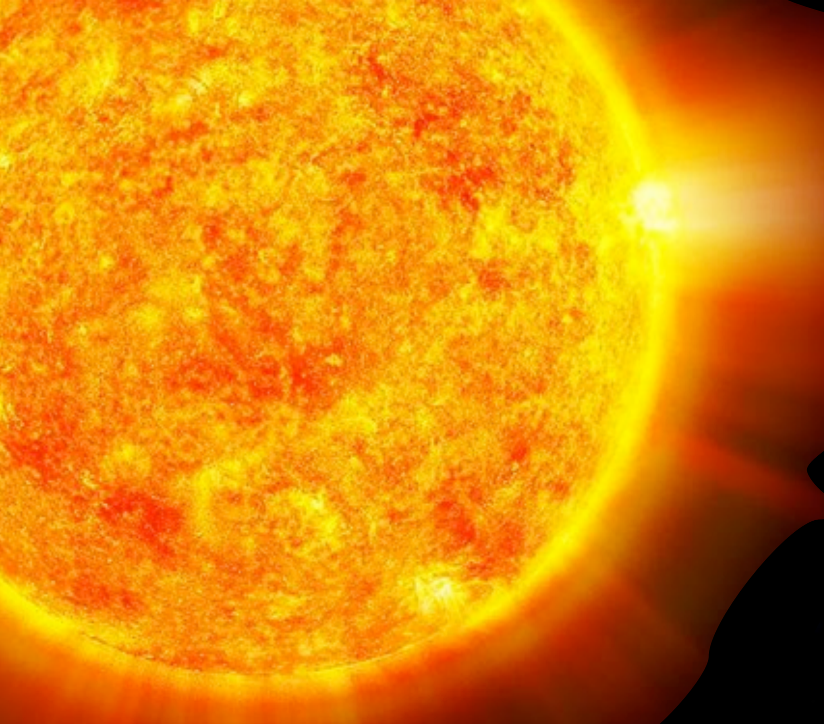
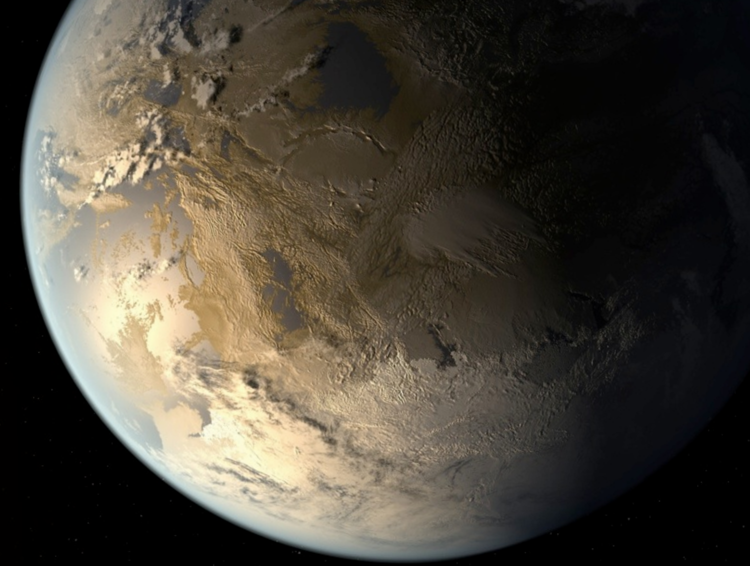
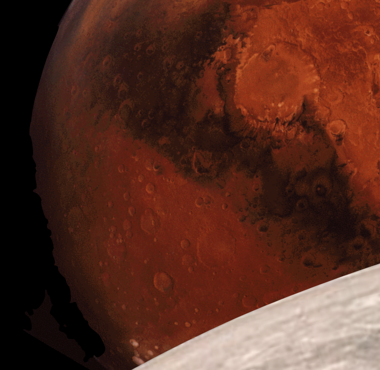


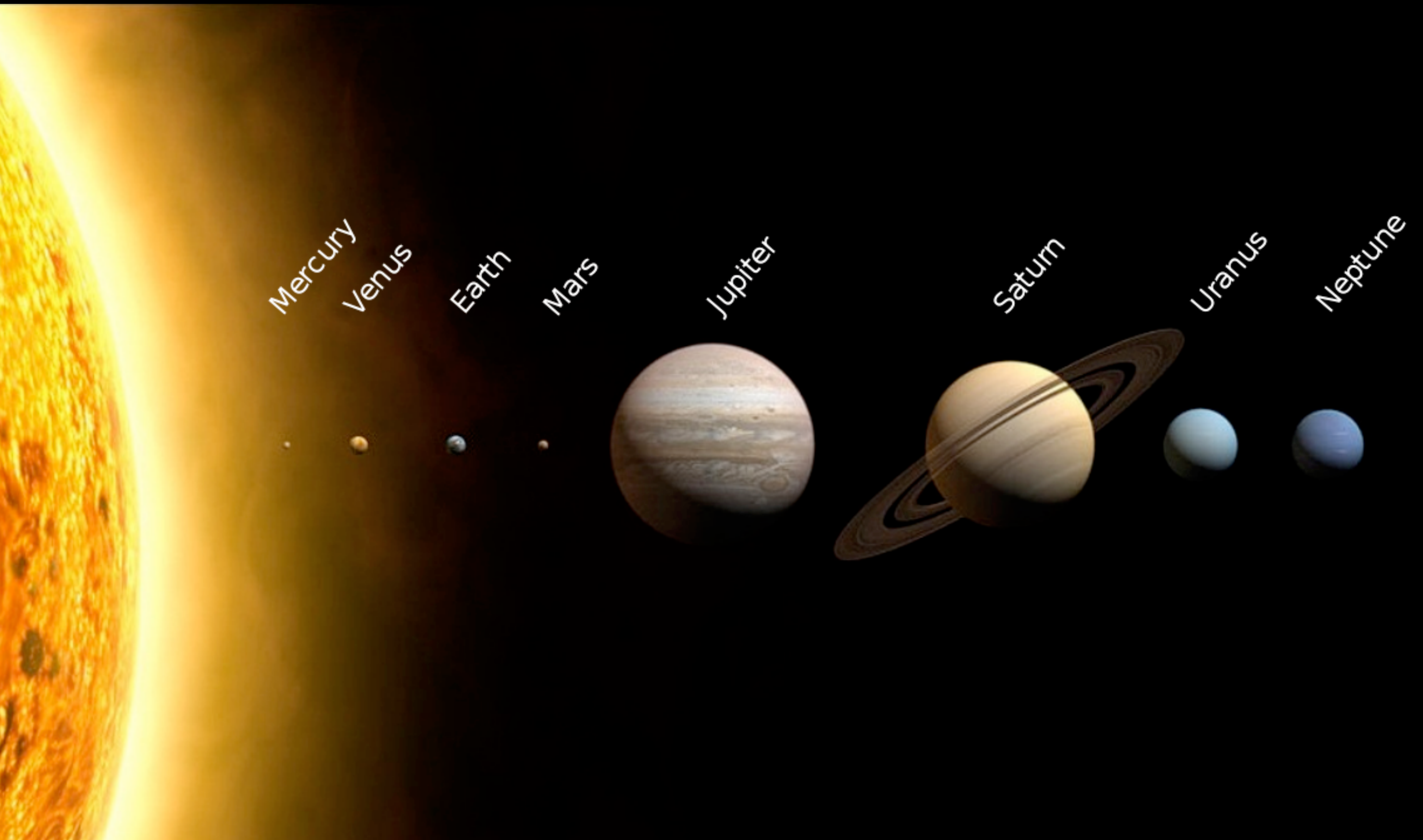



Formation pathways of rocky planets

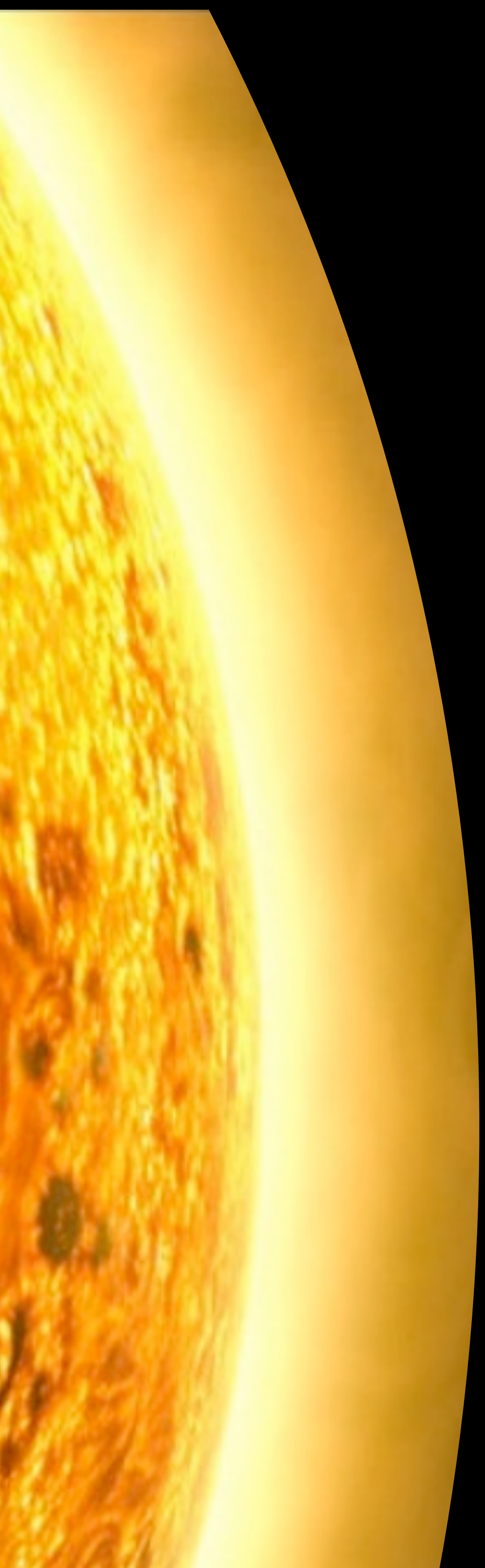
Sean Raymond
Laboratoire d'Astrophysique de Bordeaux
planetplanet.net

with A. Izidoro, A. Morbidelli, K. Walsh, E. Bolmont, P. Armitage, B. Bitsch, C. Cossou, A. Pierens

The Solar System



The exo-Solar System

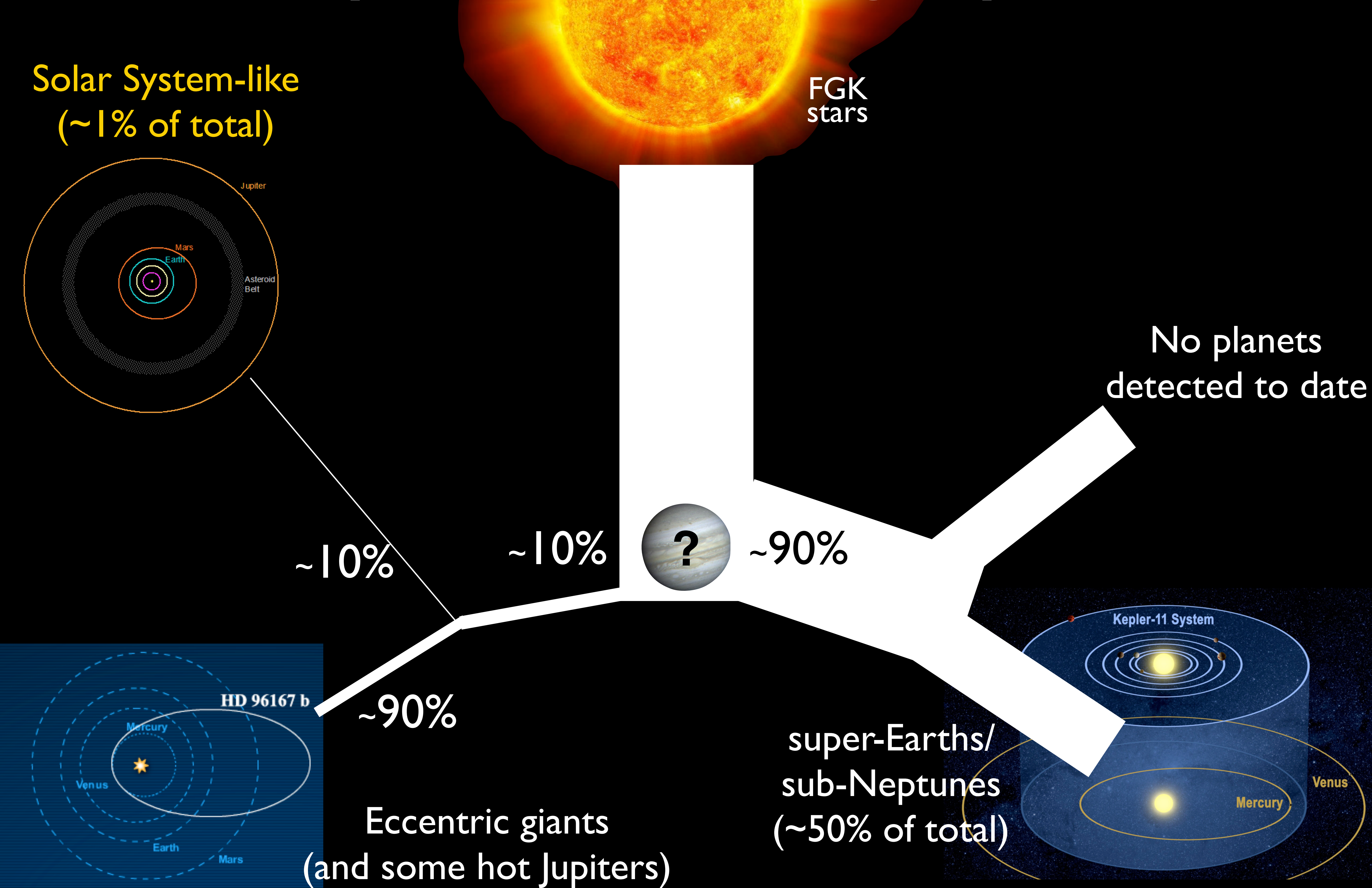


Measure:

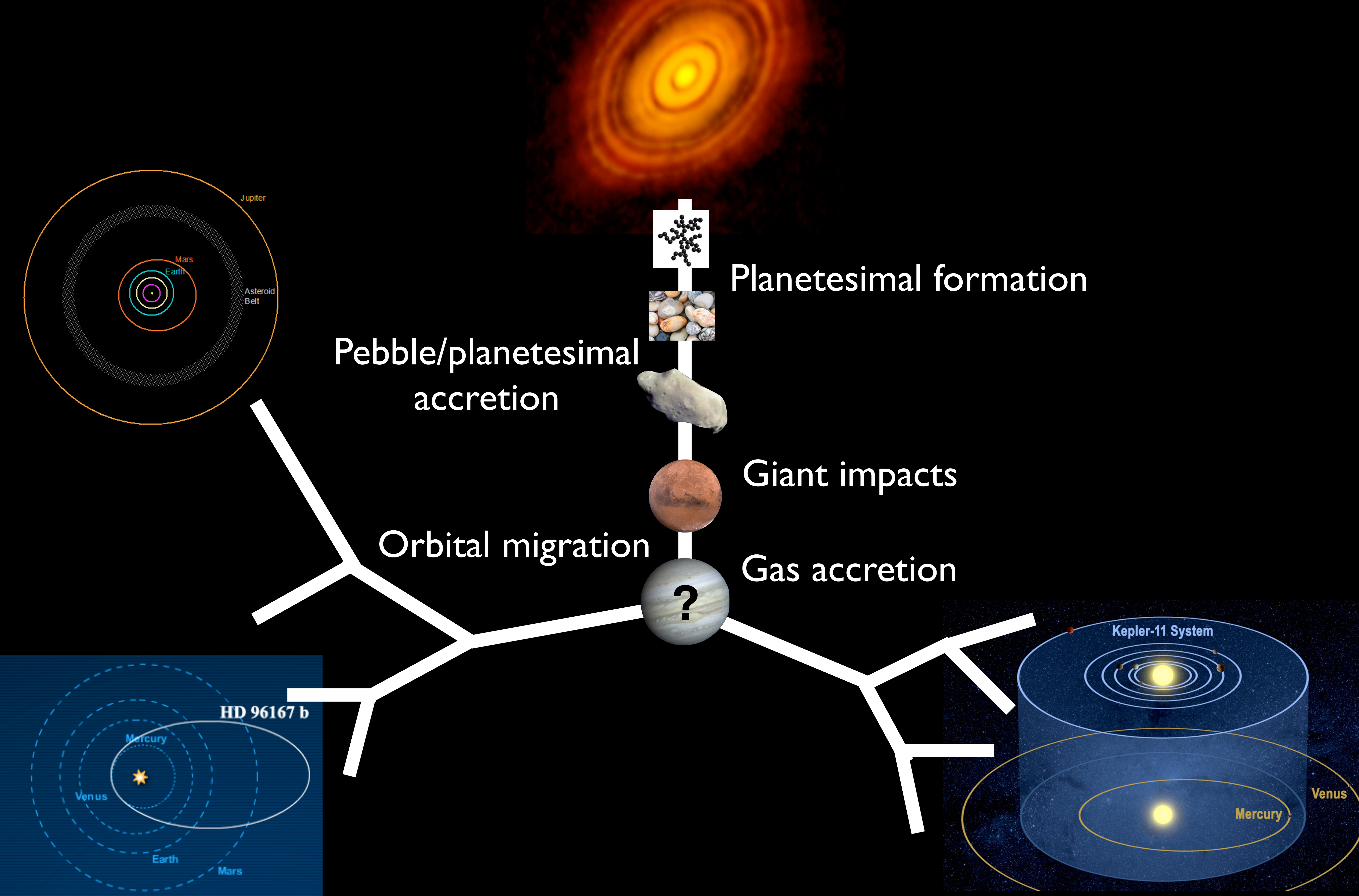
- mass (M_{Jup} sin i)
- orbital size
- orbital shape (eccentricity)

(Sun's radial velocity amplitude due to Jupiter ~12 m/s, P=12 yr)

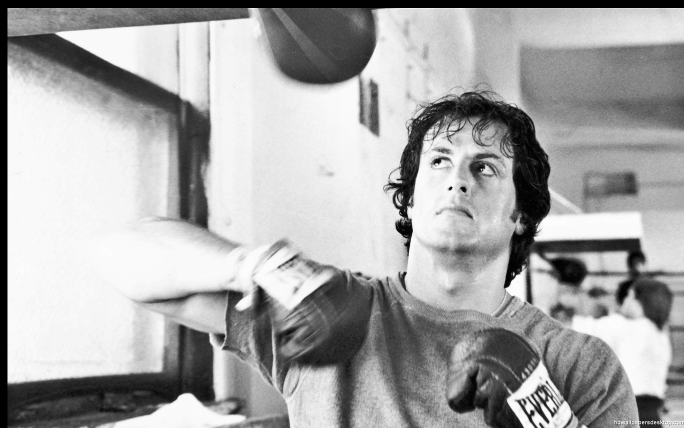
Exoplanet demographics



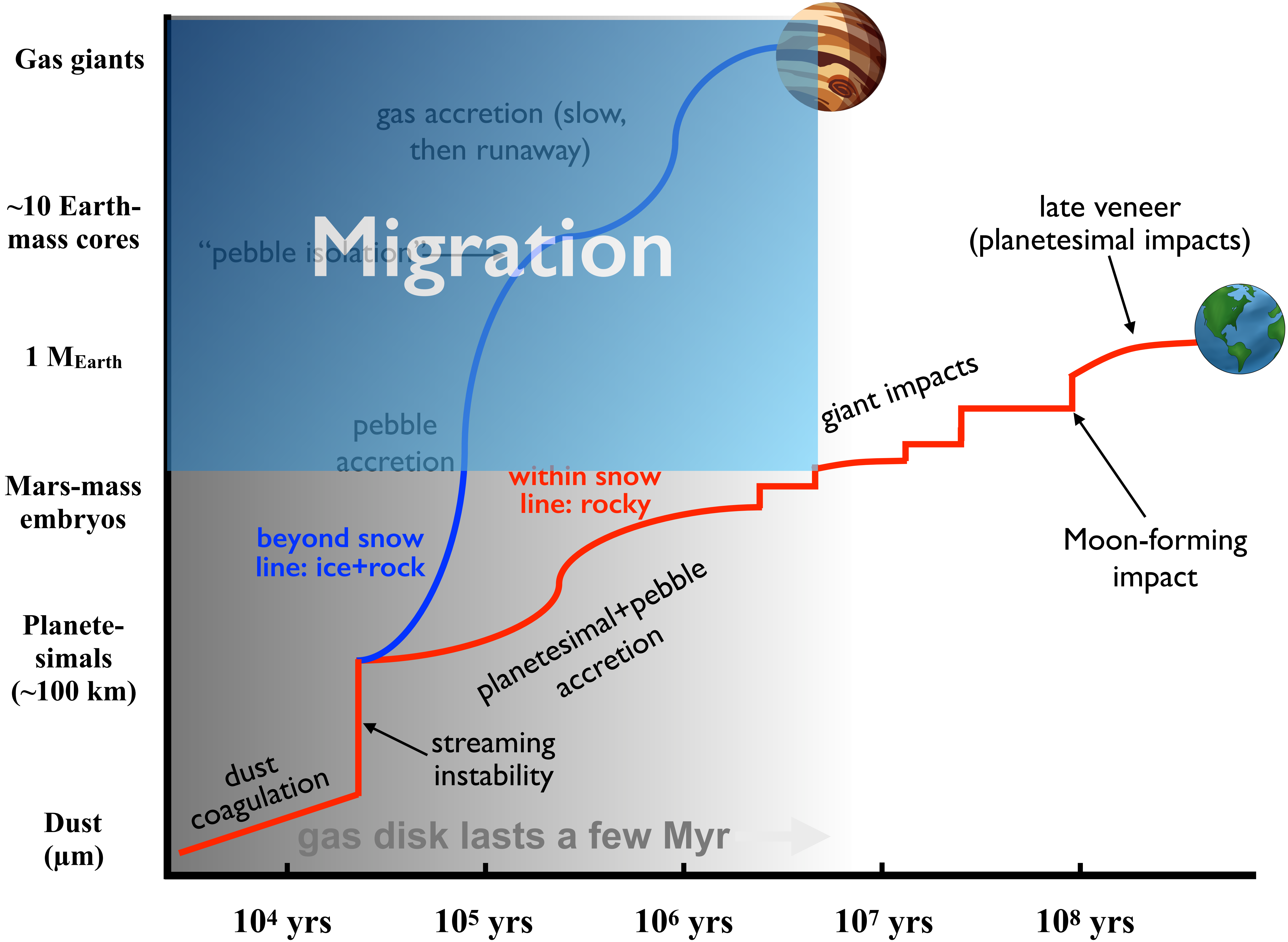
Planet formation



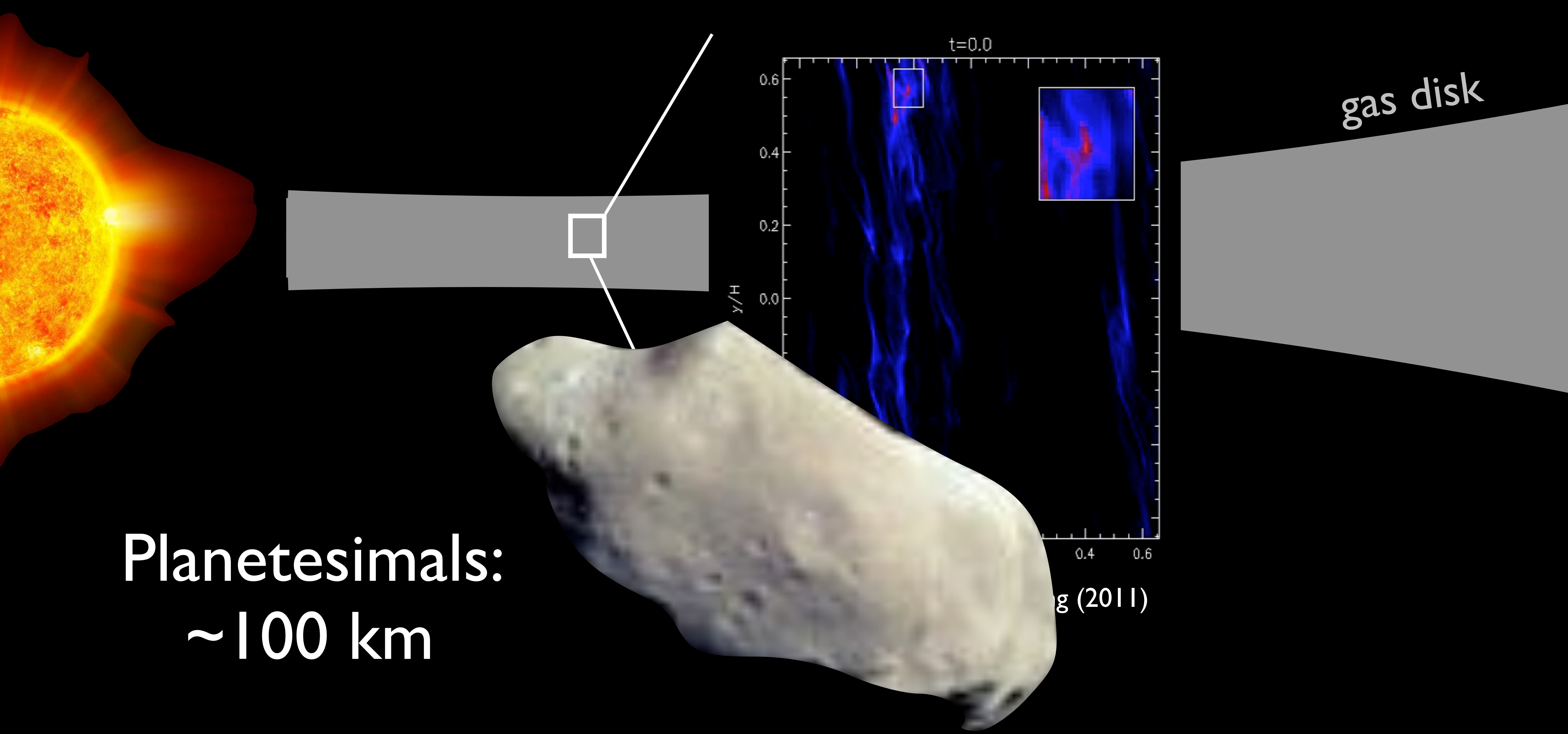
Formation models = origins stories



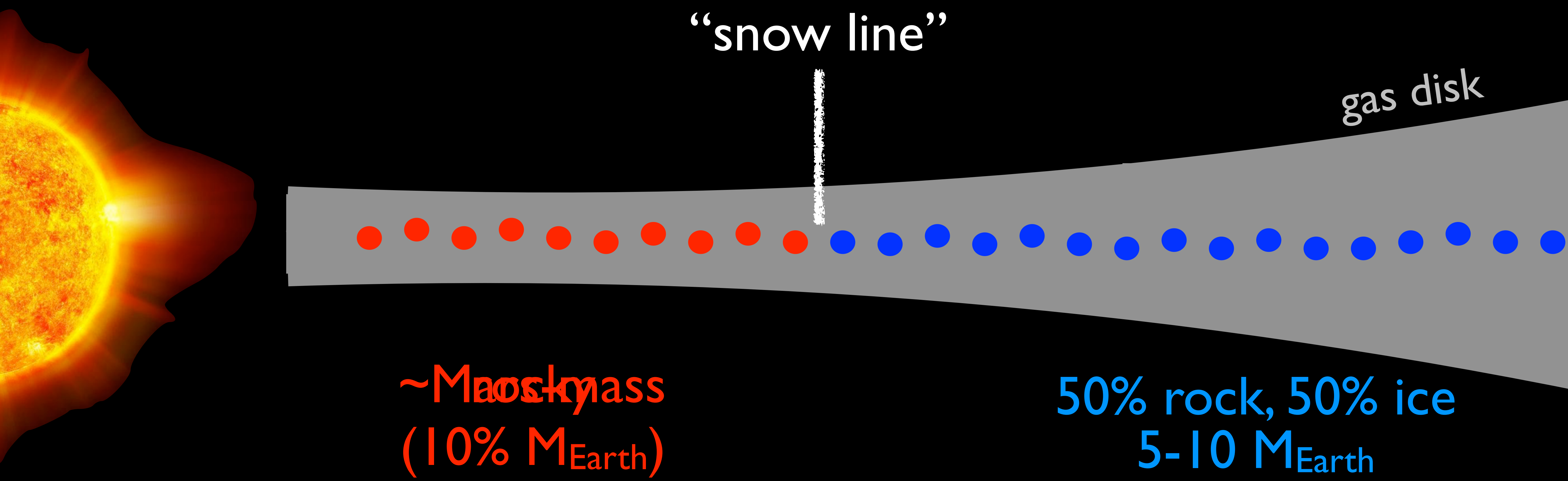




Gas giants
~10 Earth-mass cores
1 MEarth
Mars-mass embryos
Planete-simals (~100 km)
Dust (µm)
gas accretion (slow, then runaway)
Migration
"pebble isolation"
pebble accretion
beyond snow line: ice+rock
within snow line: rocky
planetesimal+pebble accretion
giant impacts
late veneer (planetesimal impacts)
Moon-forming impact
streaming instability
dust coagulation
gas disk lasts a few Myr
10^4 yrs
10^5 yrs
10^6 yrs
10^7 yrs
10^8 yrs

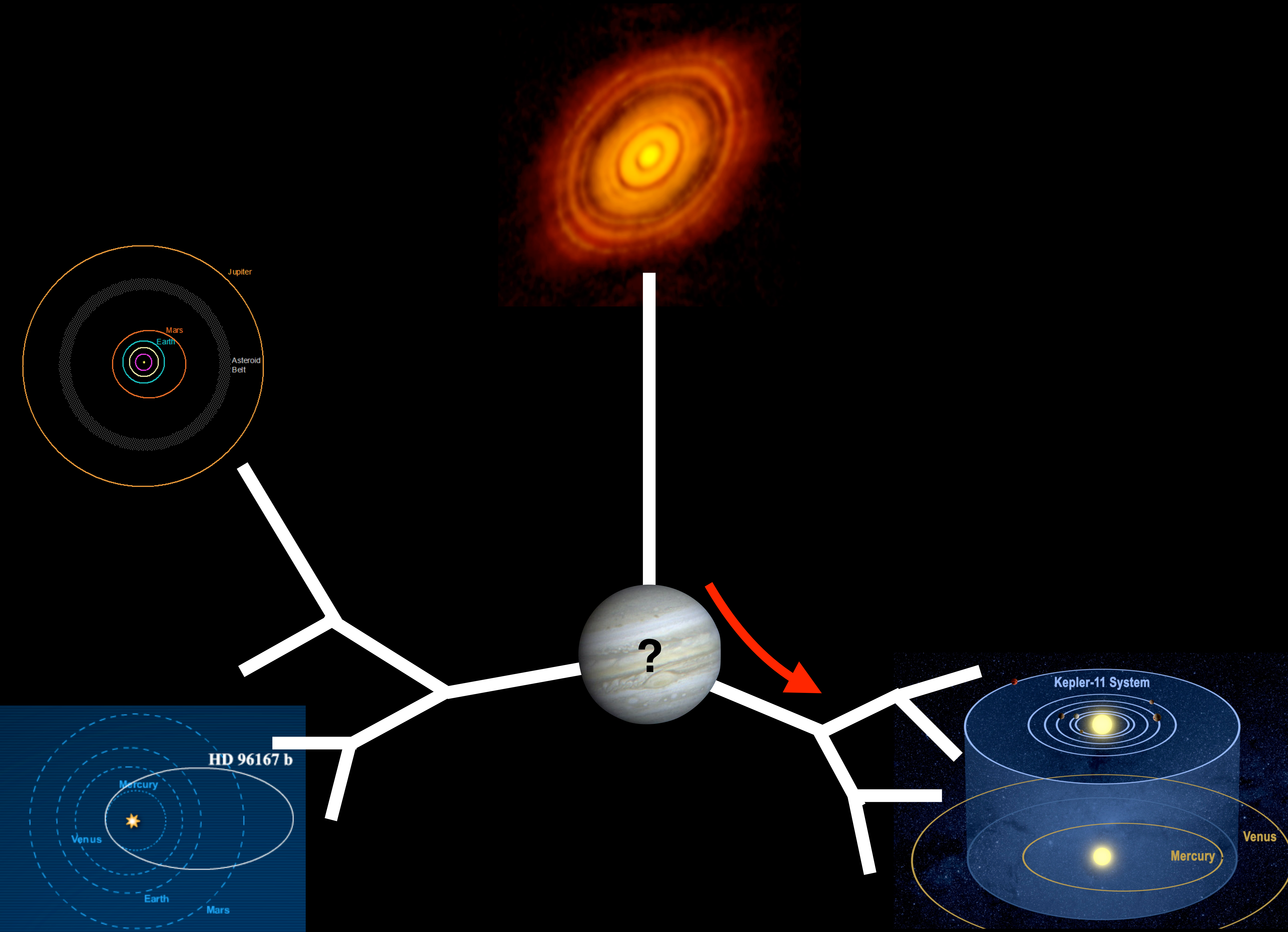

t=0.0
0.6
0.4
0.2
0.0
y/H
0.4
0.6
g (2011)
gas disk
Planetesimals:
~100 km

Planetesimals
Planetary embryos



Pebble accretion is more efficient past the snowline

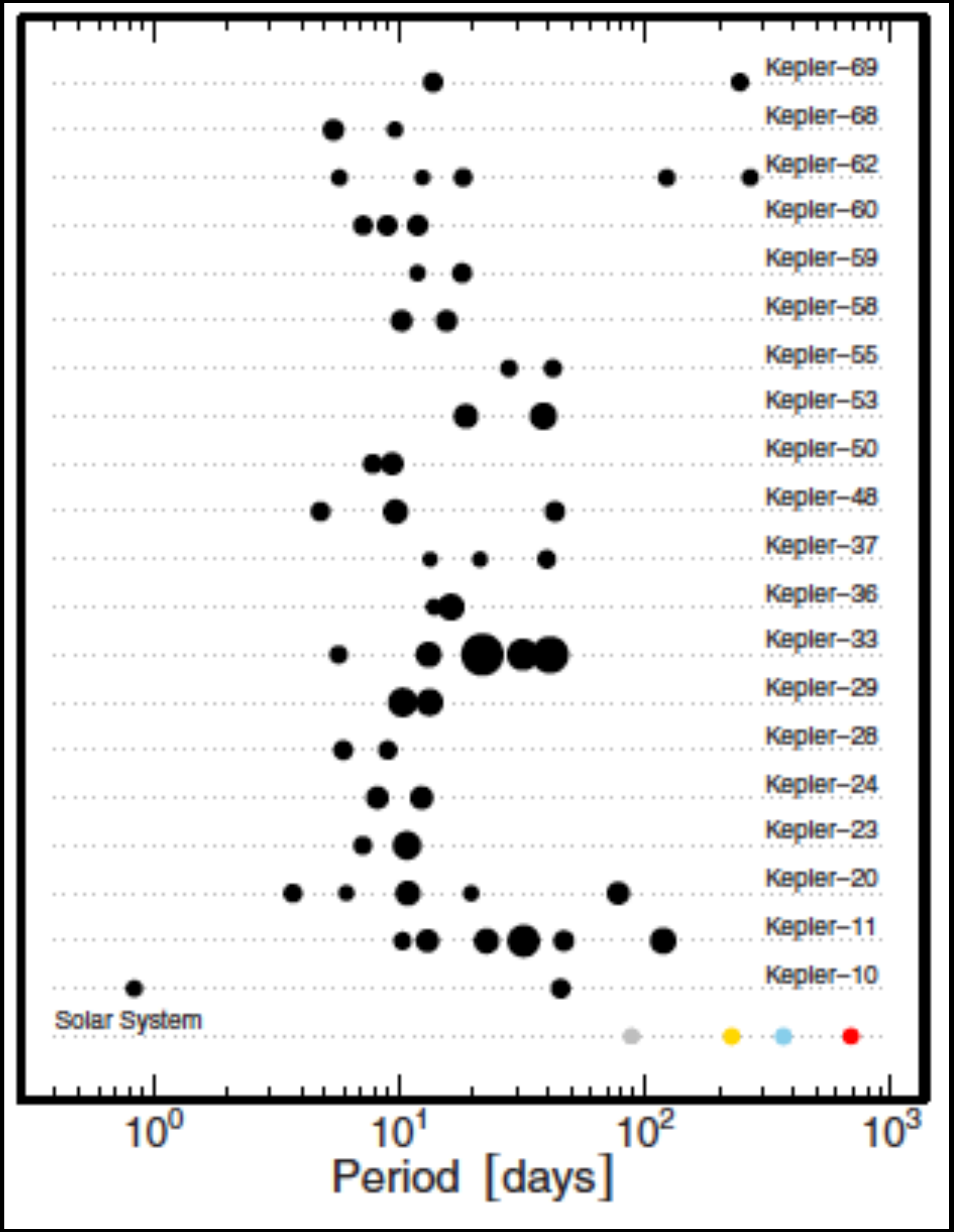
(Lambrechts et al 2014; Morbidelli et al 2015; Ormel et al 2017)


Jupiter
Mars
Earth
Asteroid
Belt
HD 96167 b
Mercury
Venus
Earth
Mars
?
Kepler-11 System
Venus
Mercury

"Super-Earths" vs. the Solar System

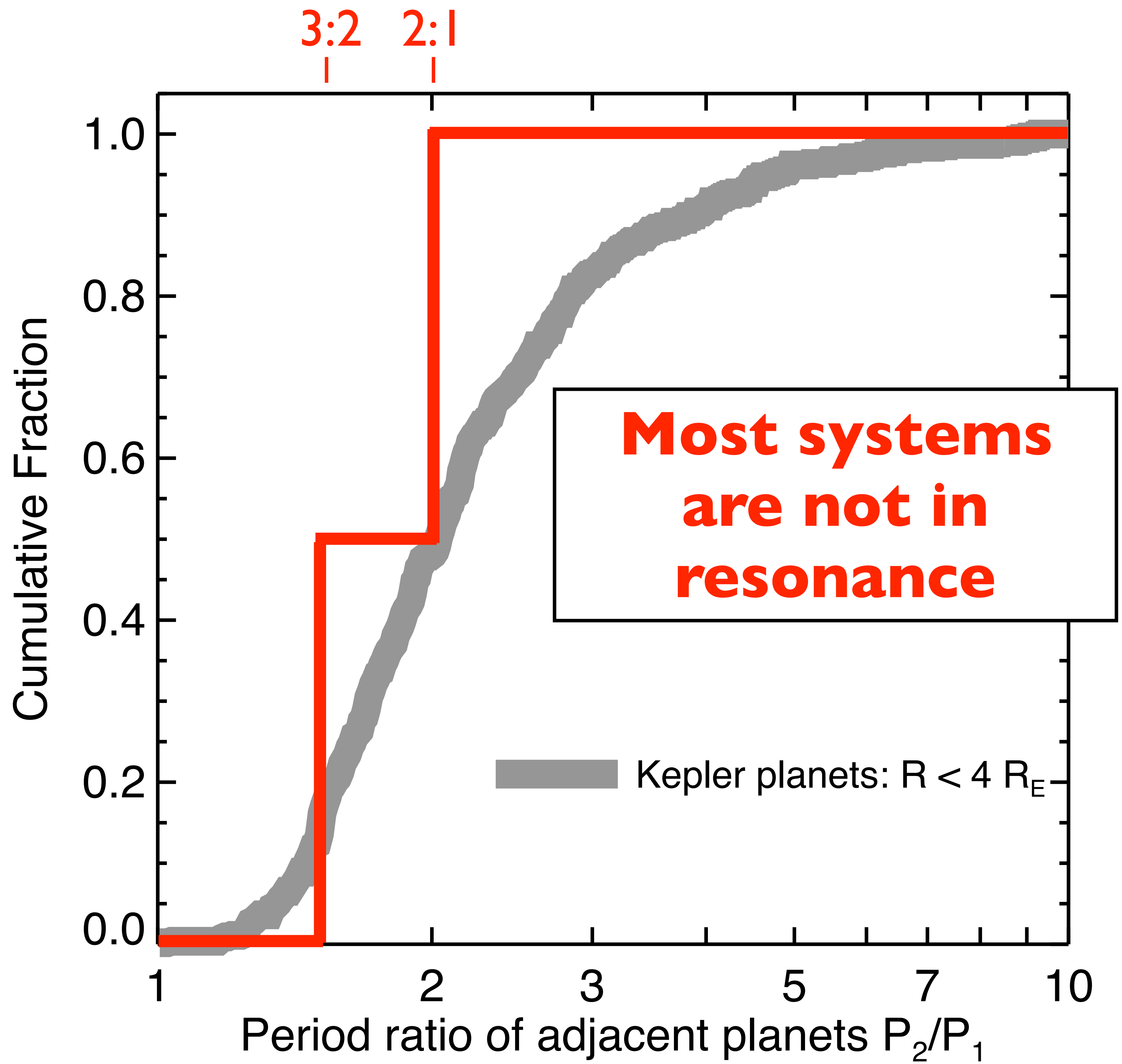
Occurrence rate:
~30-50%

(Mayor et al 2011; Howard et al 2012; Fressin et al 2013, Mulders et al 2018)



Schlaufman (2014)

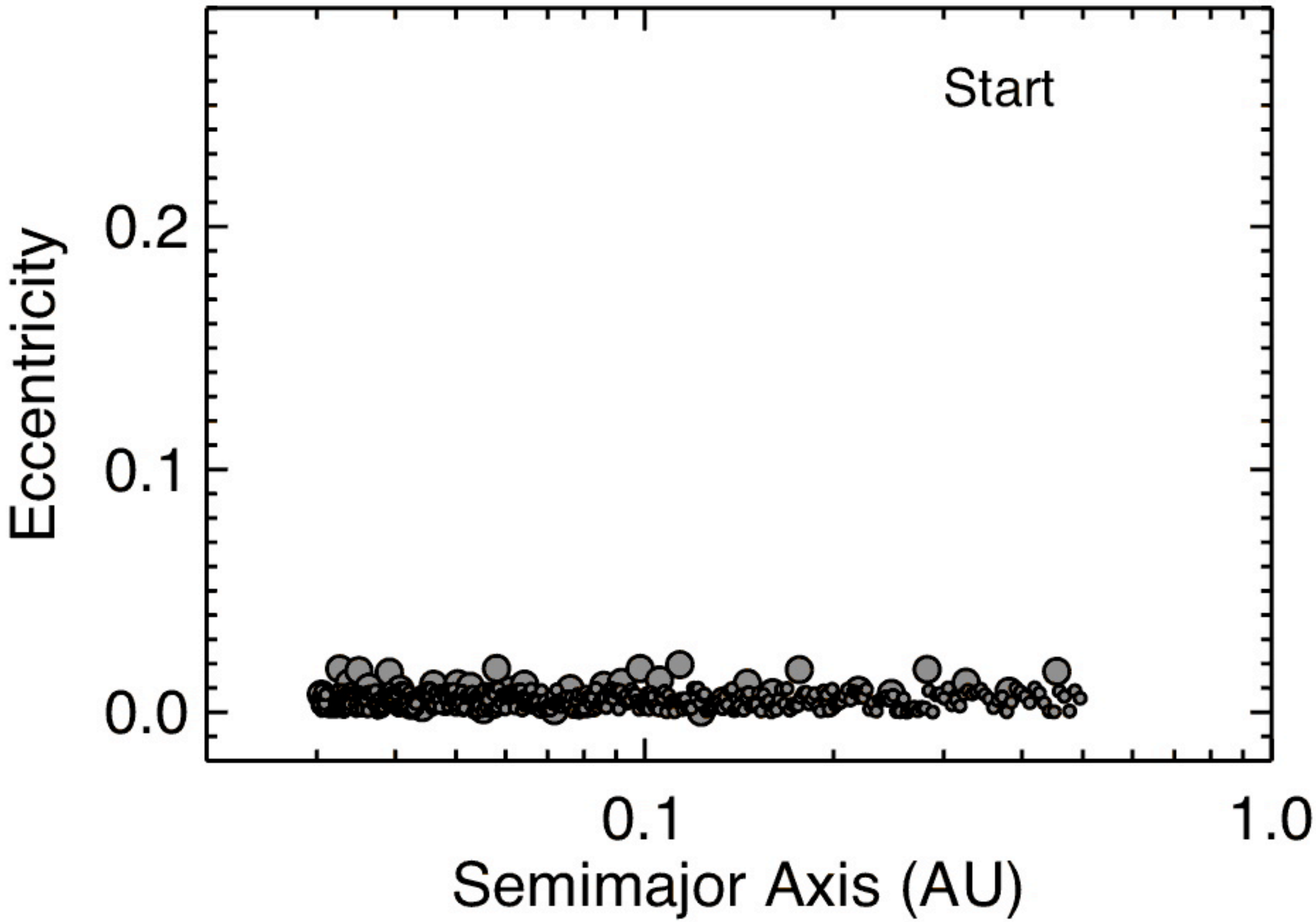
The period ratio distribution



Lissauer et al (2011); Fabrycky et al (2014)

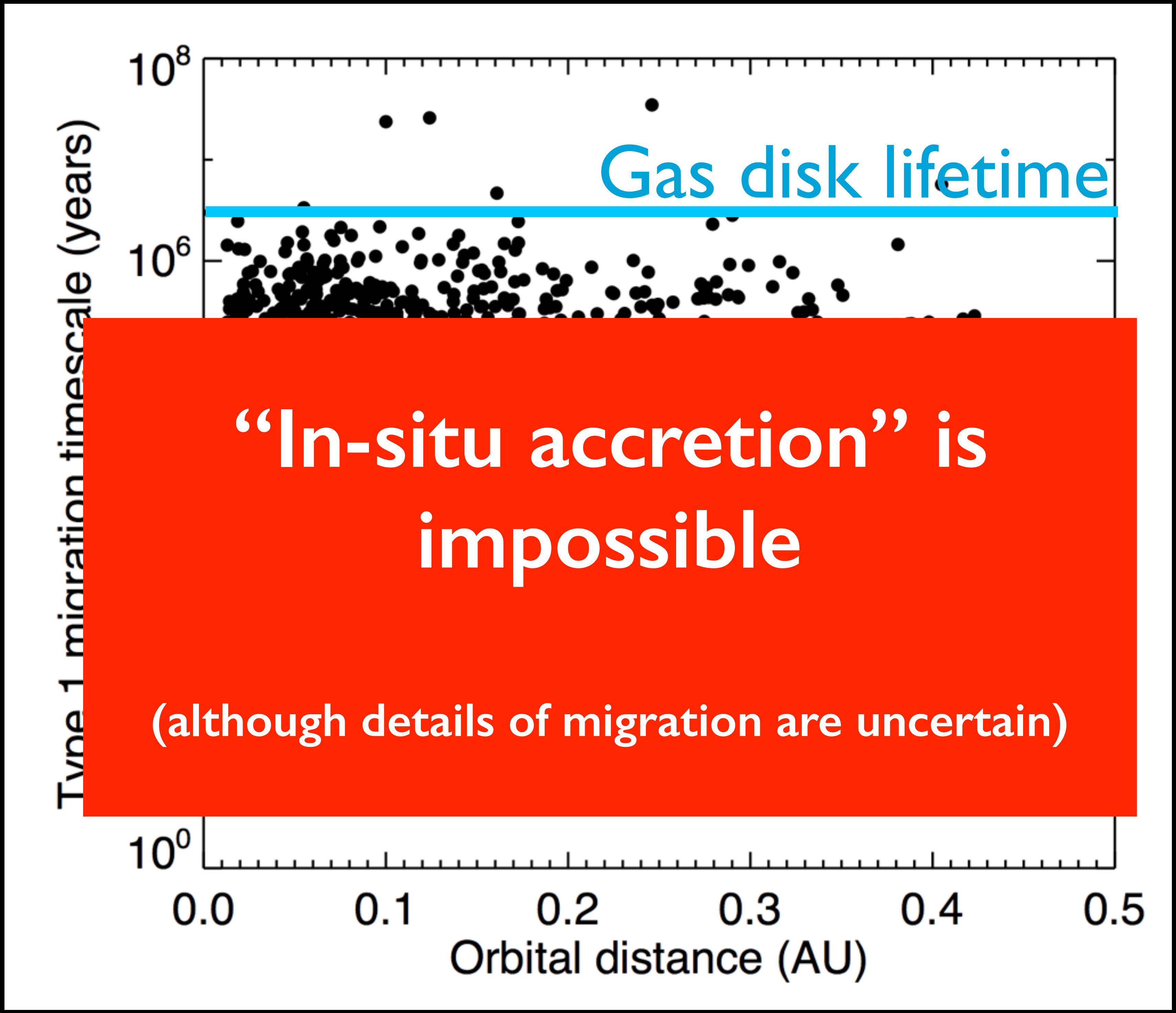
All roads lead to migration…

Growth timescales are very short



Bolmont et al 2014

Migration cannot be ignored



"In-situ accretion" is impossible

(although details of migration are uncertain)

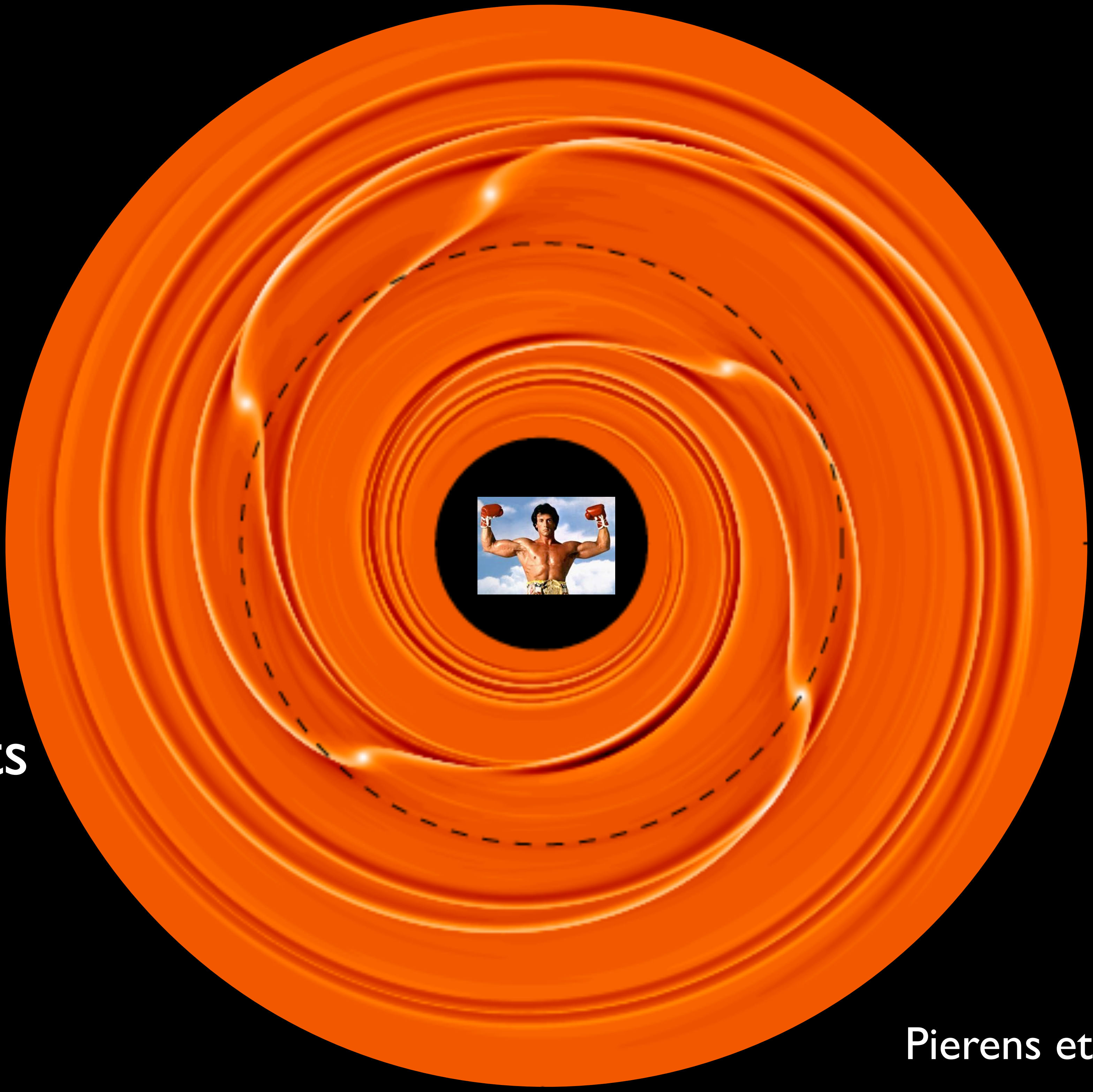
See Inamdar & Schlichting 2015, Schlichting 2014; Ogihara et al 2015; Grishin & Perets 2015

Orbital migration

recent reviews: Kley & Nelson 2012; Baruteau et al 2014

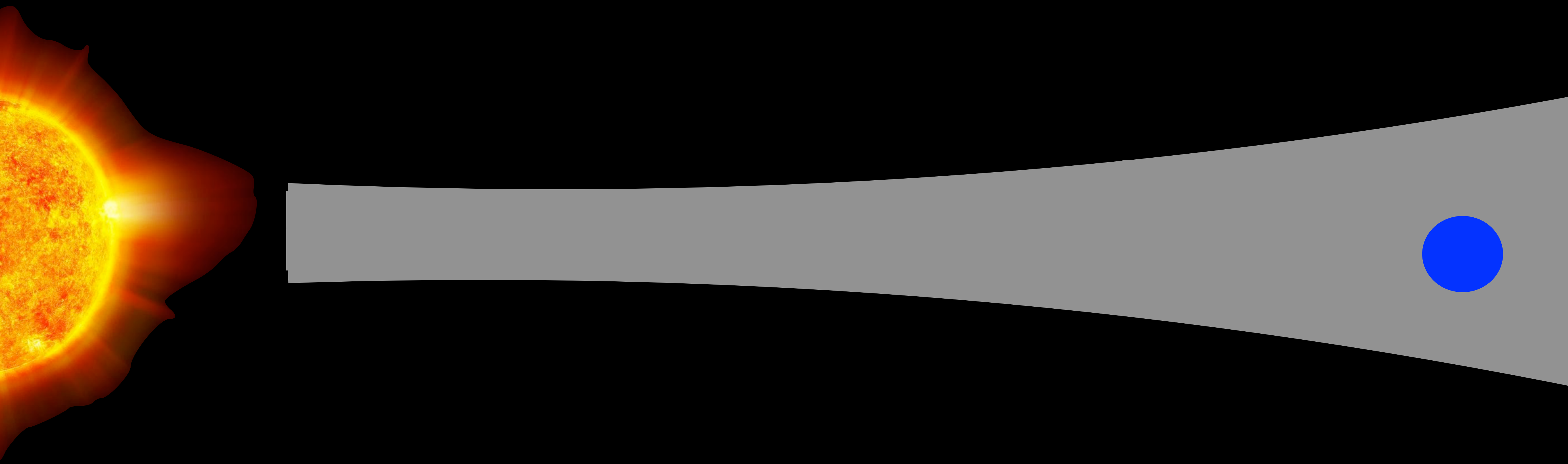
Matters for
Mp >~ MEarth

More massive planets
migrate faster



Pierens et al (2013)

Migrating planets are trapped at the inner edge of the disk

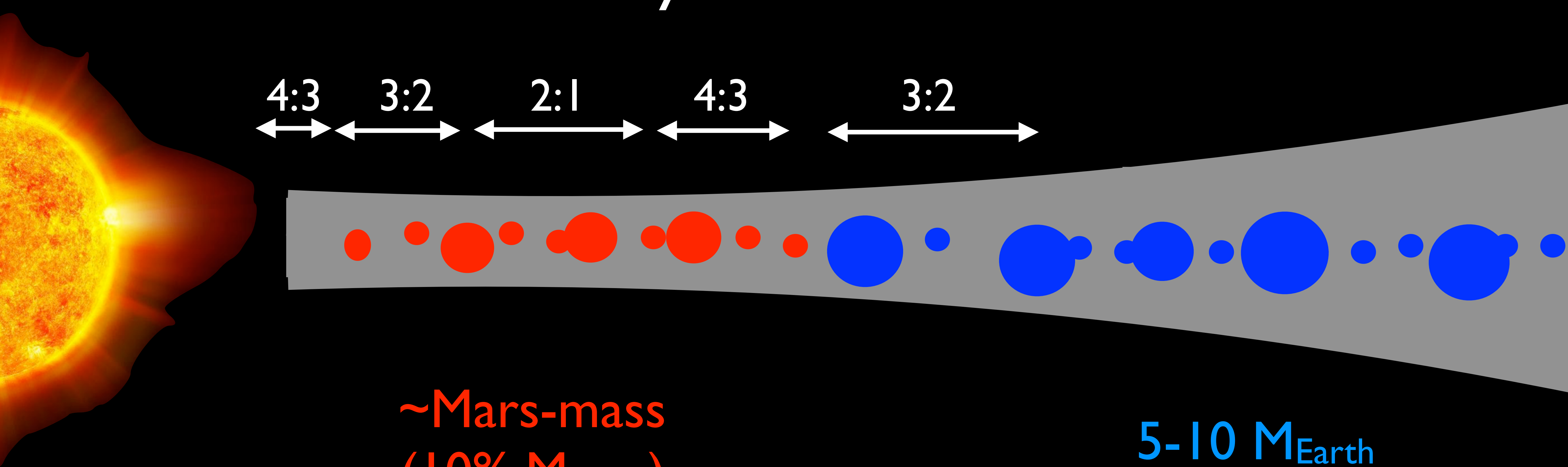


Masset et al (2006); Romanova & Lovelace (2006); Romanova et al (2019)

Planetary embryos

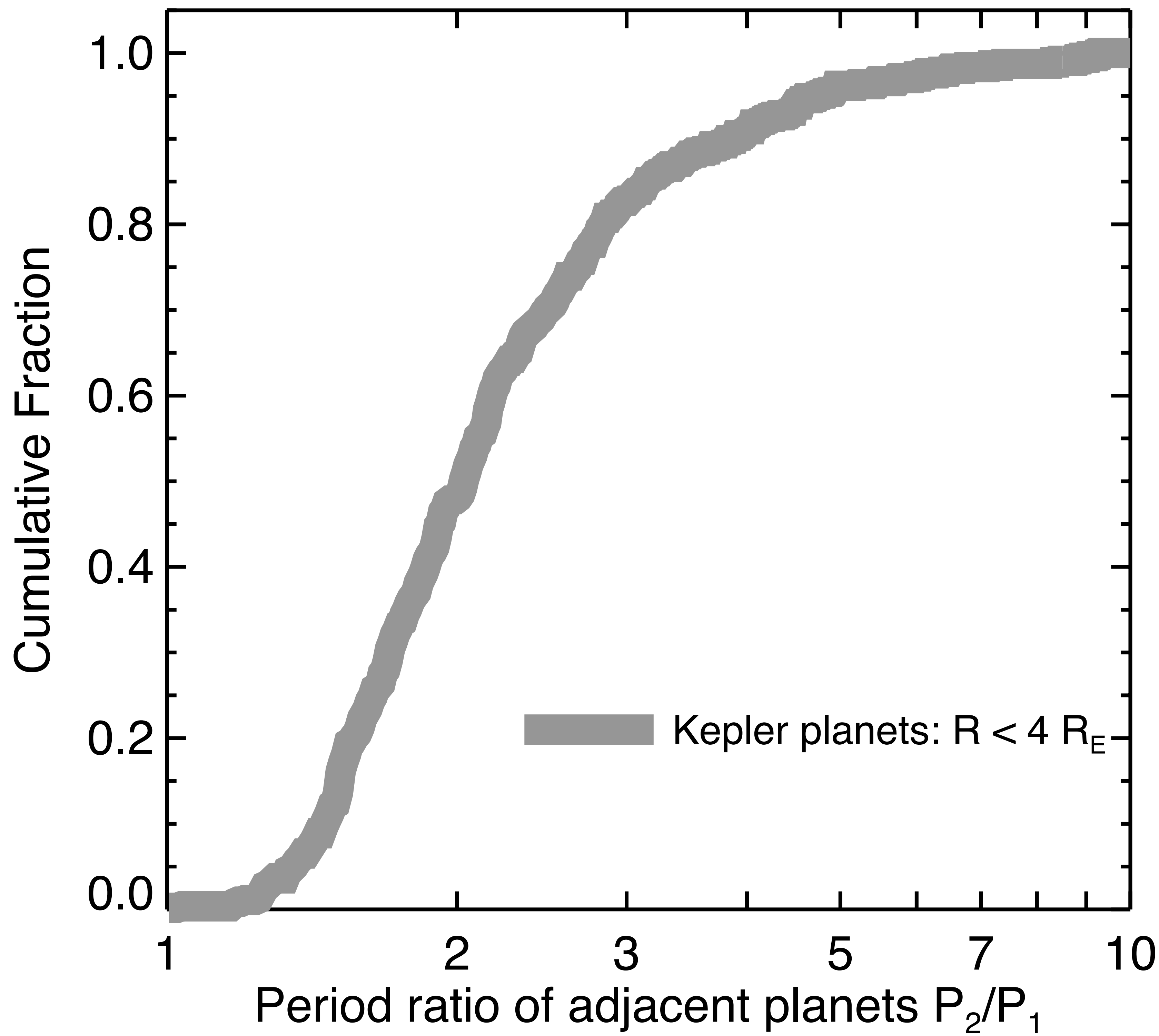
Resonant chain

Instability spreads planets out and destroys resonances

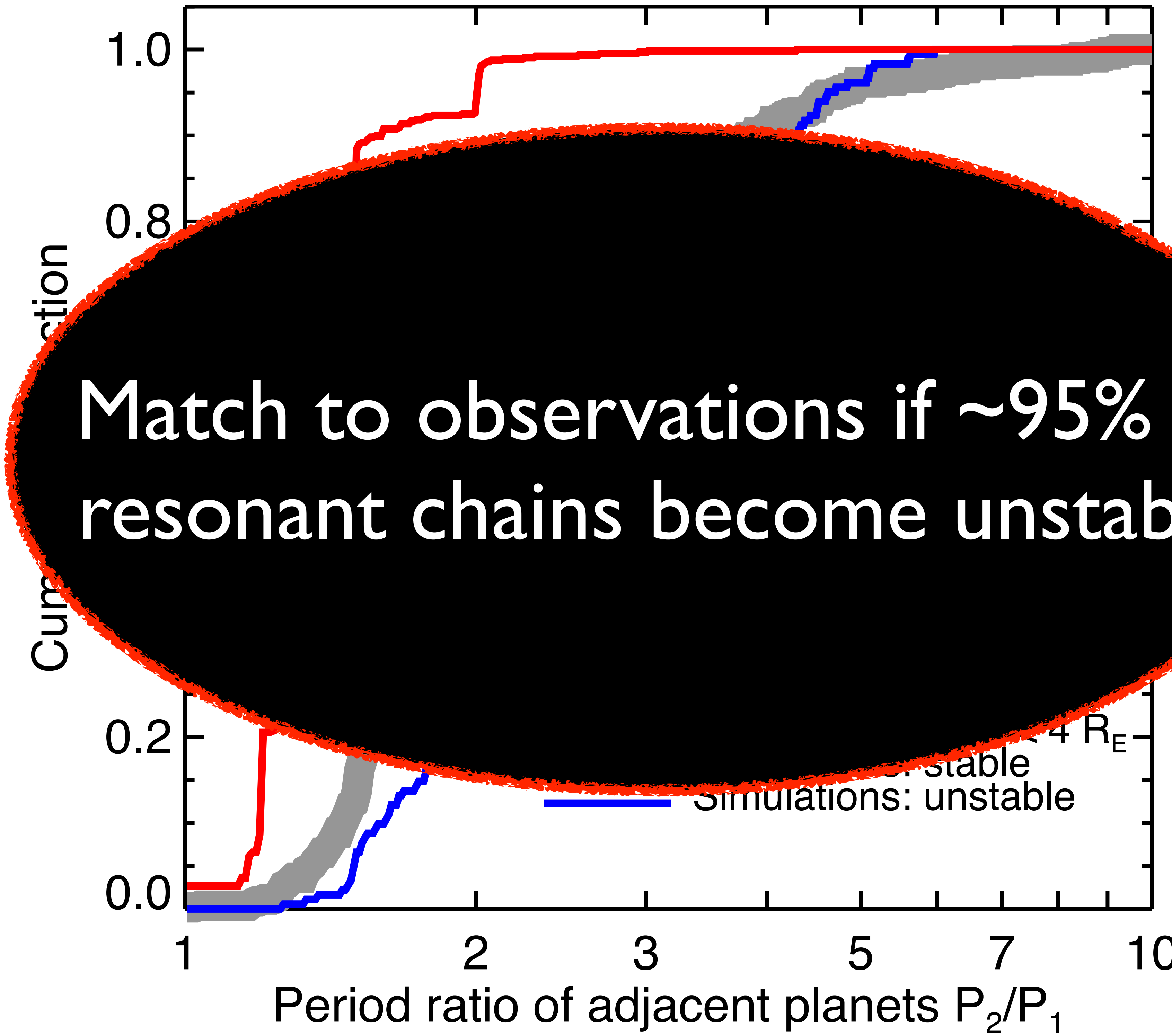


Gaseous disk dissipates after a few million years

The period ratio distribution

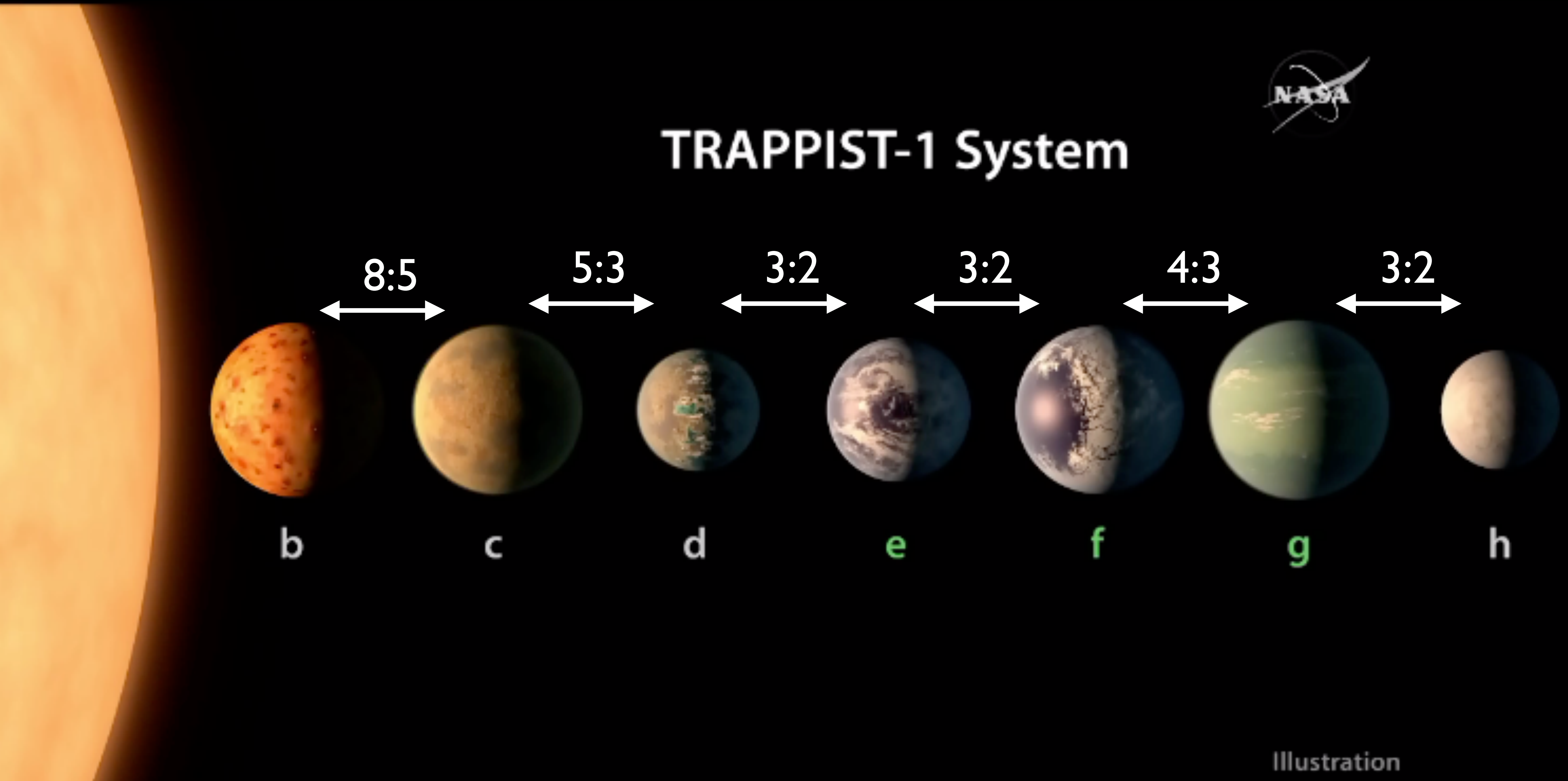


The period ratio distribution



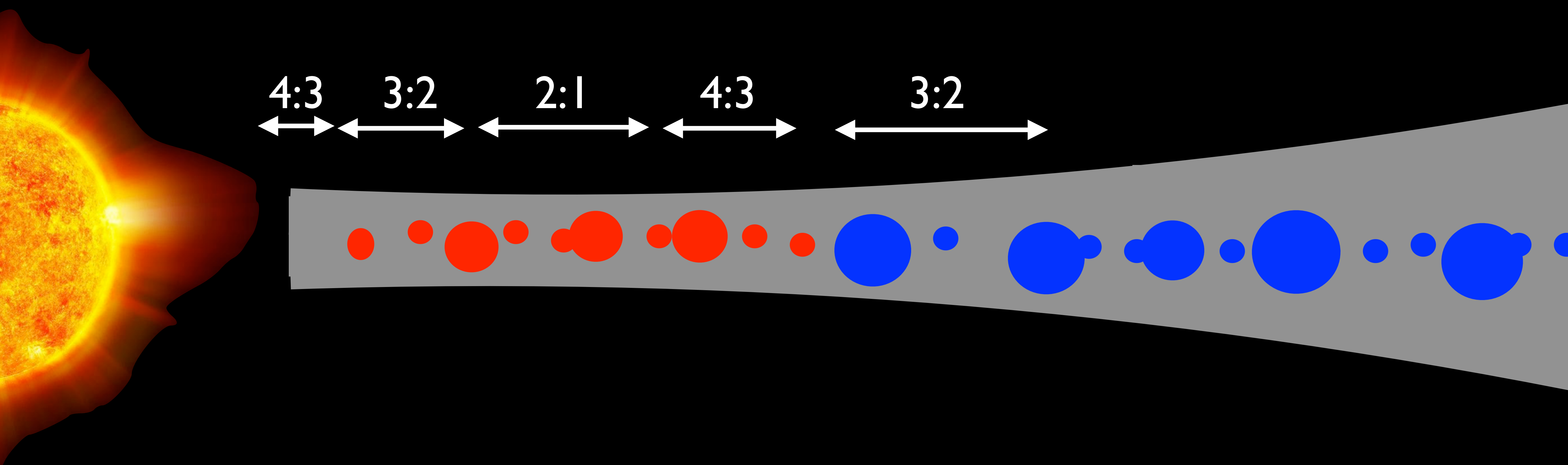
Match to observations if ~95% of resonant chains become unstable

Izidoro et al (2017, 2019)



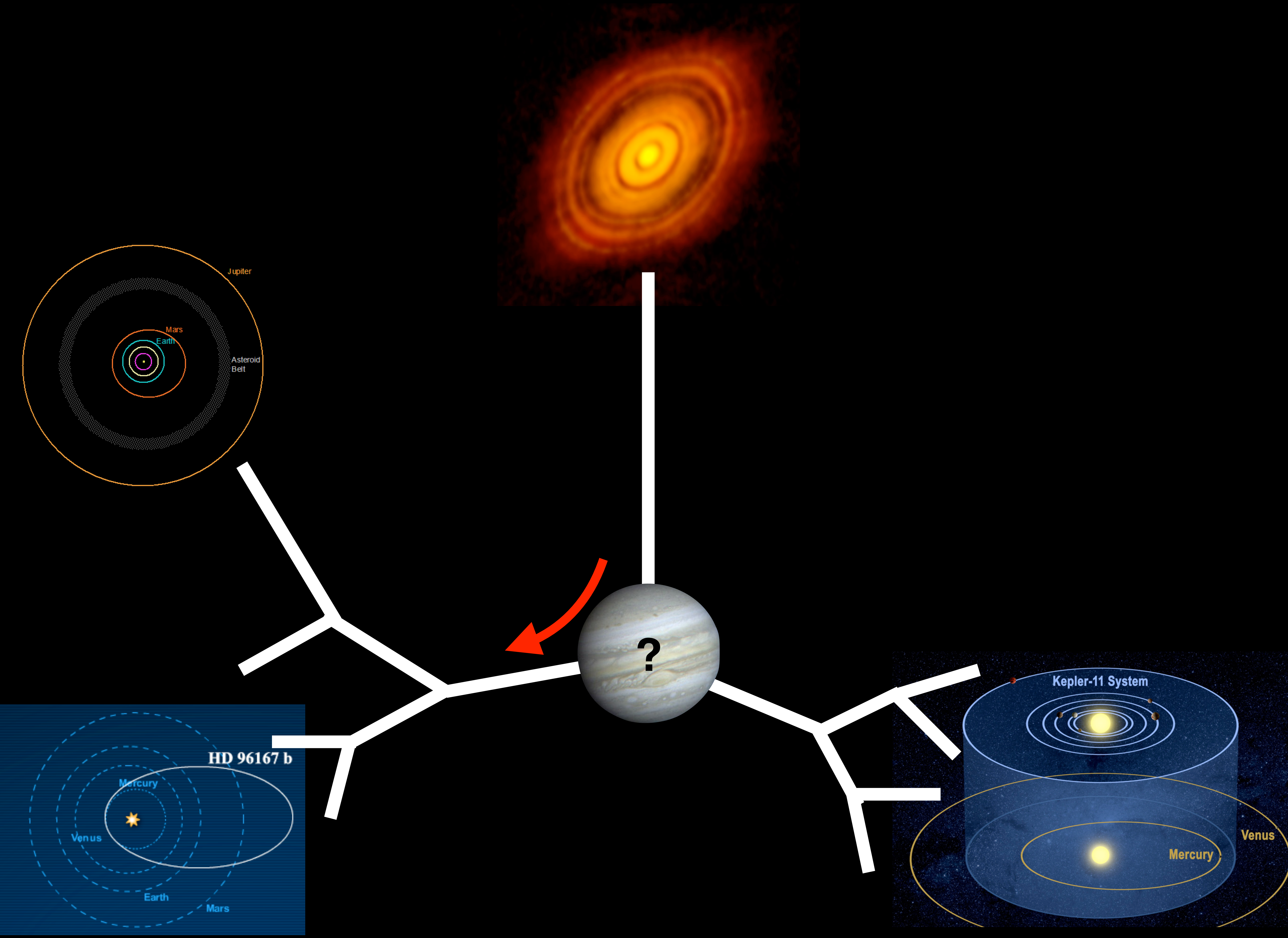
(Gillon et al 2017, Luger et al 2017)

Some super-Earths from migration are pure rock….



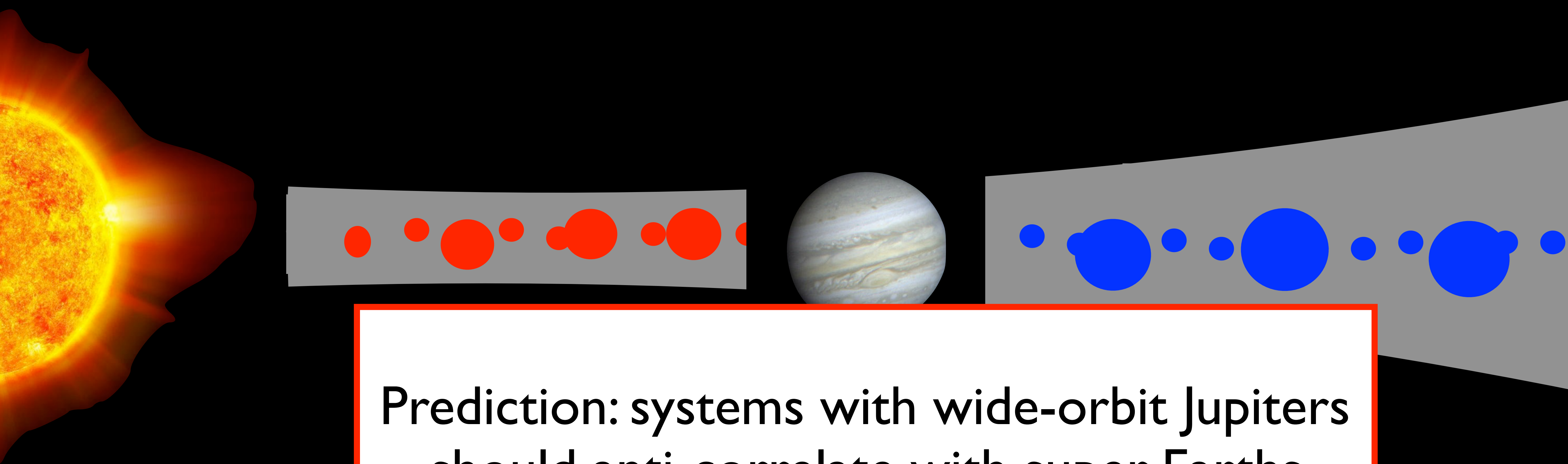
….but most are ice-rich

(**Raymond et al 2018;** also Coleman et al 2019; Bitsch et al 2019; Izidoro et al 2019)


Jupiter
Mars
Earth
Asteroid Belt
?
HD 96167 b
Mercury
Venus
Earth
Mars
Kepler-11 System
Venus
Mercury

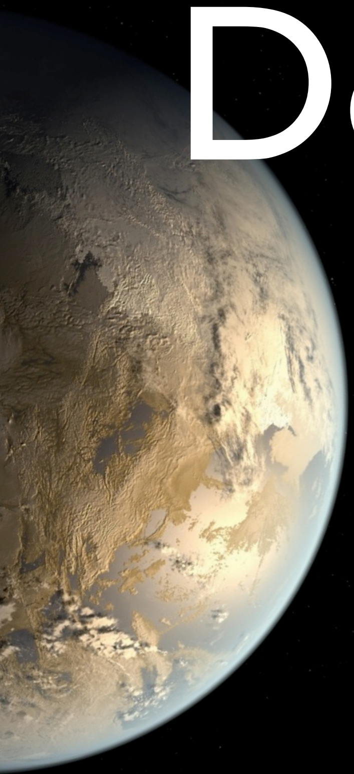
Jupiter blocks the migration of more distant, icy embryos

The young Jupiter accretes gas from the disk

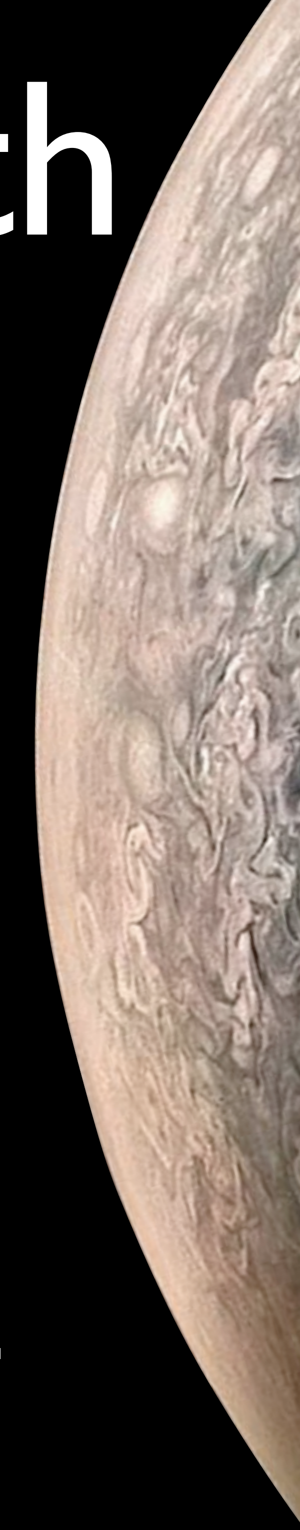


Prediction: systems with wide-orbit Jupiters should anti-correlate with super-Earths

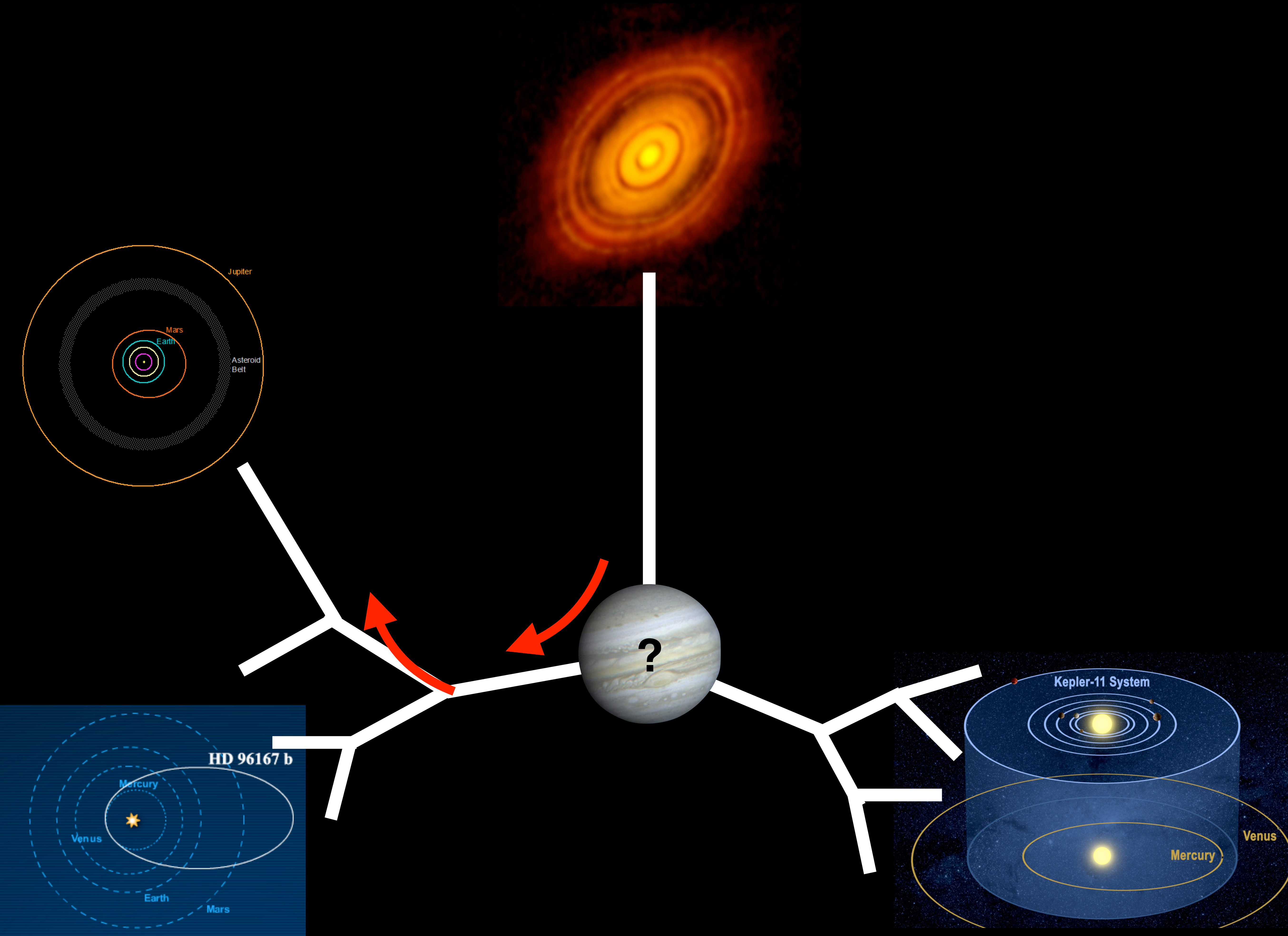
Izidoro et al (2015)



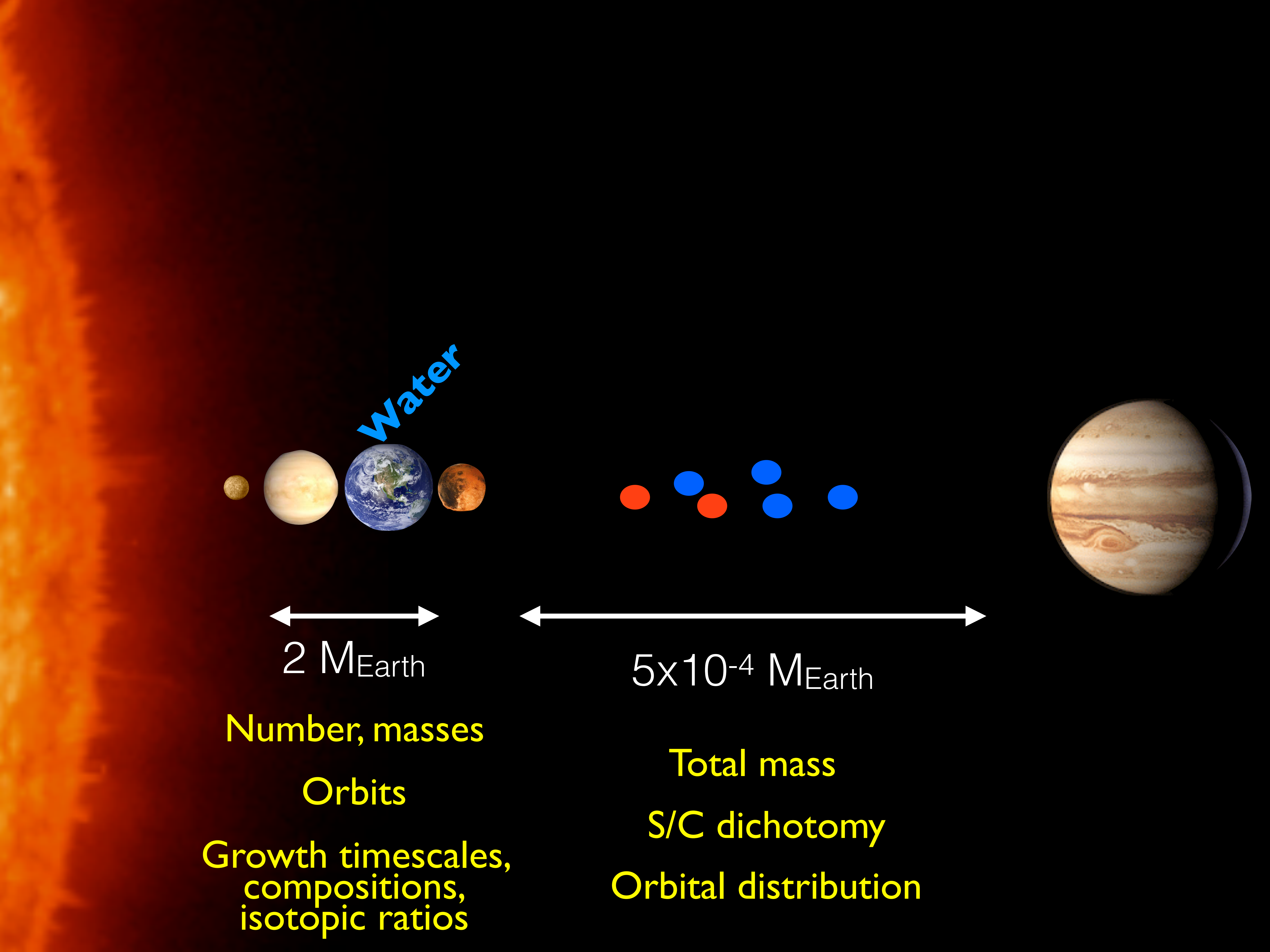
Do Jupiters correlate with super-Earths?



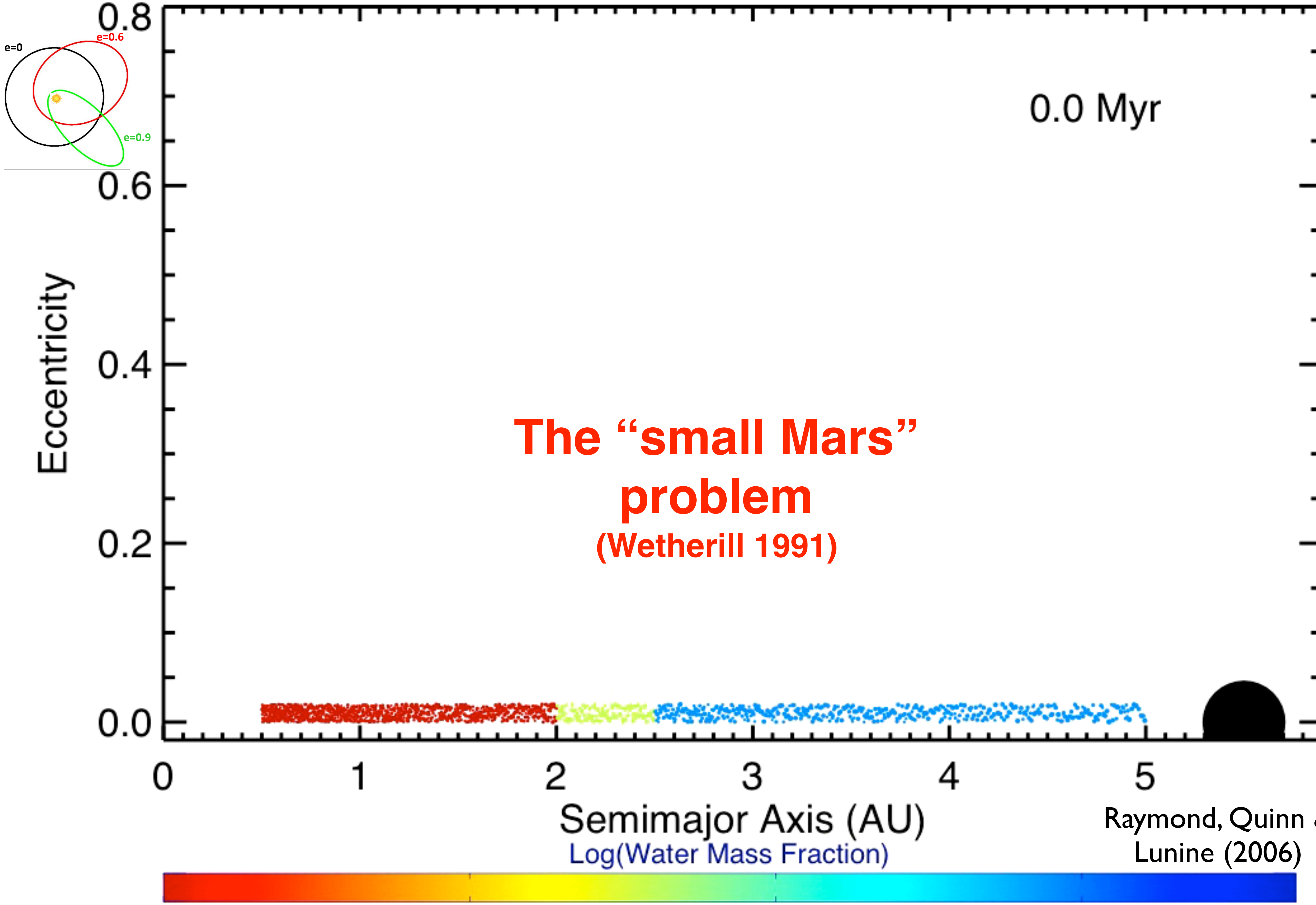
- Barbato et al (2018): RV — **Deficit** of super-Earths in systems with wide-orbit Jupiters
- Bryan et al (2019): RV — **Excess** of Jupiter-like trends in systems with super-Earths
- Zhu & Wu (2018): RV/Transit — **Excess** of Jupiters in super-Earth systems



Jupiter
Mars
Earth
Asteroid Belt
?
HD 96167 b
Mercury
Venus
Earth
Mars
Kepler-11 System
Venus
Mercury


Water
2 M Earth
5x10-4 M Earth
Number, masses
Orbits
Growth timescales, compositions, isotopic ratios
Total mass
S/C dichotomy
Orbital distribution

The “classical model”

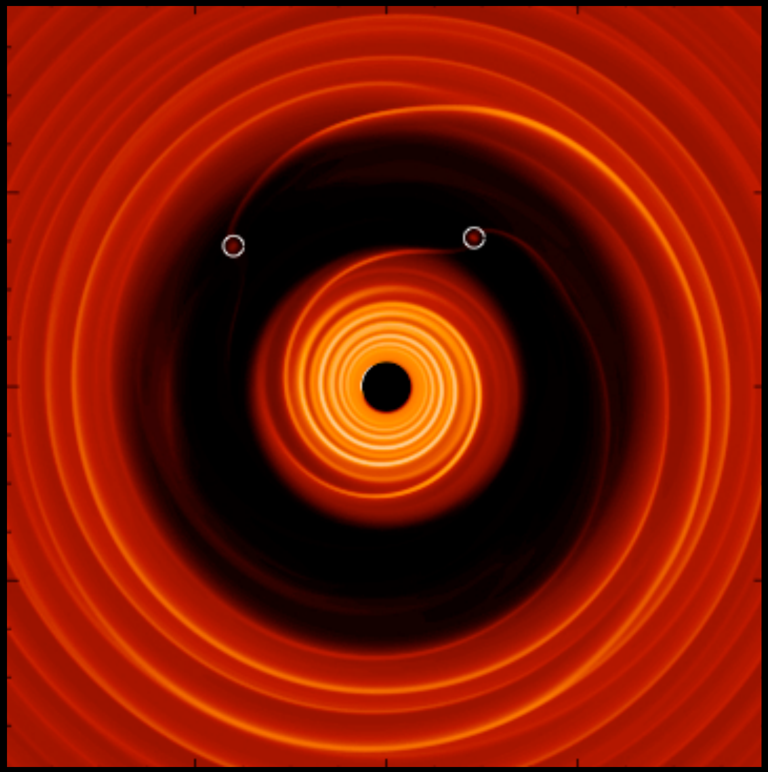


The “small Mars” problem
(Wetherill 1991)

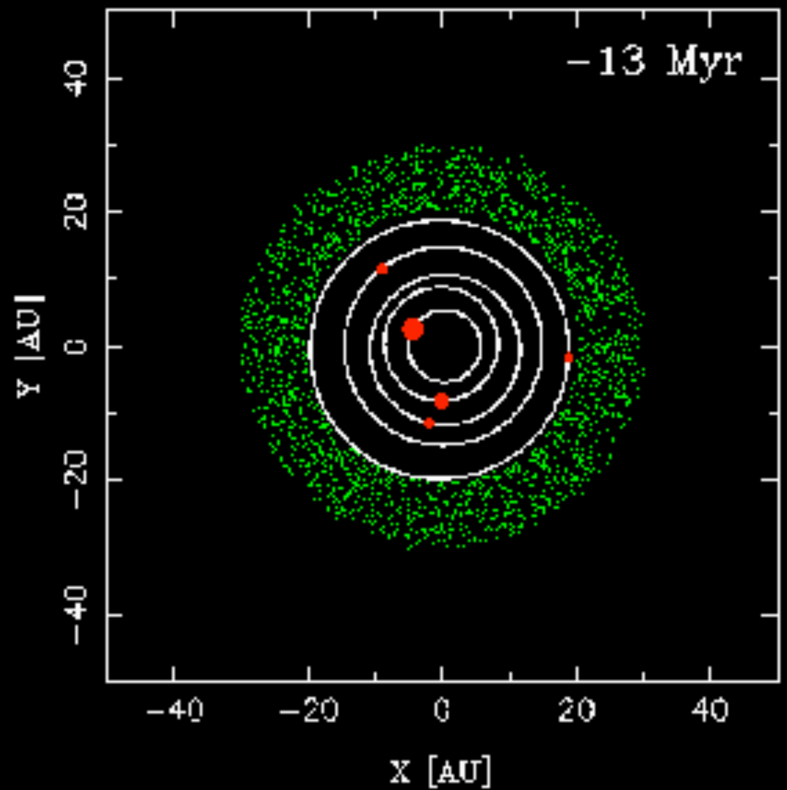
Raymond, Quinn & Lunine (2006)

3 possible solutions to the small Mars problem

"Low-mass asteroid belt"



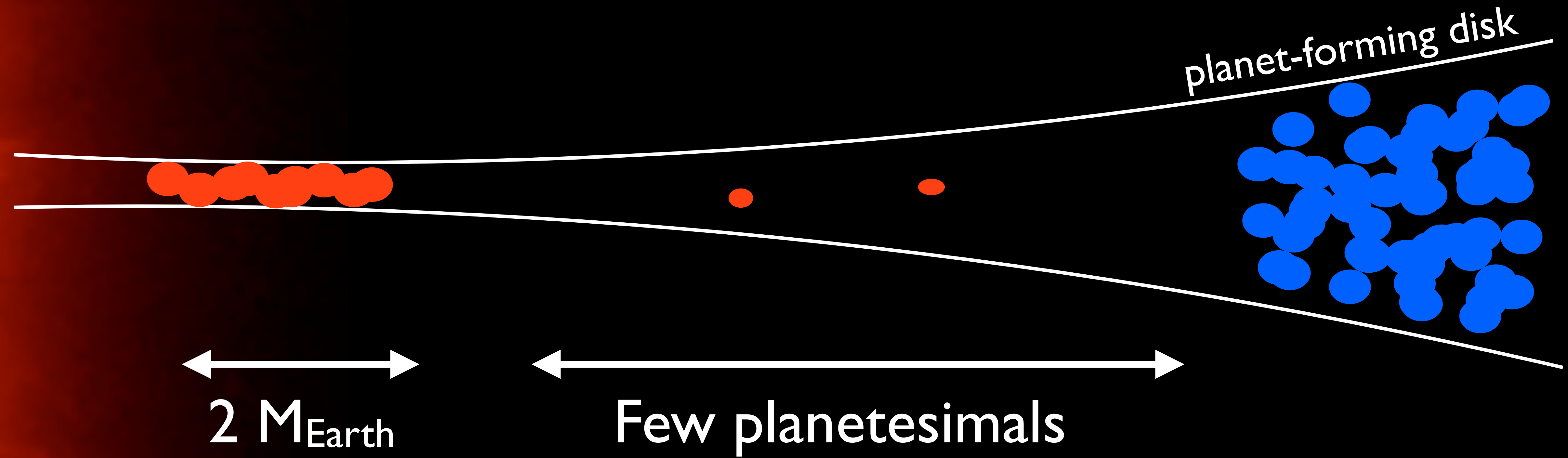
The "Grand Tack"



Early instability

1. Low-mass asteroid belt

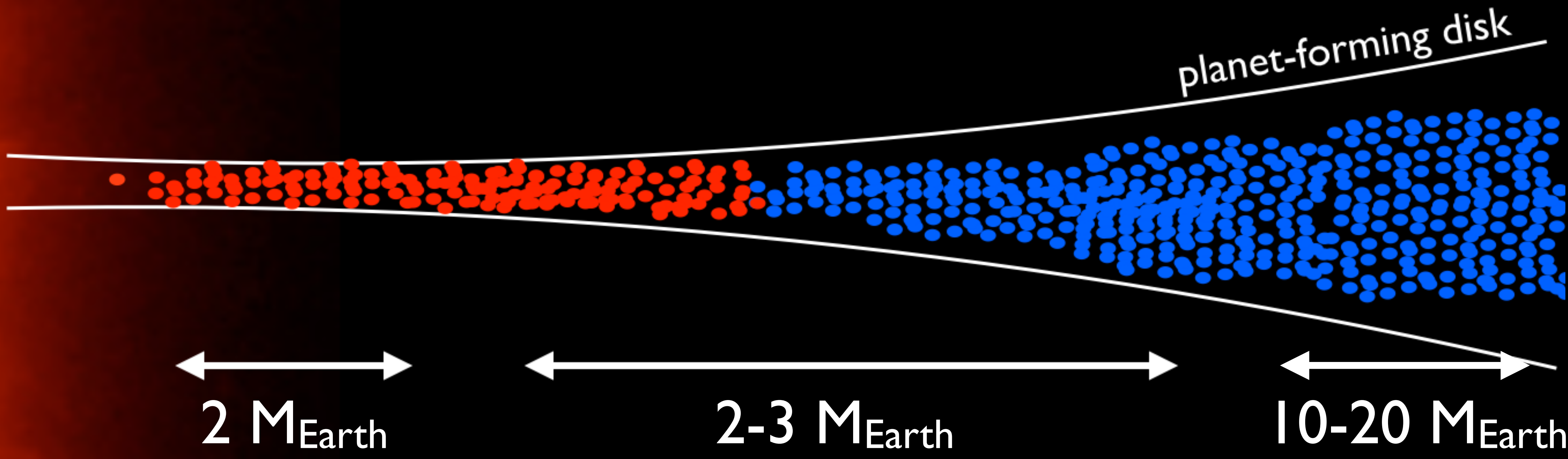
Assumption: few (if any) planetesimals formed in Mars region/asteroid belt

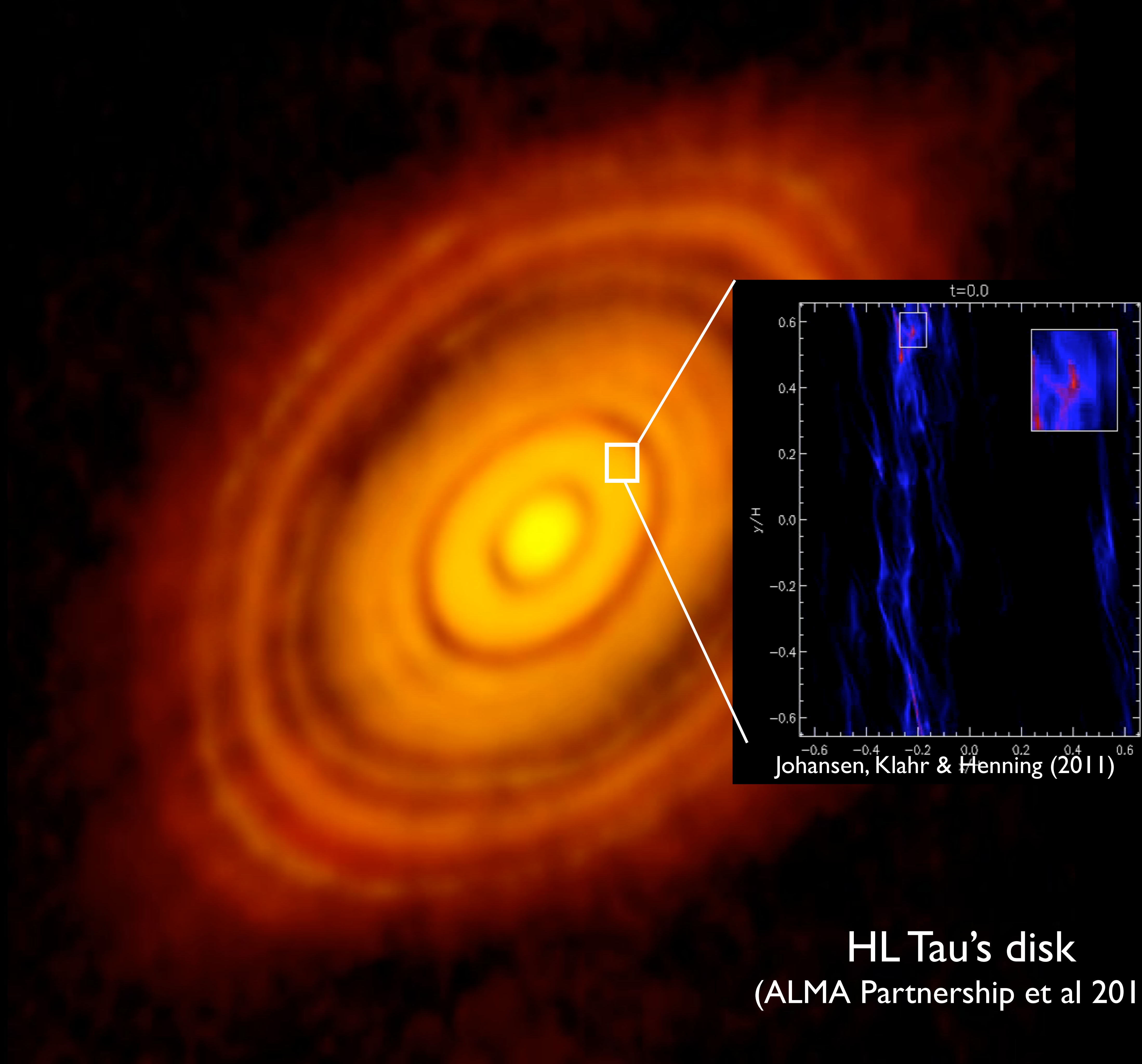


(Hansen 2009; Izidoro et al 2015; Walsh & Levison 2016; Drazkowska et al 2016; Raymond & Izidoro 2017b)

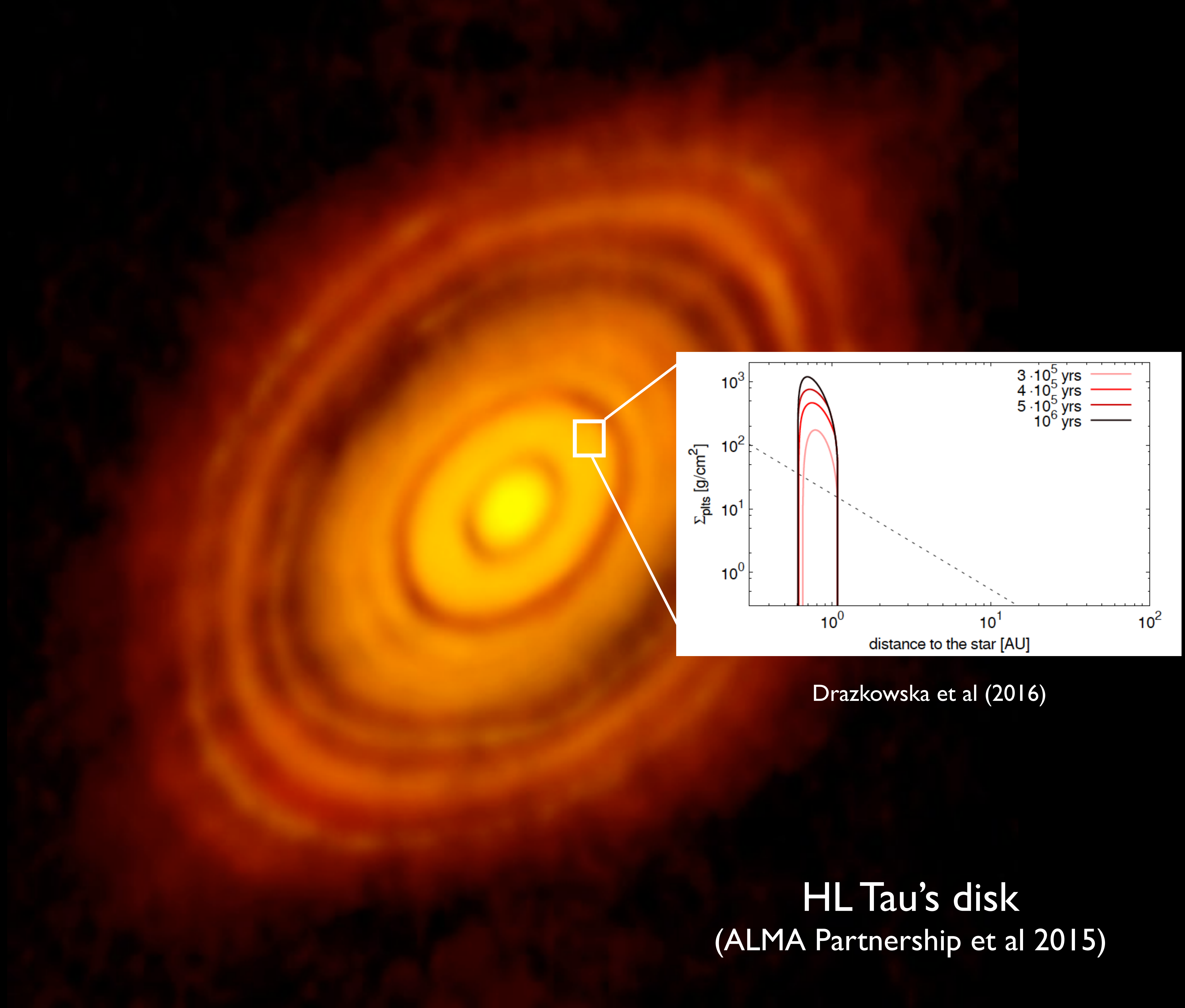
1. Low-mass asteroid belt

Dust, gas distributions were smooth(ish)





HL Tau's disk
(ALMA Partnership et al 2015)

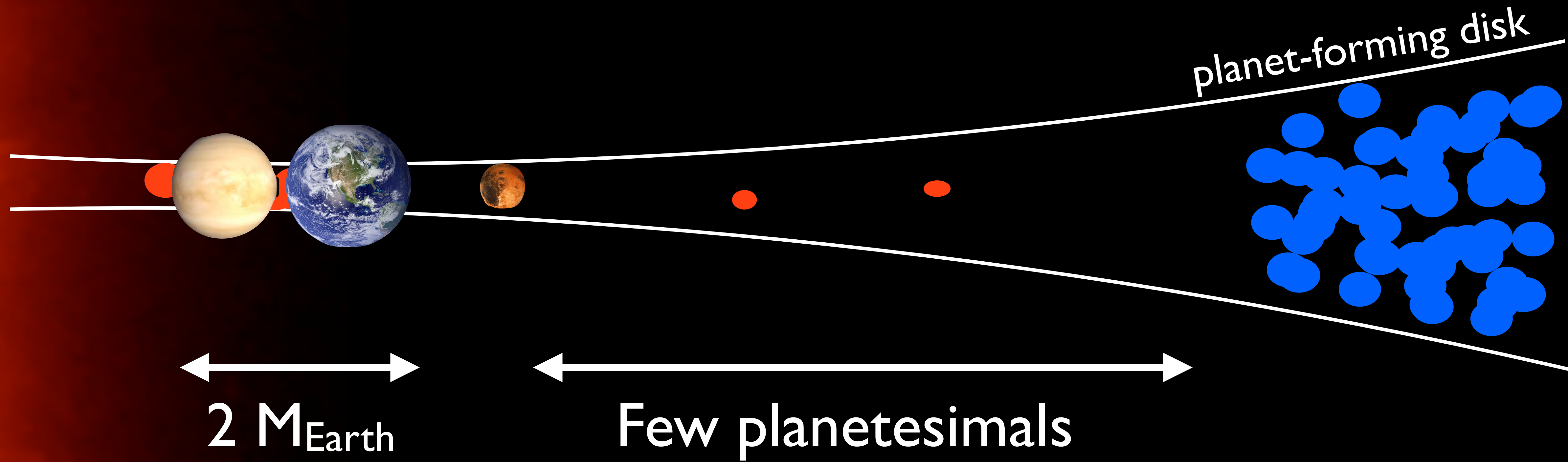


Drazkowska et al (2016)

HL Tau's disk
(ALMA Partnership et al 2015)

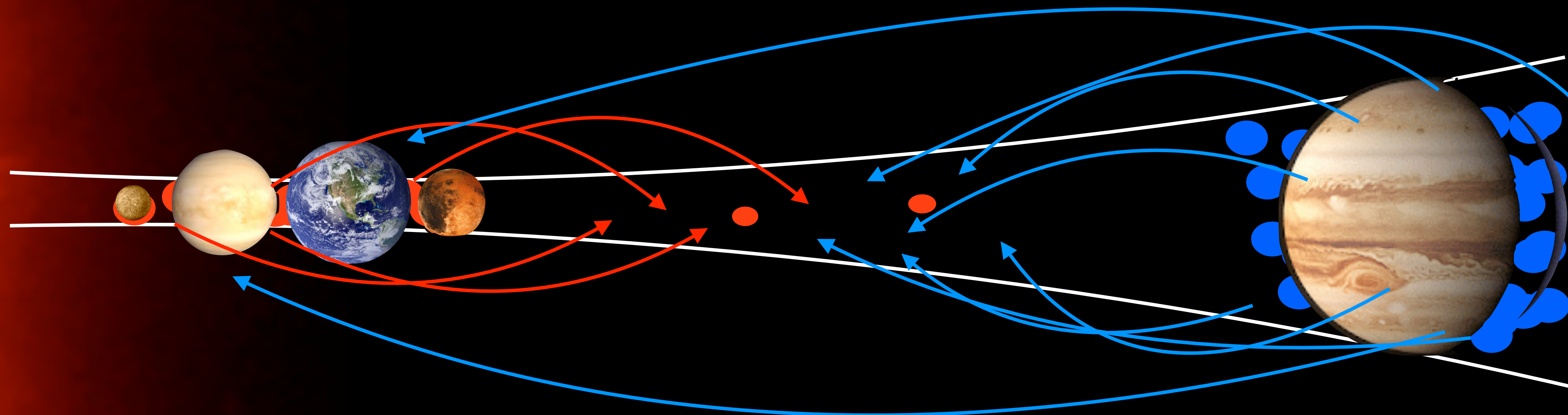
1. Low-mass asteroid belt

Assumption: few (if any) planetesimals formed in Mars region/asteroid belt



(Hansen 2009; Izidoro et al 2015; Walsh & Levison 2016; Drazkowska et al 2016; Raymond & Izidoro 2017b)

C-types and Earth's water scattered in from giant planet region

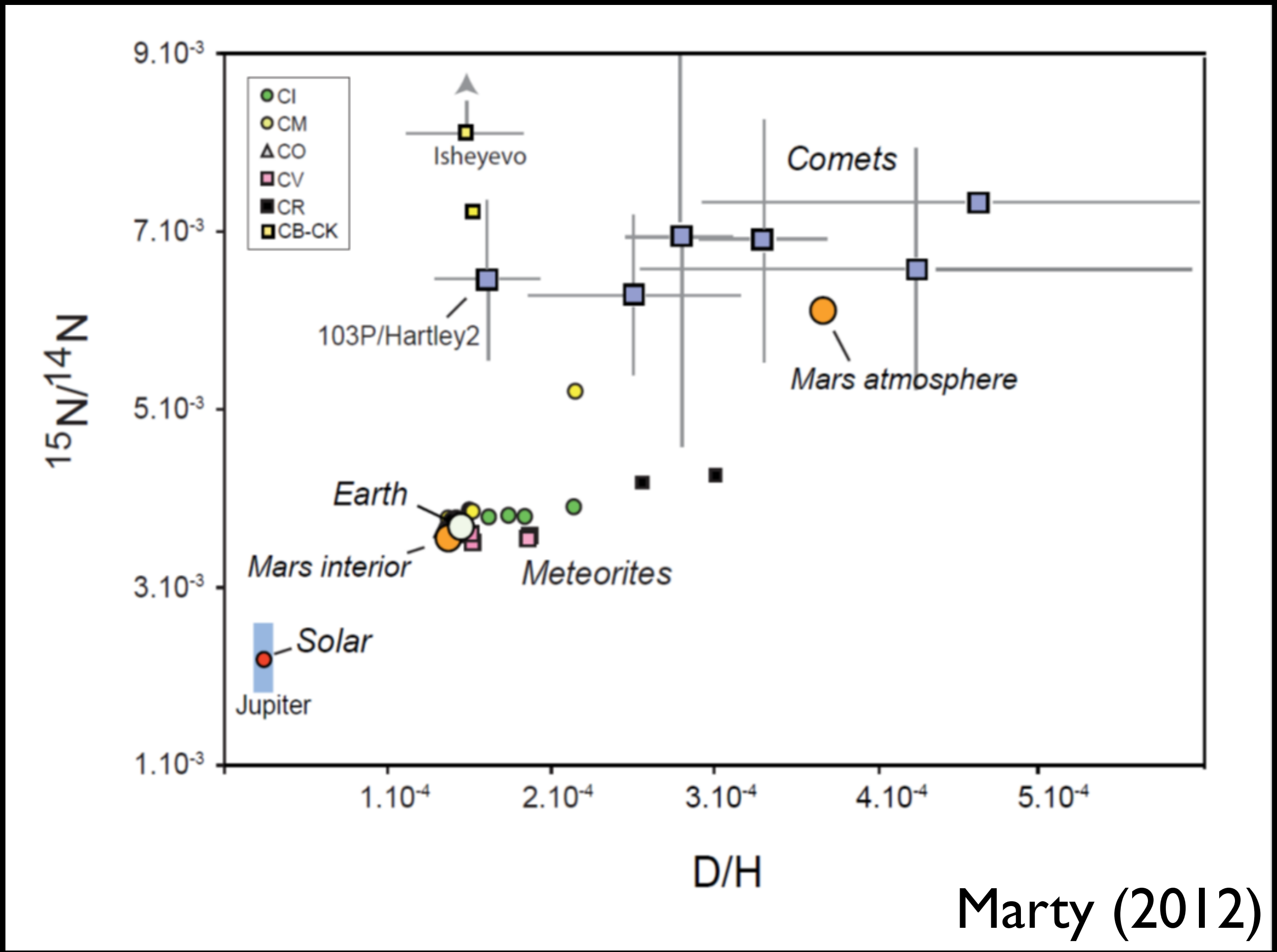


Some asteroids (Vesta? Irons? S-types?) scattered out from terrestrial planet region

Raymond & Izidoro (2017a); Ronnet et al (2018); Pirani et al (2019)
Raymond & Izidoro (2017b); Bottke et al (2006); Mastrobuono-Battisti & Perets (2017)

Water on Earth

- M_{water} ~ 0.1% M_{Earth}
- Isotopic match to carbonaceous chondrites (from C-type asteroids; e.g., Marty 2012; Alexander et al 2012)

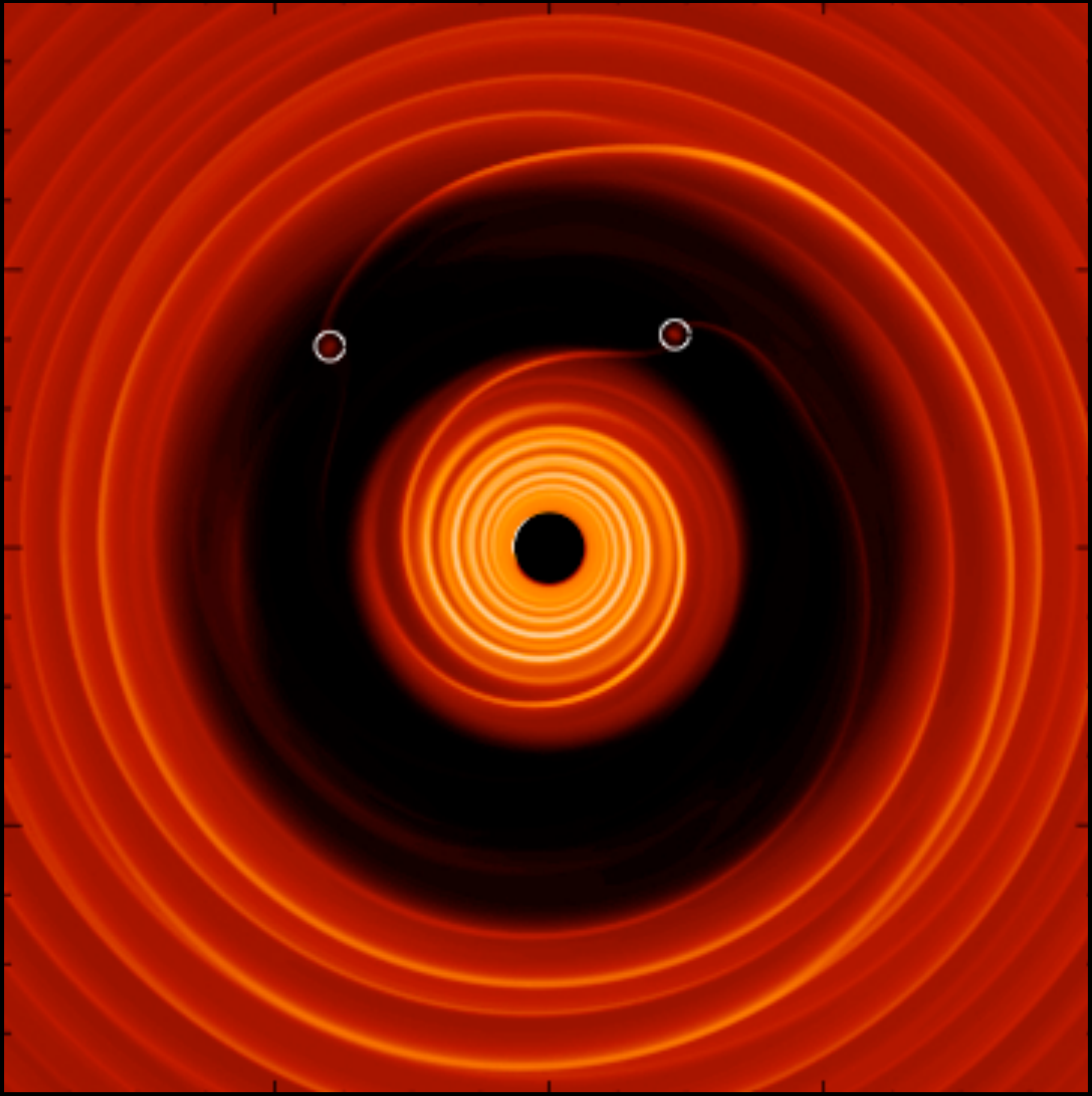


Classical model: primitive C-types delivered Earth's water
(Morbidelli et al 2000; Raymond et al 2004, 2007)

New story: water was delivered to Earth by same population that was implanted into asteroid belt as C-types
(Walsh et al 2011; O'Brien et al 2014; Raymond & Izidoro 2017)

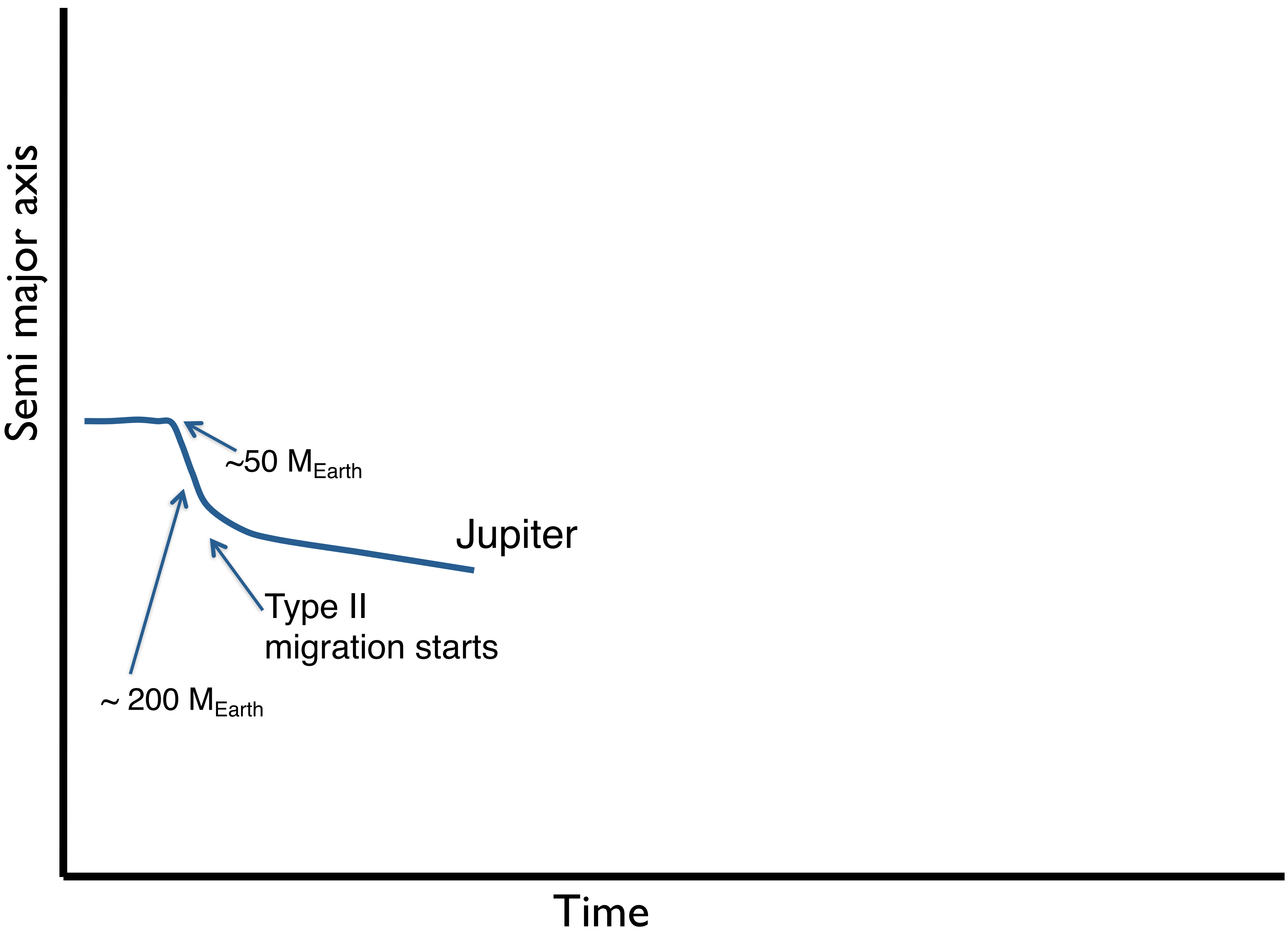
2. The Grand Tack

(Walsh et al 2011)

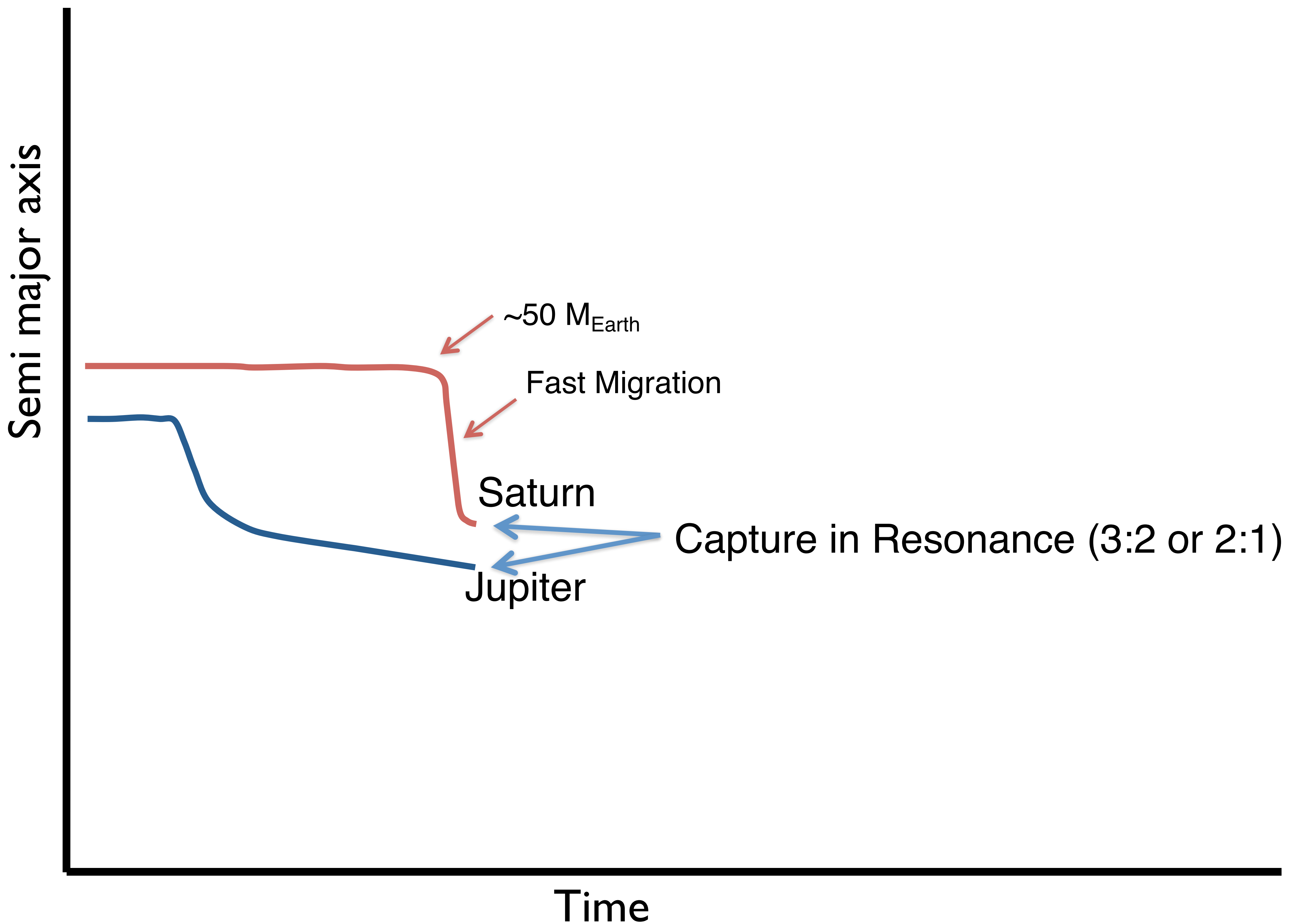


Pierens &
Raymond (2011)

Jupiter in the gaseous disk

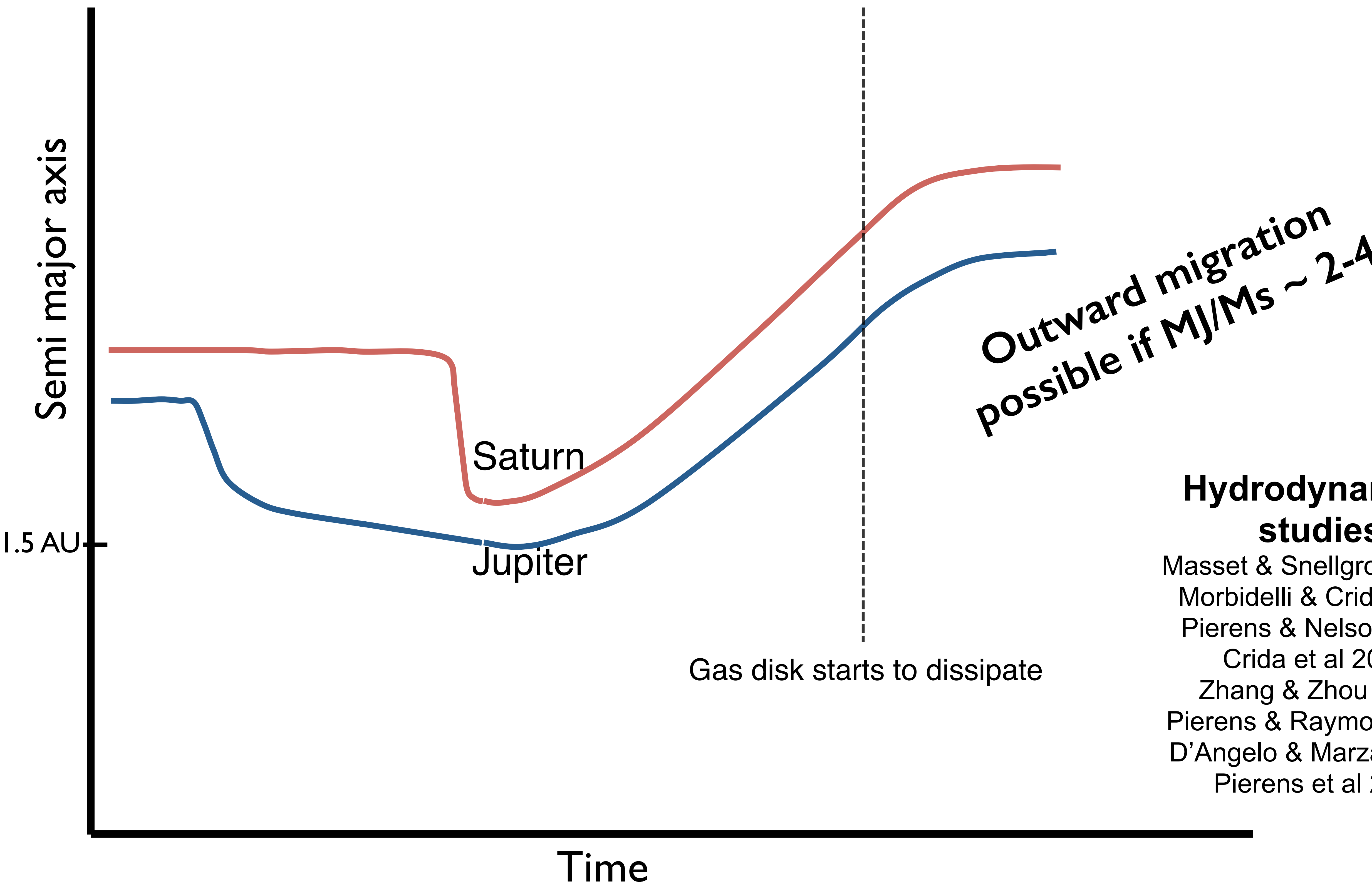


Jupiter and Saturn in the gaseous disk



The Grand Tack model

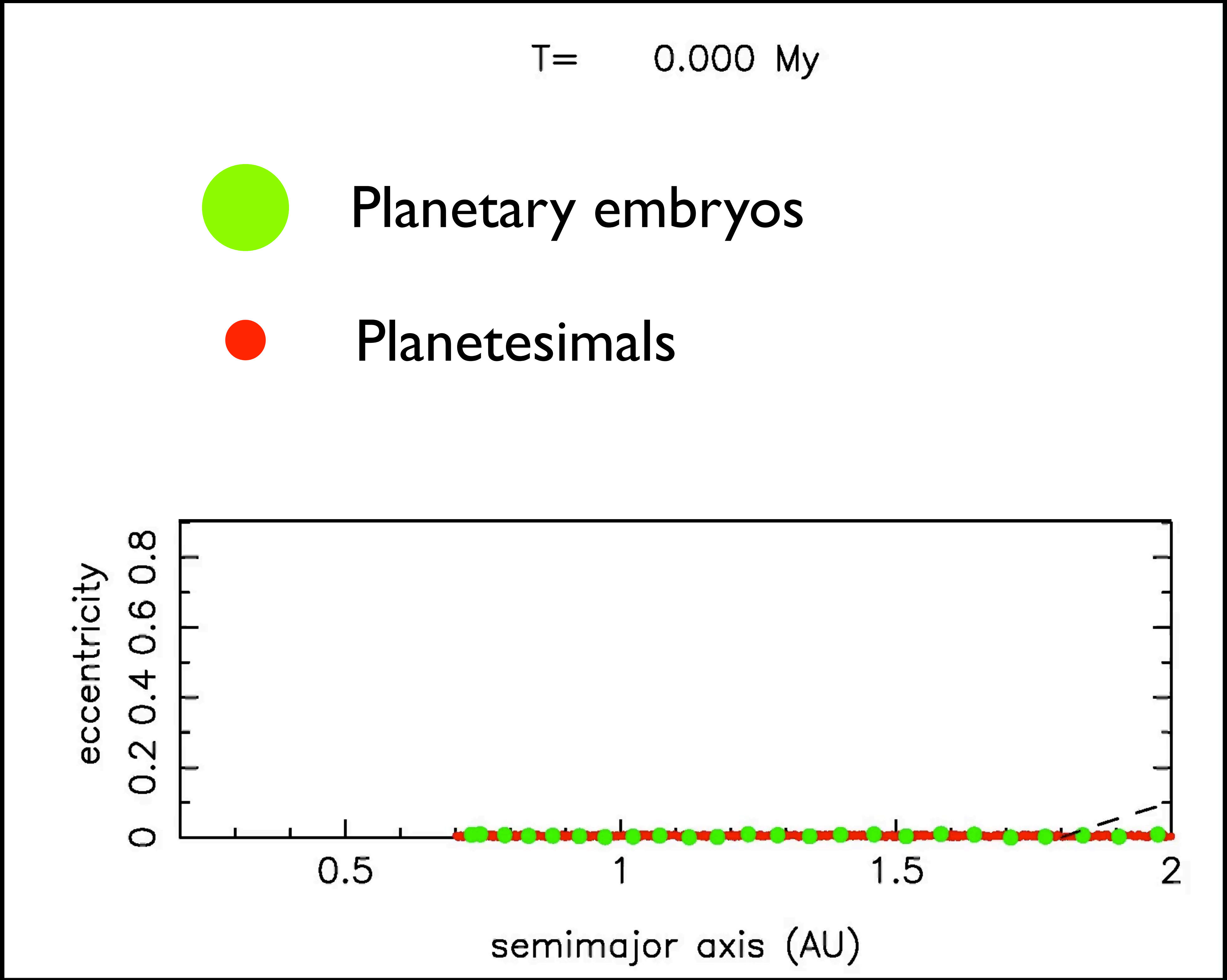
(Walsh et al 2011)



Hydrodynamical studies

Masset & Snellgrove 2001;
Morbidelli & Crida 2007;
Pierens & Nelson 2008;
Crida et al 2009;
Zhang & Zhou 2010;
Pierens & Raymond 2011;
D'Angelo & Marzari 2012;
Pierens et al 2014

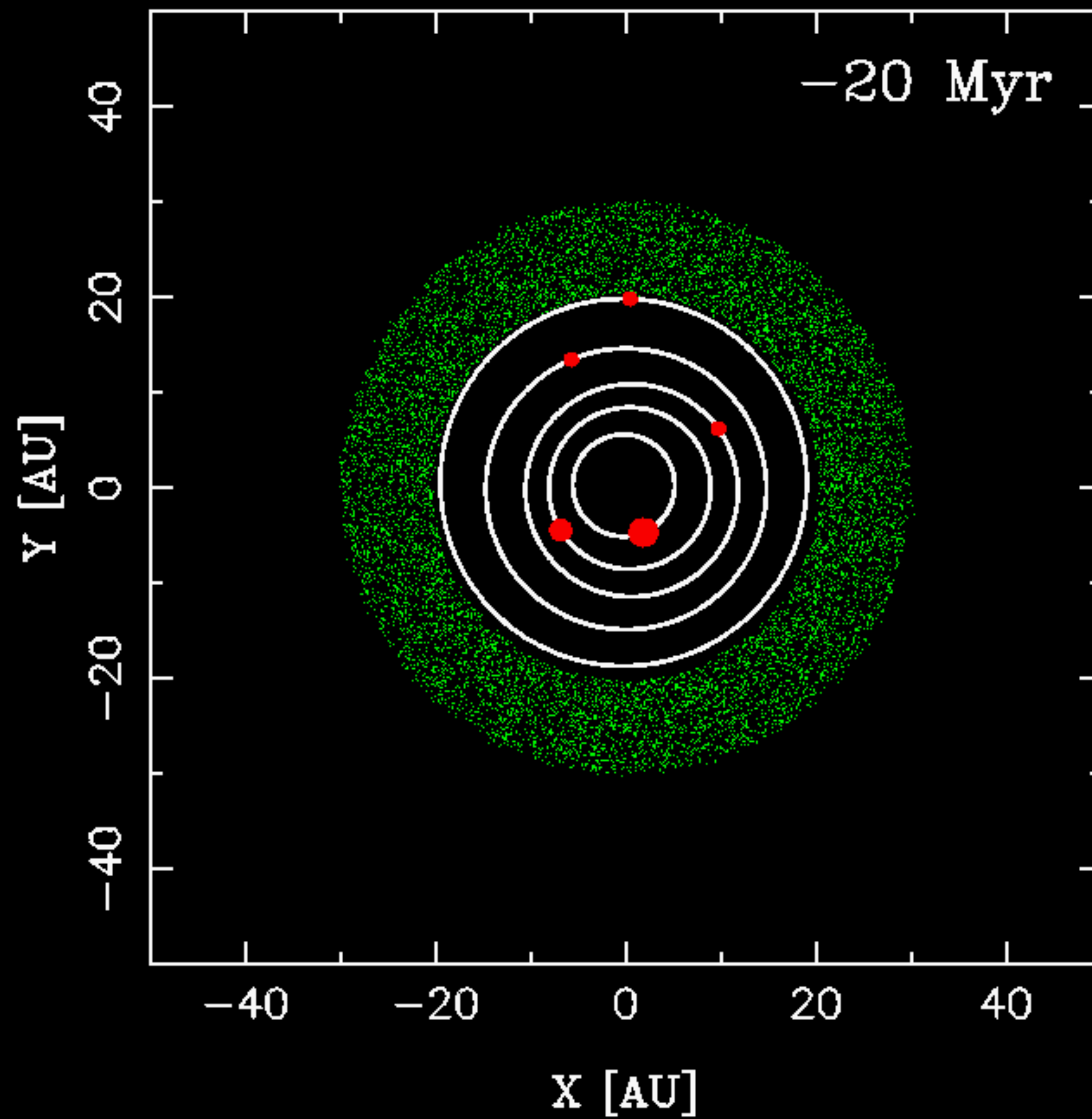
The Grand Tack model



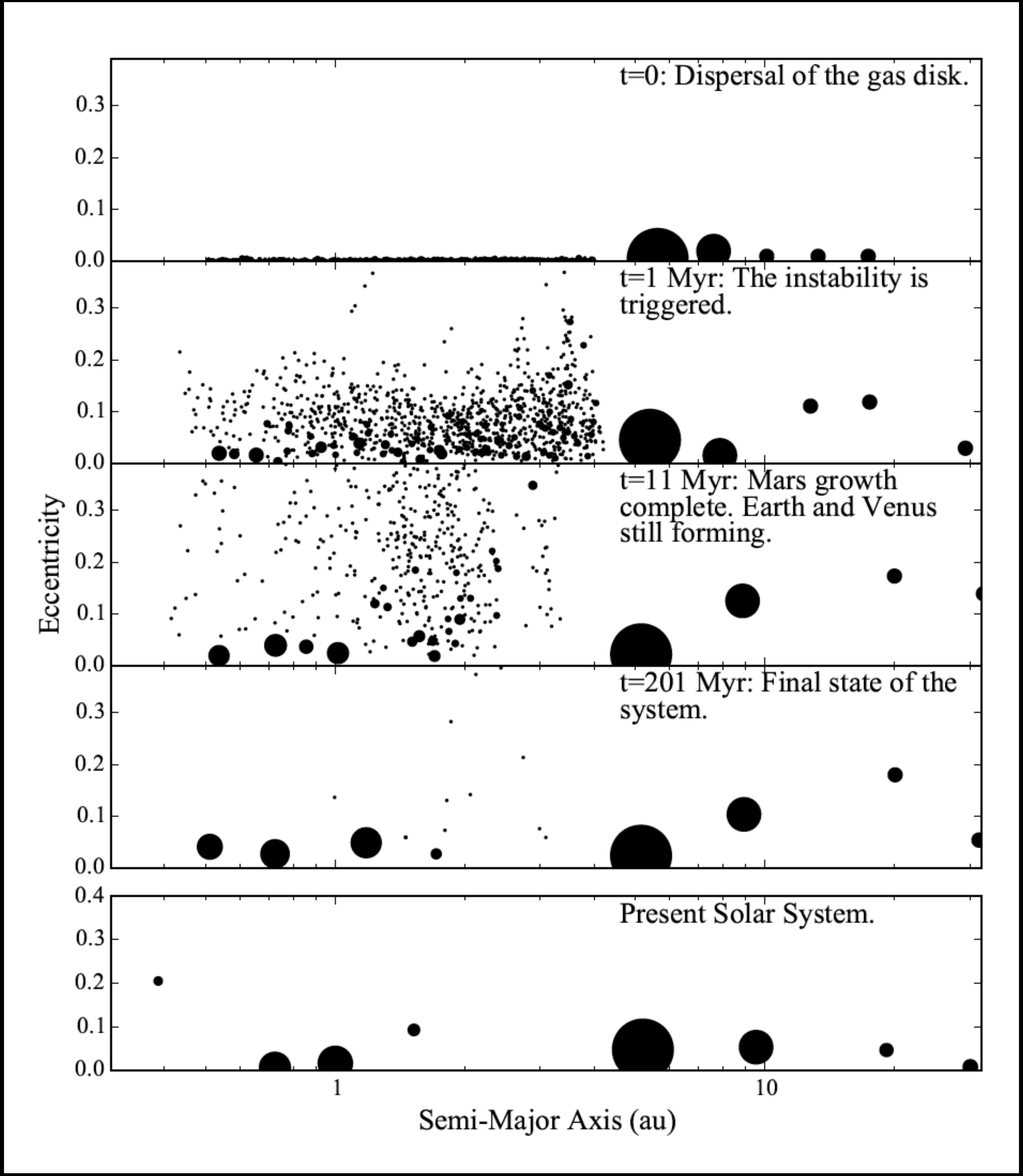
credit: David O'Brien

3. The Solar System's instability
(the "Nice model")

- NEW: Timing is uncertain — anytime before ~100 Myr
  (Chapman et al 2007; Zellner 2017; Morbidelli et al 2018; Nesvorny et al 2018; Mojzsis et al 2019; Hartmann 2019)

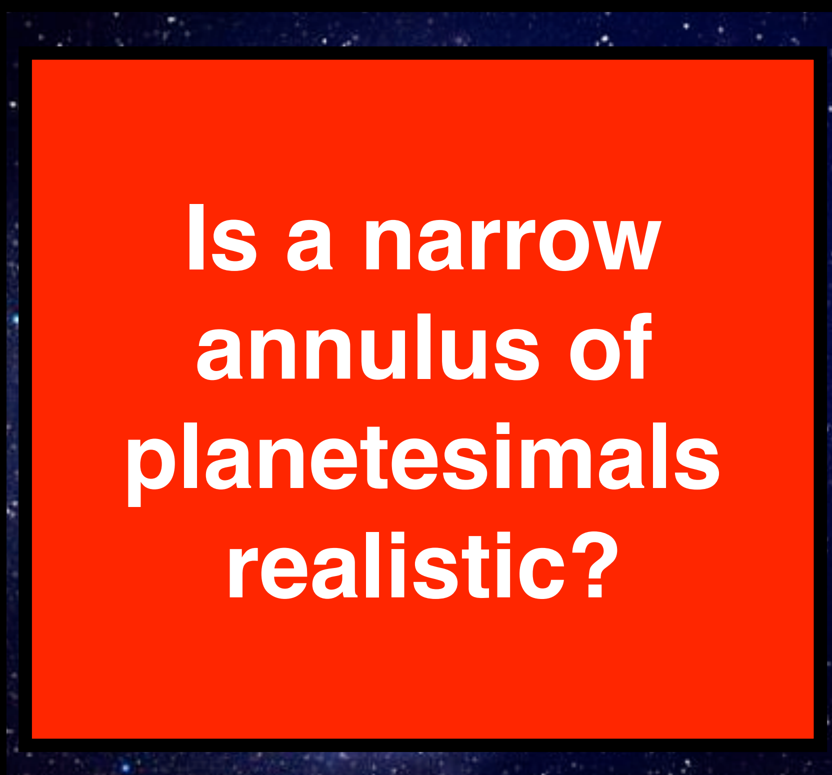


Nesvorny (2011)



Clement et al (2019)

3 possible solutions to the small Mars problem

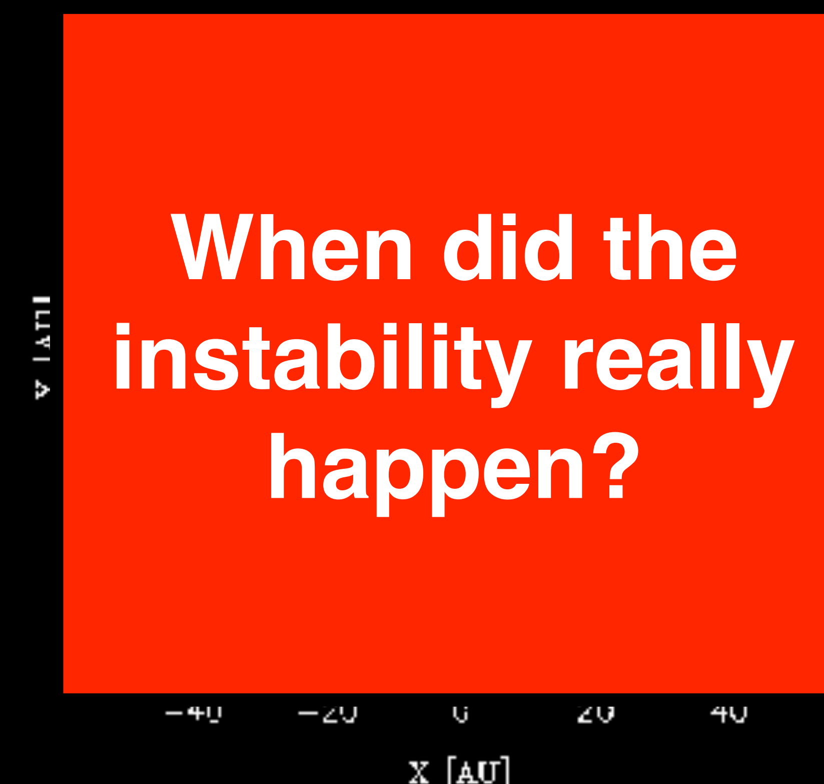


Is a narrow annulus of planetesimals realistic?

"Low-mass asteroid belt"

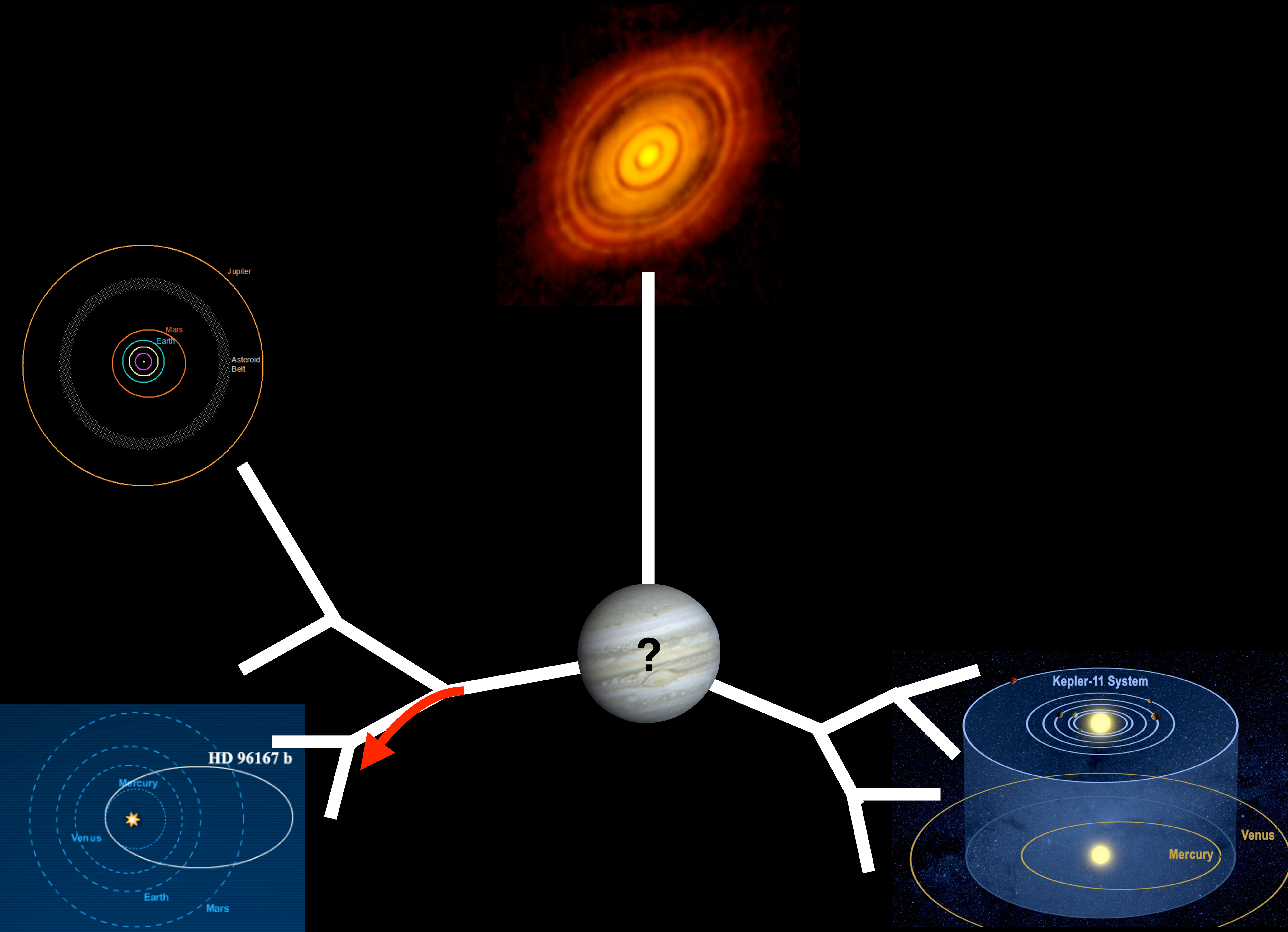
Does outward migration work with gas accetion?

The "Grand Tack"



When did the instability really happen?

Early instability


Jupiter
Mars
Earth
Asteroid Belt
?
HD 96167 b
Mercury
Venus
Earth
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Kepler-11 System
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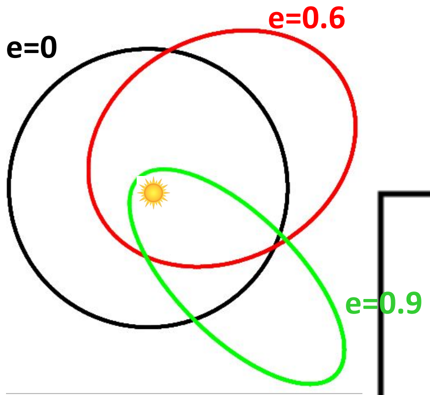
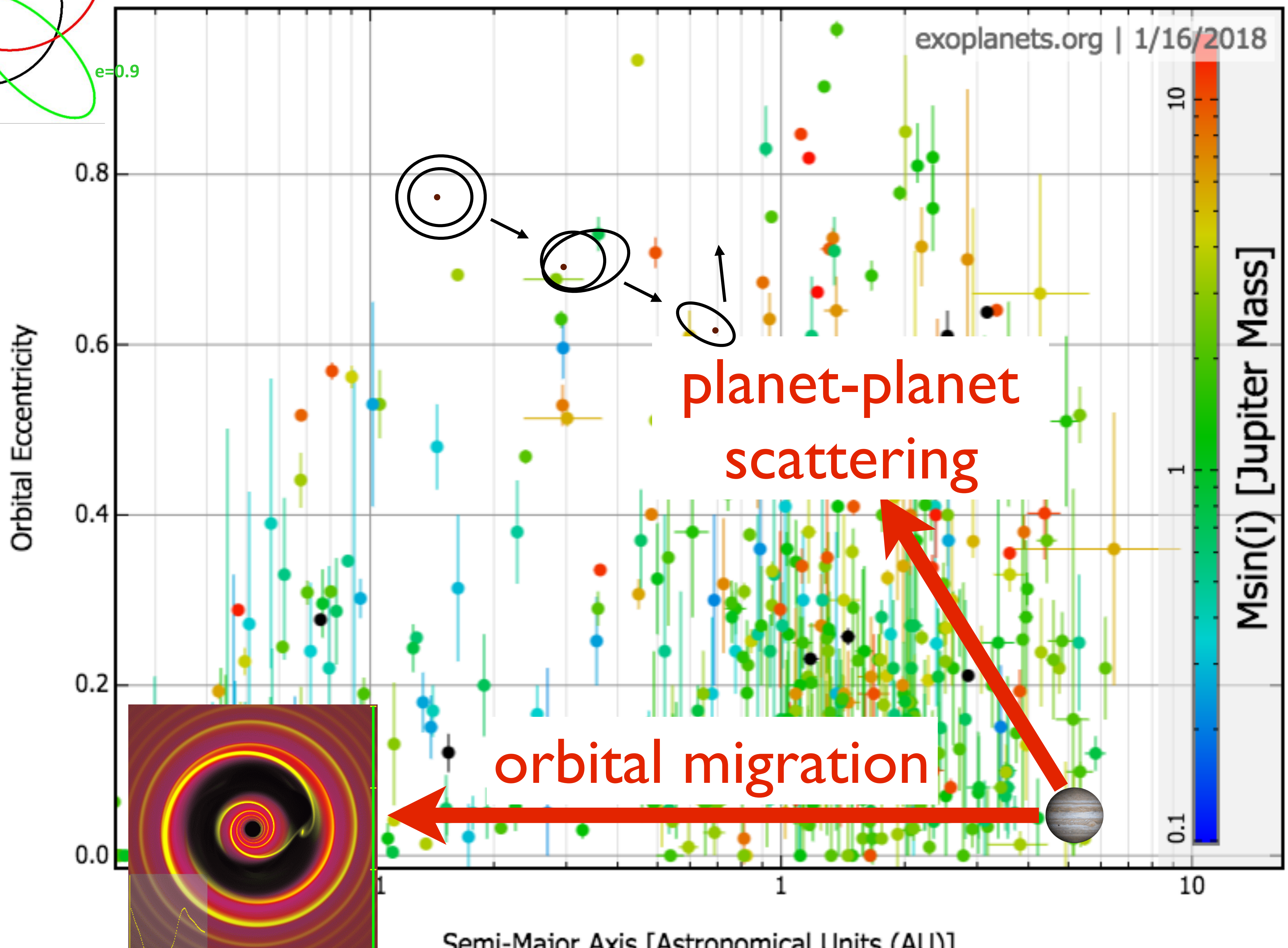
Mercury

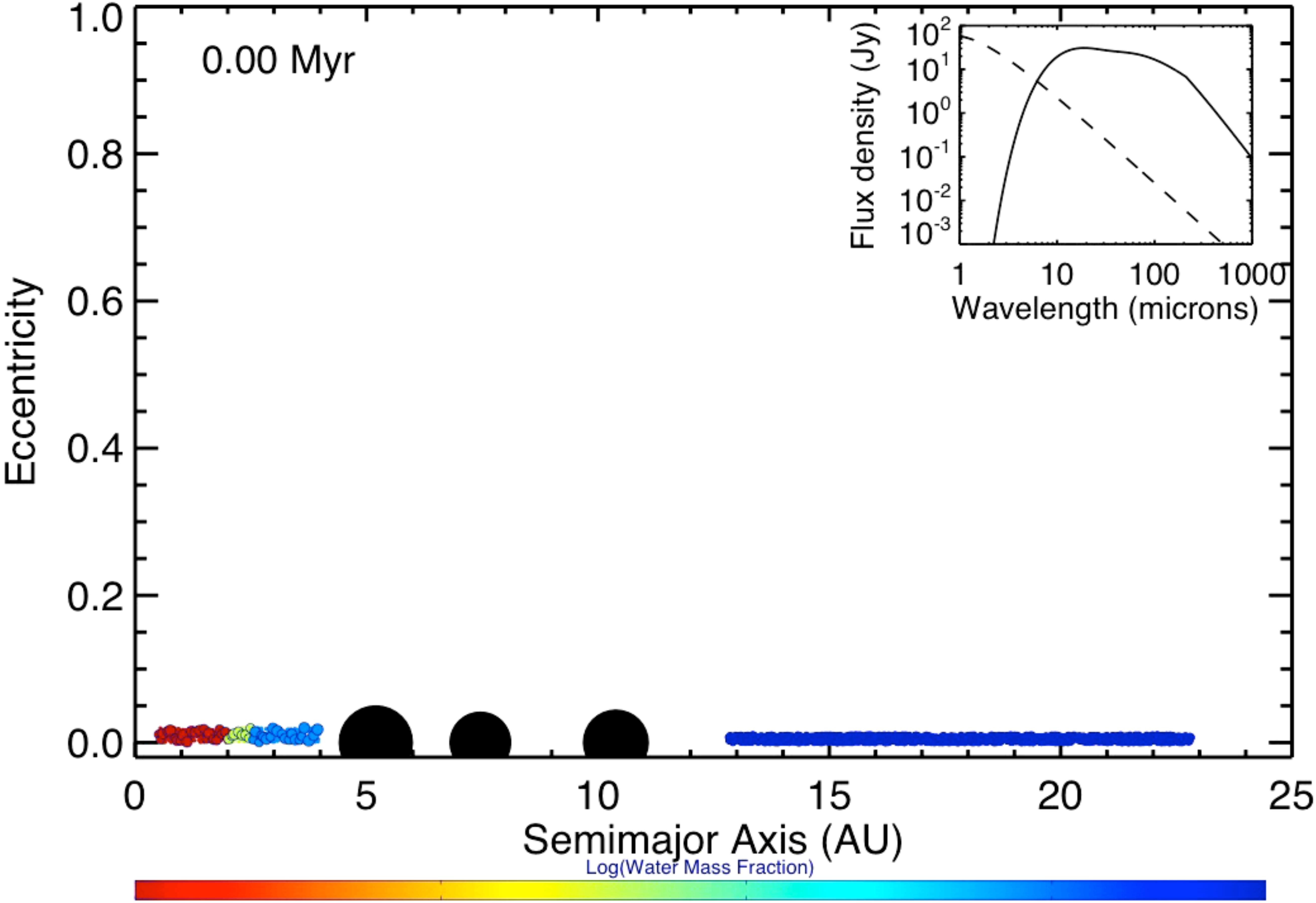
Giant exoplanets





Planet-planet scattering

Credit: Eric Ford

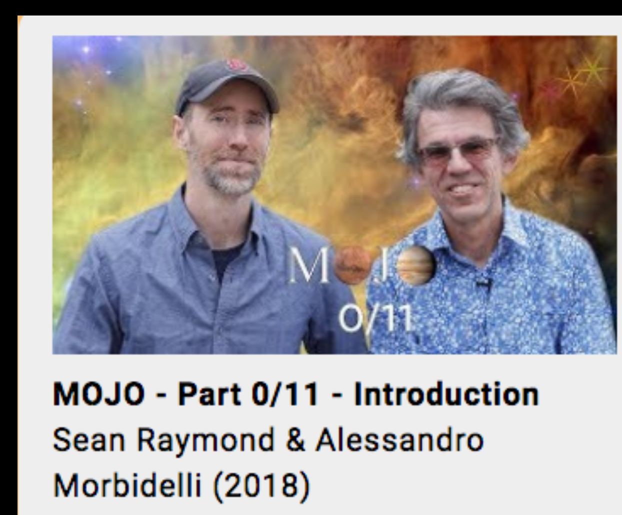


Raymond et al 2012

More information

- *Solar System formation in the context of extra-solar planets*
  Raymond, Izidoro, & Morbidelli 2018 (*arxiv:1812.01033*)

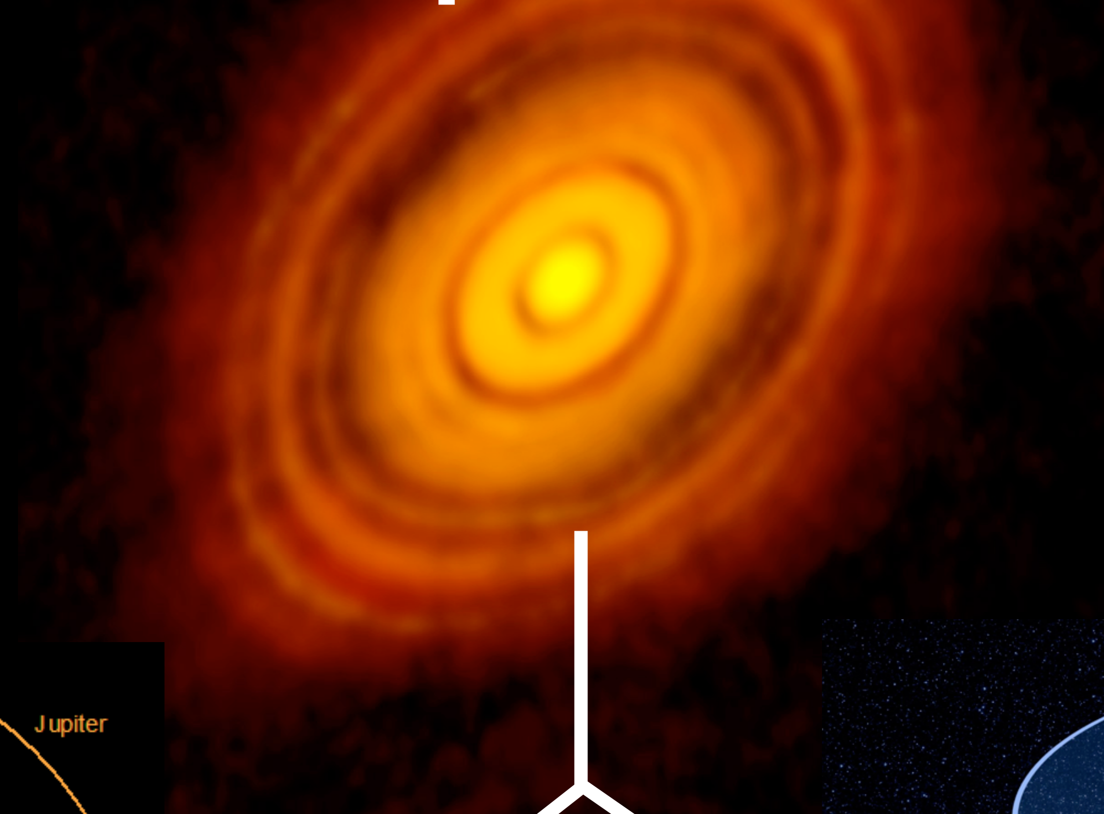
- MOJO videos (YouTube)

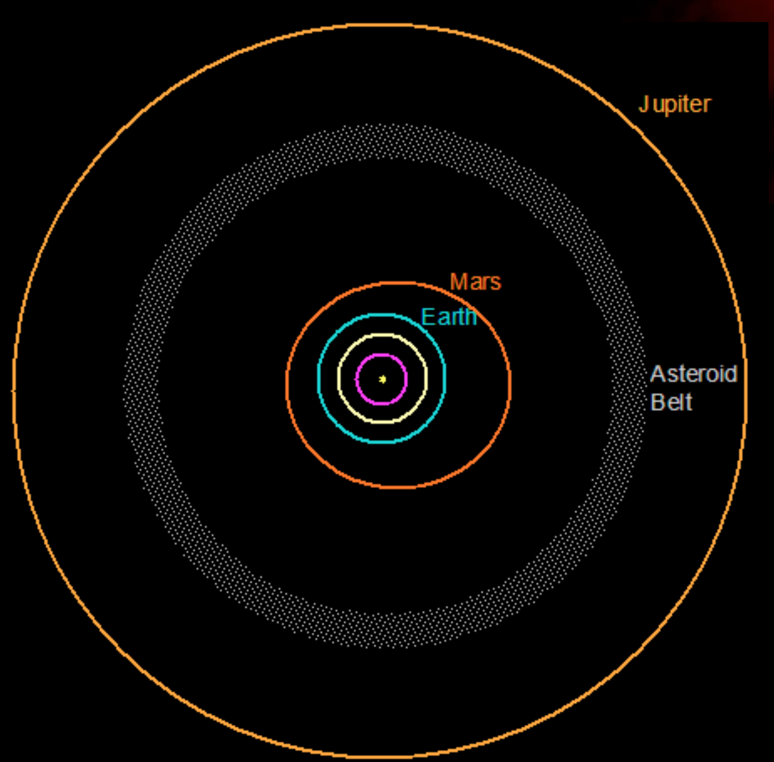


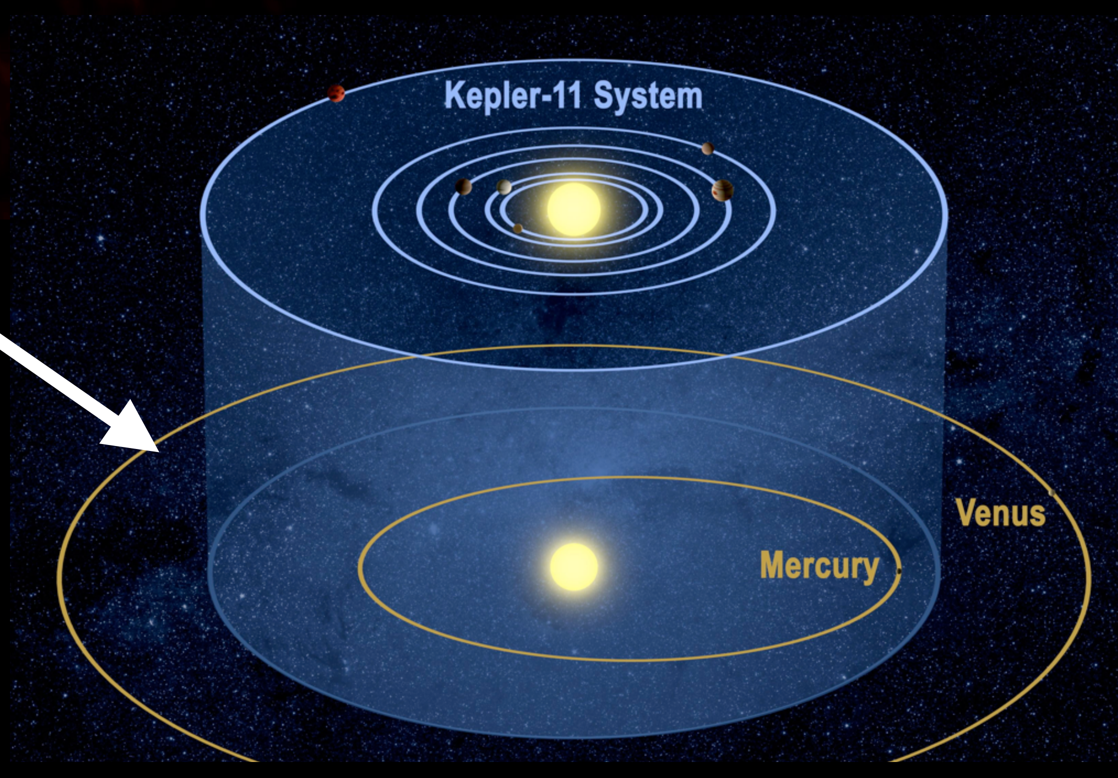
- planetplanet.net

Extra Slides

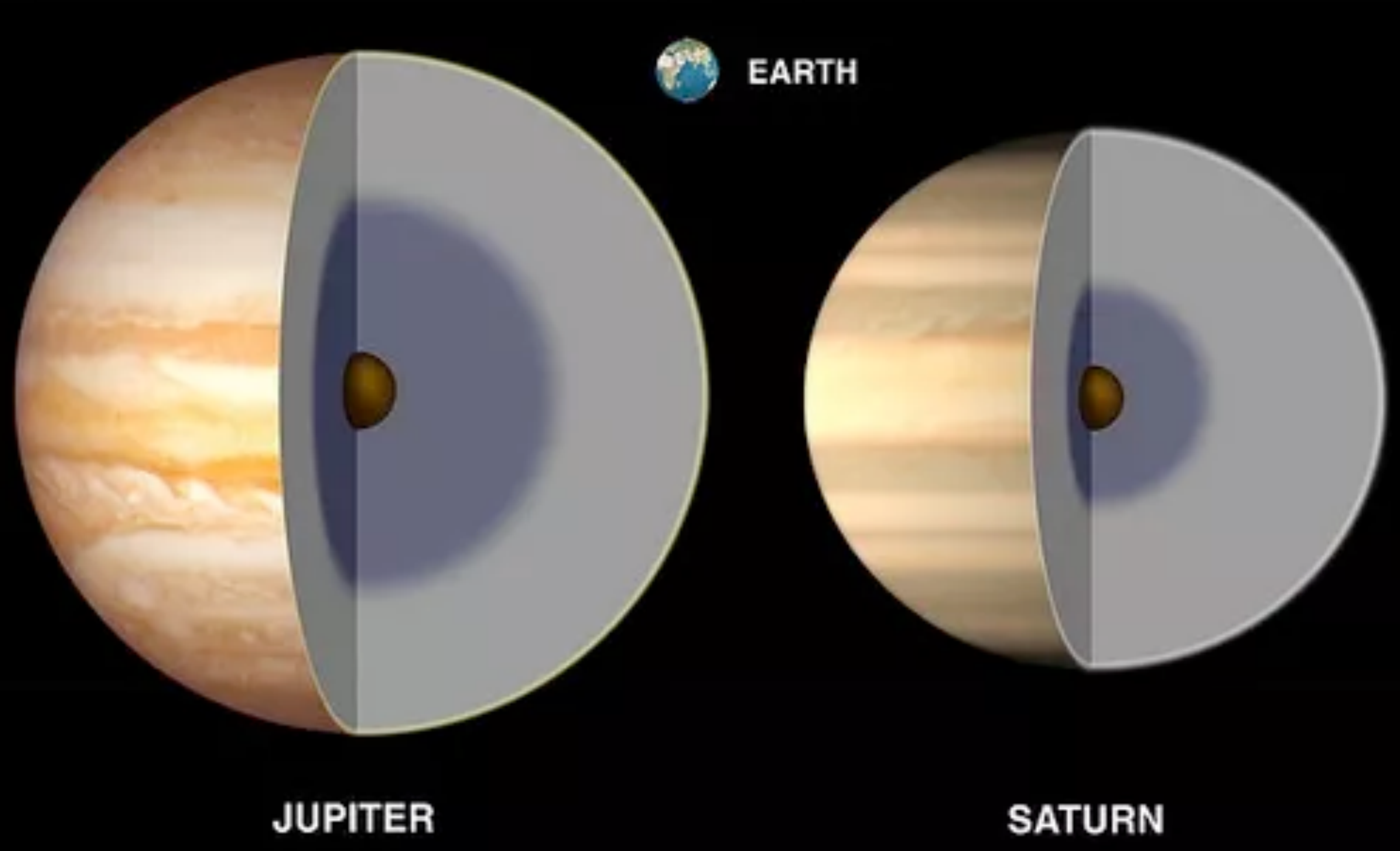
What controls the branching between Solar System-like systems and super-Earth systems?





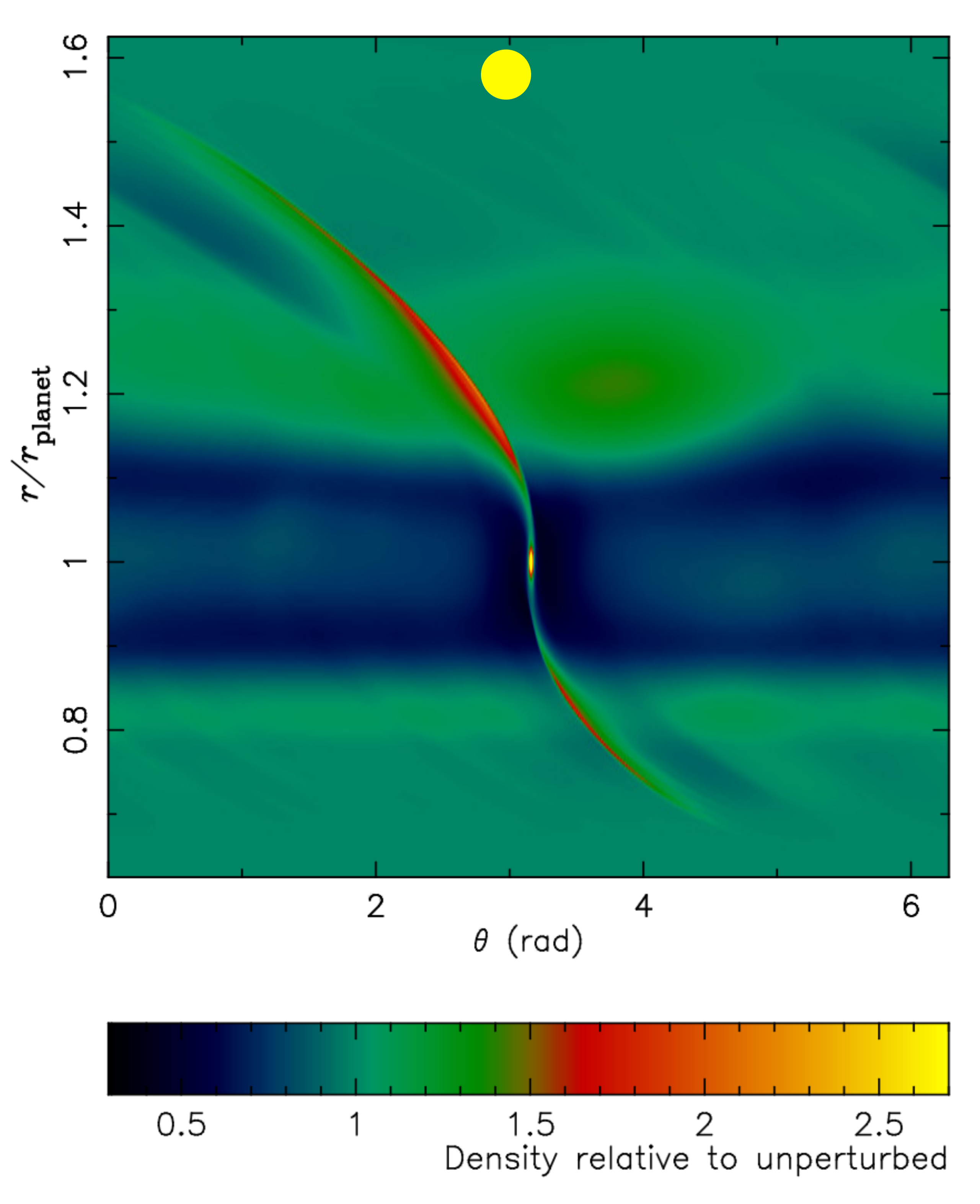


Core accretion



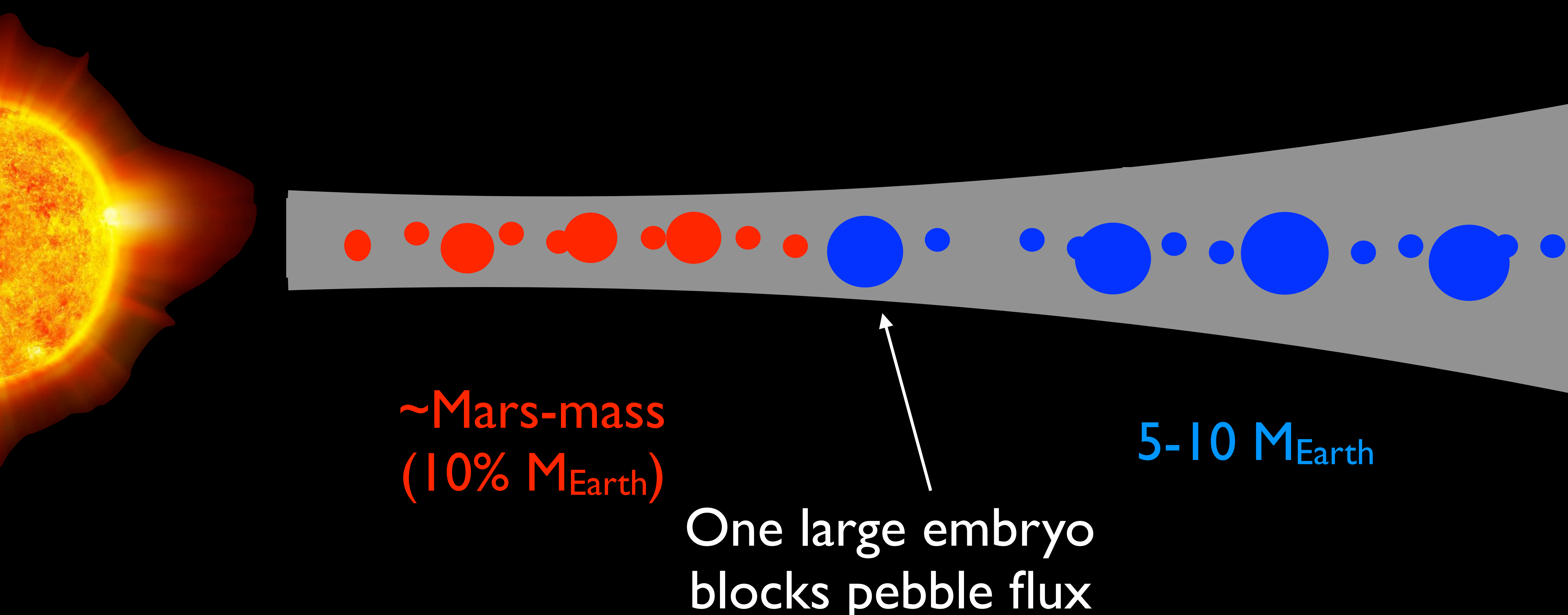
Large cores block pebble flux

"Pebble isolation" mass: ~20 ME for typical disk at Jup's orbit



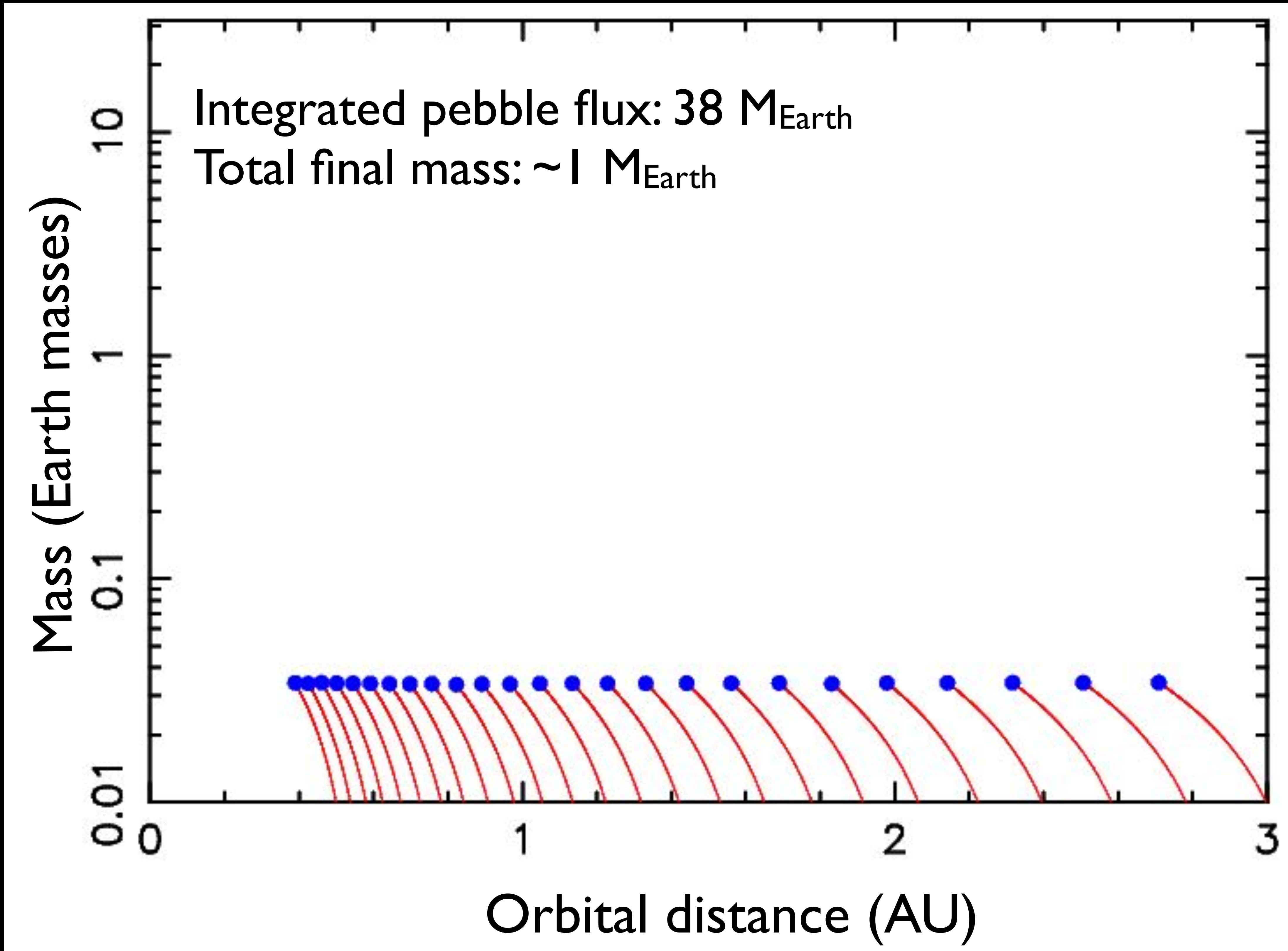
Lambrechts et al (2014); Bitsch et al (2018)

Jupiter's core blocks the inward flux of pebbles, starving the growing terrestrial planets



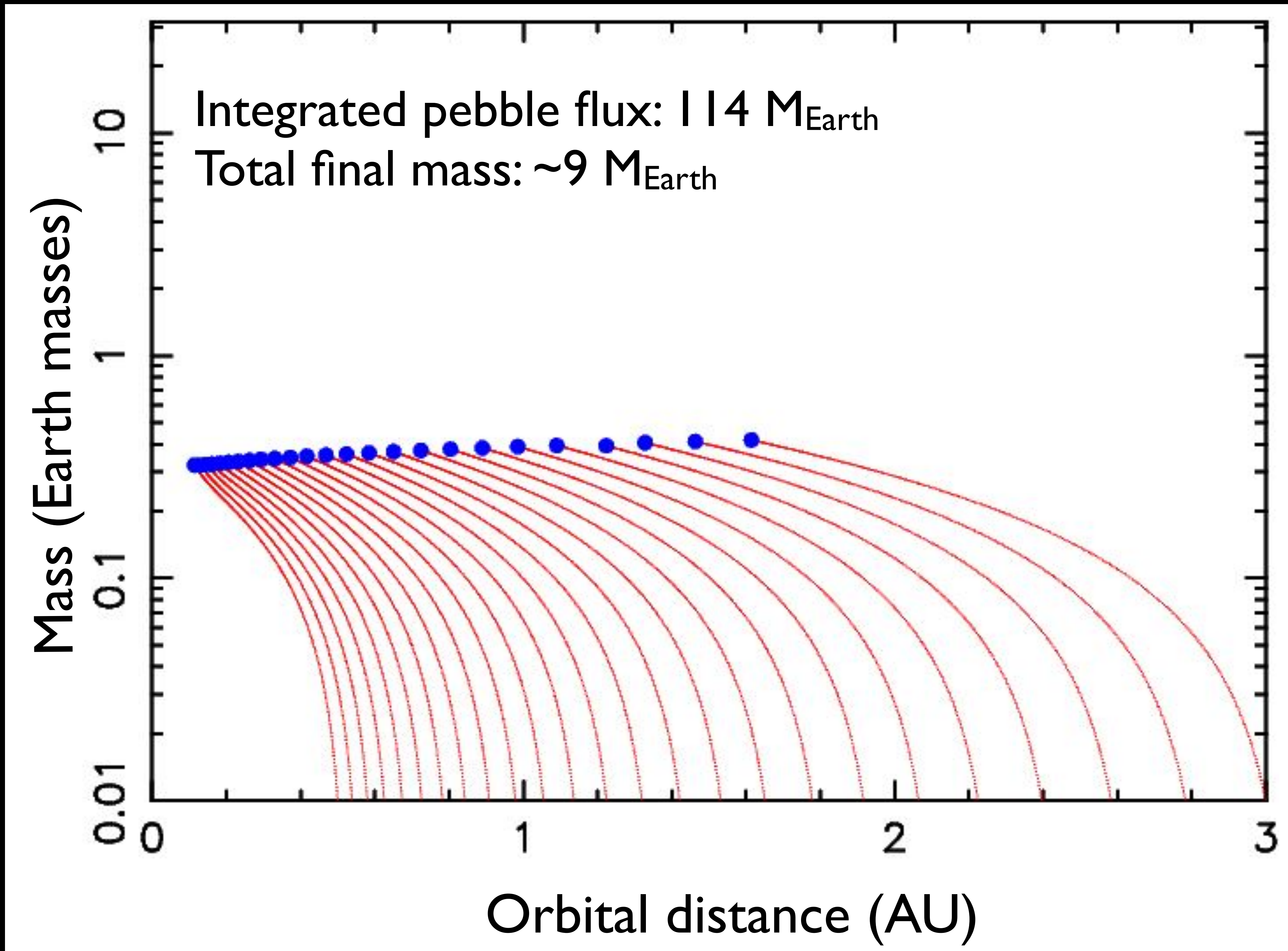
Morbidelli et al (2015); Lambrechts et al (2019)

Slide courtesy Seth Jacobson

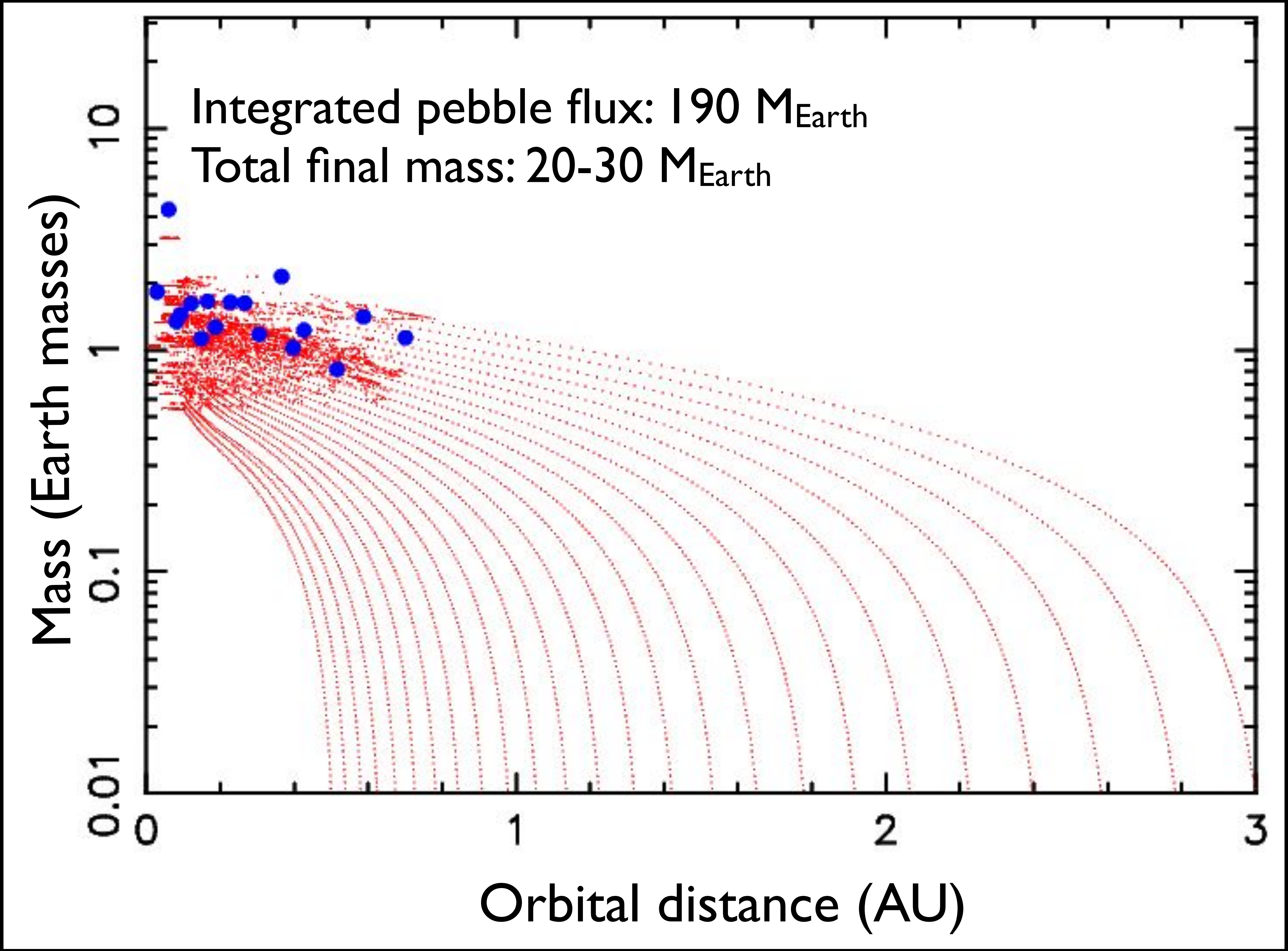


Lambrechts et al (2019)

Slide courtesy Seth Jacobson

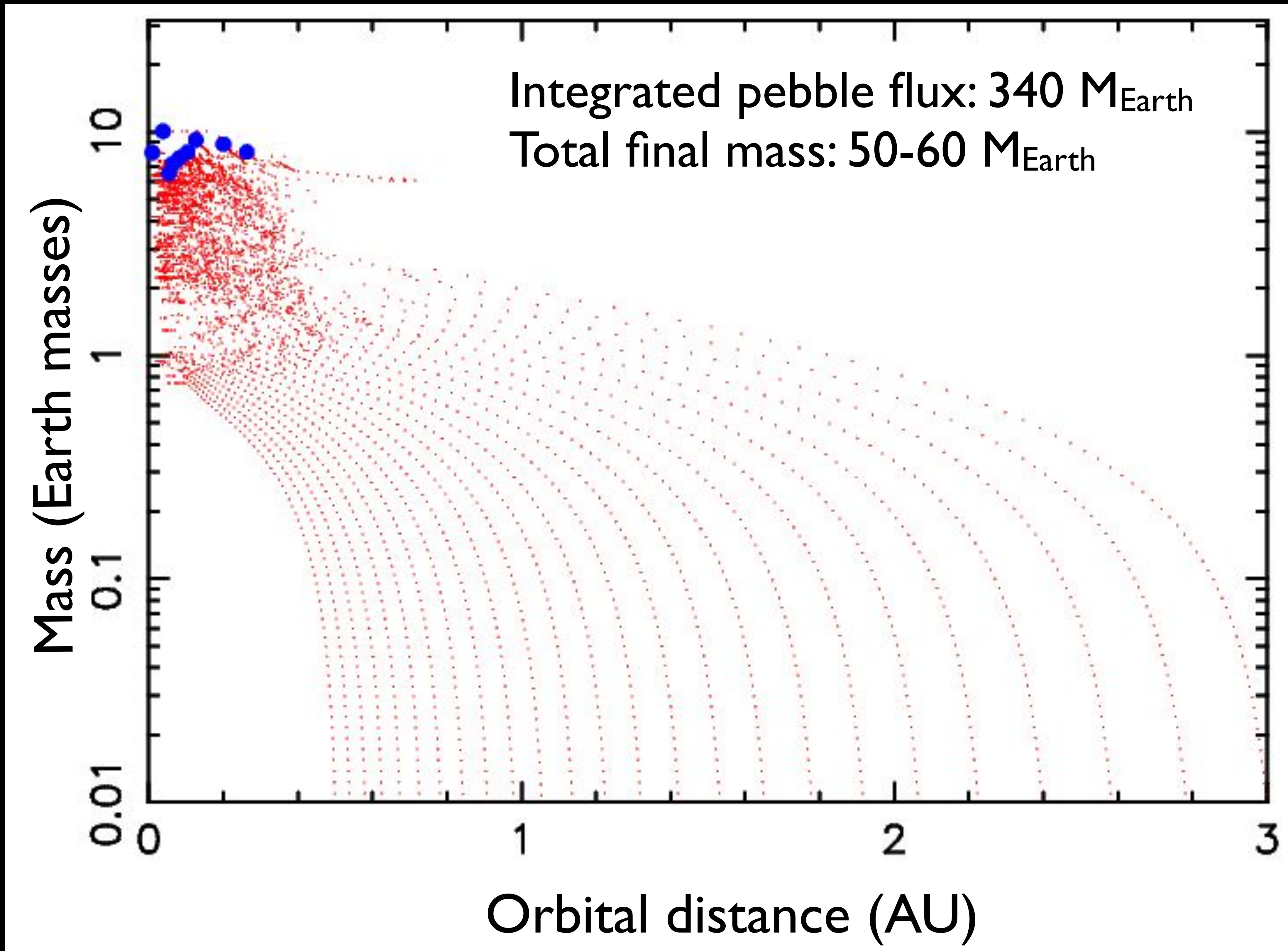


Lambrechts et al (2019)

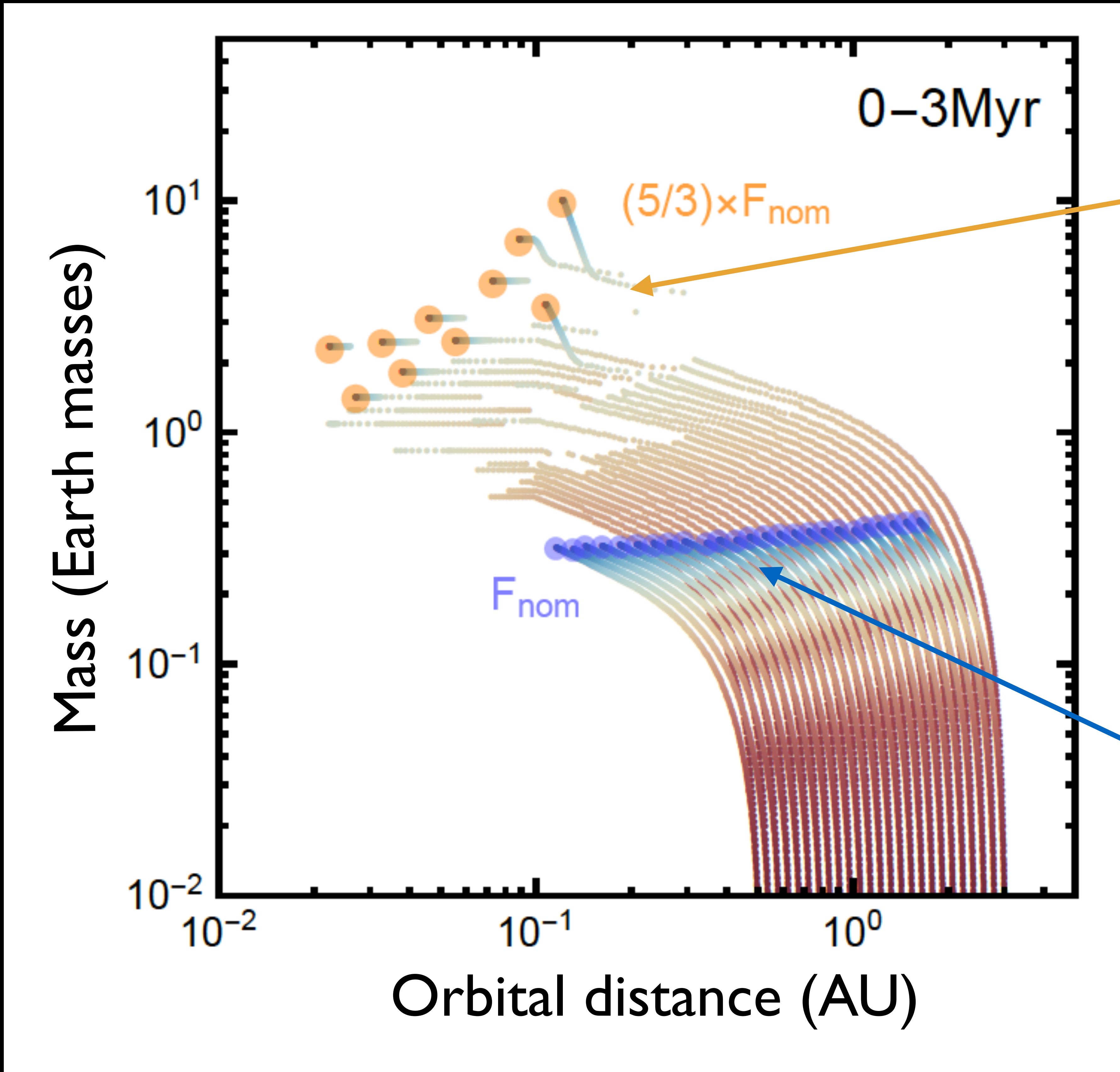


Lambrechts et al (2019)

Slide courtesy Seth Jacobson



Lambrechts et al (2019)

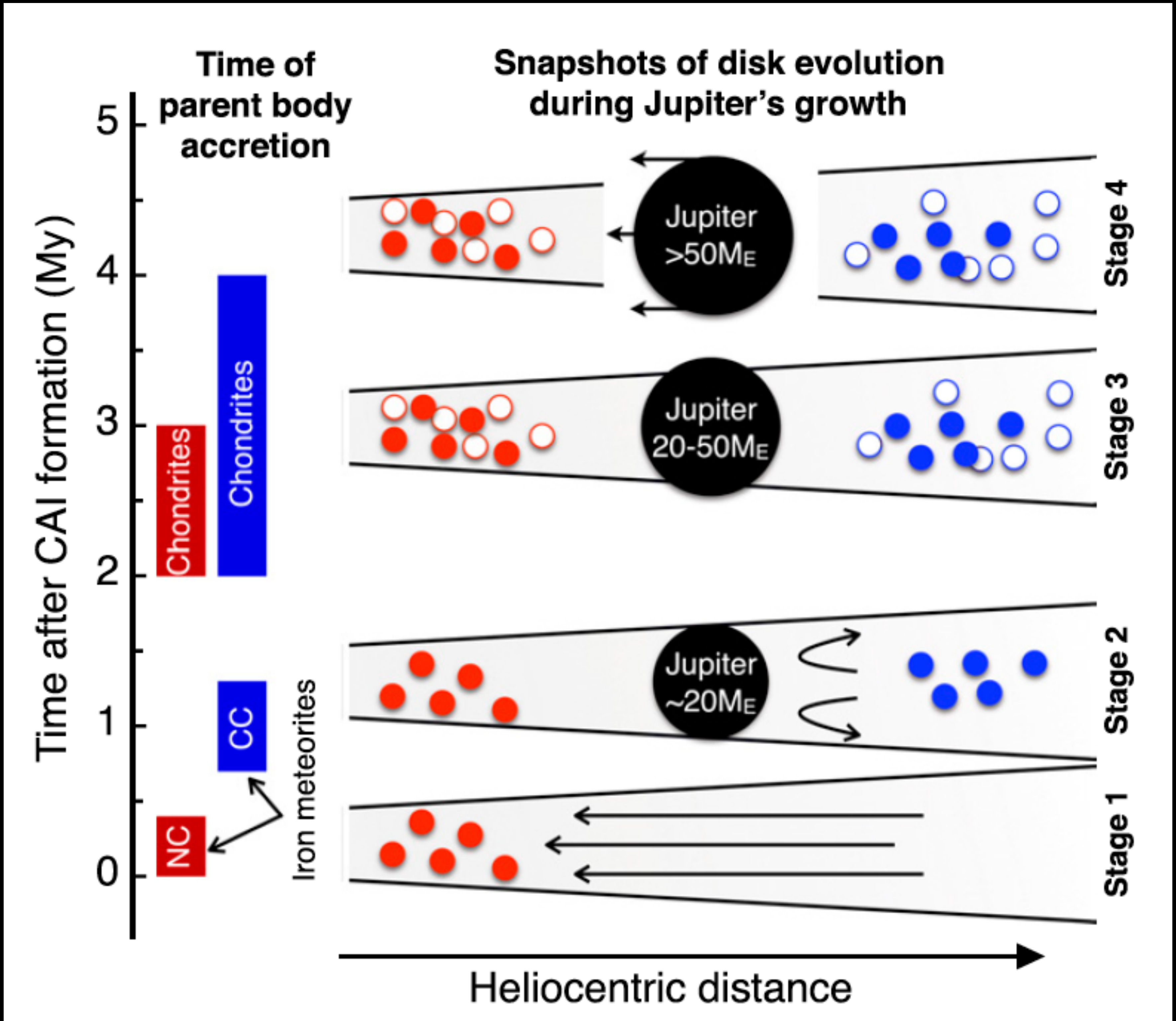


Continuous pebble flux: **super-Earths**

Pebble flux blocked: **terrestrials**

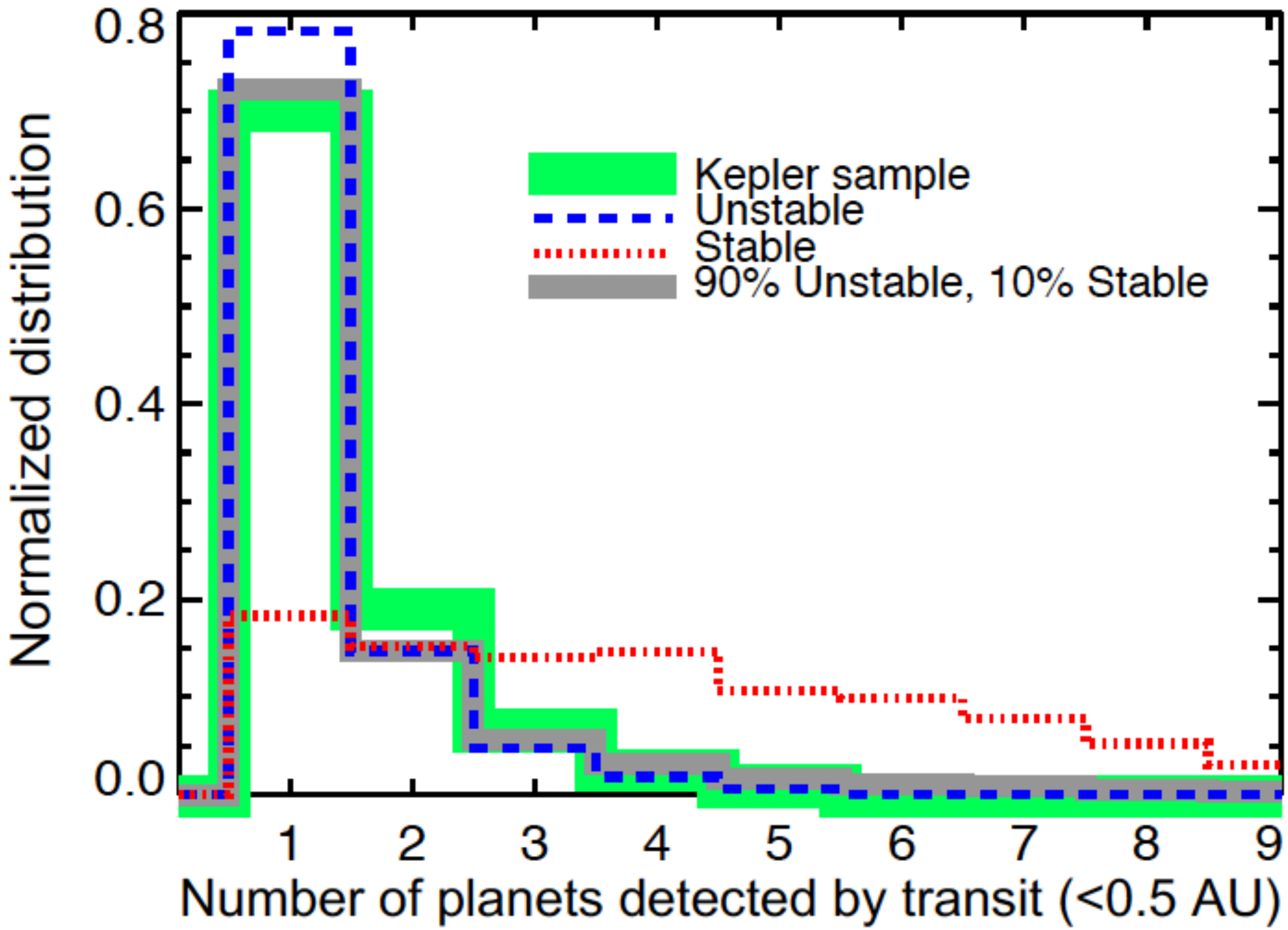
Lambrechts, Morbidelli, Jacobson et al (2019)

Meteoritic evidence for early growth of Jupiter's core



Kruijer et al 2017

Also match multiplicity distribution (the "Kepler dichotomy")



Izidoro et al (2017)