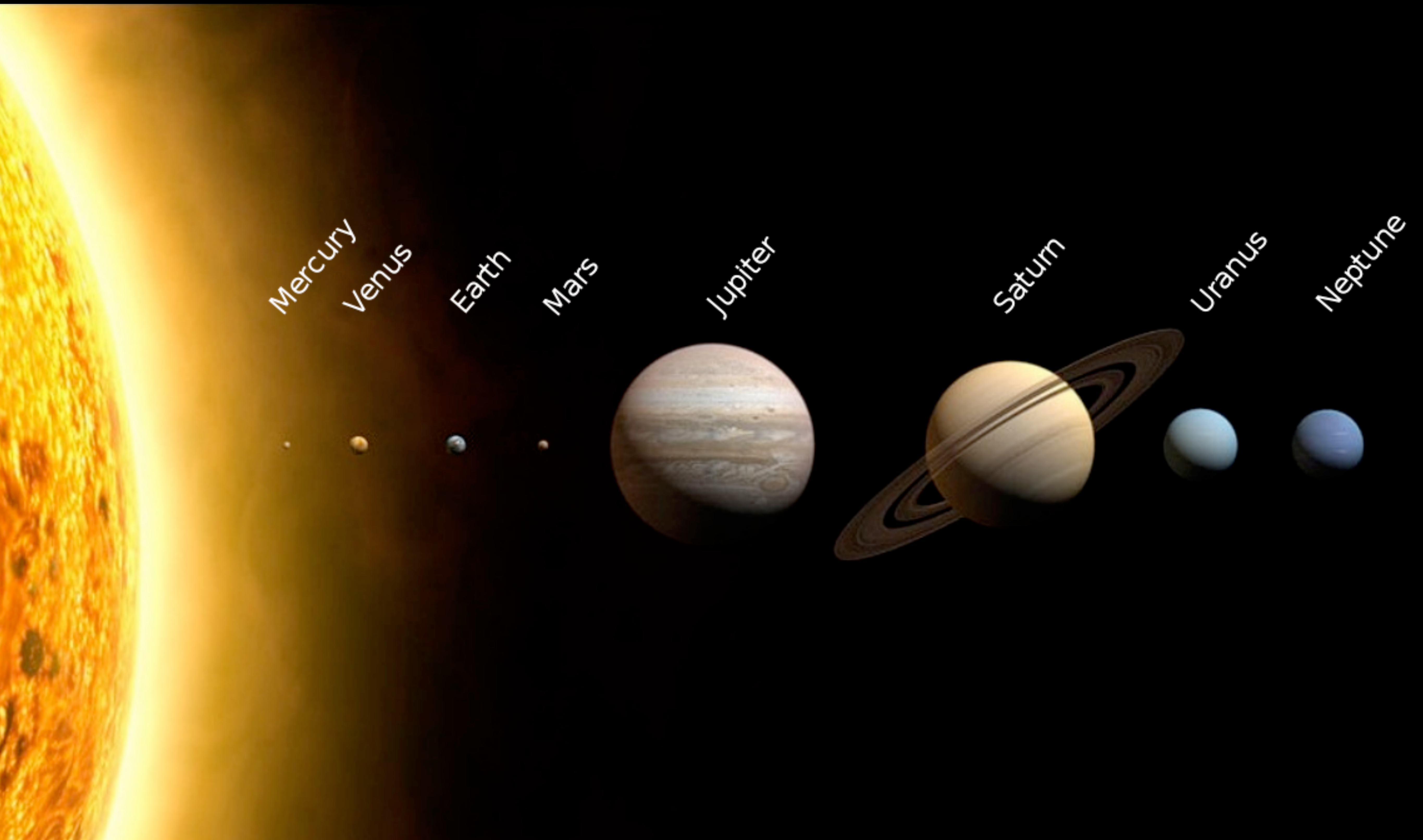
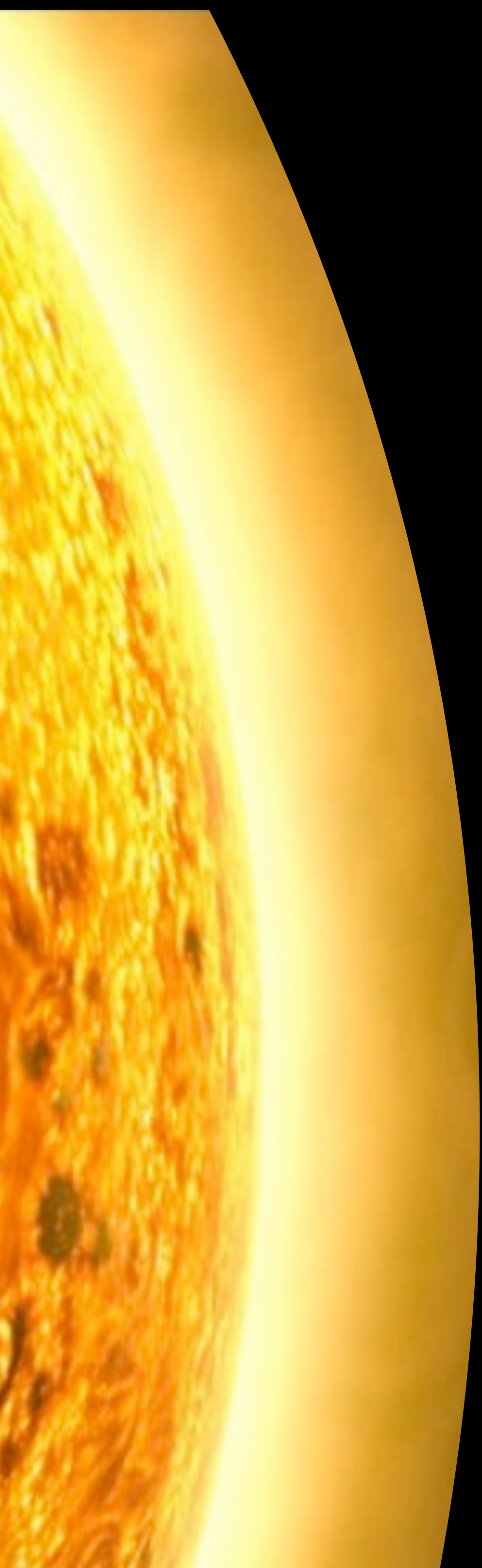

Terrestrial planet formation
at home and abroad
Sean Raymond
Laboratoire d'Astrophysique de Bordeaux
planetplanet.net

The Solar System



The exo-Solar System

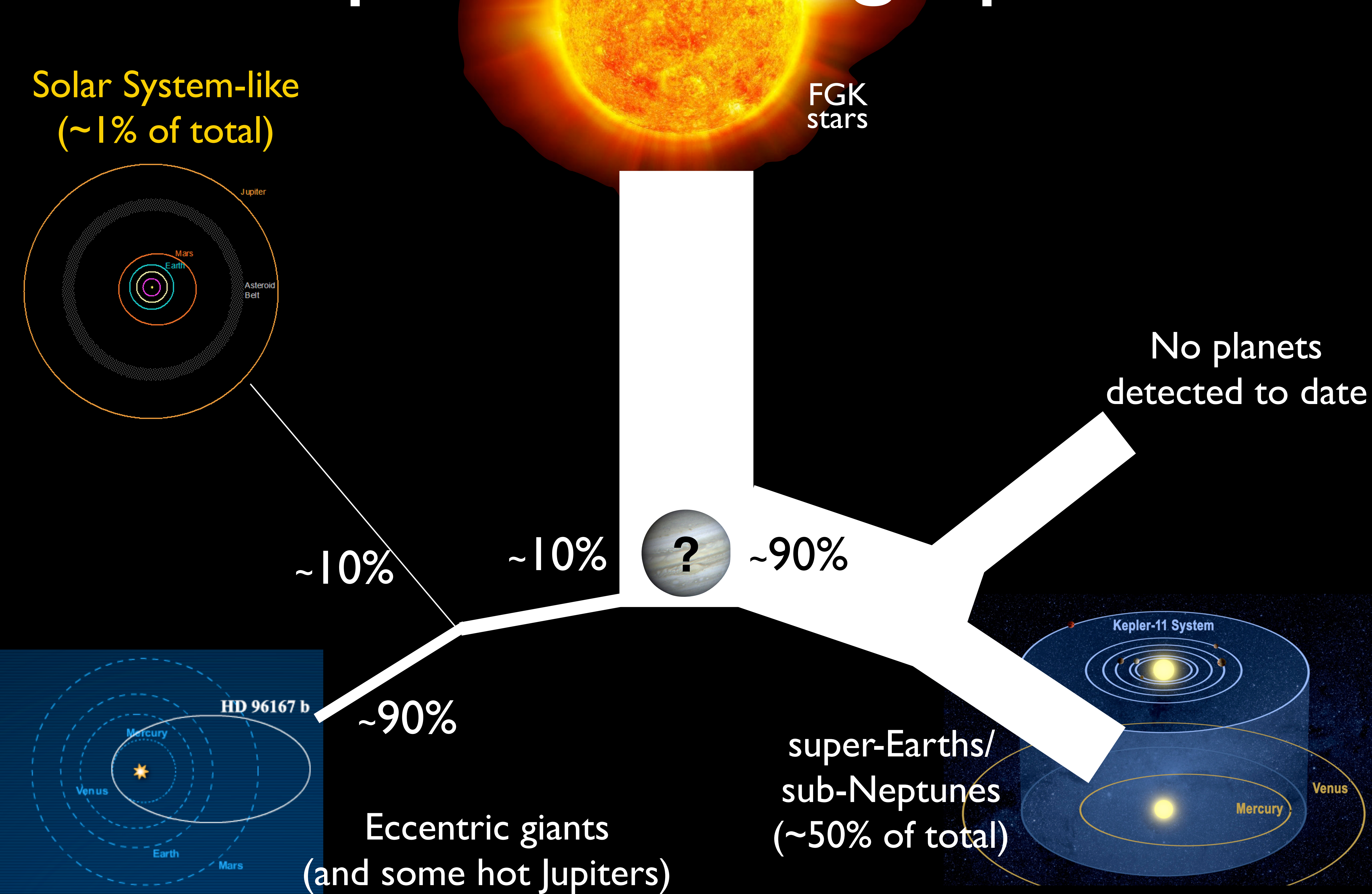


Measure:

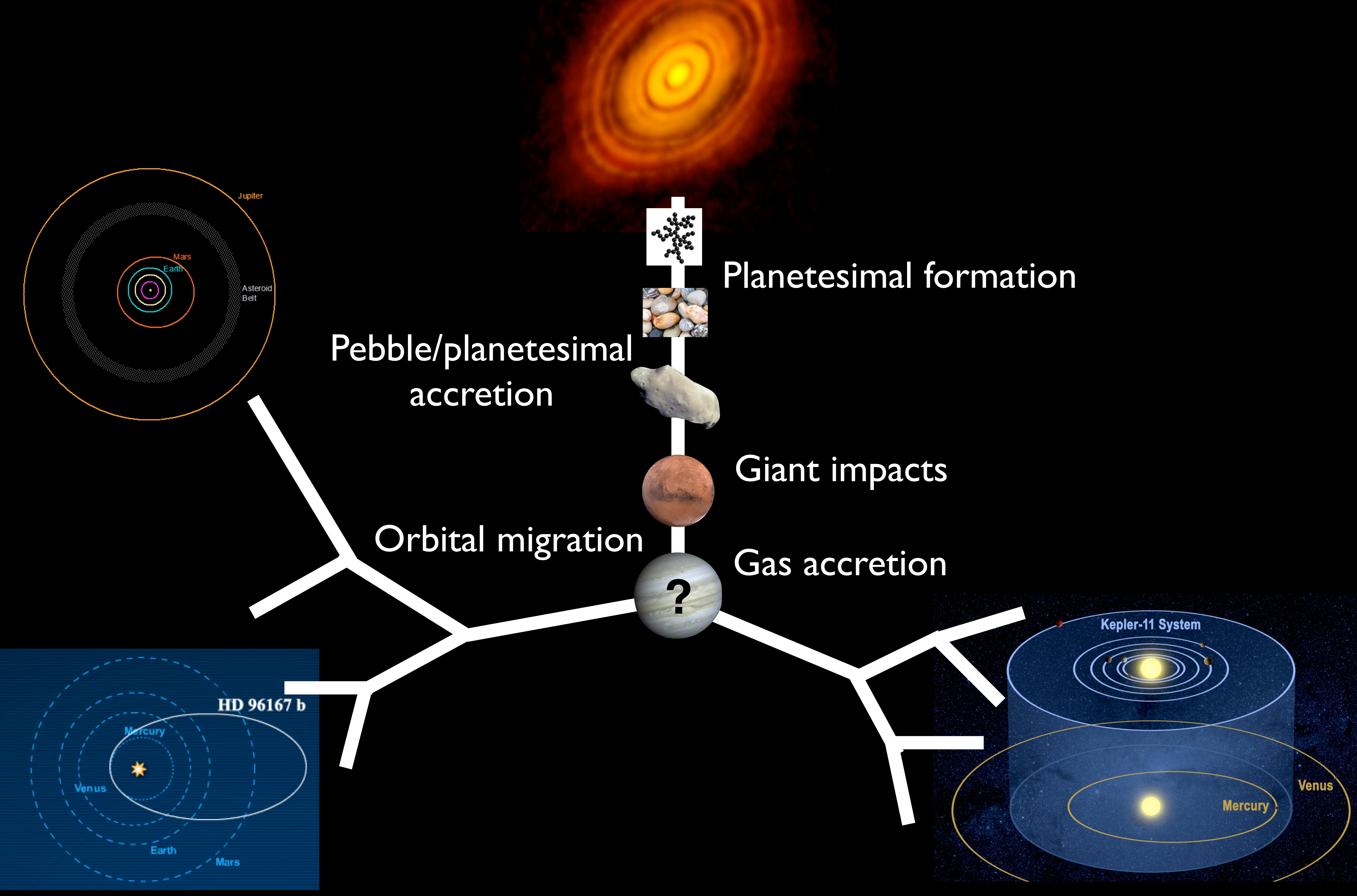
- mass (M_{Jup} sin i)
- orbital size
- orbital shape (eccentricity)

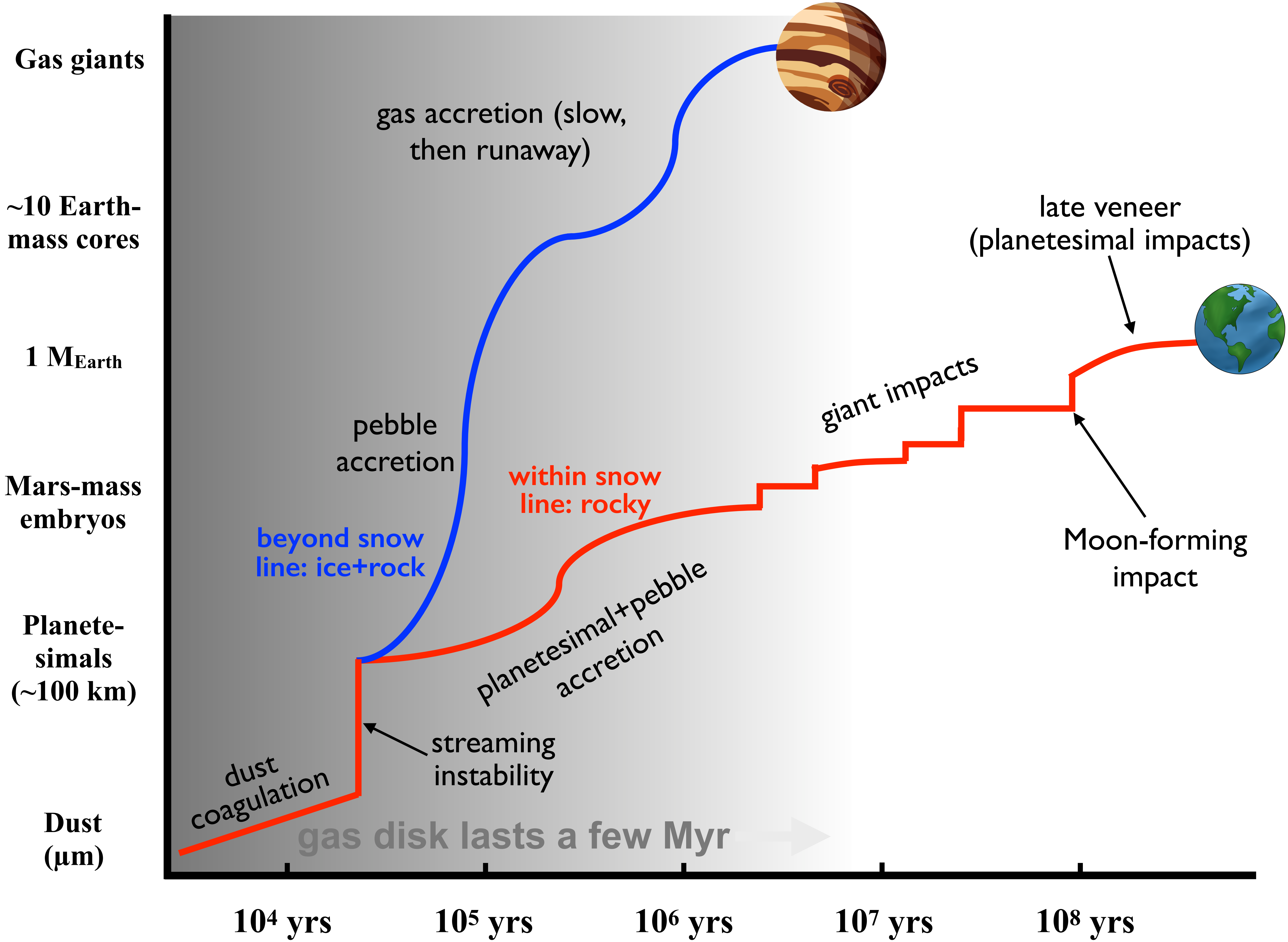
(Sun's radial velocity amplitude due to Jupiter ~12 m/s, P=12 yr)

Exoplanet demographics

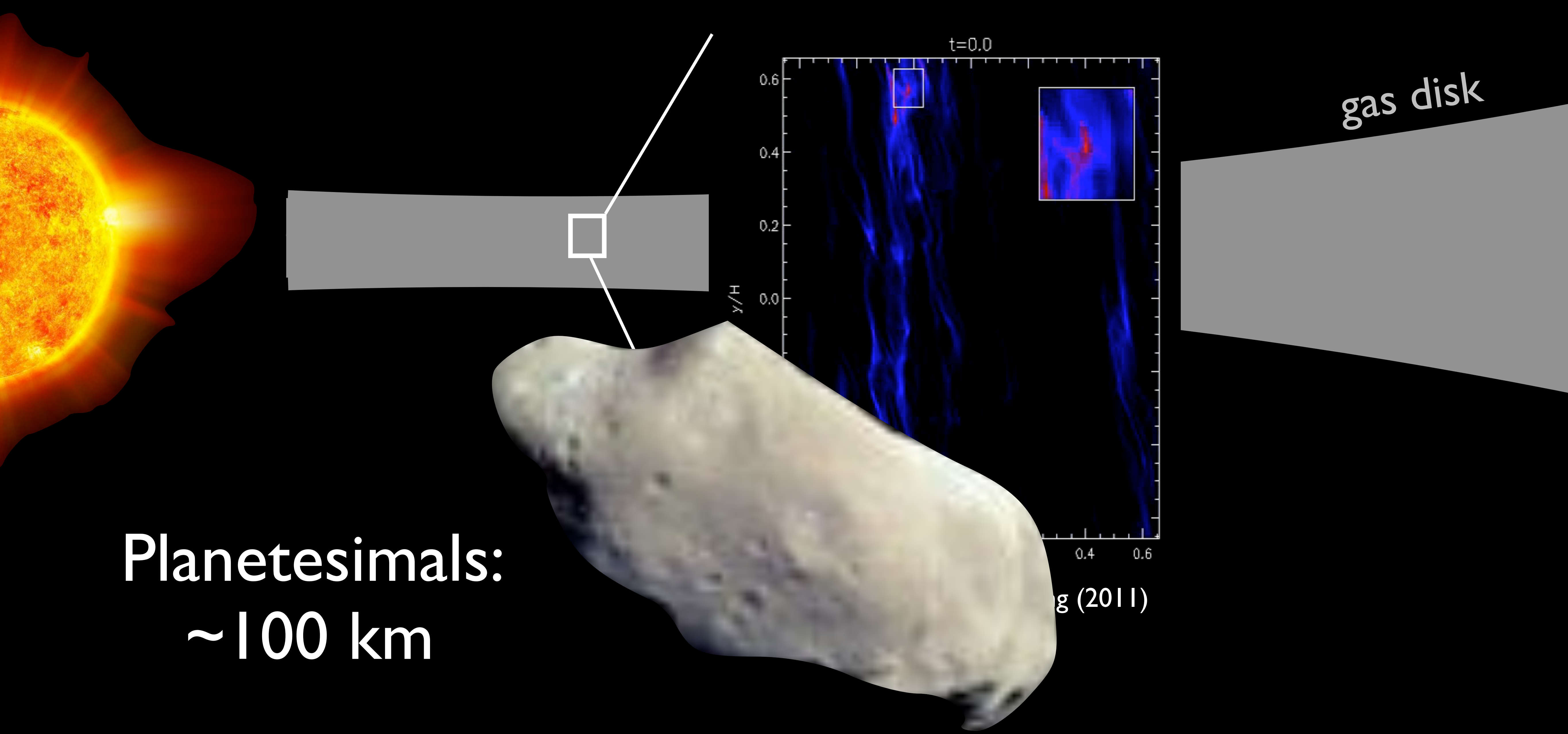


Planet formation





Gas giants
~10 Earth-mass cores
1 MEarth
Mars-mass embryos
Planetesimals (~100 km)
Dust (µm)
gas accretion (slow, then runaway)
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
10⁴ yrs
10⁵ yrs
10⁶ yrs
10⁷ yrs
10⁸ yrs

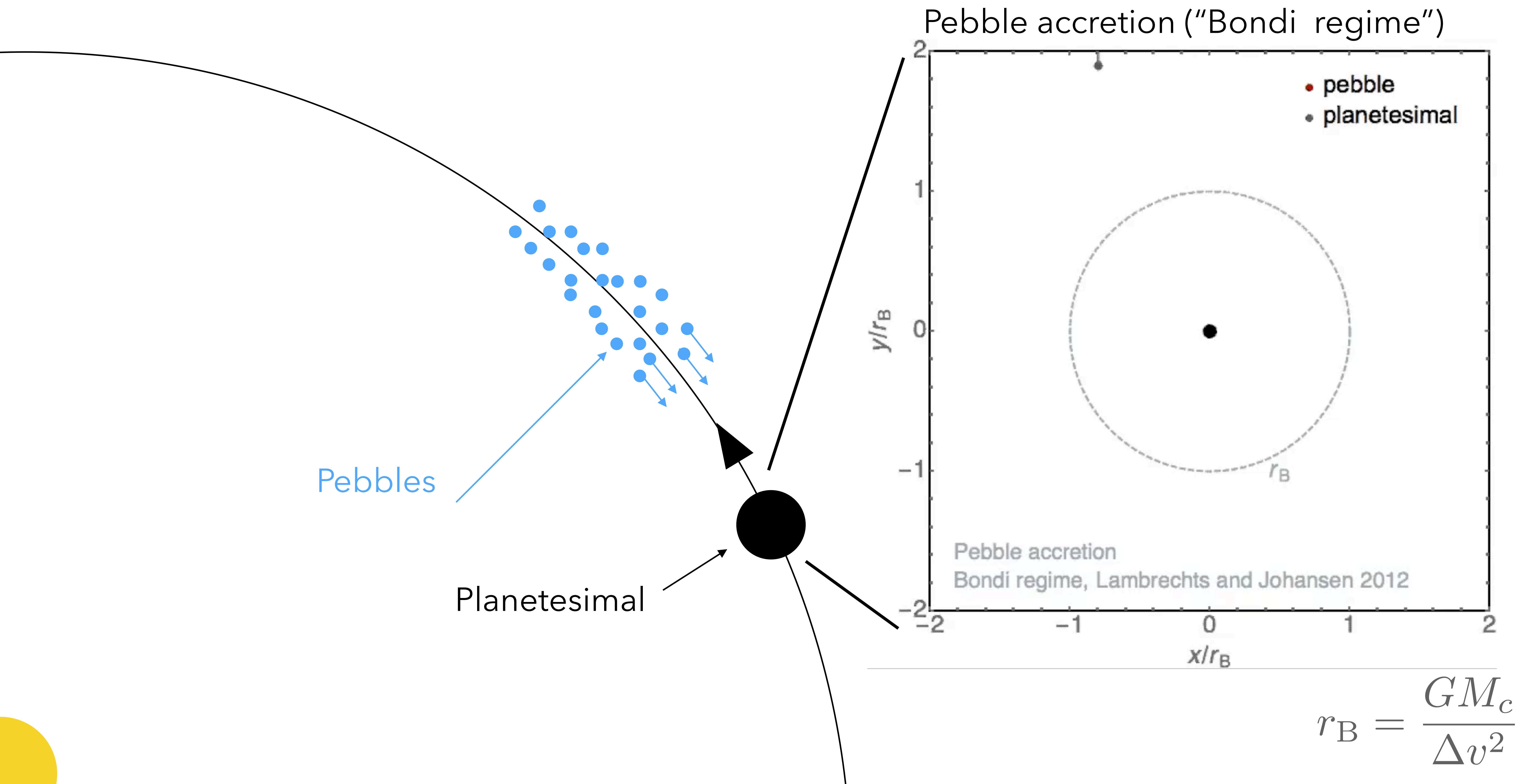


Planetesimals:
~100 km

Slide courtesy M. Lambrechts

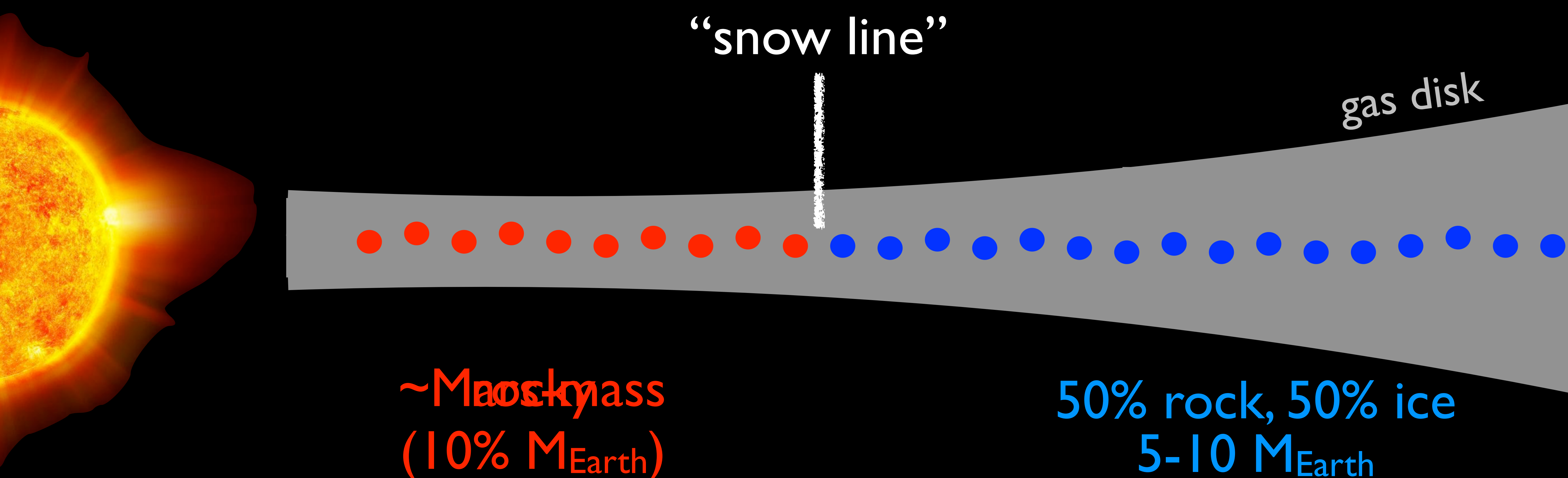
Pebble accretion

Johansen & Lacerda 2010; Ormel & Klahr 2010; Lambrechts & Johansen 2012, 2014; Morbidelli & Nesvorny 2012, …



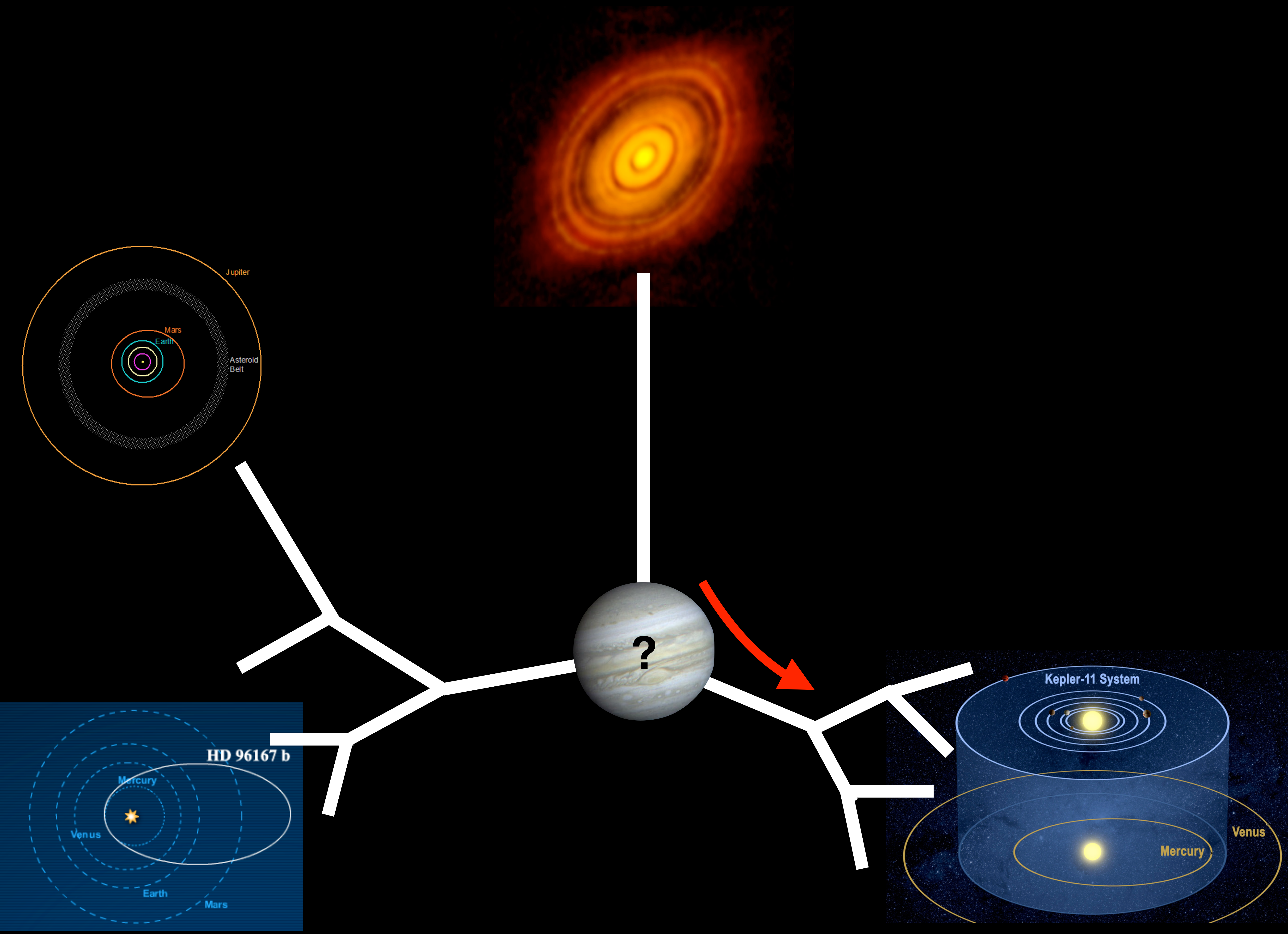
$$r_{\mathrm{B}} = \frac{GM_c}{\Delta v^2}$$

Planetesimals
Planetary embryos



Pebble accretion is more efficient past the snowline

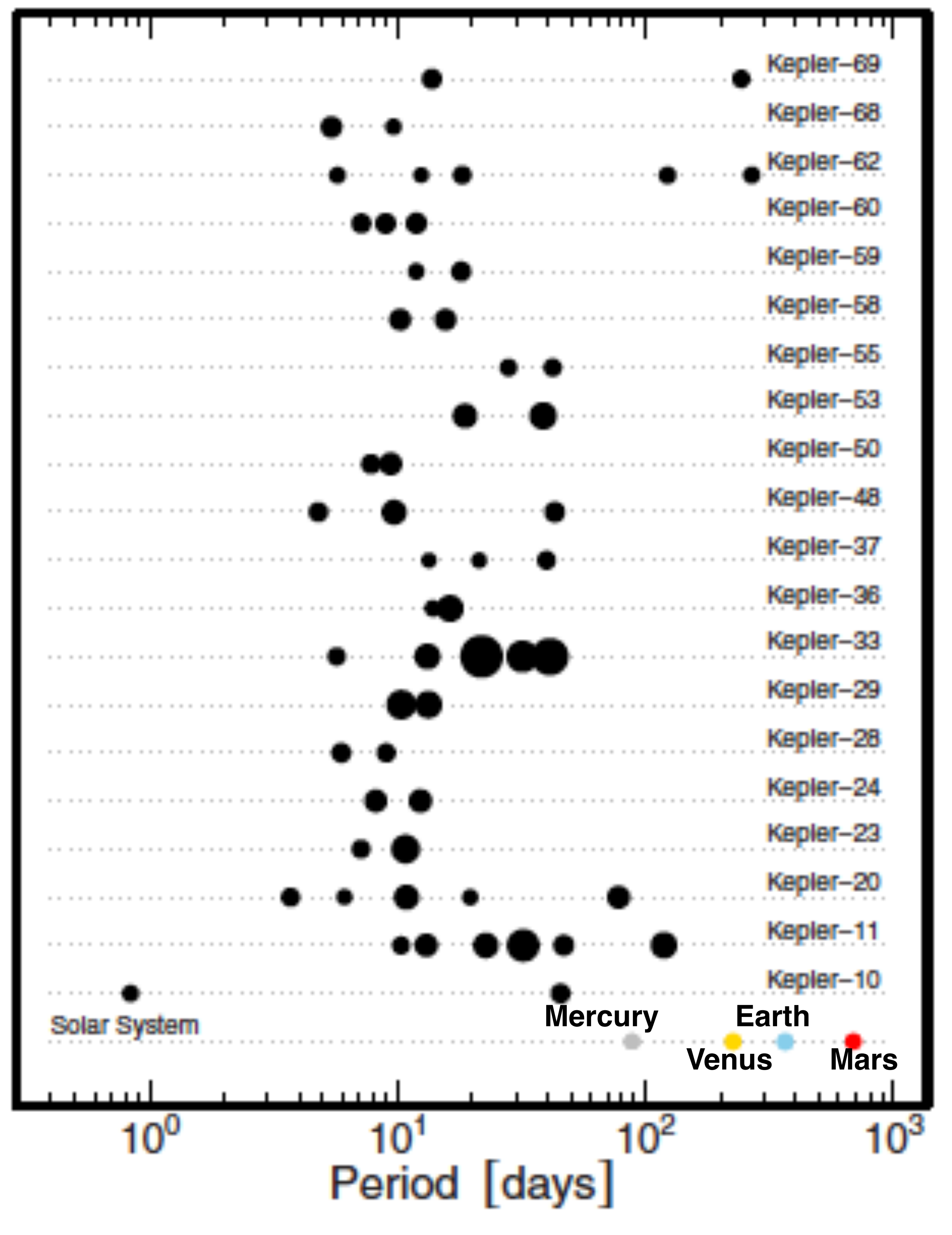
(Lambrechts et al 2014; Morbidelli et al 2015; Ormel et al 2017)


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

Super-Earths and the Solar System

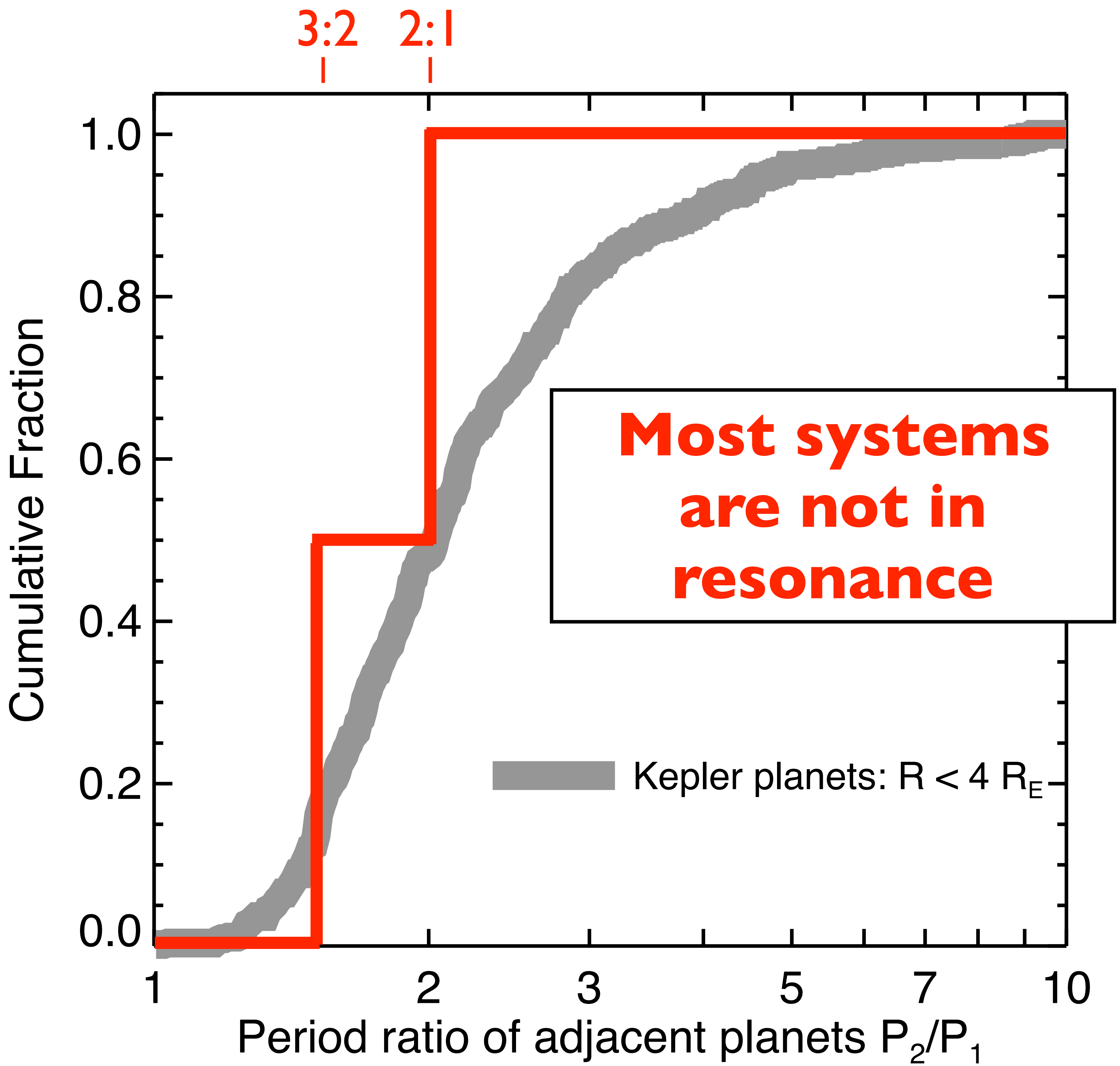
Occurrence rate:
~30-50%

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



Schlaufman (2014)

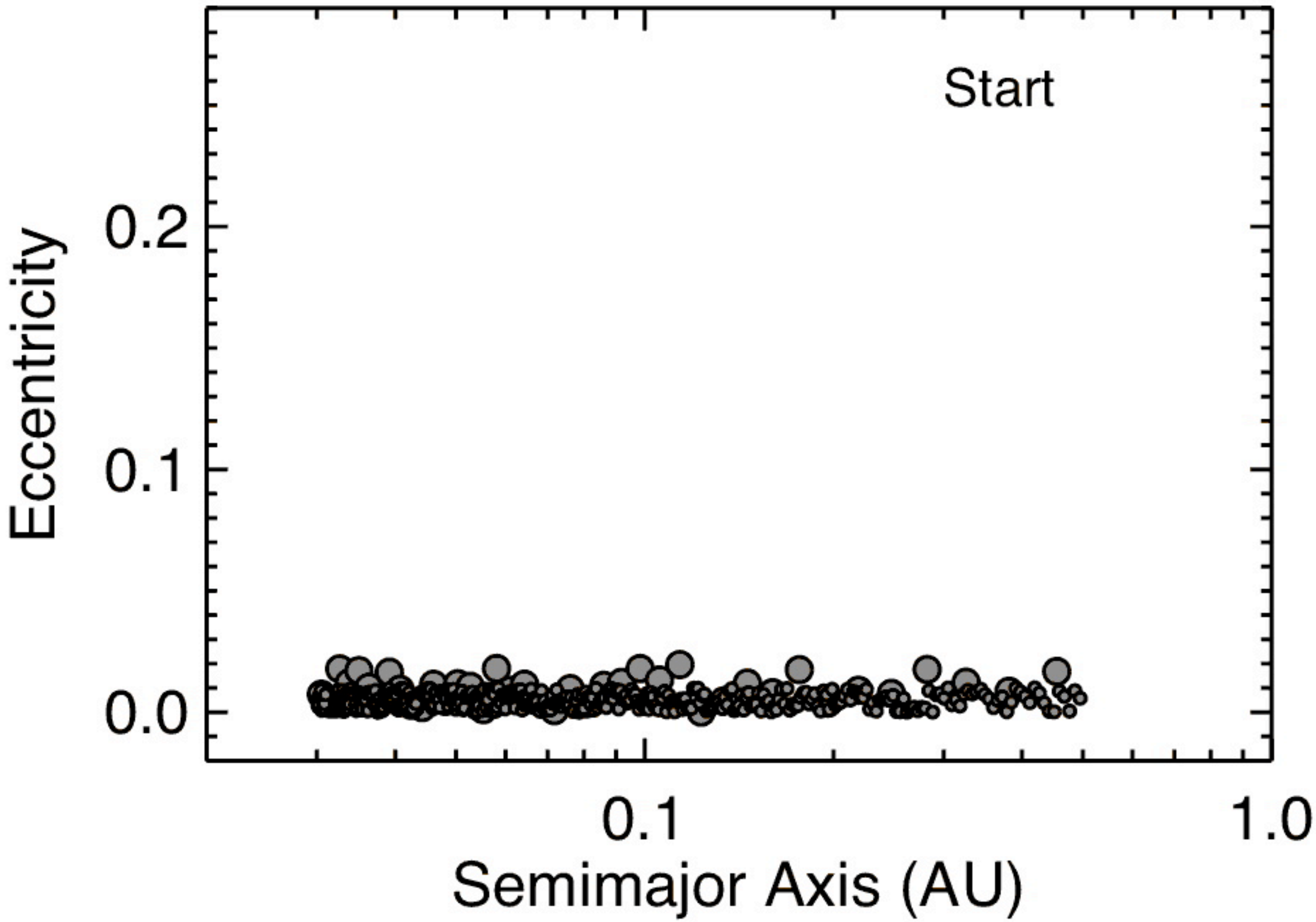
The period ratio distribution



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

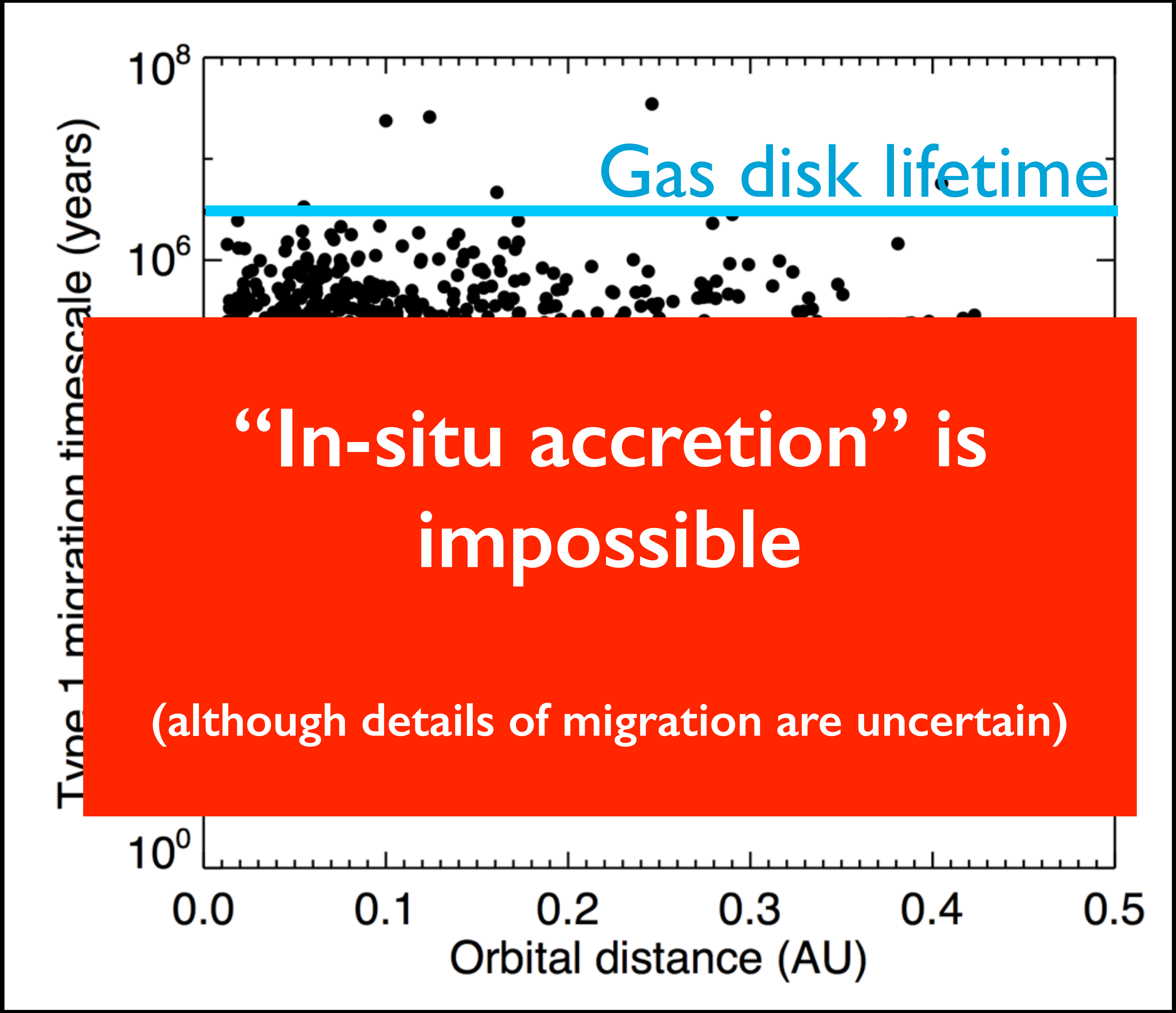
All roads lead to migration…

Growth timescales are very short



Bolmont et al 2014

Migration cannot be ignored



"In-situ accretion" is impossible

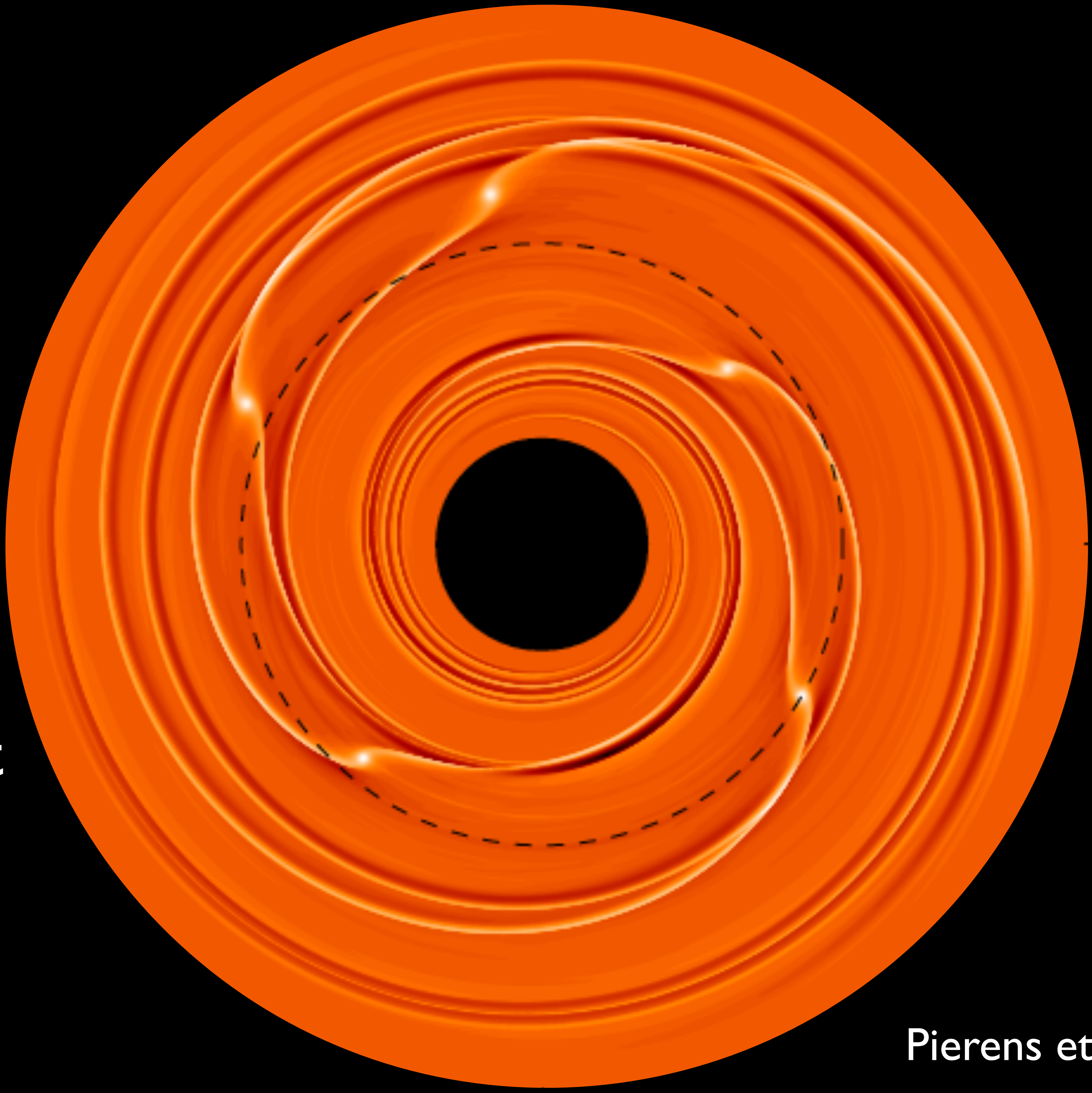
(although details of migration are uncertain)

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

Orbital migration

Matters for
Mp >~ MEarth

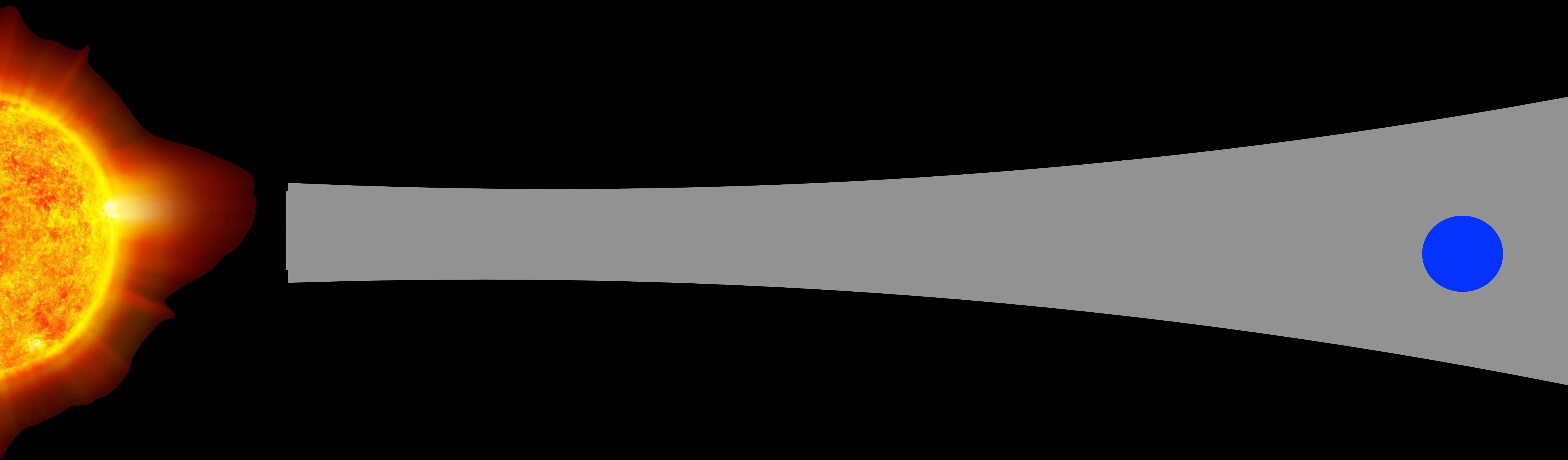
More massive planet
=> faster migration



Pierens et al (2013)

Golreich & Tremaine 1980; Ward 1986, 1997; Kley & Crida 2008; Paardekooper et al 2010, 2011; Pierens et al 2013; Lega et al 2014; Bitsch et al 2014; Kley & Nelson 2012

Migrating planets are trapped at the inner edge of the disk

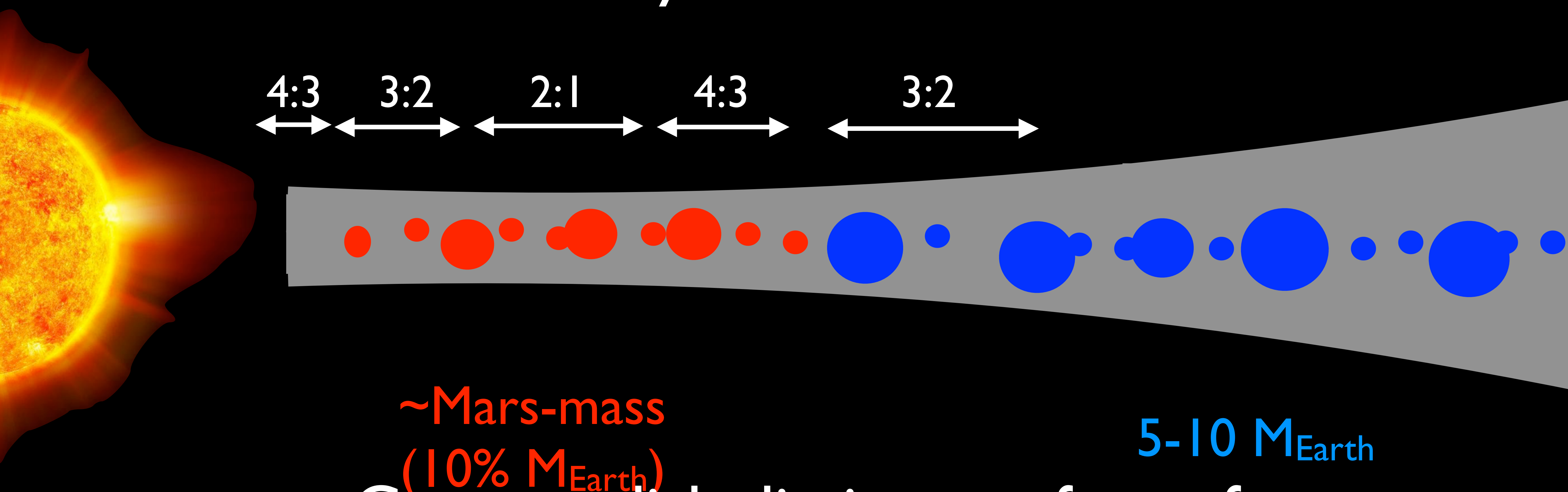


Masset et al (2006); Romanova & Lovelace (2006)

Planetary embryos

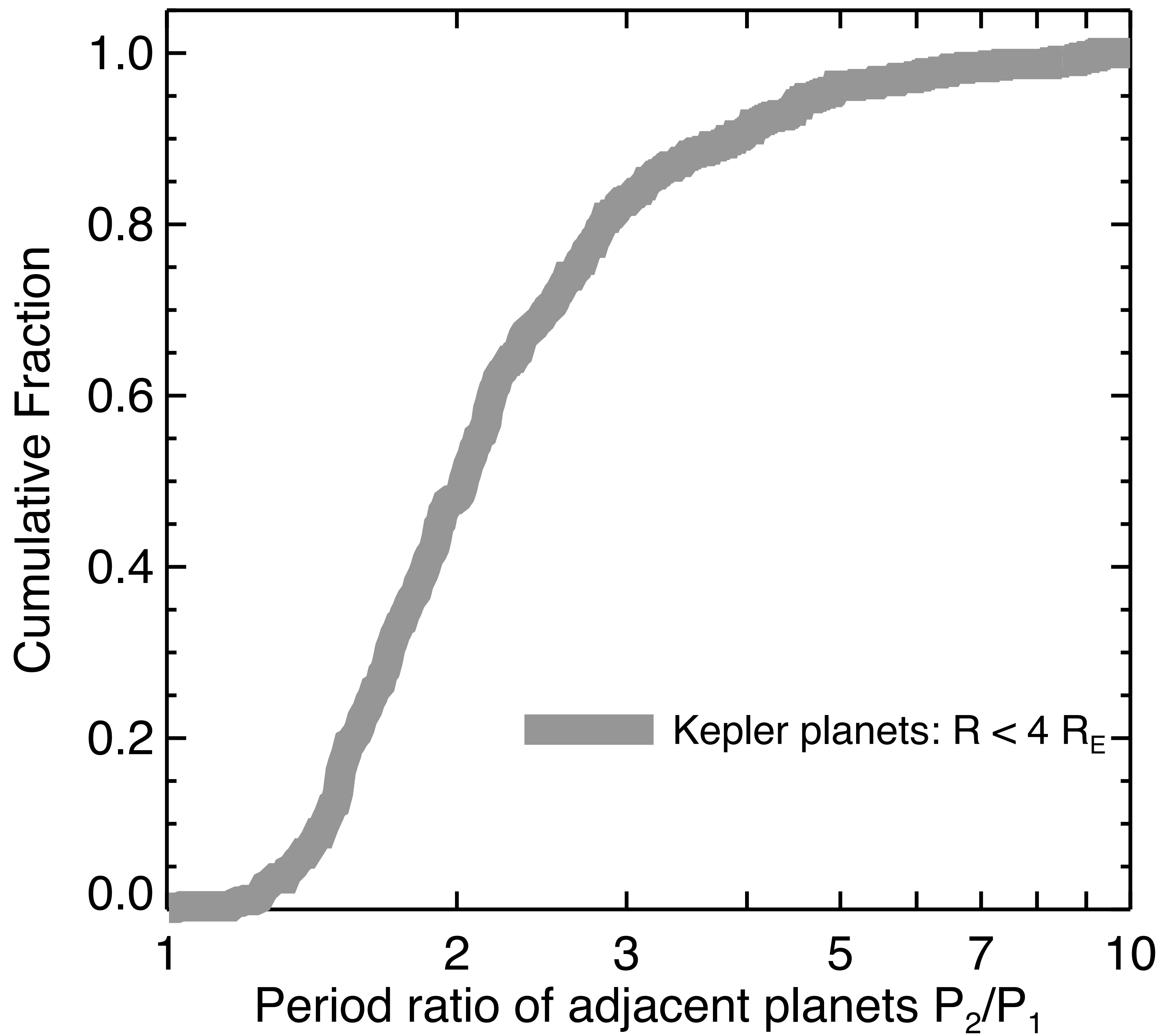
Resonant chain

Instability spreads planets out and destroys resonances

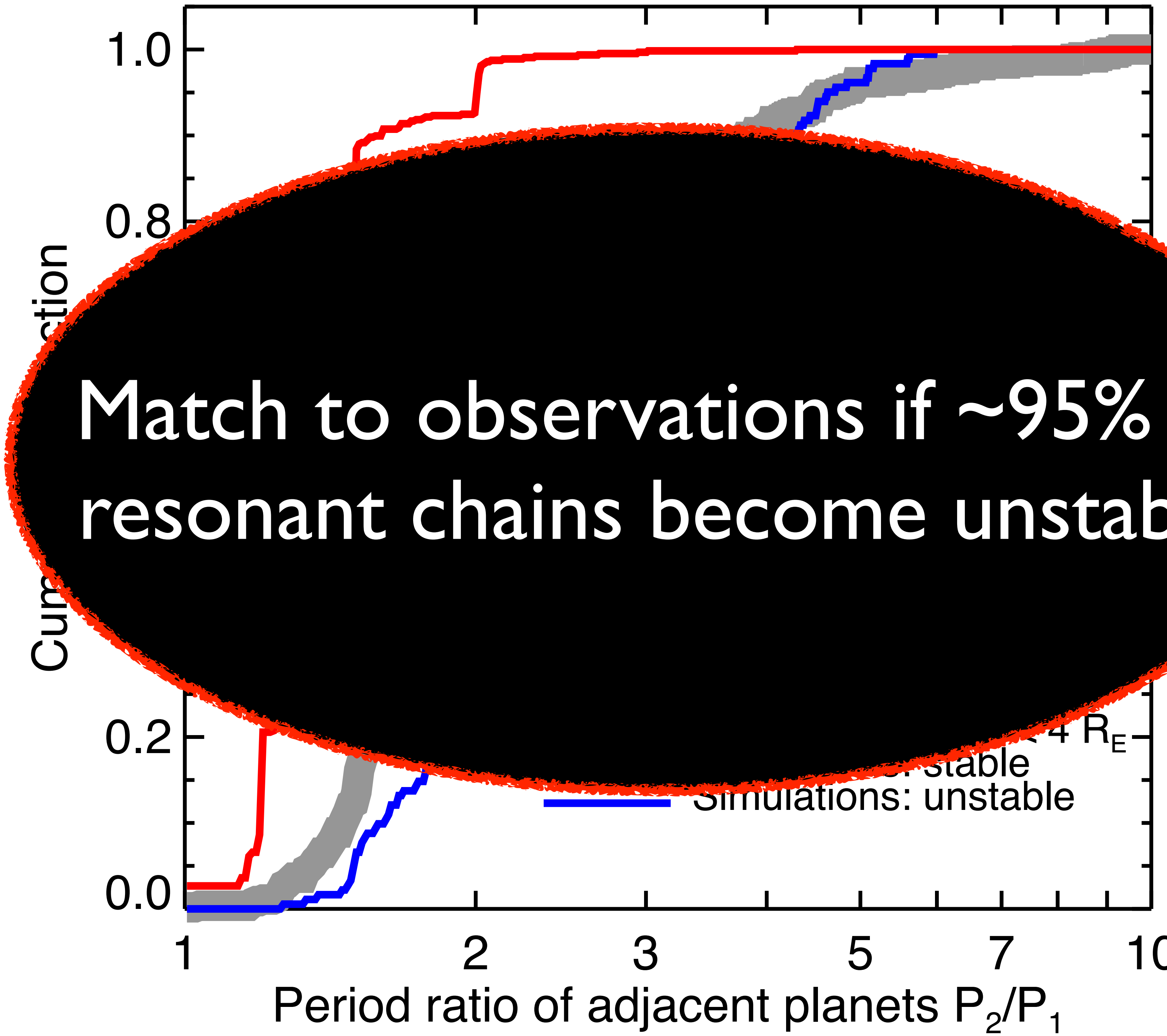


Gaseous disk dissipates after a few million years

The period ratio distribution

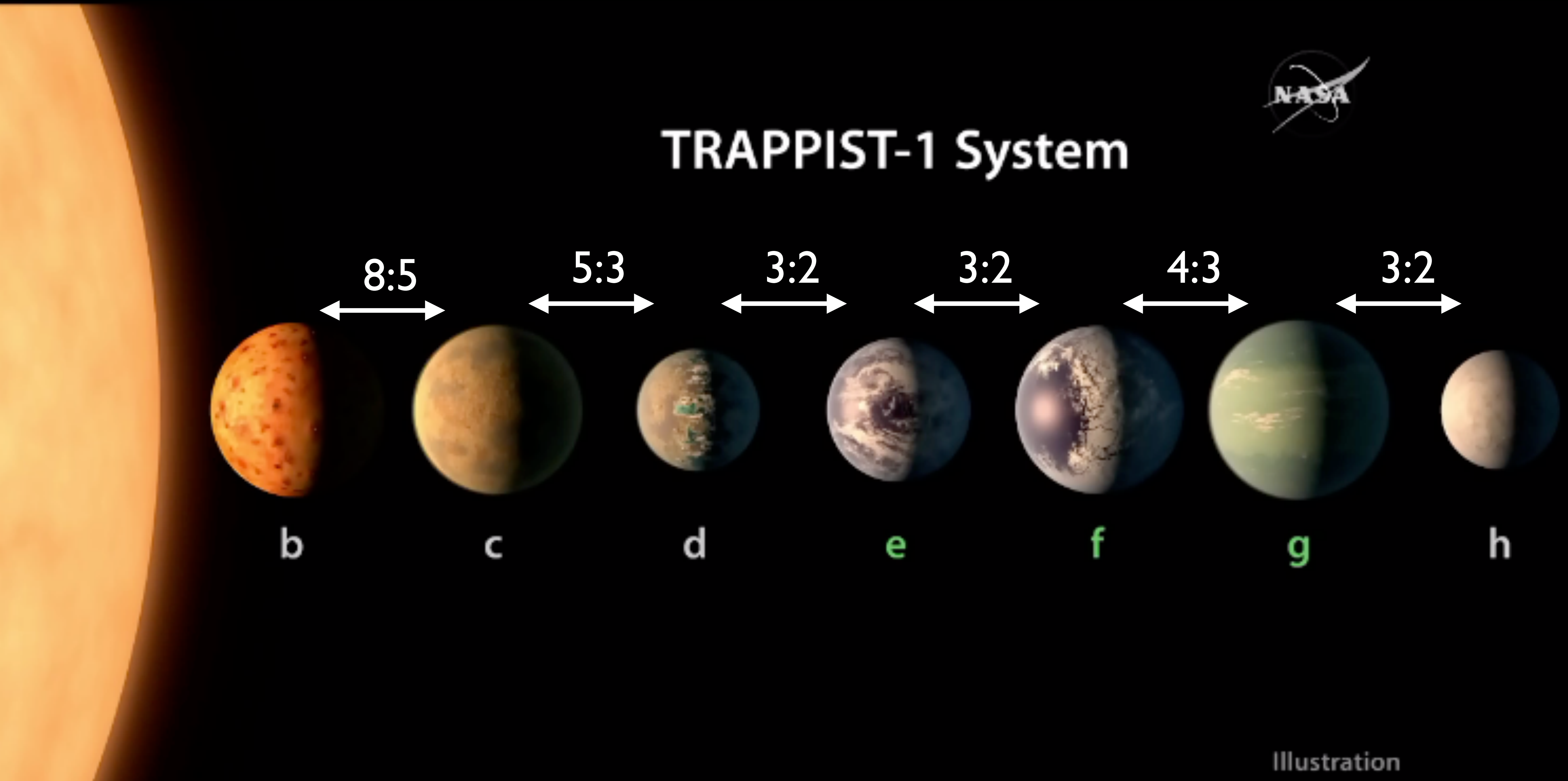


The period ratio distribution

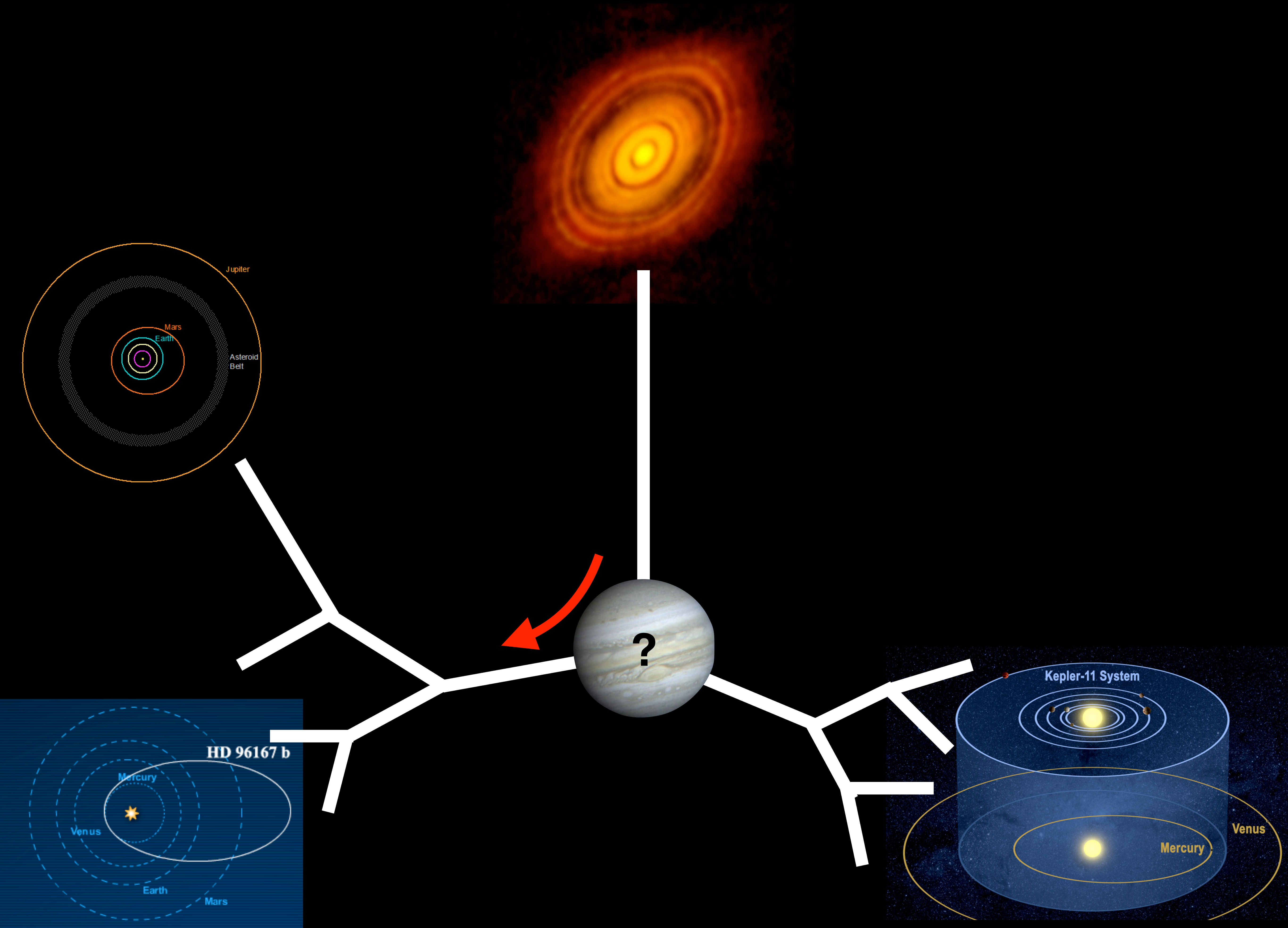


Match to observations if ~95% of resonant chains become unstable

Izidoro et al (2017, 2019)



(Gillon et al 2017, Luger et al 2017)


Jupiter
Mars
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Asteroid
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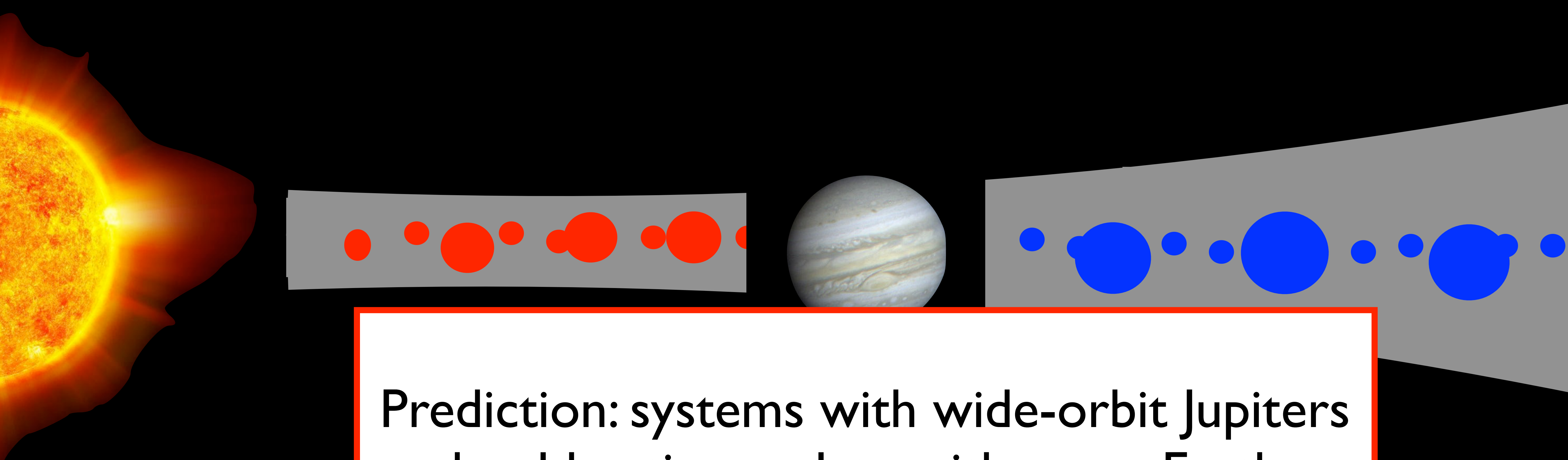
Kepler-11 System
Venus
Mercury

Jupiter blocks the migration of more distant, icy embryos

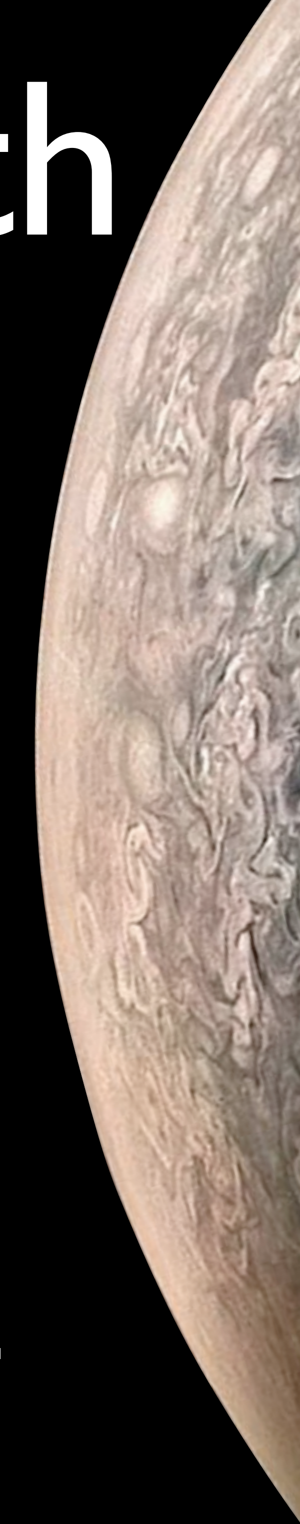
The young Jupiter accretes gas from the disk



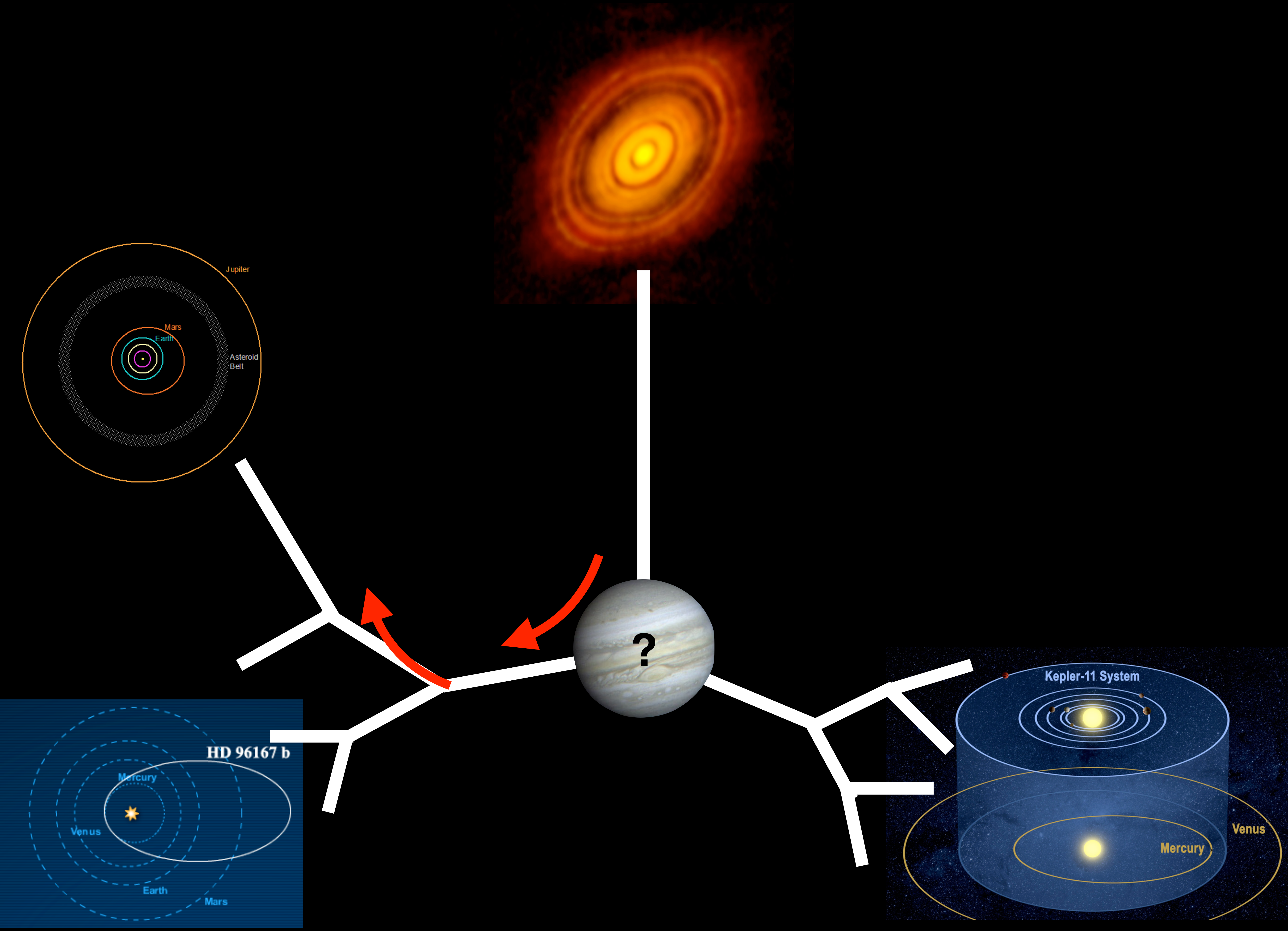
Prediction: systems with wide-orbit Jupiters should anti-correlate with super-Earths

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
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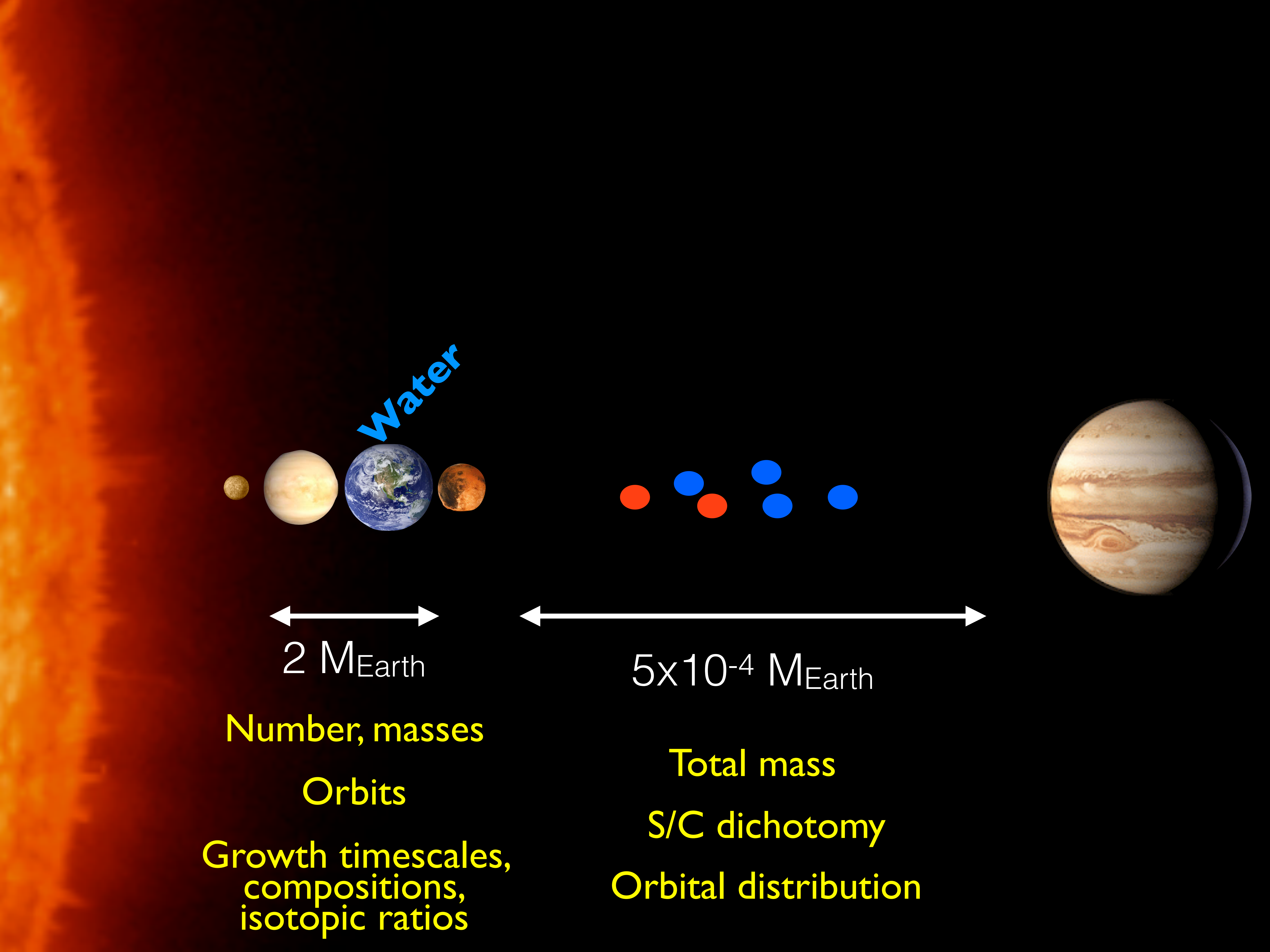
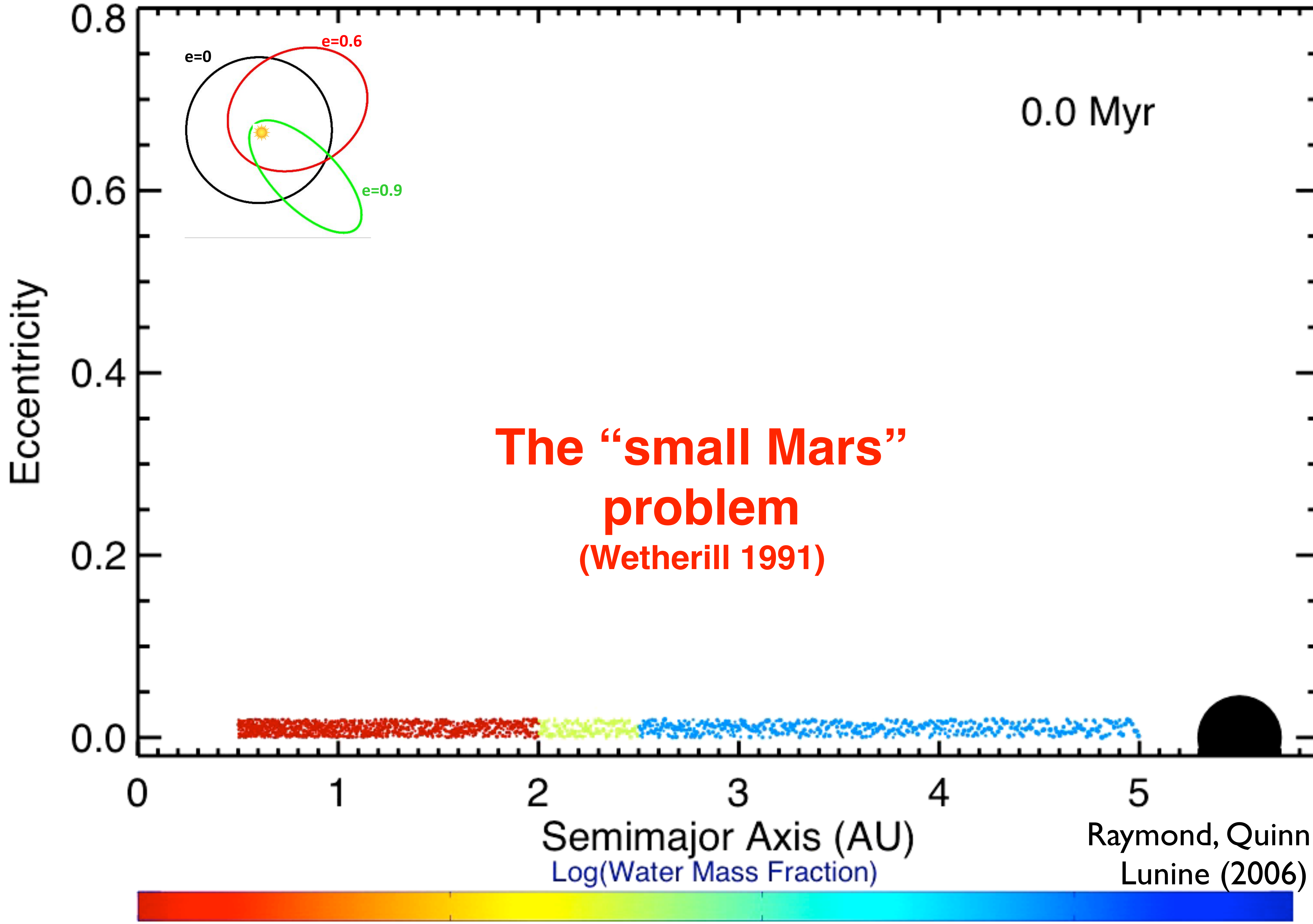

Water
2 M_{Earth}
$5x10^{-4}$ M_{Earth}
Number, masses
Orbits
Growth timescales,
compositions,
isotopic ratios
Total mass
S/C dichotomy
Orbital distribution

The “classical model”

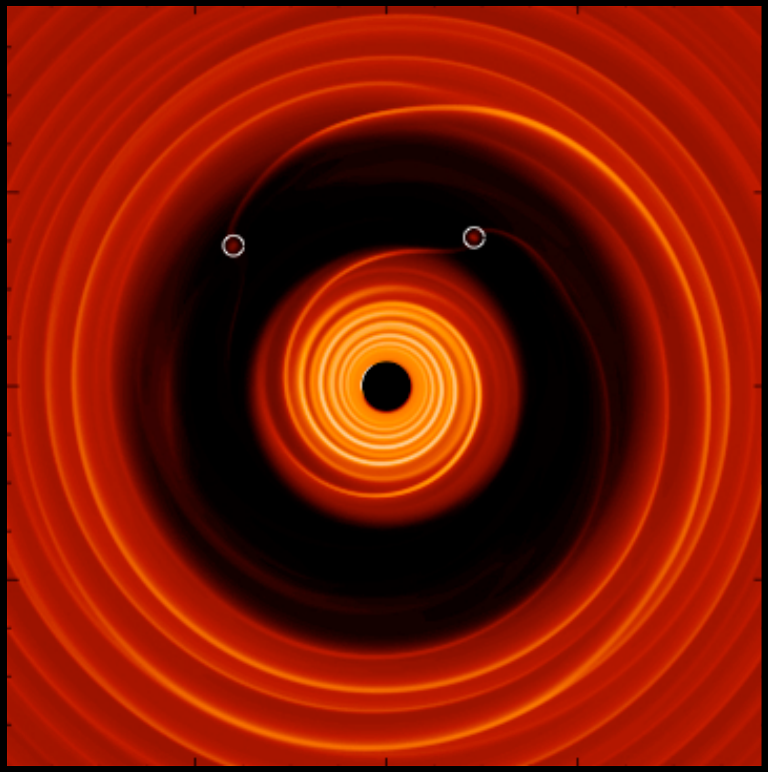


The “small Mars” problem
(Wetherill 1991)

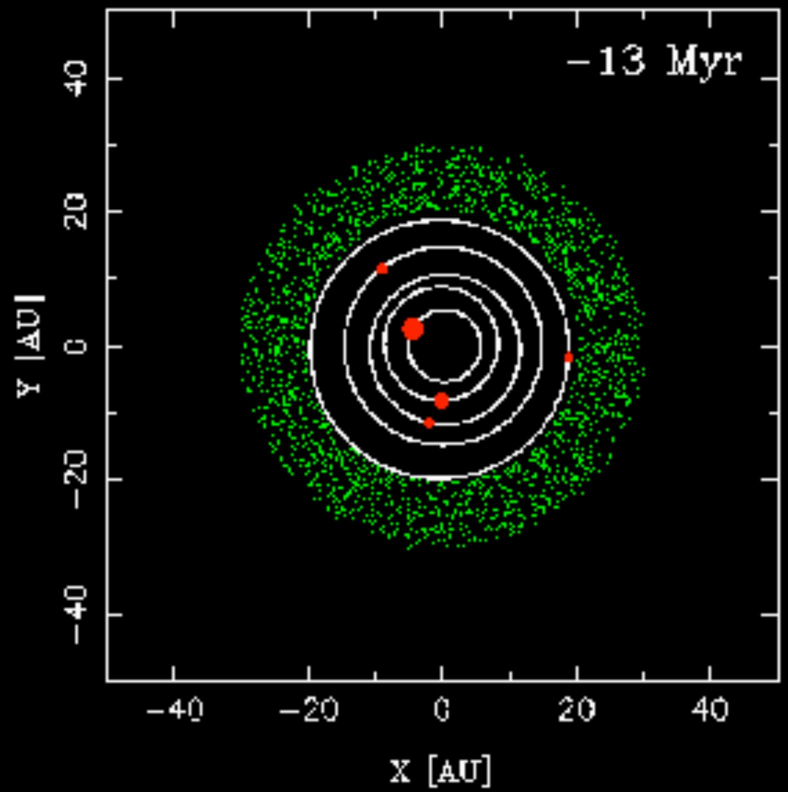
Raymond, Quinn & Lunine (2006)

3 possible solutions to the small Mars problem

"Low-mass asteroid belt"



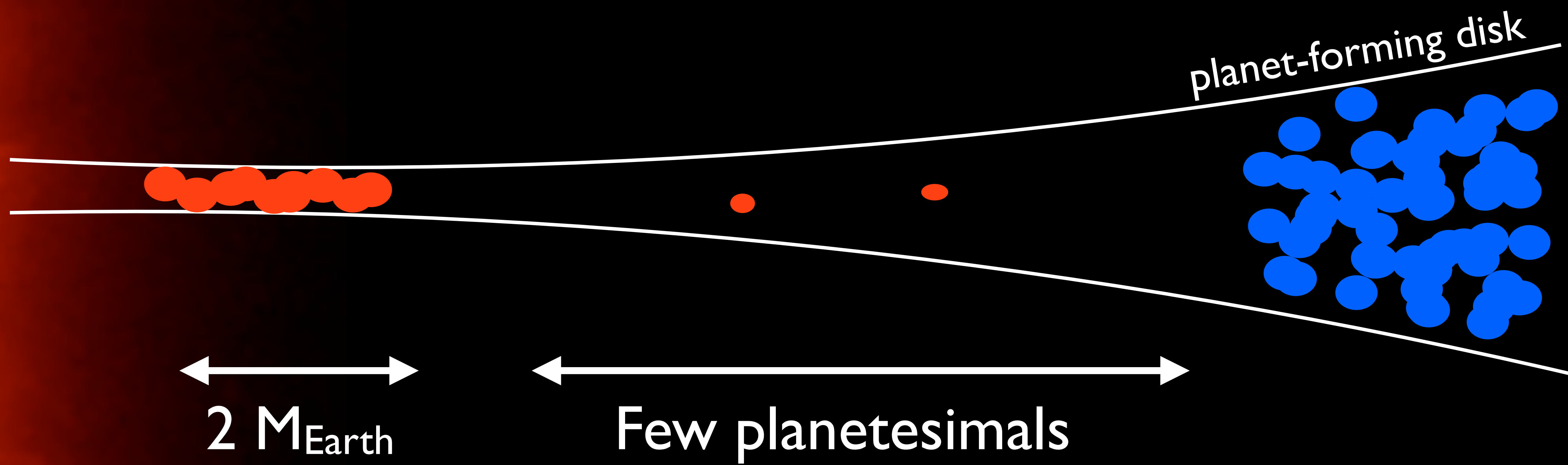
The "Grand Tack"



Early instability

1. Low-mass asteroid belt

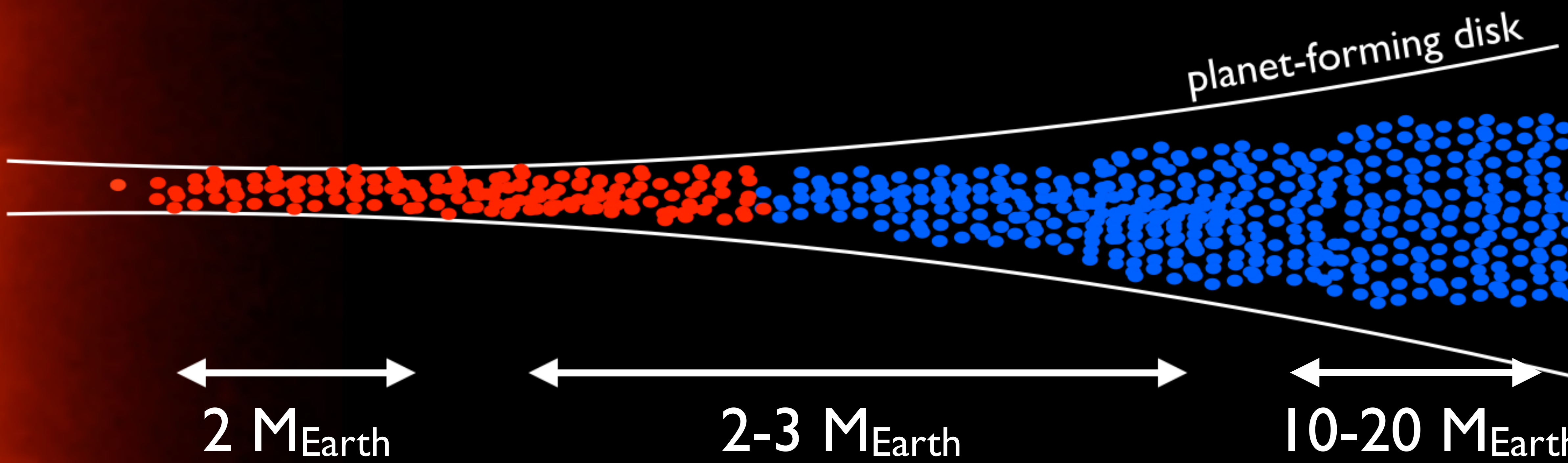
Assumption: few (if any) planetesimals formed in Mars region/asteroid belt

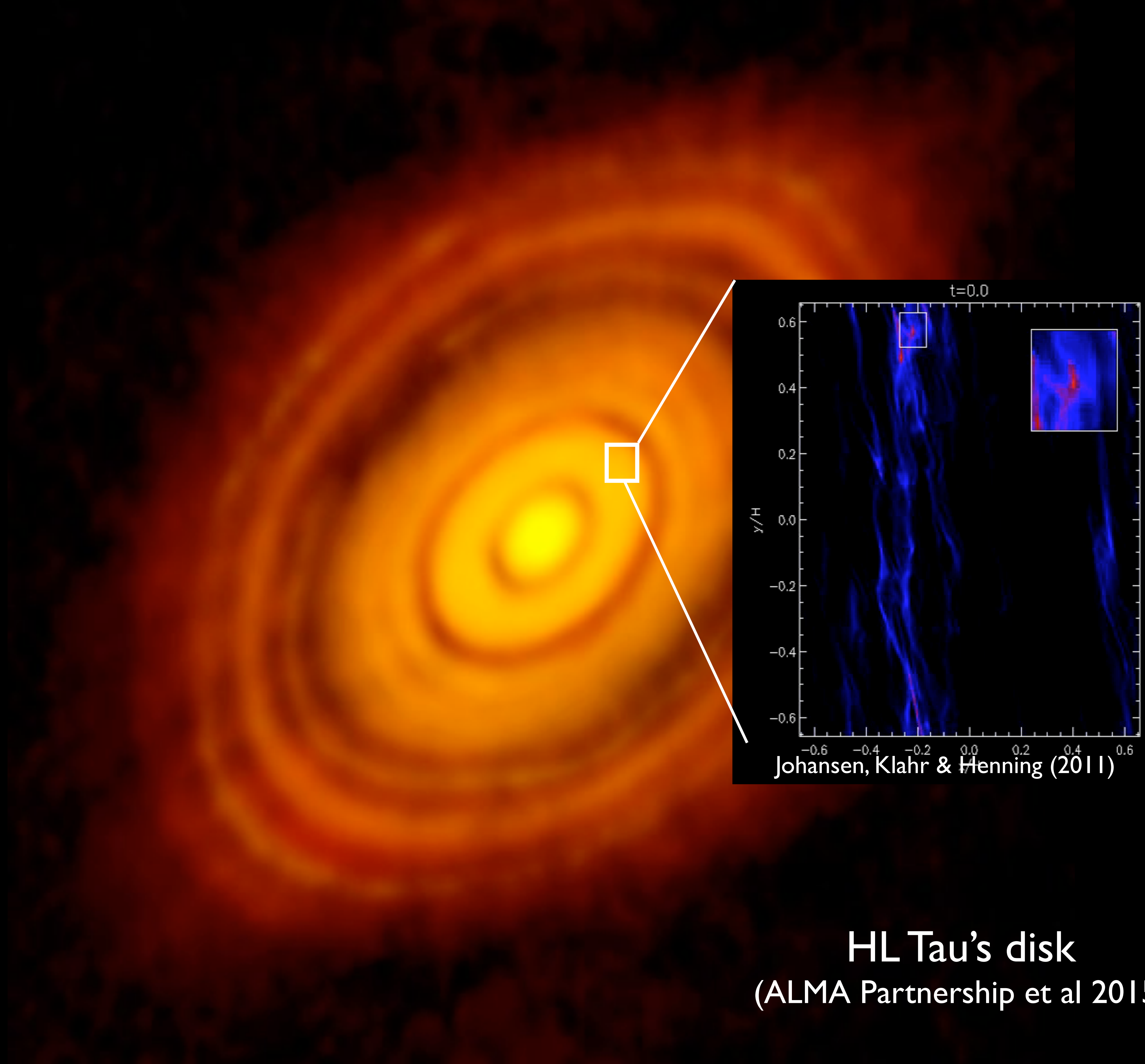


(Hansen 2009; Izidoro et al 2015; Walsh & Levison 2016; Drazkowska et al 2016; Raymond & Izidoro 2017b)

1. Low-mass asteroid belt

Dust, gas distributions were smooth(ish)





Johansen, Klahr & Henning (2011)

HL Tau's disk

(ALMA Partnership et al 2015)

1. Low-mass asteroid belt

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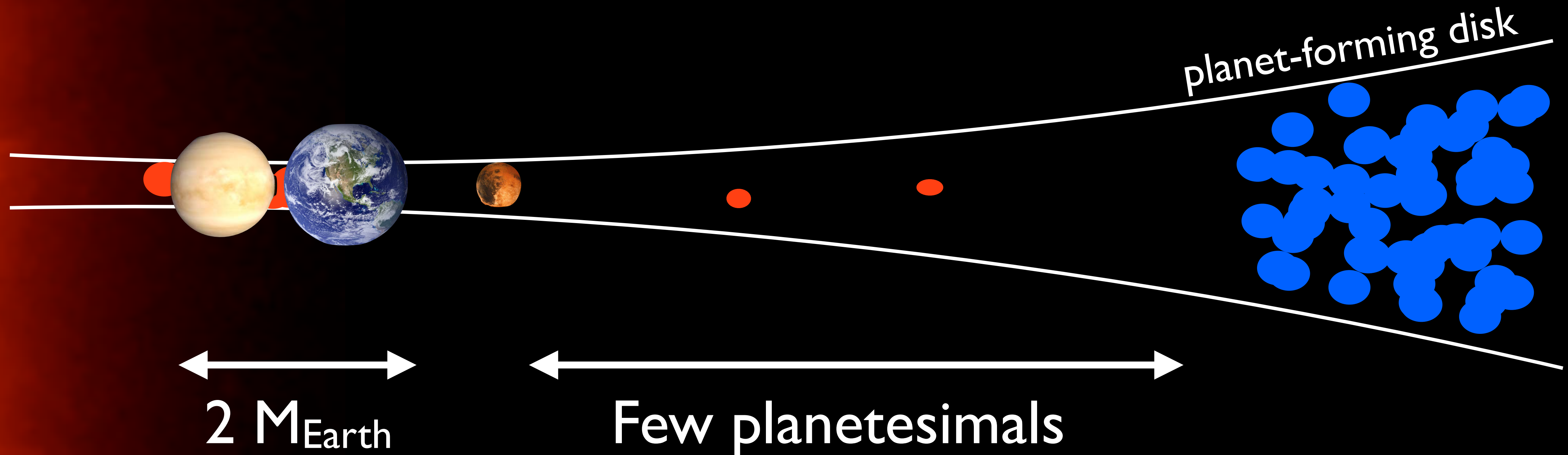
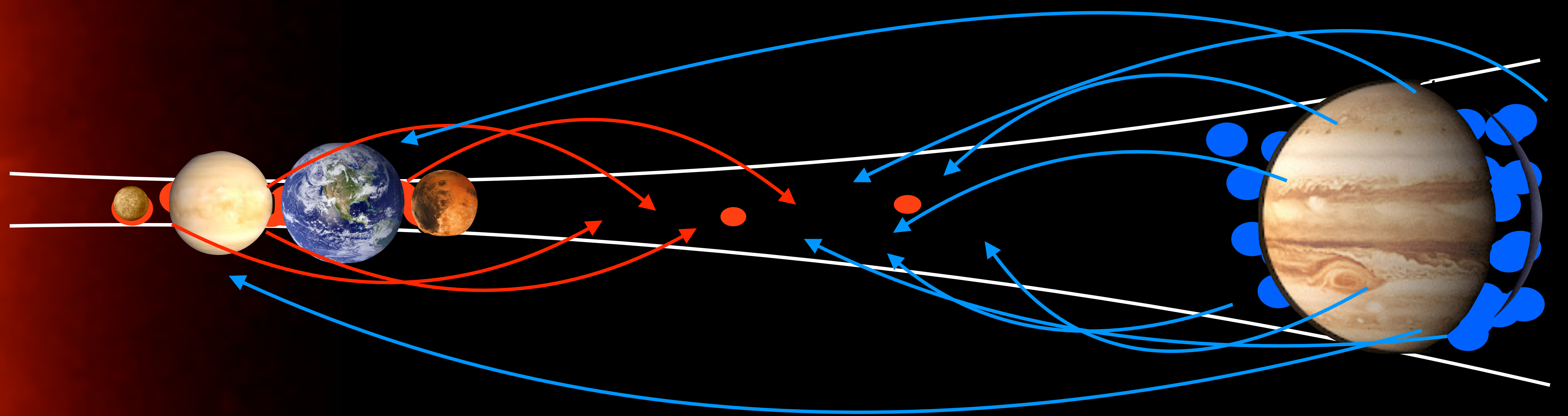


(Hansen 2009; Izidoro et al 2015; Walsh & Levison 2016; Drazkowska et al 2016; Raymond & Izidoro 2017b)

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

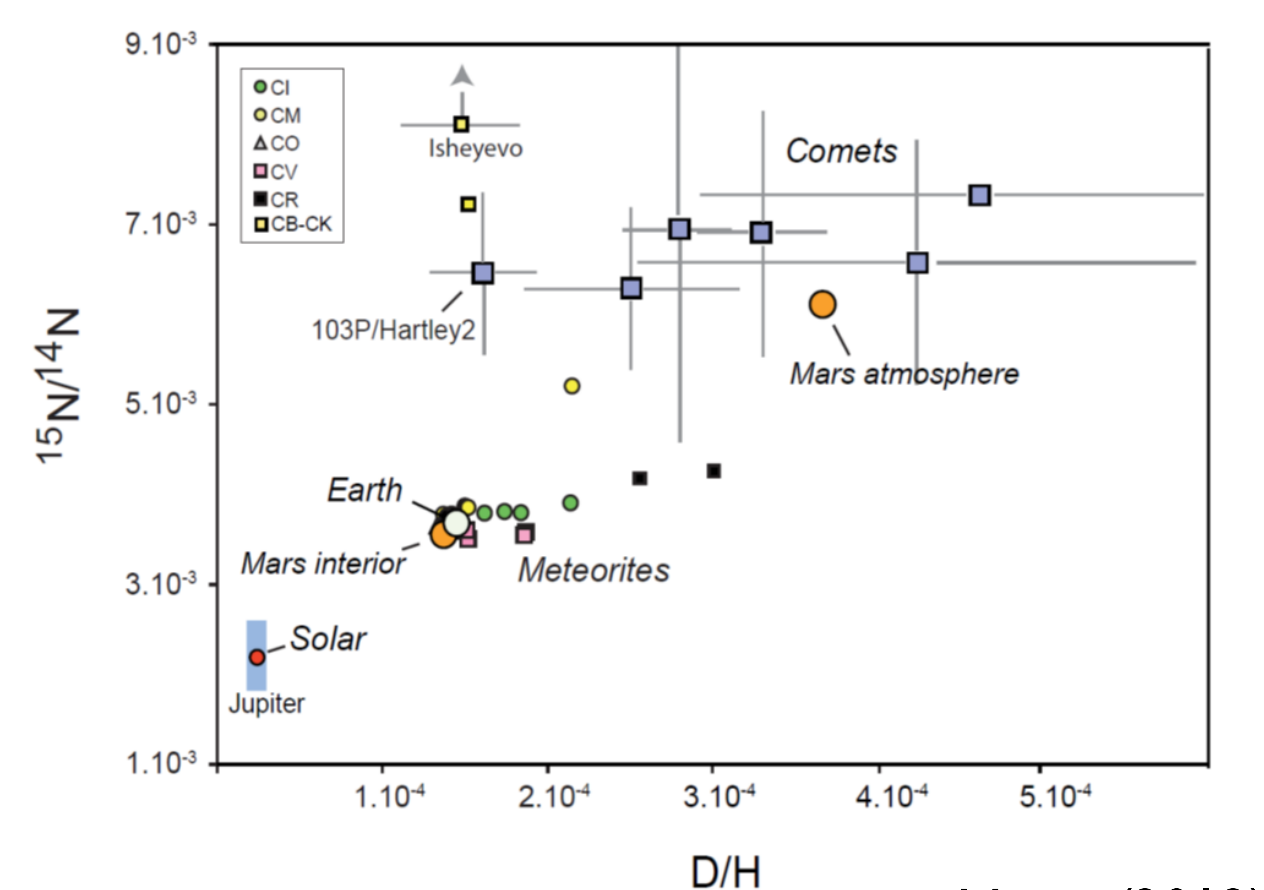


Some asteroids (Vesta? Irons? S-types?) scattered out from terrestrial planet region

Raymond & Izidoro (2017a,b)

Water on Earth

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



Marty (2012)

Classical model: primitive C-types delivered Earth's water

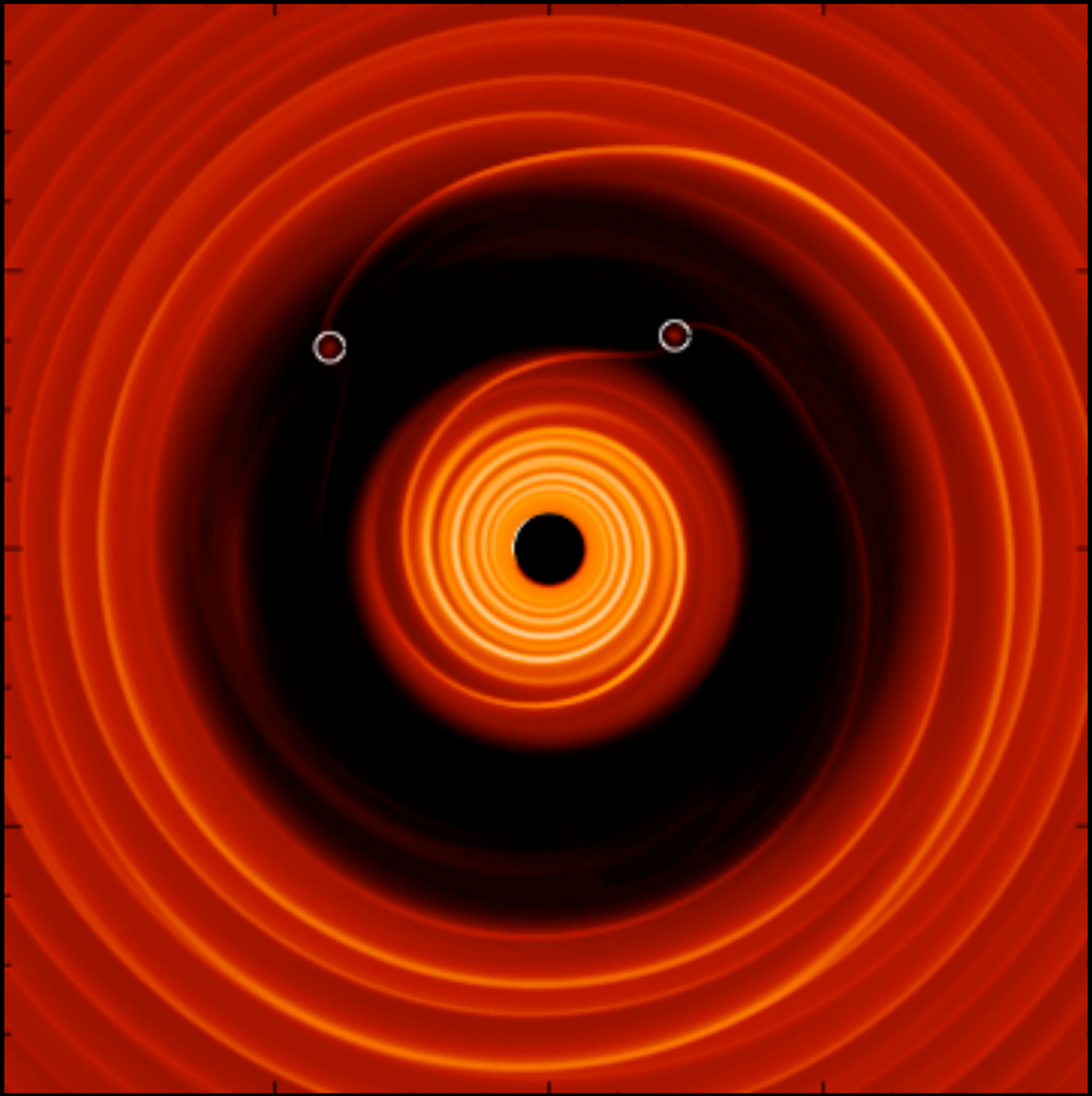
(Morbidelli et al 2000; Raymond et al 2004, 2007)

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)

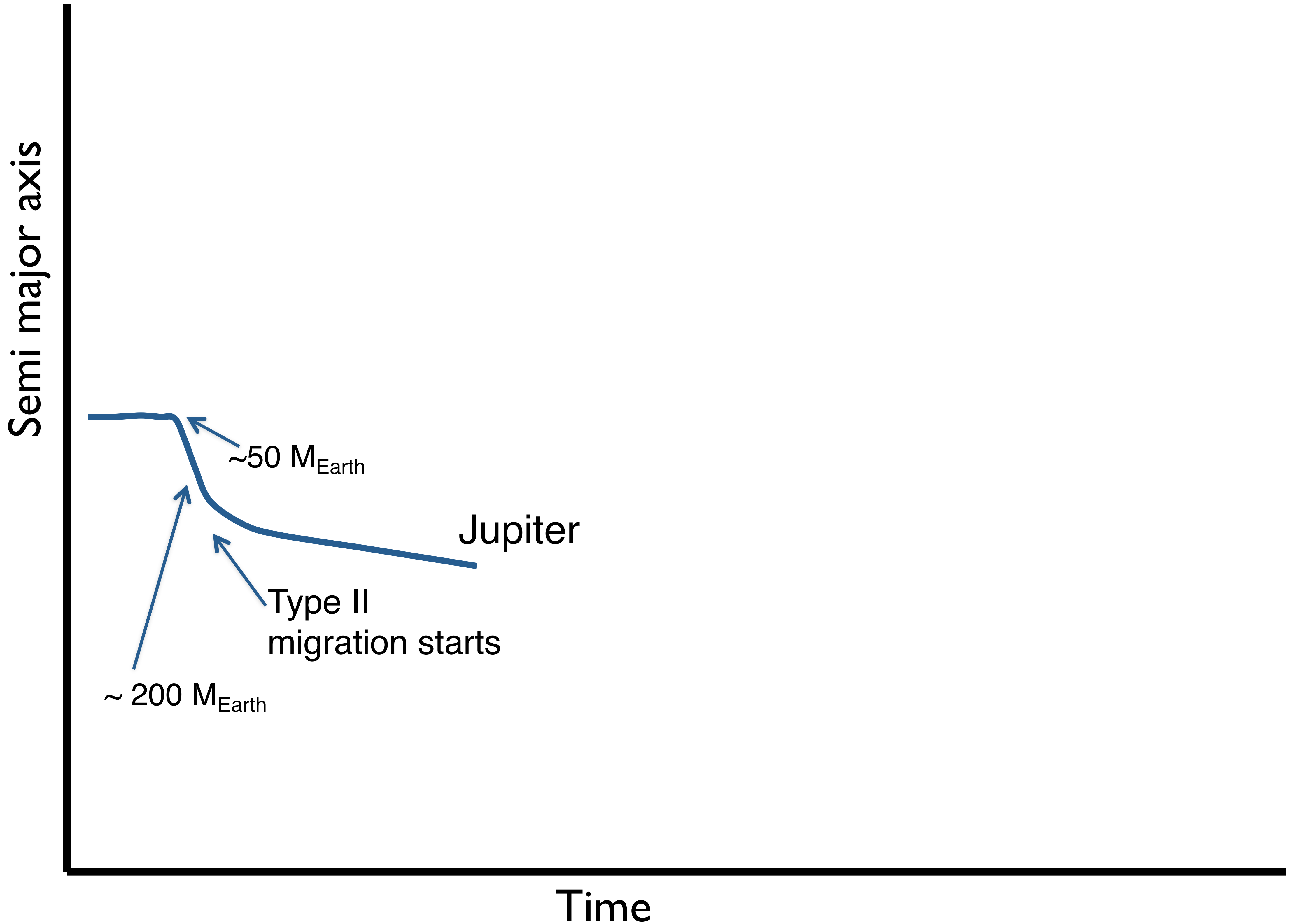
2. The Grand Tack

(Walsh et al 2011)

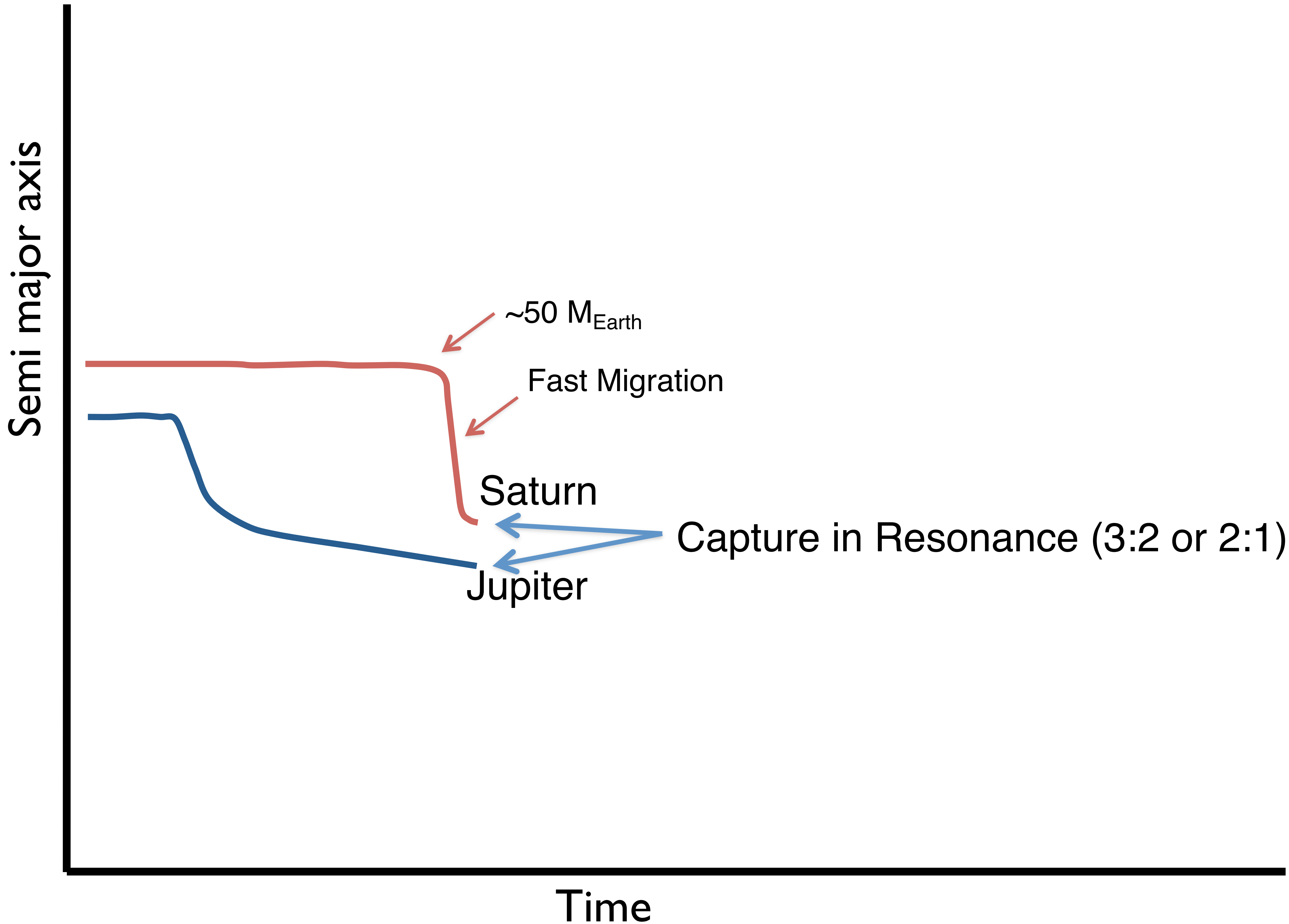


Pierens & Raymond (2011)

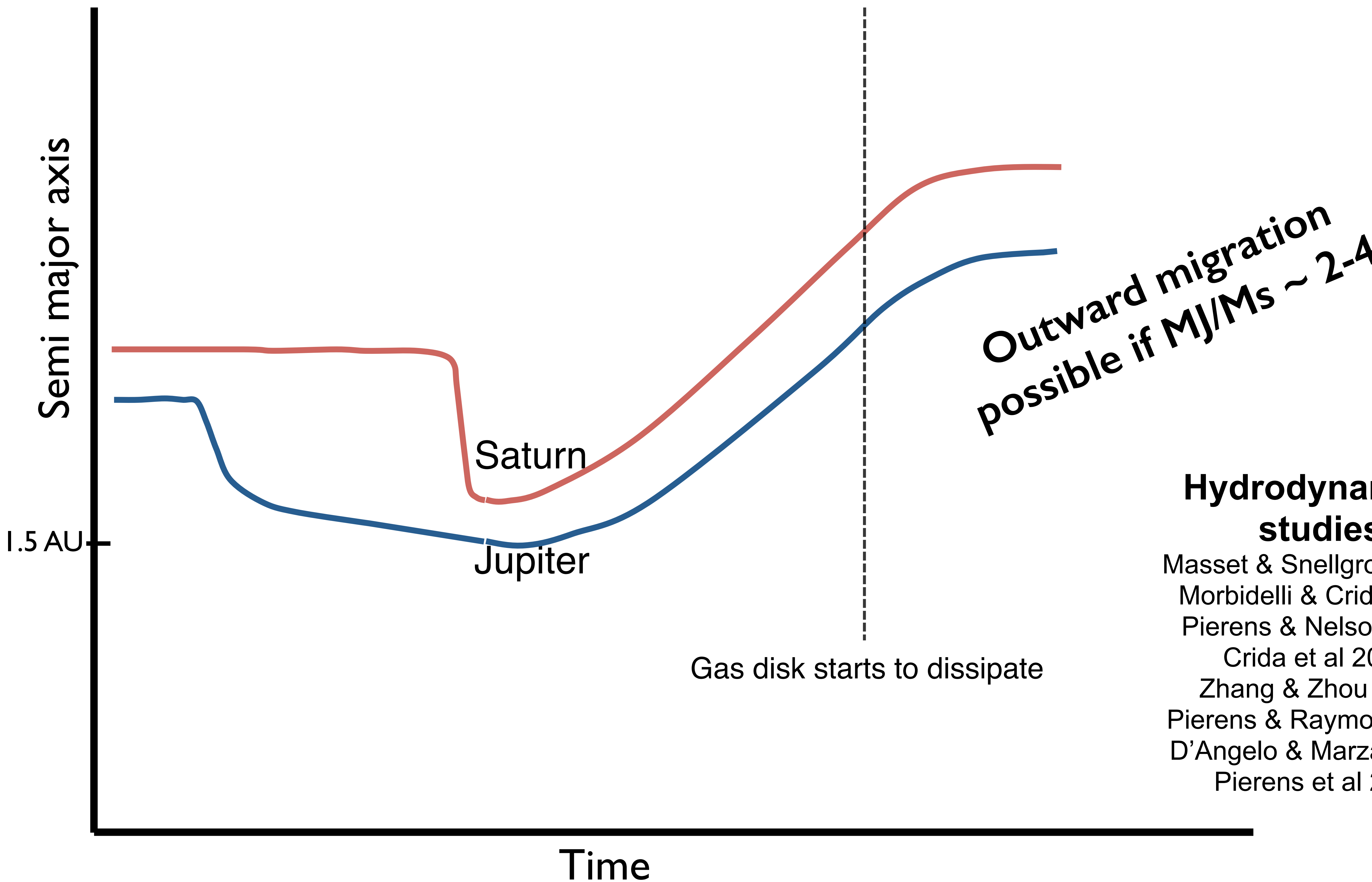
Jupiter in the gaseous disk



Jupiter and Saturn in the gaseous disk



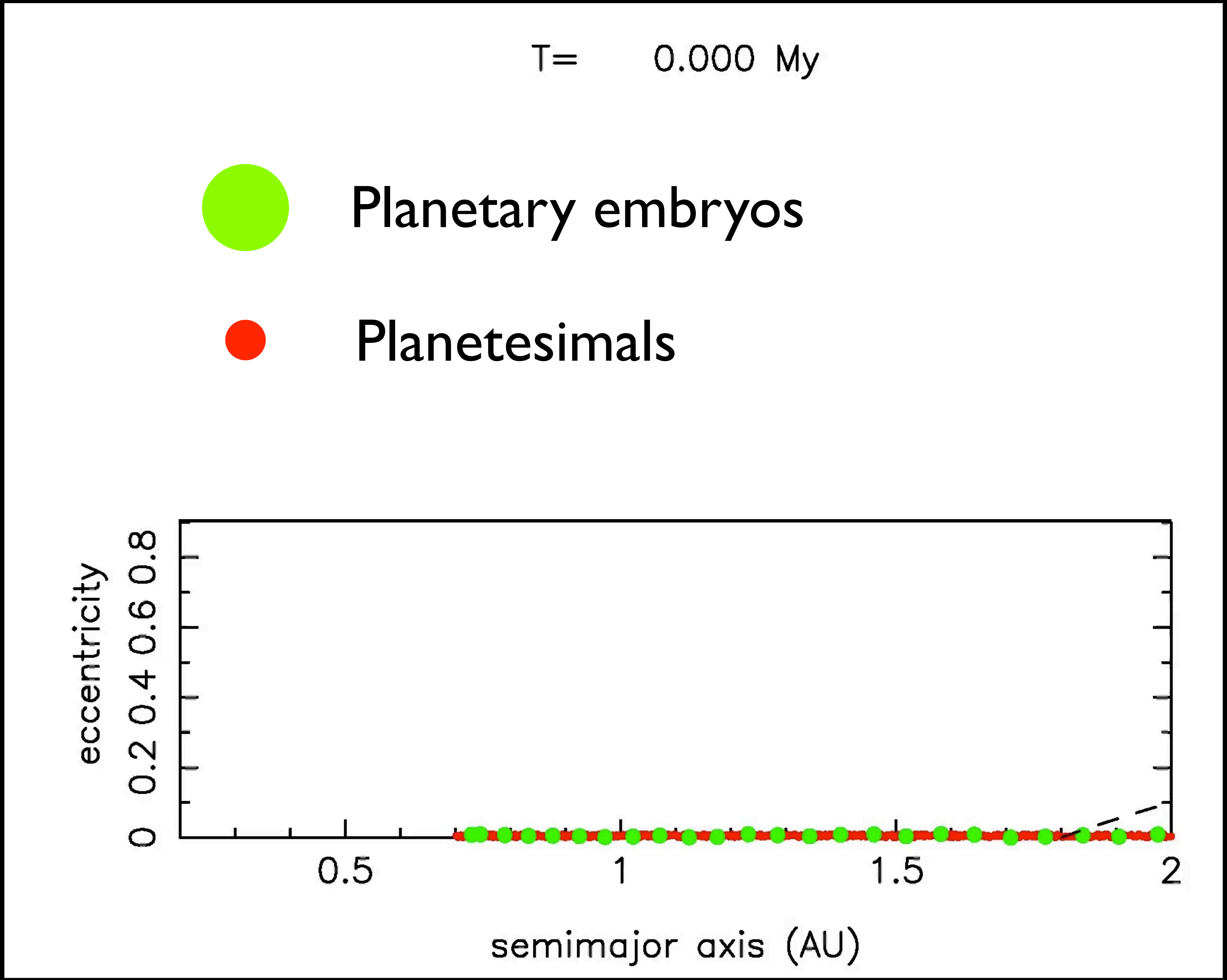
The Grand Tack model
(Walsh et al 2011)



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

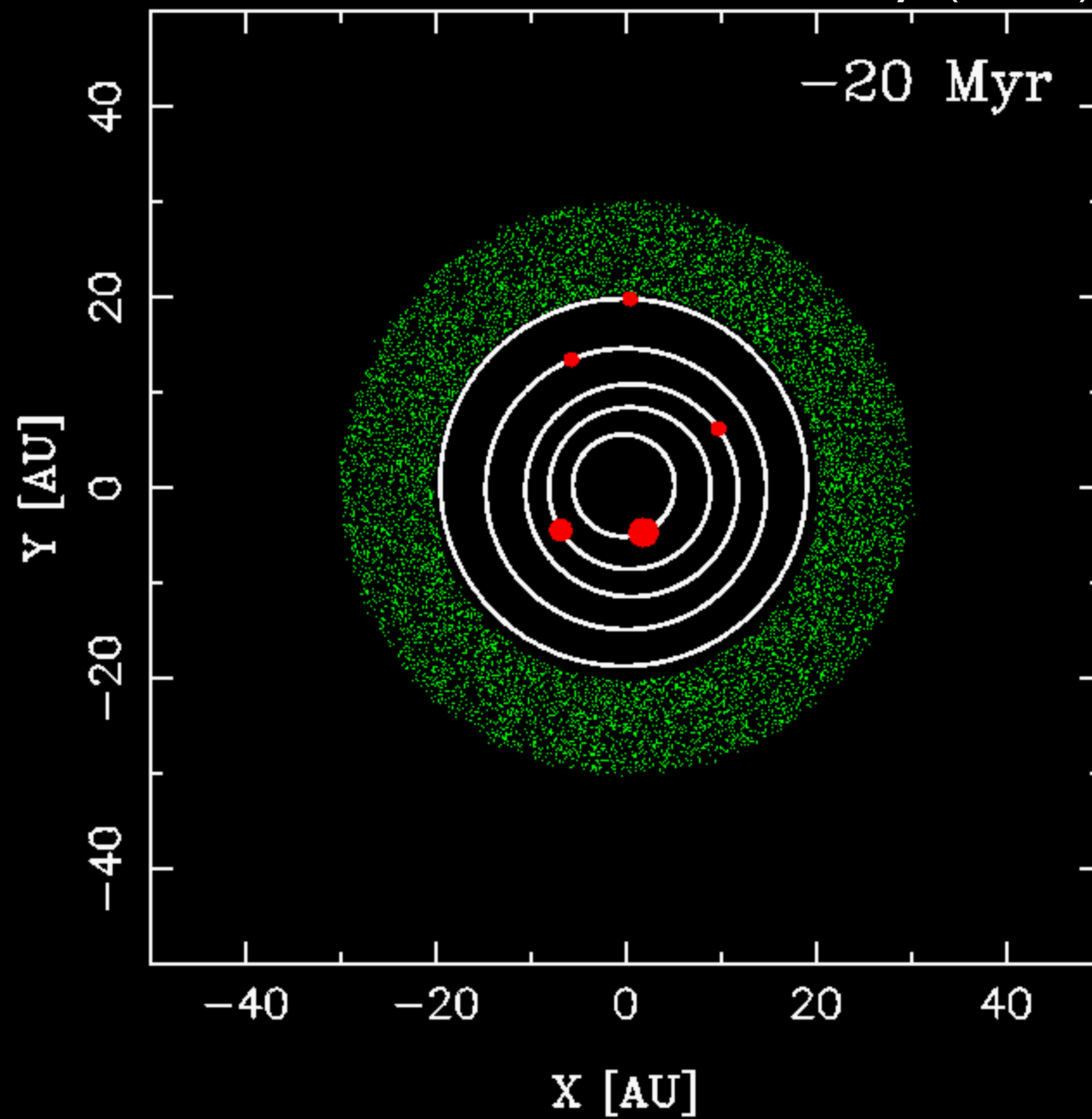
The Grand Tack model



Walsh et al (2011); Jacobson & Morbidelli (2014)

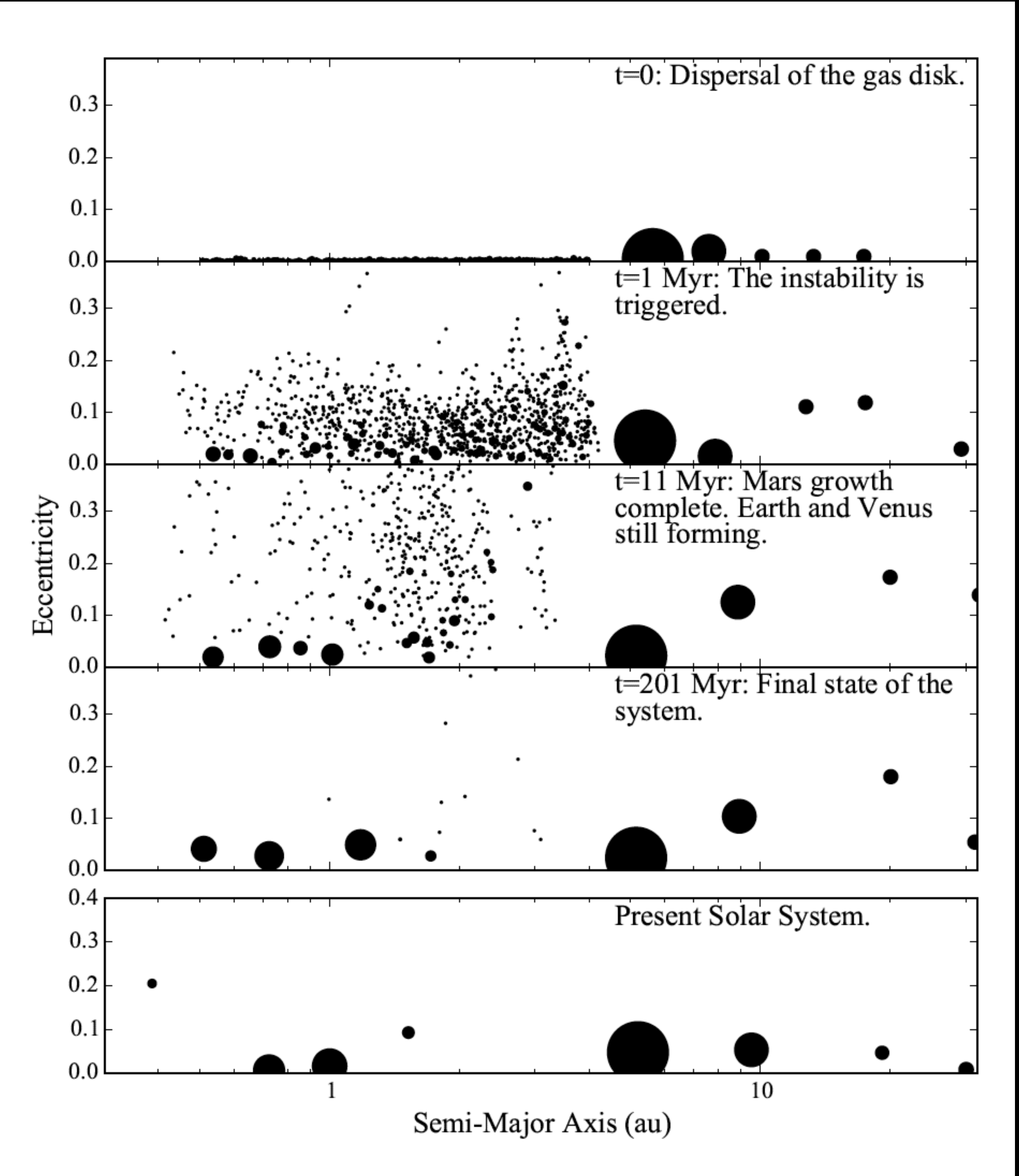
3. The Solar System's instability
(the "Nice model")

Nesvorny (2011)



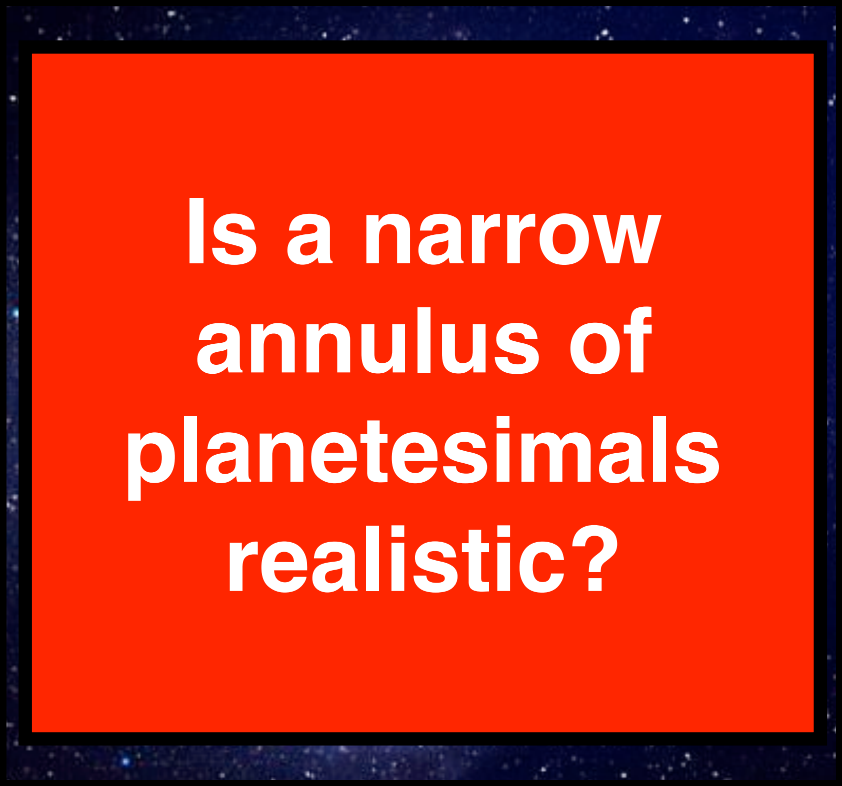
- NEW: Timing is uncertain — anytime before ~100 Myr
(Zellner 2017; Morbidelli et al 2018; Nesvorny et al 2018; Mojzsis et al 2019; Hartmann 2019)

Tsiganis et al 2005; Morbidelli et al 2007; Levison et al 2011; Nesvorny & Morbidelli 2012; Batygin & Brown 2012



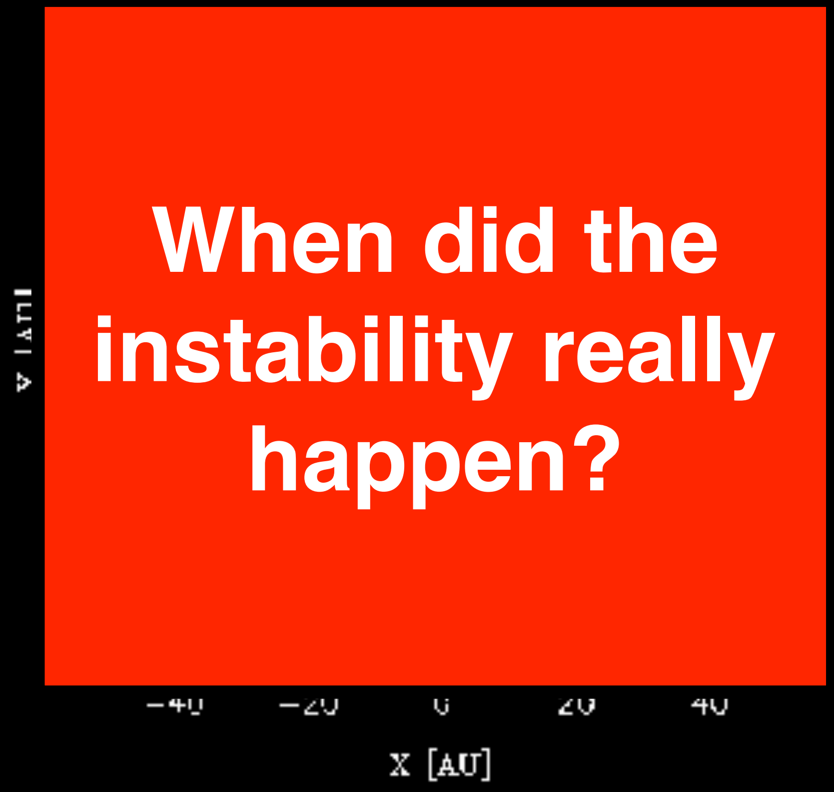
Clement et al (2019)

3 possible solutions to the small Mars problem

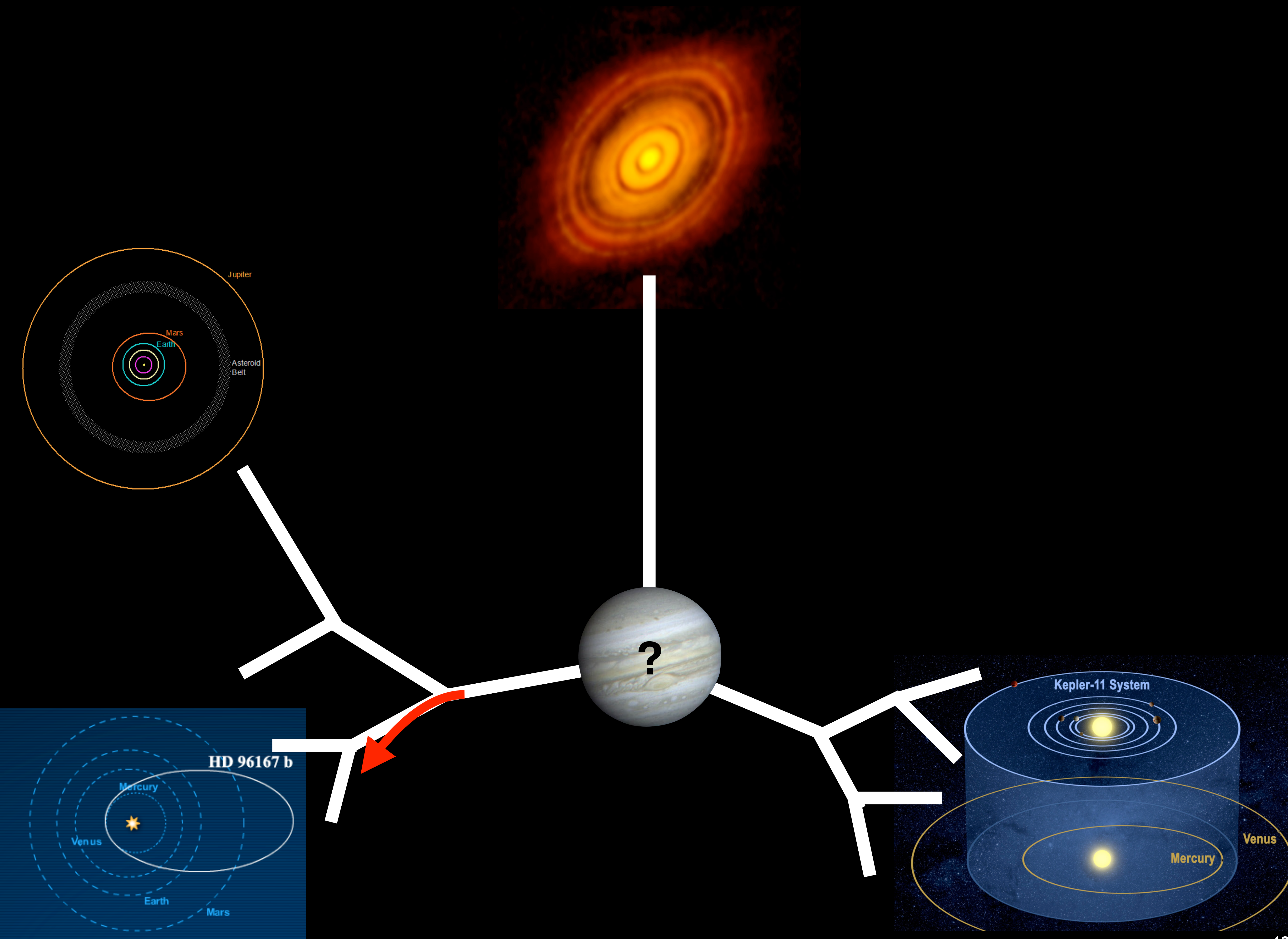


“Low-mass asteroid belt”

The “Grand Tack”



Early instability


Jupiter
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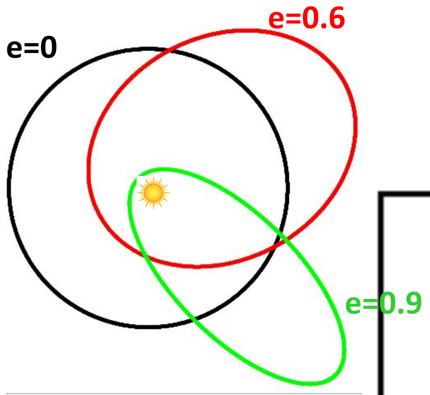
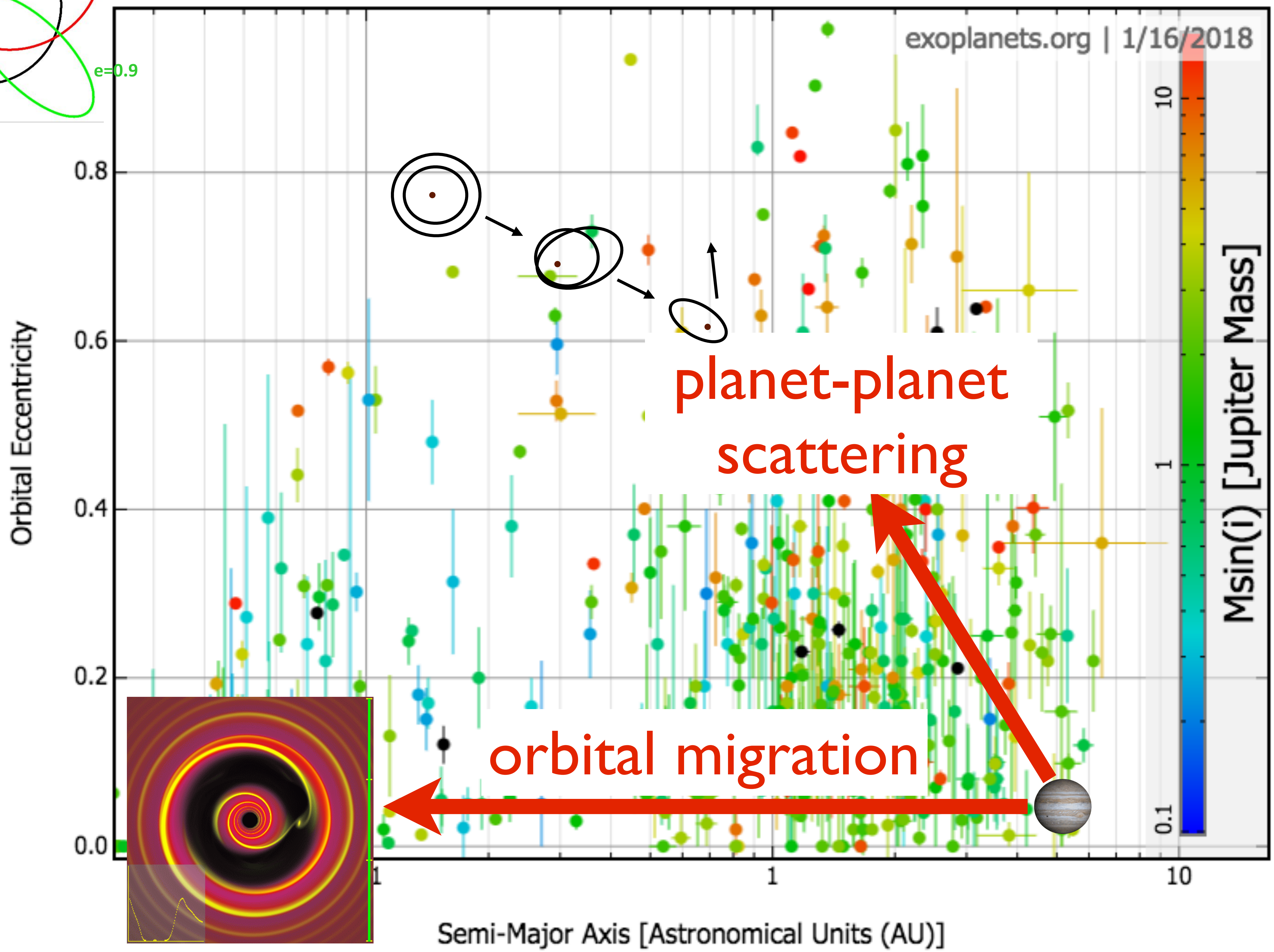
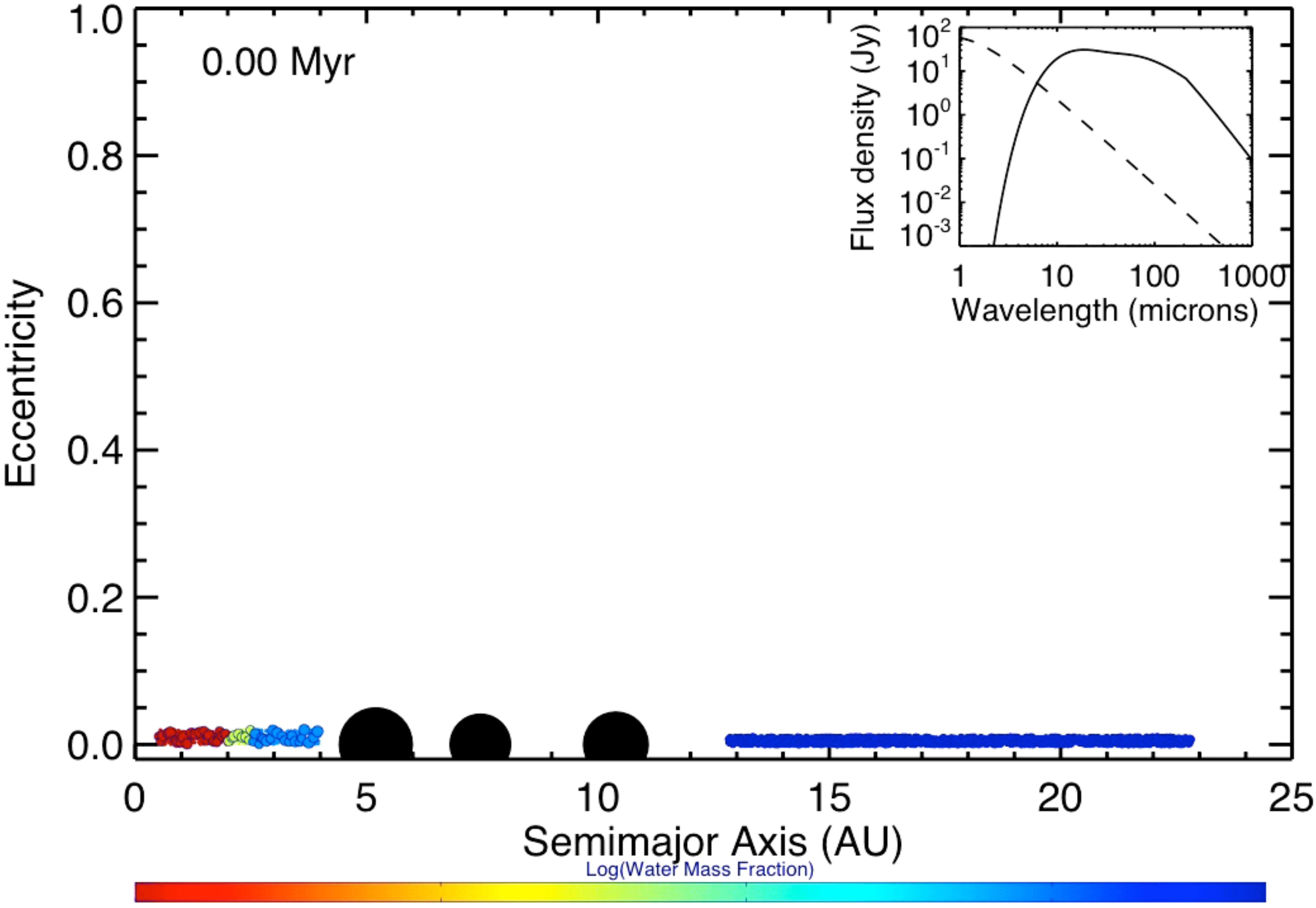
Giant exoplanets





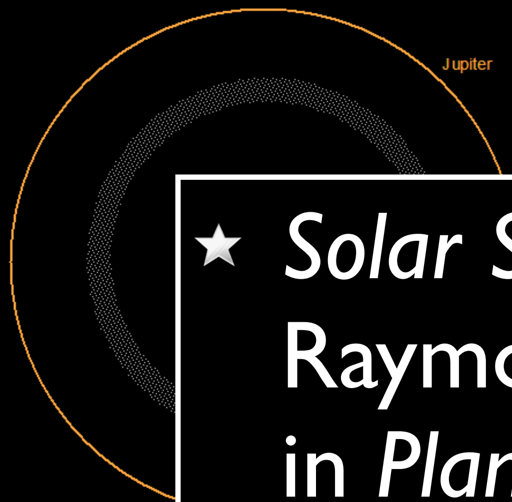
Planet-planet scattering

Credit: Eric Ford



Raymond et al 2012

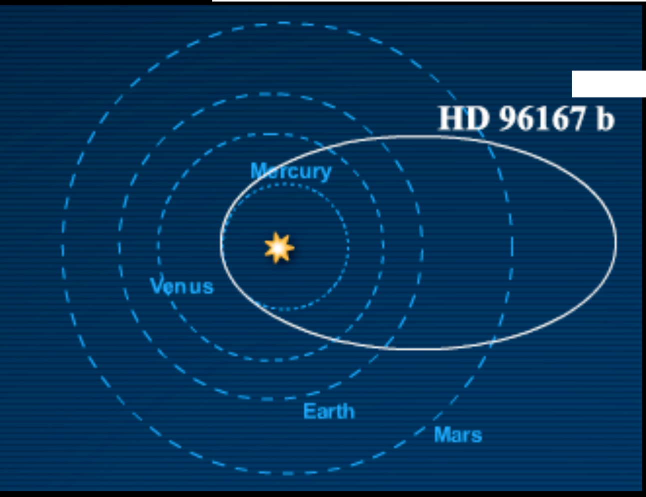
More information

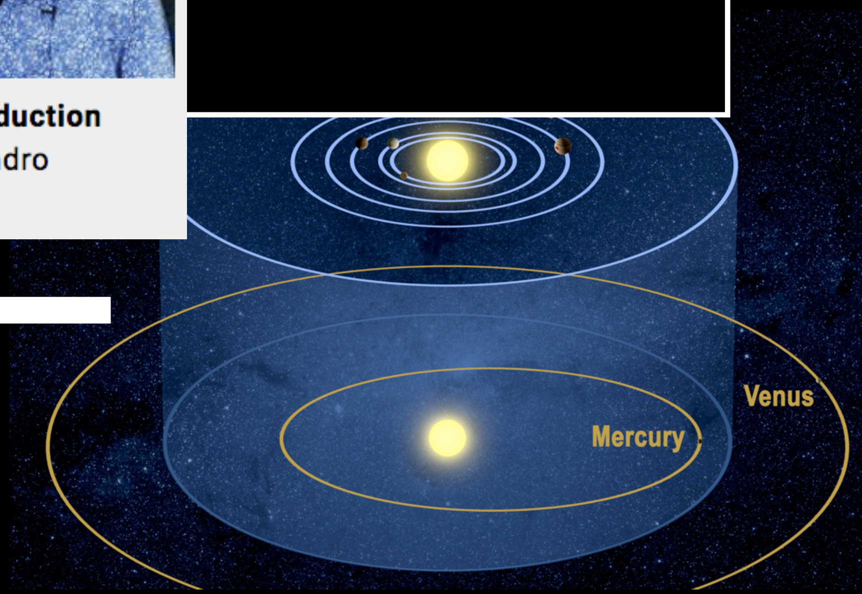


- *Solar System formation in the context of extra-solar planets* Raymond, Izidoro, & Morbidelli 2018 (Chapter to appear in *Planetary Astrobiology*; arxiv:1812.01033)

- The MOJO videos (YouTube)

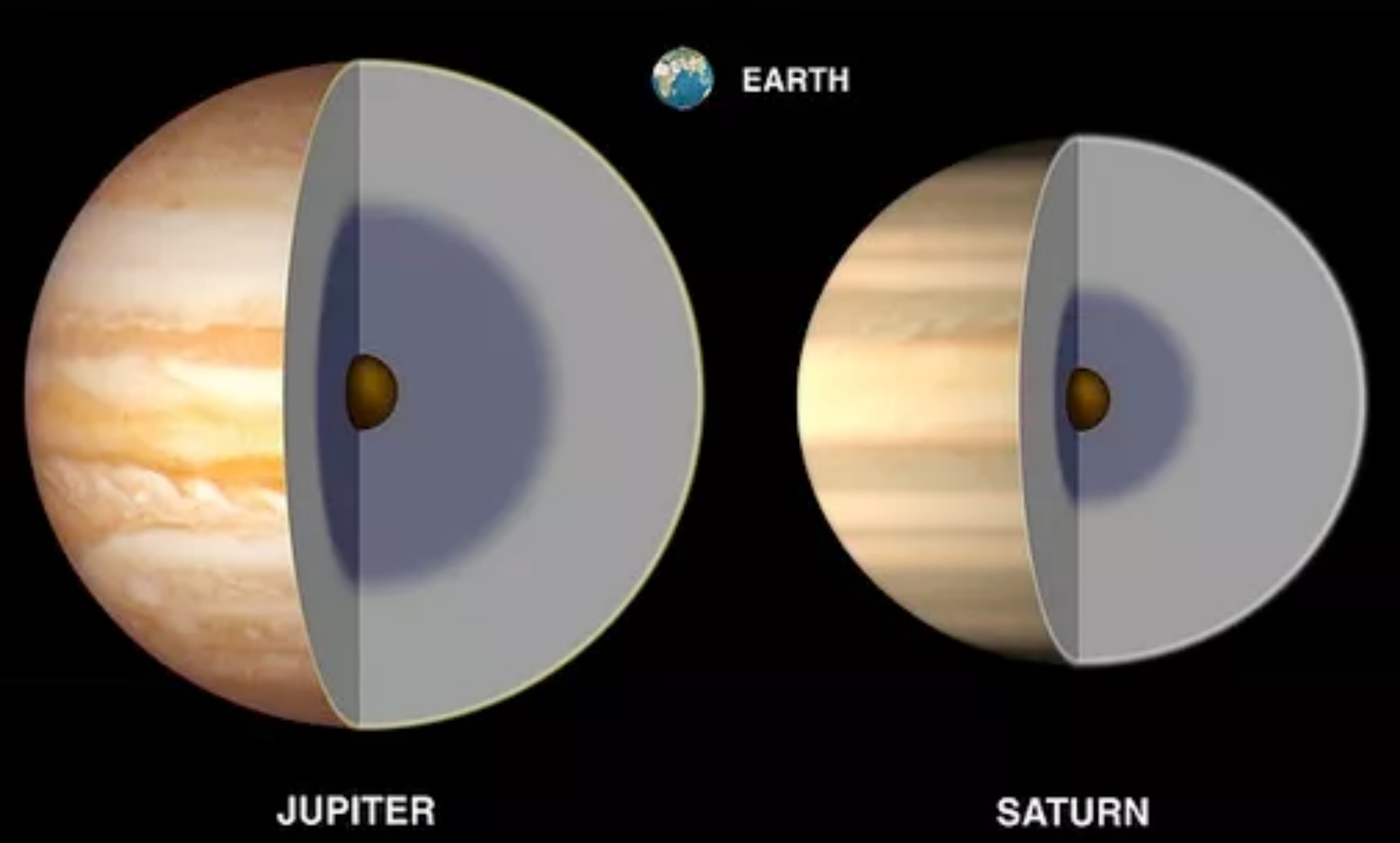
- planetplanet.net





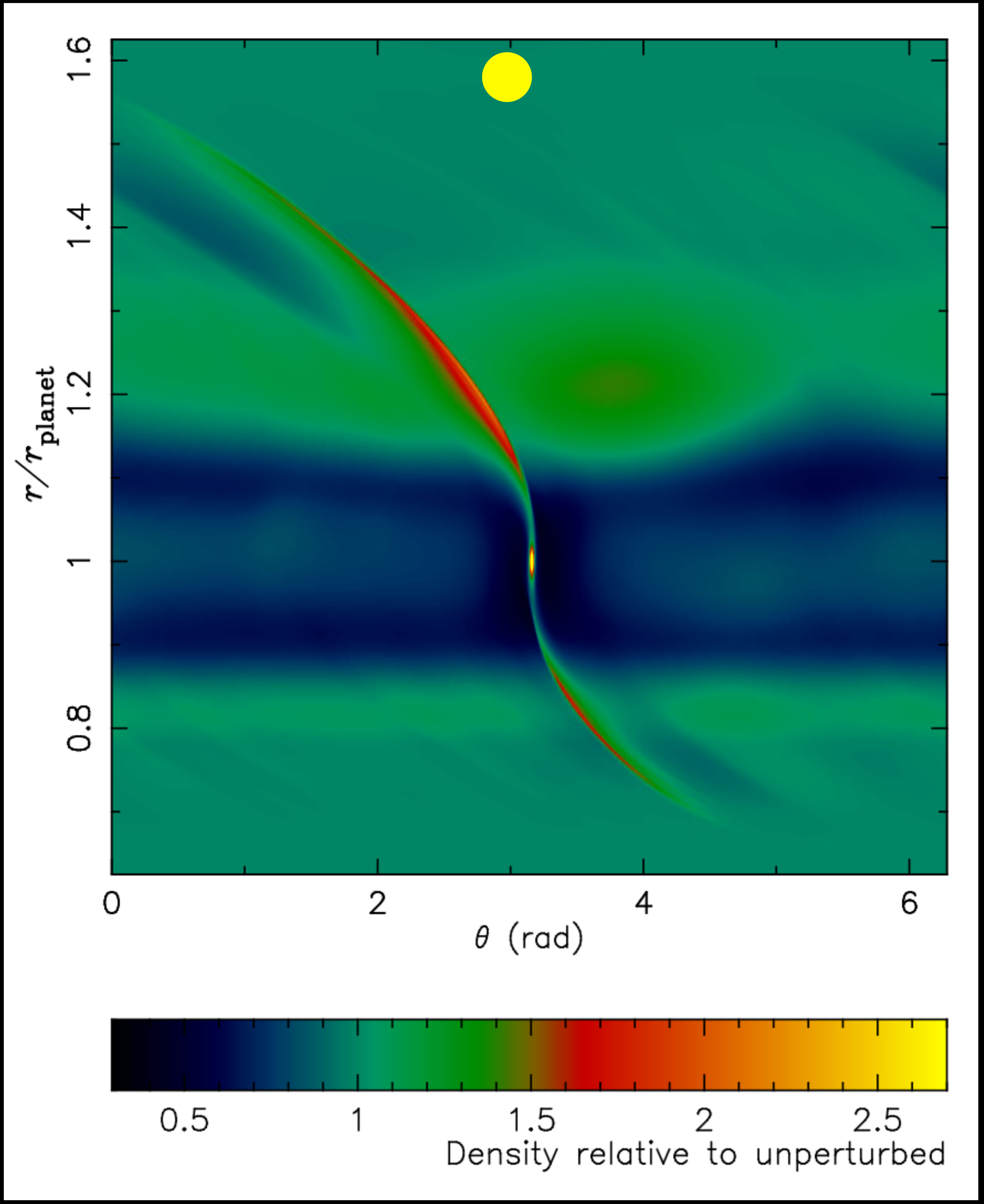
Extra Slides

Core accretion



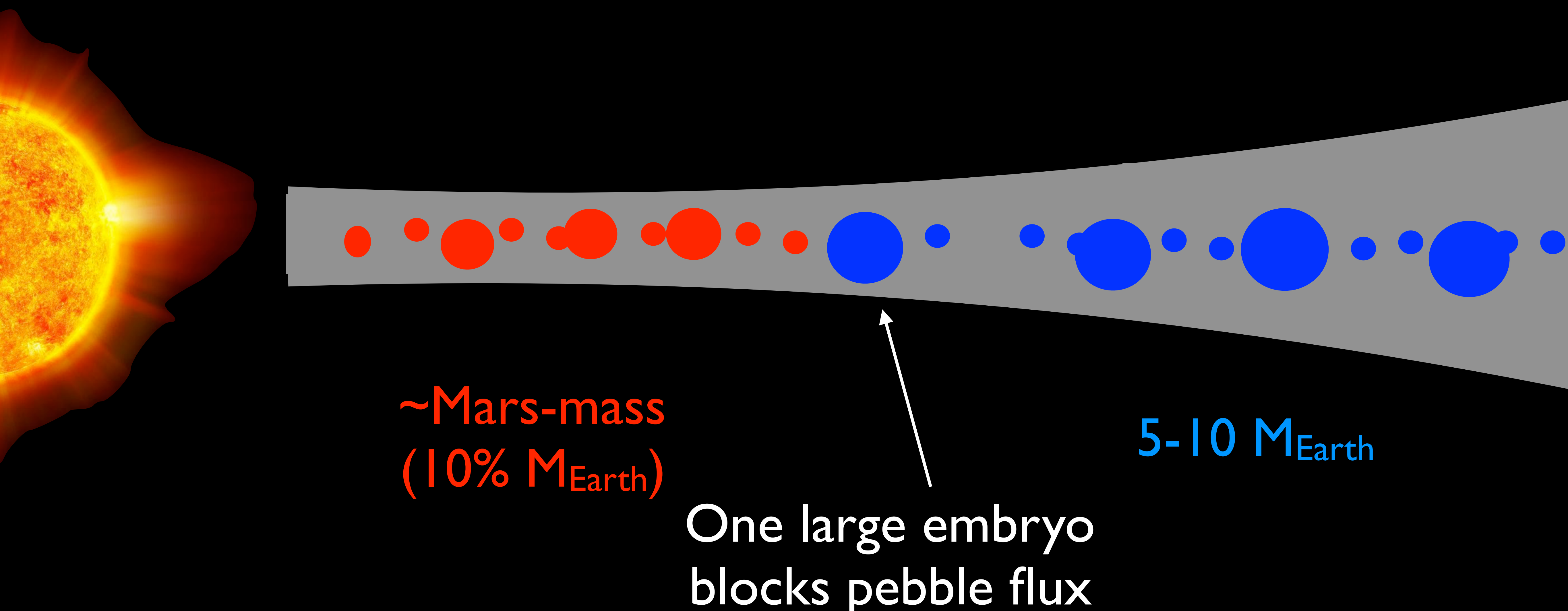
Large cores block pebble flux

“Pebble isolation” mass:
~20 ME for typical disk at Jup’s orbit

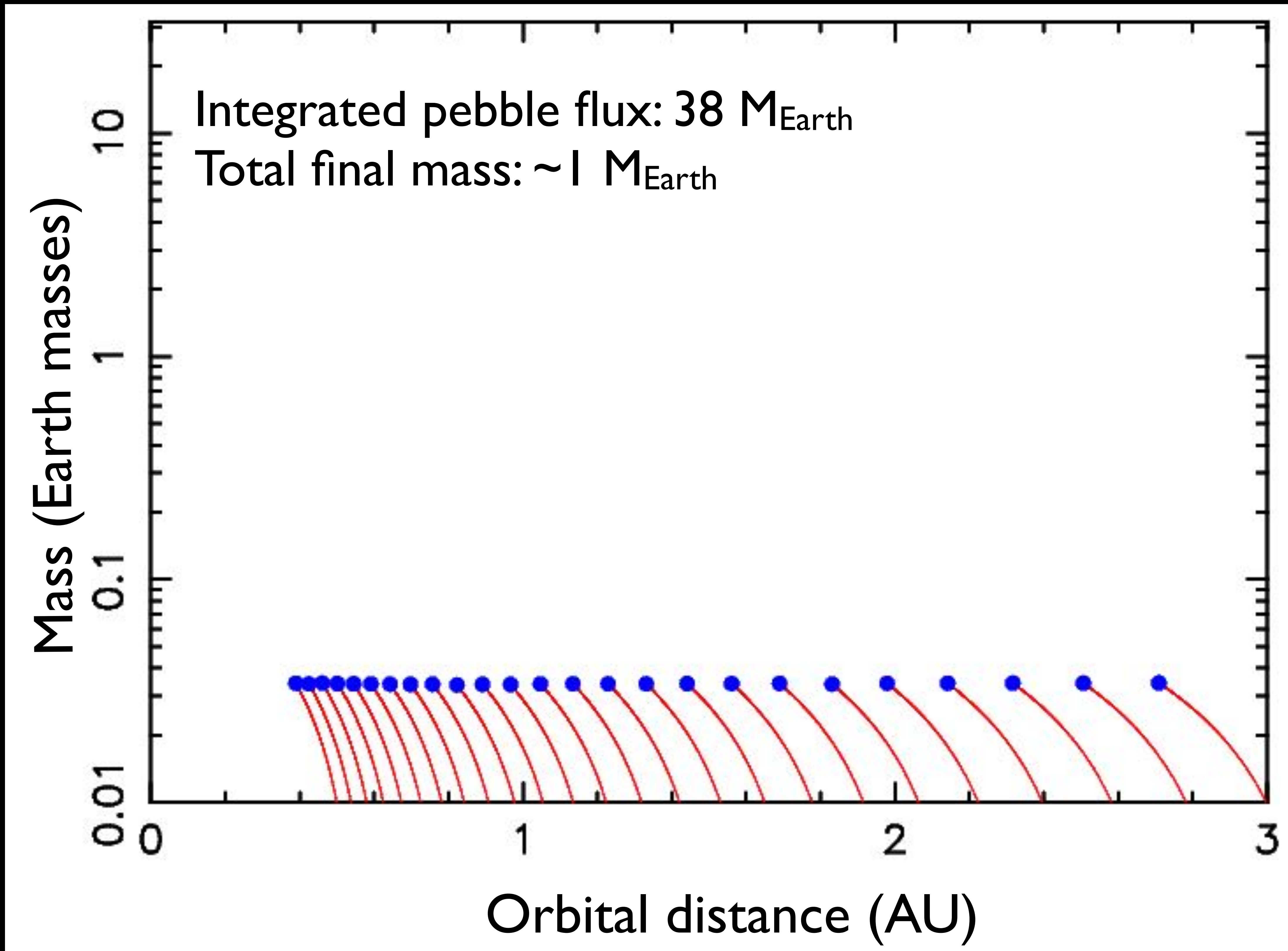


Lambrechts et al (2014); Bitsch et al (2018)

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

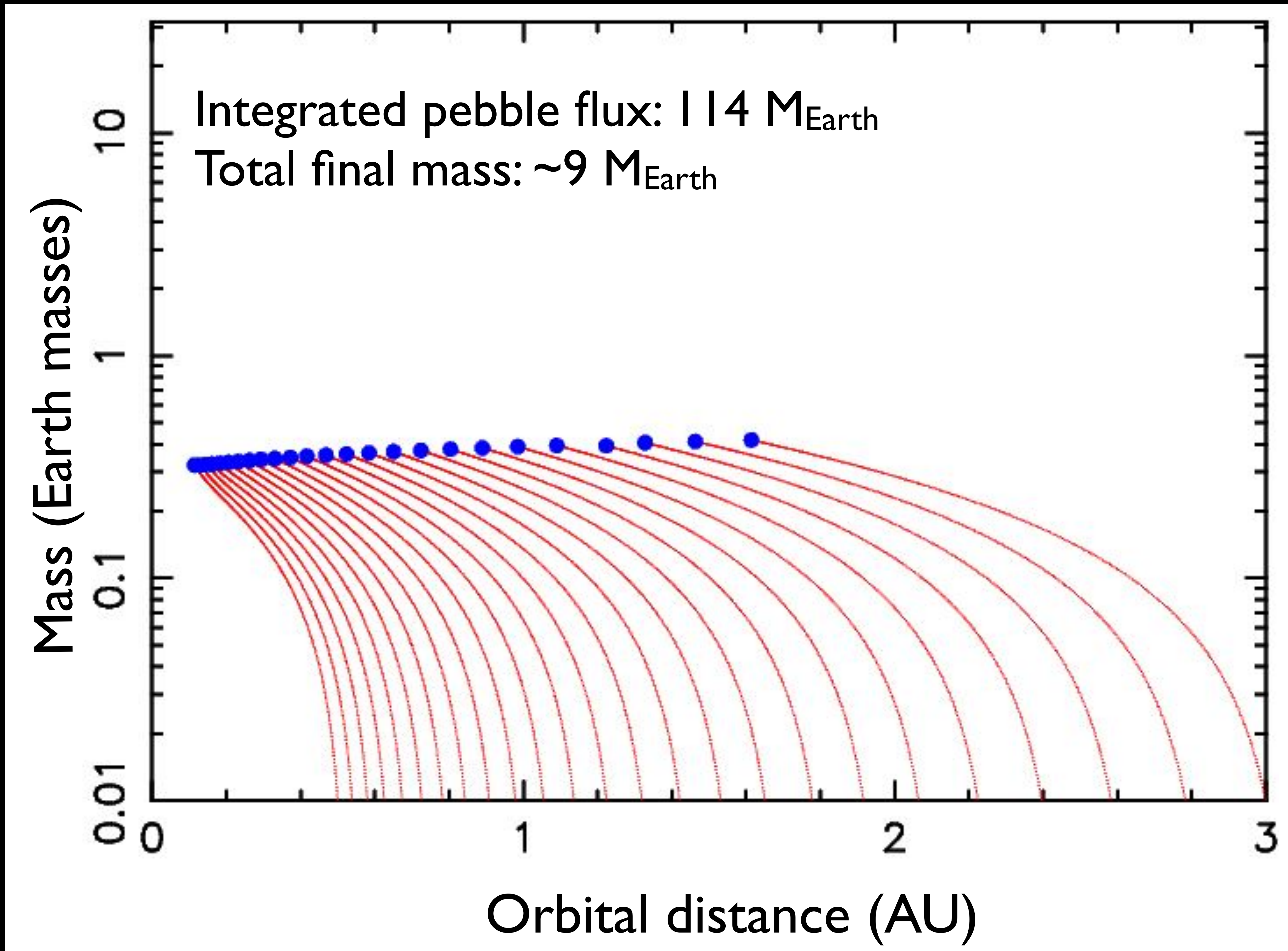


Morbidelli et al (2015); Lambrechts et al (2019)



Lambrechts et al (2019)

Slide courtesy Seth Jacobson



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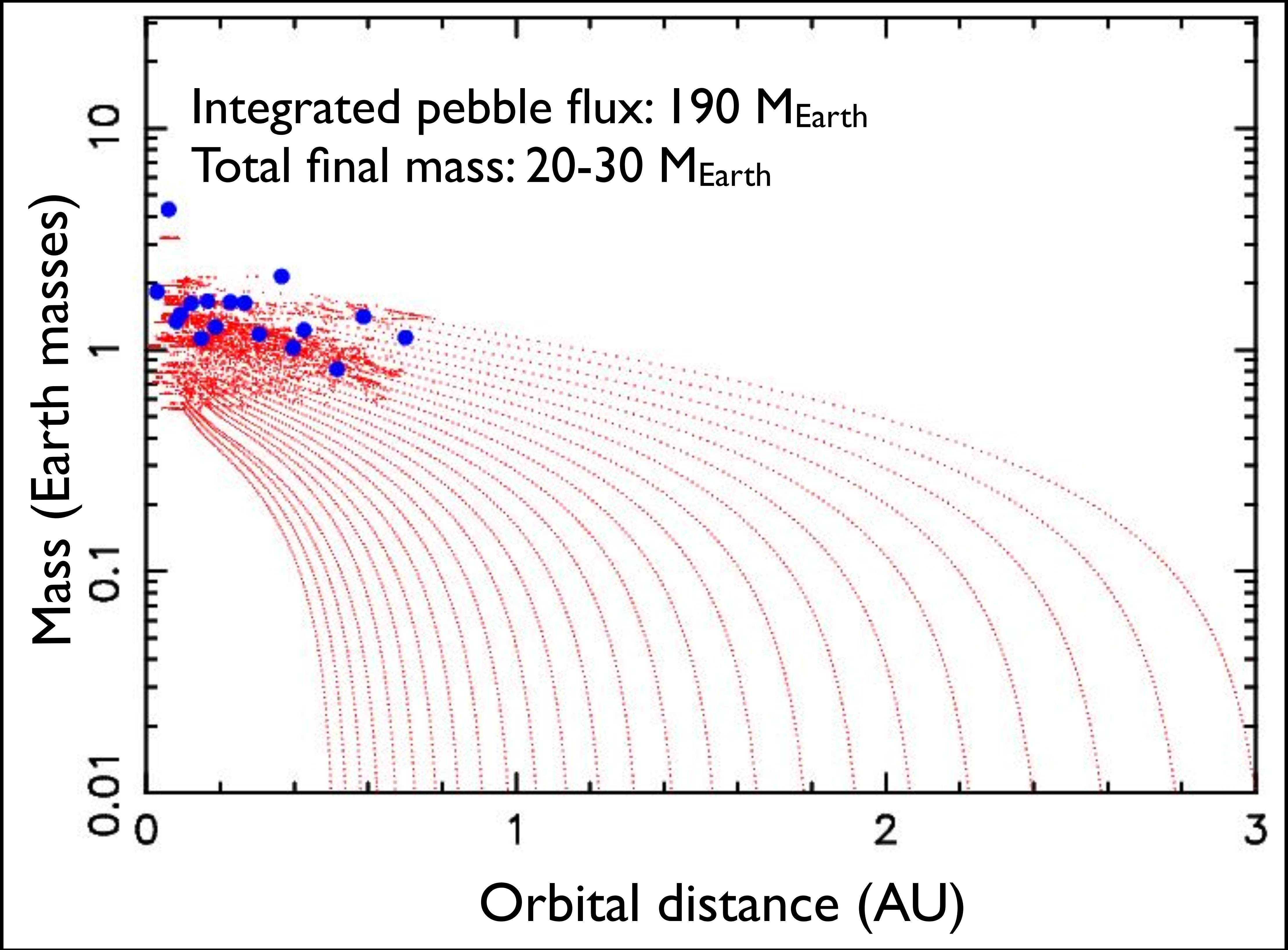

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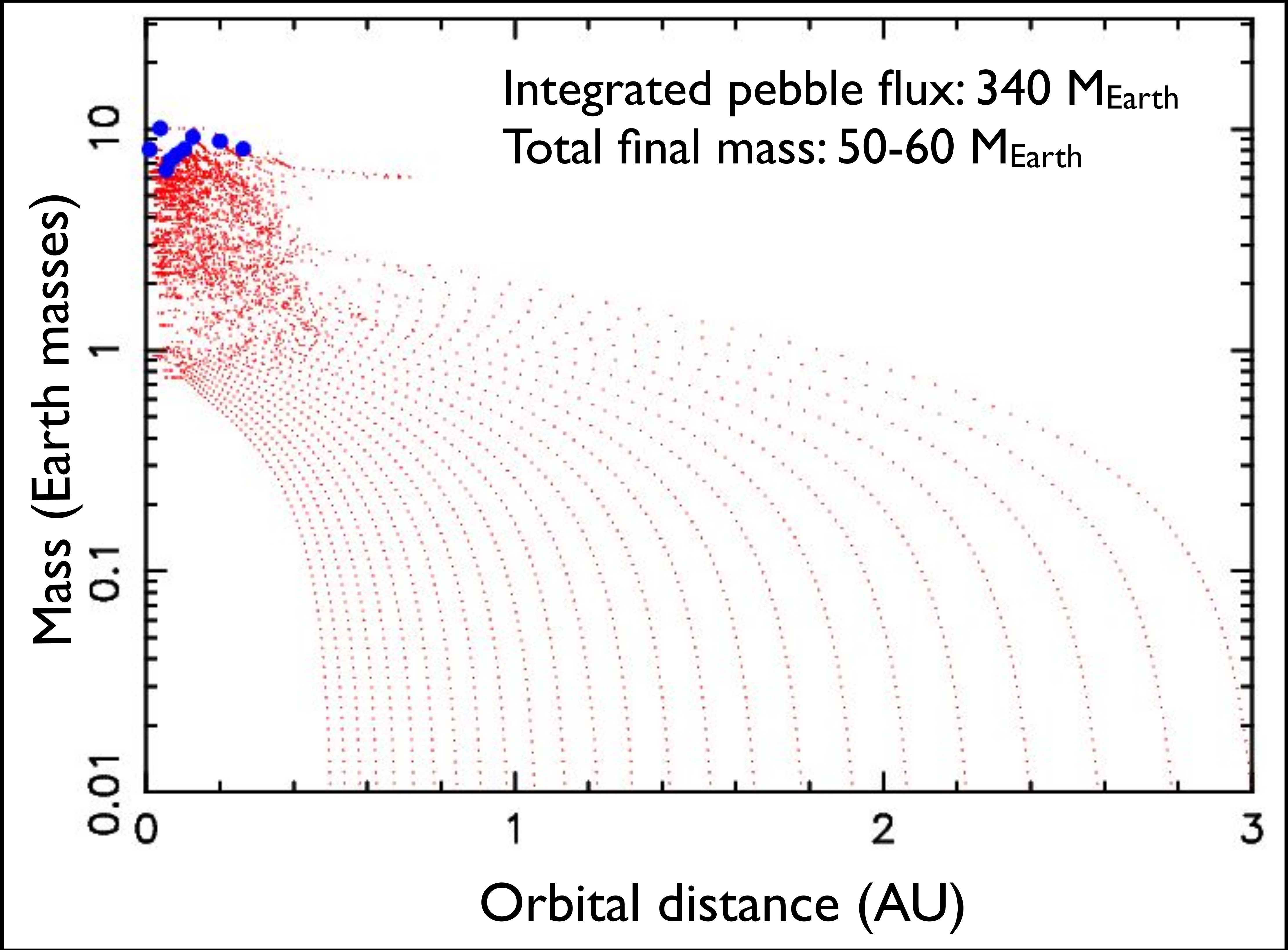
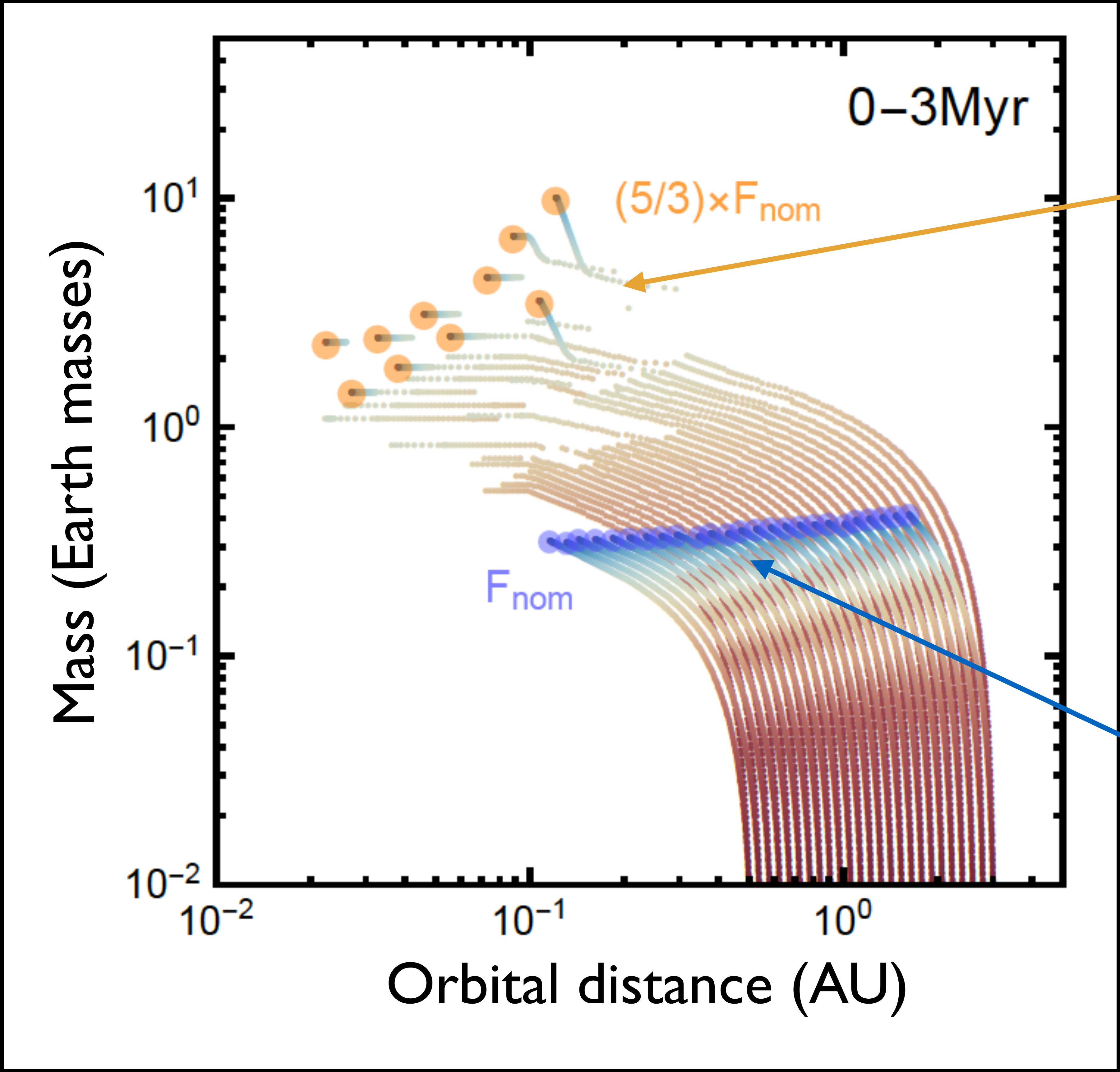


Lambrechts et al (2019)

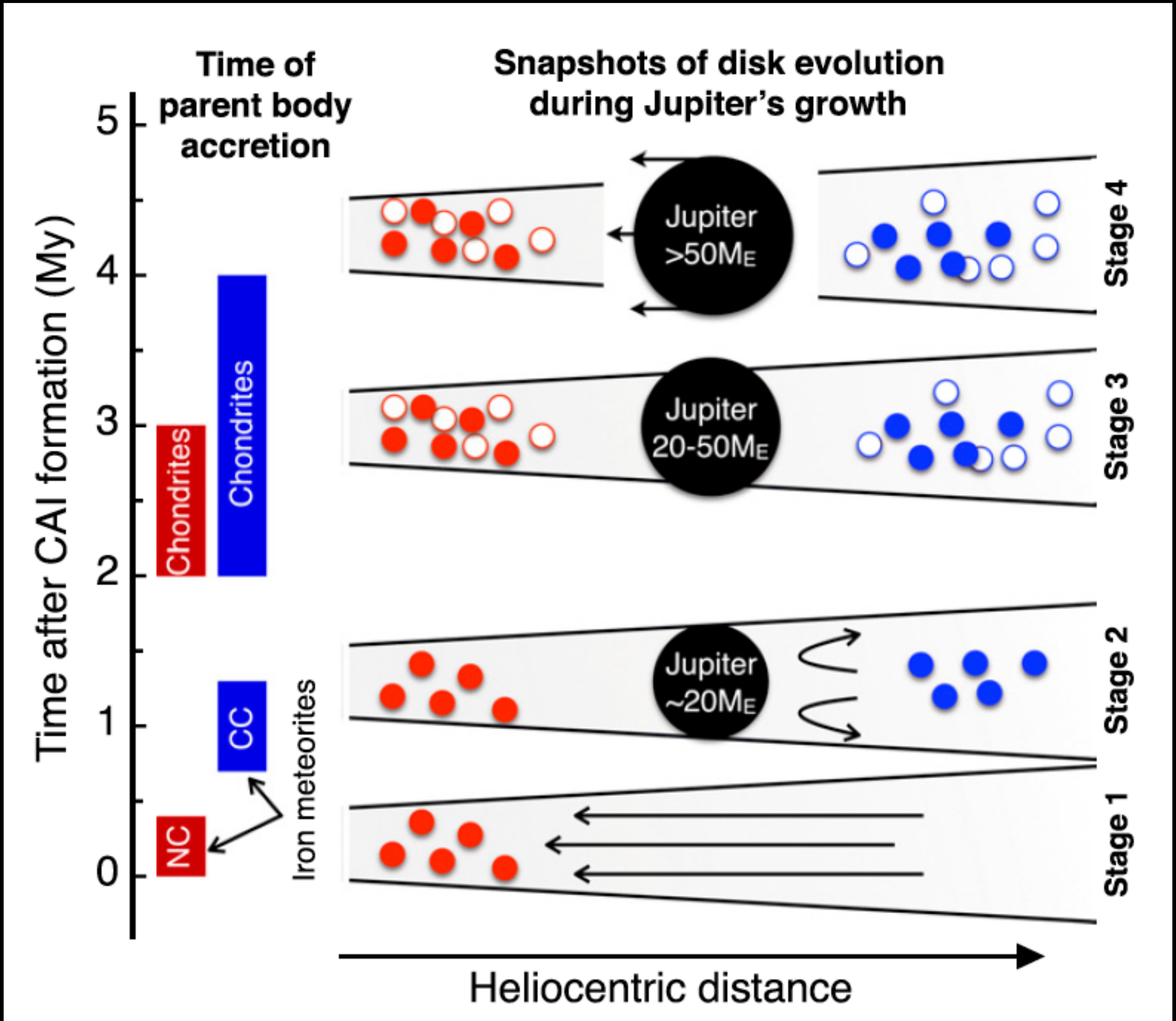


Continuous pebble flux: **super-Earths**

Pebble flux blocked: **terrestrials**

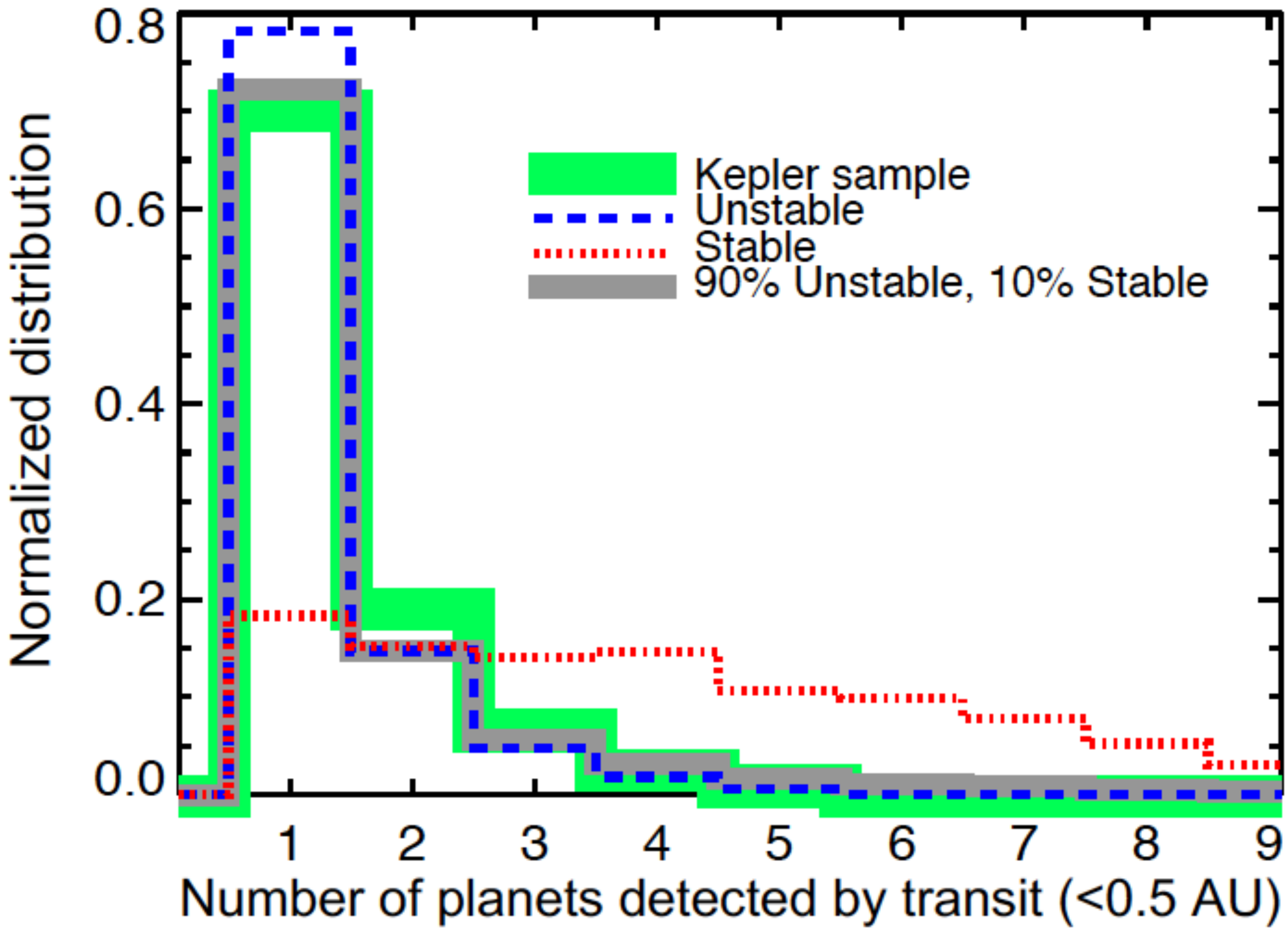
Lambrechts, Morbidelli, Jacobson et al (2019)

Meteoritic evidence for early growth of Jupiter's core



Kruijer et al 2017

Also match multiplicity distribution (the "Kepler dichotomy")



Izidoro et al (2017)