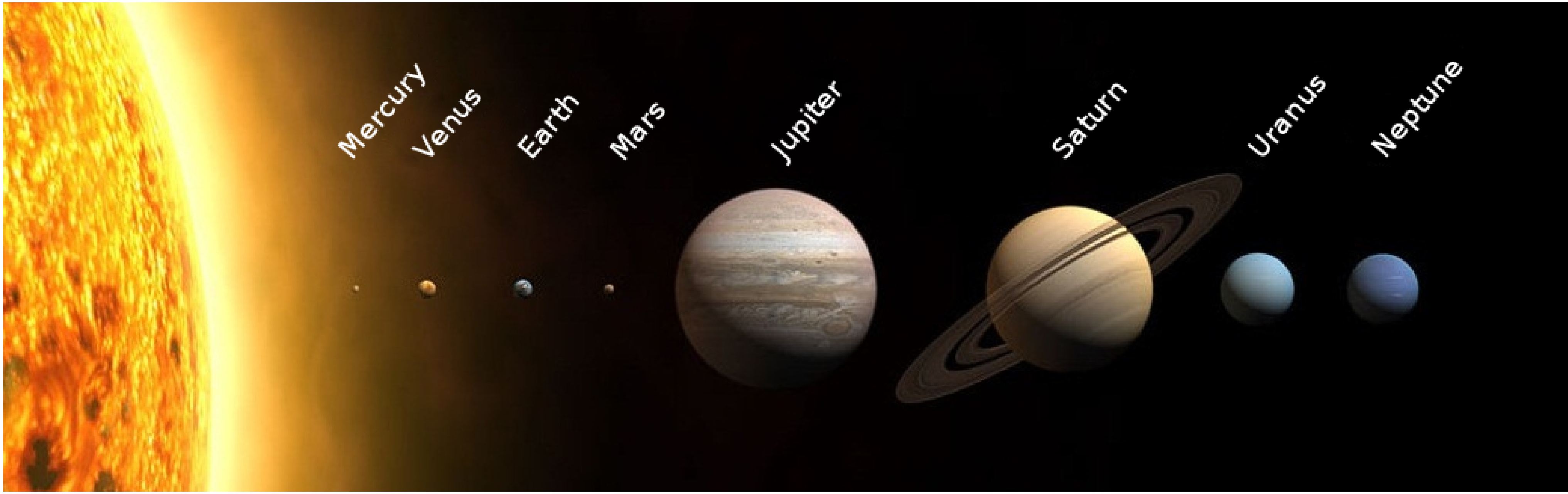
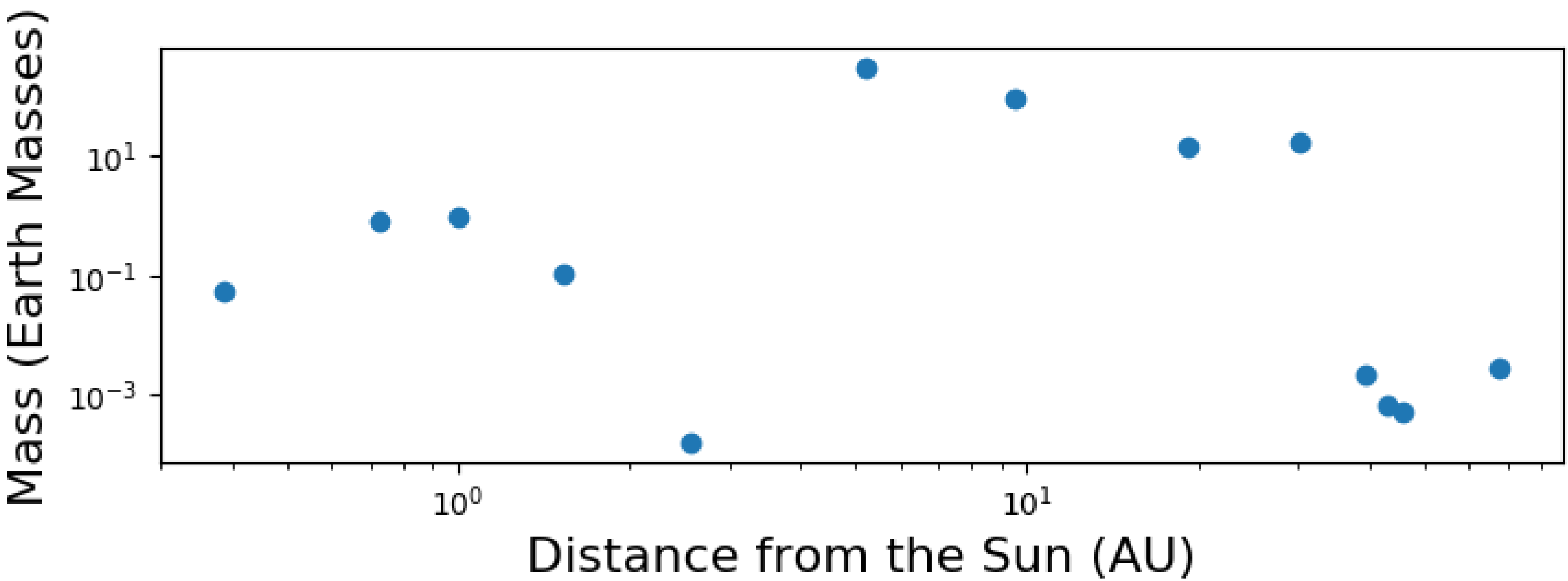
Making Mars:
The story Mars tells about planet formation and migration in the early Solar System

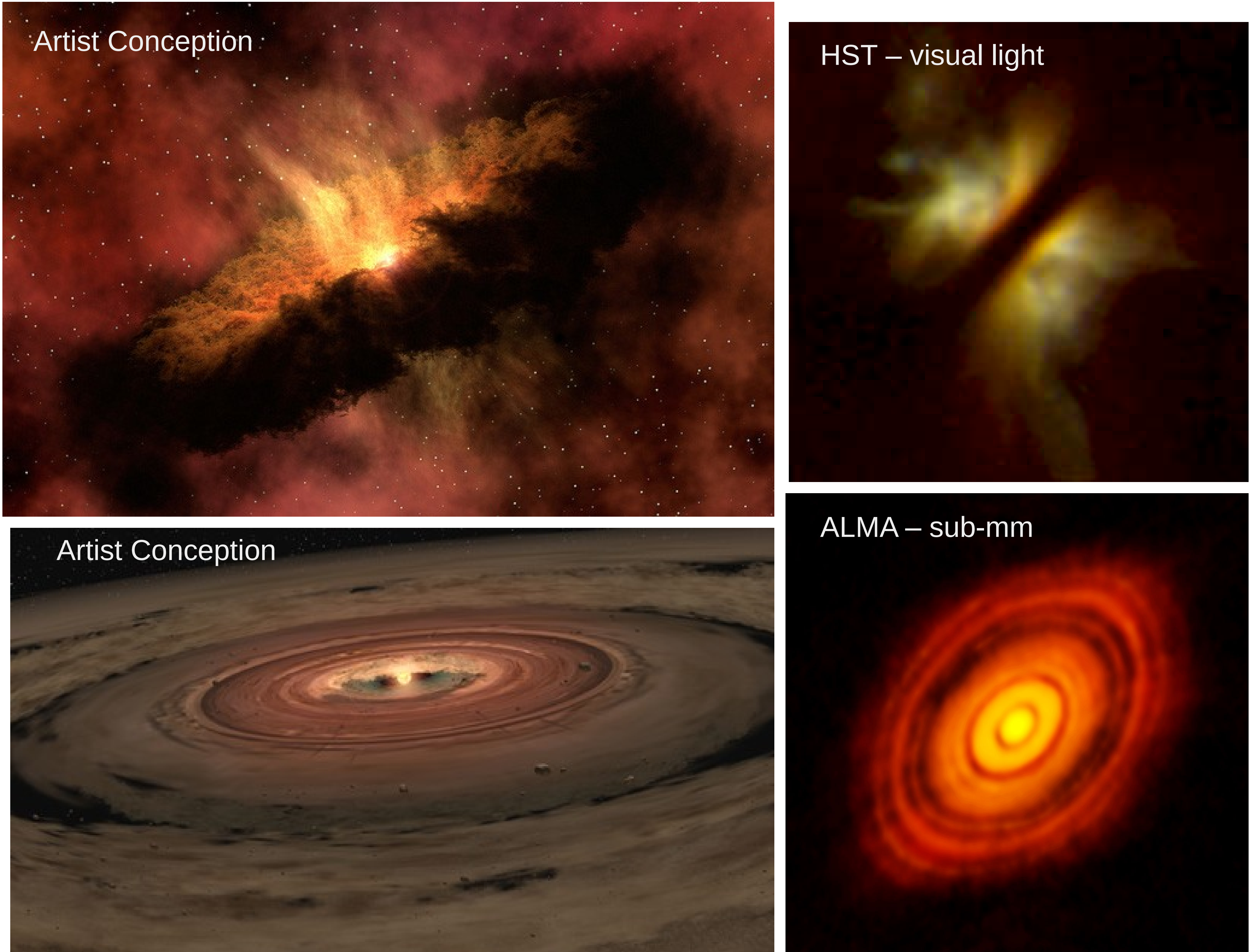
Katherine Kretke
Southwest Research Institute

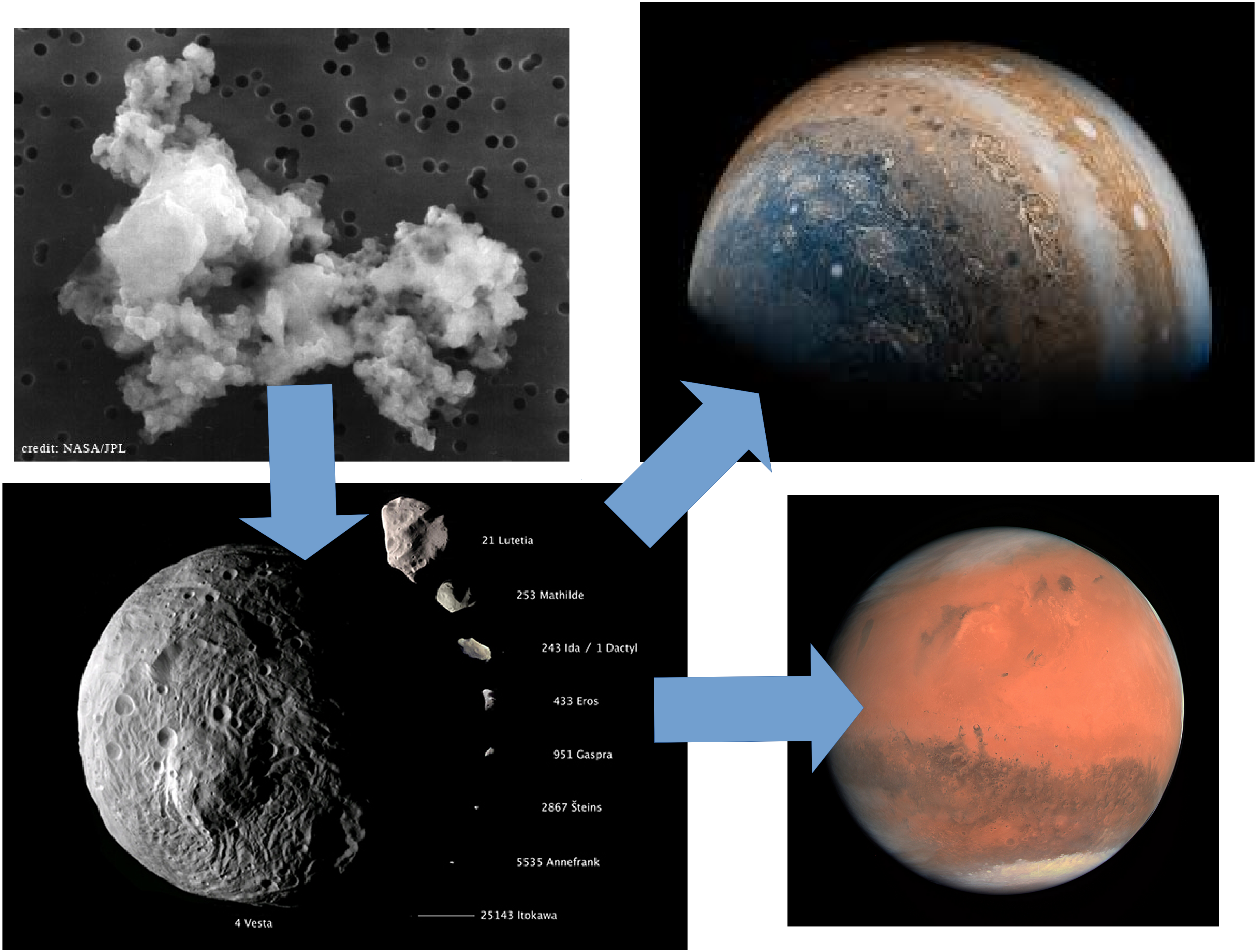


Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune

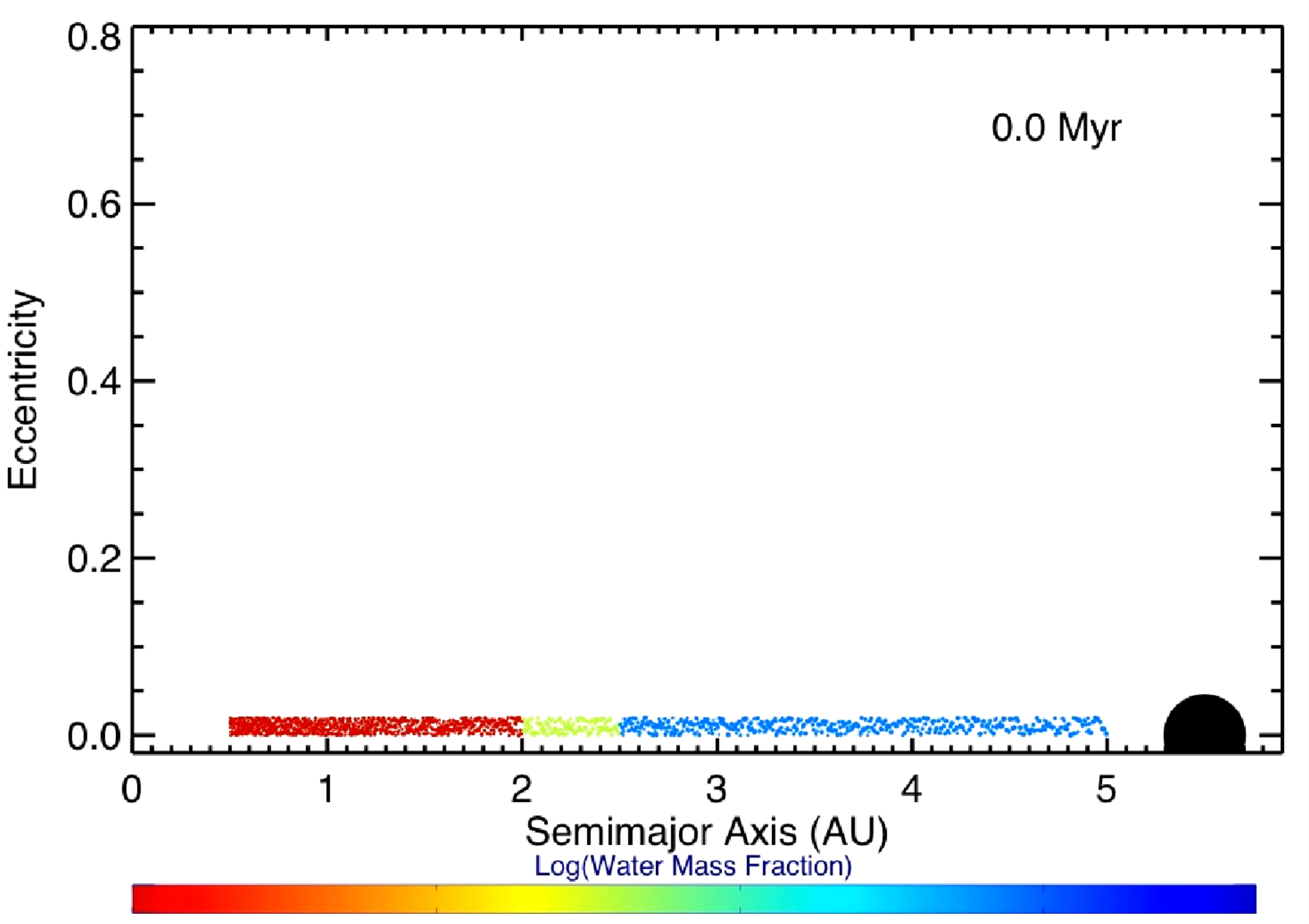


Mass (Earth Masses)
10^1
10^{-1}
10^{-3}
10^0
10^1
Distance from the Sun (AU)


Artist Conception
HST – visual light
Artist Conception
ALMA – sub-mm

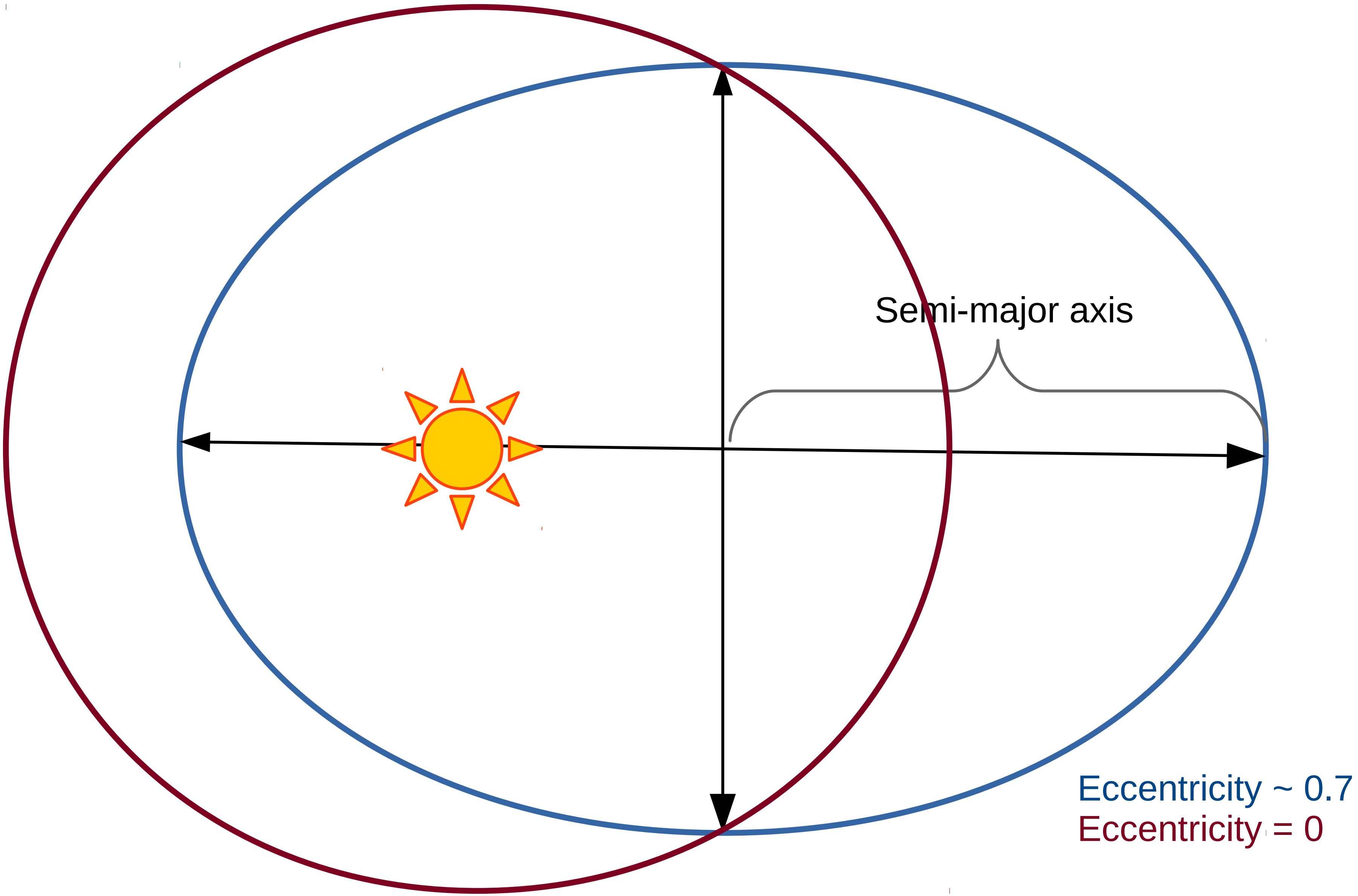

credit: NASA/JPL
21 Lutetia
253 Mathilde
243 Ida / 1 Dactyl
433 Eros
951 Gaspra
2867 Šteins
5535 Annefrank
25143 Itokawa
4 Vesta

Forming the Terrestrial Planets

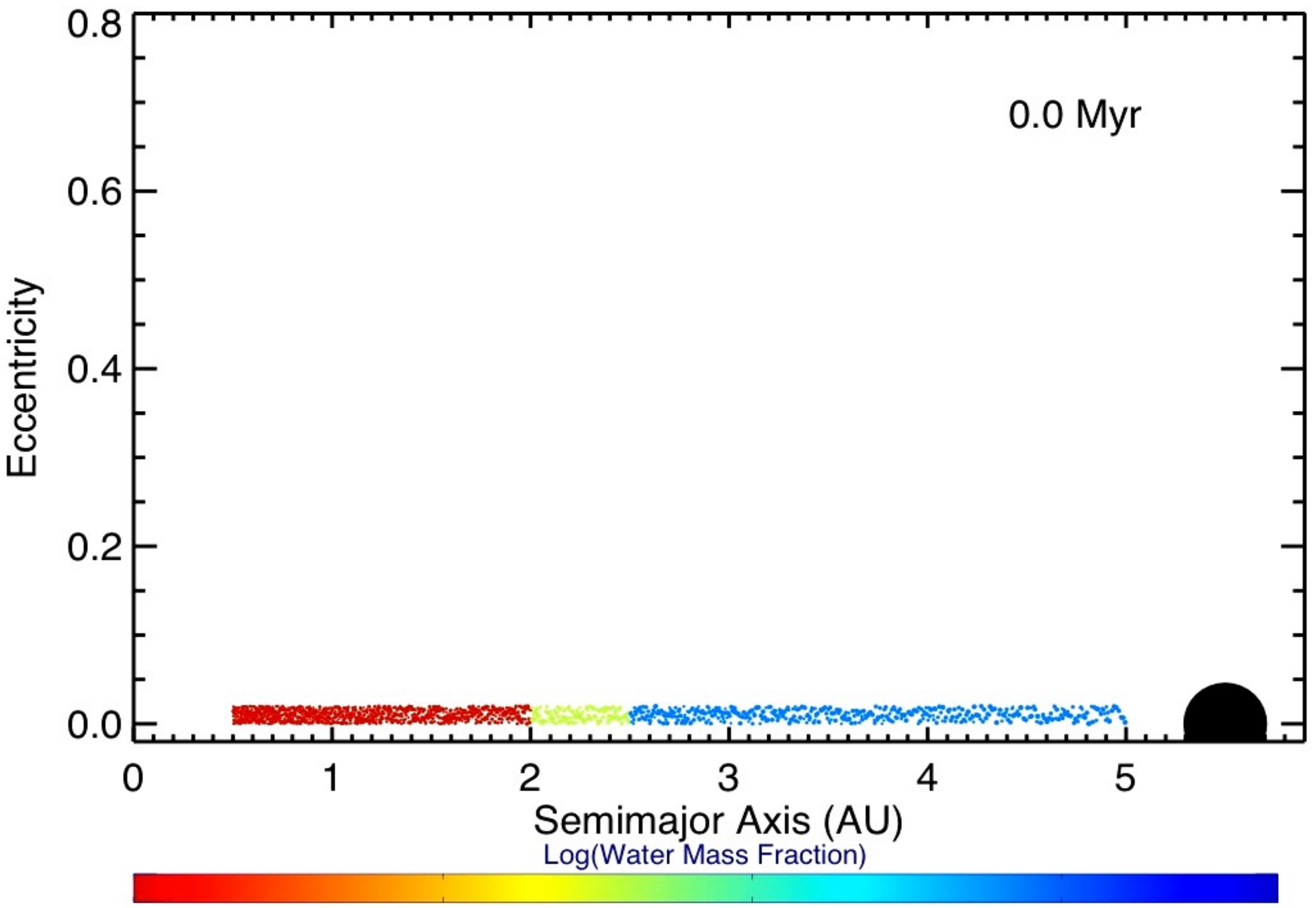


Raymond et al 2006

Anatomy of an orbit

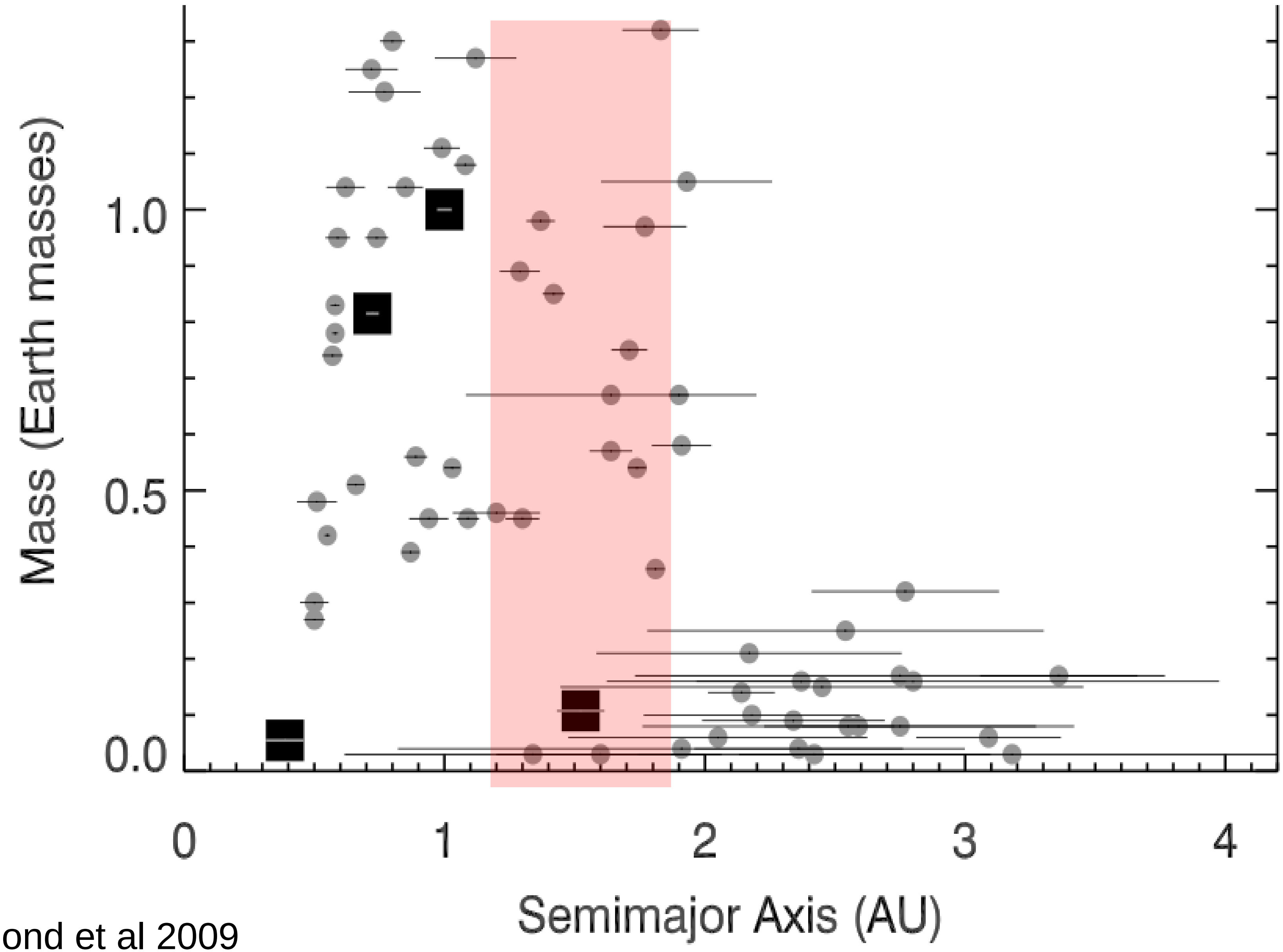


Forming the Terrestrial Planets



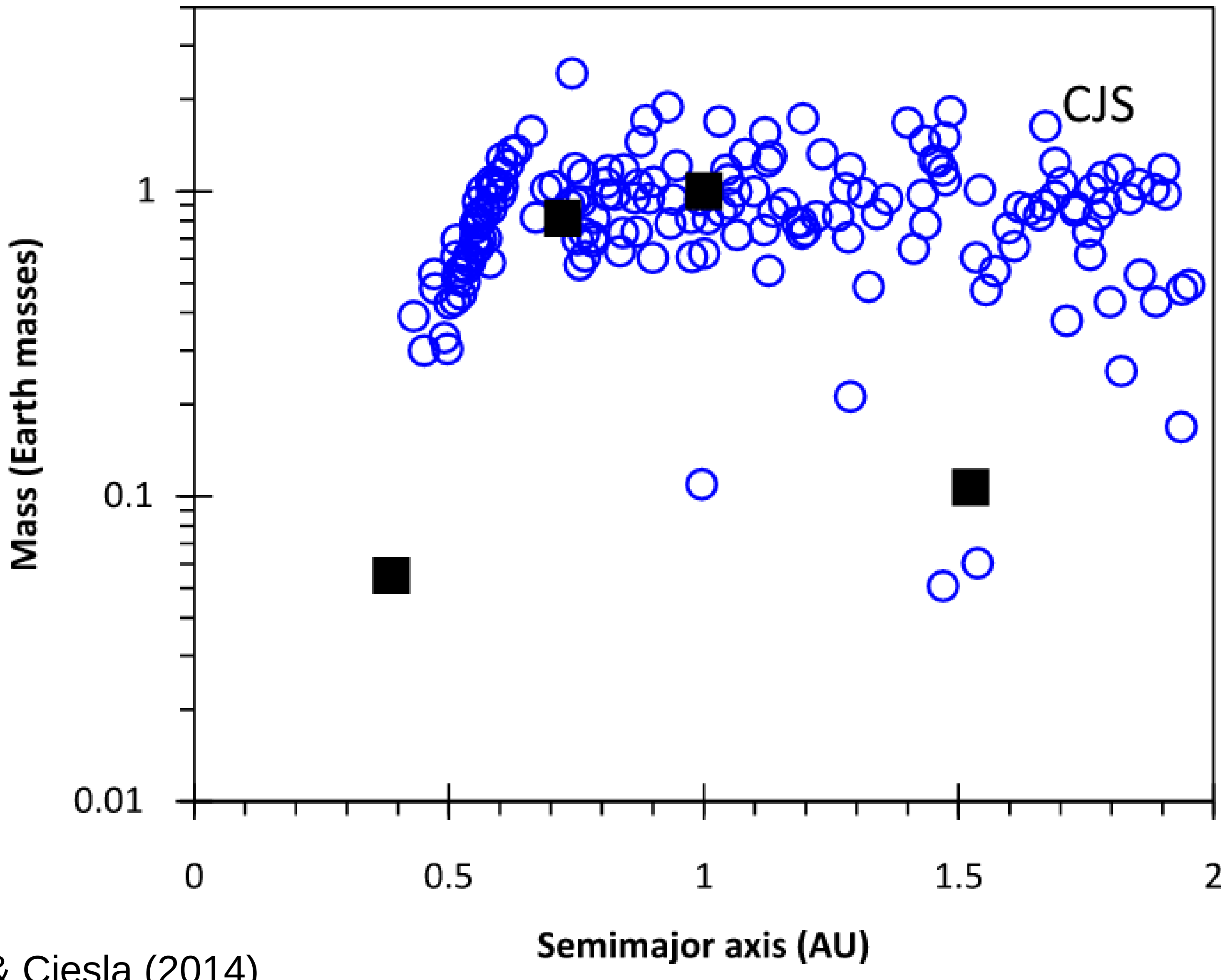
Raymond et al 2006

Problem with Mars



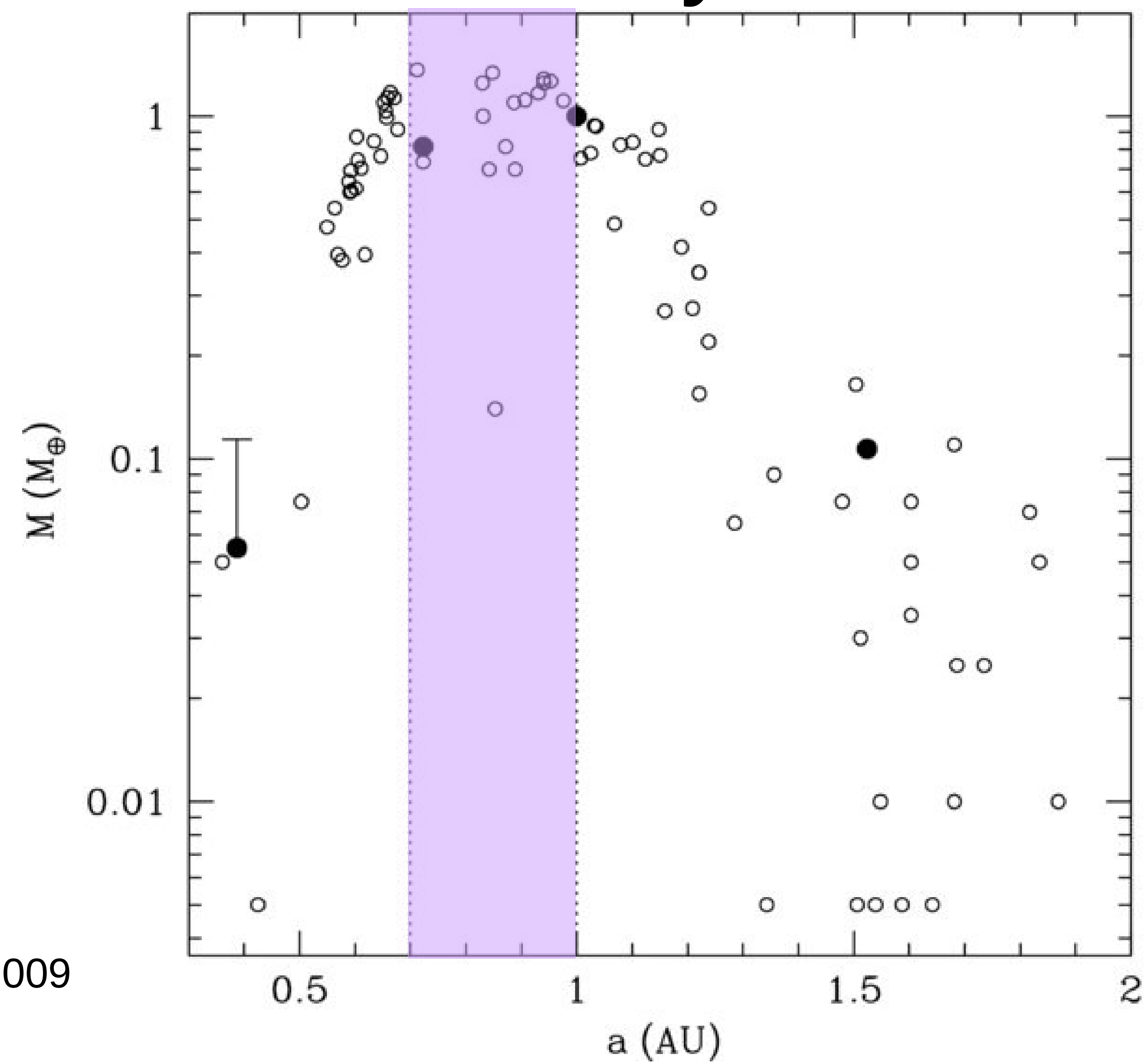
Raymond et al 2009

Maybe we're just "lucky" that Mars is small



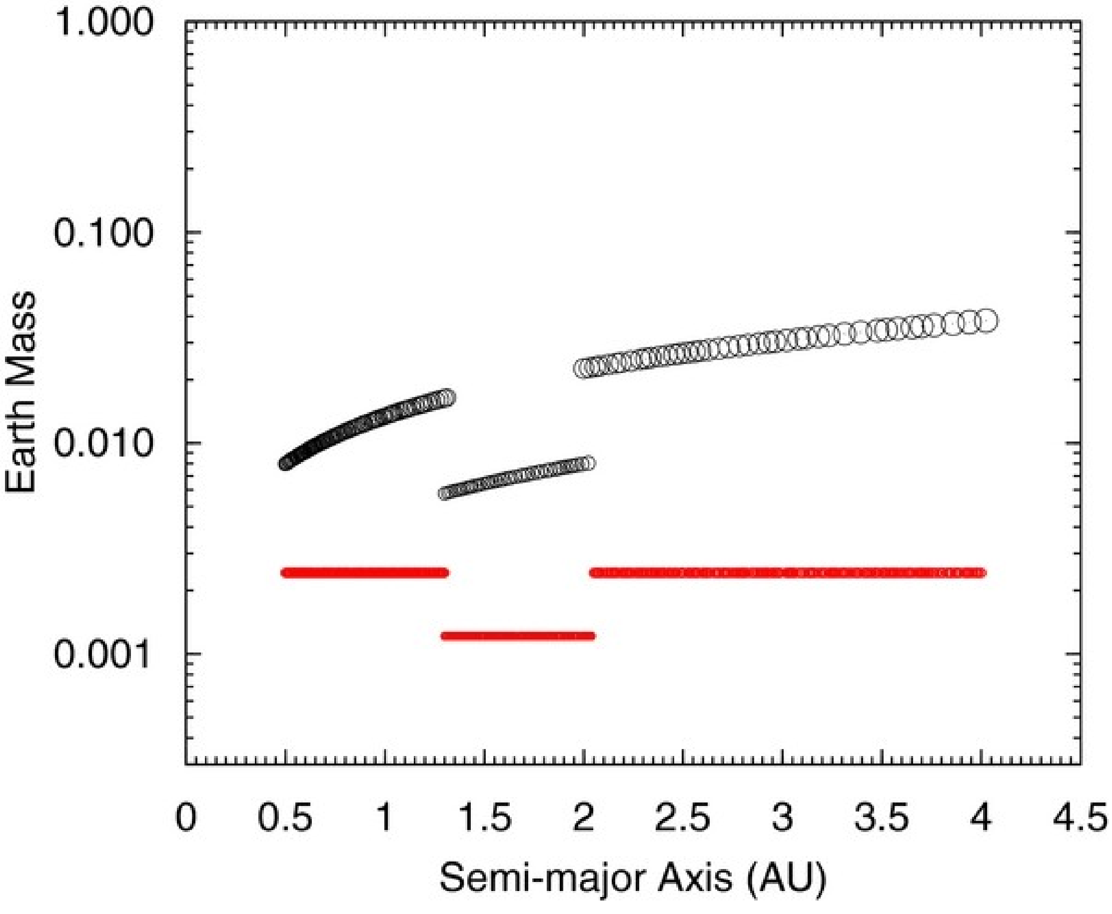
Fischer & Ciesla (2014)

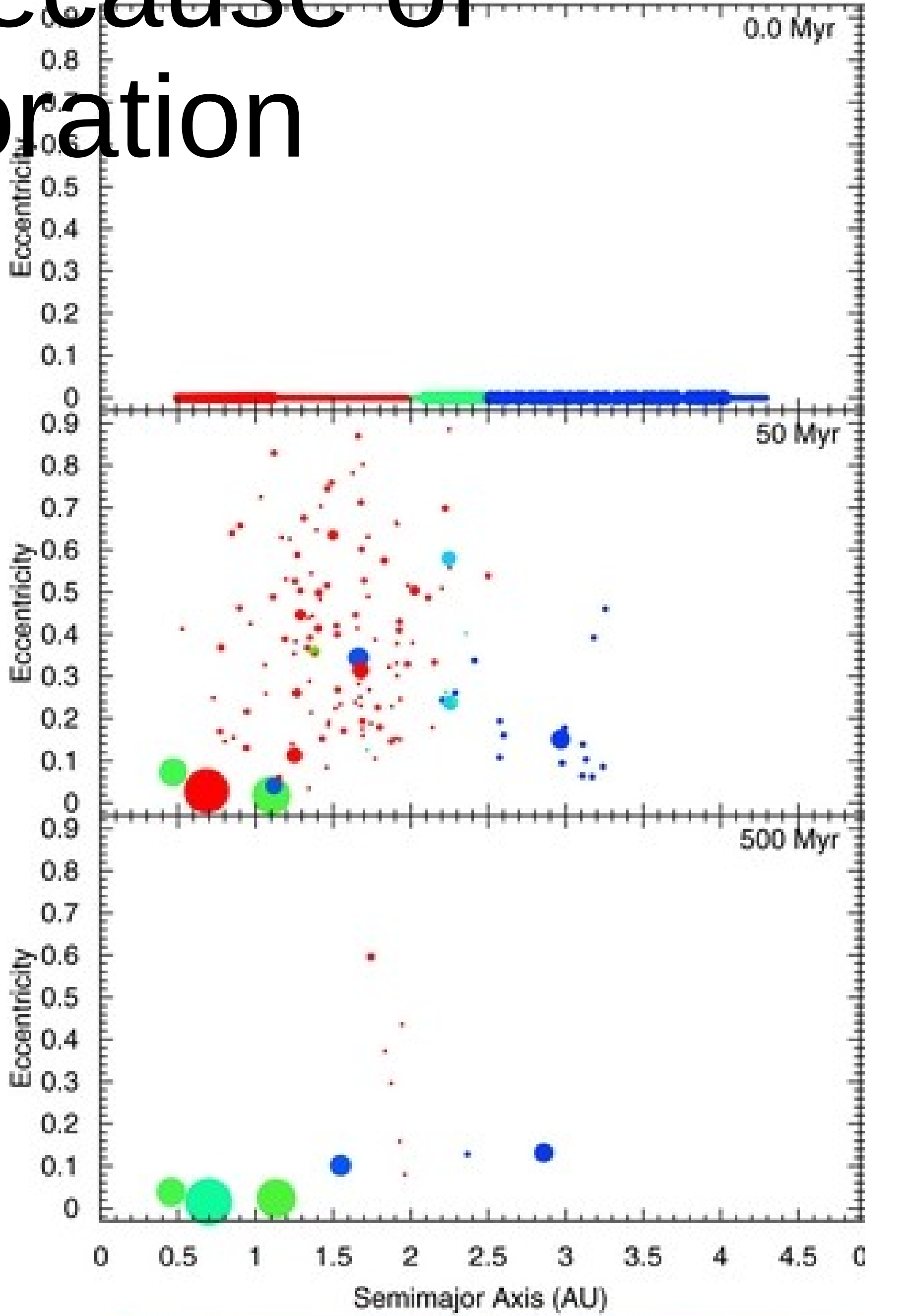
Maybe planetary building blocks weren't uniformly distributed



Hansen 2009

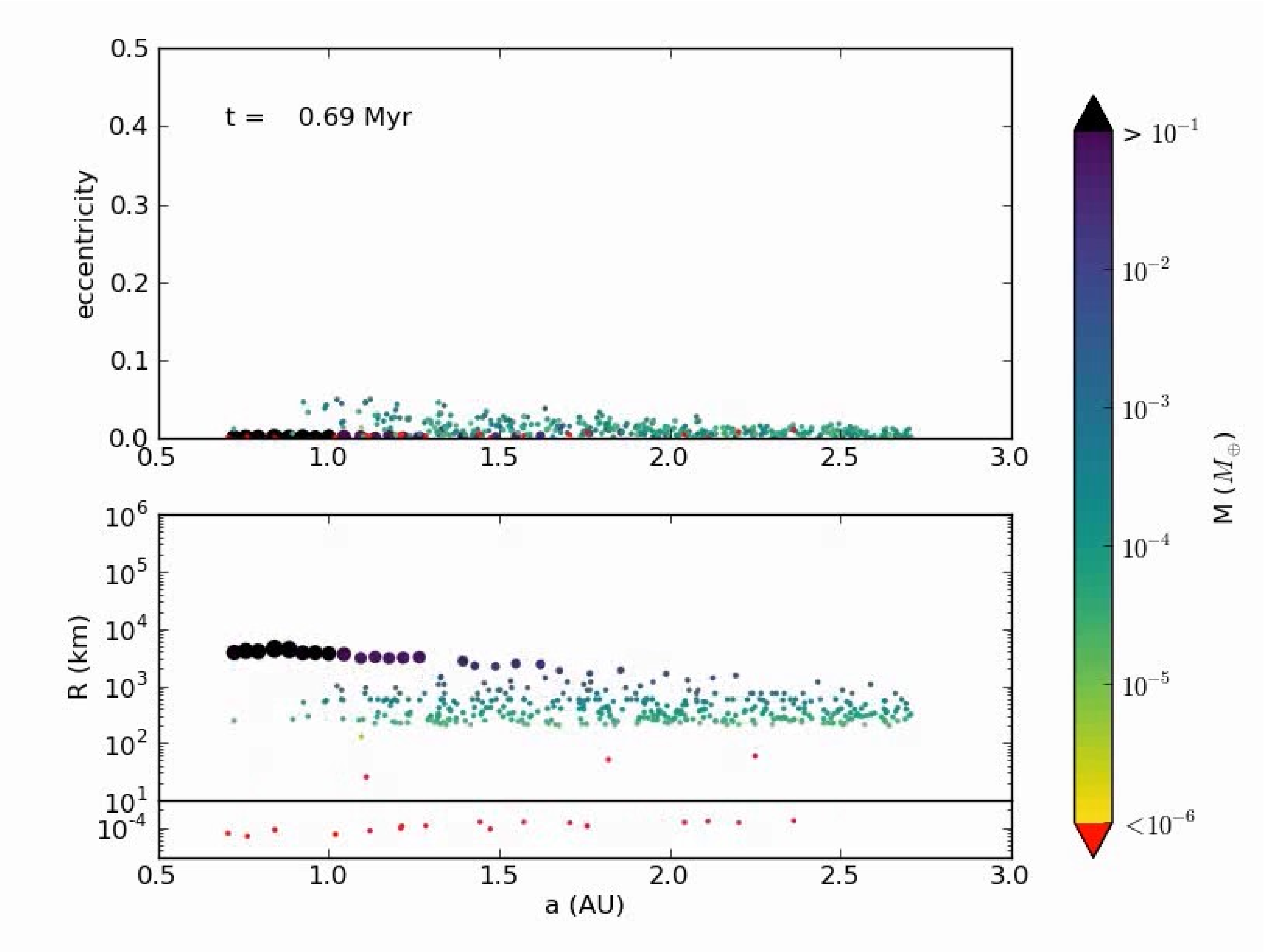
Maybe there was never much mass there initially because of photoevaporation





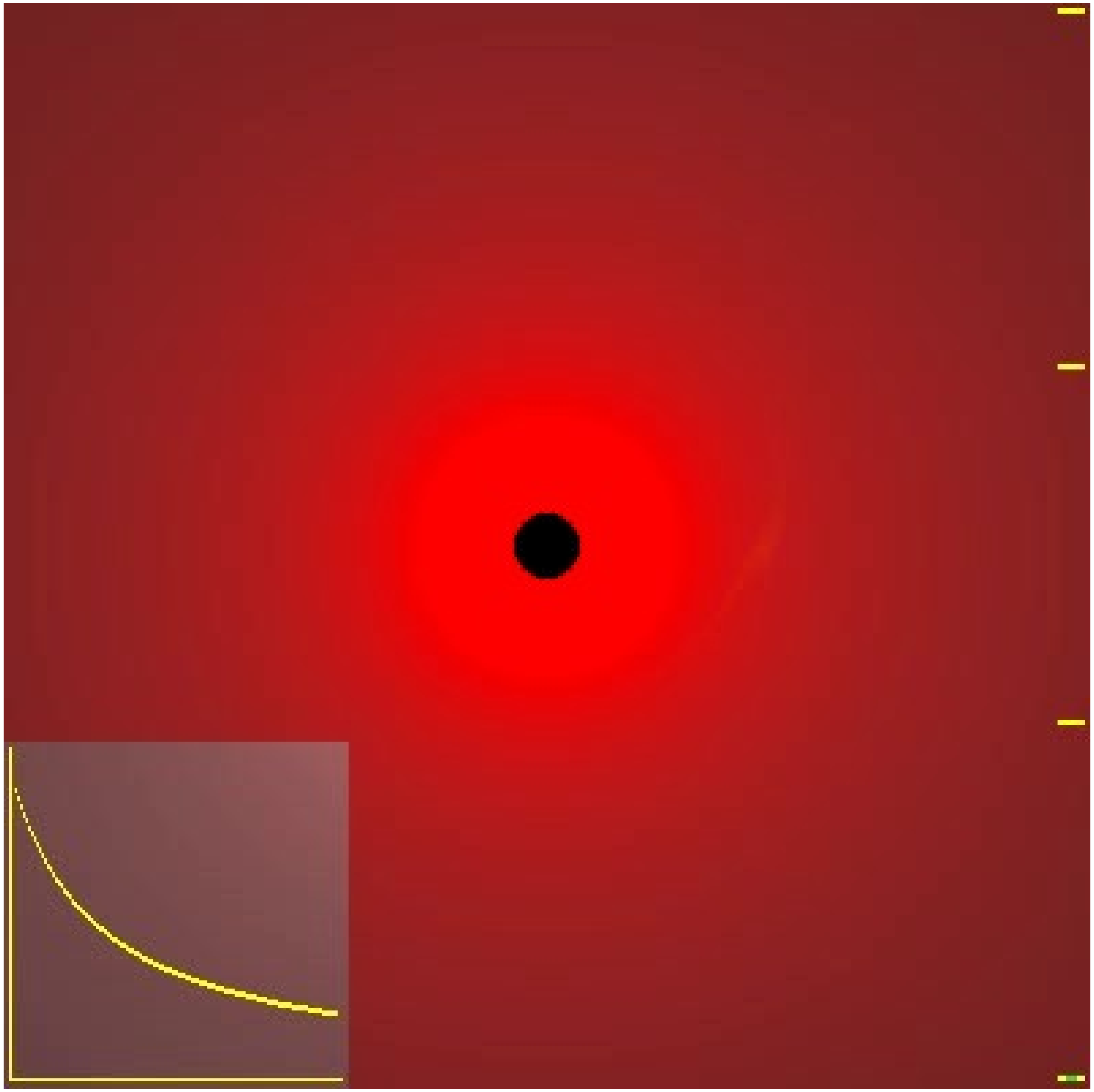
Izidoro et al 2014

Or because planets grew by accreting pebbles

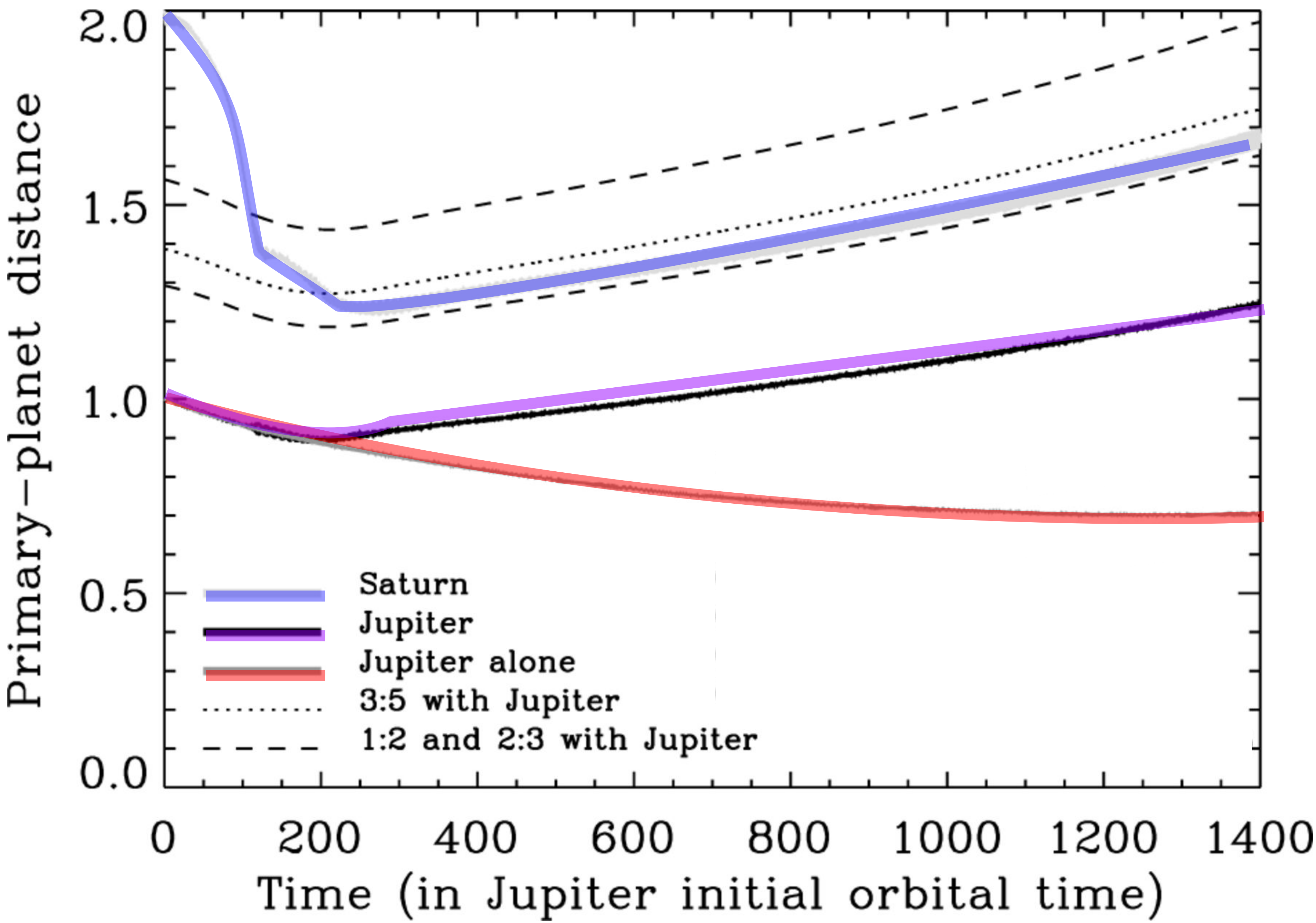


Levison et al 2015b

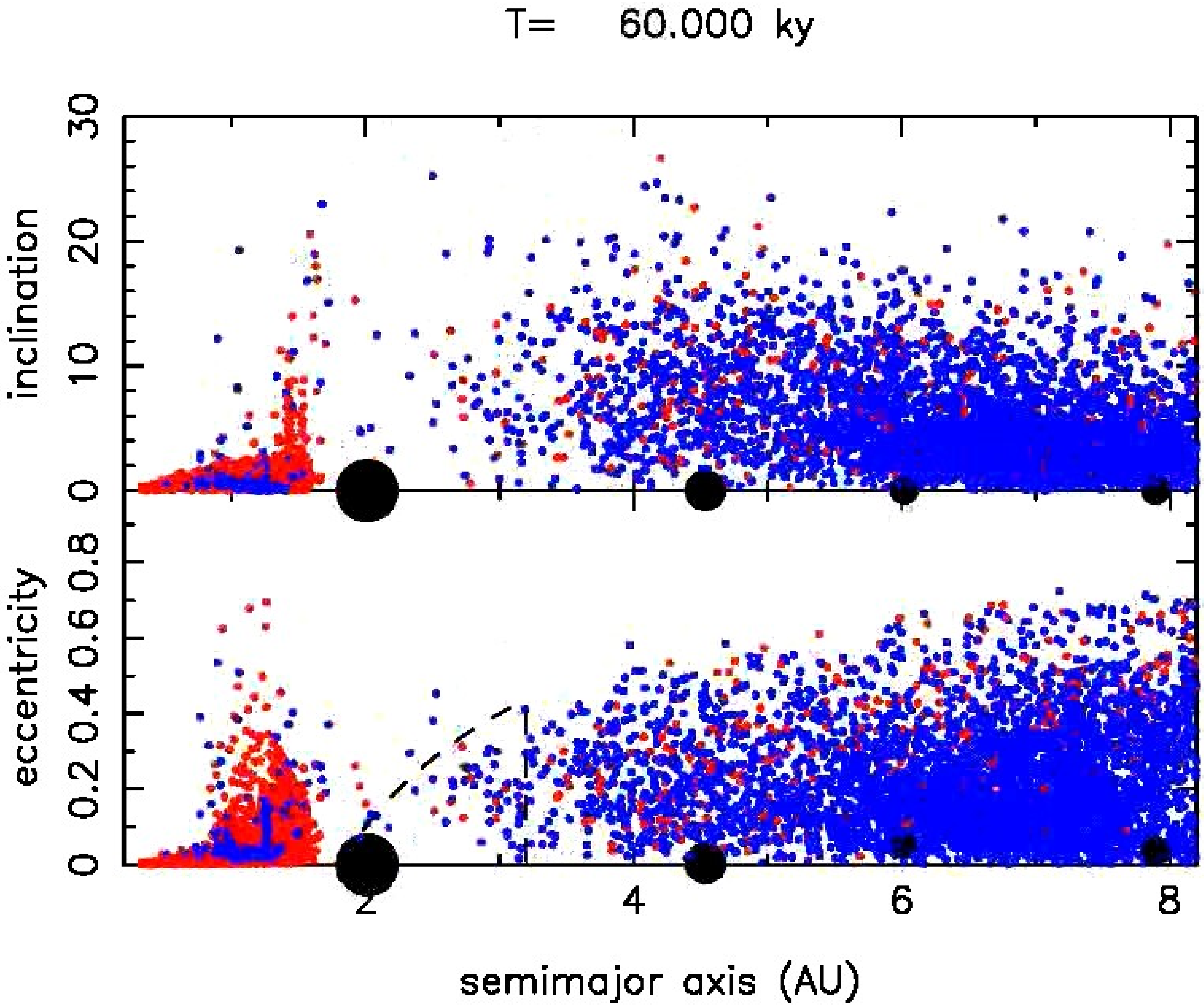
Planet Migration



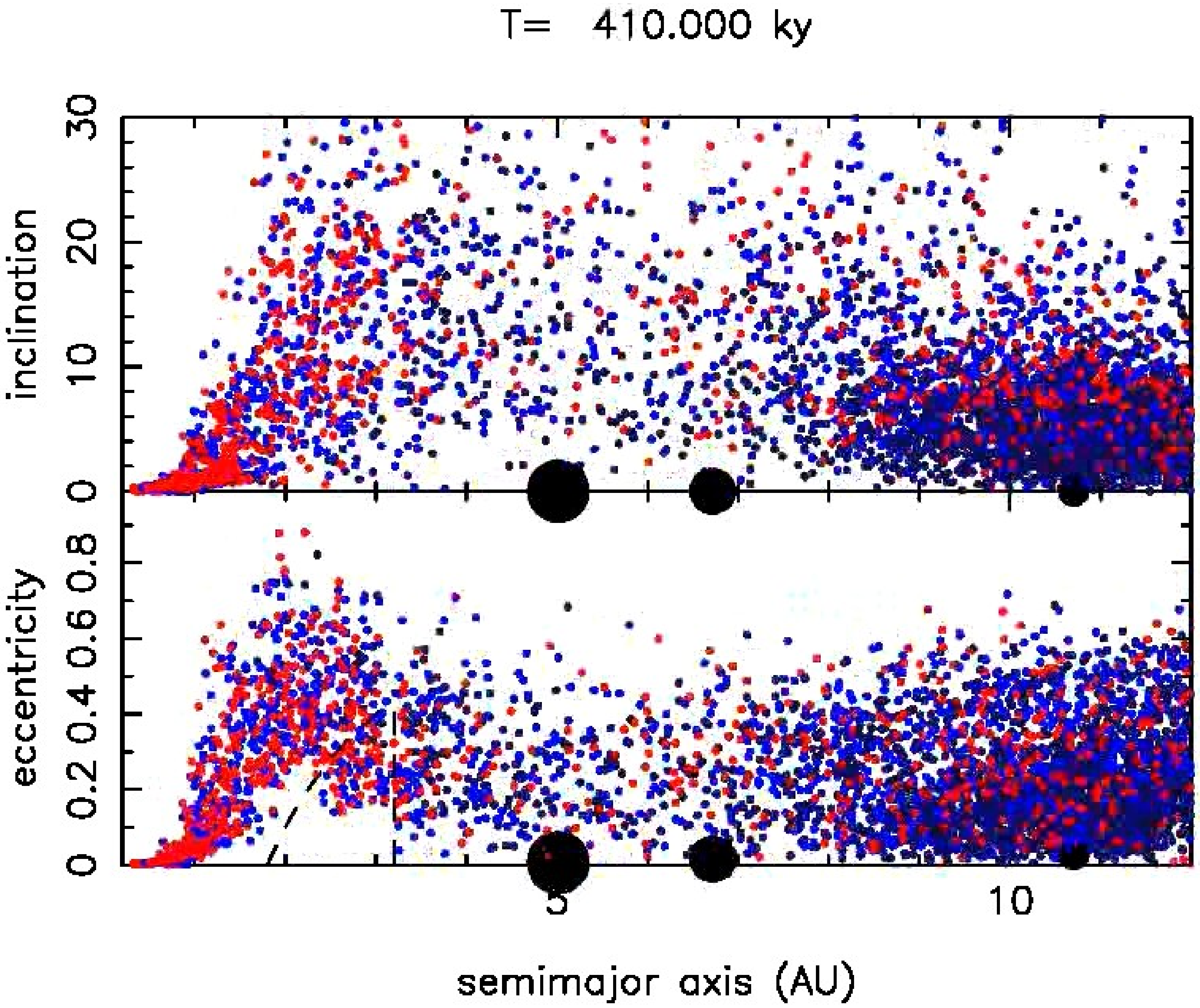
Courtesy of
Phil Armitage



Masset & Snellgrove

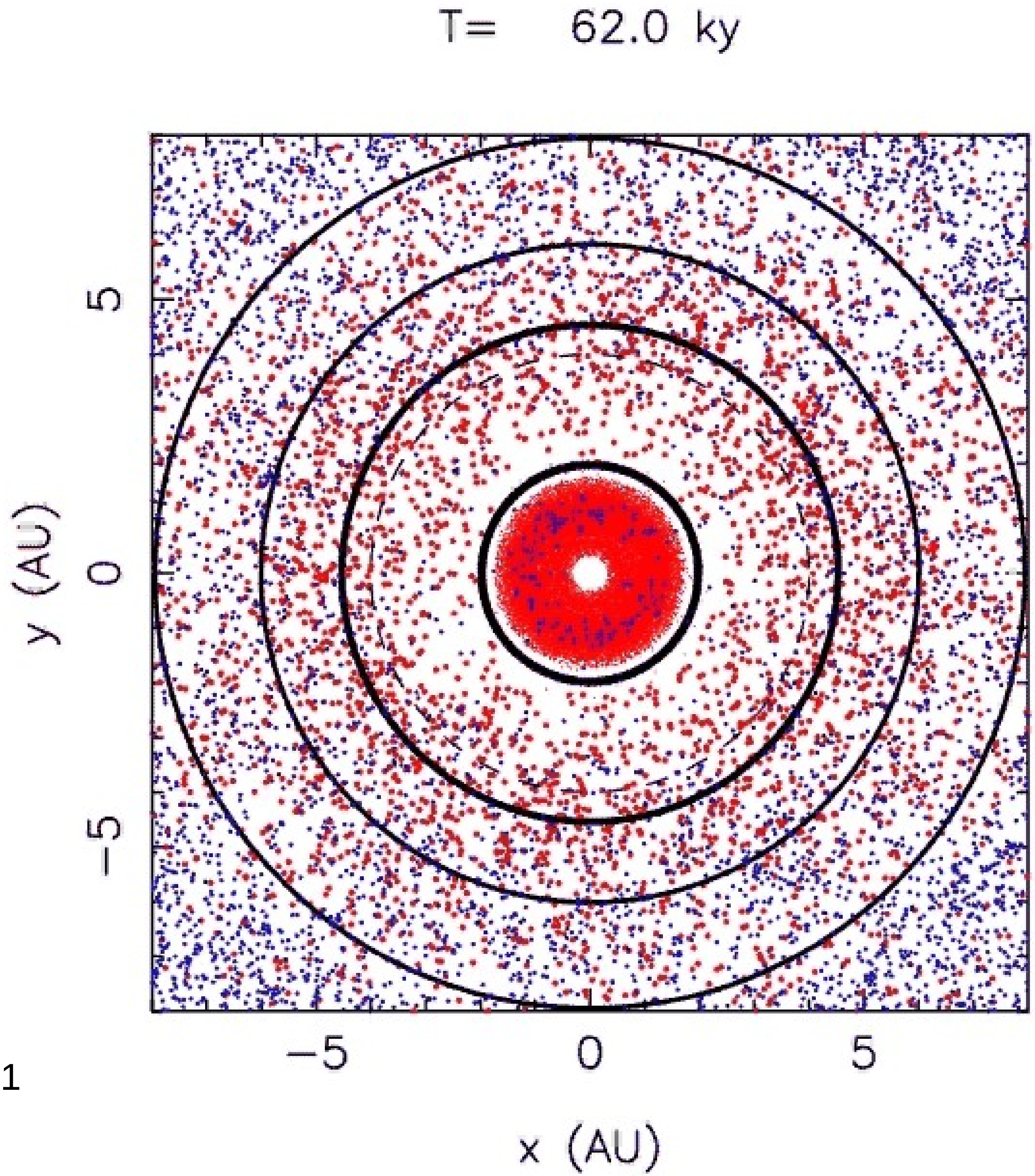


Walsh et al 2011

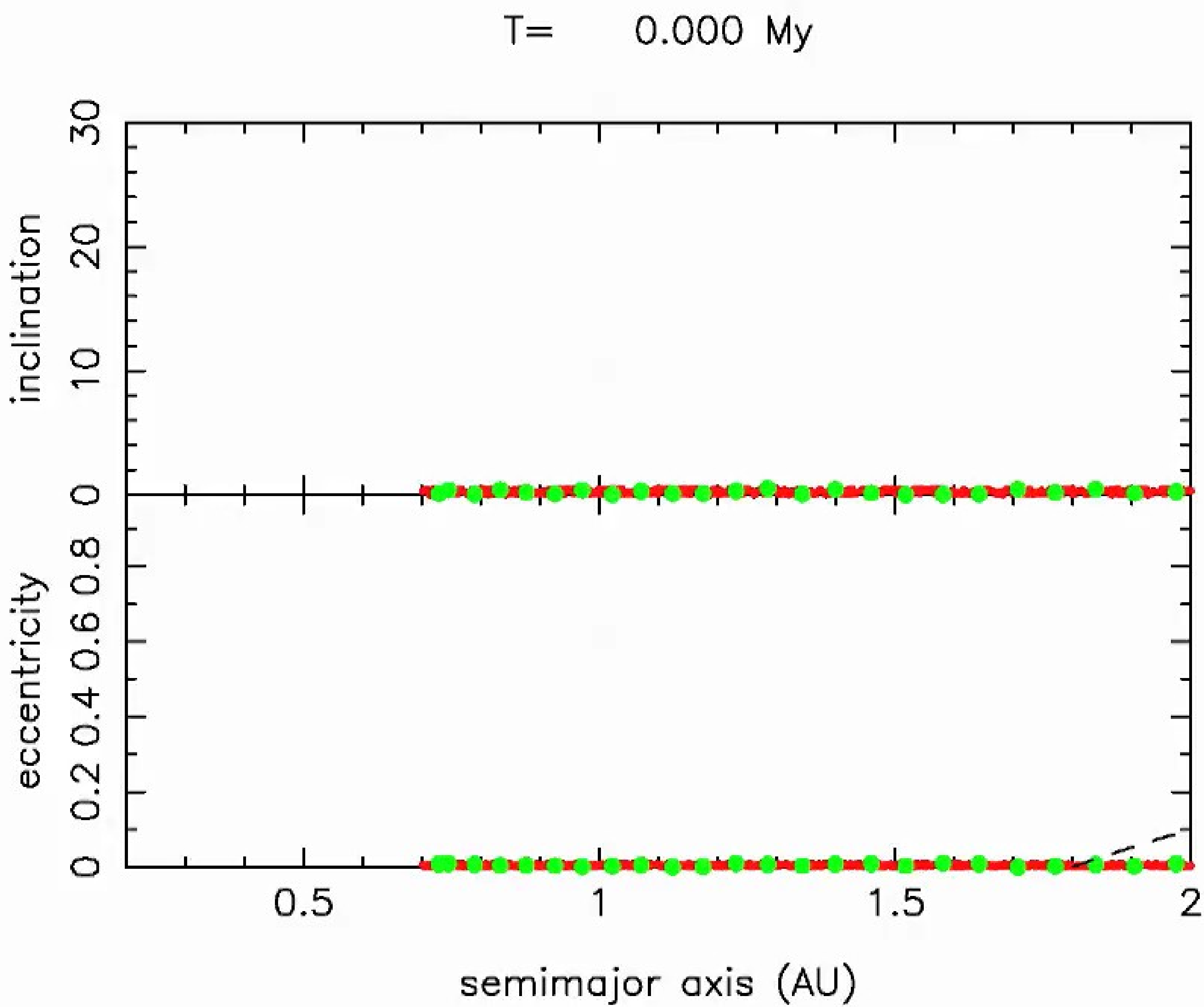


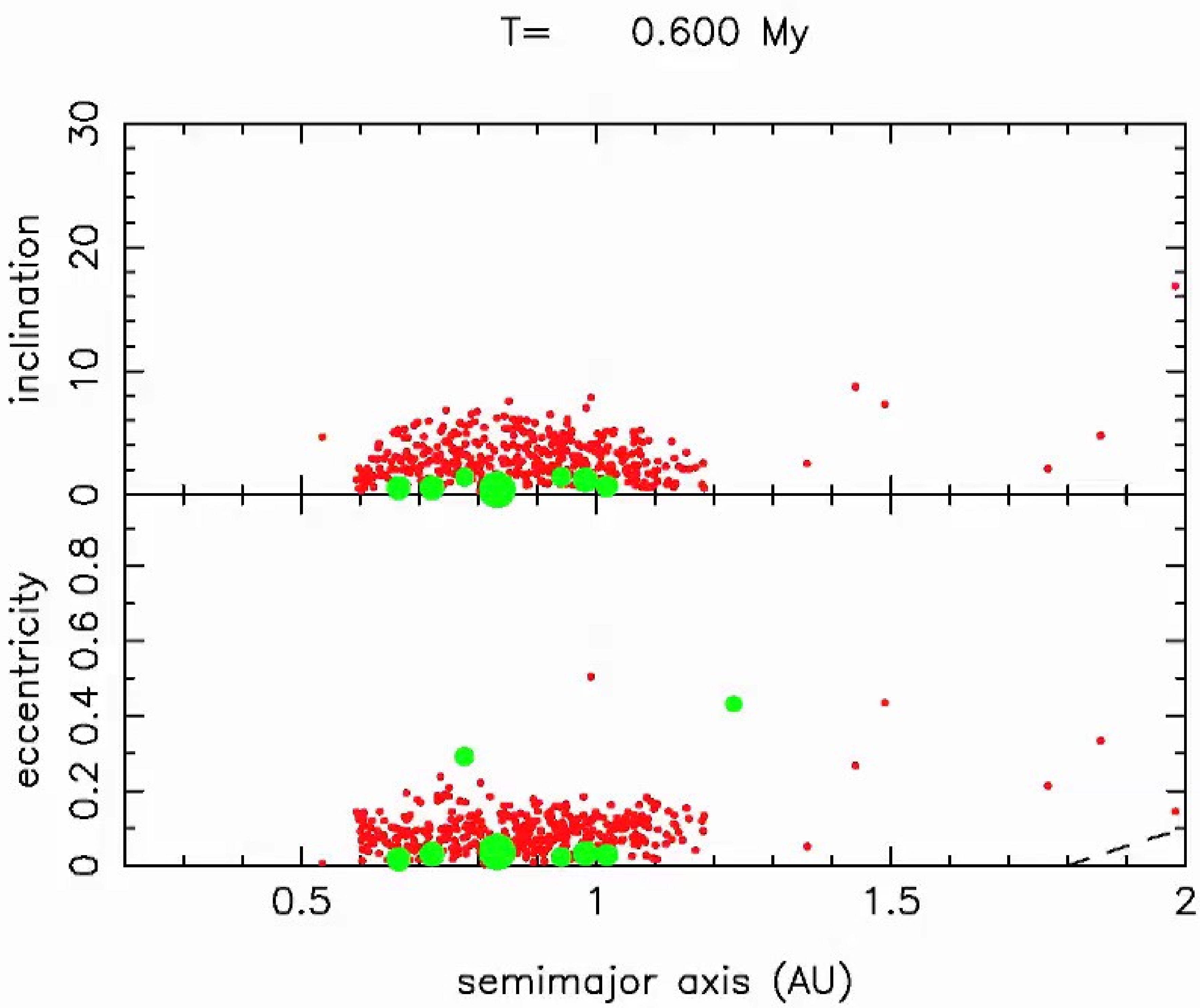
Walsh et al 2011

“Grand Tack”

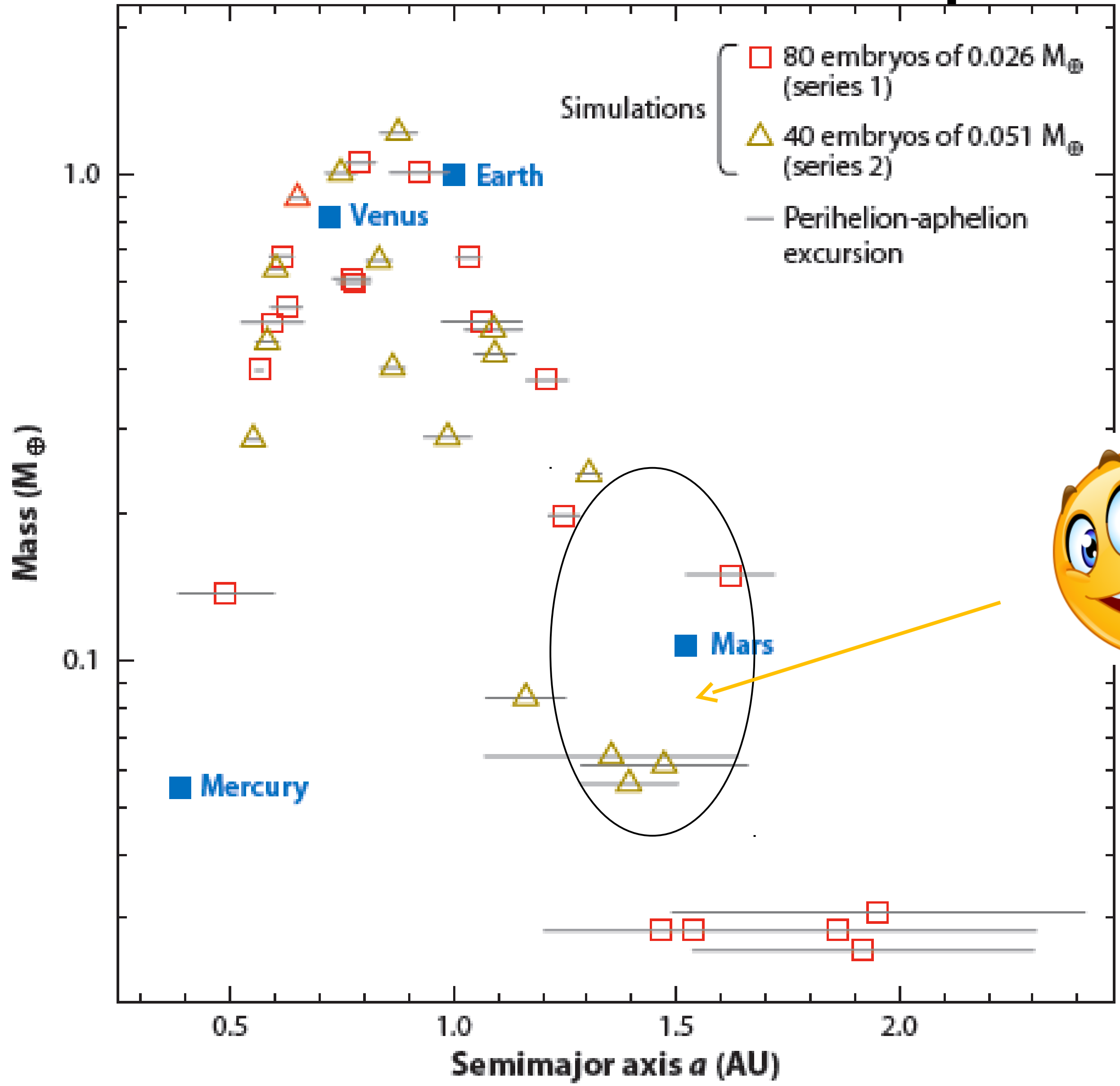


Walsh et al 2011


T= 0.000 My
inclination
30
20
10
0
eccentricity
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
semimajor axis (AU)


T= 0.600 My
inclination
eccentricity
semimajor axis (AU)
0
10
20
30
0.2
0.4
0.6
0.8
0.5
1
1.5
2

The Grand Tack terrestrial planets



Walsh et al 2011; Morbidelli et al 2012; O'Brien et al, 2014; Raymond et al 2014; Jacobson et al 2014; Jacobson & Morbidelli 2014; Raymond & Morbidelli 2014; Jacobson & Walsh 2015; Brasser et al 2016

Digression on Composition

$$\delta^{18}O = \left[\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right] \times 1,000 \qquad \epsilon^{143}Nd = \left[\frac{\left(\frac{^{143}Nd}{^{144}Nd}\right)_{sample}}{\left(\frac{^{143}Nd}{^{144}Nd}\right)_{standard}} - 1 \right] \times 10,000$$

$$\Delta^{17}O = \delta^{17}O - \delta^{17}O_{standard}$$

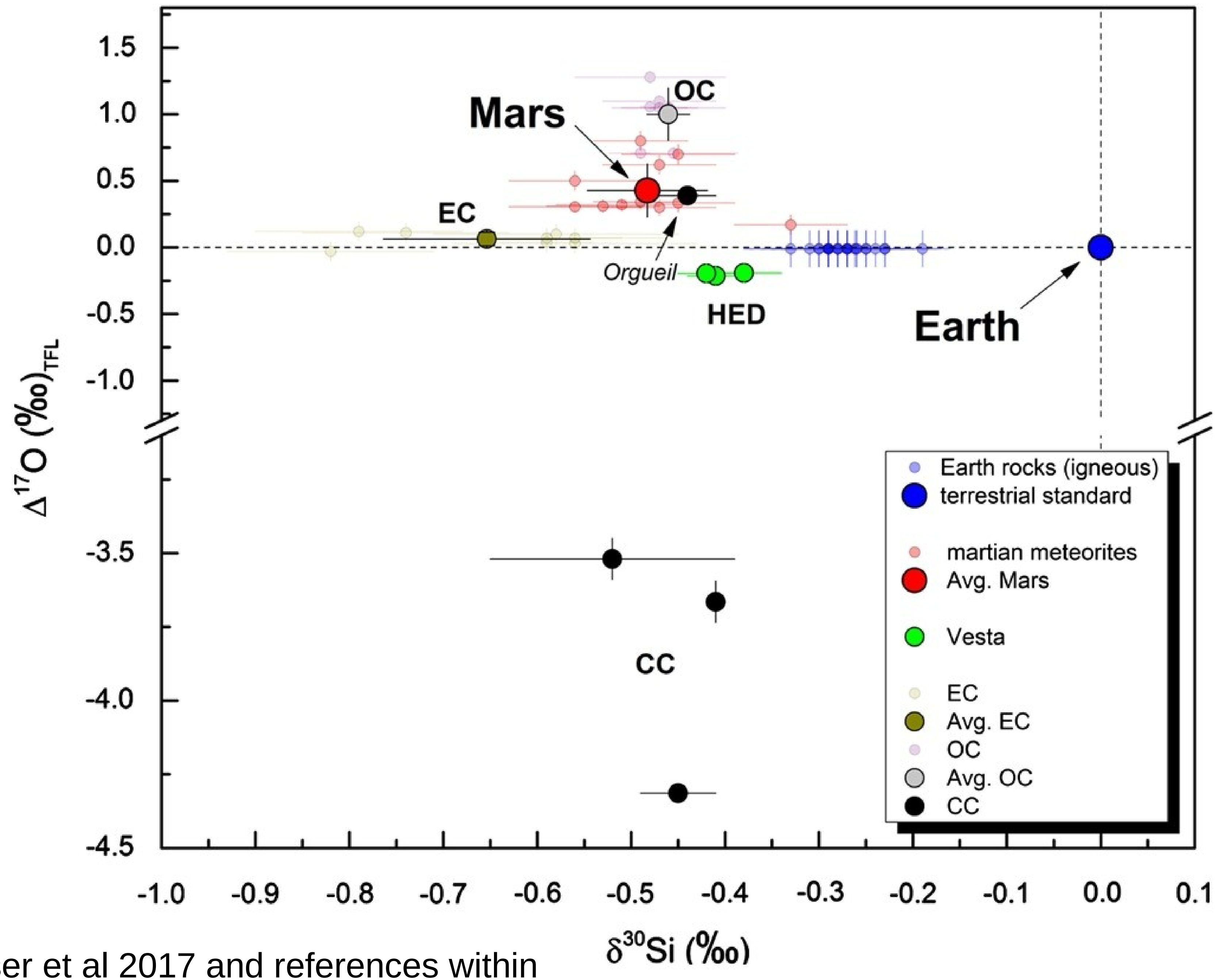
More Volatile Rich

Enstatite Chondrites

Ordinary Chondrites

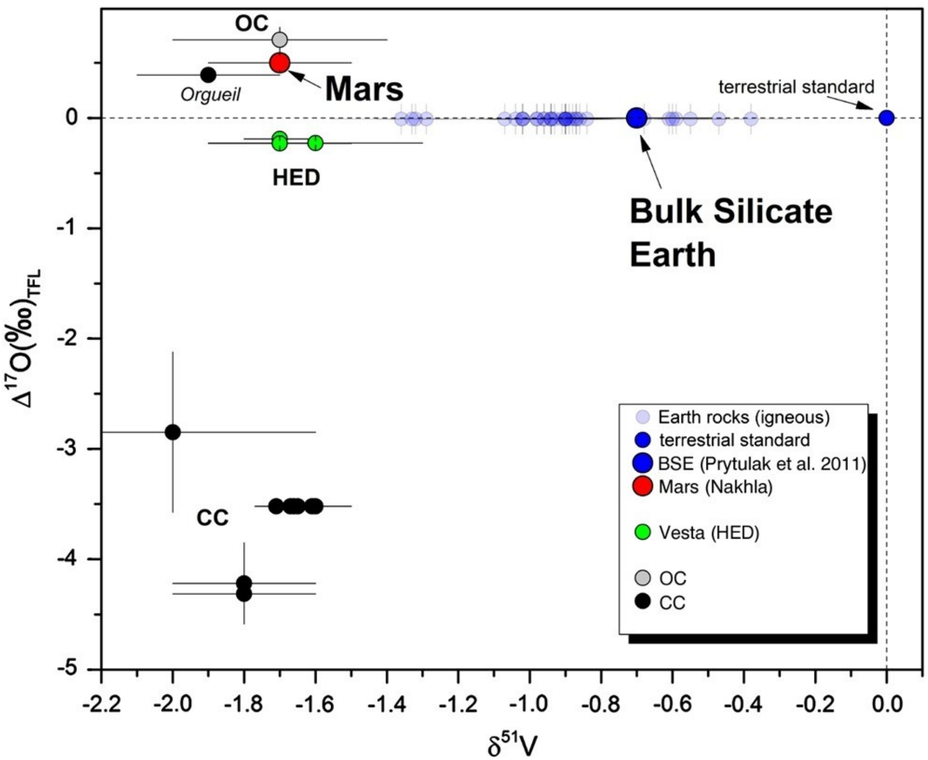
Carbonaceous Chondrites

Mars is different than the Earth

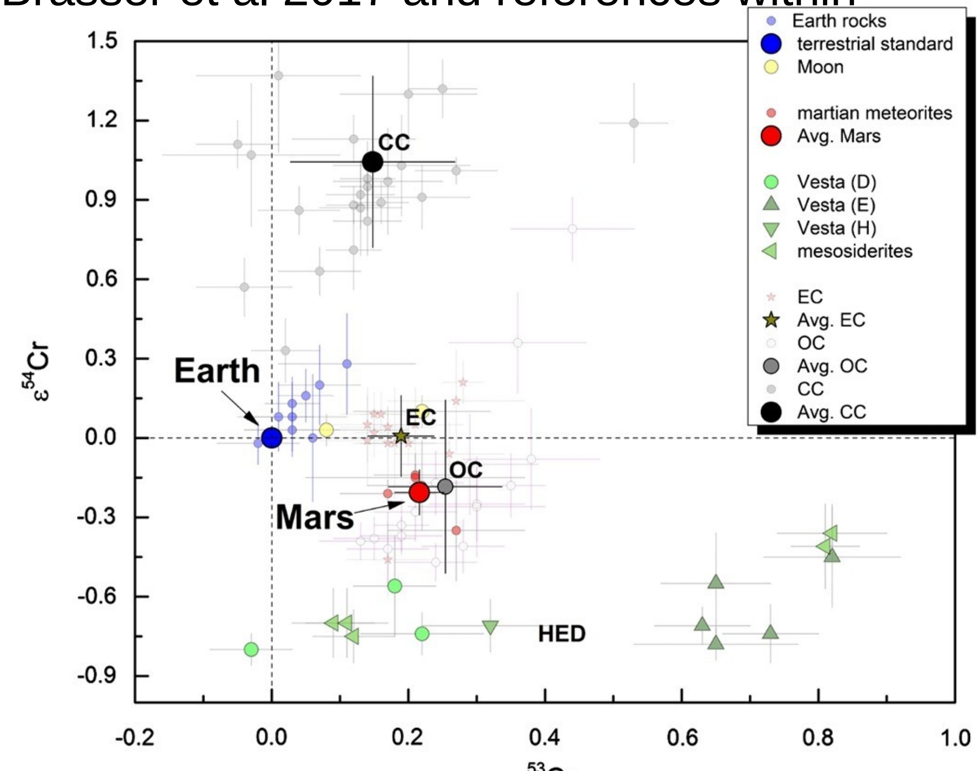


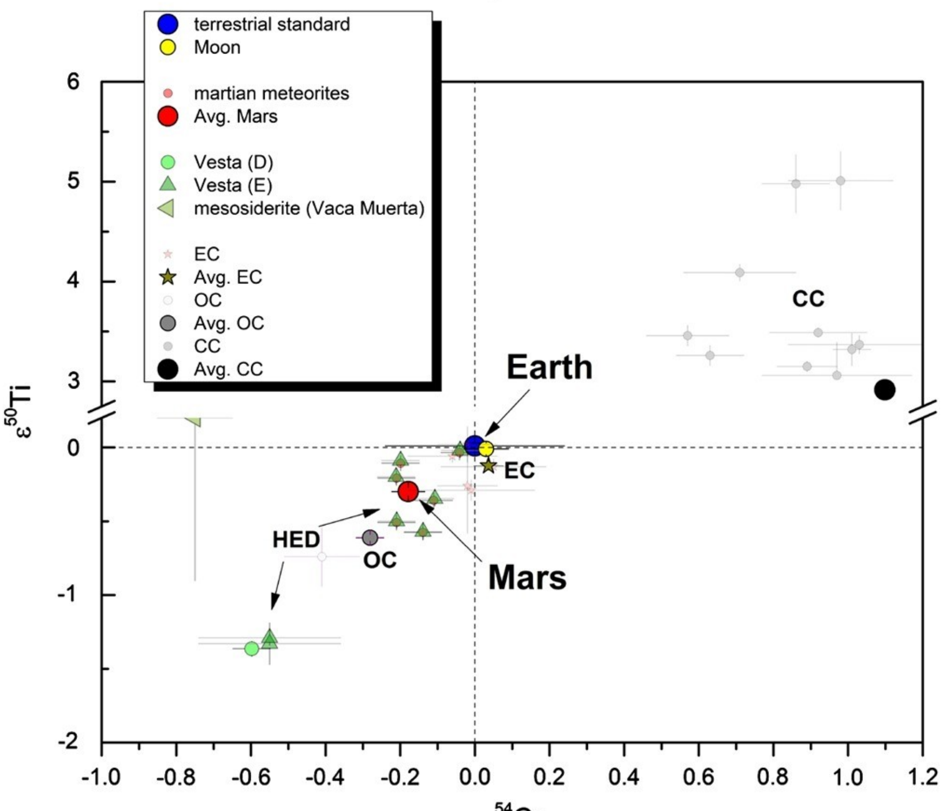
Brasser et al 2017 and references within

And more similar to the ordinary Chondrites

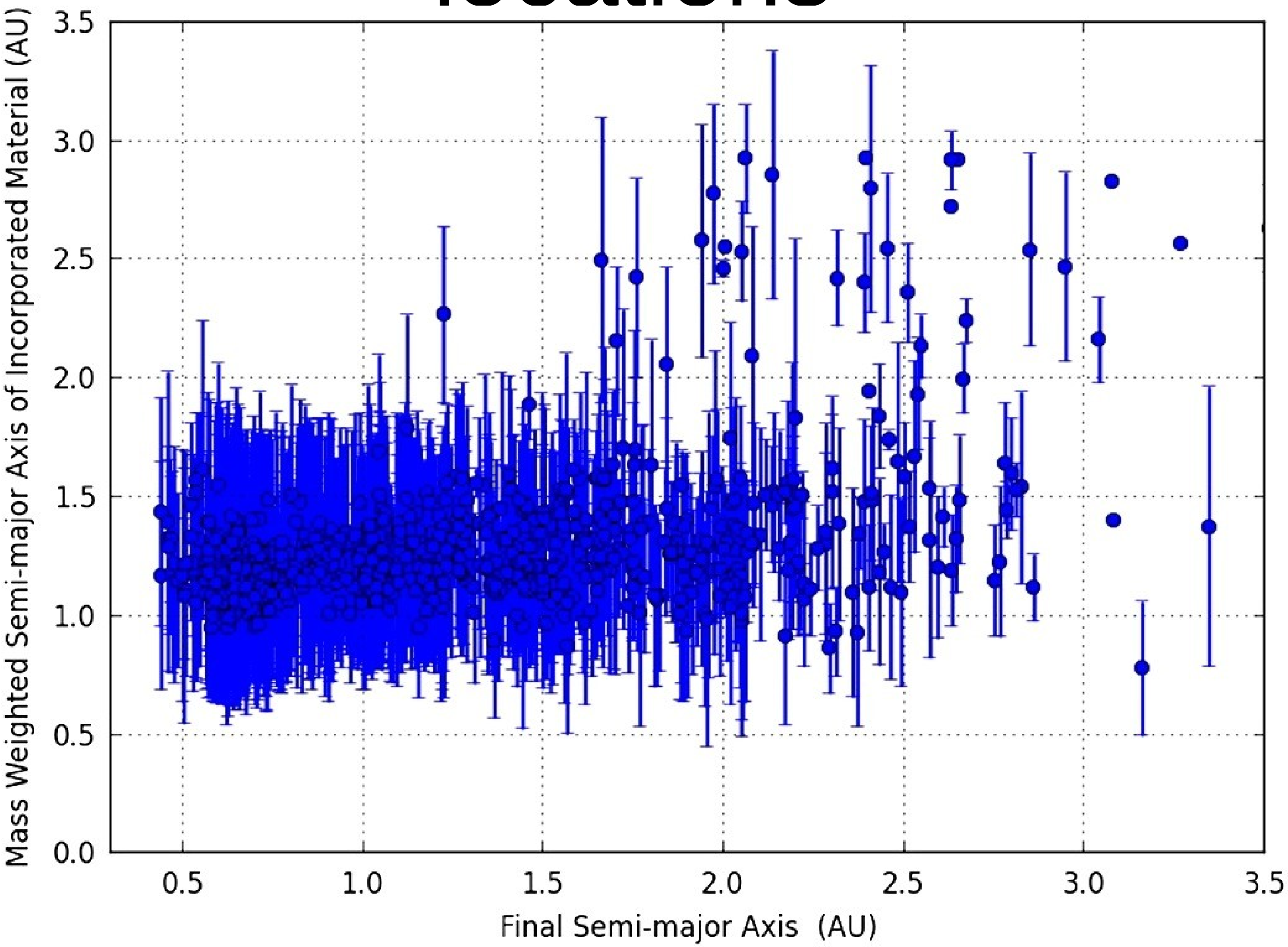


Brasser et al 2017 and references within

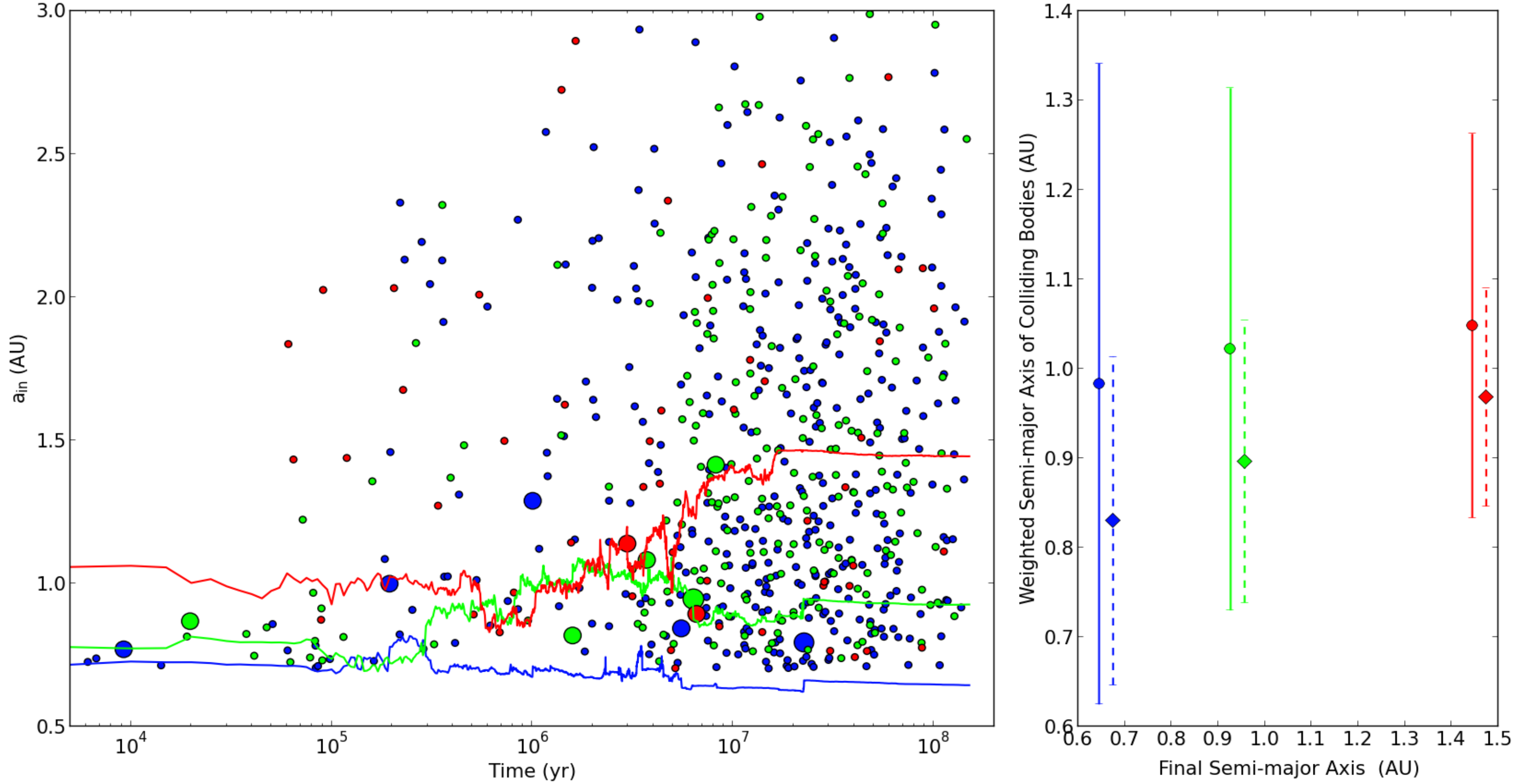


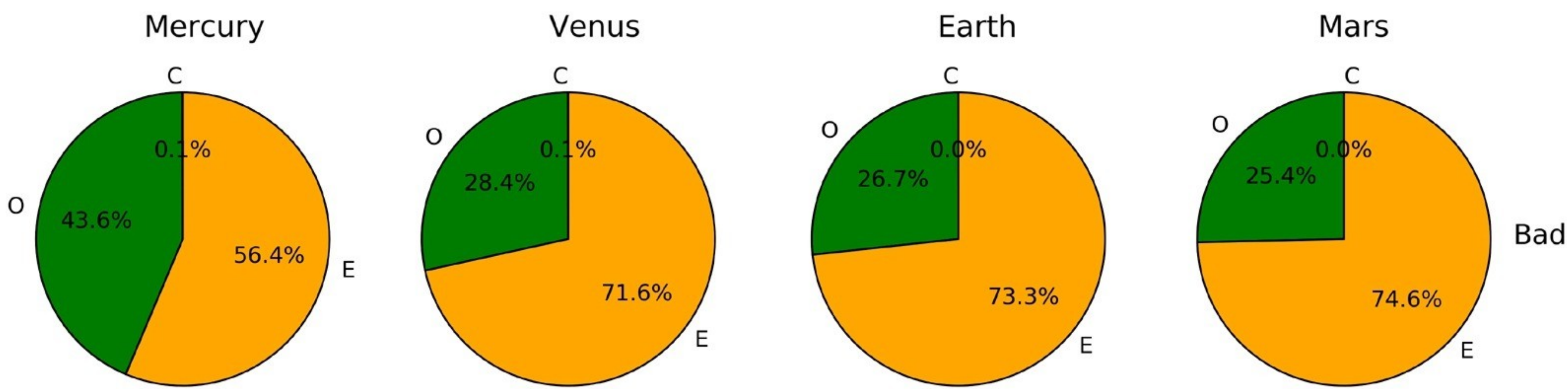


In the Grand Tack planets get their building blocks from different initial locations



Brasser et al 2017

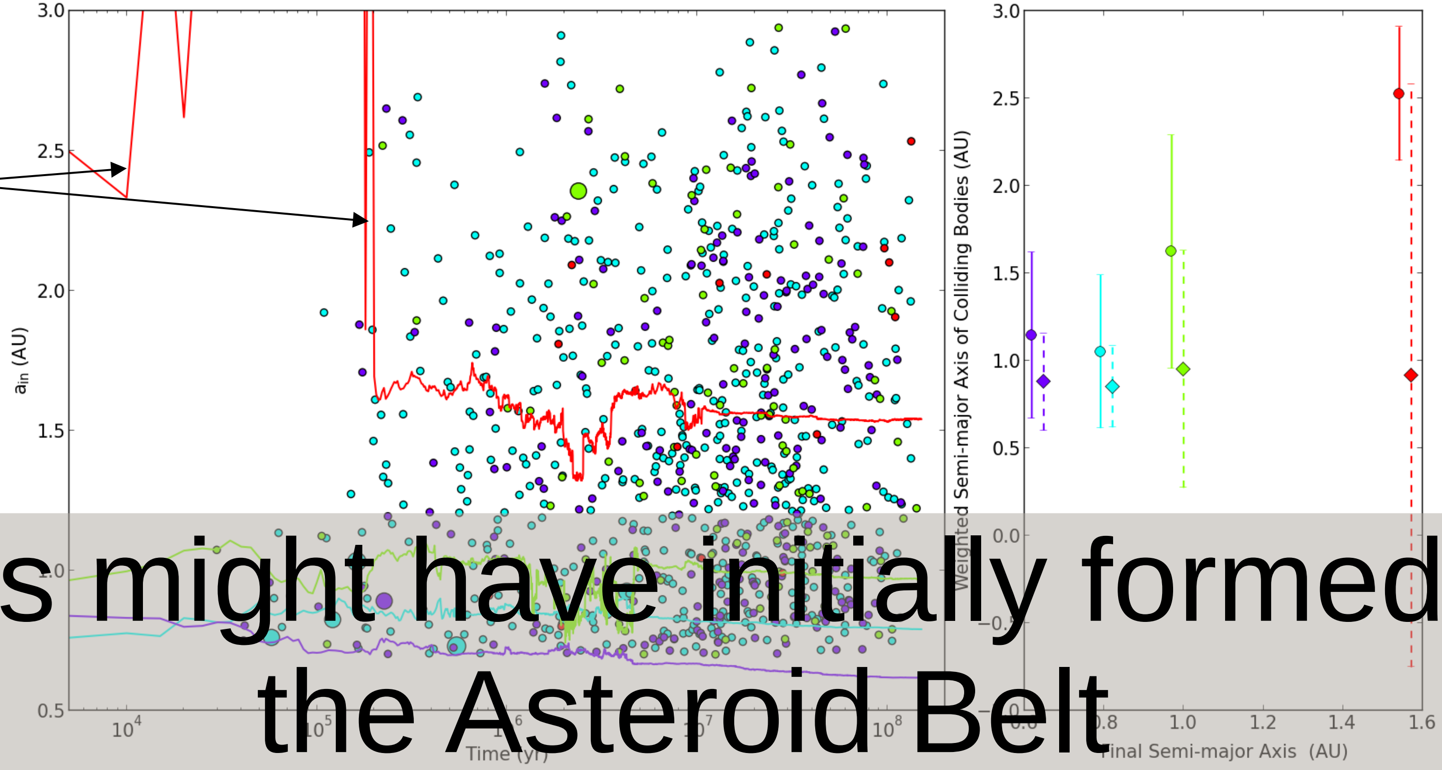


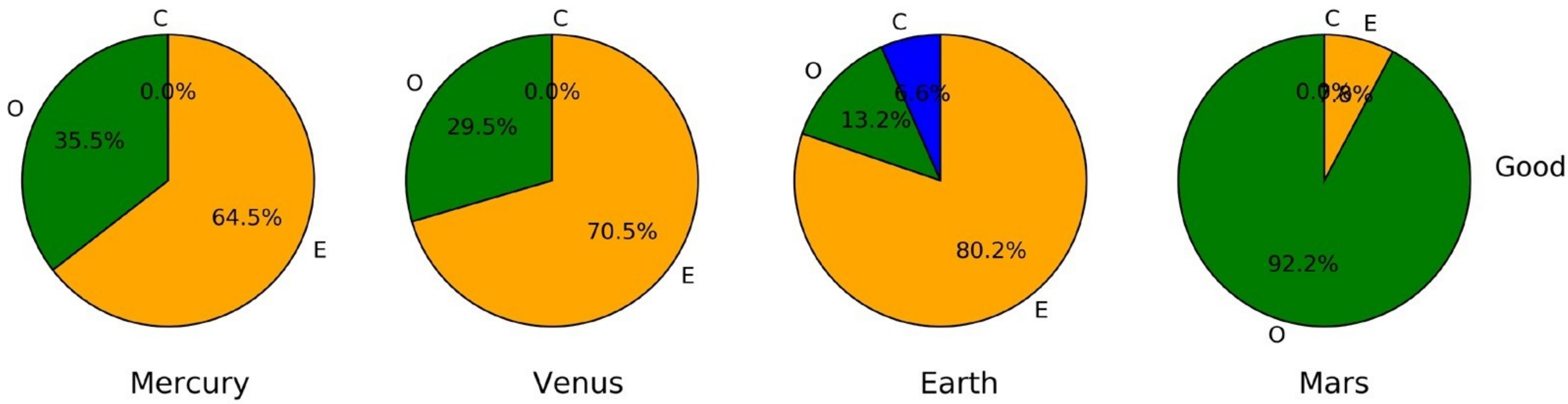


Brasser et al 2017

Mars might have initially formed in the Asteroid Belt

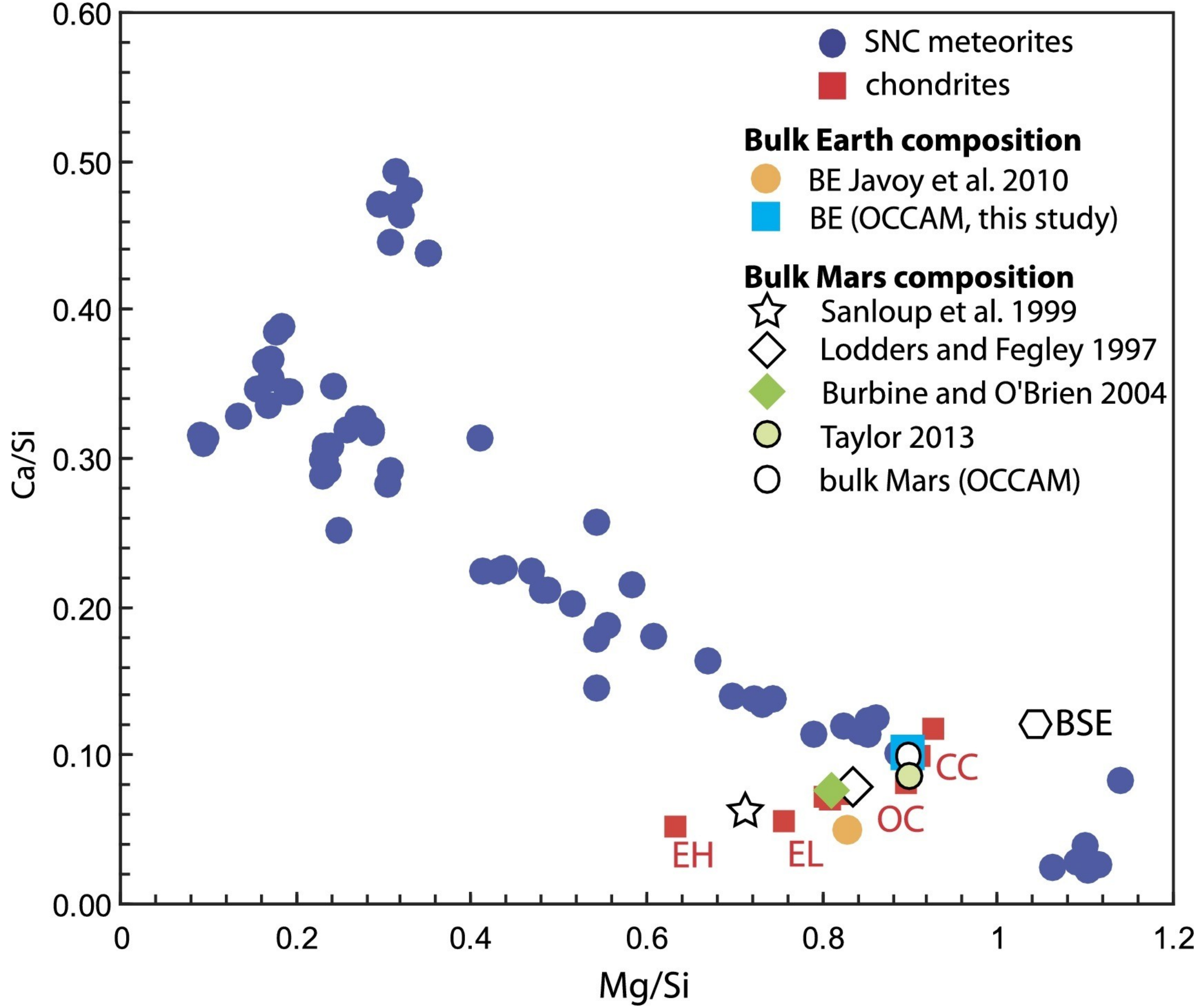
Encounters with Jupiter





Brasser et al 2017

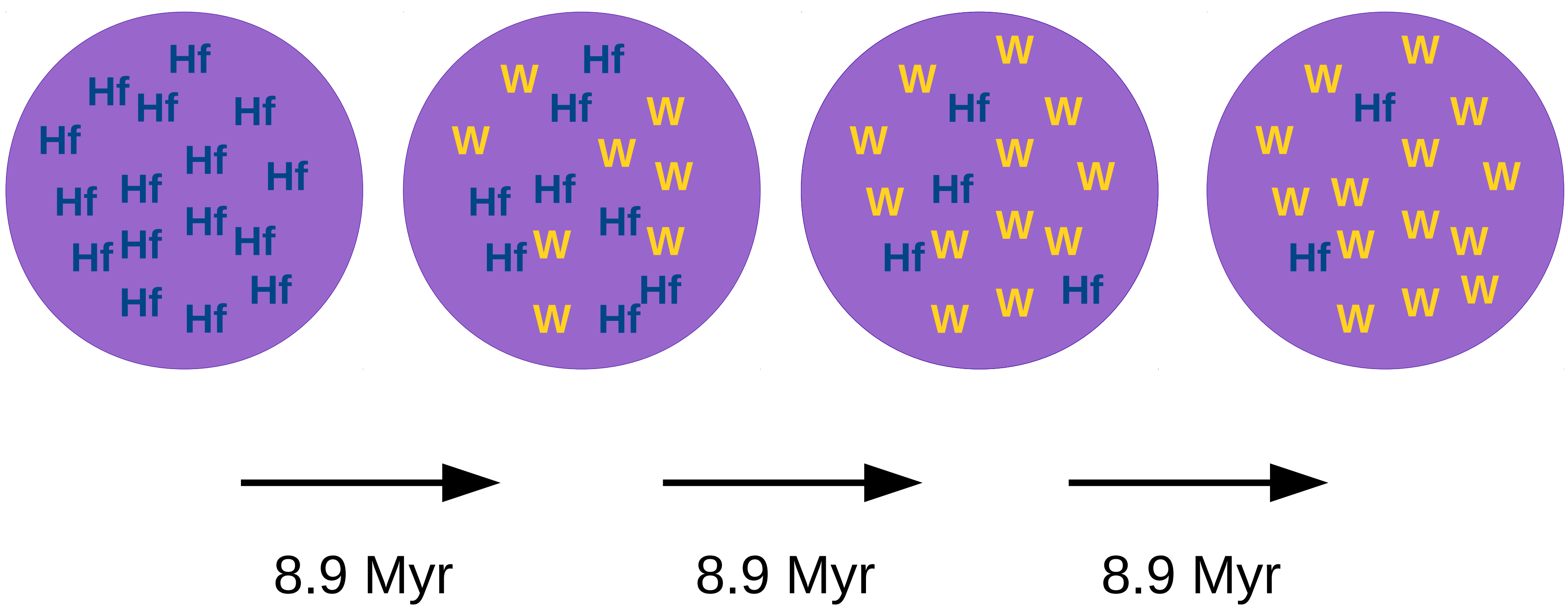
Not Everyone Agrees



Fitoussi et al 2016

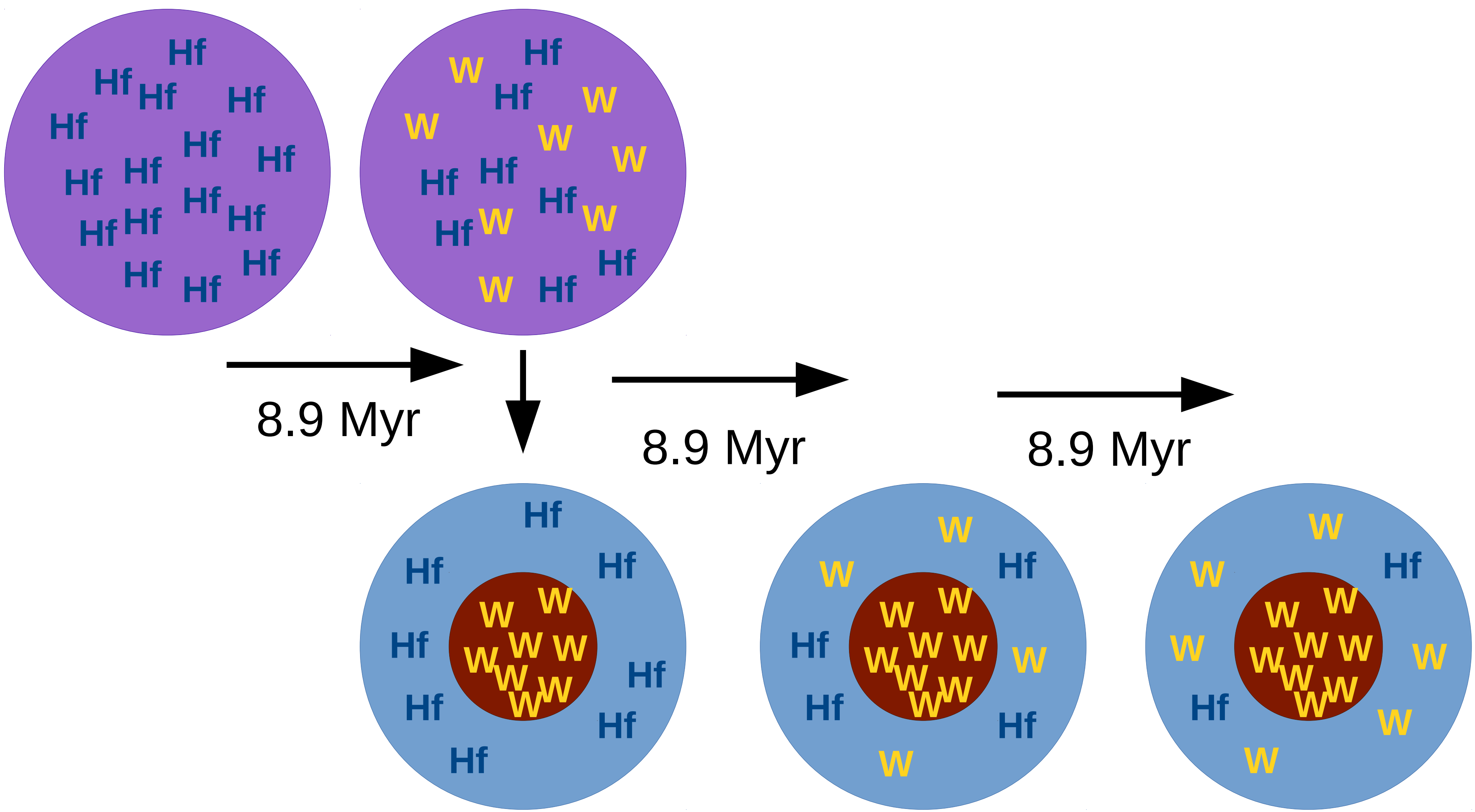
One thing we do know is that Mars formed quickly

Radioactive Decay ($^{182}Hf \rightarrow {}^{182}W$)

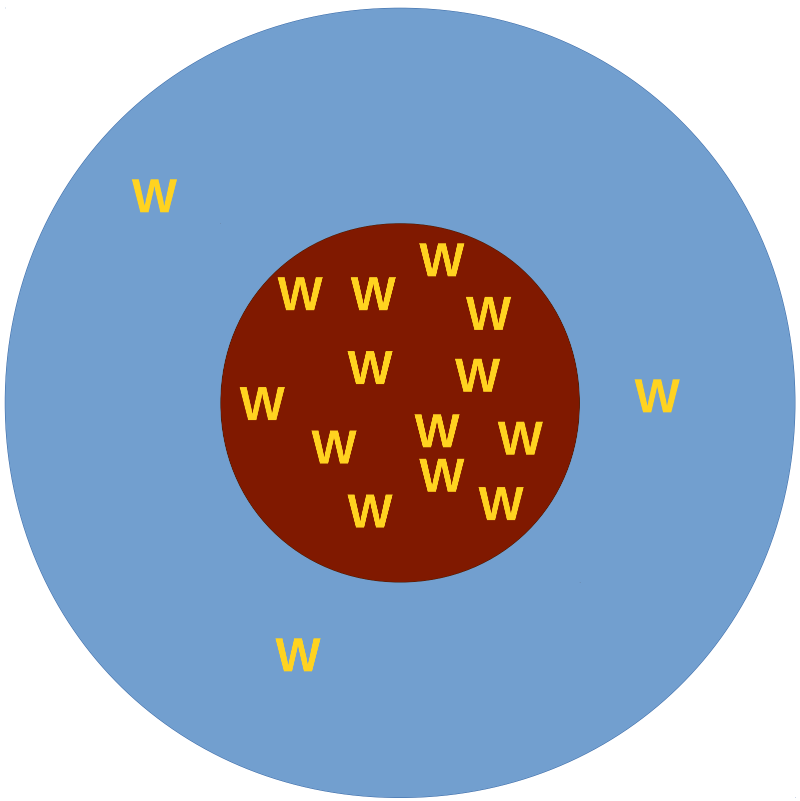


Radioactive Isotopes

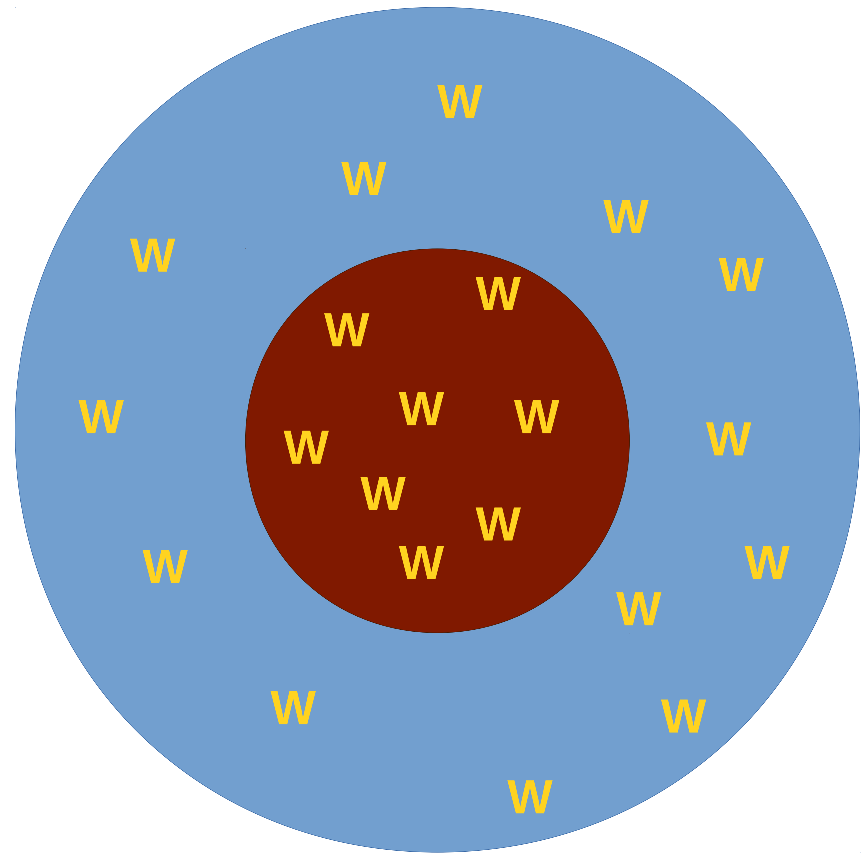
- Hf = Lithophile (prefers the Silicate Mantle)
- W = Siderophile (prefers the Iron Core)



Radioactive Isotopes

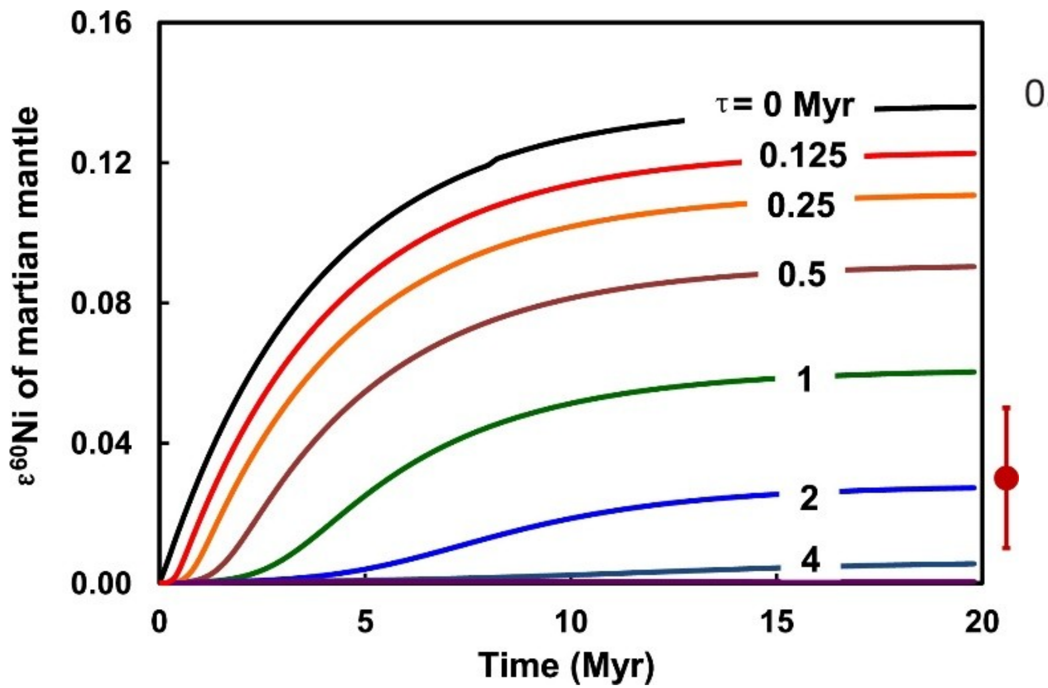


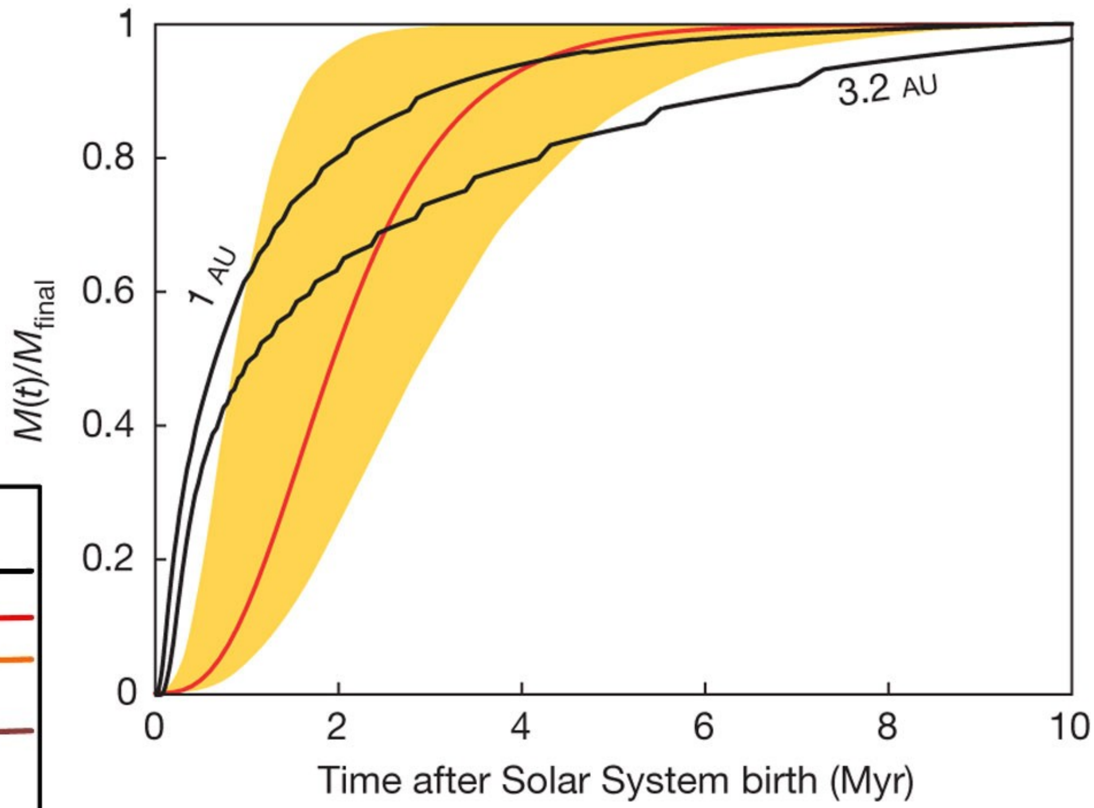
Planet Formed &
Differentiated Late



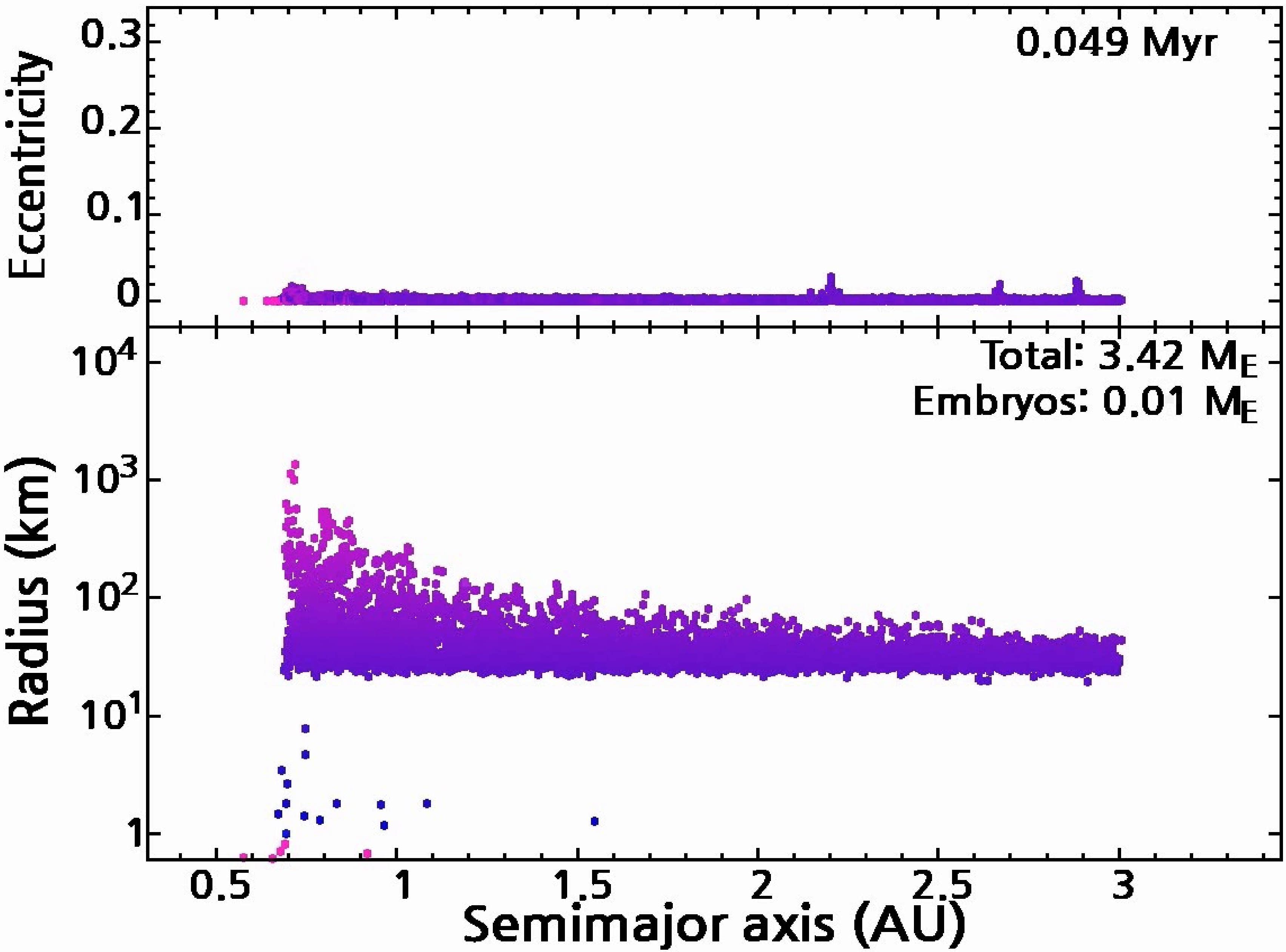
Planet Formed &
Differentiated Early

Mars formed quickly, within 2-5 Myr





Dayphas & Pourmand (2011) Tan & Dauphas (2014)



Walsh et al 2018

Conclusions

- Mars is both a puzzle and a very important clue in our understanding of how the Solar System formed
- Planets and all Solar System bodies have the tendency to move… we cannot assume that everything formed where we see them now
- Mars witnessed our very early Solar System
- We need more data, both about Mars to better understand its composition and from Venus (at least the atmosphere) and Mercury to really understand the composition of the early Solar System