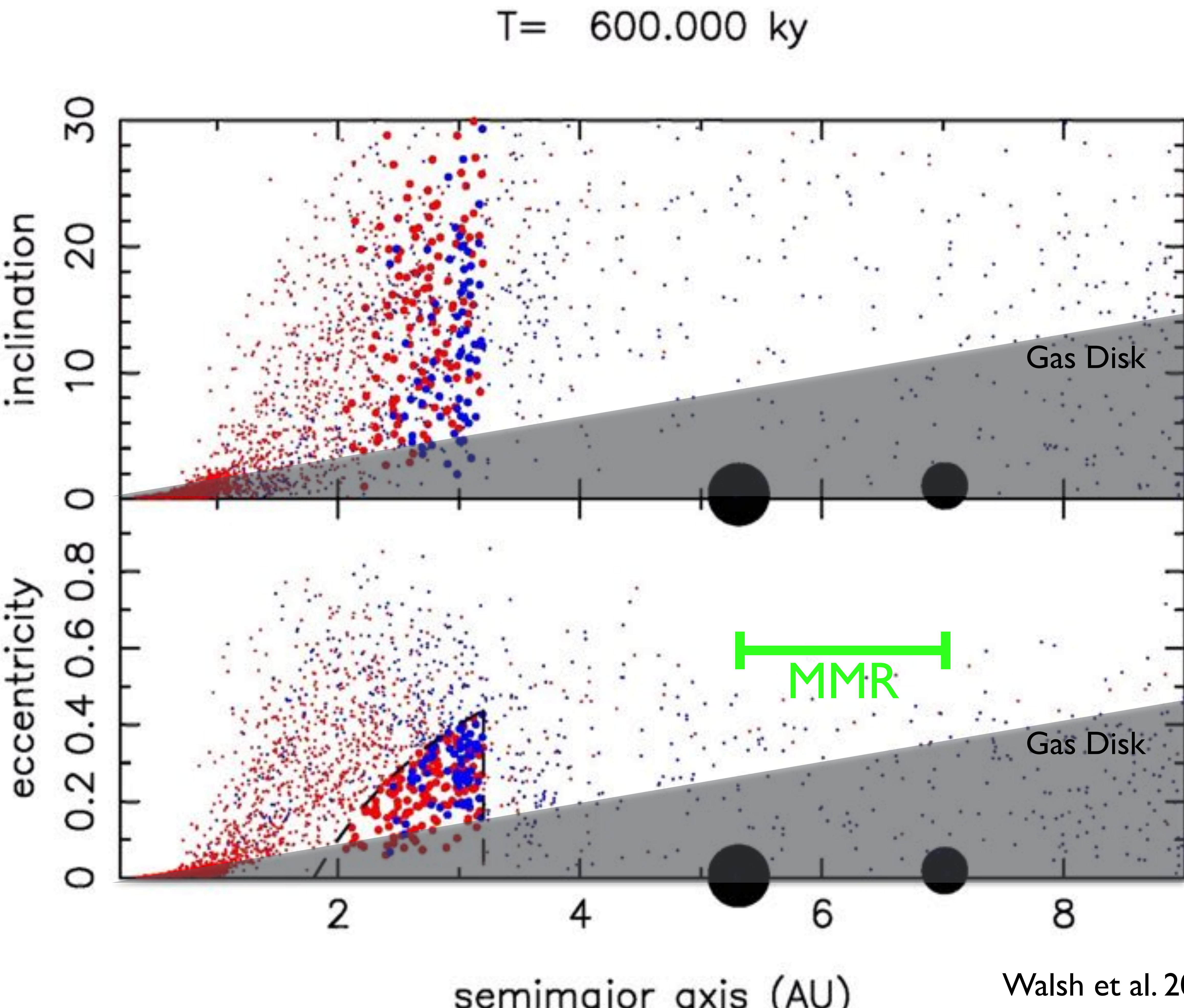

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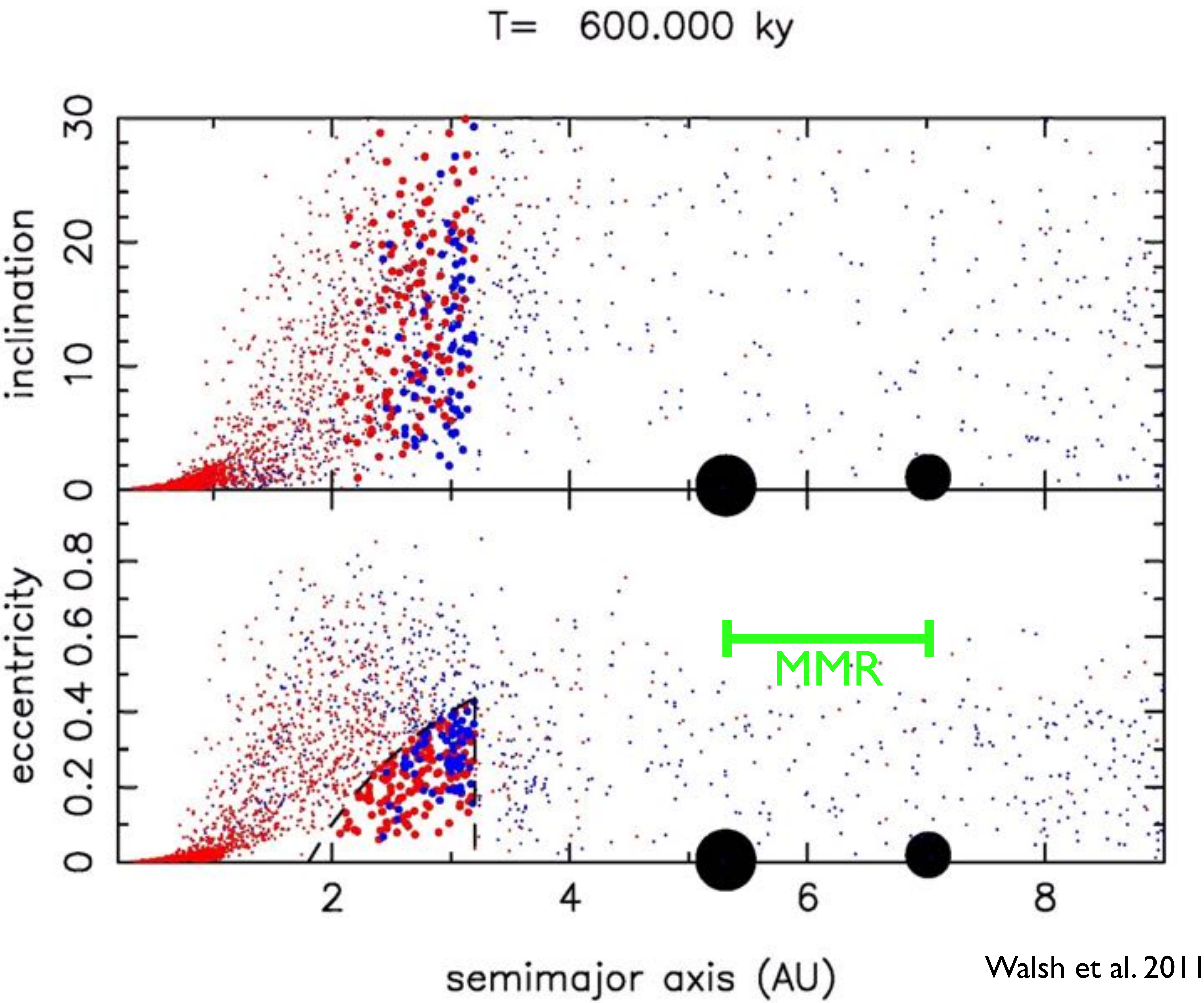
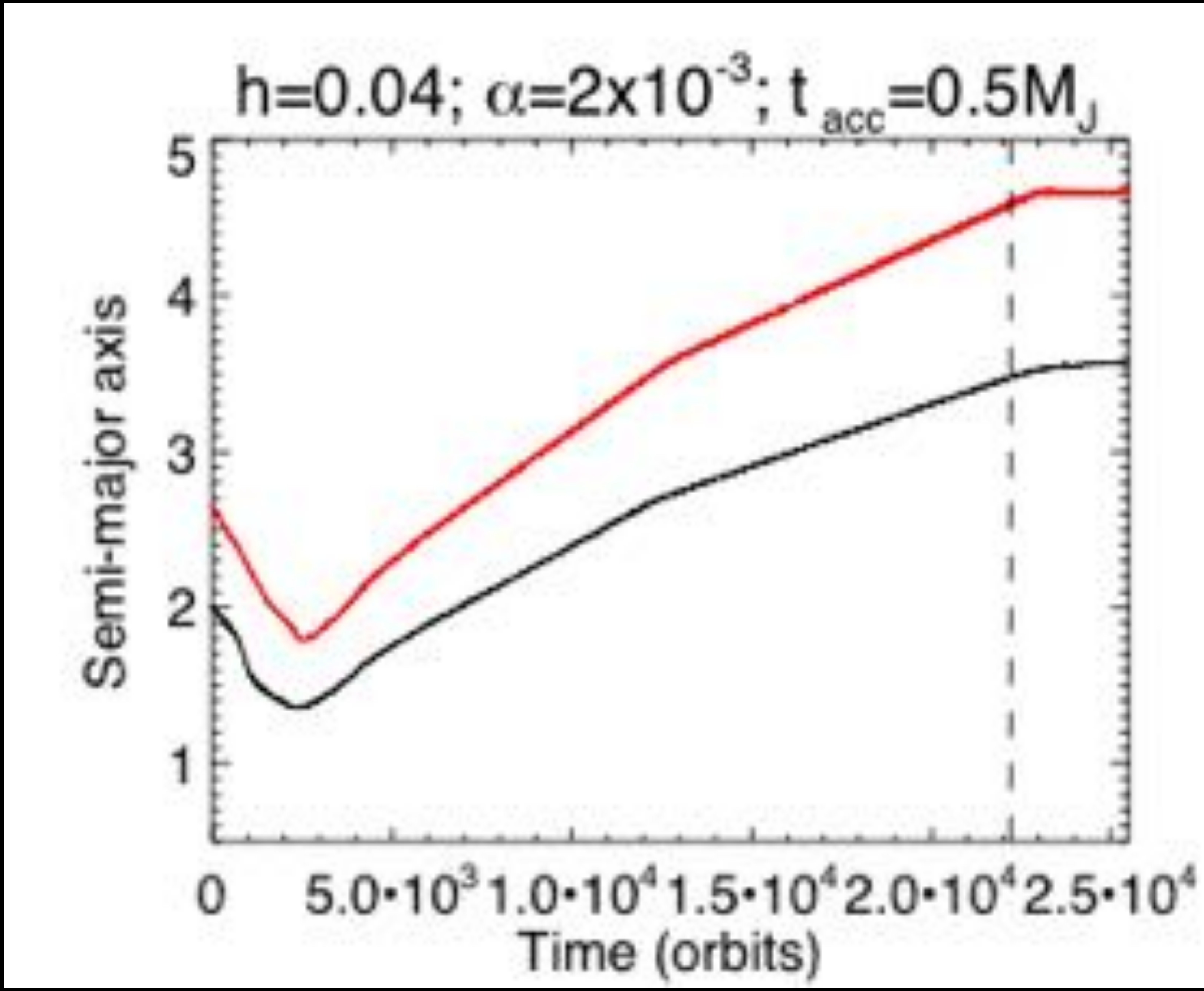

T= 600.000 ky
inclination
30
20
10
0
eccentricity
0.8
0.6
0.4
0.2
0
2
4
6
8
semimajor axis (AU)
MMR
Walsh et al. 2011

Grand Tack model invokes a specific migration history of the giant planets



Hydrodynamical simulation with Jup, Sat accreting gas from disk (Pierens & Raymond 2011, A&A, 533, A131.)

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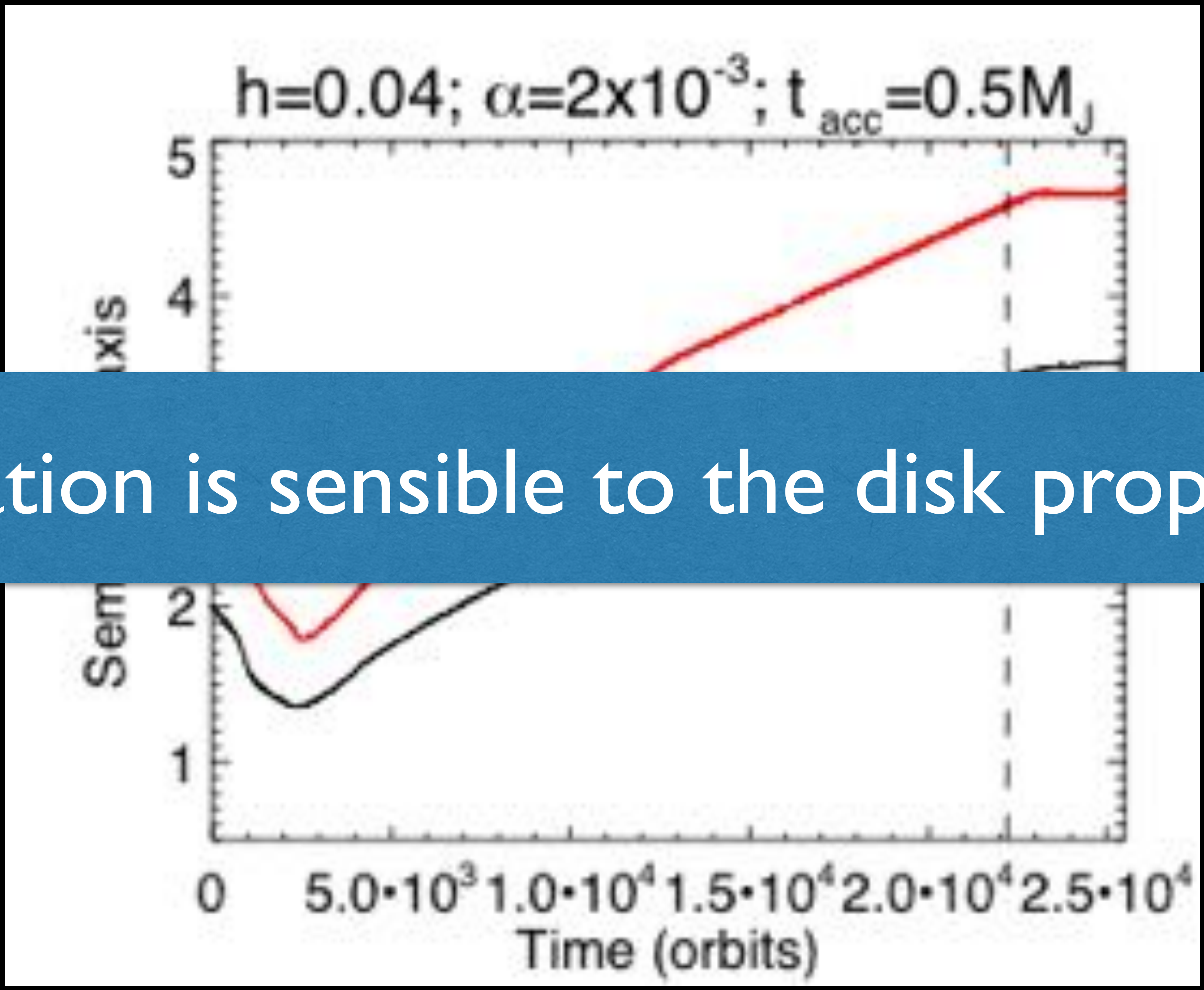

Migration is sensible to the disk properties

Hydrodynamical simulation with Jup, Sat accreting gas from disk (Pierens & Raymond 2011, A&A, 533, A131.)

THE GRAND TACK SCENARIO

Walsh et al 2011, Nature

✓ To produce Mars it is needed a mass deficit beyond 1 AU

Hansen 2009; Walsh et al., 2011; Izidoro et al., 2014

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- Is there another way to create a truncated (Hansen-style) disk?

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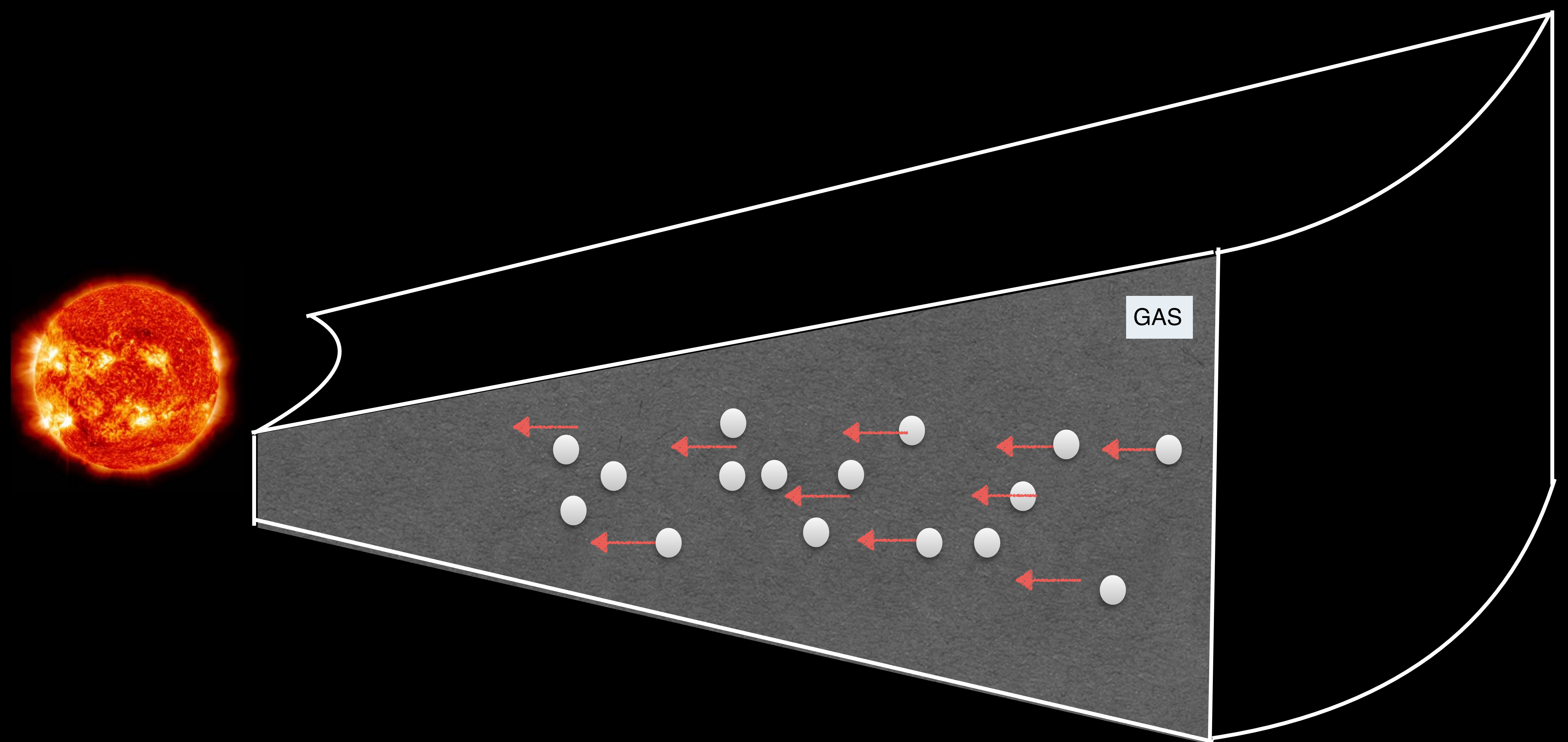
YES!!

Radial drift of solids (peebles or planetesimals) in the protoplanetary disk due to **gas-drag**



Levison et al., 2015; Moriarty & Fischer, 2015

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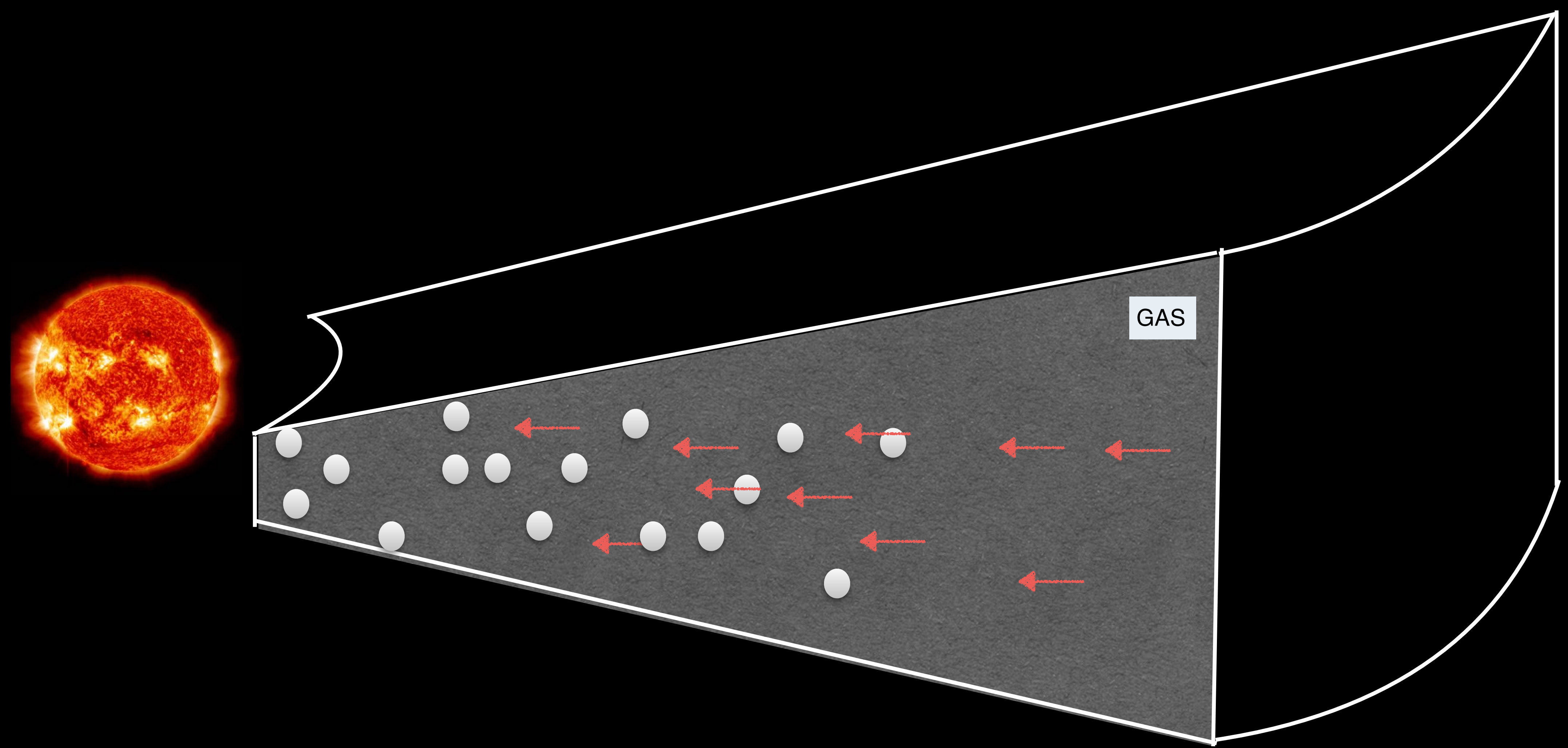

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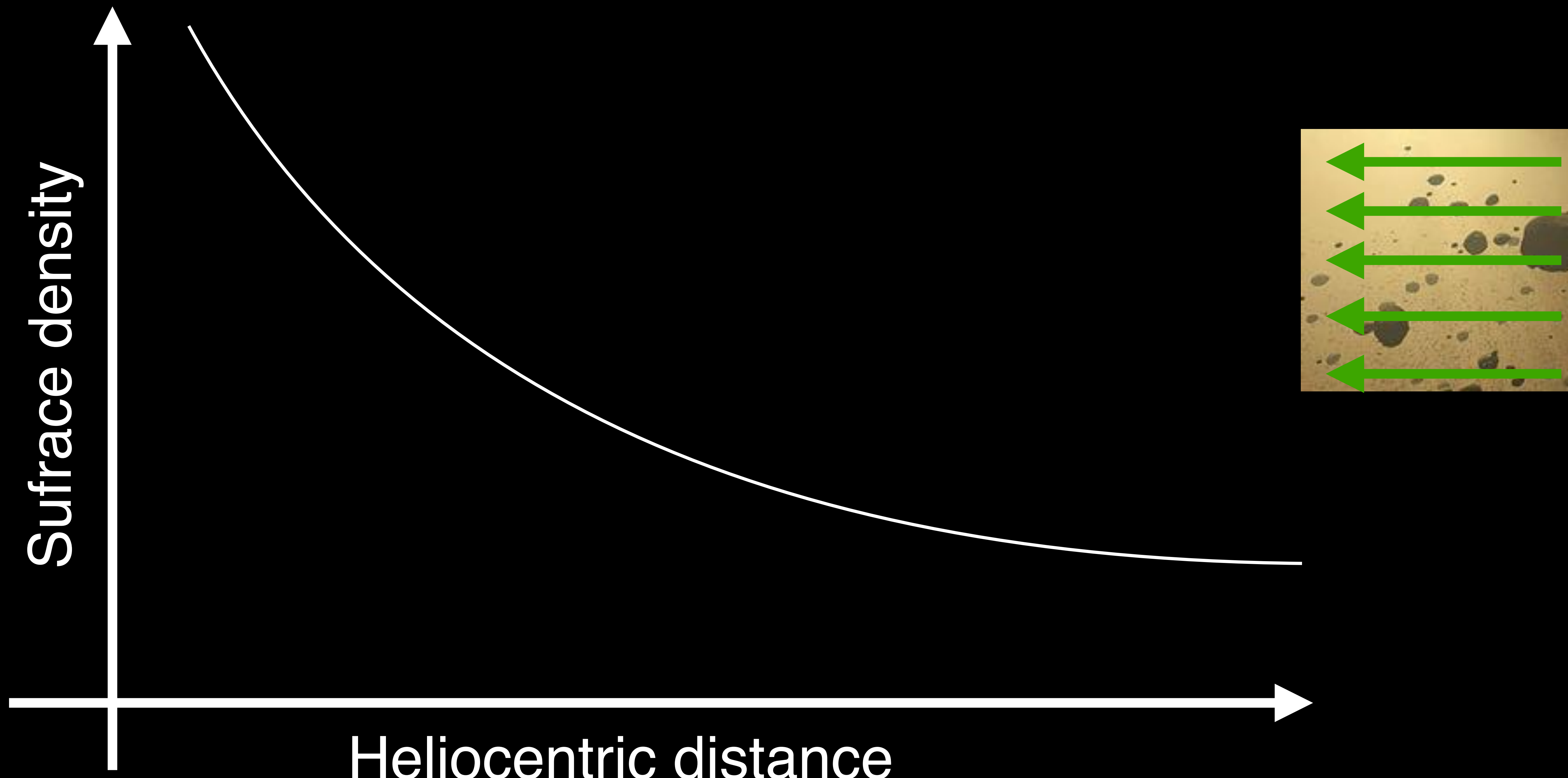
Radial drift of solids/migration in the protoplanetary disk: enhancing the surface density in the terrestrial region



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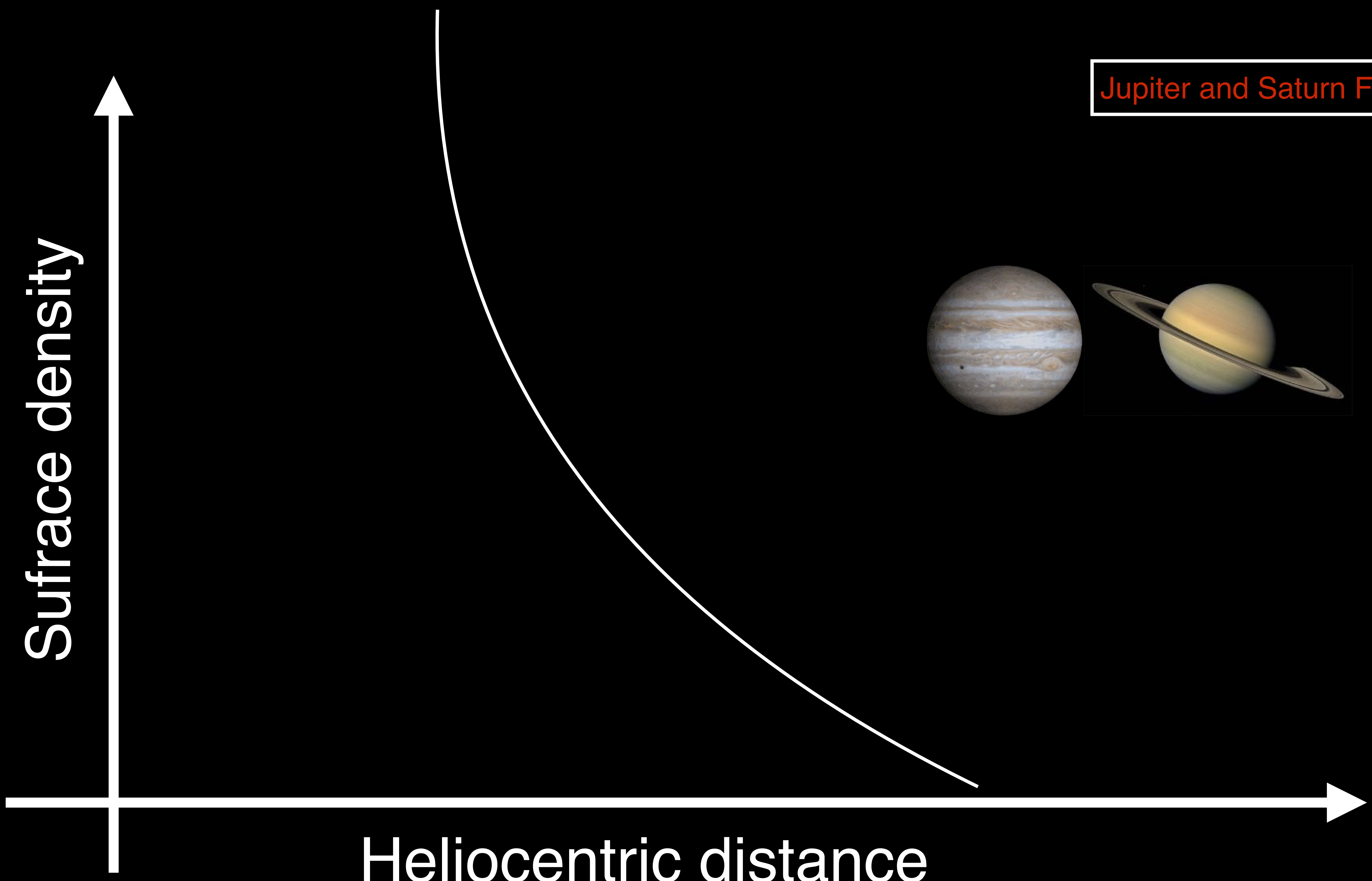
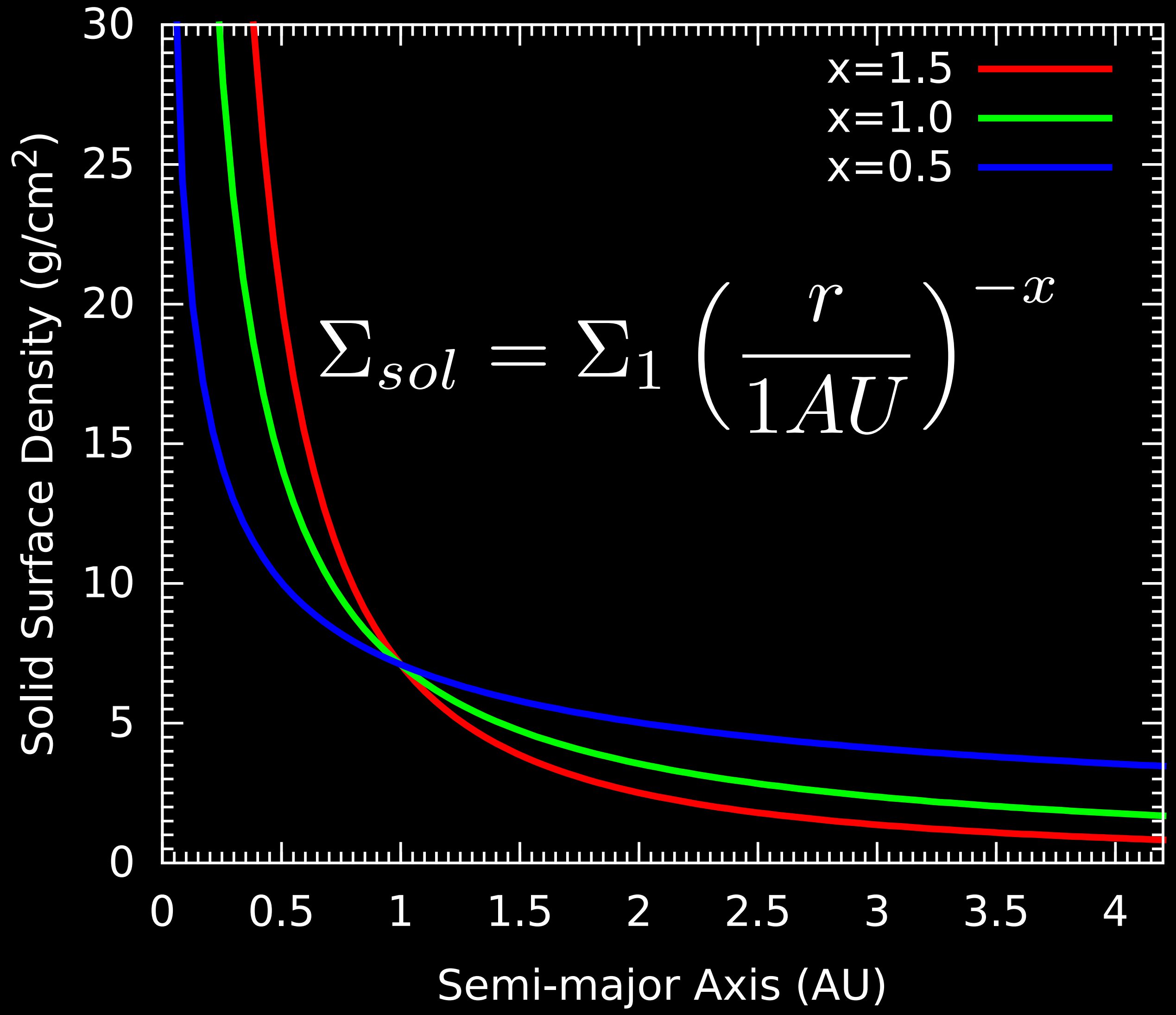


The distribution of mass in solids in the terrestrial region?



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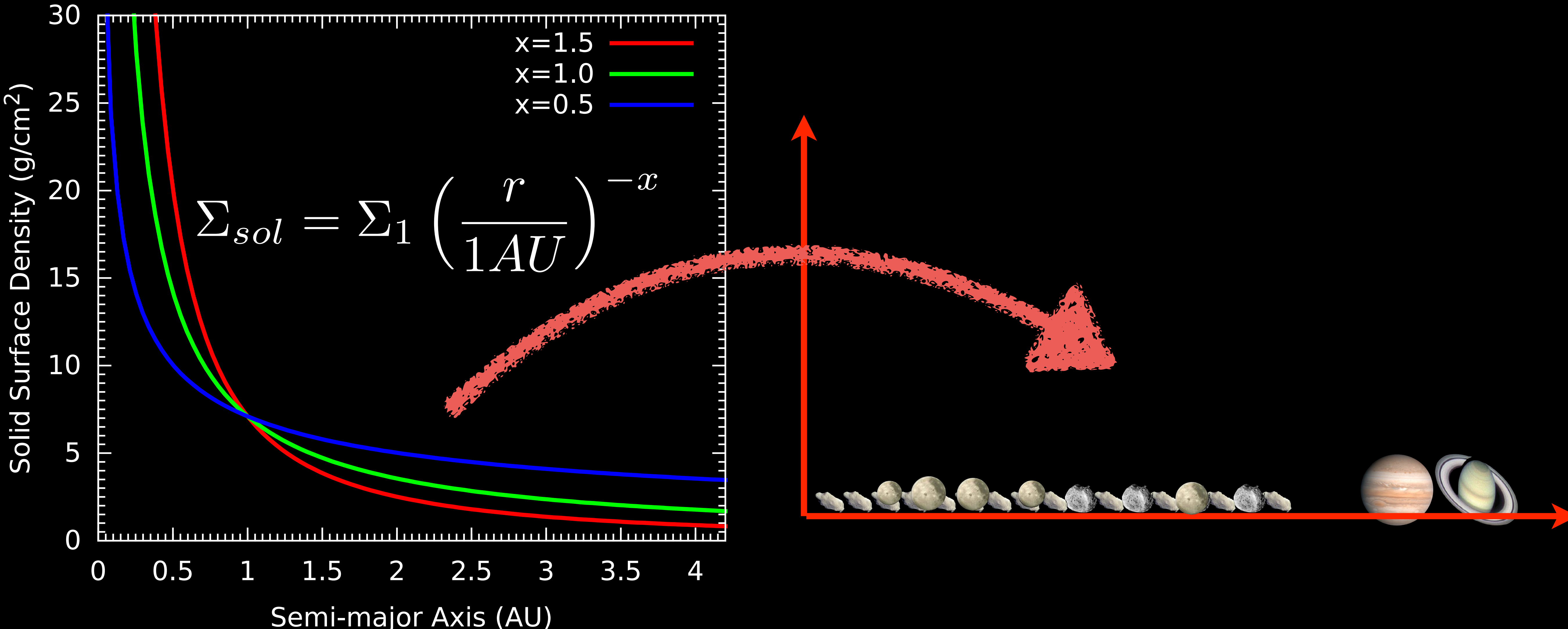

$$\Sigma_{sol} = \Sigma_1 \left(\frac{r}{1AU} \right)^{-x}$$

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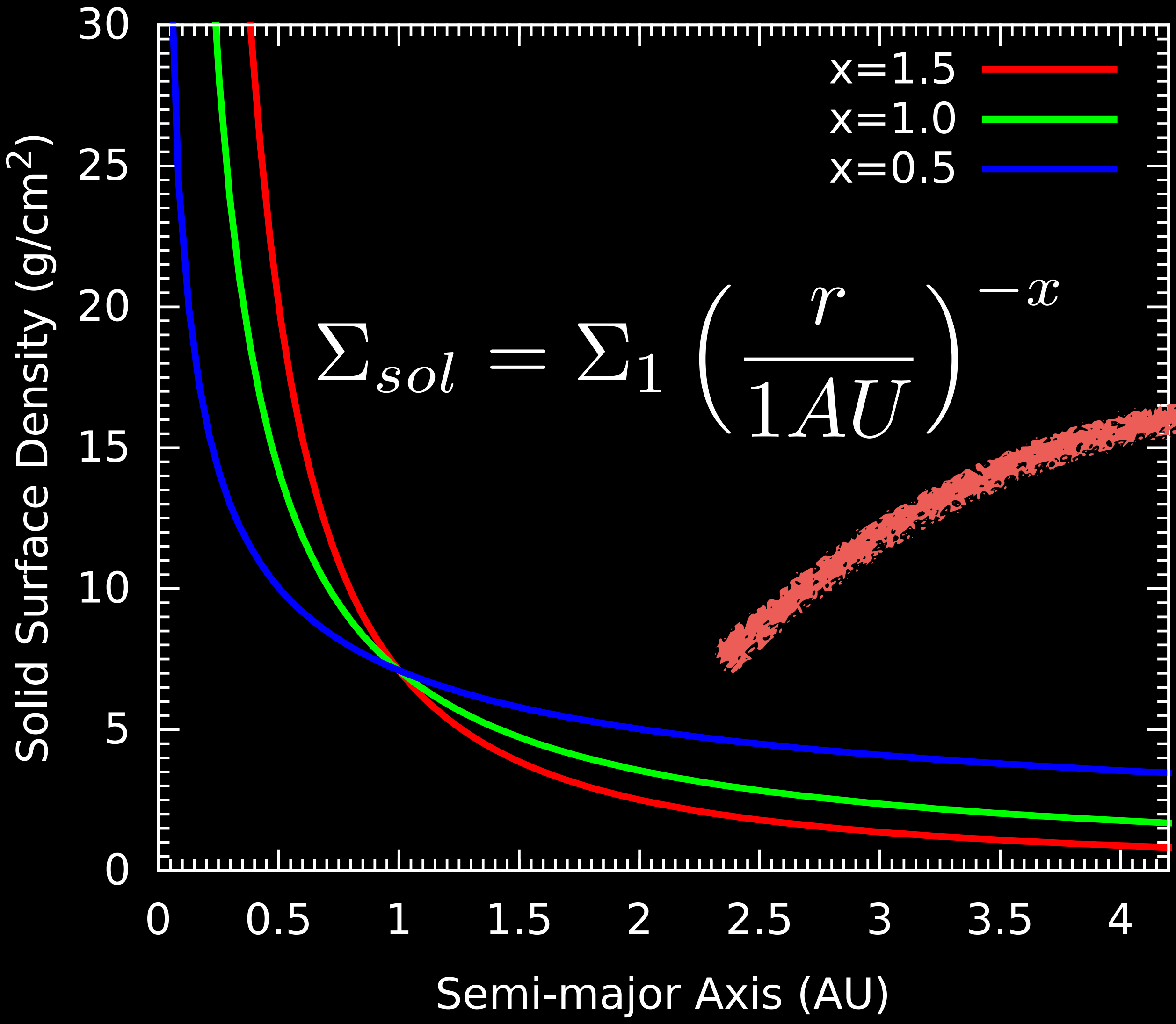

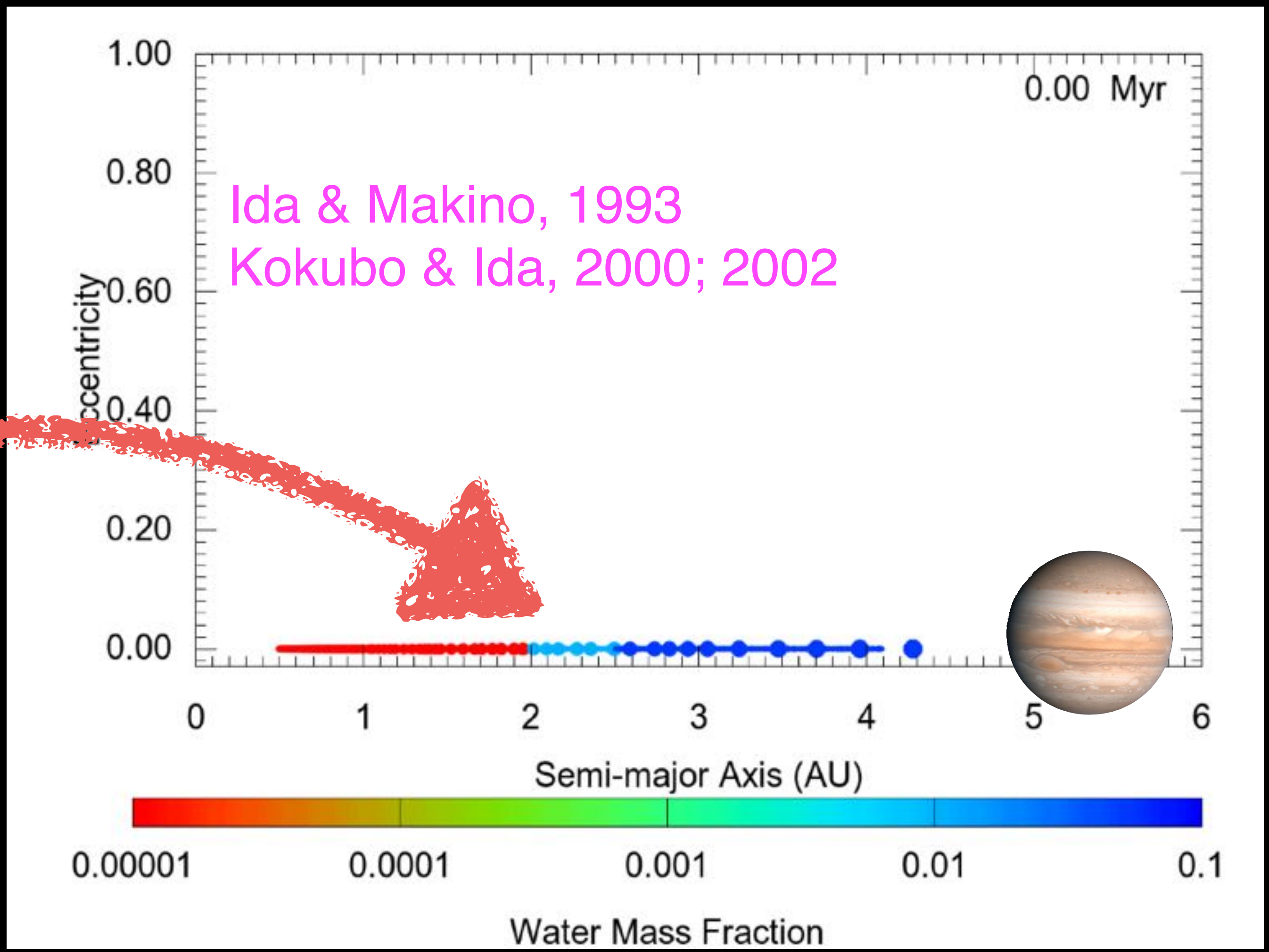

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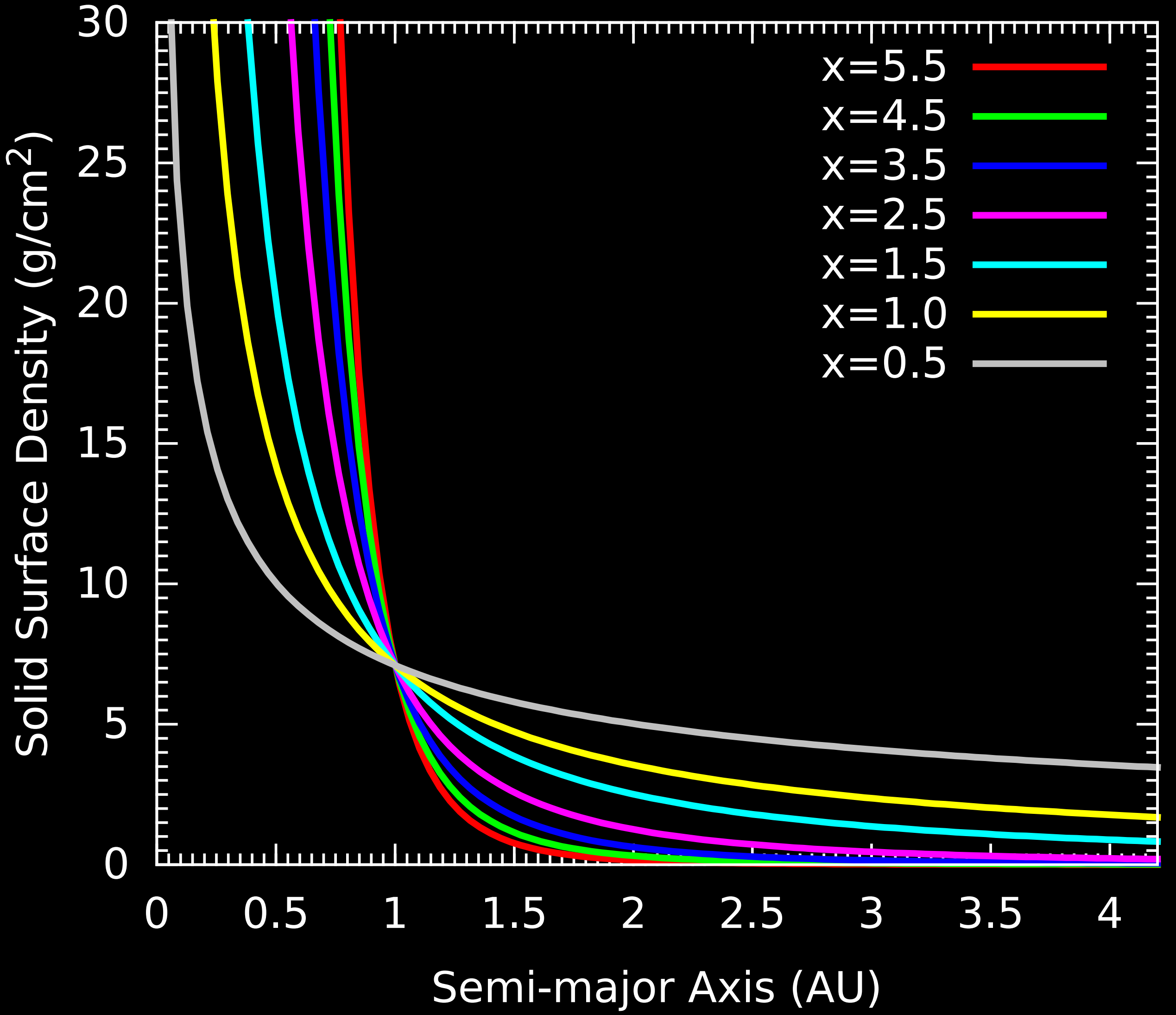

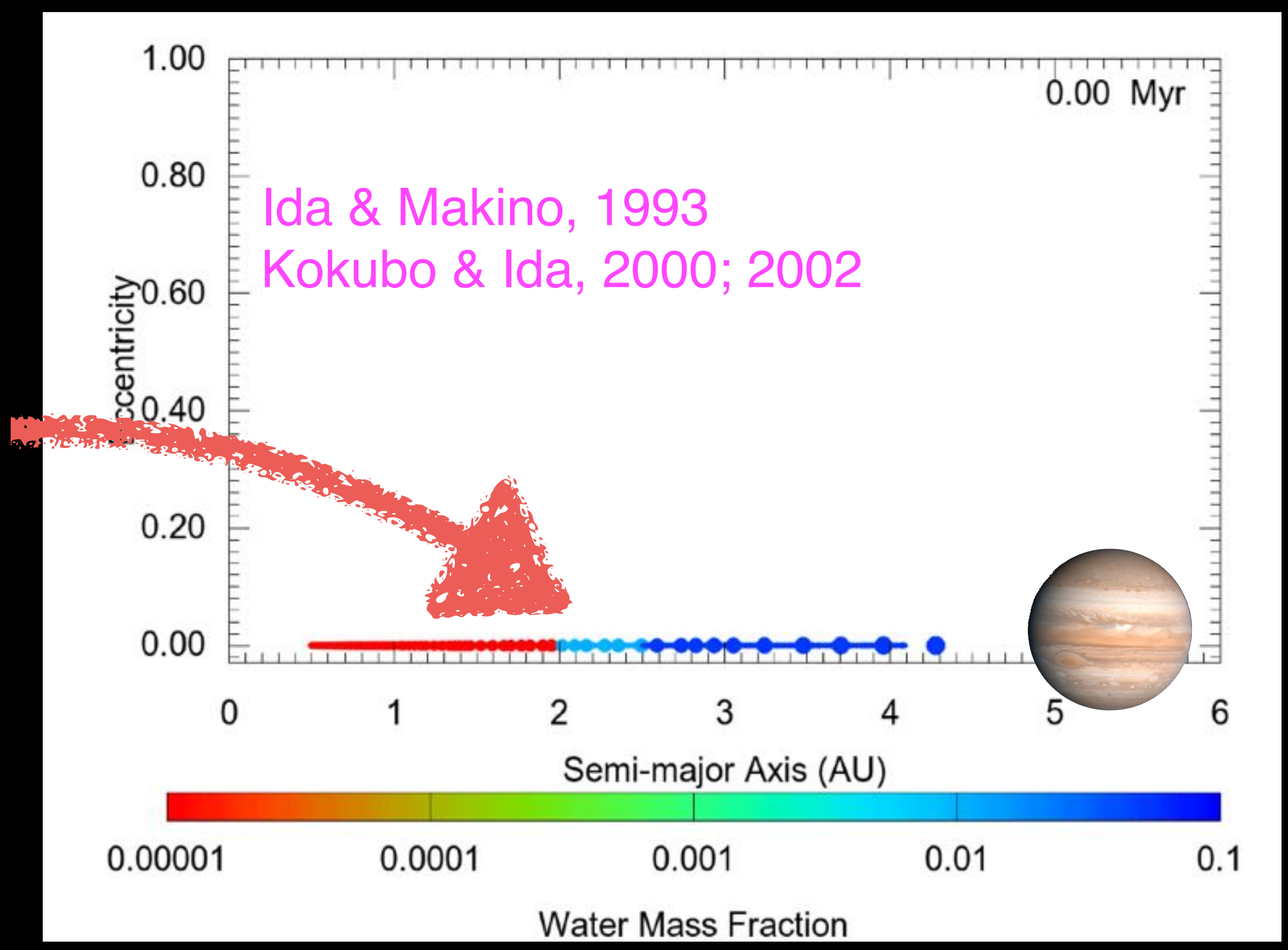

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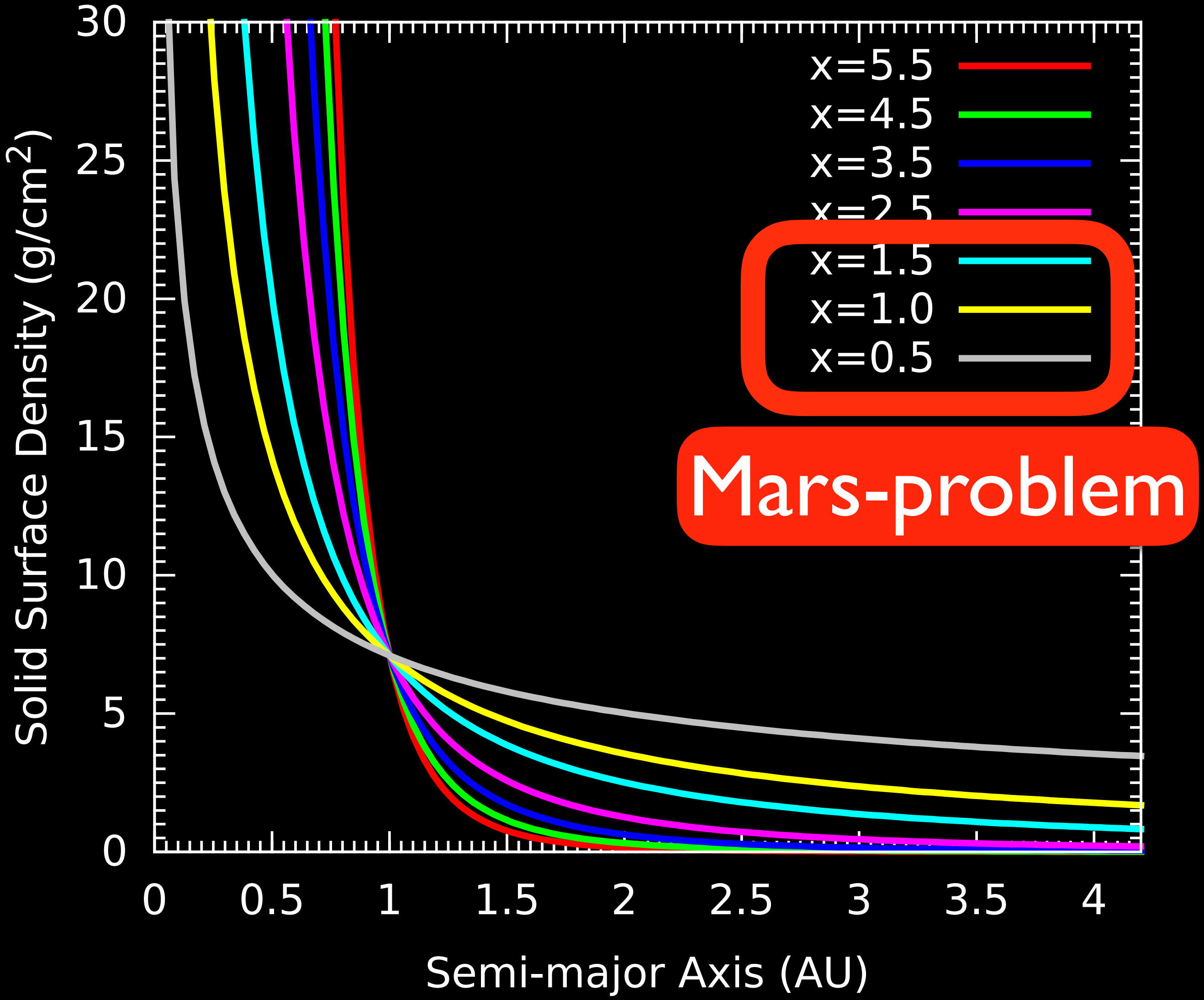

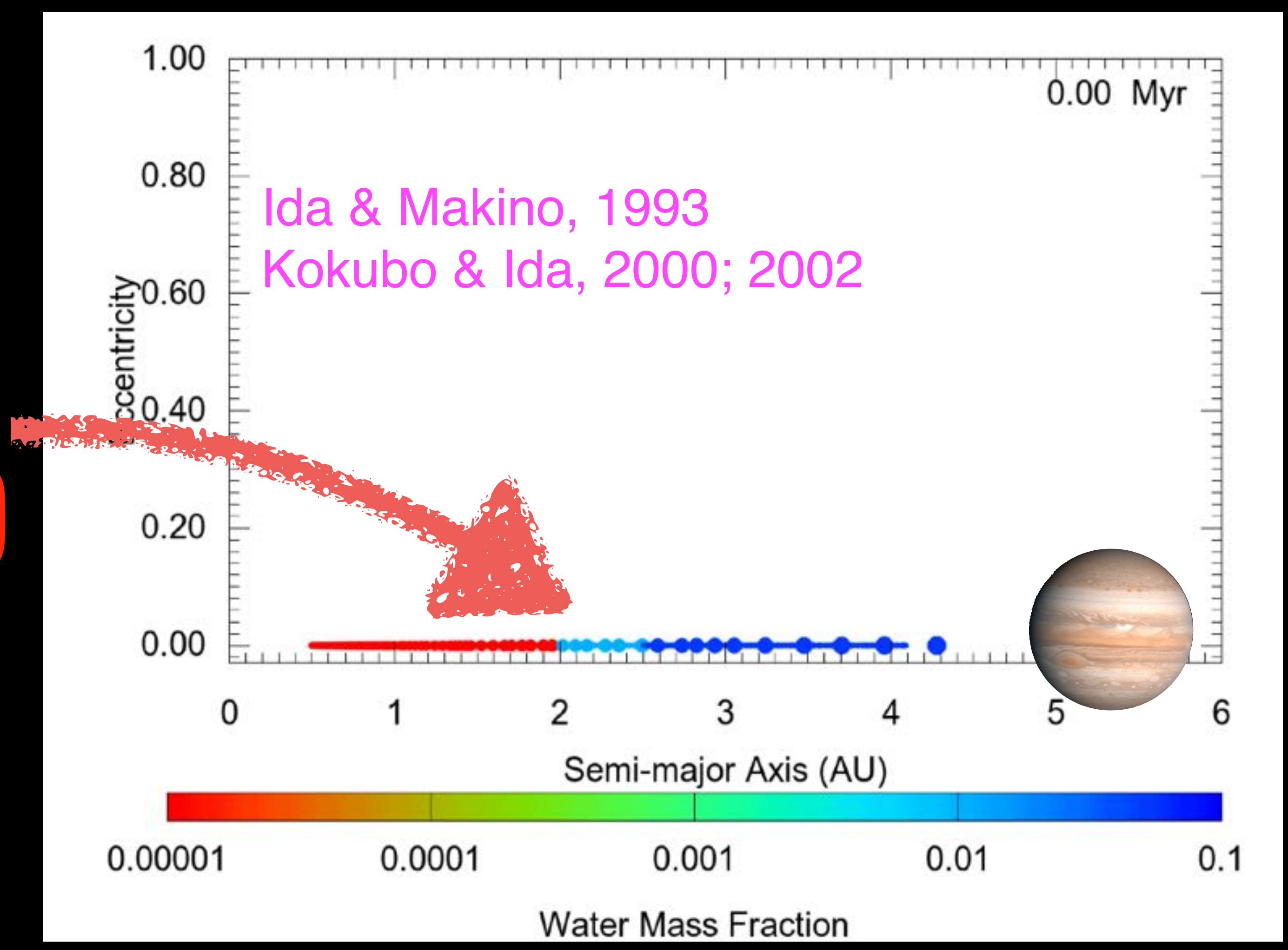

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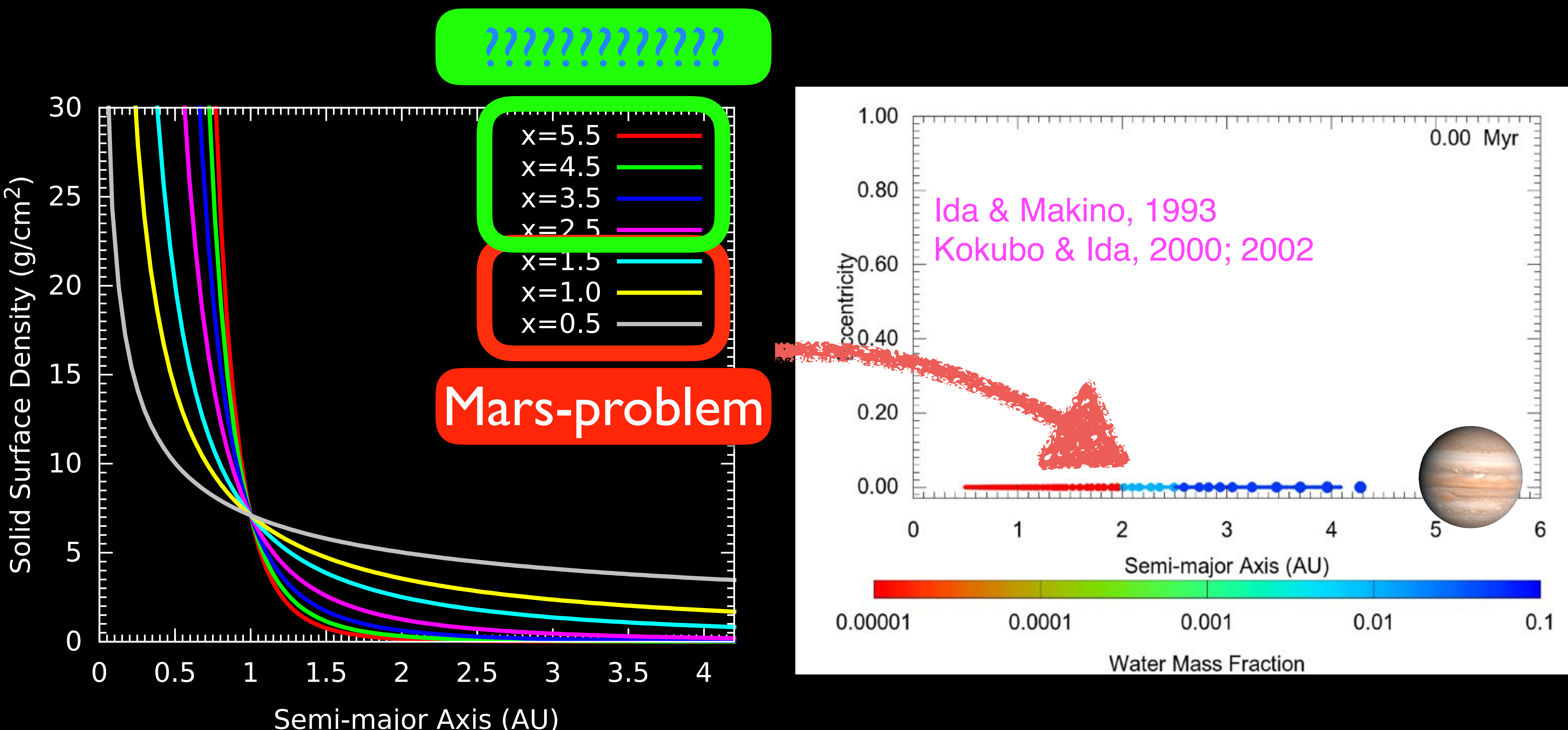

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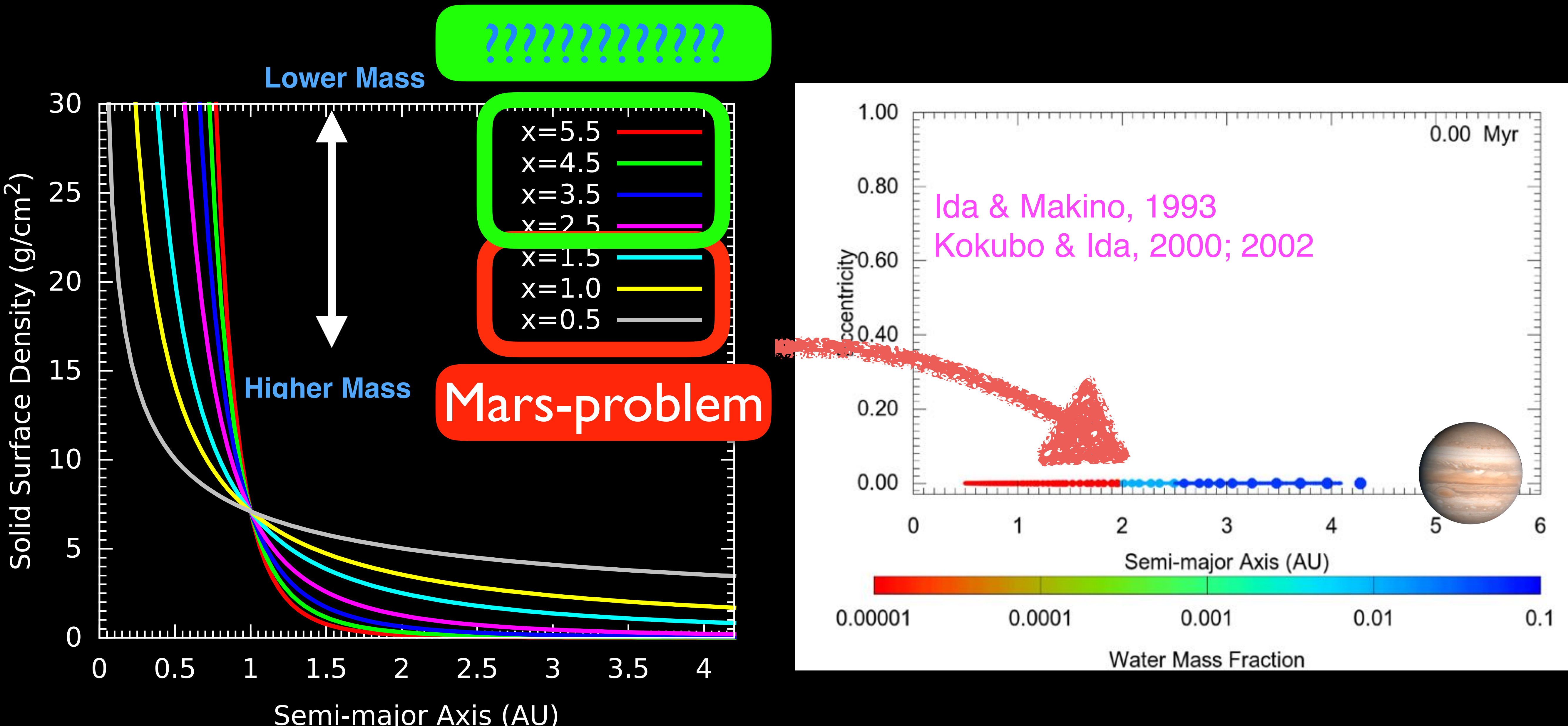
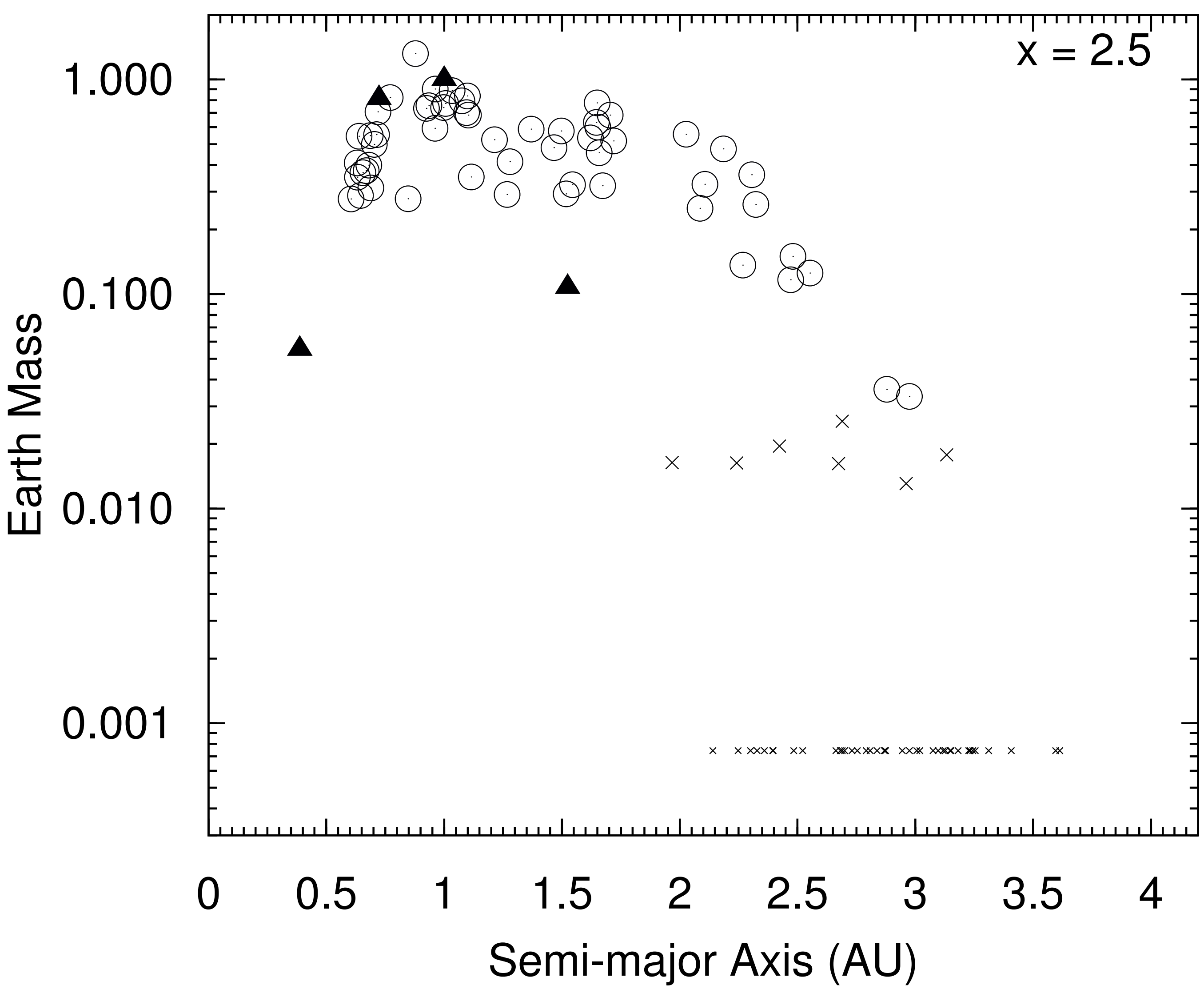
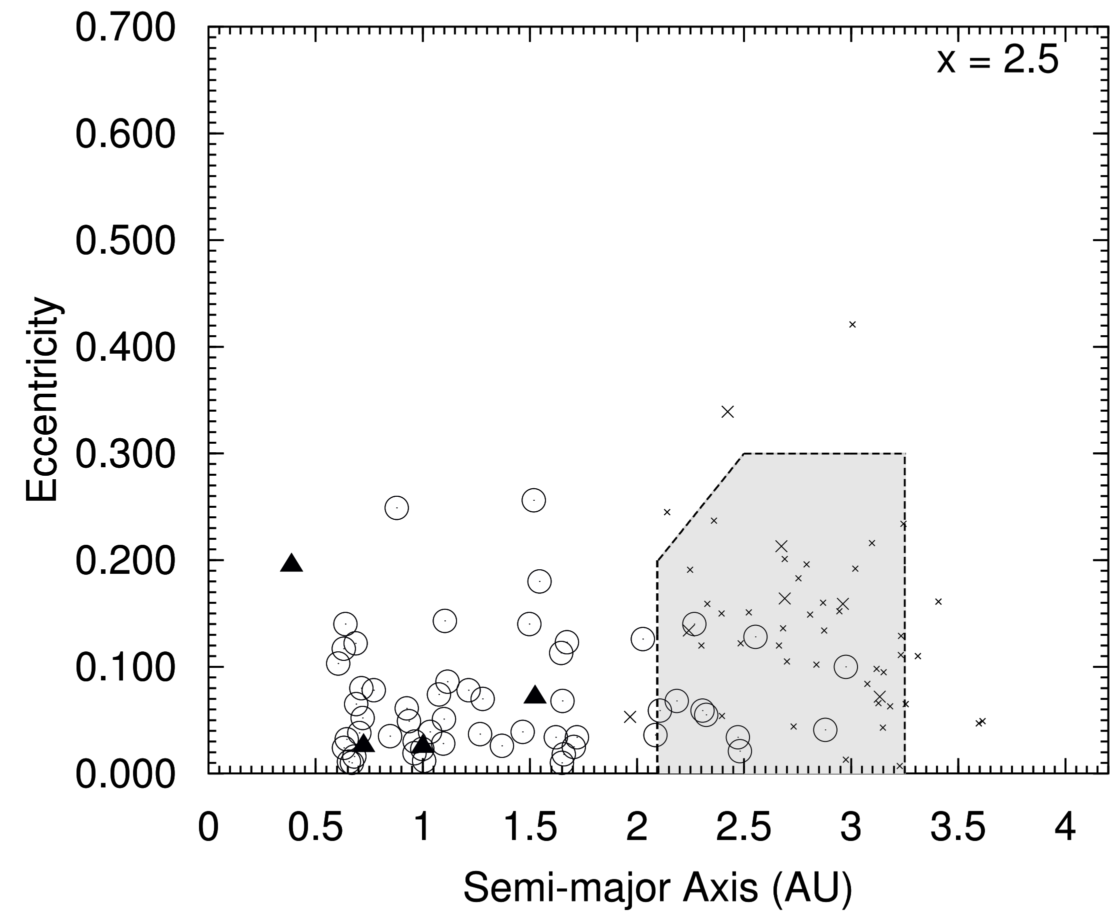
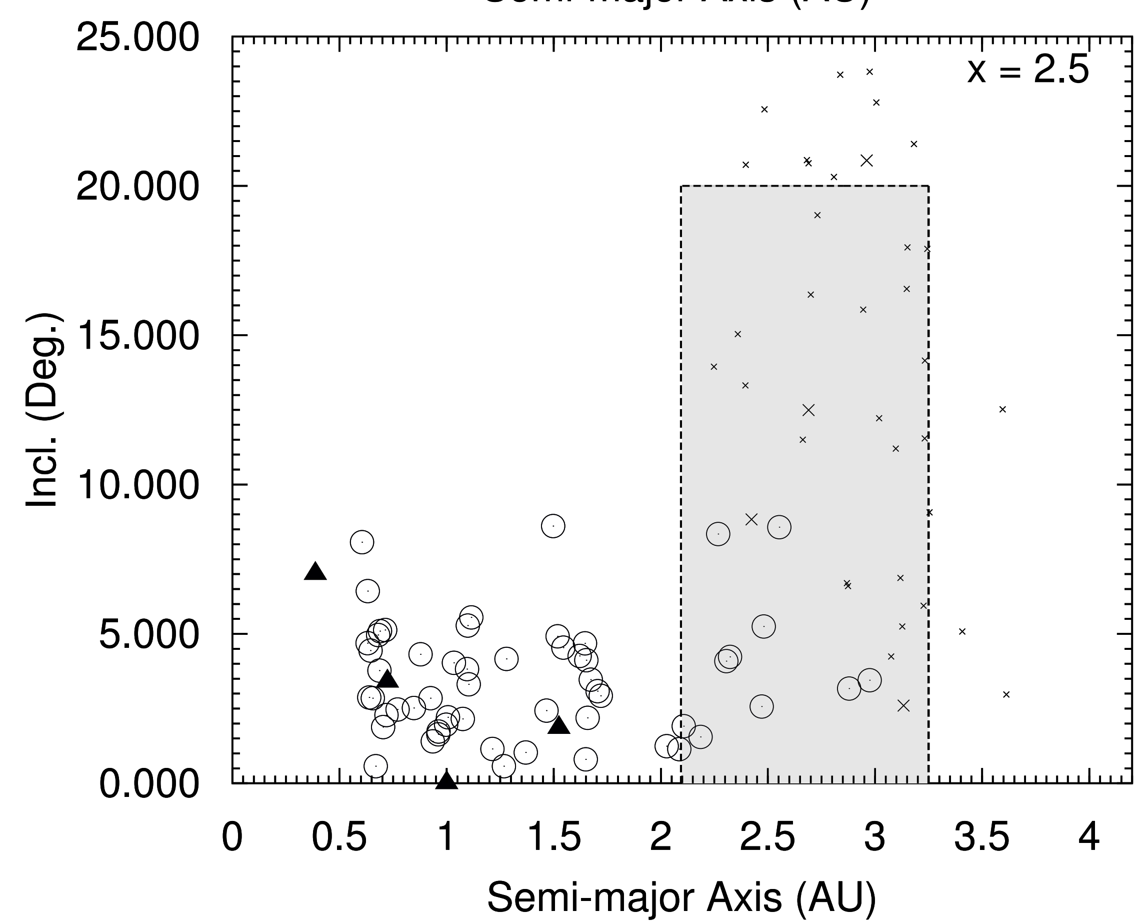


A high-mass asteroid belt has excited orbits but a huge Mars







Izidoro et al., 2015, MNRAS

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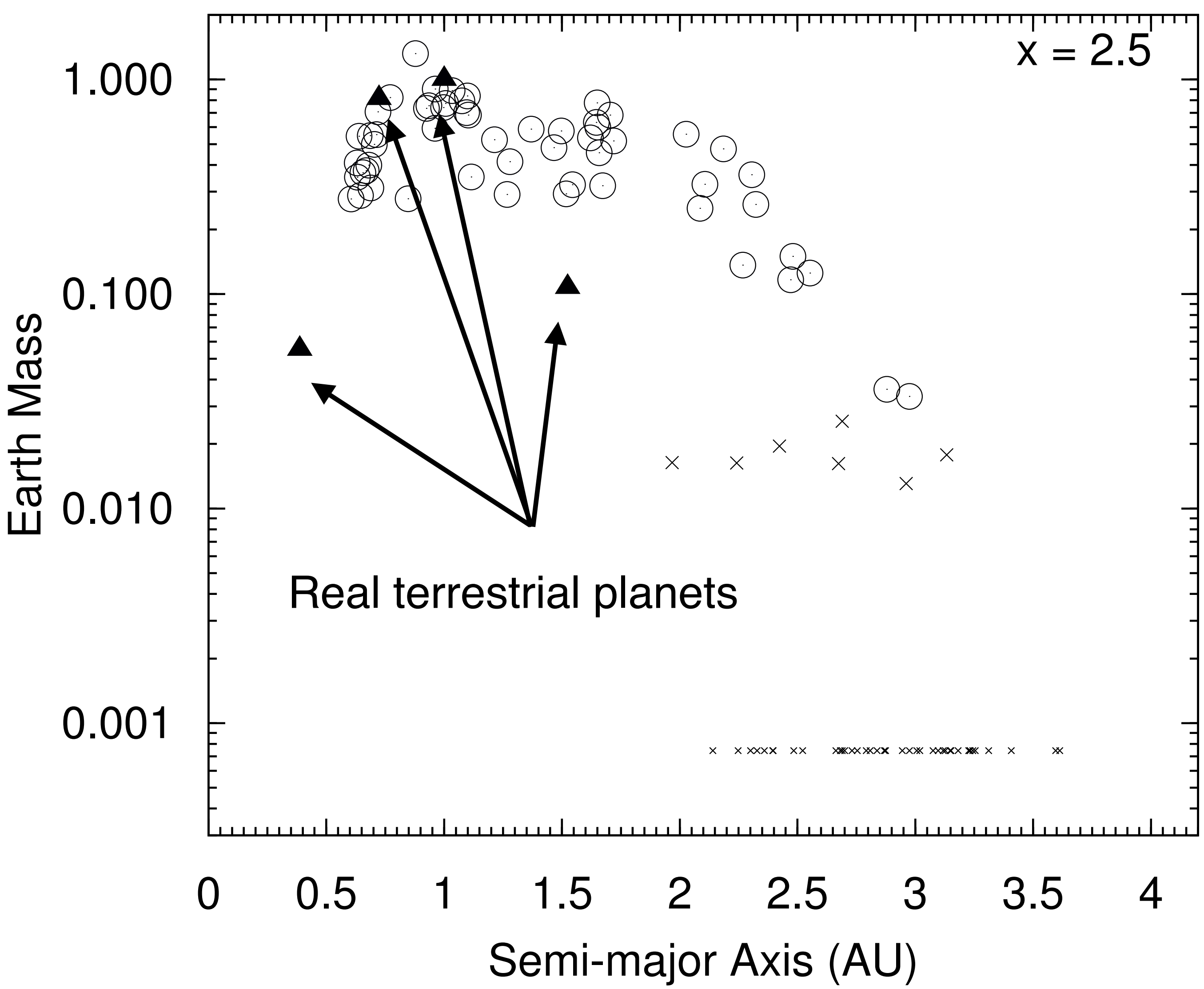

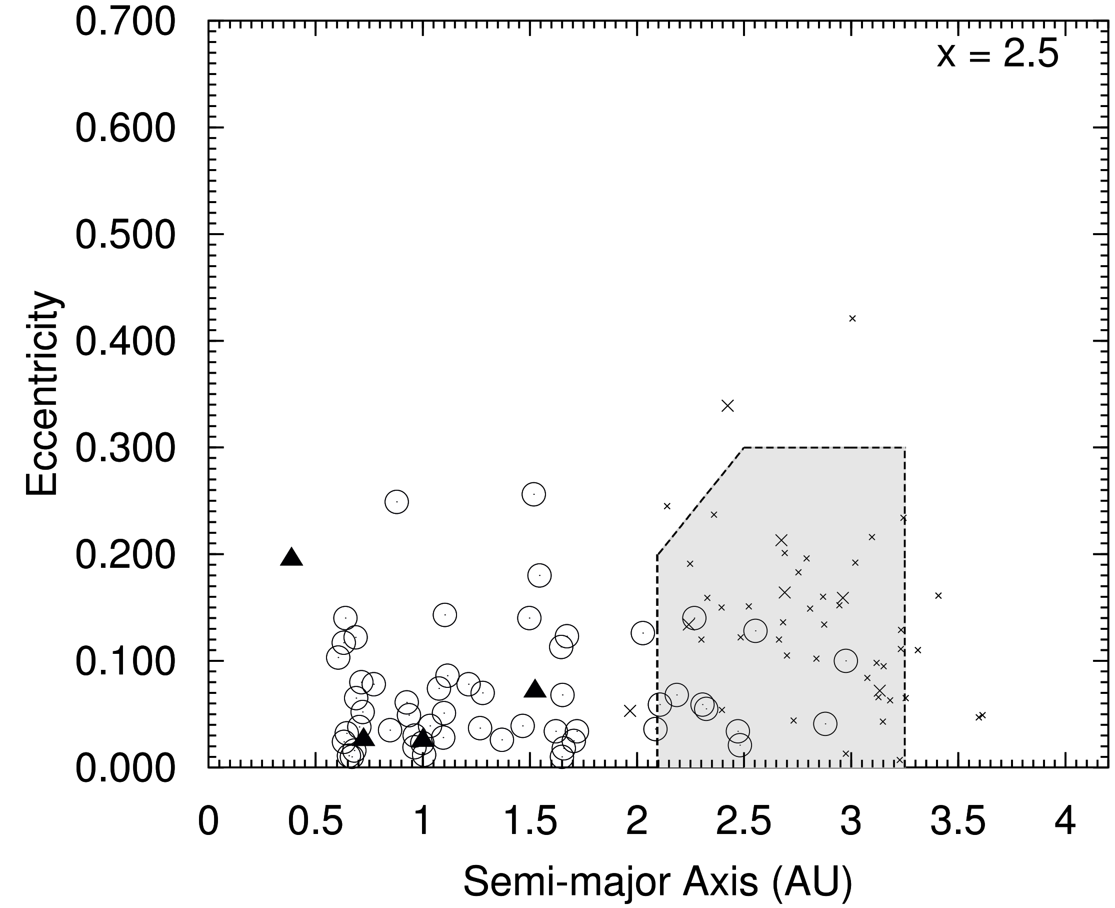

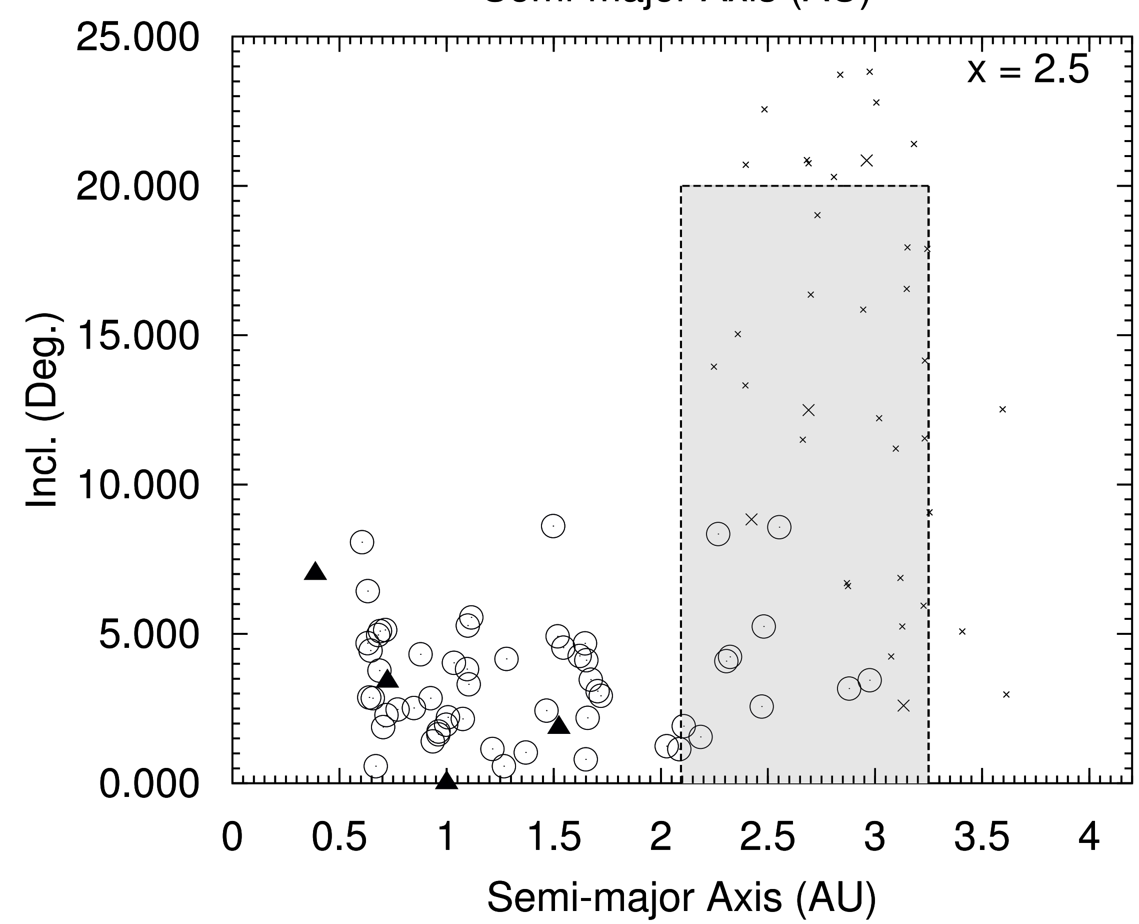

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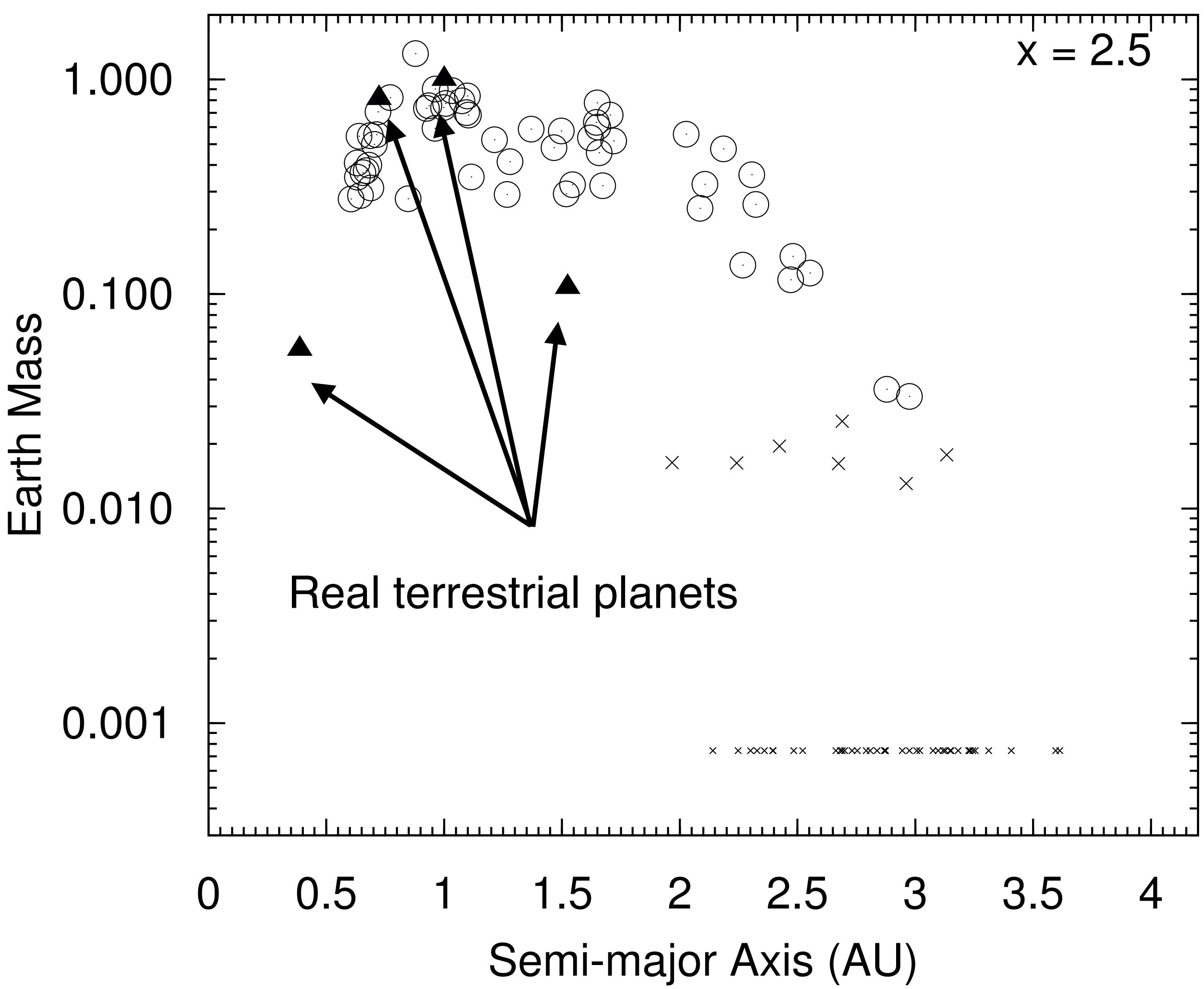

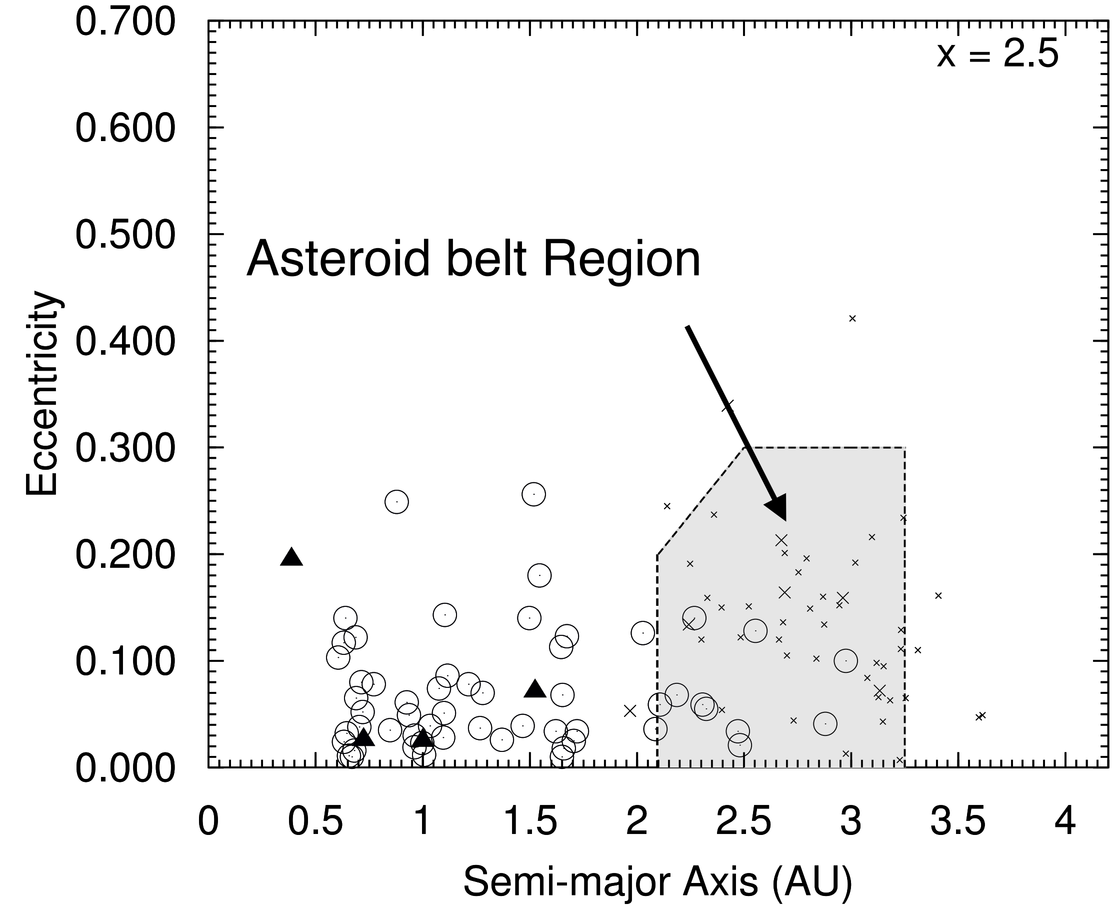

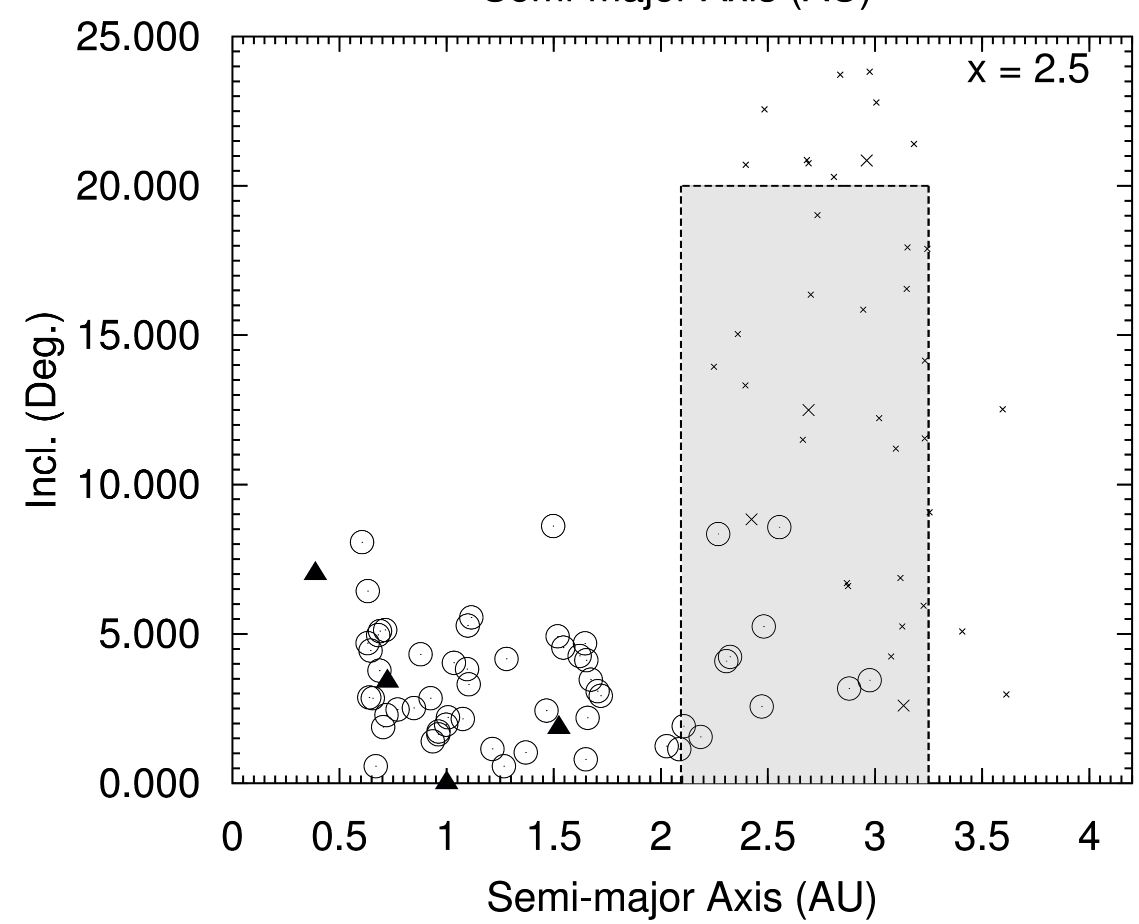

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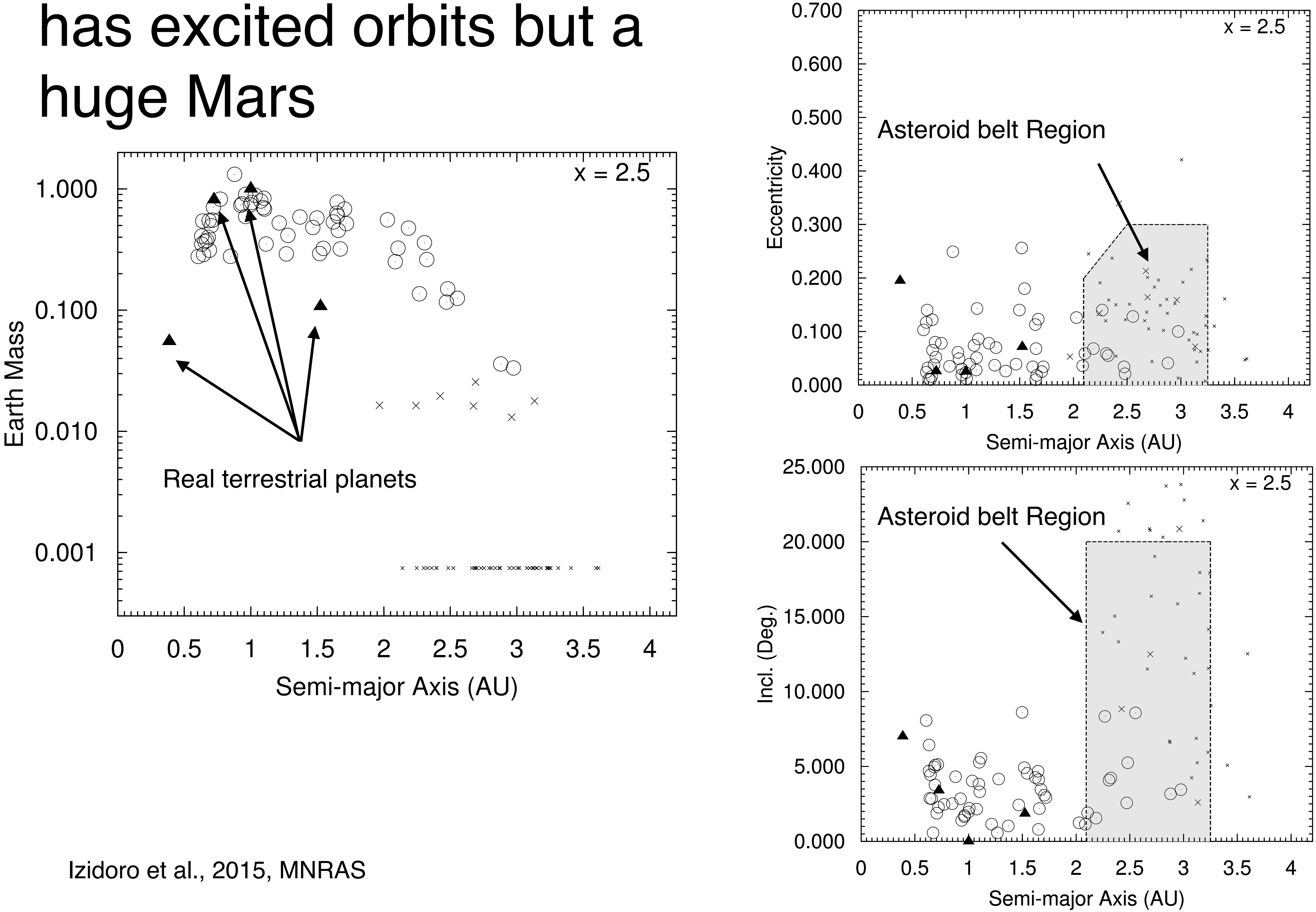

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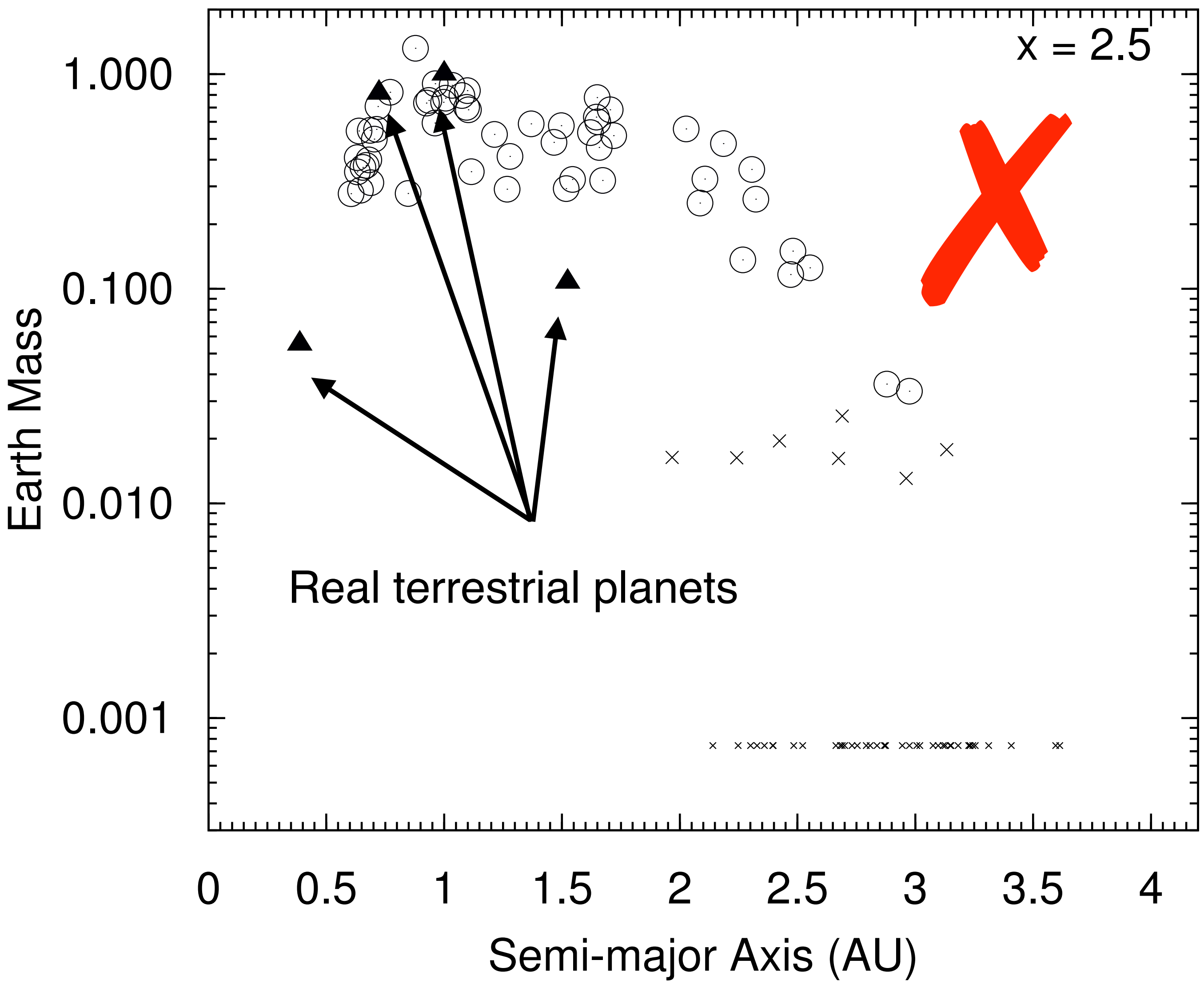
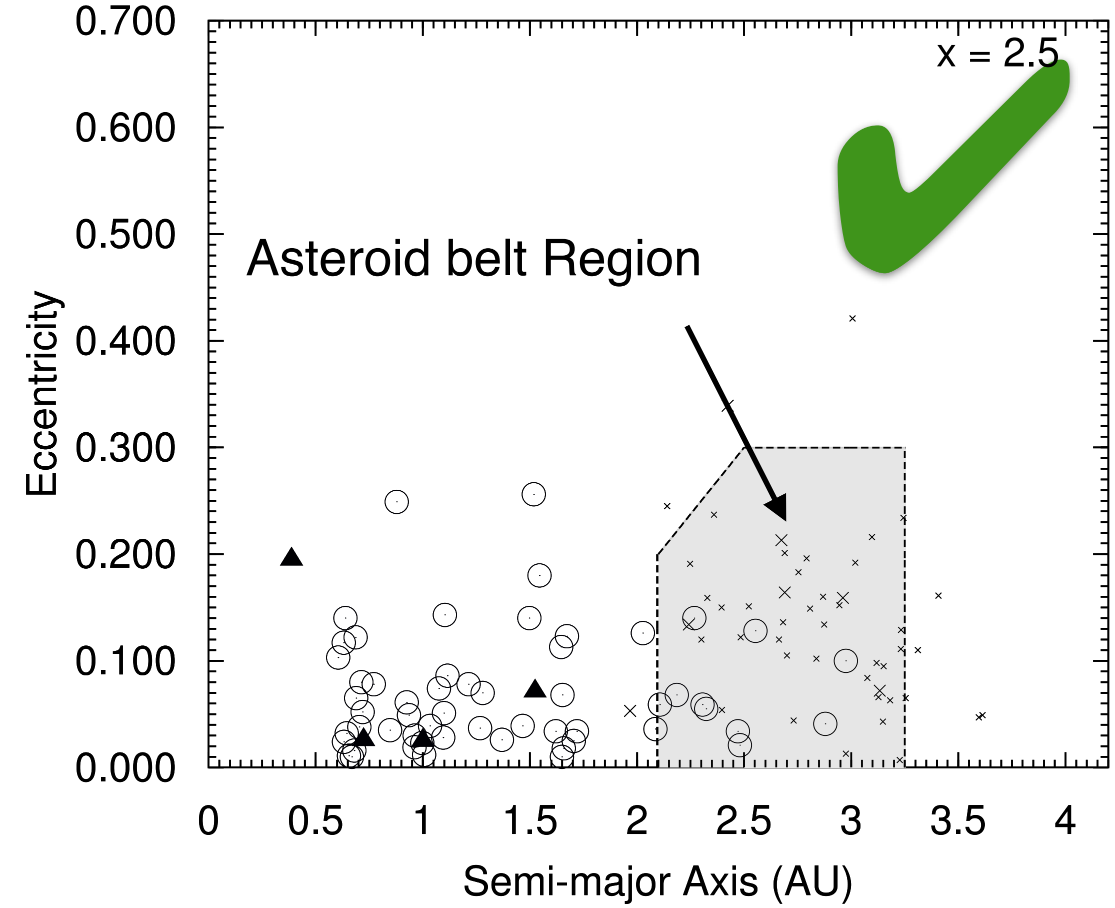
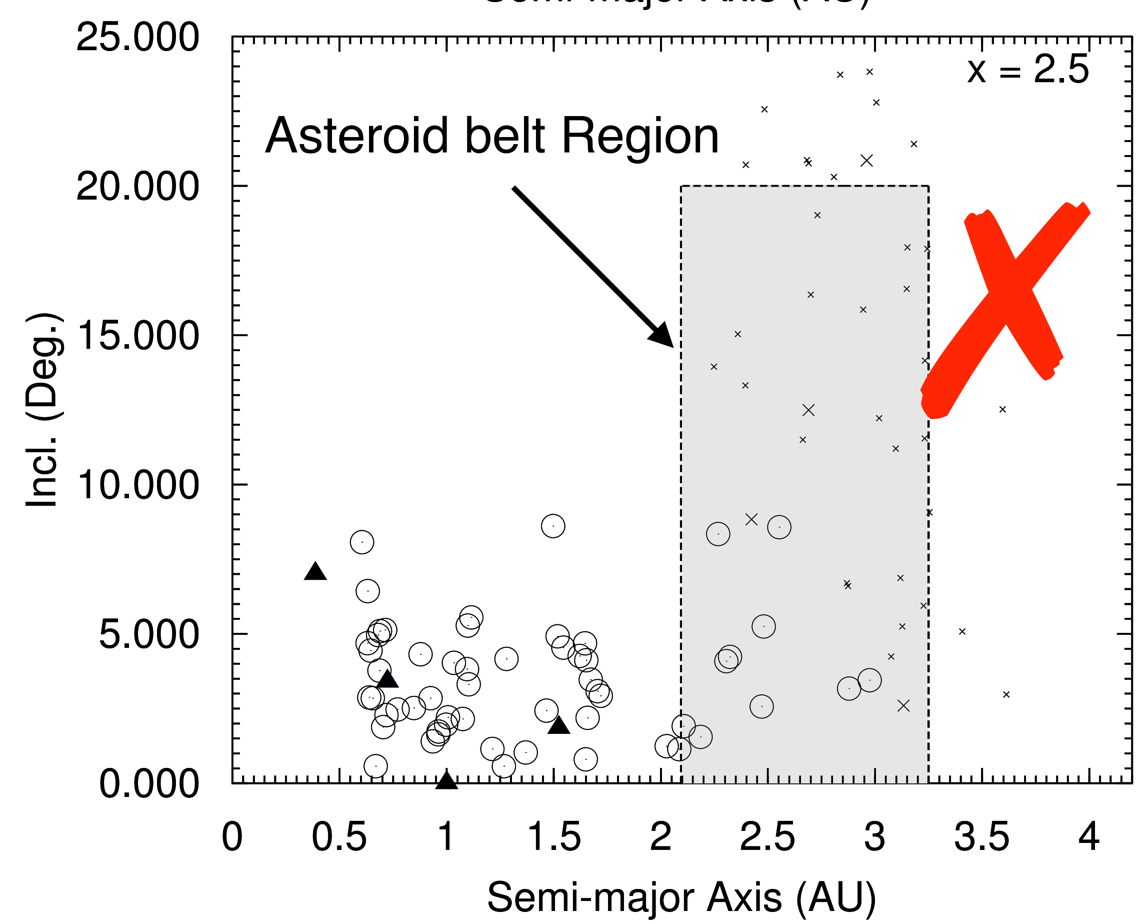
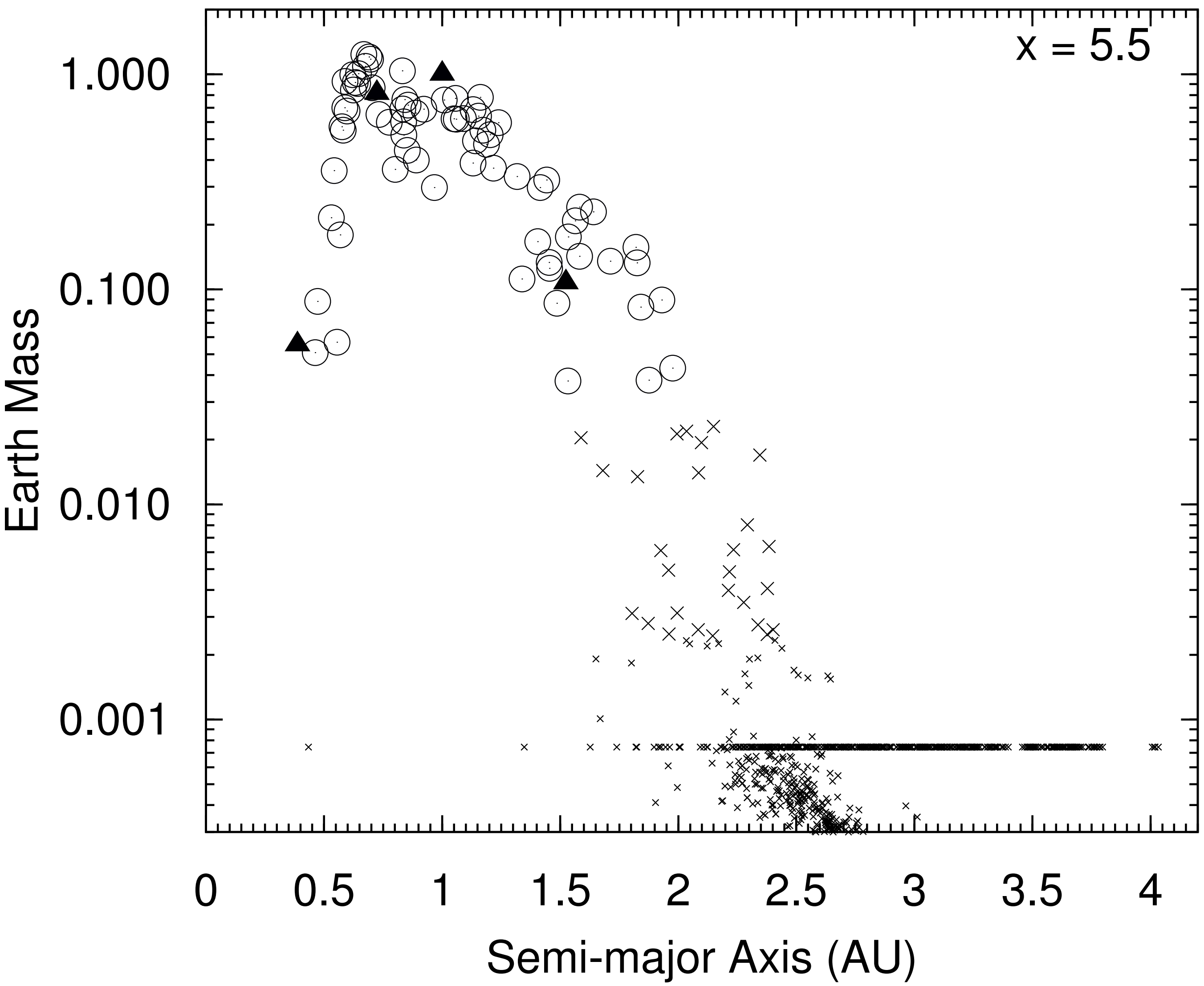


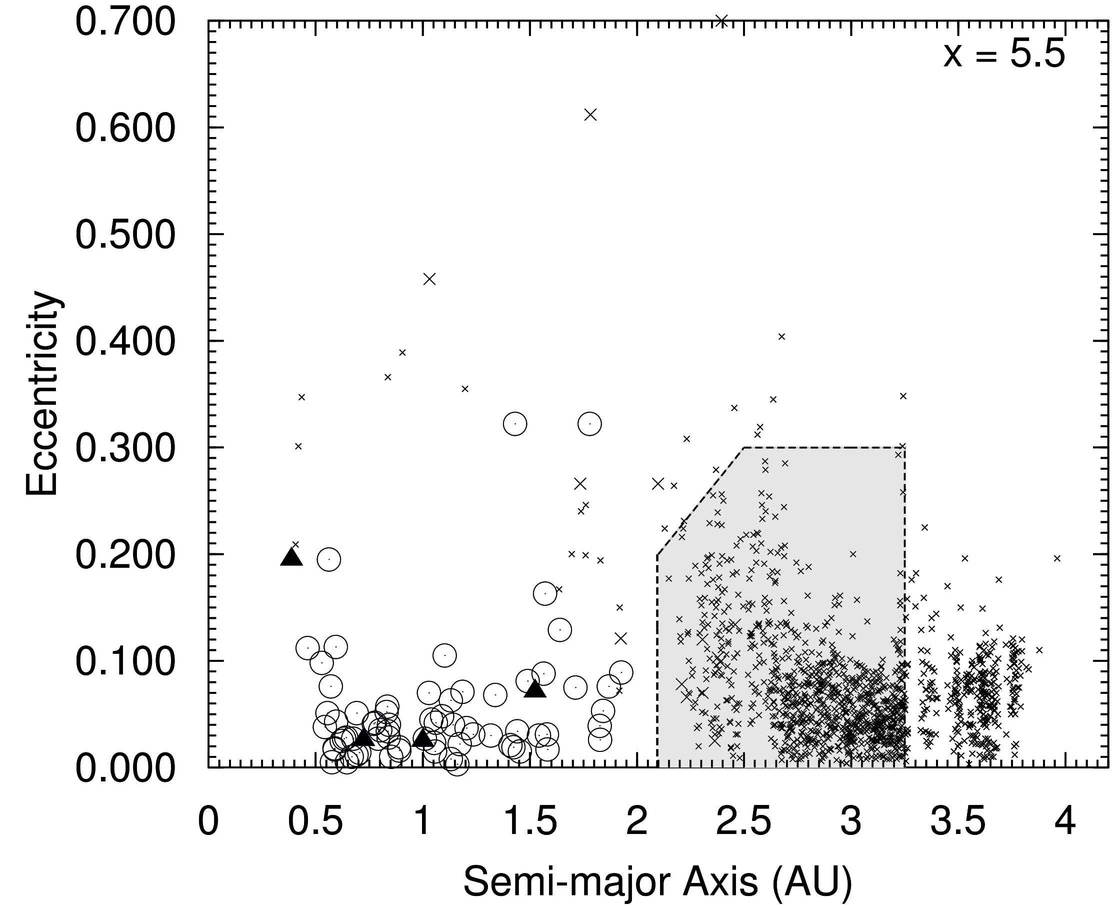


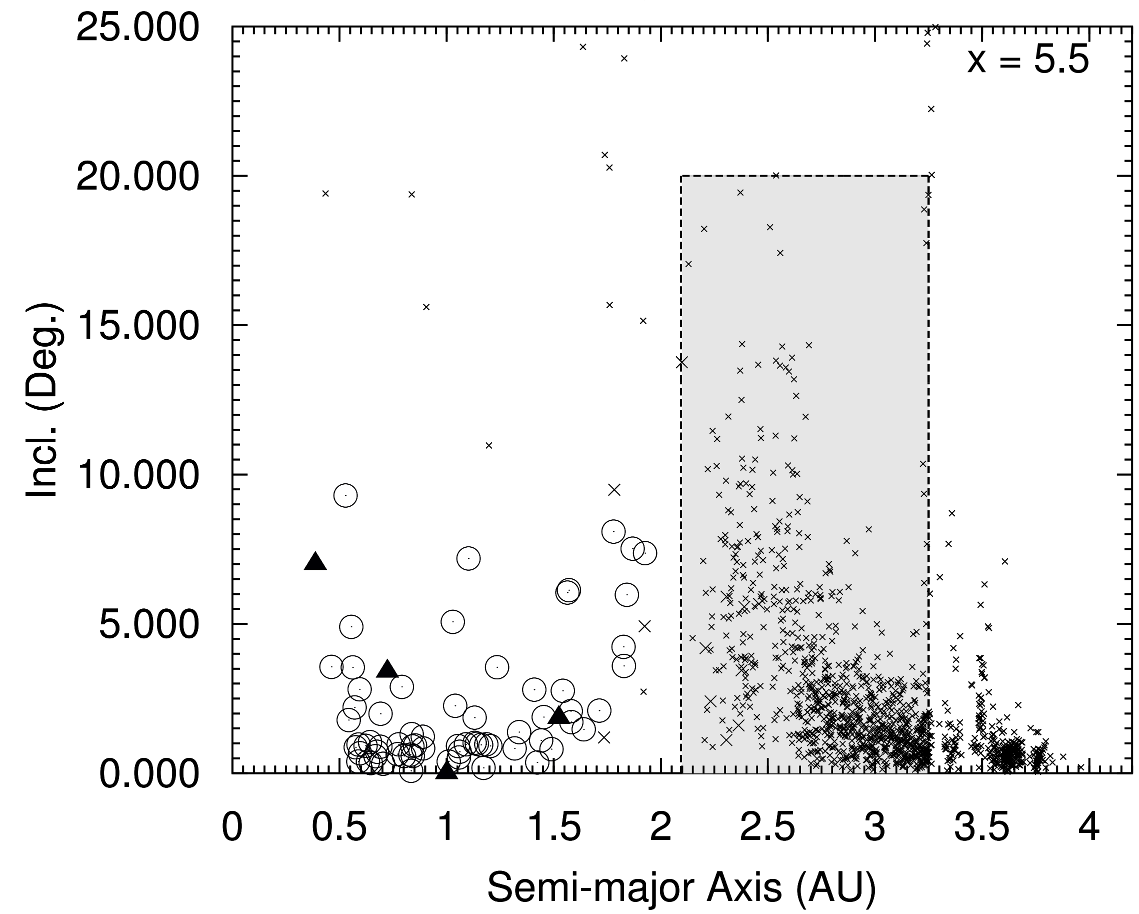


Izidoro et al., 2015, MNRAS

A low-mass asteroid belt is under-excited

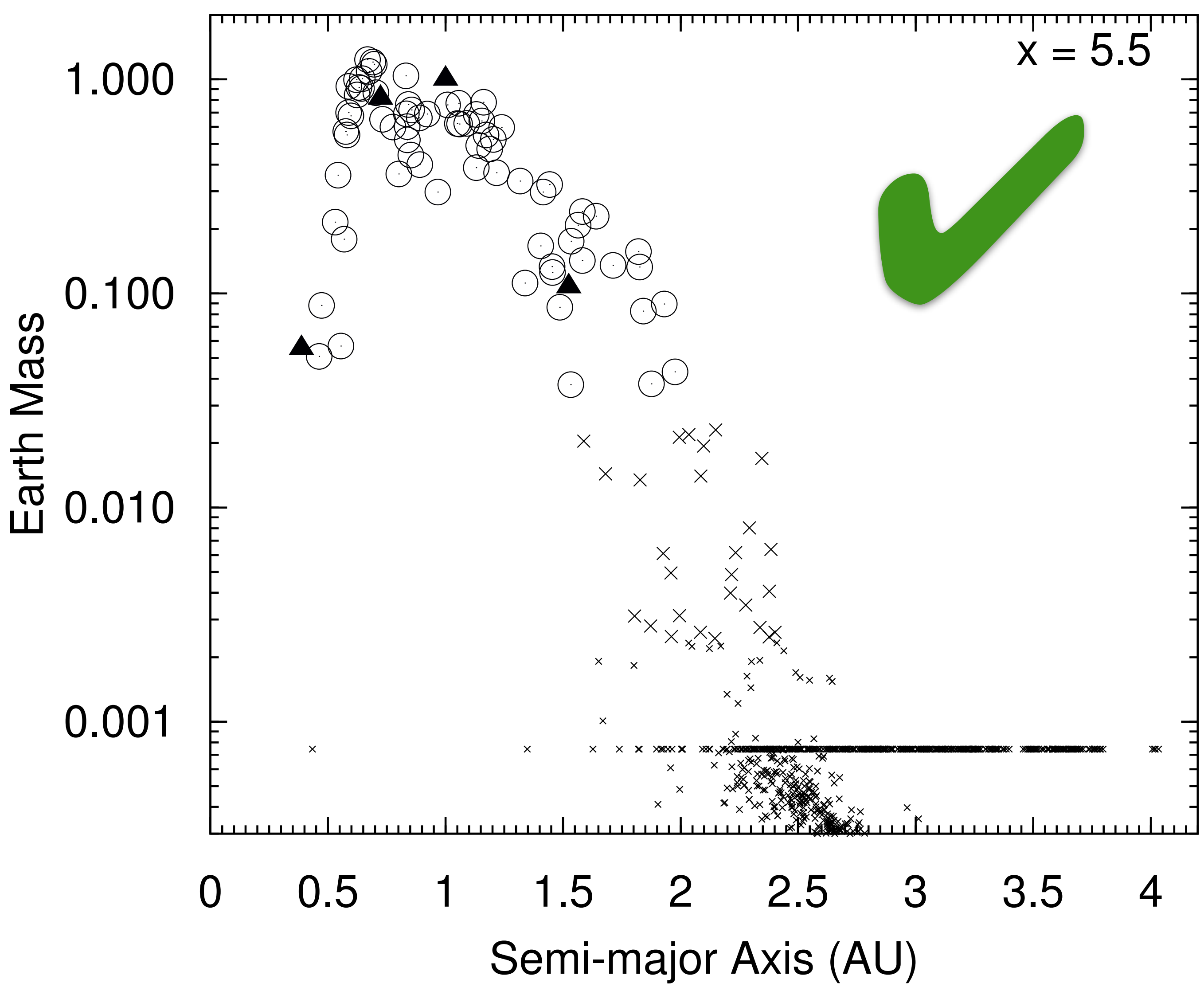


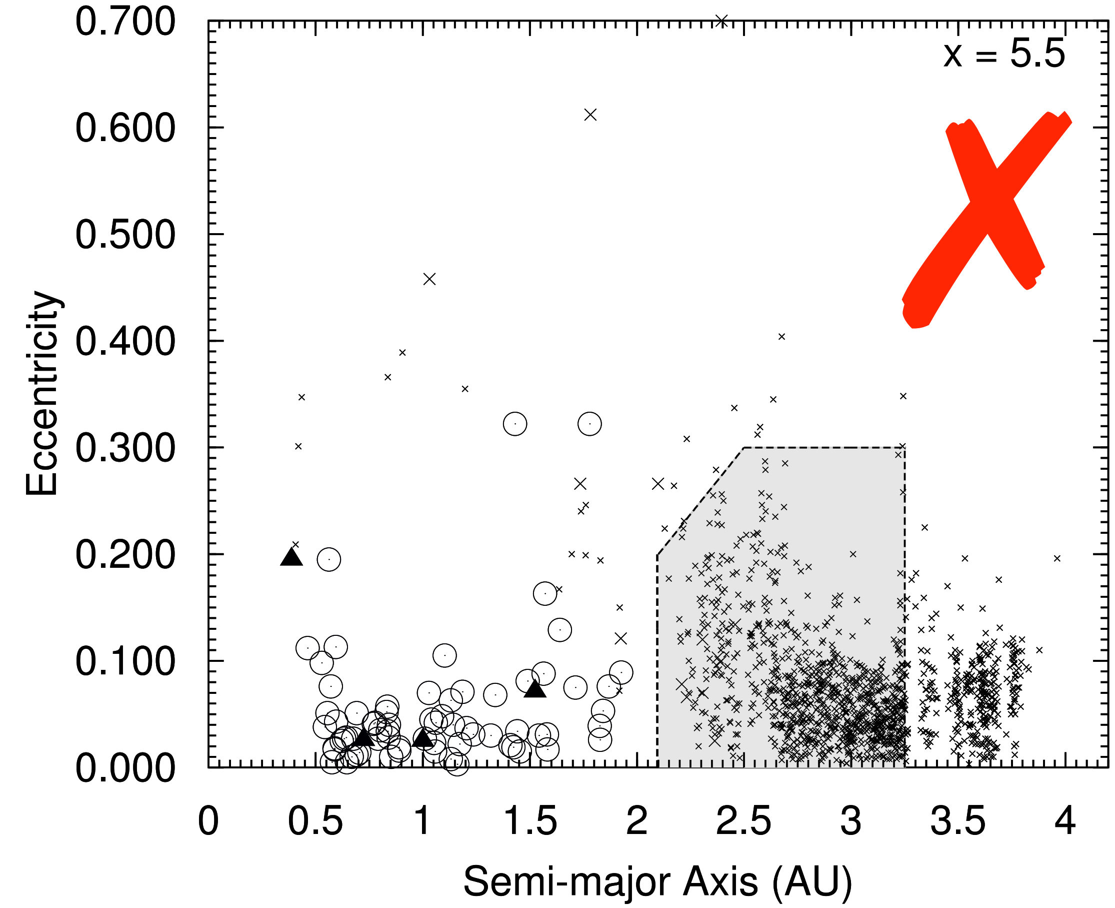


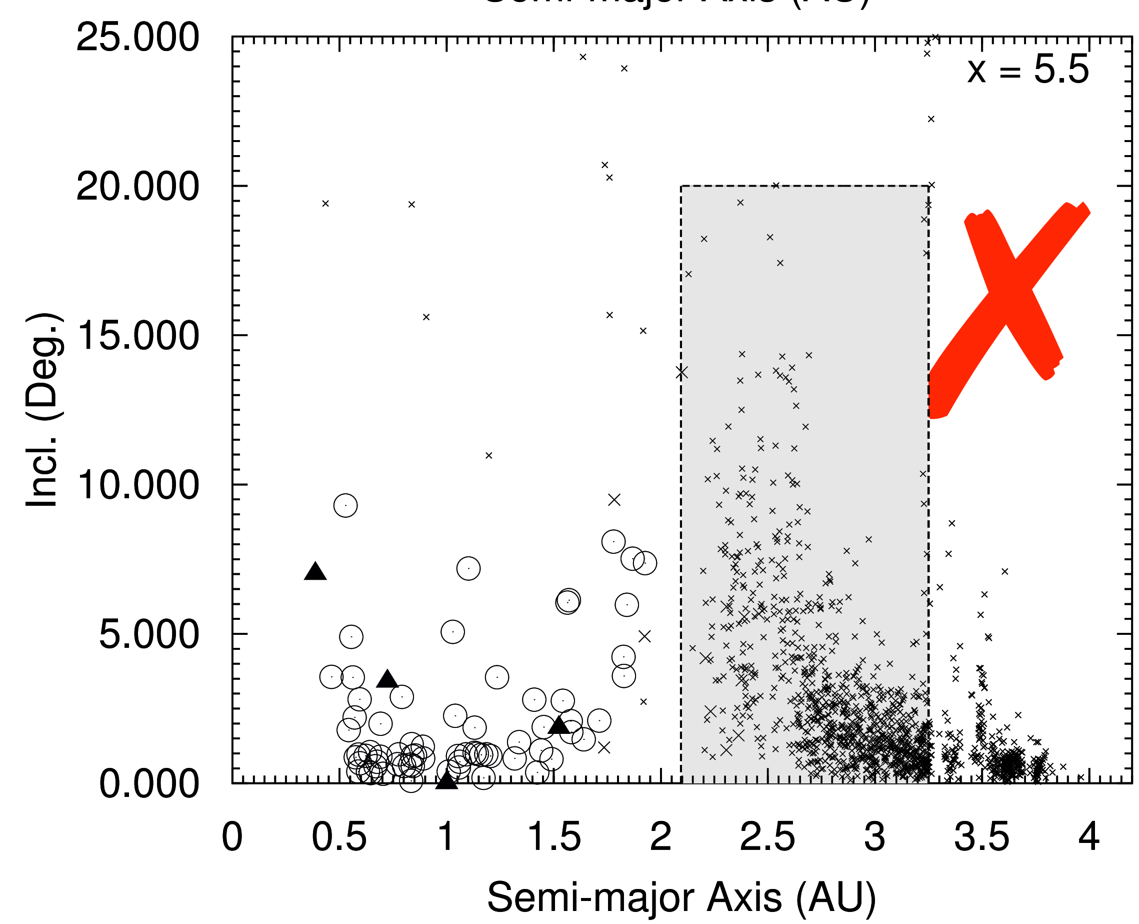


Izidoro et al., 2015, MNRAS

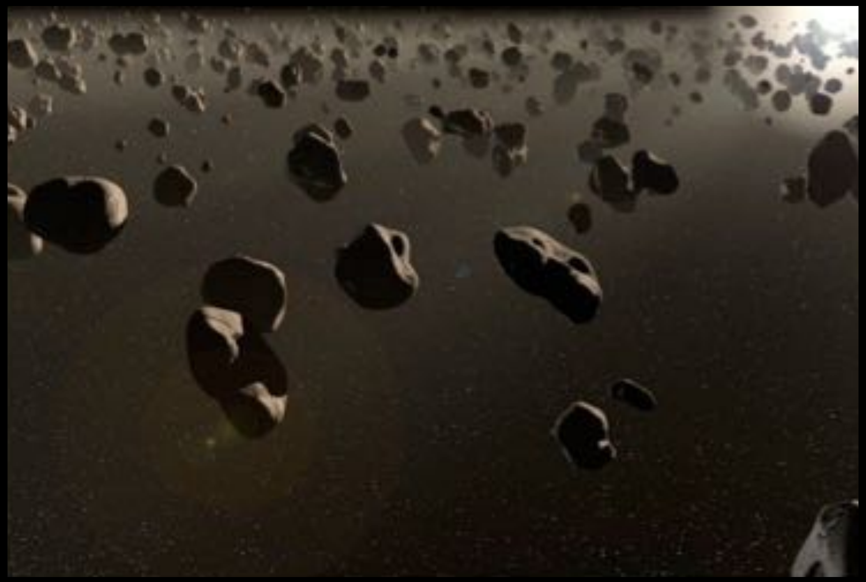
A low-mass asteroid belt is under-excited

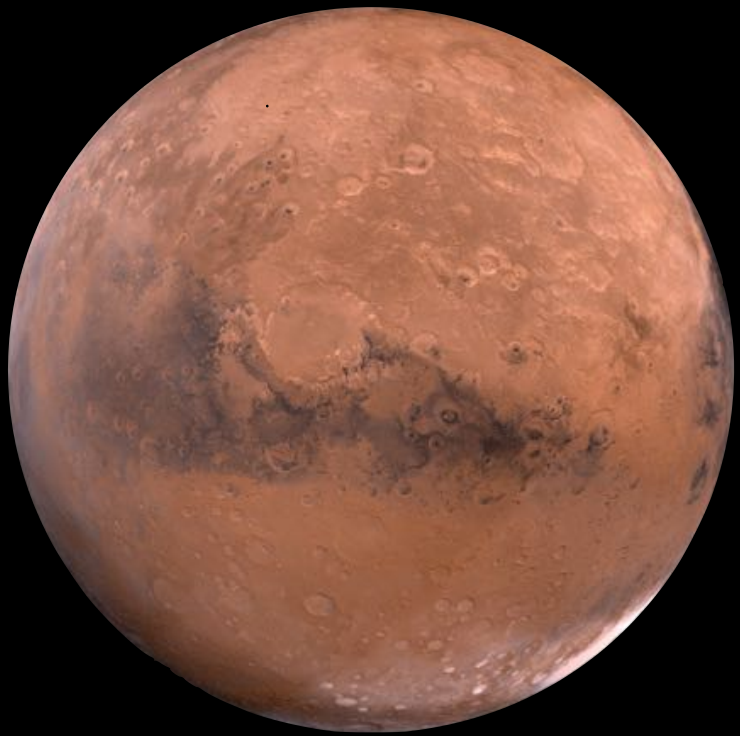


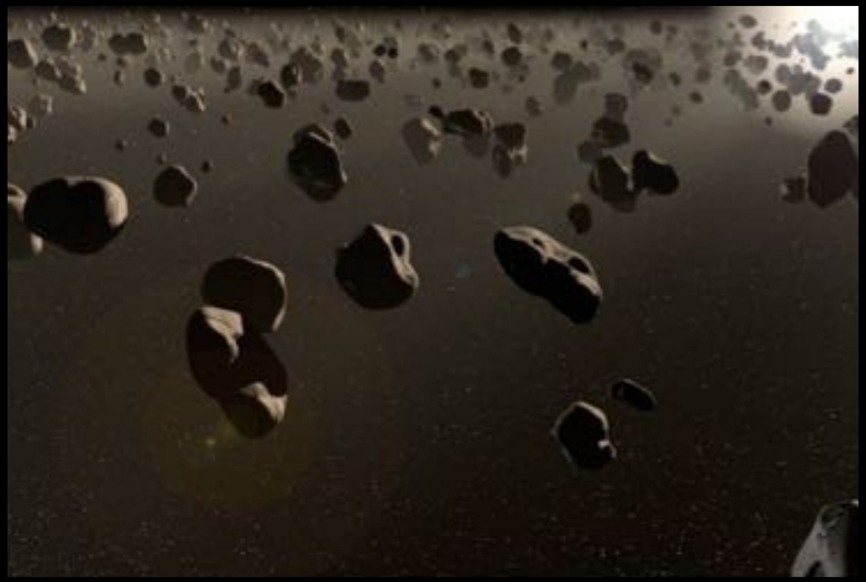




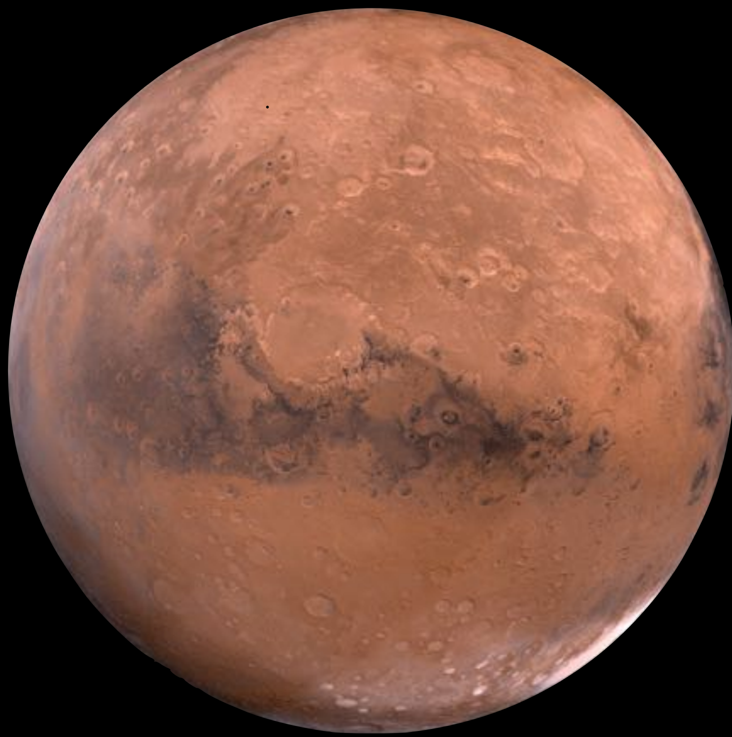
Izidoro et al., 2015, MNRAS

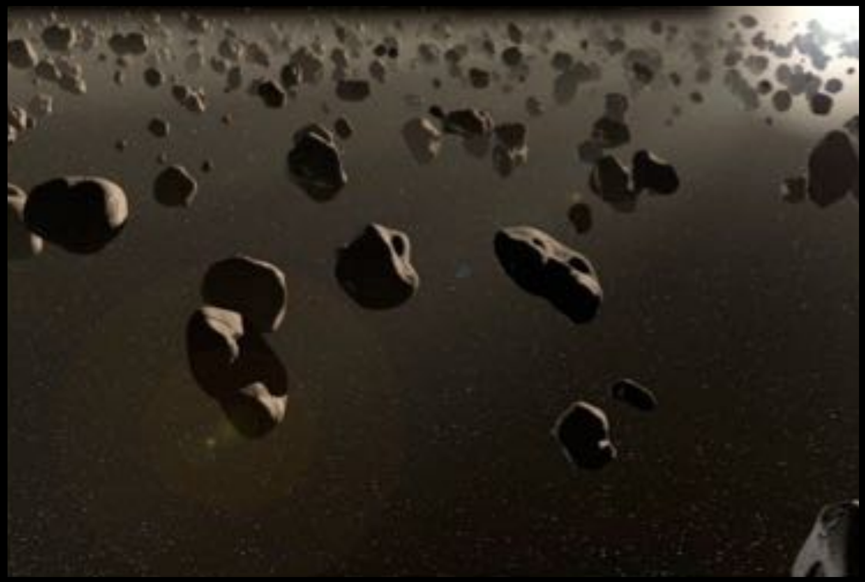







For small Mars,
need mass deficit





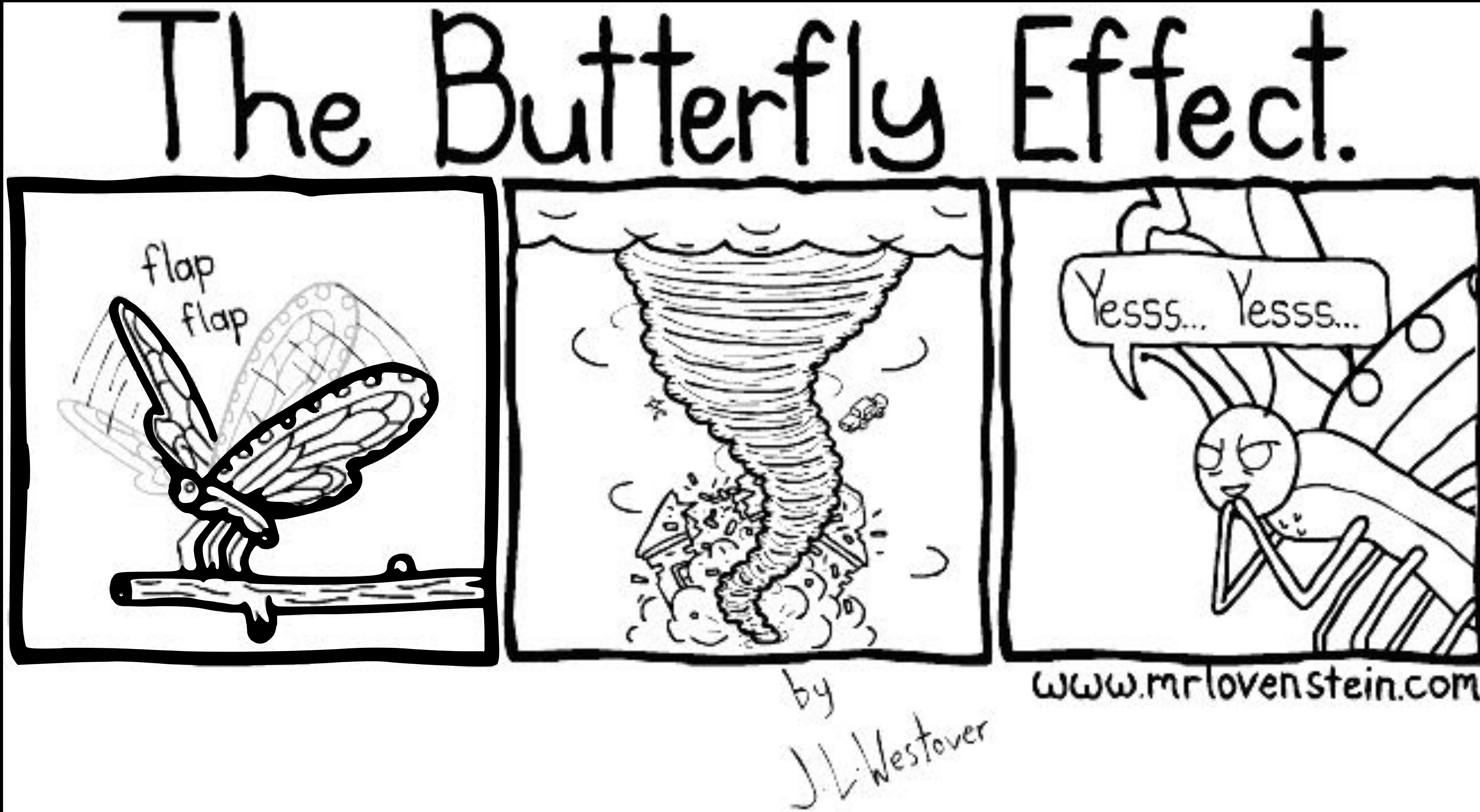
For small Mars,
need mass deficit

With mass deficit,
asteroid belt is
under-excited

Izidoro et al (2015, MNRAS)

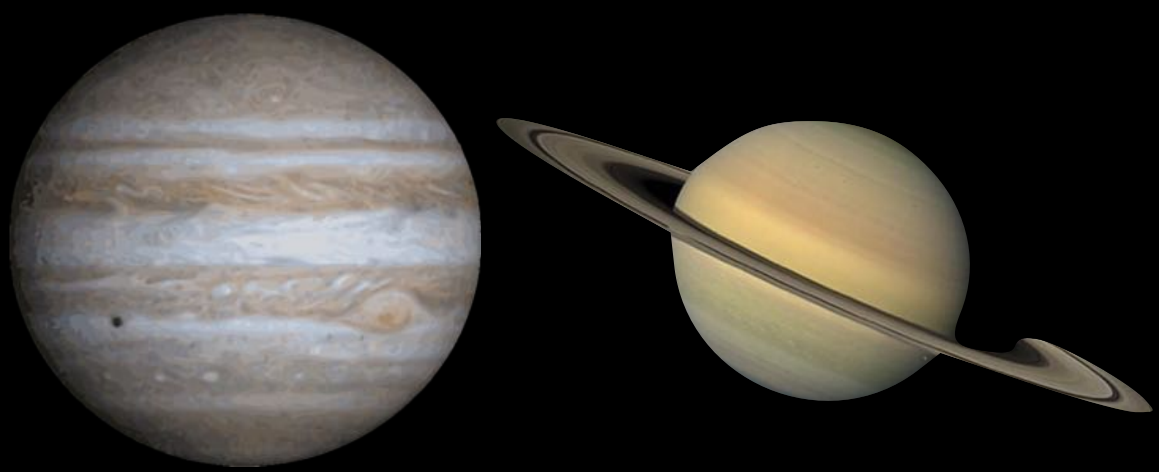
The Missing Ingredient…

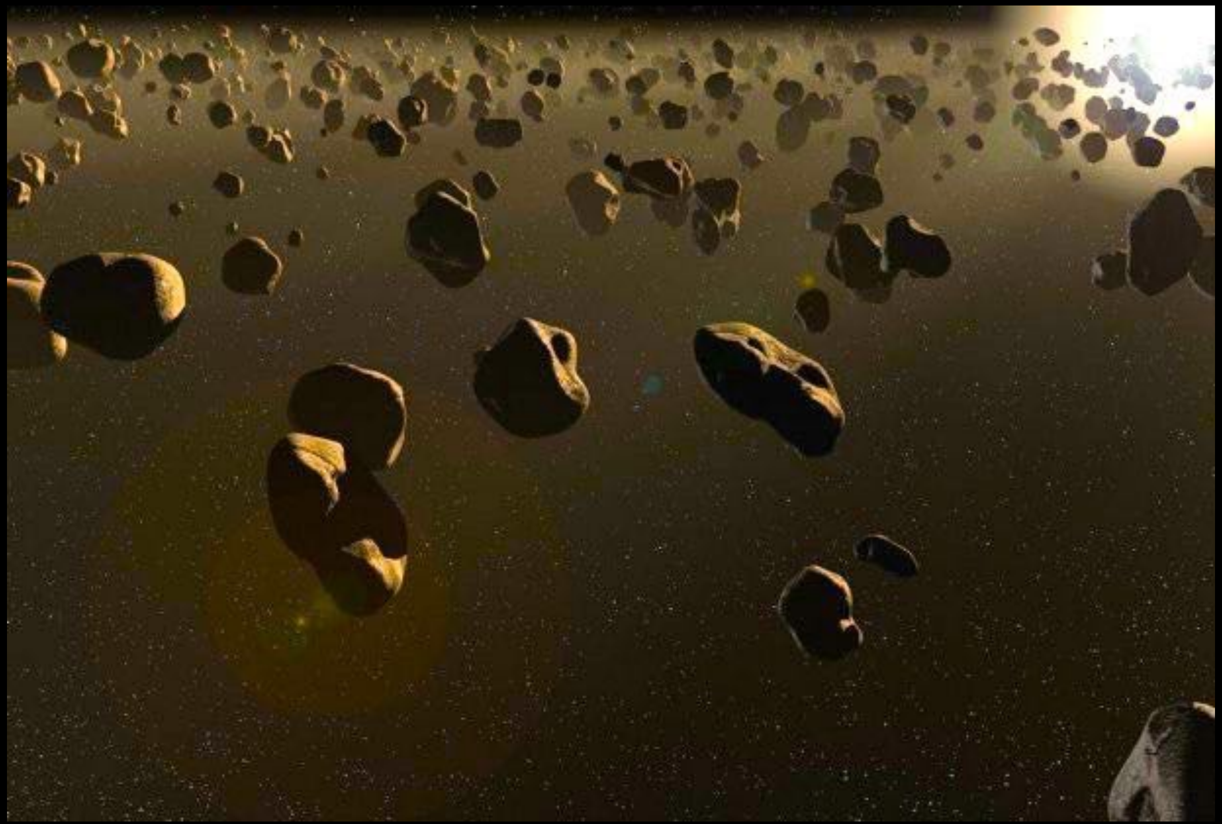
The Missing Ingredient…



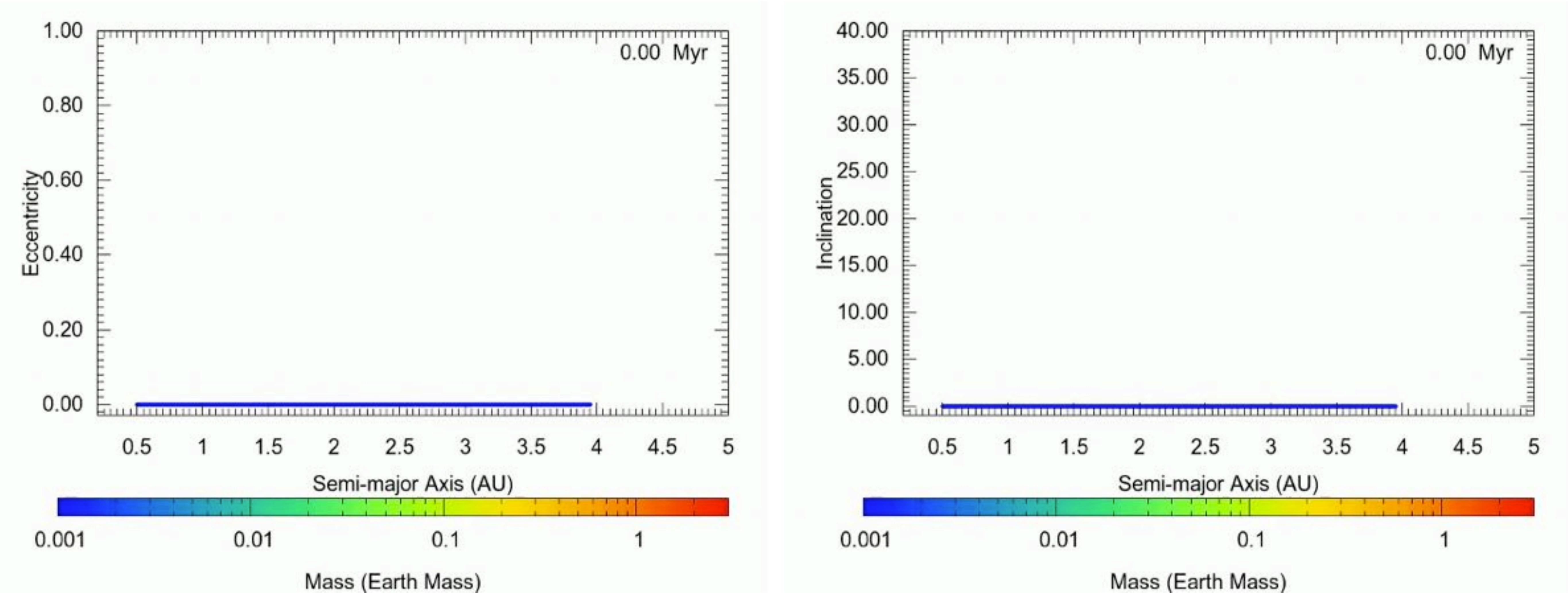
The Butterfly Effect.
flap
flap
Yesss... Yesss...
www.mrlovenstein.com
by J.L.Westover

The Butterfly Effect.



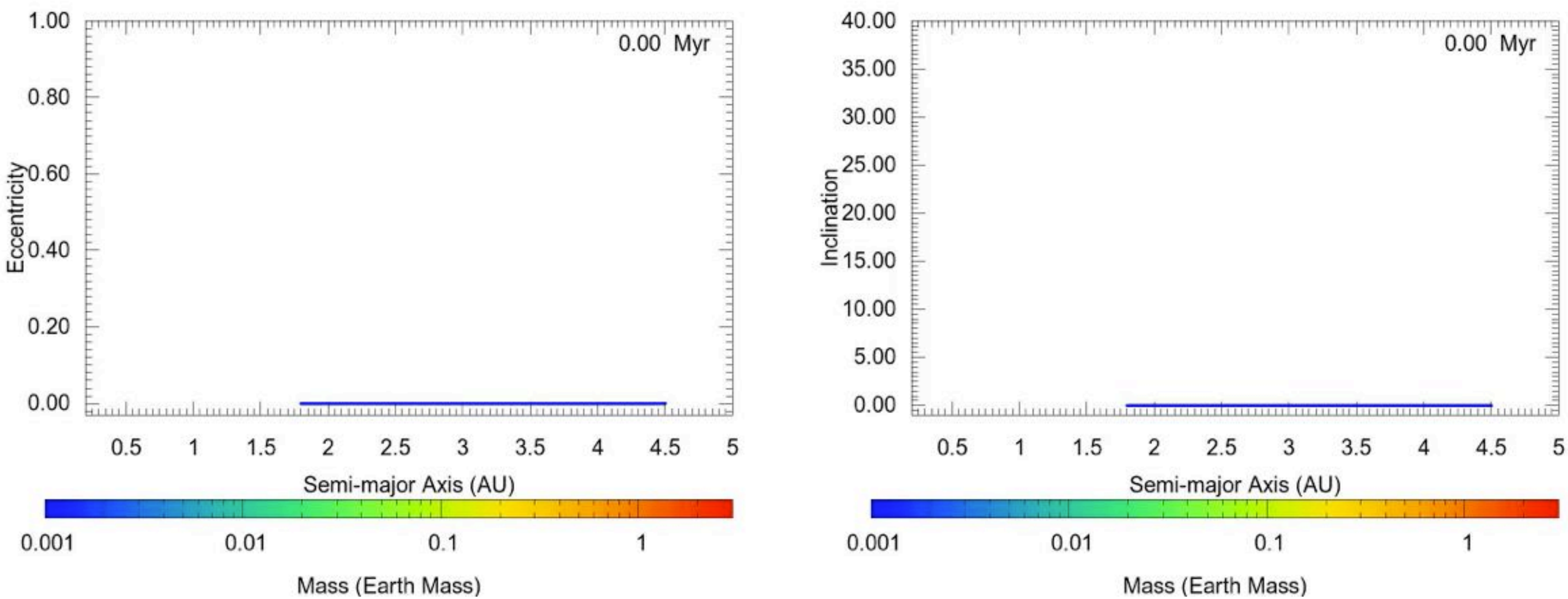


Experiment 1:
Jup & Sat in 2:1 resonance with e=0.025



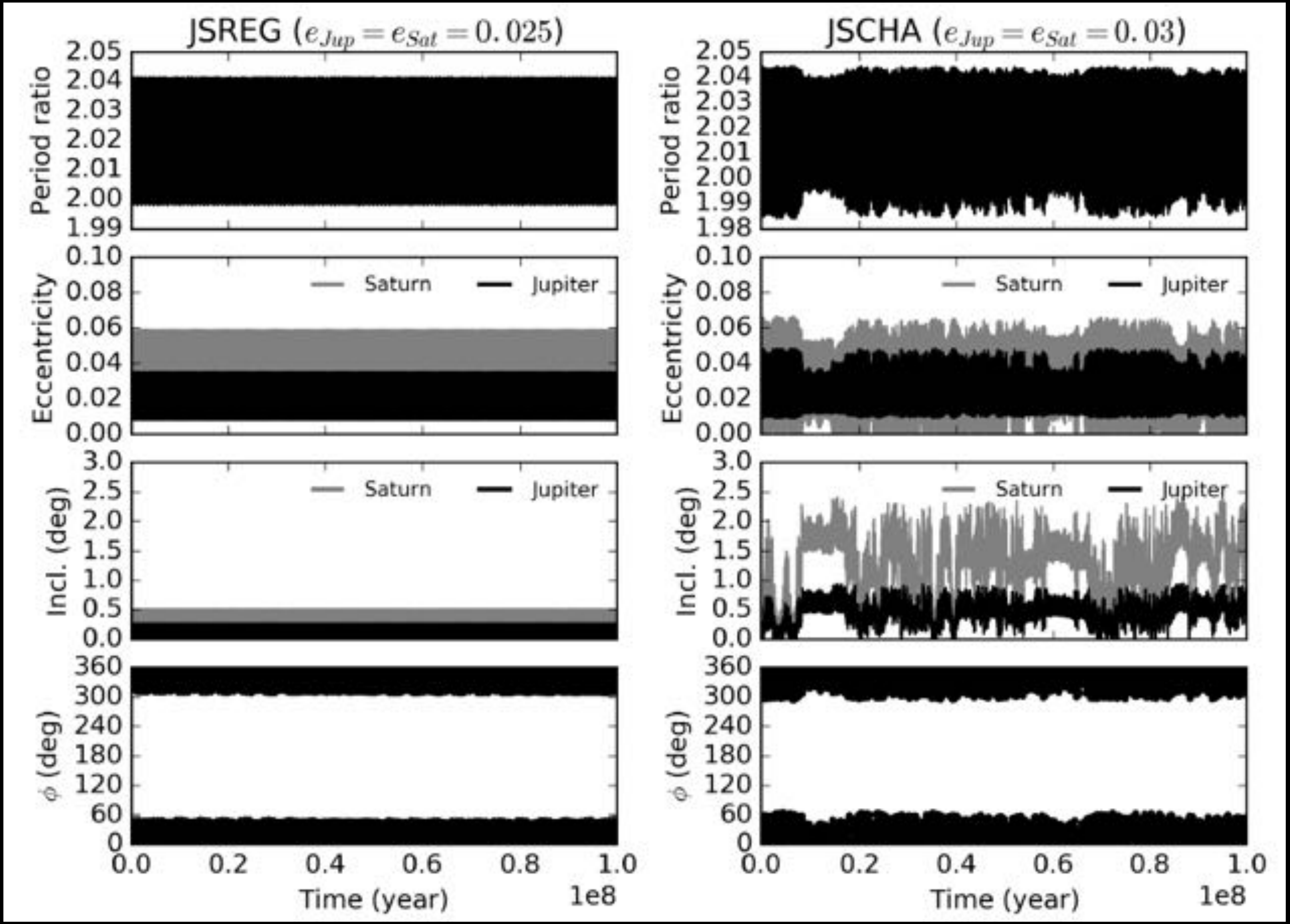
Regular evolution of Jupiter and Saturn
Izidoro et al. 2016, ApJ

Experiment 2:
Jup & Sat in 2:1 resonance with e=0.03



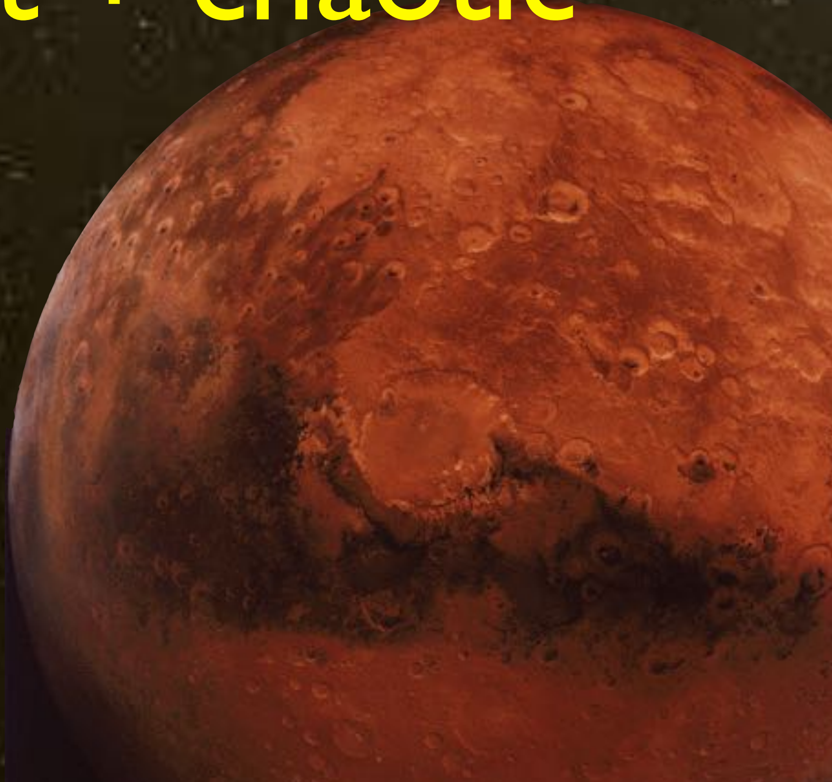
Chaotic evolution of Jupiter and Saturn
Izidoro et al. 2016, ApJ

Dynamical evolution of Jupiter and Saturn

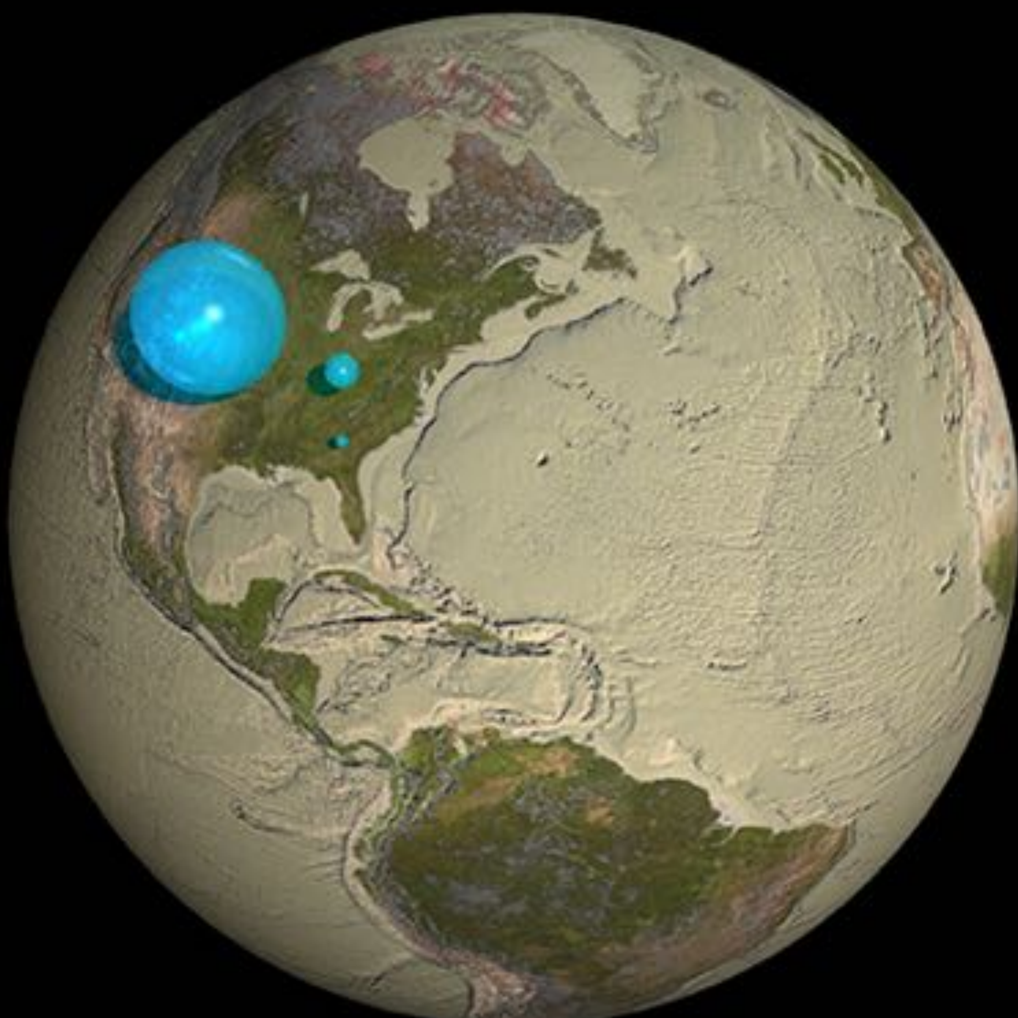


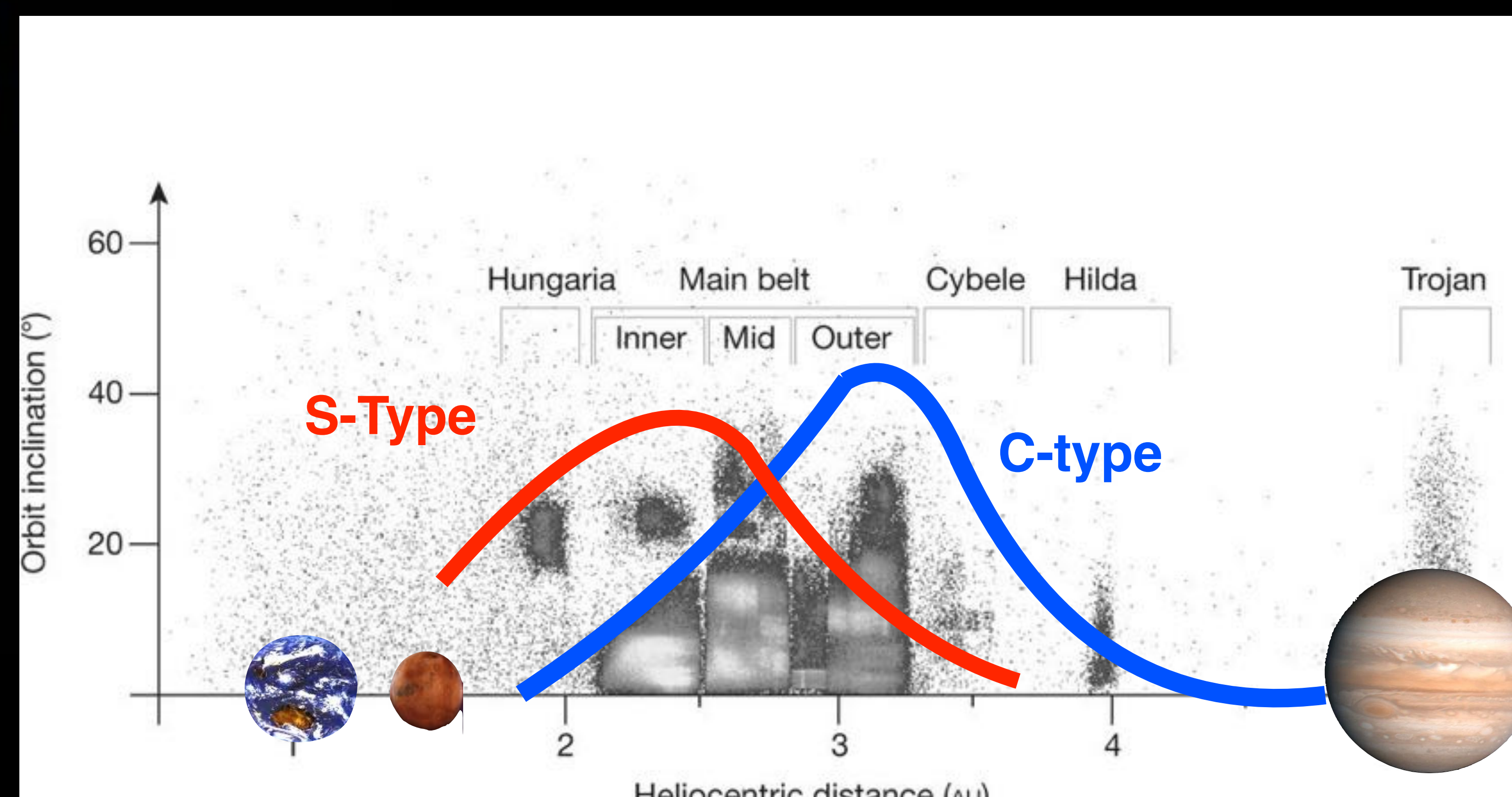
Why is Mars so small? And why are the asteroids' orbits excited?

- Low-mass (empty) asteroid belt + chaotic gas giants?
- Grand Tack?

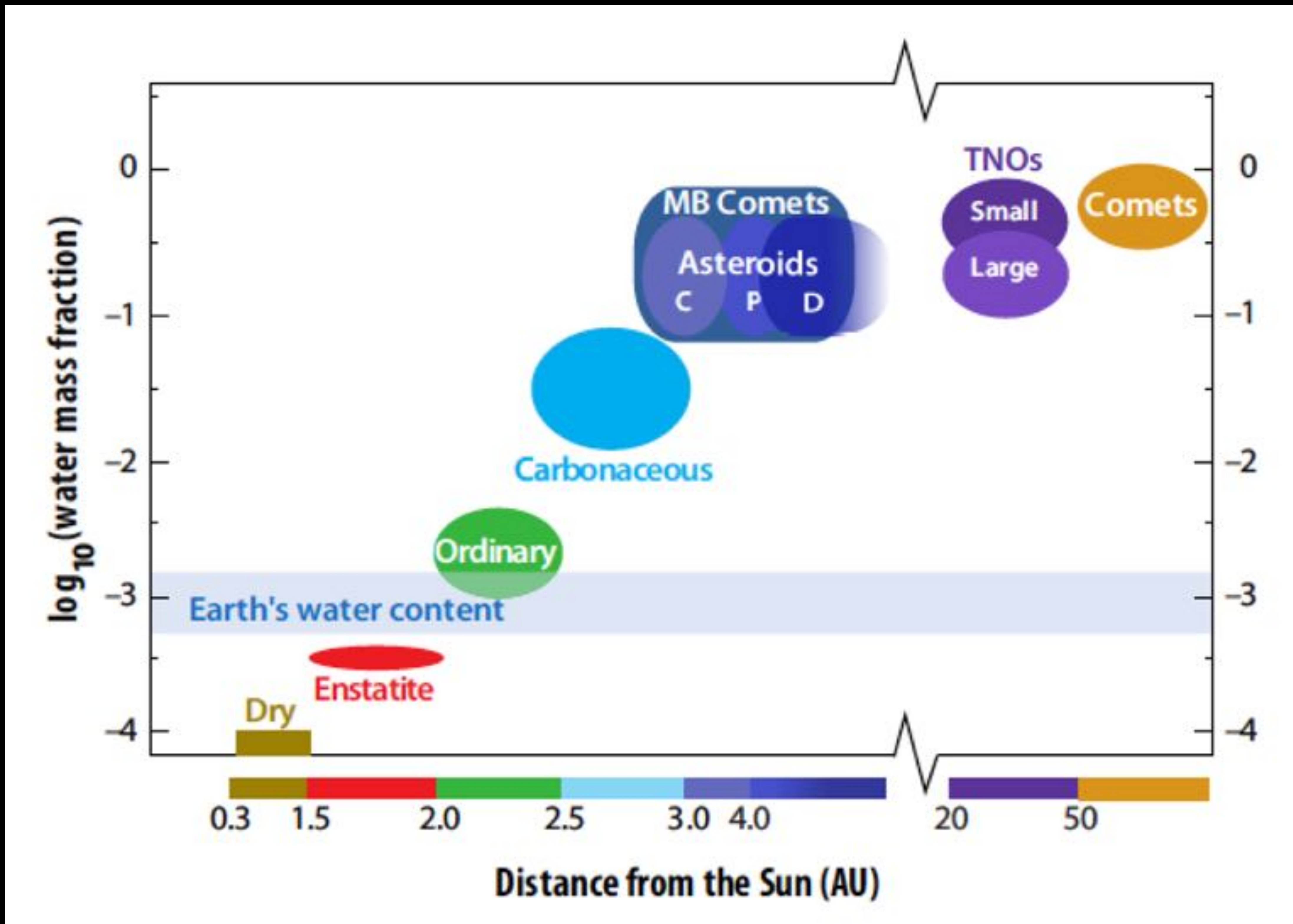


Where did Earth's water and C-type asteroids come from?



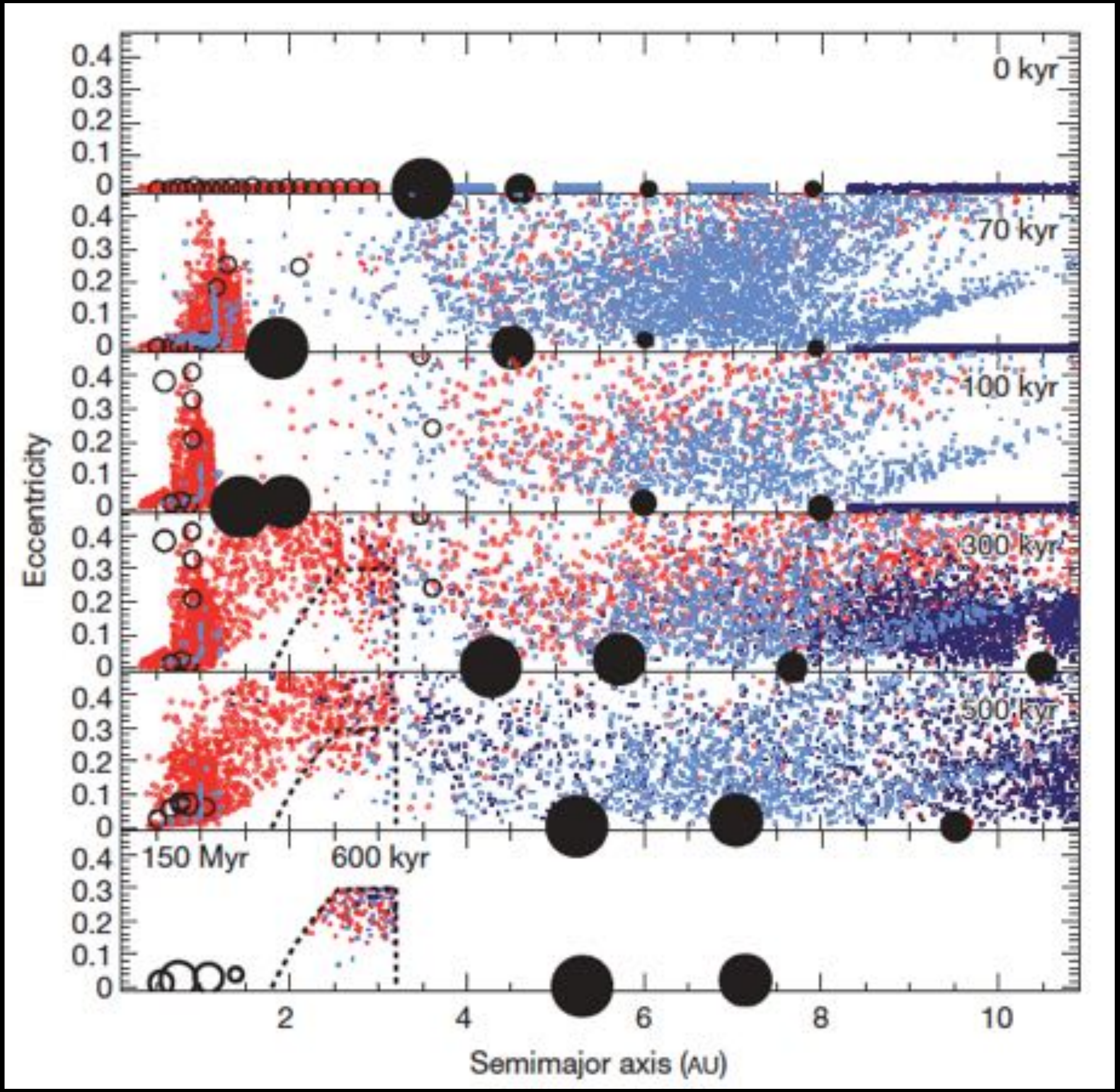


Water in small bodies



von Dishoeck et al (2014)

The Grand Tack



Walsh et al 2011

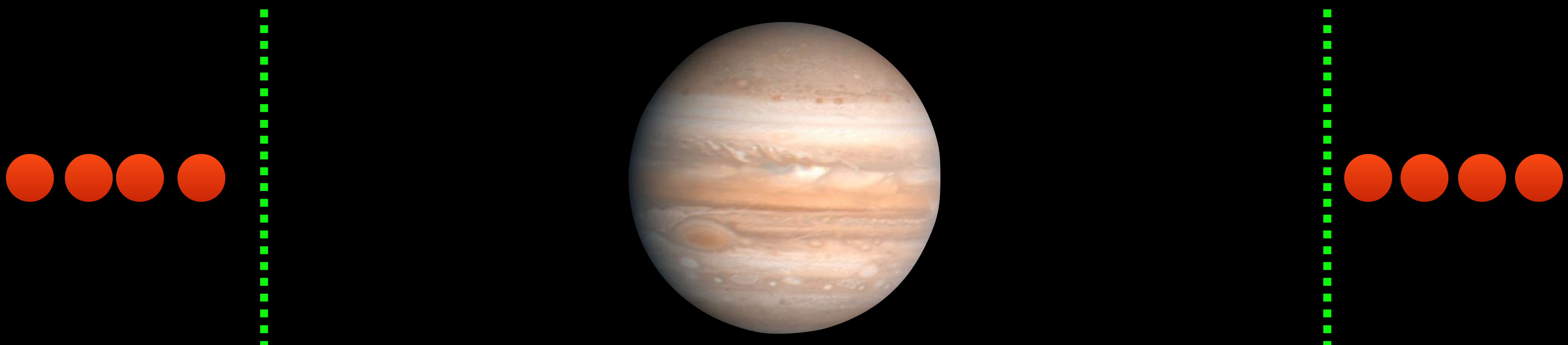
In the Grand Tack model water is delivered to Earth by the same population that was implanted into the asteroid belt as C types
(Walsh et al 2011; O'Brien et al 2014)

The Grand-Tack is also broadly consistent with the structure of the asteroid belt
(Deienno et al 2016)

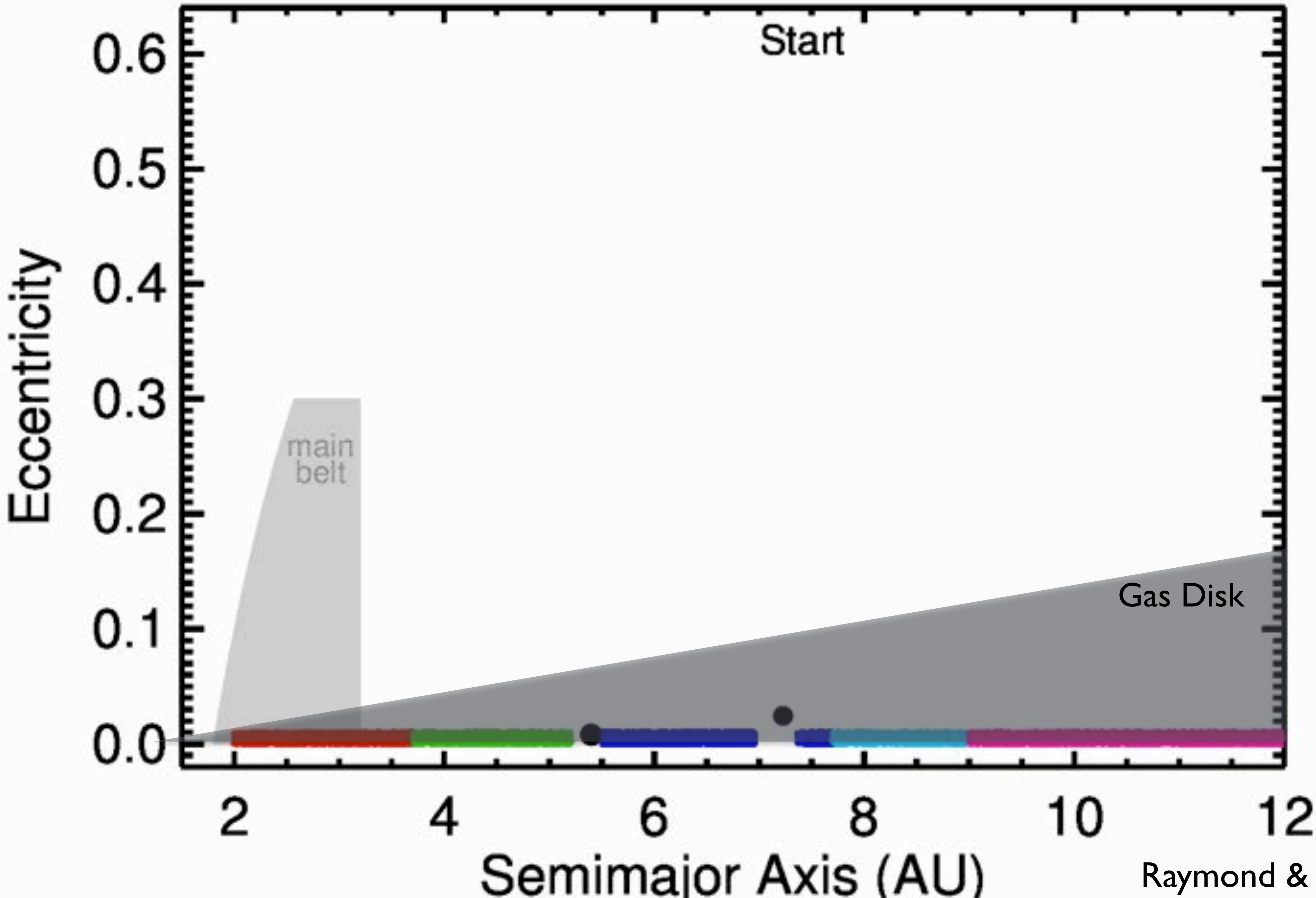
A new mechanism: Jupiter's growth affected nearby

Stability limit for nearby orbits (~3.5 R_{Hill} ~$M^{1/3}$)

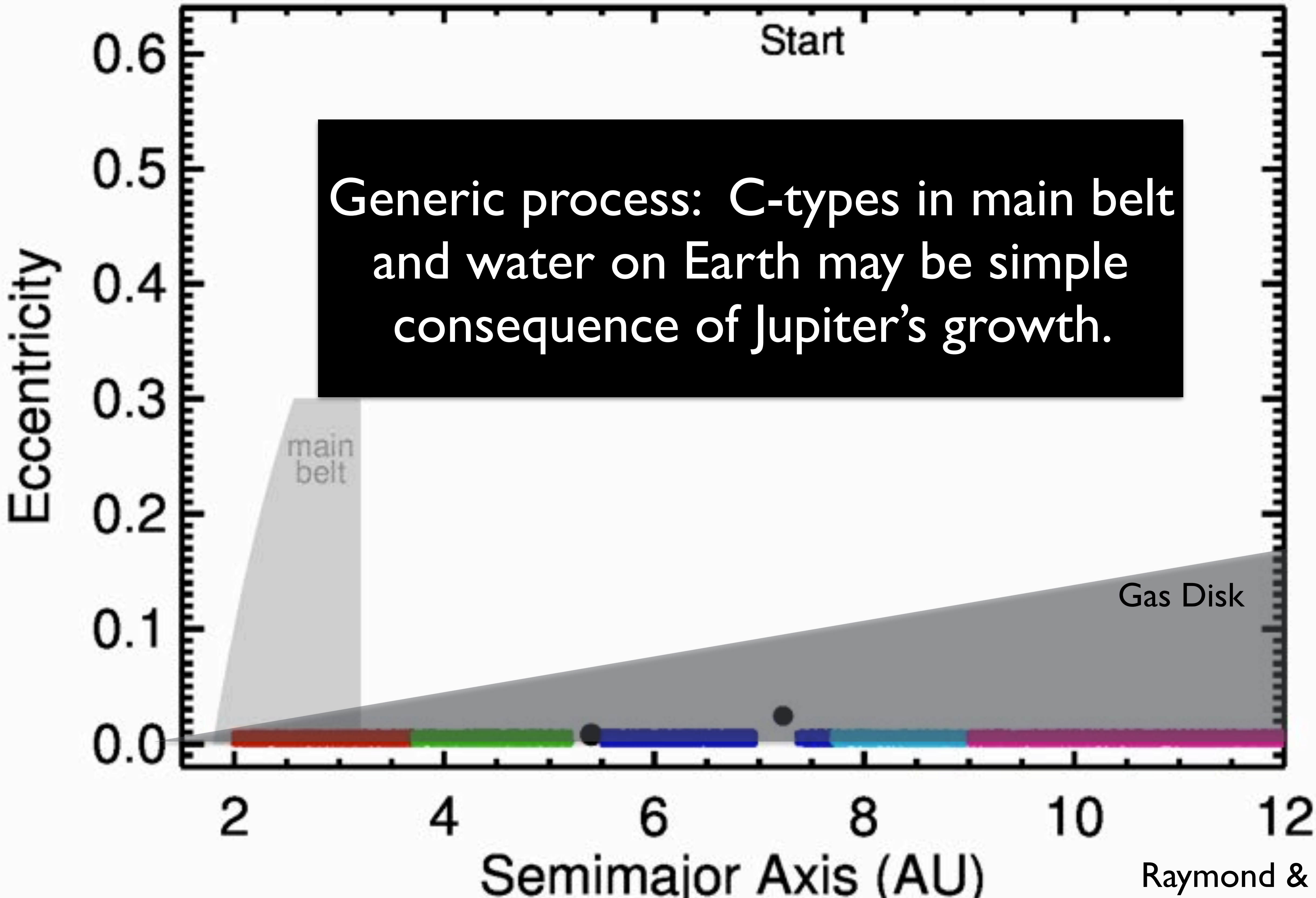
A new mechanism:
Jupiter's growth affected nearby



Stability limit for nearby orbits (~3.5 R_{Hill} ~$M^{1/3}$)



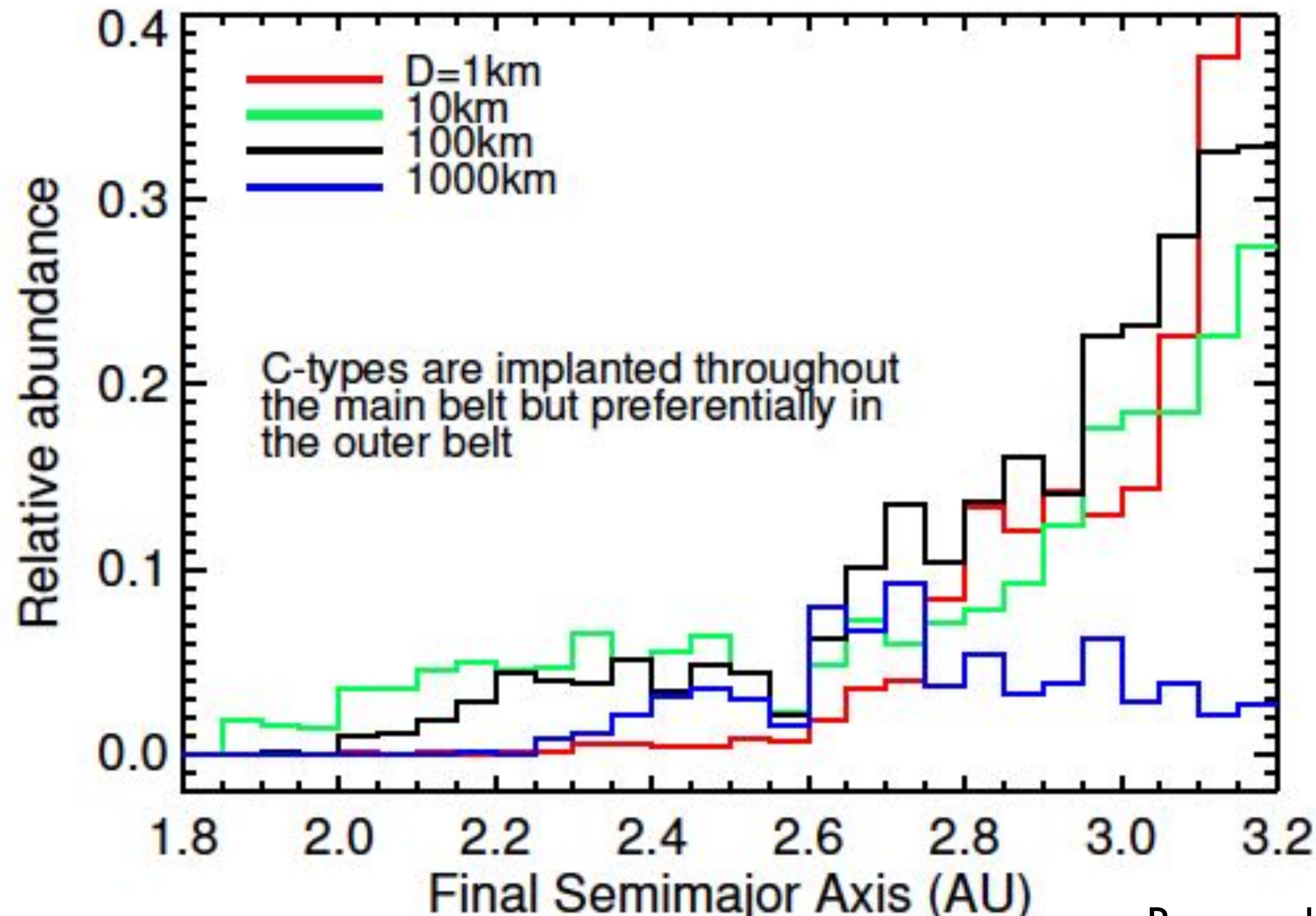
Raymond & Izidoro (2017)



Generic process: C-types in main belt and water on Earth may be simple consequence of Jupiter's growth.

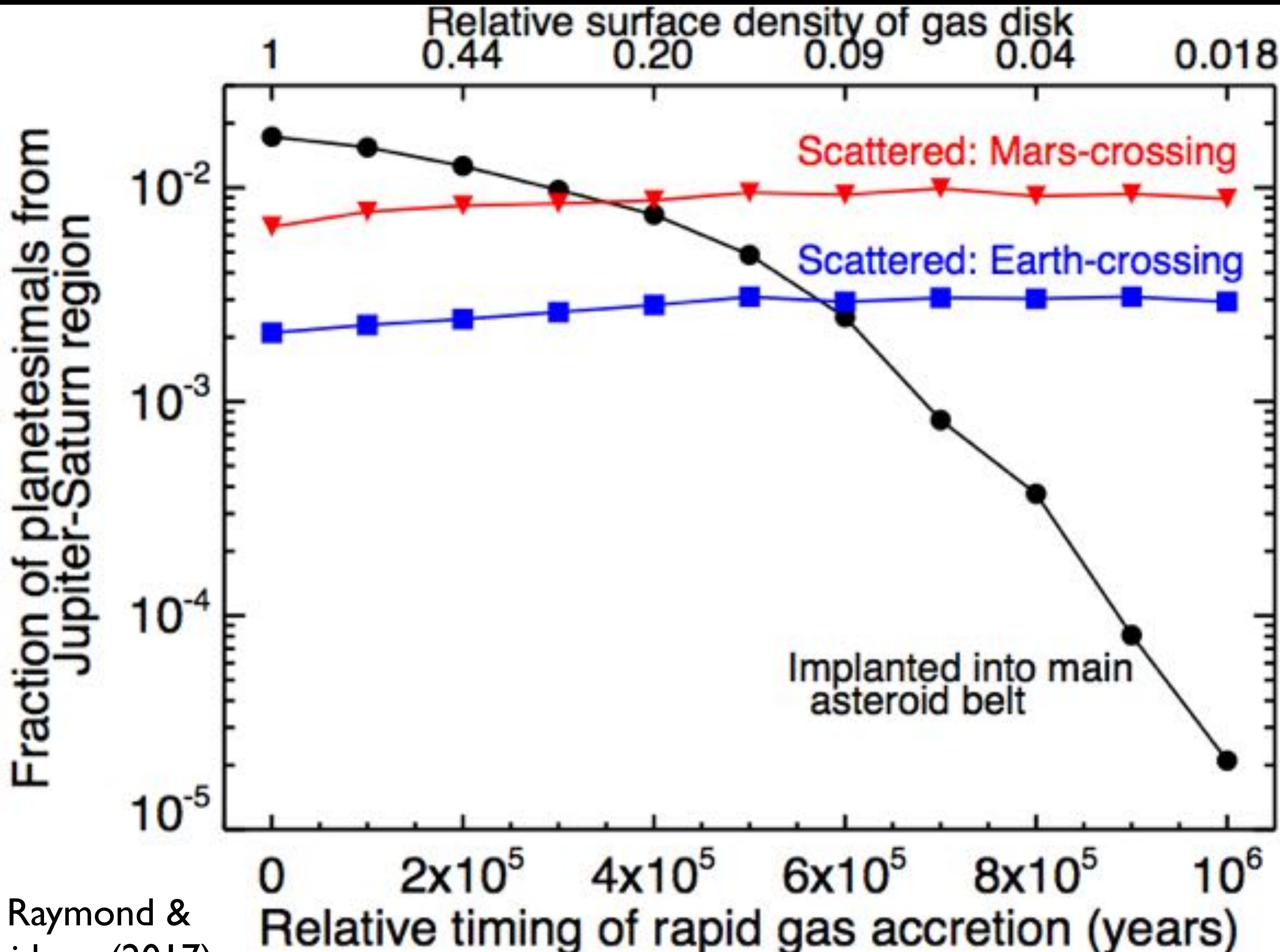
Raymond & Izidoro (2017)

Implantation of planetesimals with different sizes



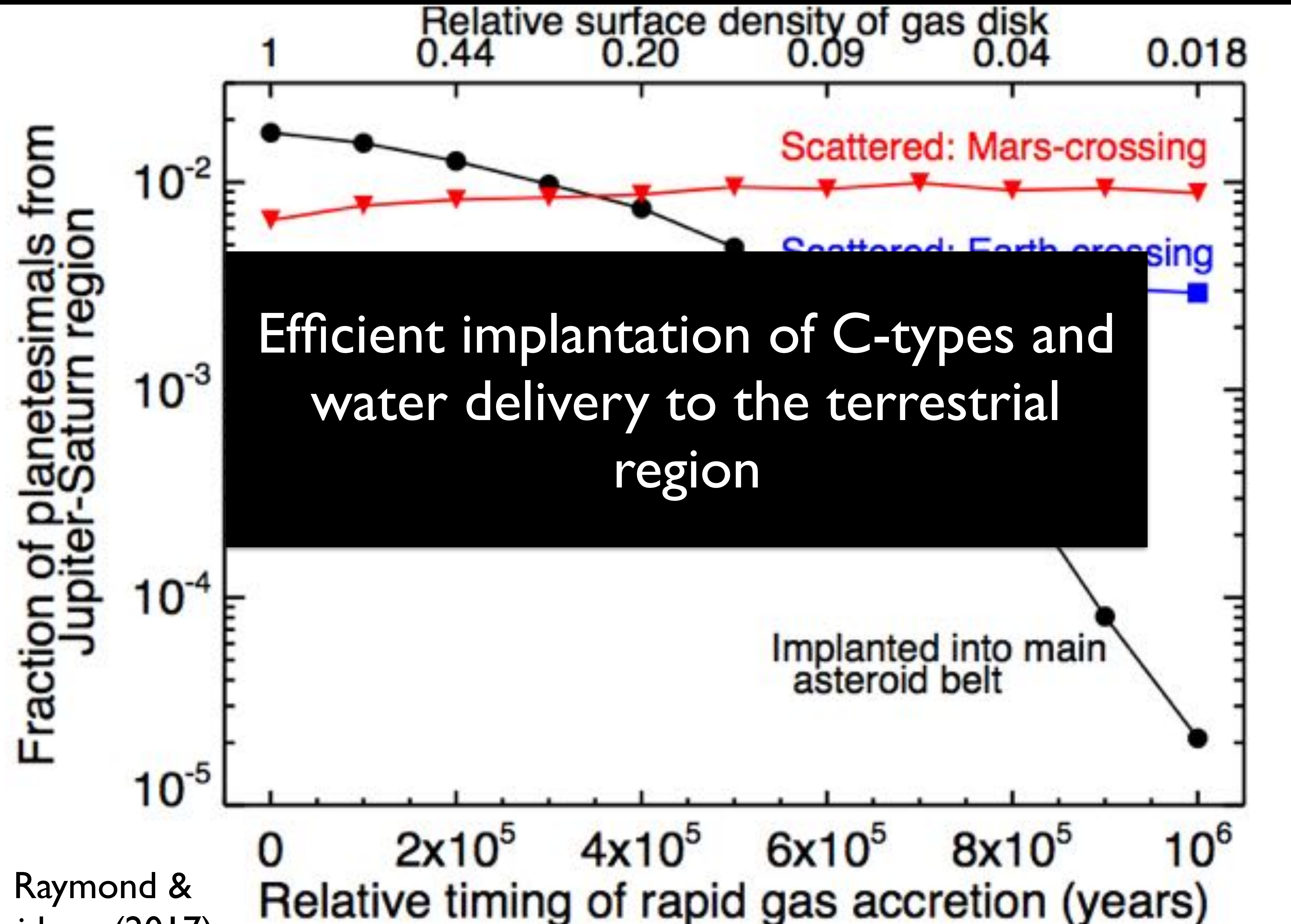
Raymond & Izidoro (2017)

Delivery to terrestrial planets vs. injection into asteroid belt



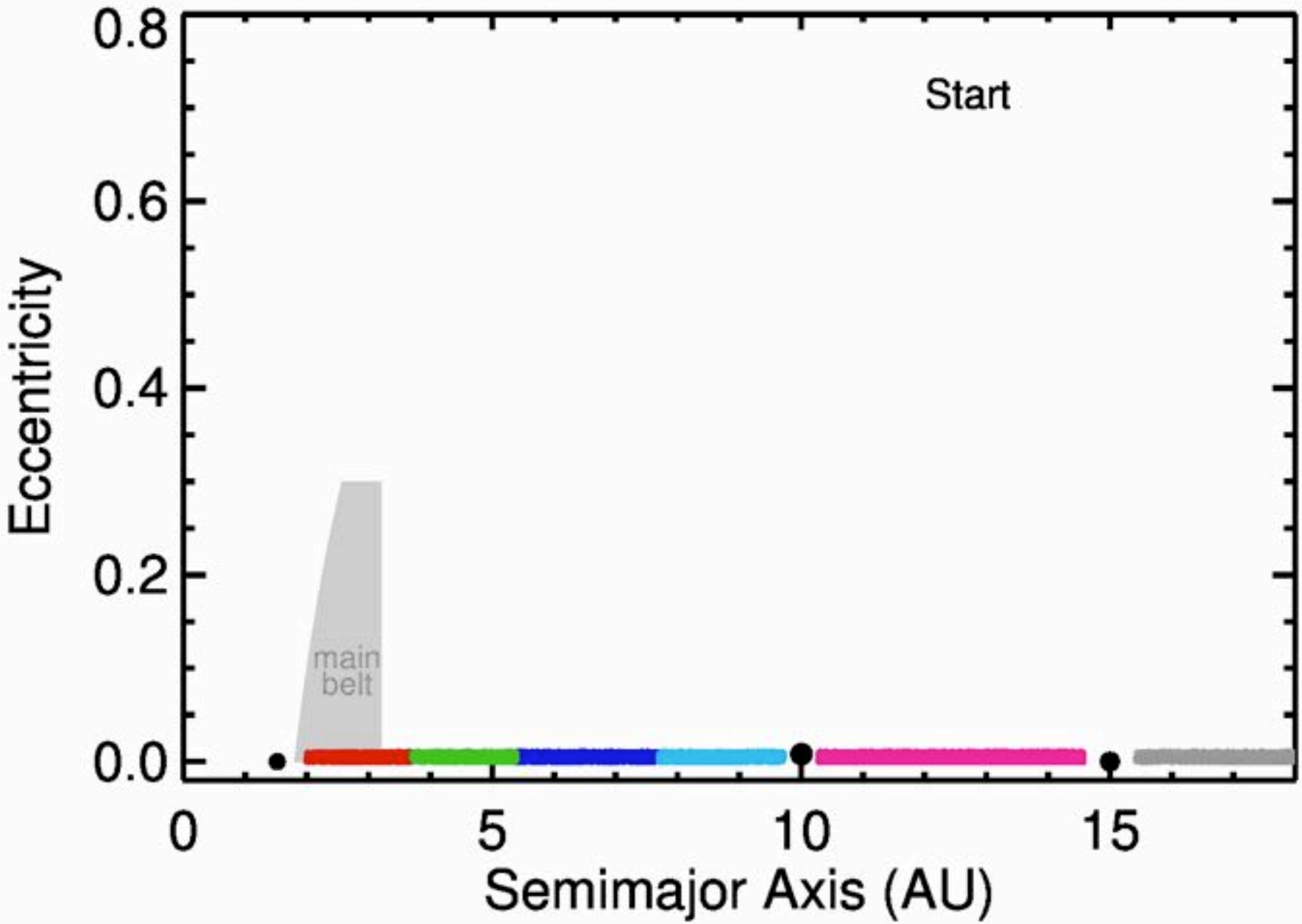
Raymond & Izidoro (2017)

Delivery to terrestrial planets vs. injection into asteroid belt

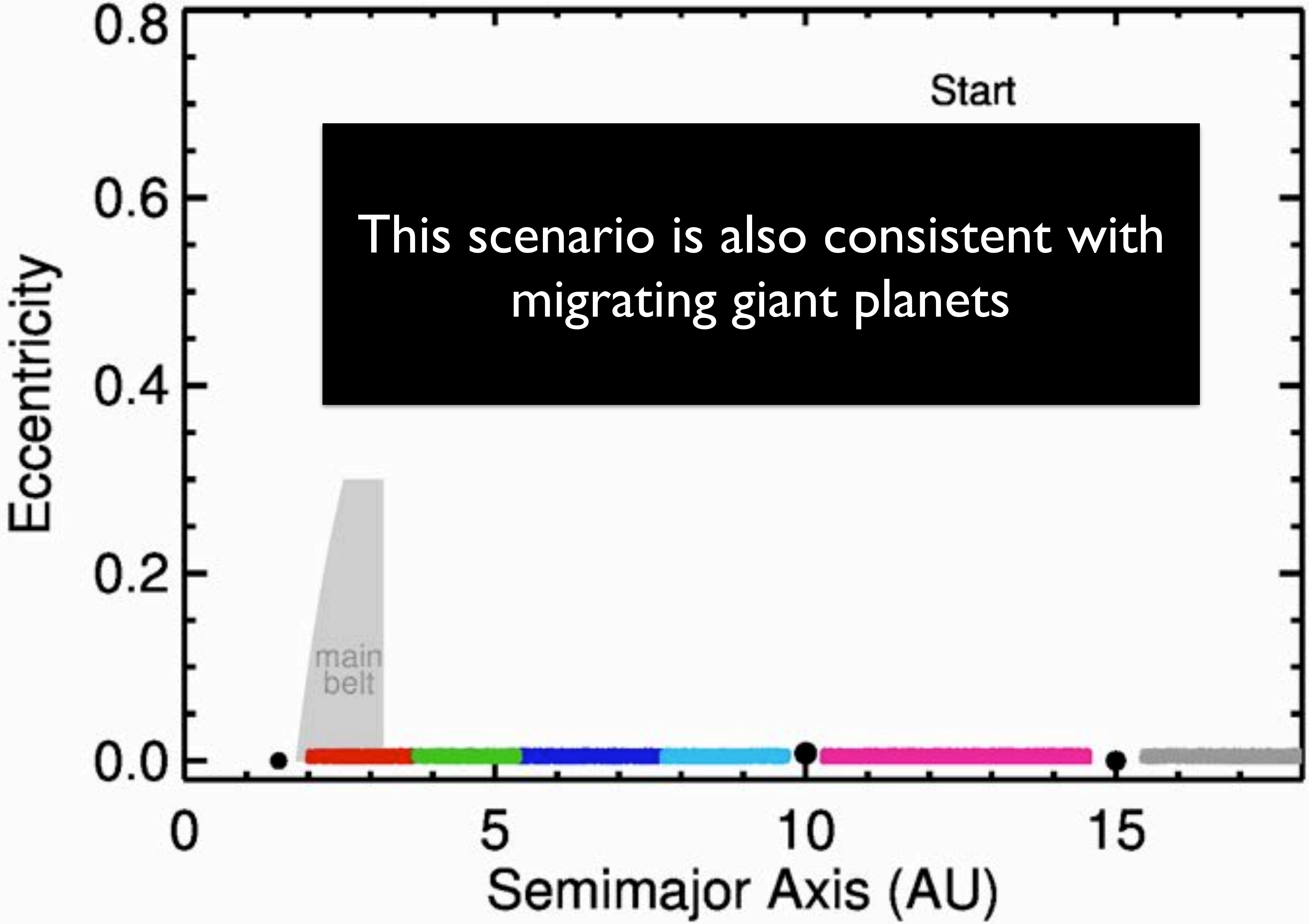


Efficient implantation of C-types and water delivery to the terrestrial region

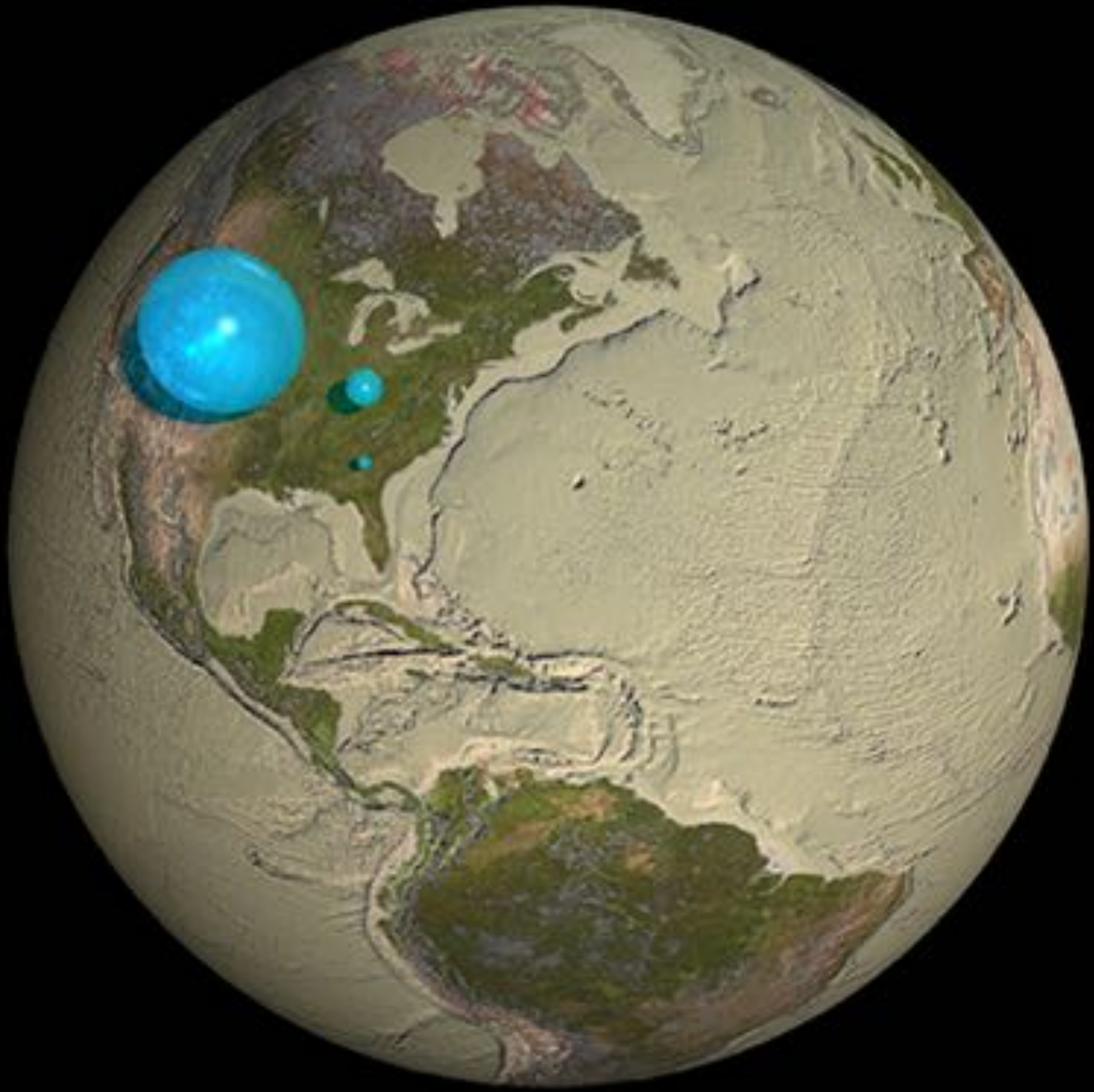
Raymond & Izidoro (2017)


Start
main belt
Eccentricity
0.8
0.6
0.4
0.2
0.0
0
5
10
15
Semimajor Axis (AU)

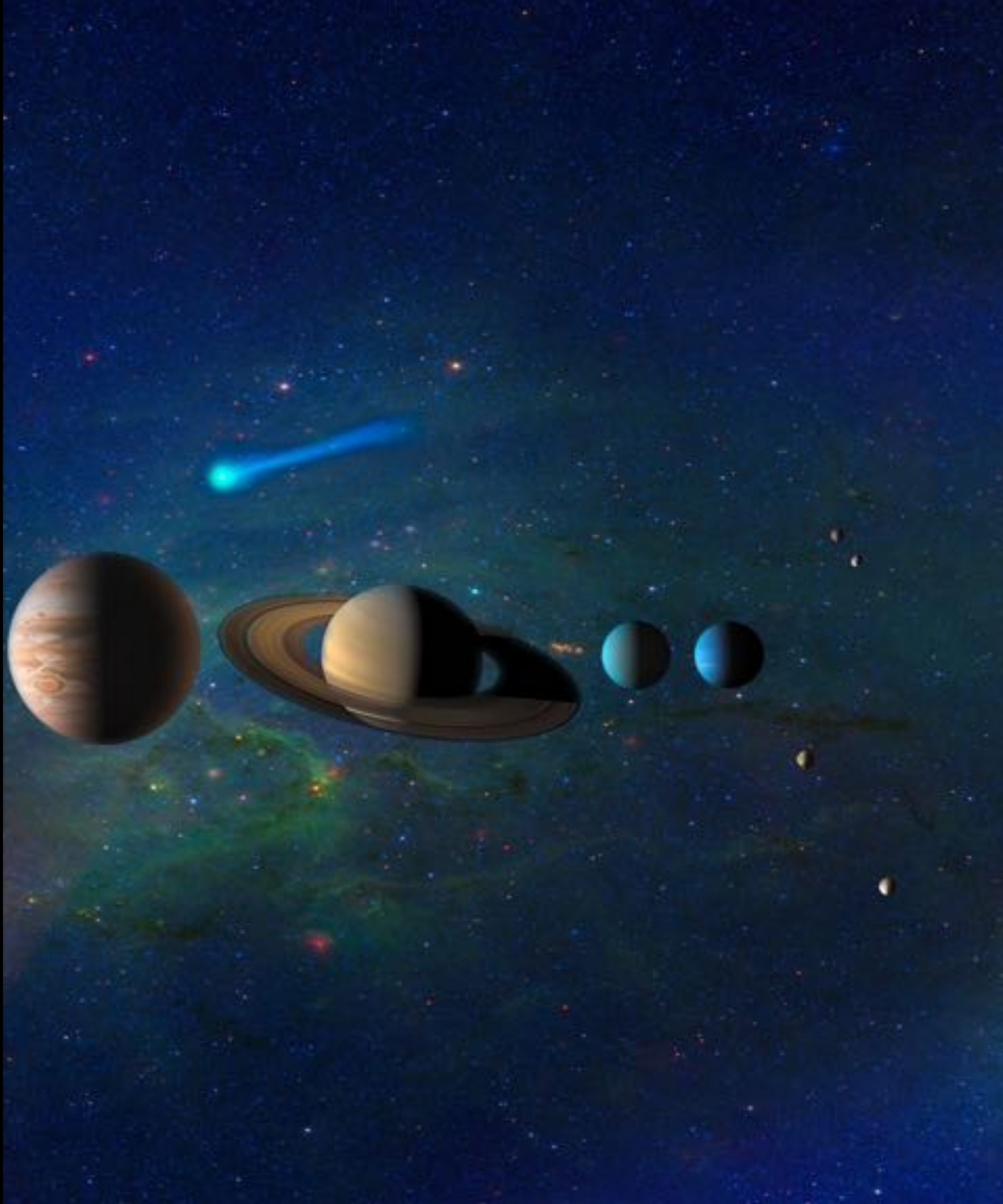
This scenario is also consistent with migrating giant planets



Where did Earth's water and C-types come from?

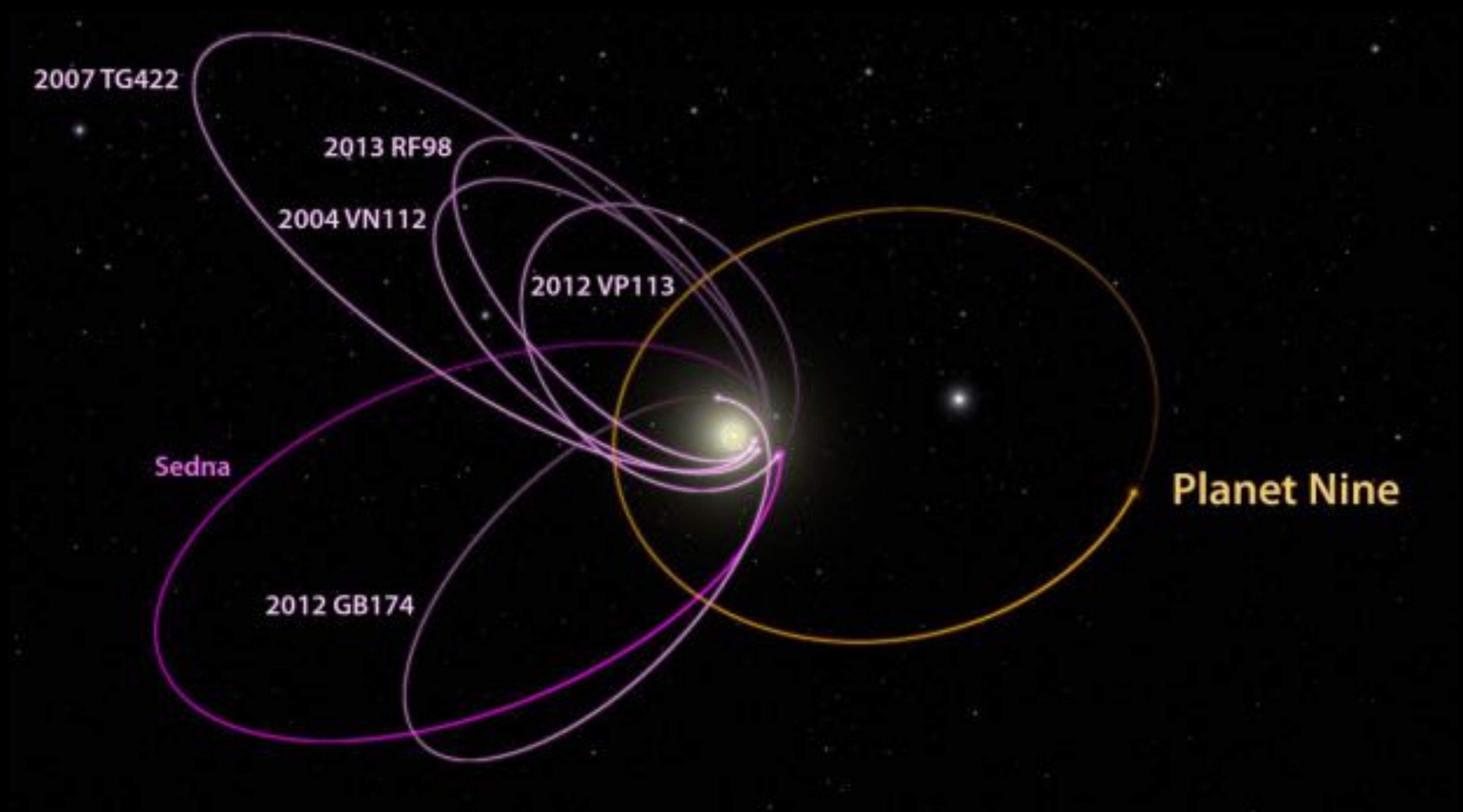


- Scattered planetesimals during Jup/Sat's growth
- Grand Tack?



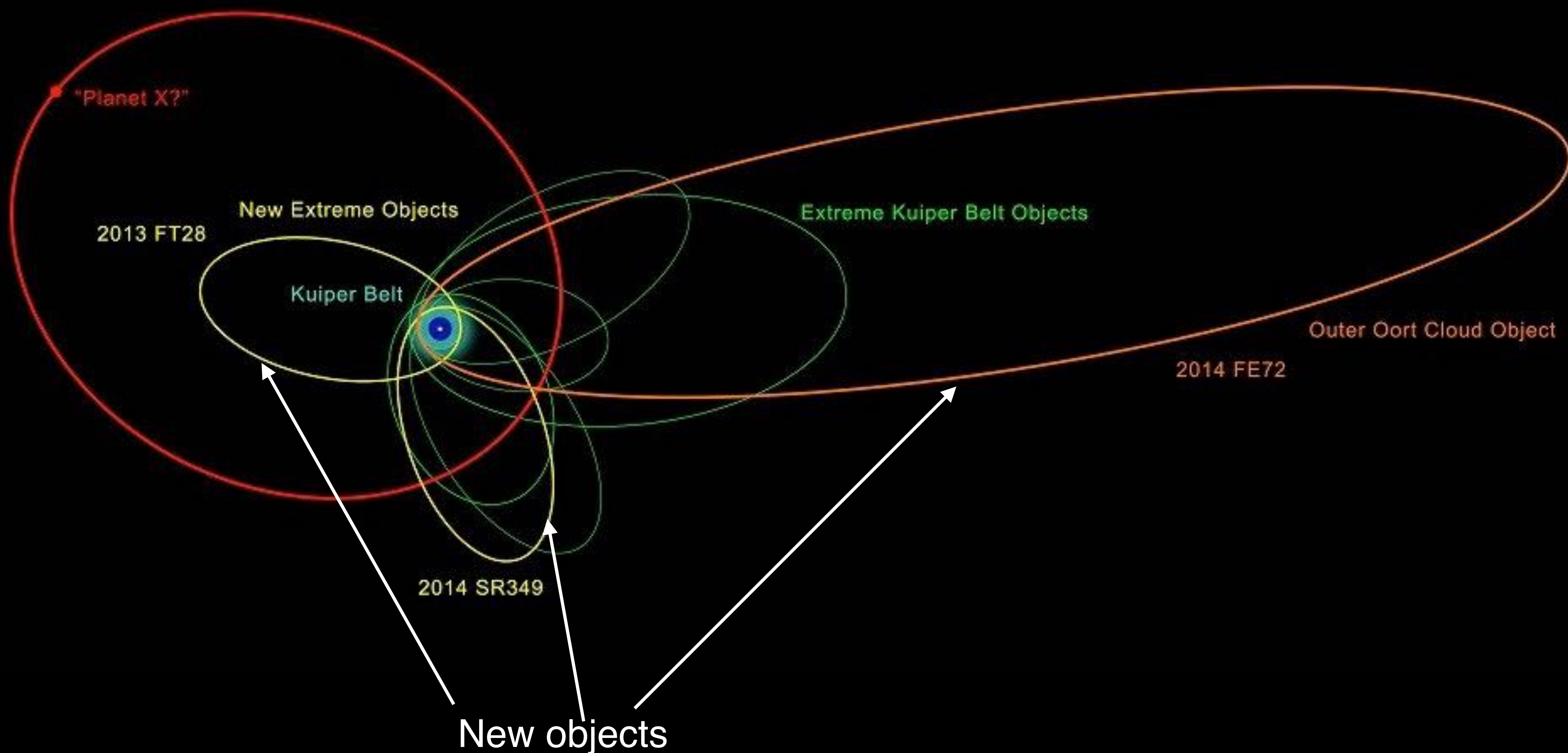

Where did Planet Nine
come from?
Enigma #6

"…the observed orbital alignment can be maintained by a distant eccentric planet with mass **~10 $m_\oplus$** …"
— Batygin & Brown (2016)

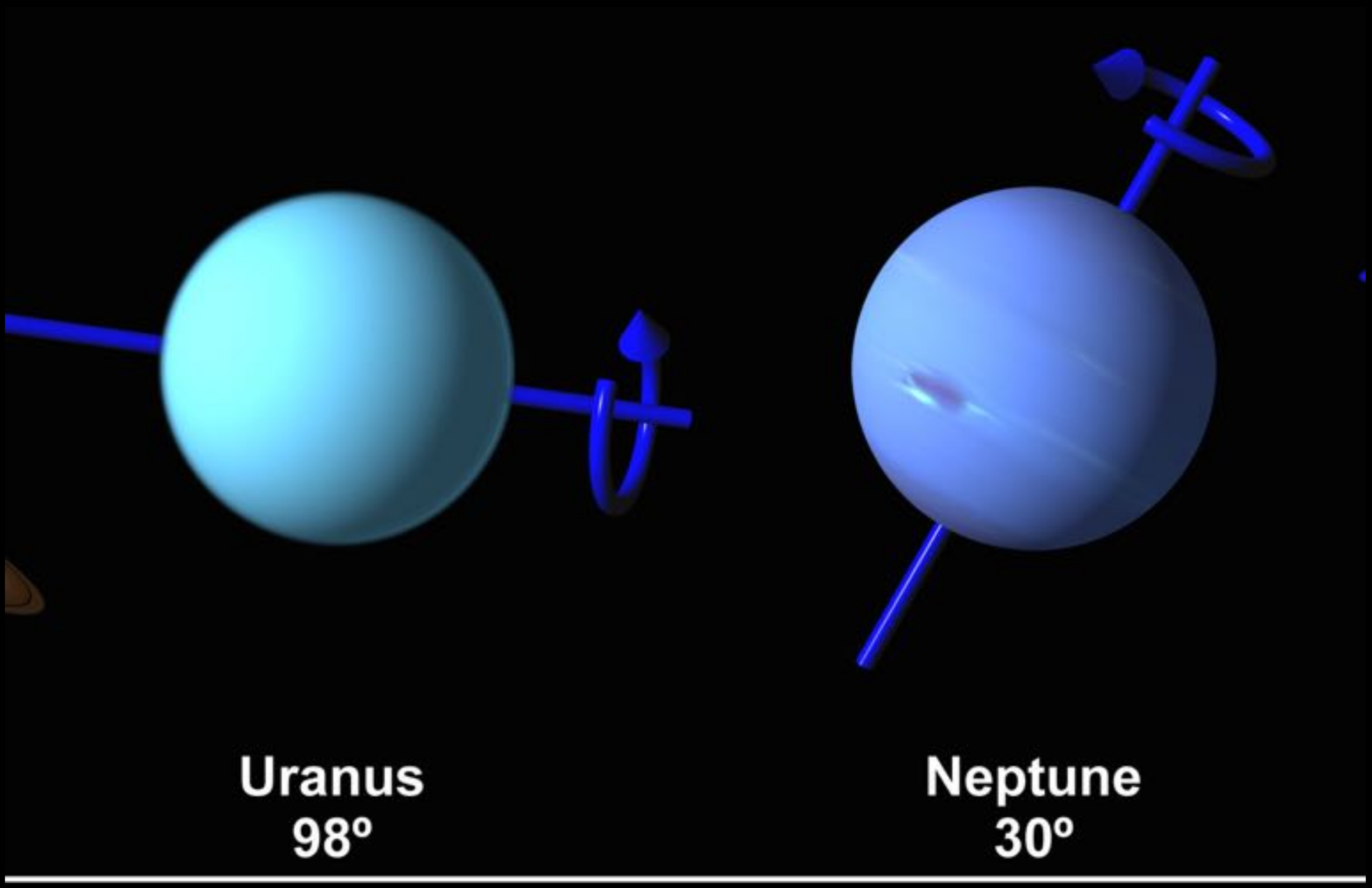


Additional evidence for Planet 9?

Trujillo & Sheppard (2016)



Ice Giants Tilt

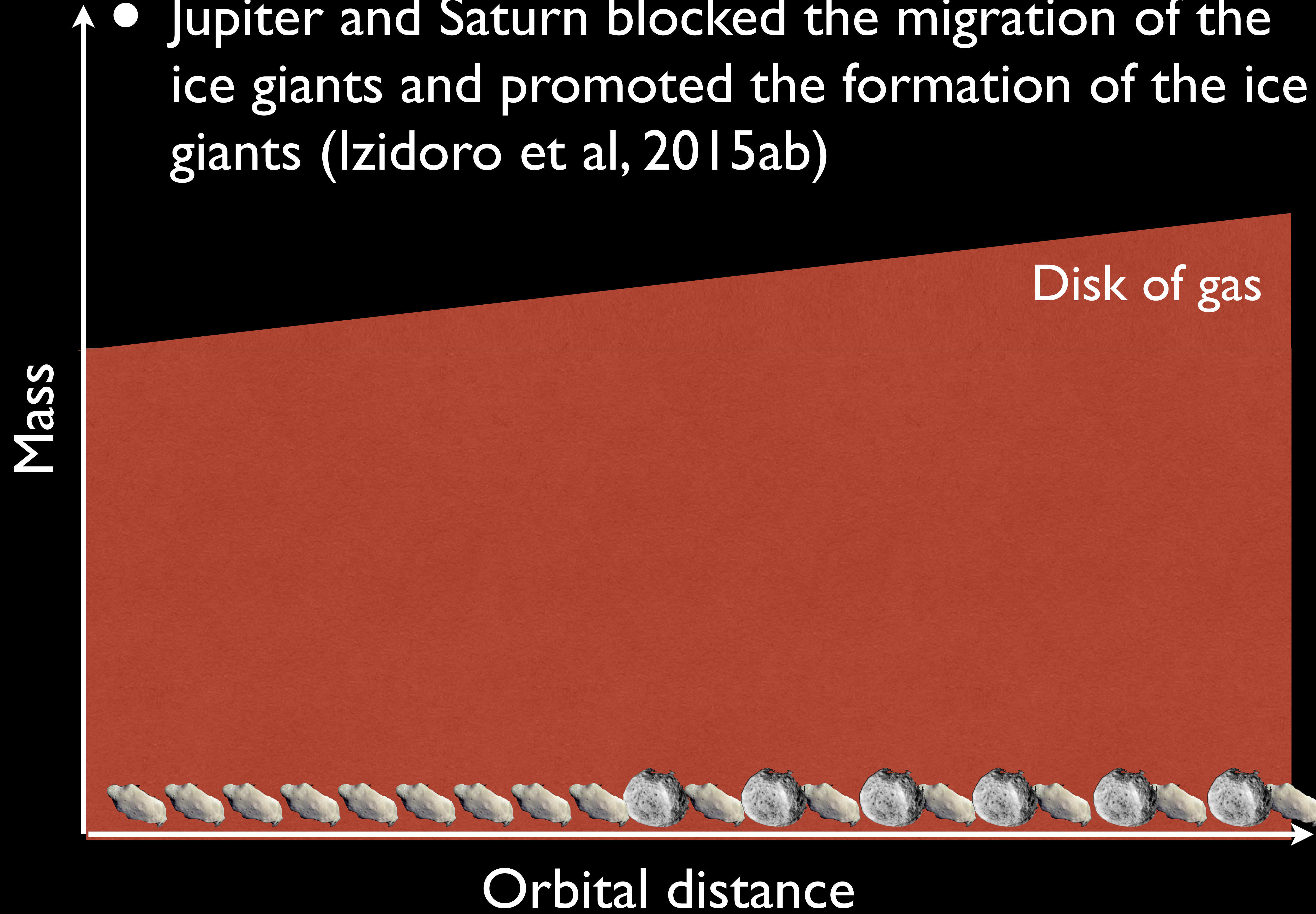


Planetesimals accretion fails in explaining their formation (Levison et al. 2010)

Pebble accretion alone fails in explaining their obliquities (Johansen et al 2009)

One and preferably 2 giant collisions during their growth (Morbidelli et al., 2012)

- Jupiter and Saturn blocked the migration of the ice giants and promoted the formation of the ice giants (Izidoro et al, 2015ab)



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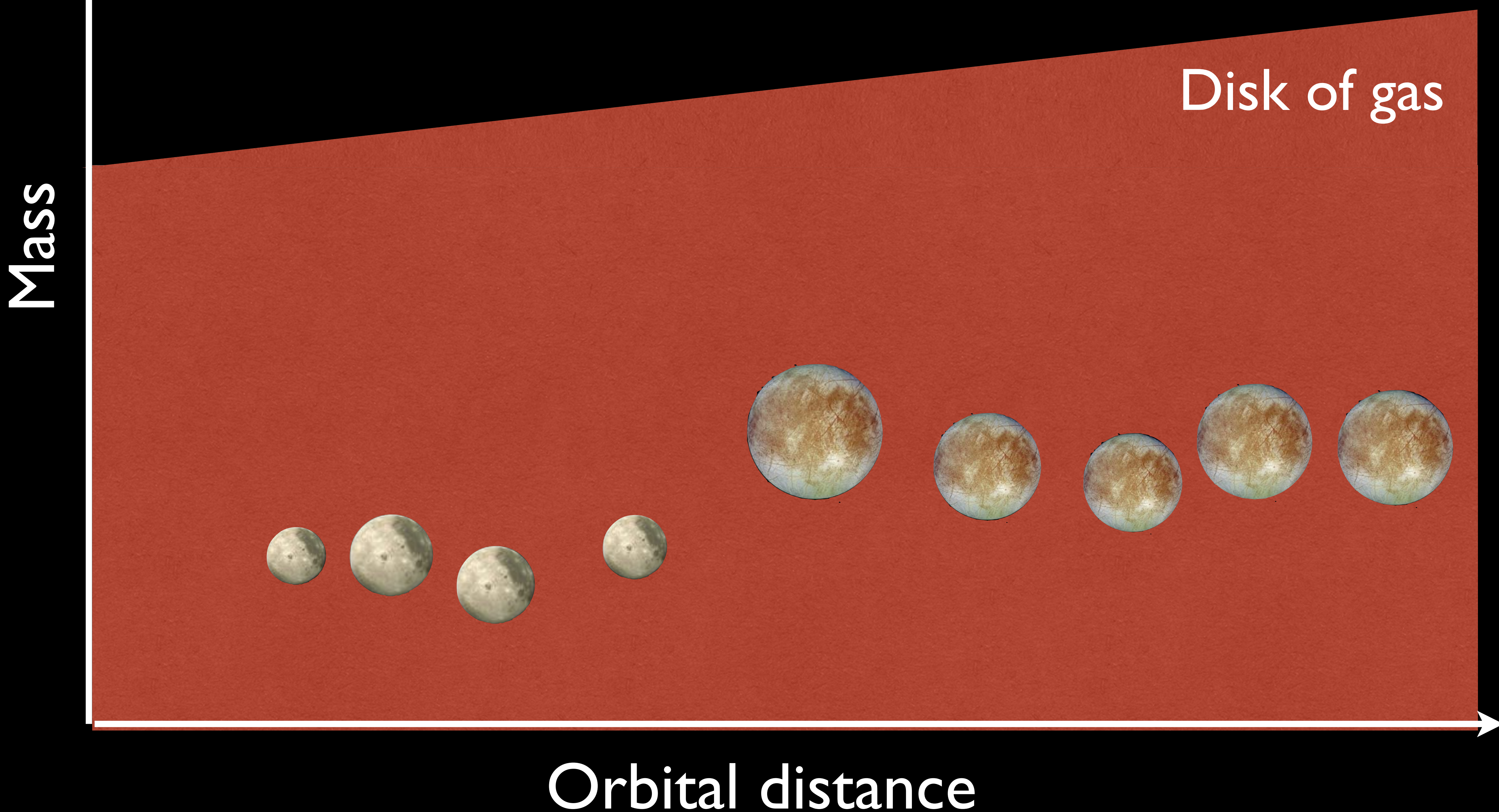

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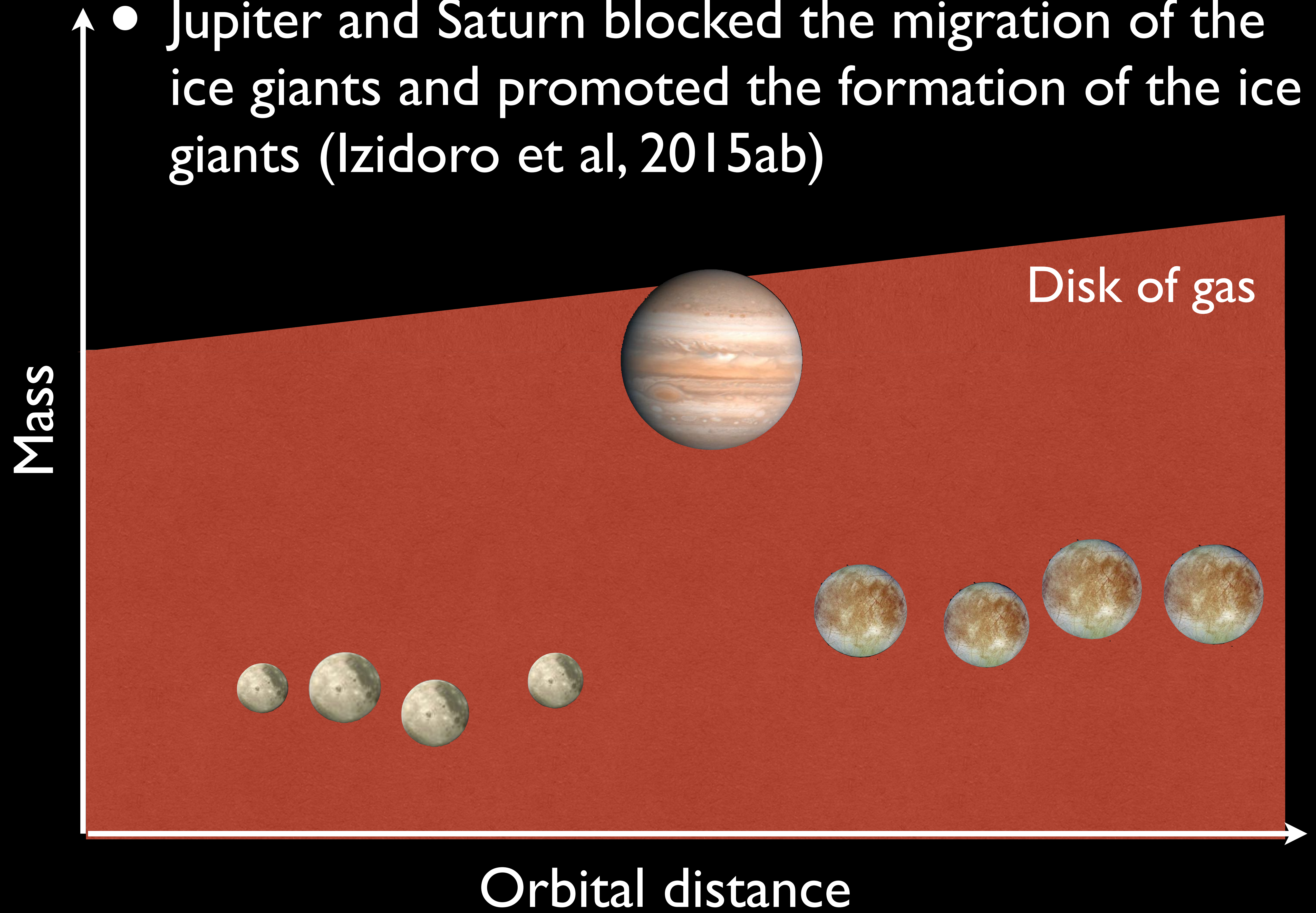

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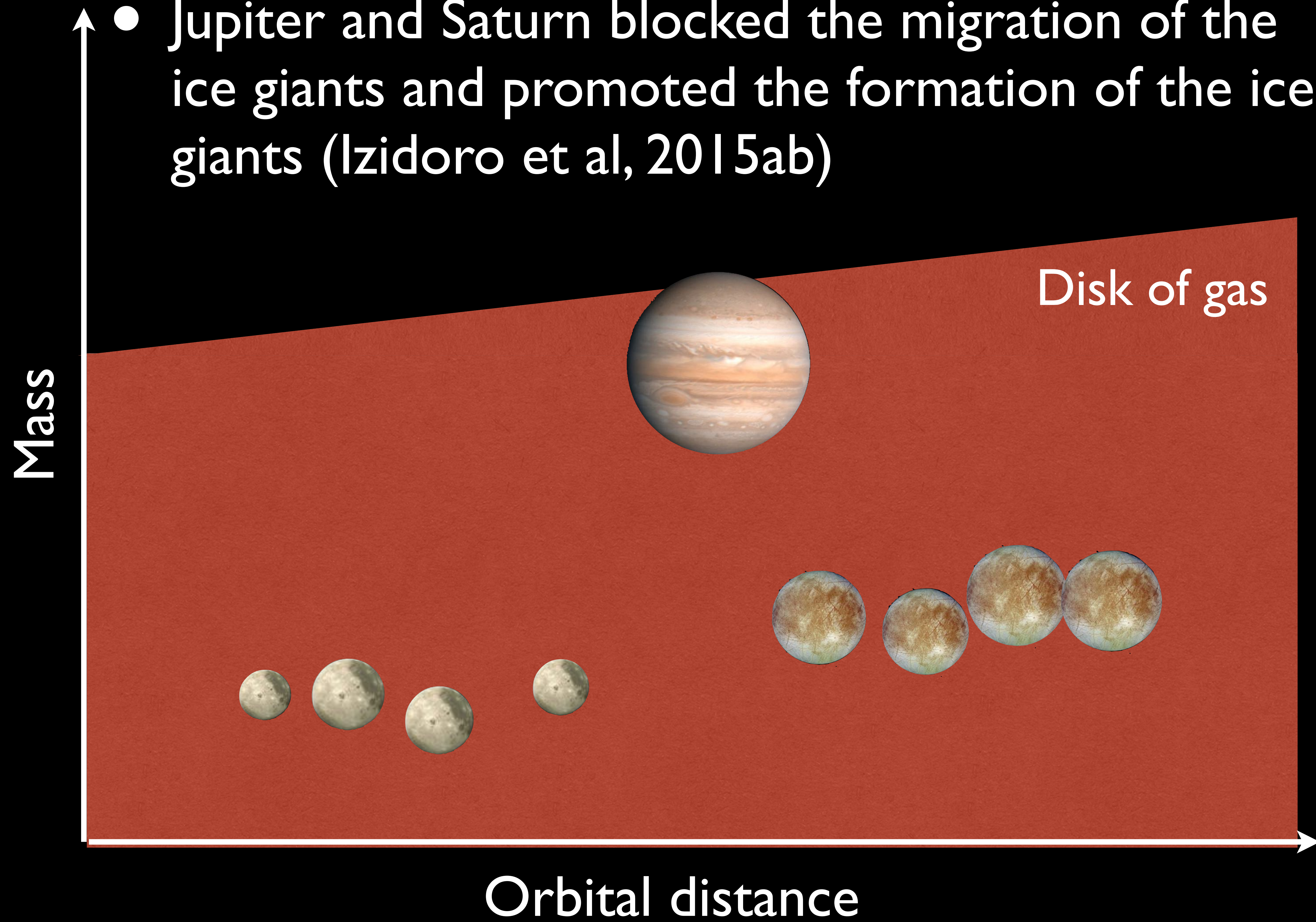

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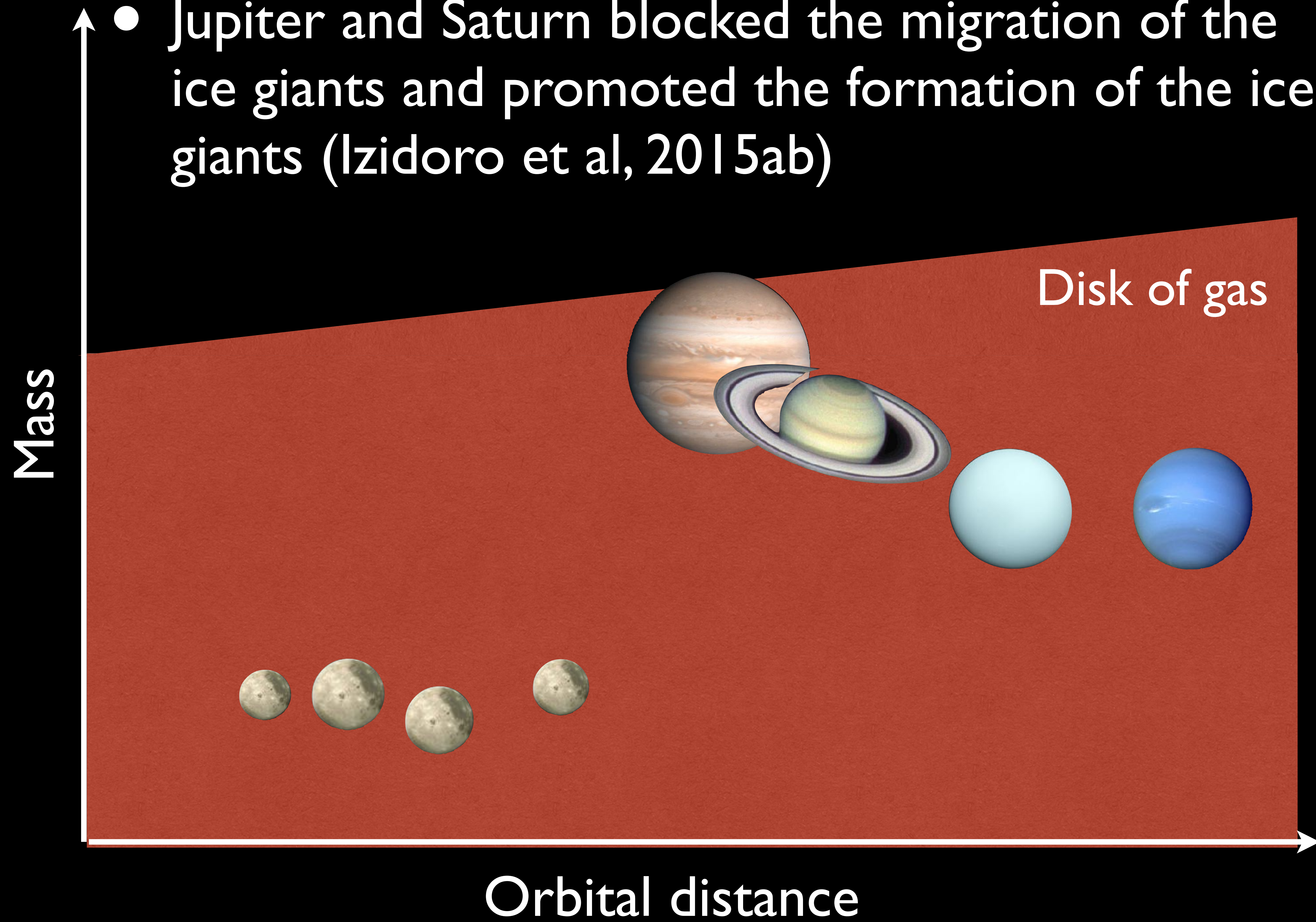

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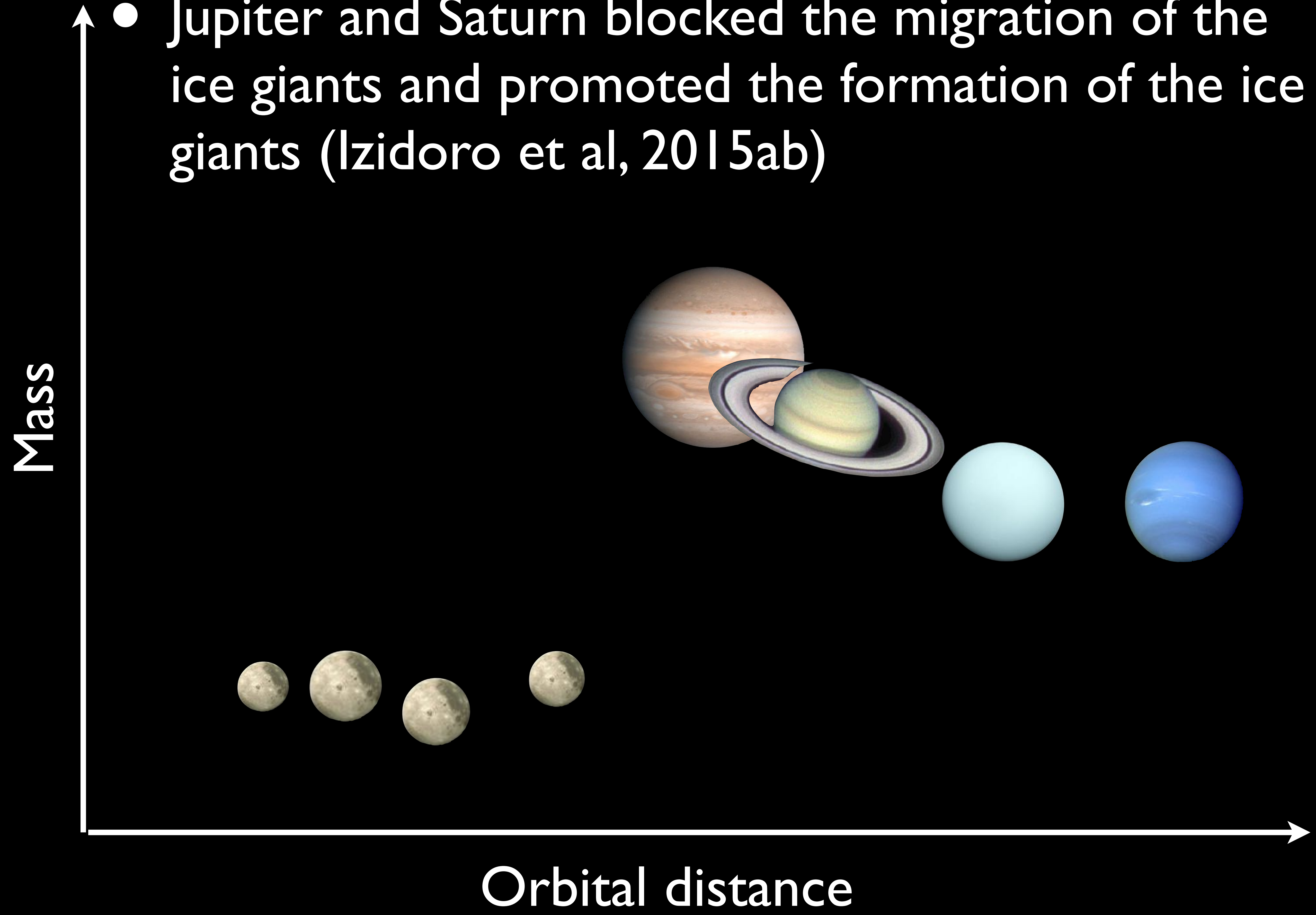

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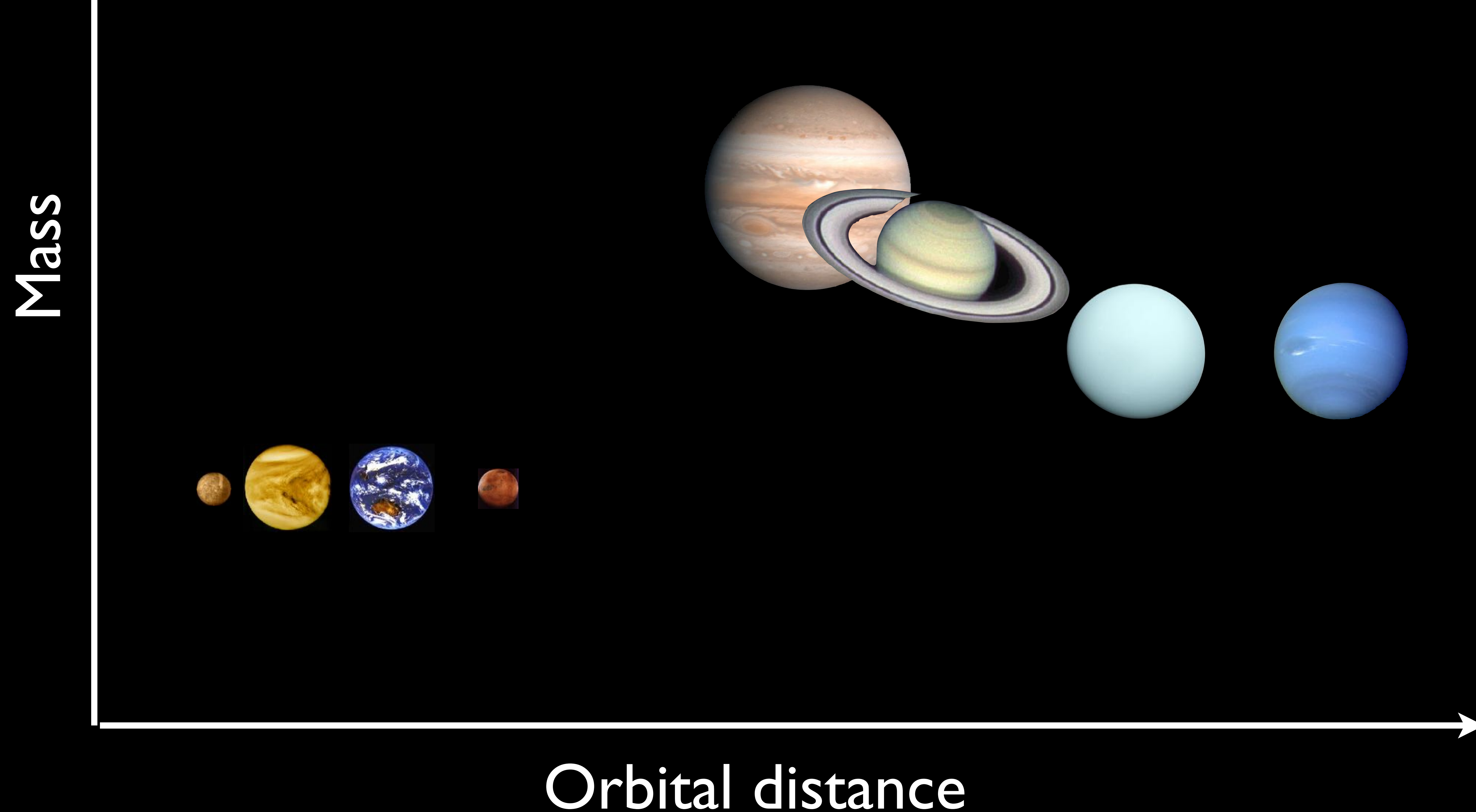
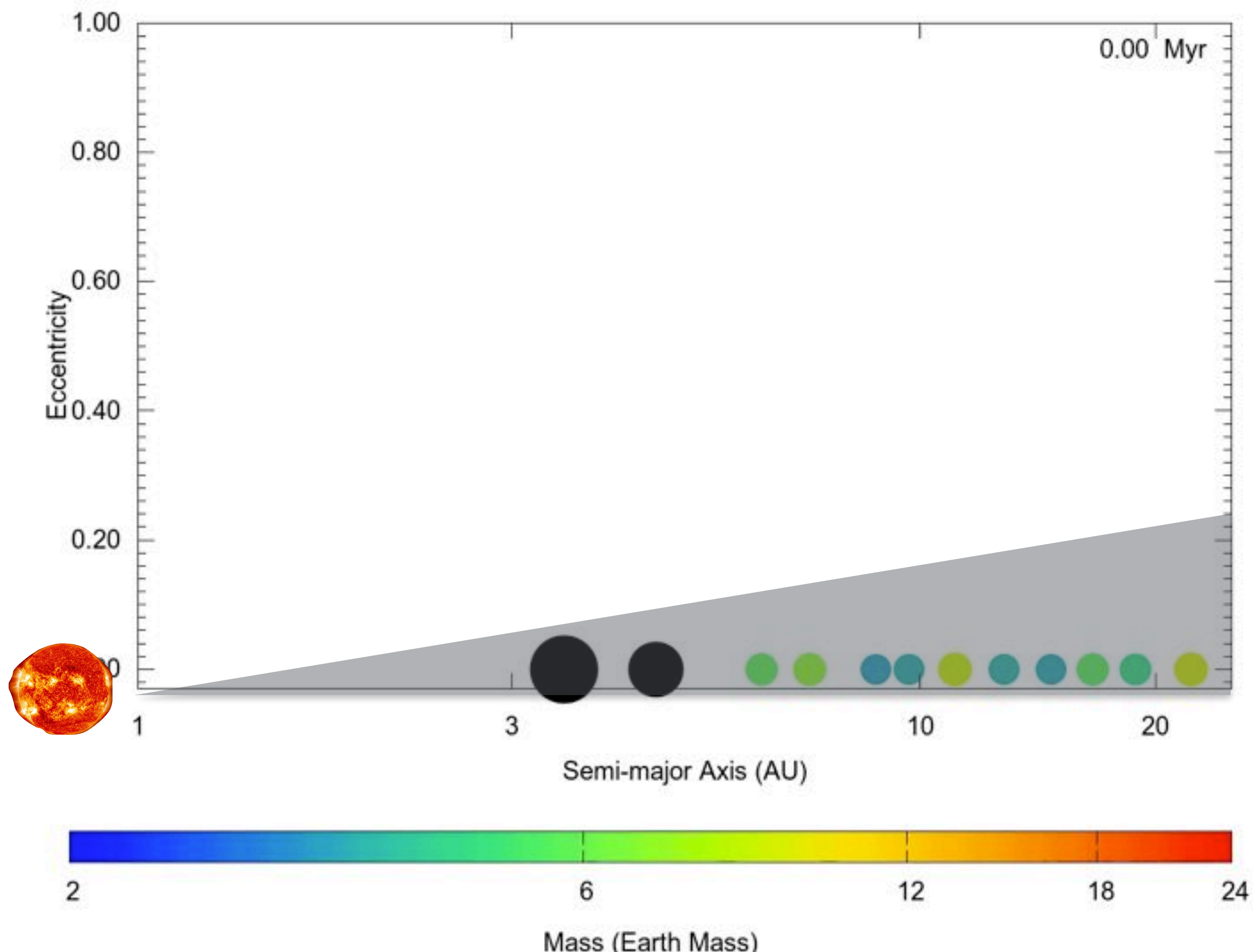
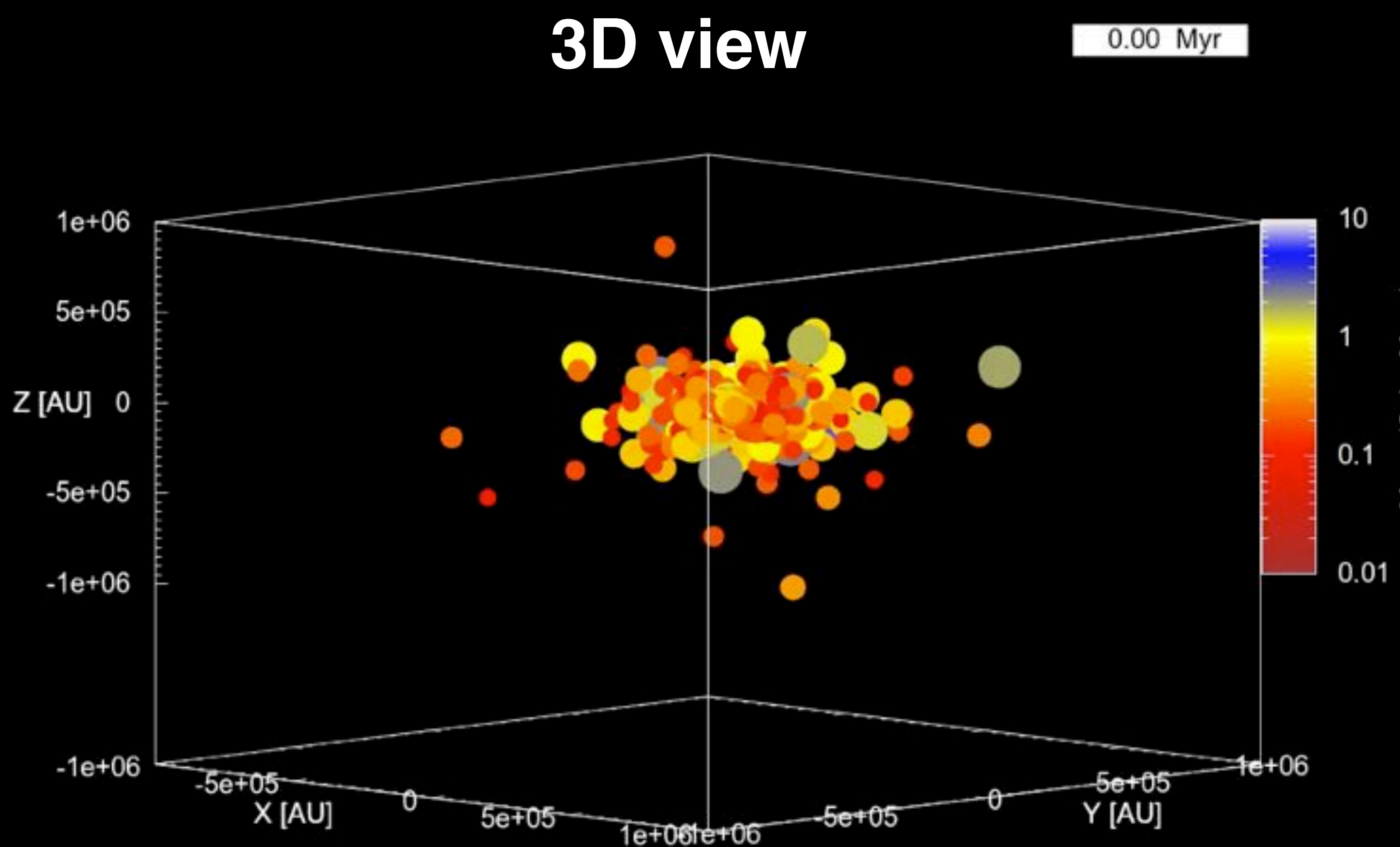


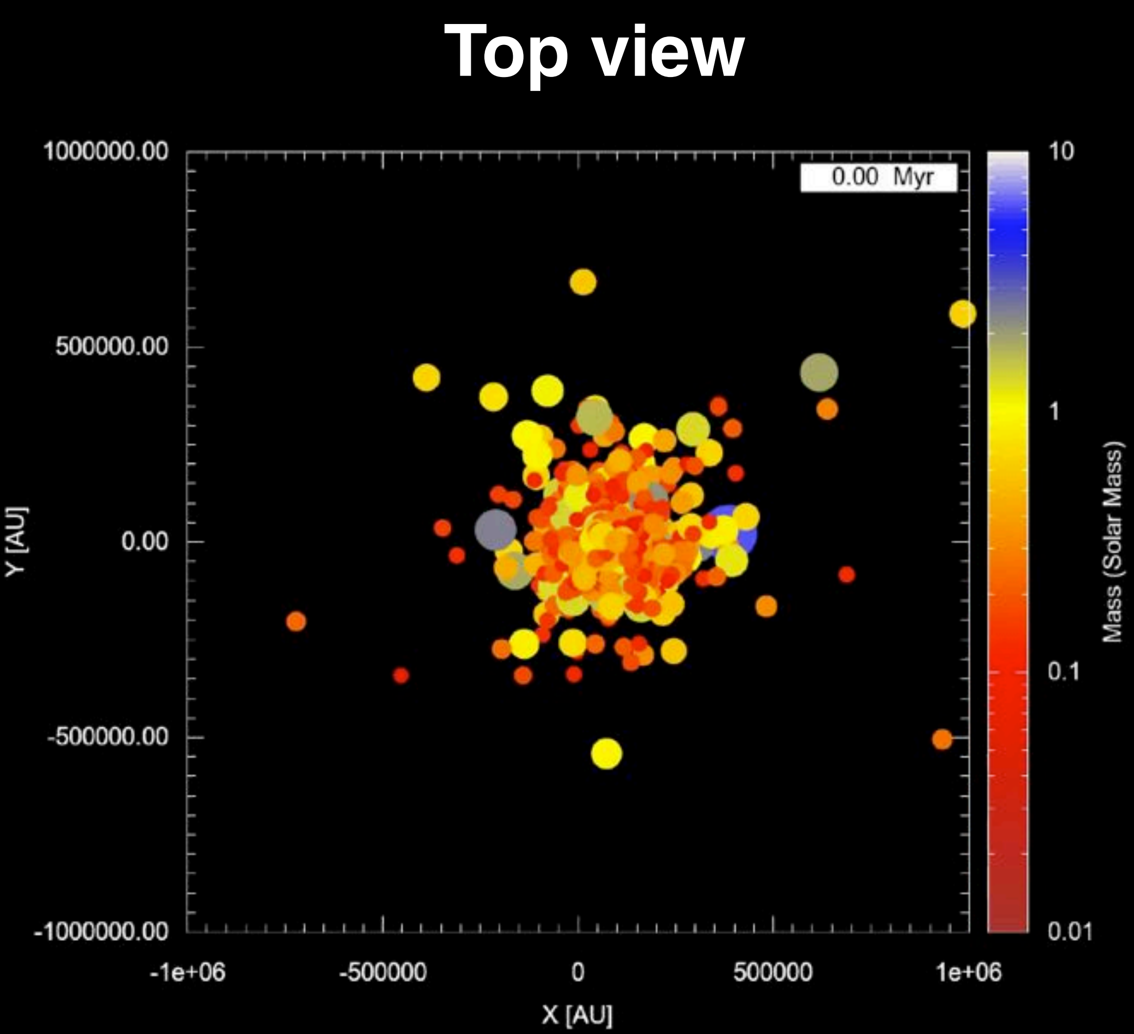
Scattering of planetary embryos during the ice giants accretion



Izidoro et al., 2015, A&A

The Sun was born in a cluster of ~1000 stars (e.g., Adams 2010)





Izidoro et al in prep

Planet 9: a scattered ice giant?

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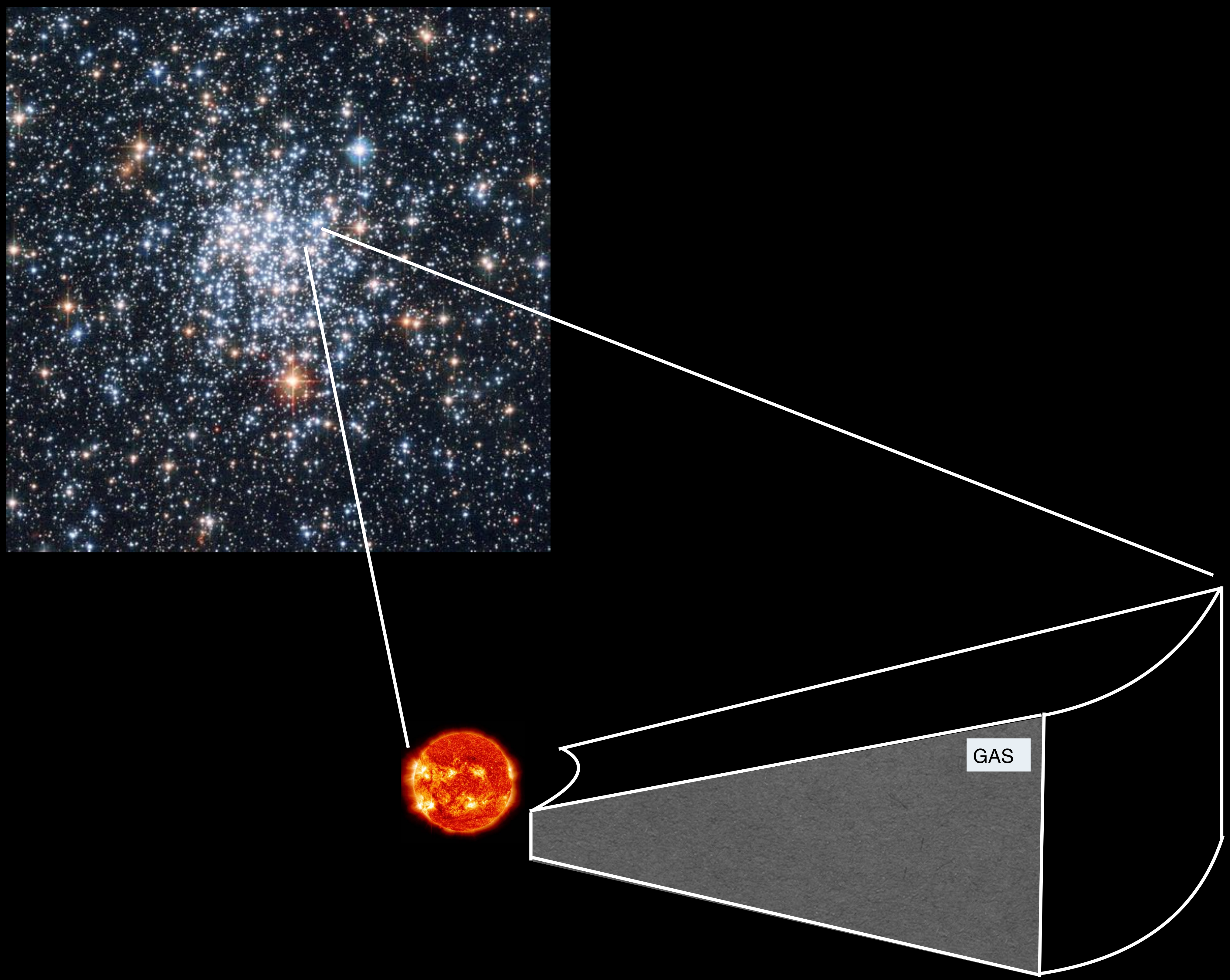
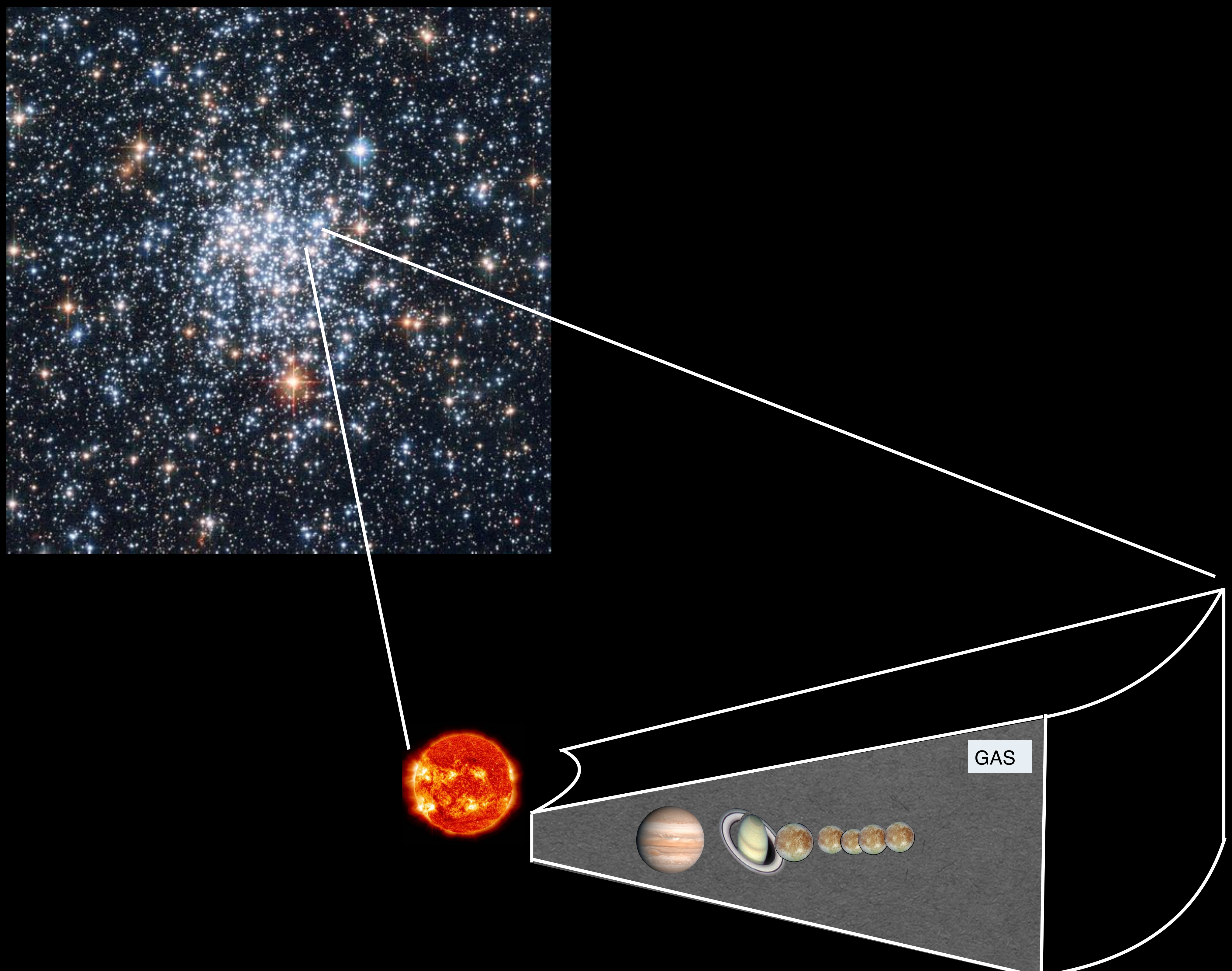
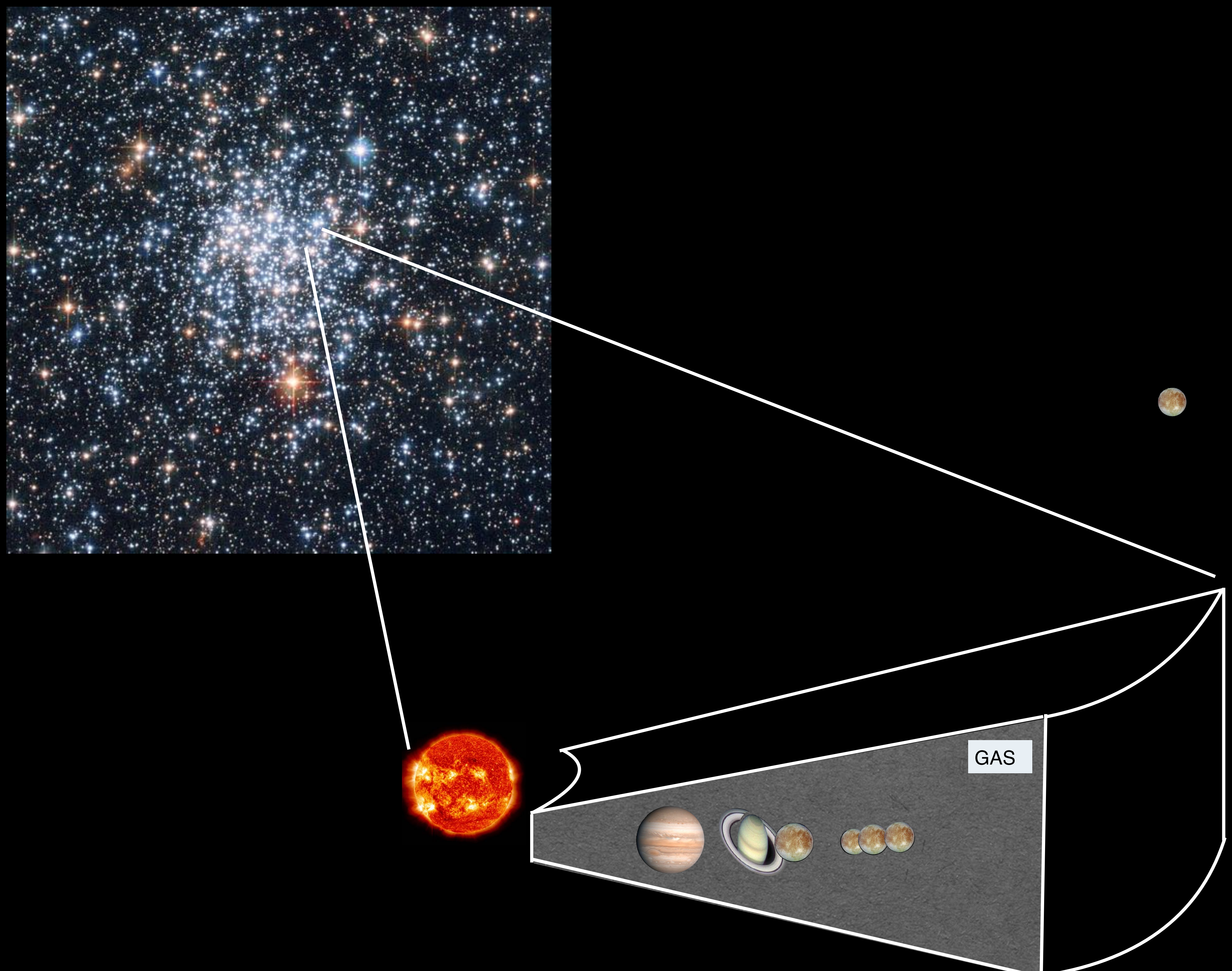


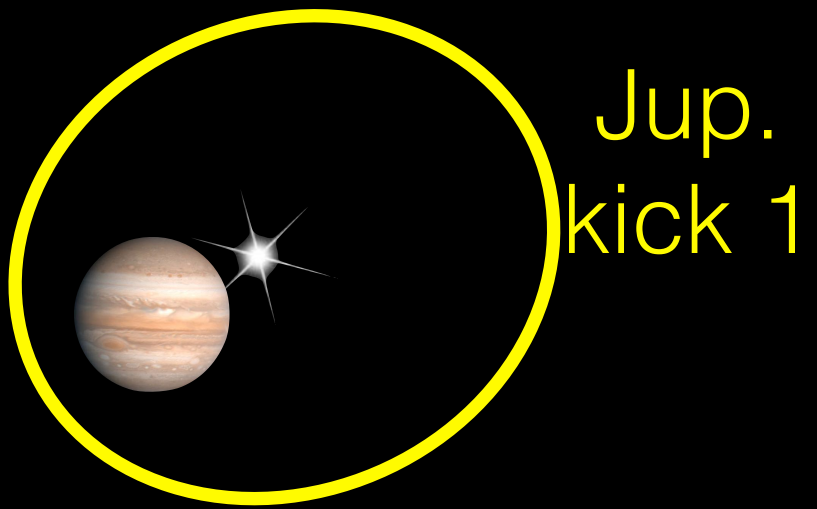
Planet 9: a scattered ice giant?



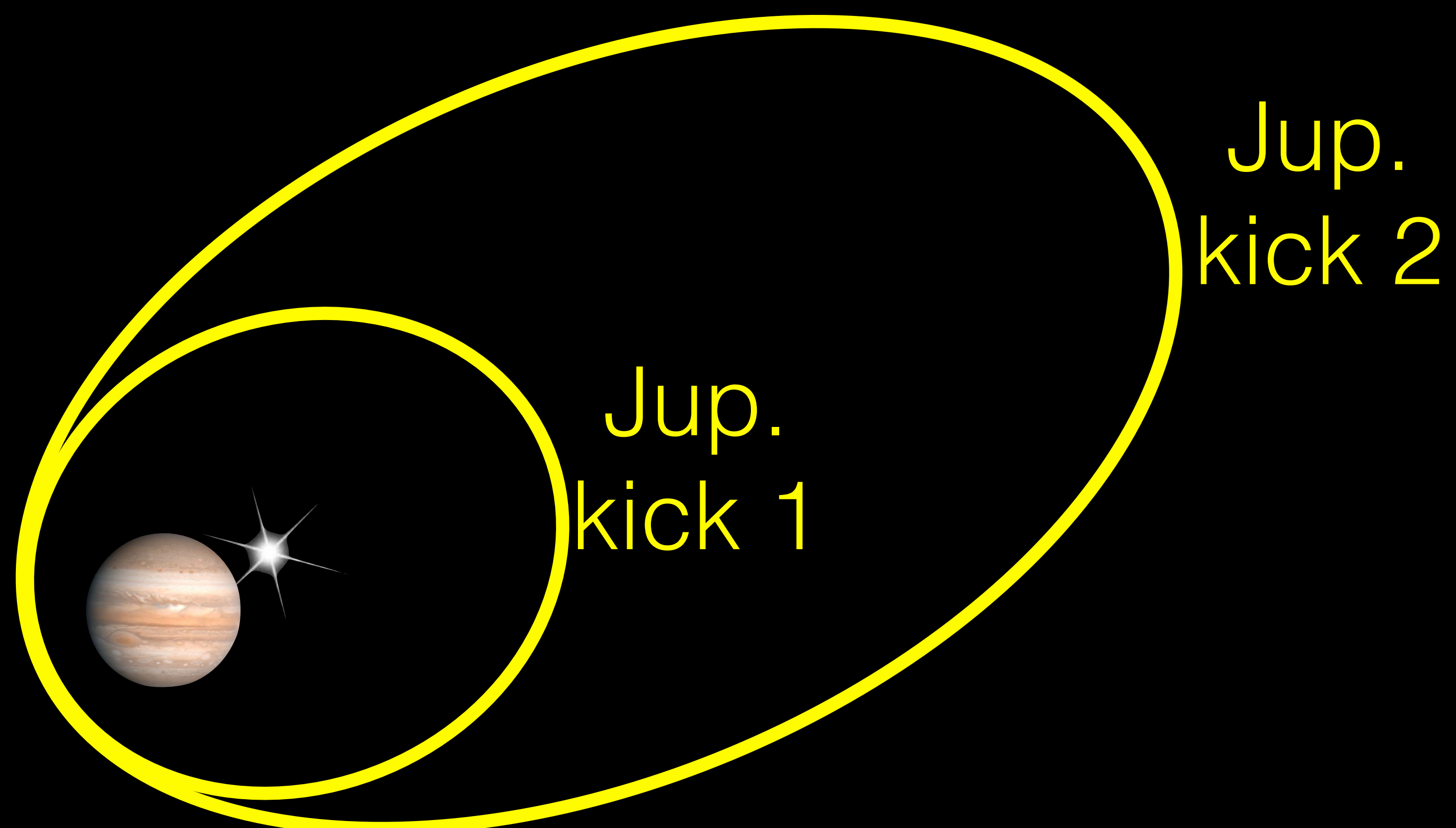
Planet 9: a scattered ice giant?

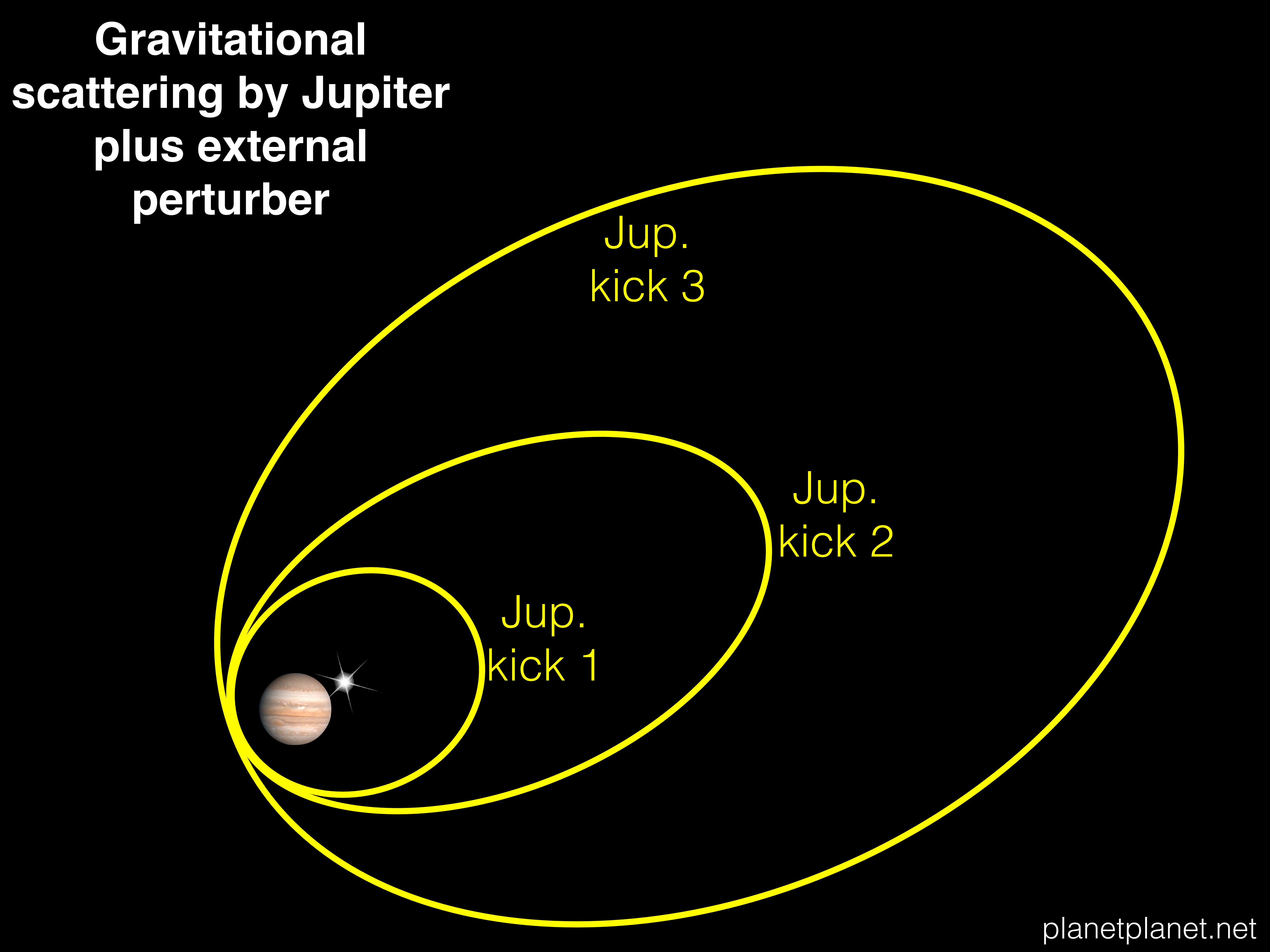


Gravitational scattering by Jupiter plus external perturber

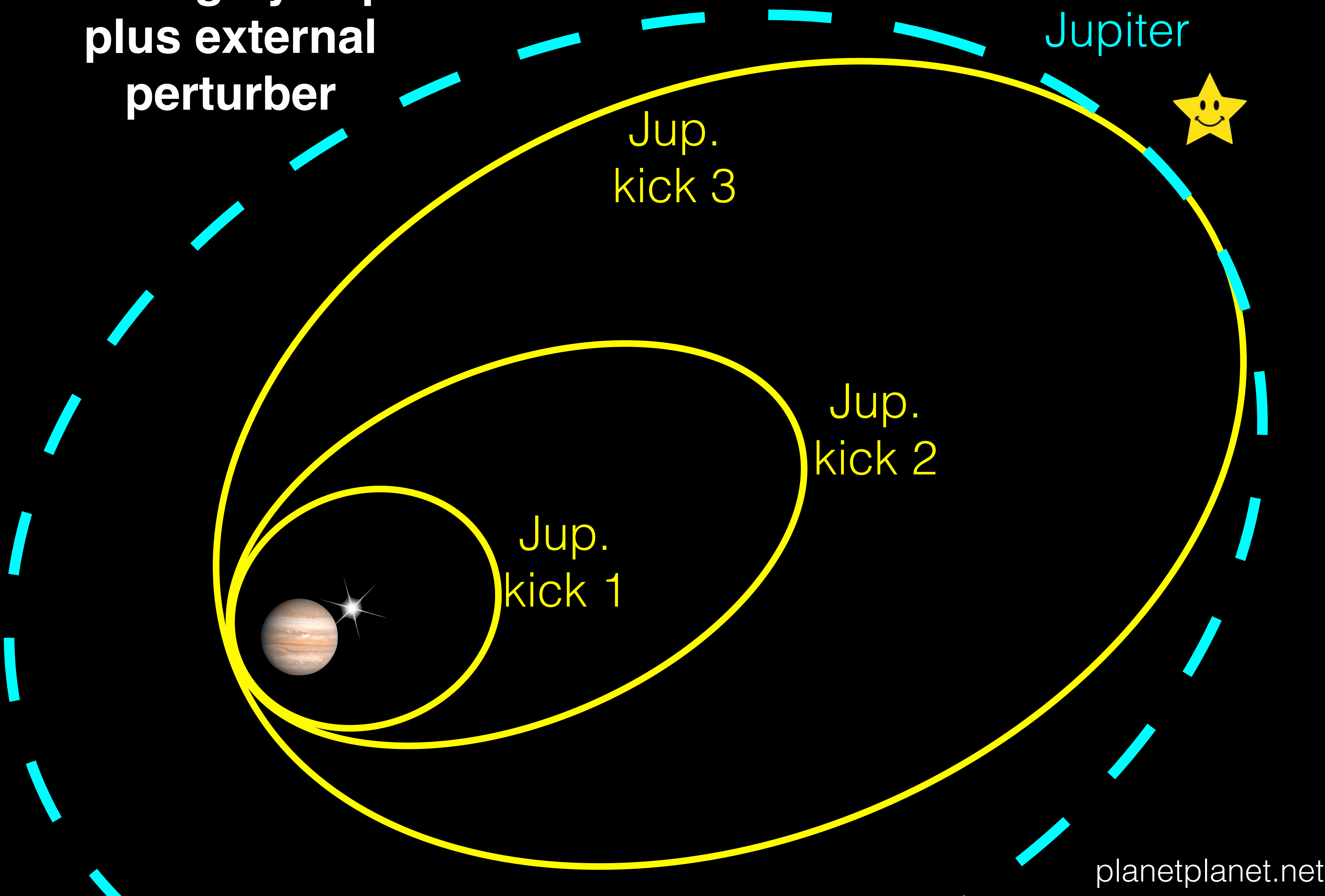


Gravitational scattering by Jupiter plus external perturber



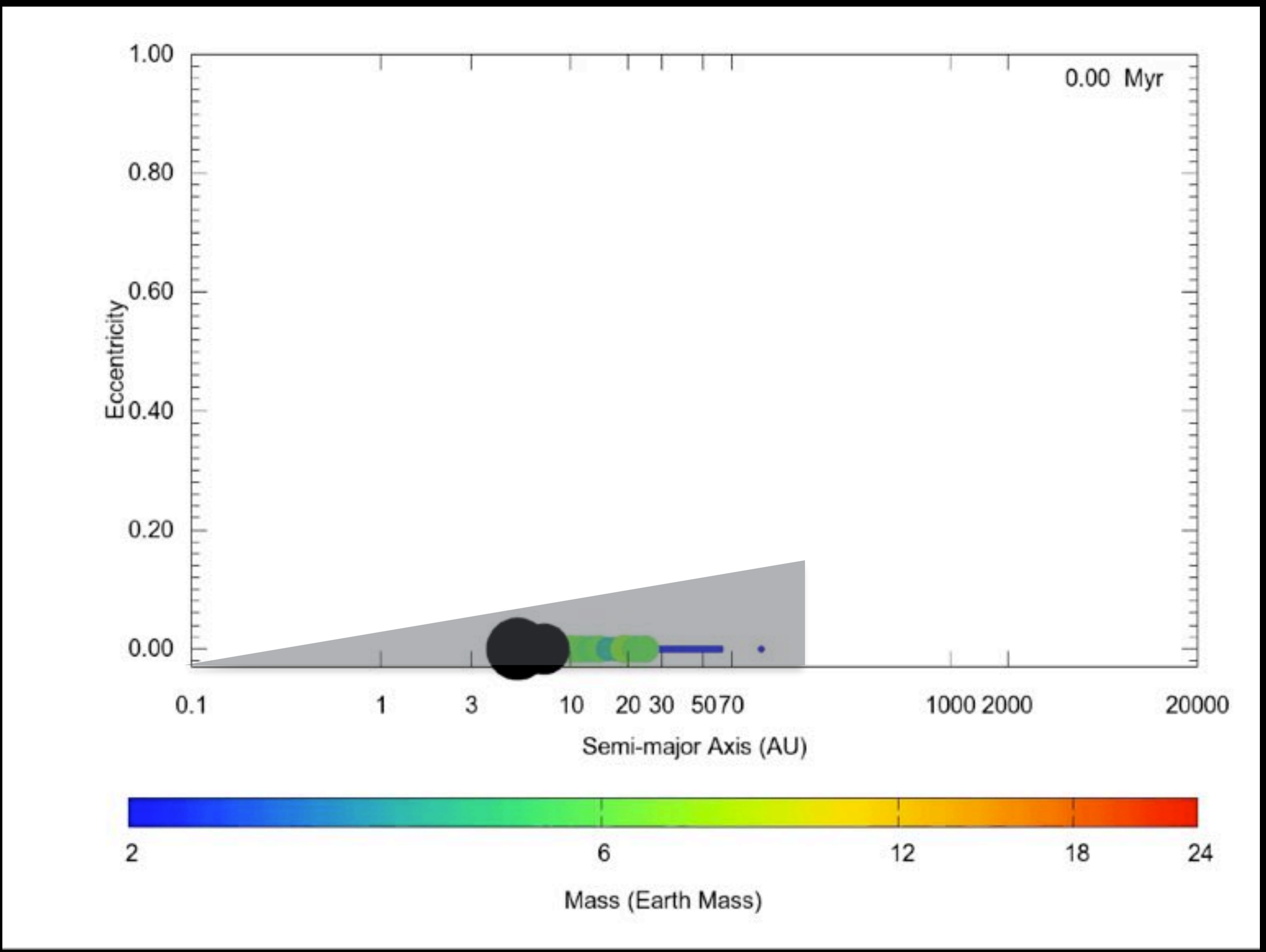

Gravitational scattering by Jupiter plus external perturber
Jup. kick 3
Jup. kick 2
Jup. kick 1
planetplanet.net

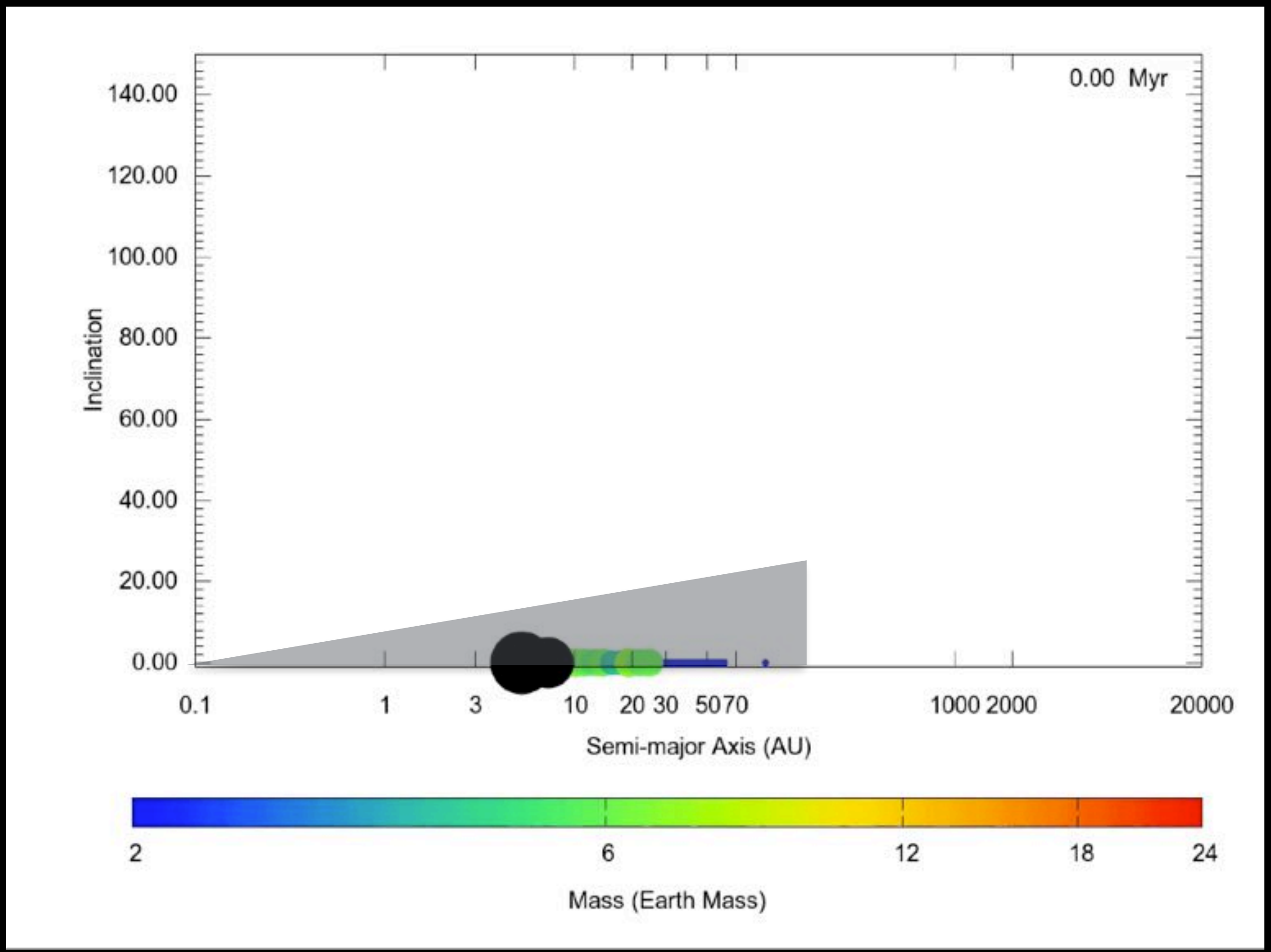
Gravitational scattering by Jupiter plus external perturber



planetplanet.net

Planet 9: a scattered ice giant?





Here cluster of 200 stars, rc=10,000AU
Izidoro, Kaib, Raymond & Morbidelli (in prep).

Explaining the Solar System:


Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Planet 9

Planetesimals
scattered during
Jup/Sat's growth

Planetesimals
scattered during
Jup/Sat's growth

Jup/Sat's
Grand Tack?

Planetesimals scattered during Jup/Sat's growth

Low-mass asteroid belt? Chaotic early Jup/Sat?

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Jup/Sat's Grand Tack?

Giant impacts explain the masses and tilt of the ice giants