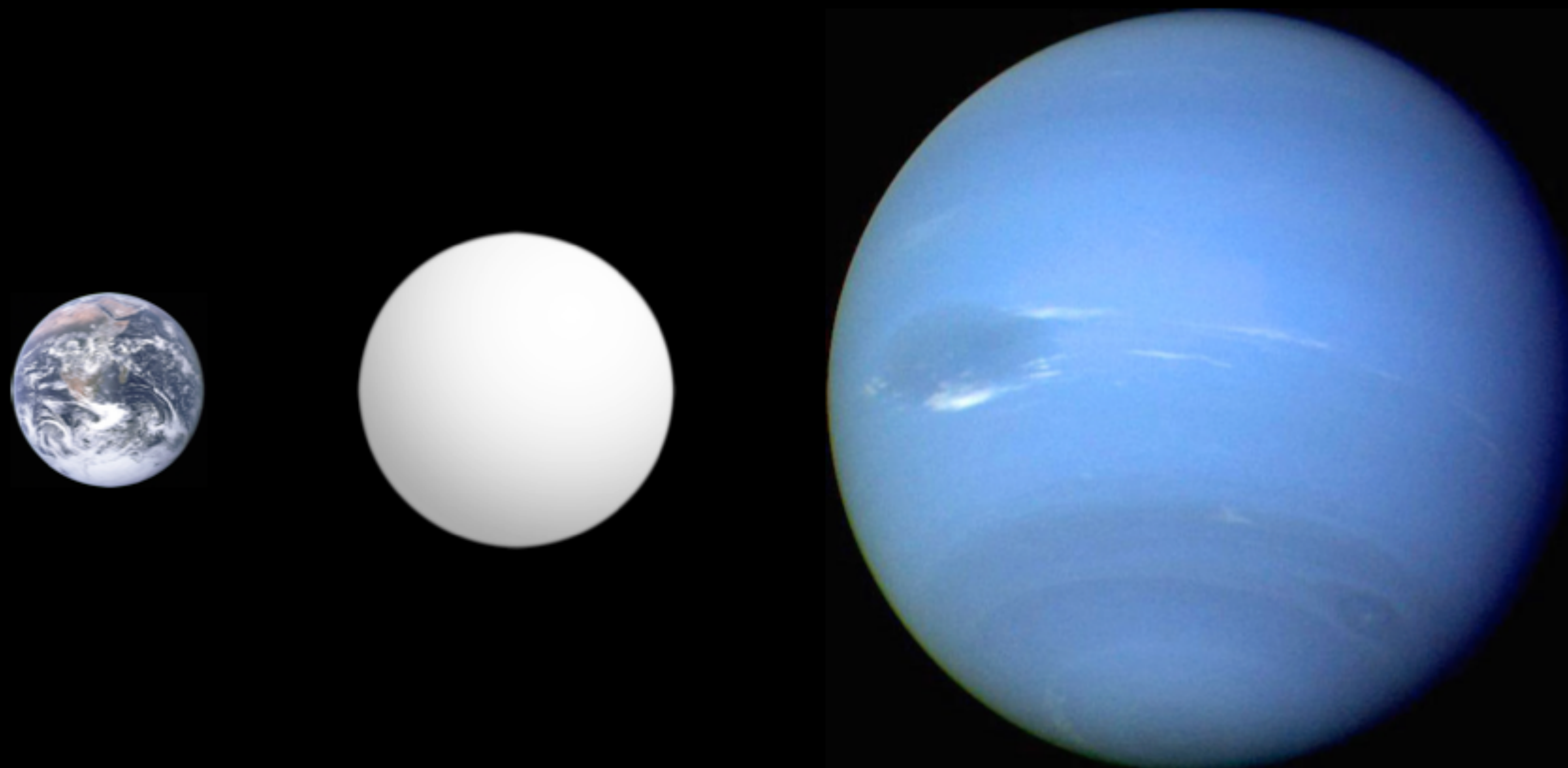
How do hot super-Earths and mini-Neptunes form?

Sean Raymond
Laboratoire d'Astrophysique de Bordeaux

Collaborators: C. Cossou, A. Izidoro, A. Morbidelli, A. Pierens, F. Hersant, R. Barnes, A. Mandell

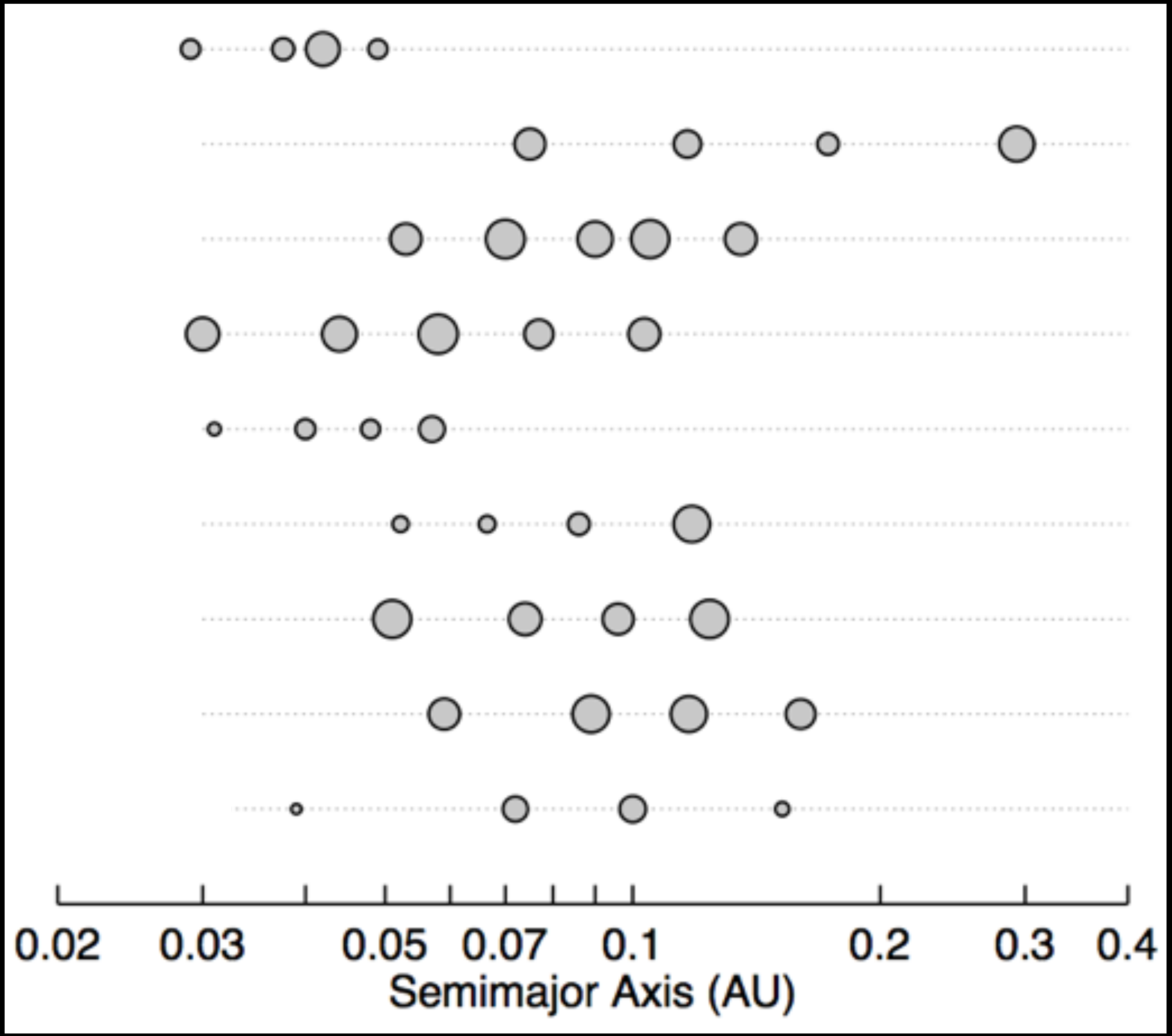


$R = 1\text{-}4\ R_{Earth}$

$M \sim 1\text{-}30\ M_{Earth}$

Hot Super Earths

- Exist around 30-50% of MS stars (Mayor et al 2011; Howard et al 2010, 2012; Fressin et al 2013; Petigura et al)
- Multiple systems (e.g., Lovis et al 2011; Lissauer et al 2011)
- Compact, non-resonant orbits (Lissauer et al 2011b)



Raymond et al PP6 review; Kepler data from Batalha et al 2013 and Rowe et al 2014

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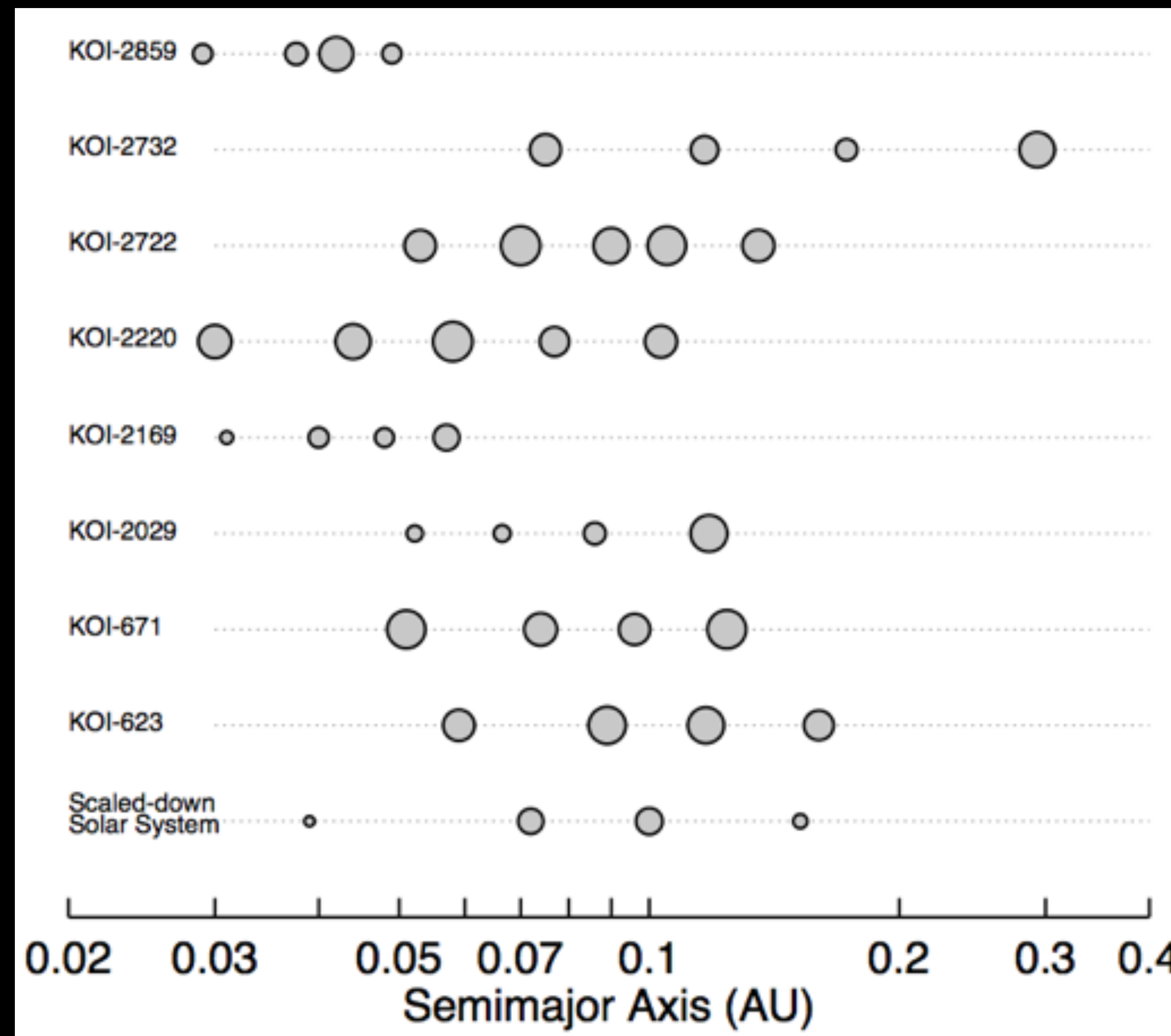

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"Hot Earth" form. model	System Architecture	Hot Earth Composition
In Situ Formation	Several hot Earths, spaced by ~40 R_{Hill}	Dry
Type 1 Migration	Chain of hot Earths in/near resonance	Icy
Giant planet shepherding	Hot Earth just inside strong giant planet resonances (2:1)	Moderate: few percent water by mass
Sec. Res. shepherding	Hot Earths with two interacting giants	?
Photo-evaporation	Correlation with stellar age	Icy (giant planet core)
Tidal Circularization	Isolated hot Earth, eccentricity source	?

Raymond, Barnes & Mandell 2008

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Still viable

Raymond, Barnes & Mandell 2008

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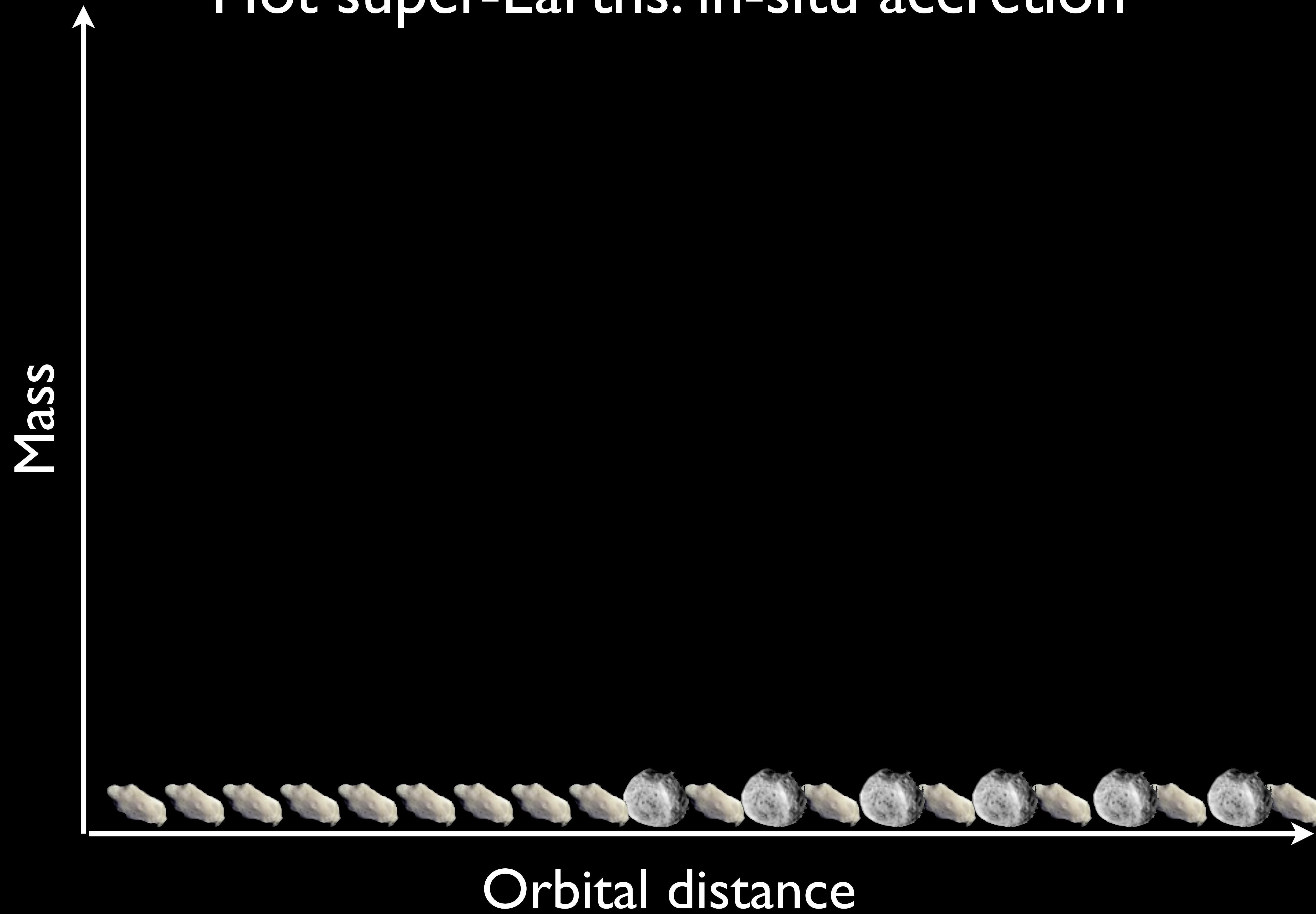
Hot super-Earths: in-situ accretion



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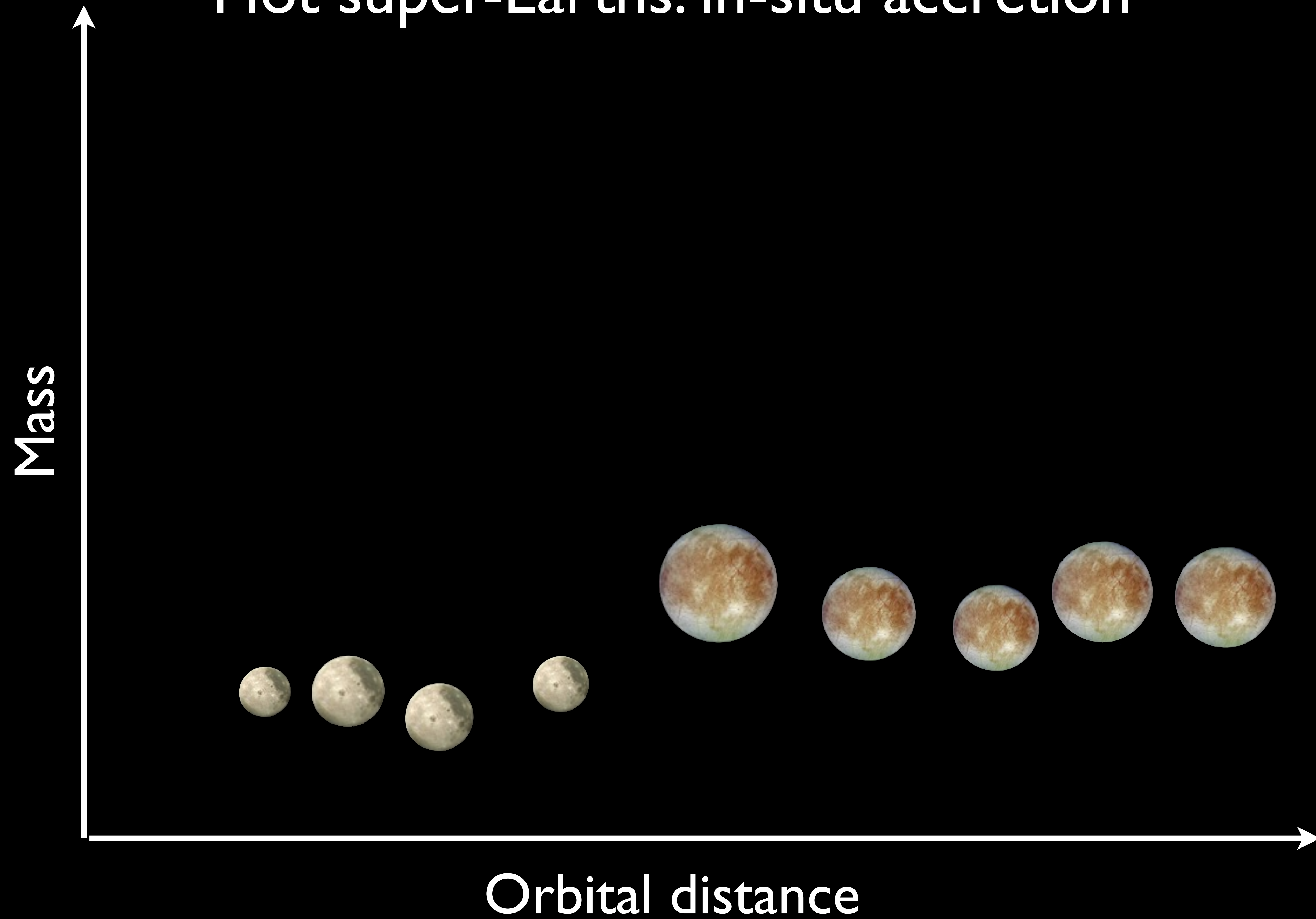

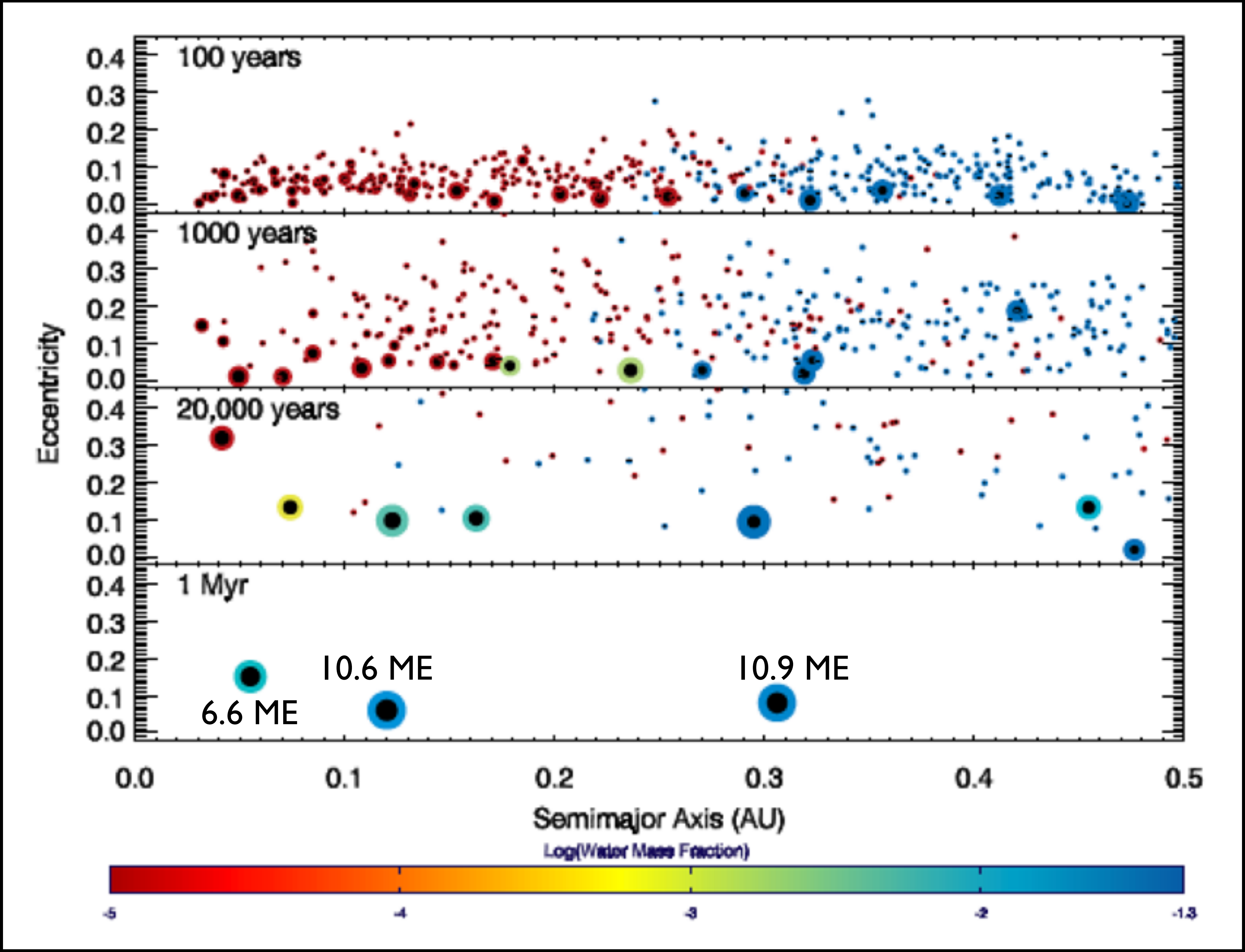

Raymond et al 2008

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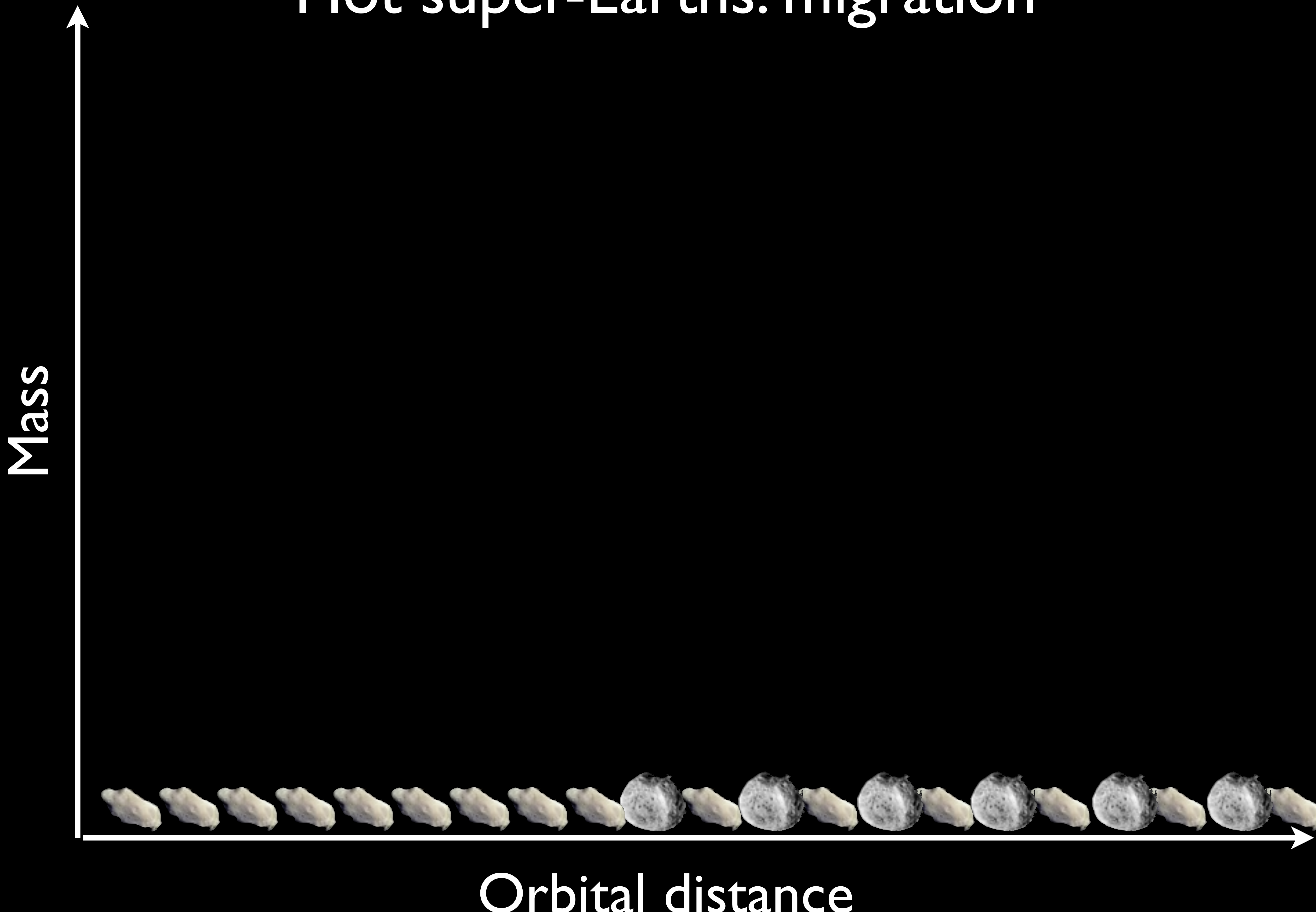
- Difficult to retain atmospheres more massive than 10^{-3} or so of solid mass (Inamdar & Schlichting 2015)

Hot super-Earths: migration



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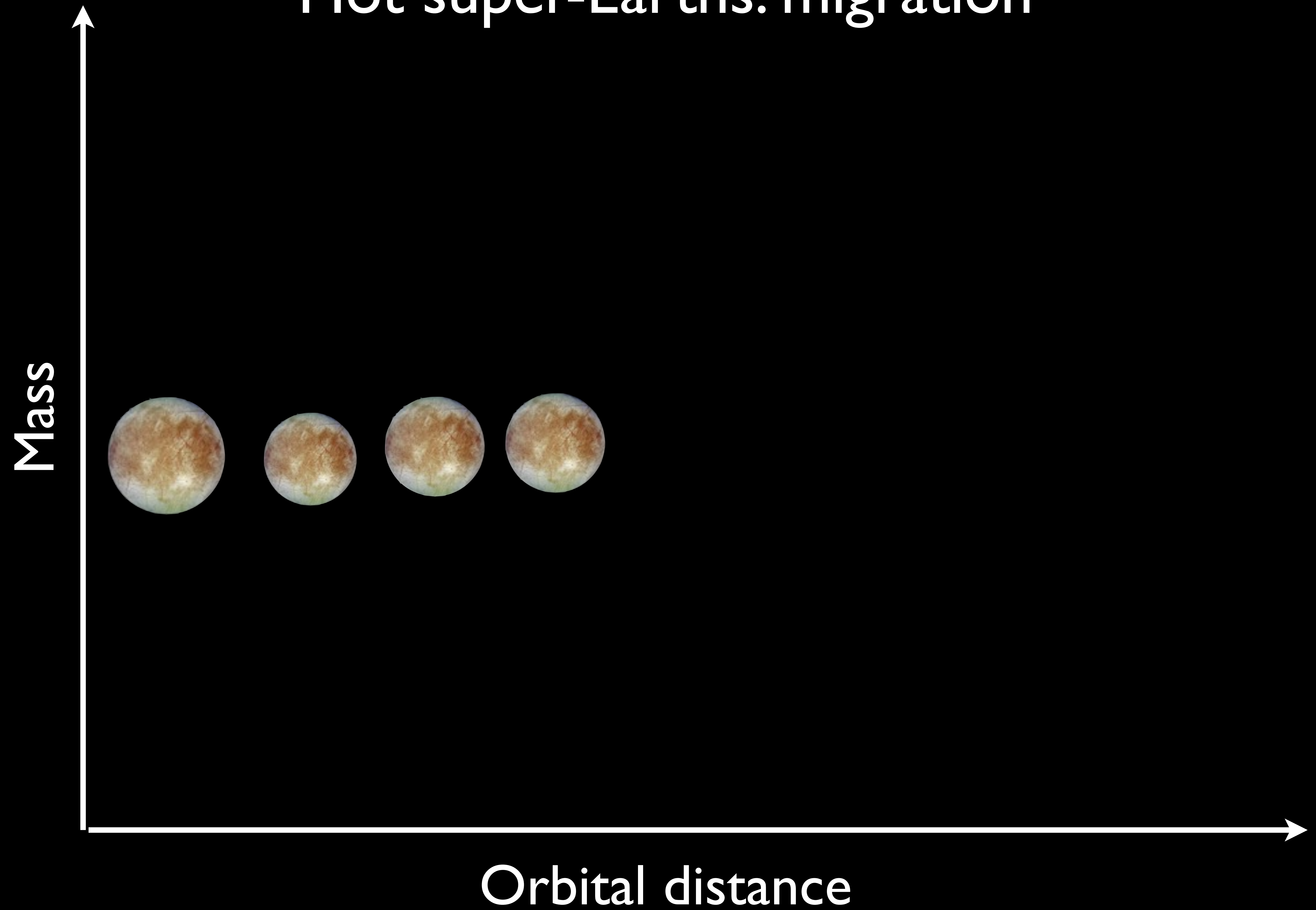
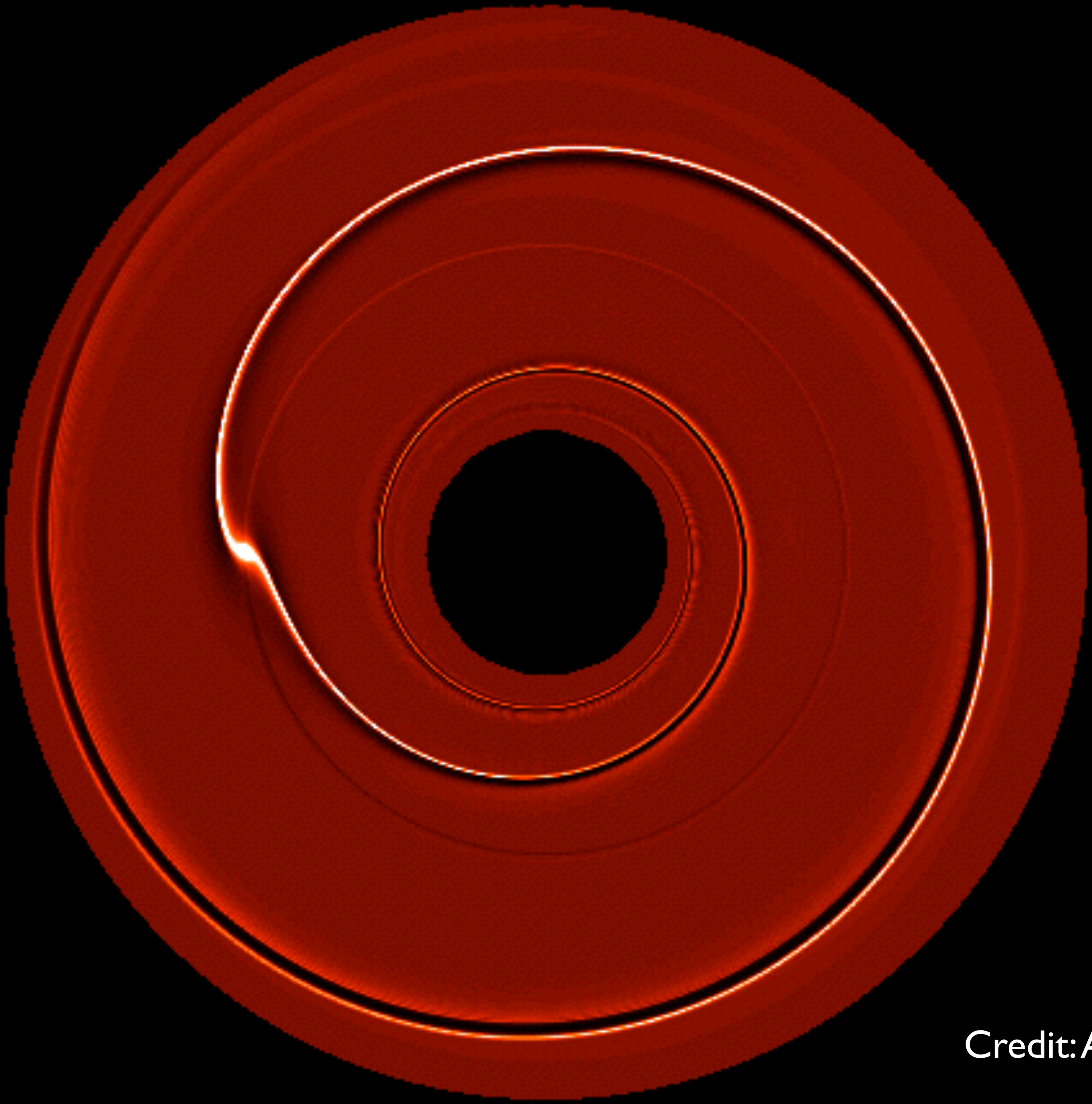


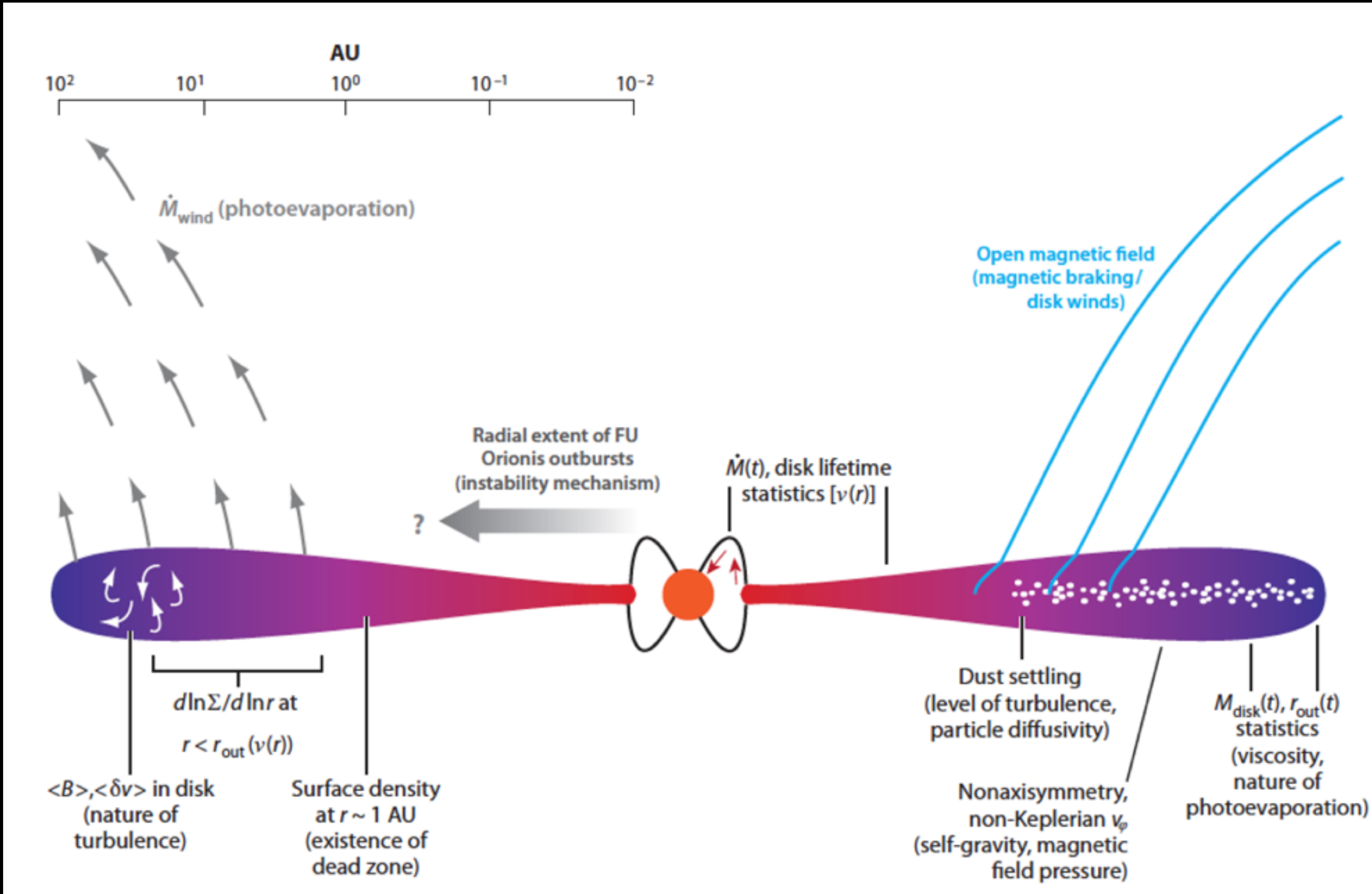
Type 1 migration

- Inward or outward
- Timescale ~10-100 kyr (bigger=faster)



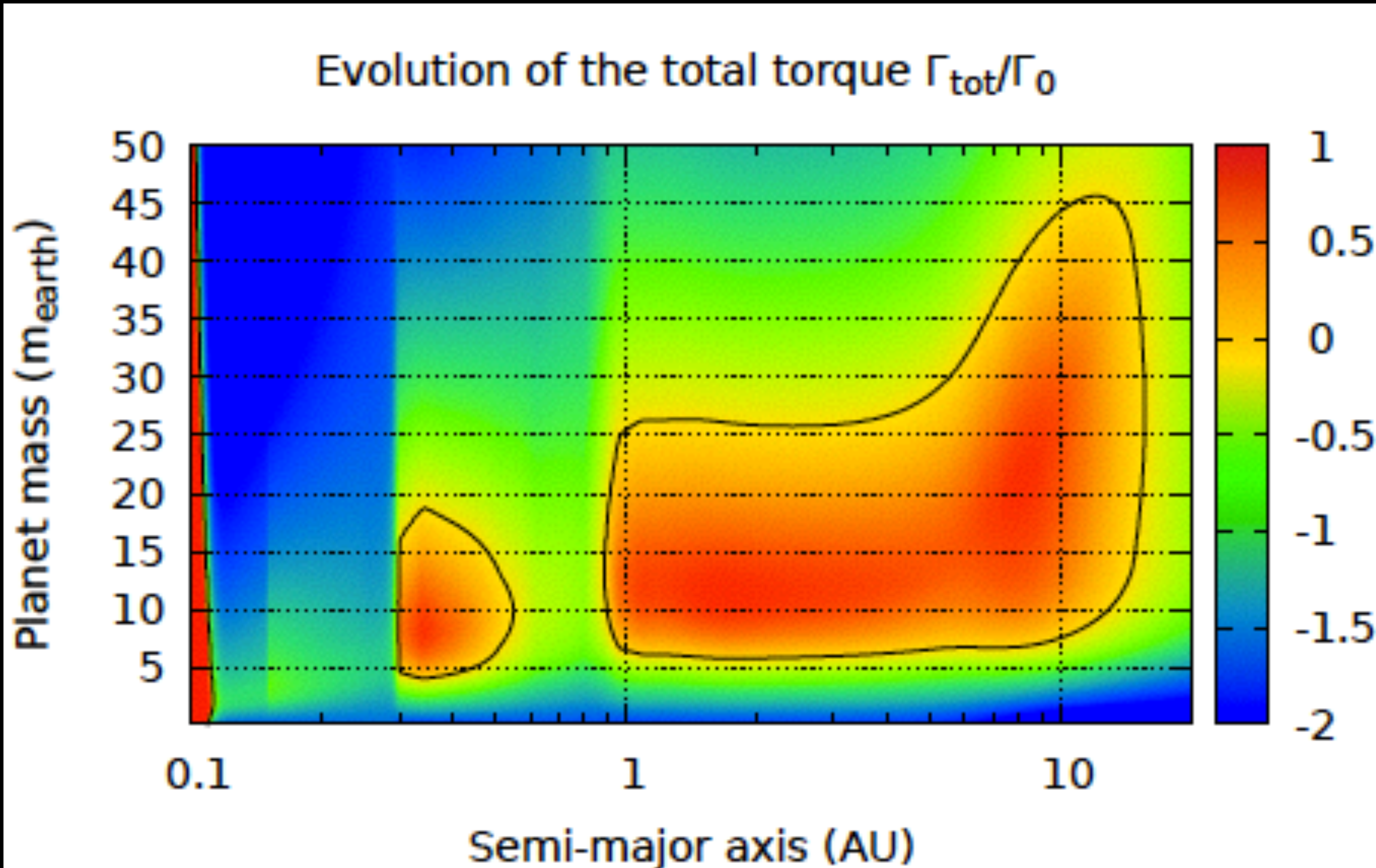
Credit: A. Pierens

Golreich & Tremaine 1980; Ward 1986, 1997; Tanaka et al 2002; Kley & Crida 2008; Paardekooper et al 2010, 2011; Pierens et al 2013; Lega et al 2014; Bitsch et al 2014

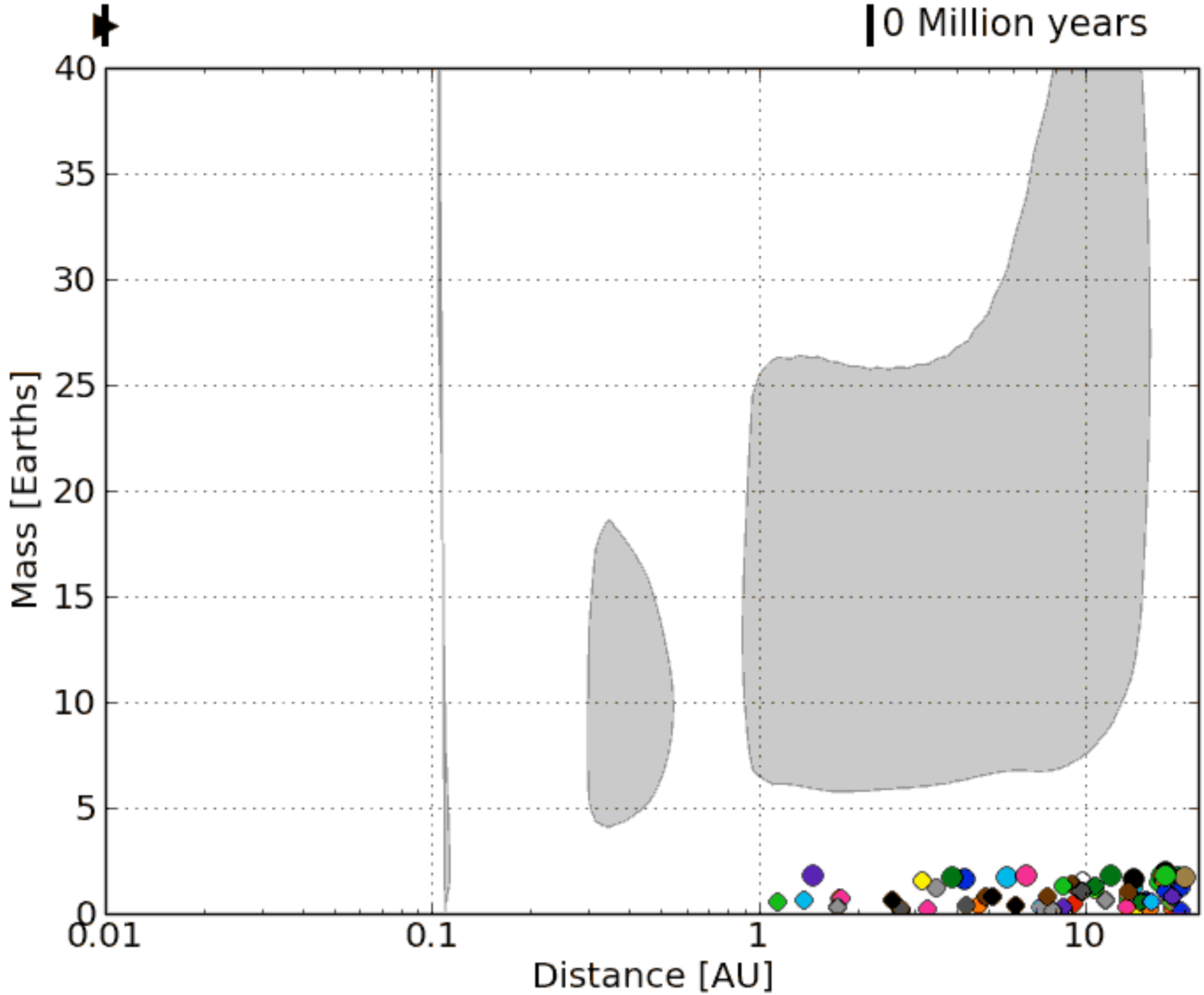


Armitage 2011

A type 1 migration “map”



Cossou et al 2014; see also Kretke & Lin 2012; Bitsch et al 2013, 2014abc



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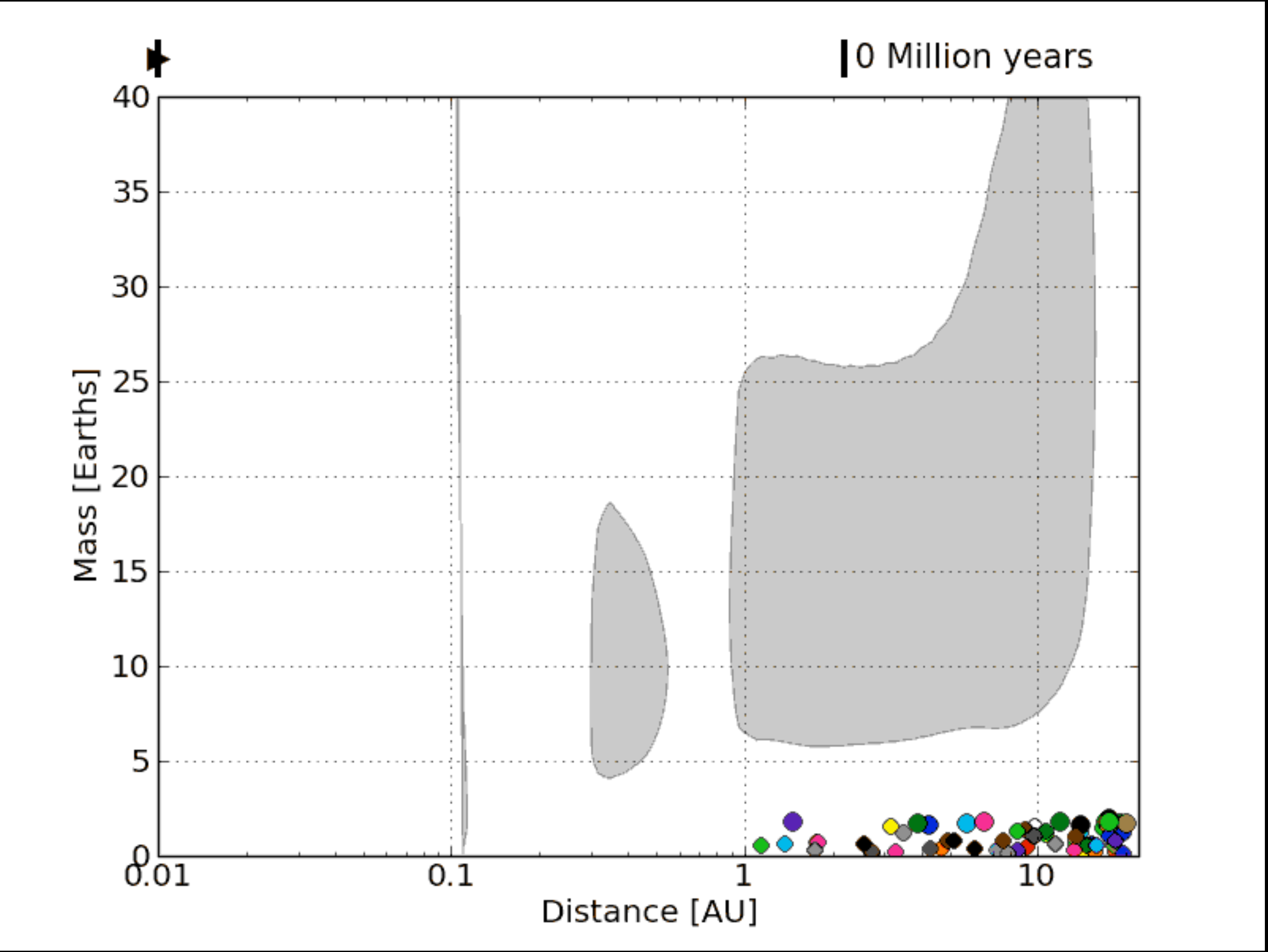

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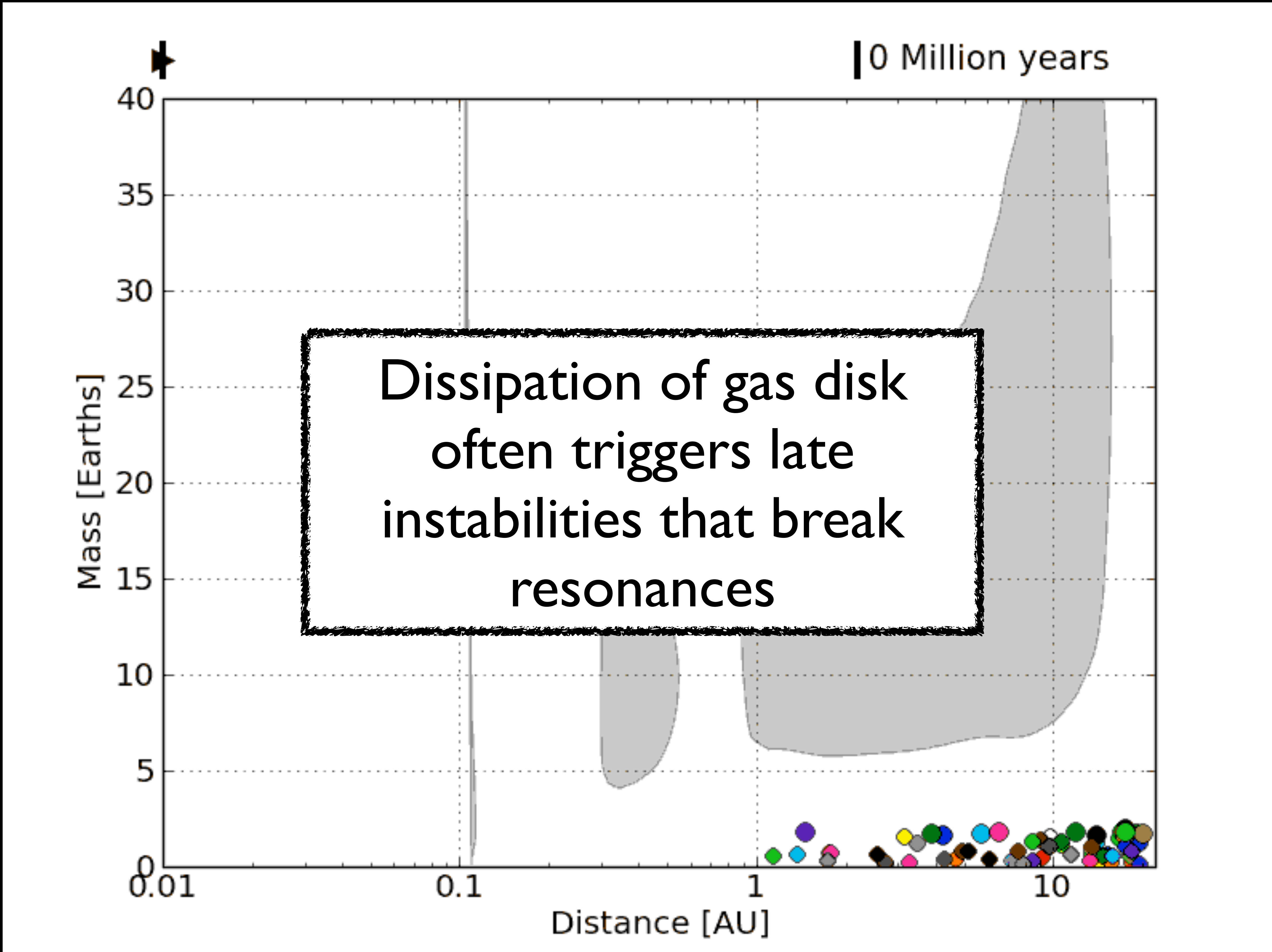
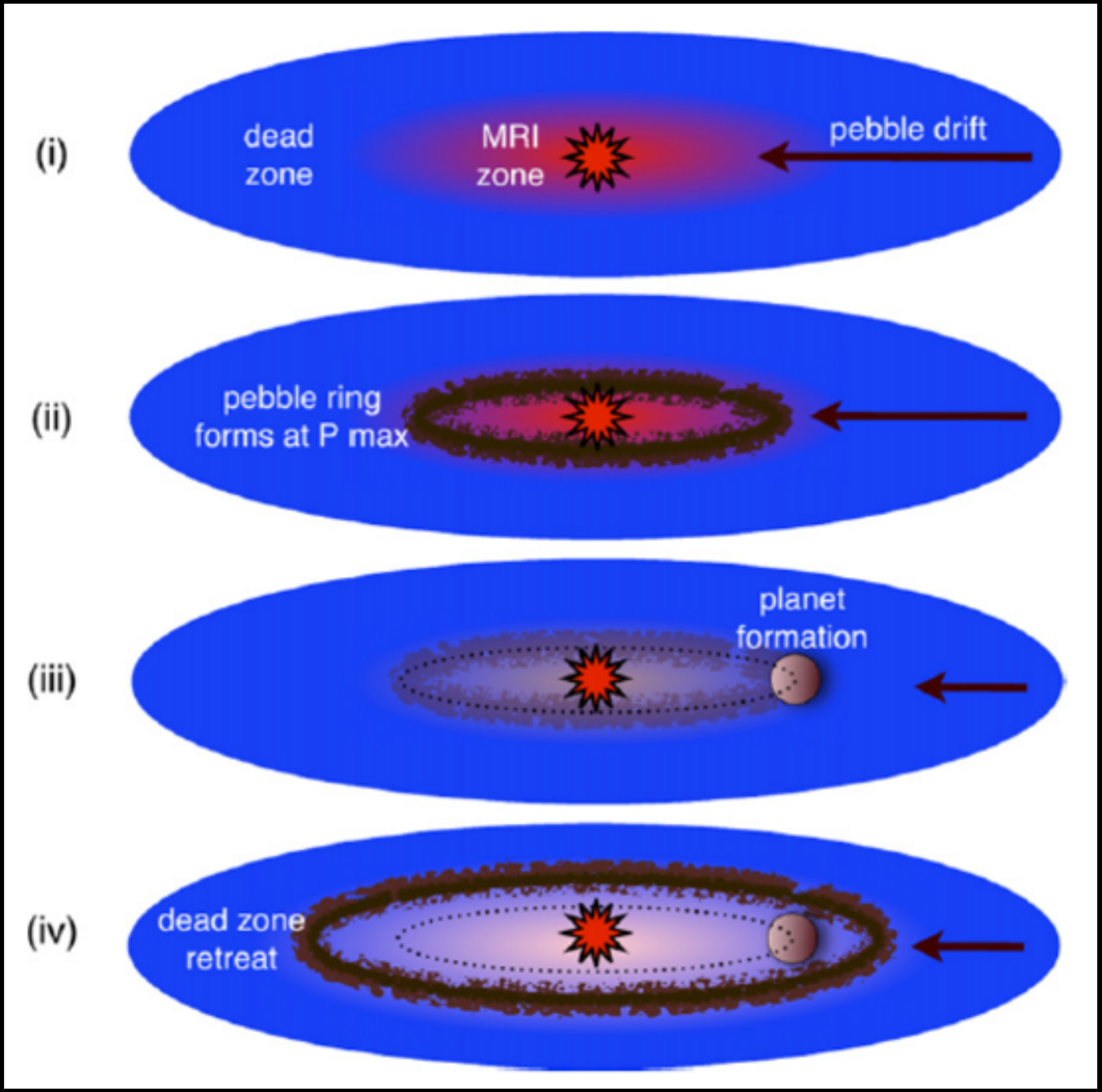


Dissipation of gas disk often triggers late instabilities that break resonances

Cossou et al 2014

Radial drift of small bodies

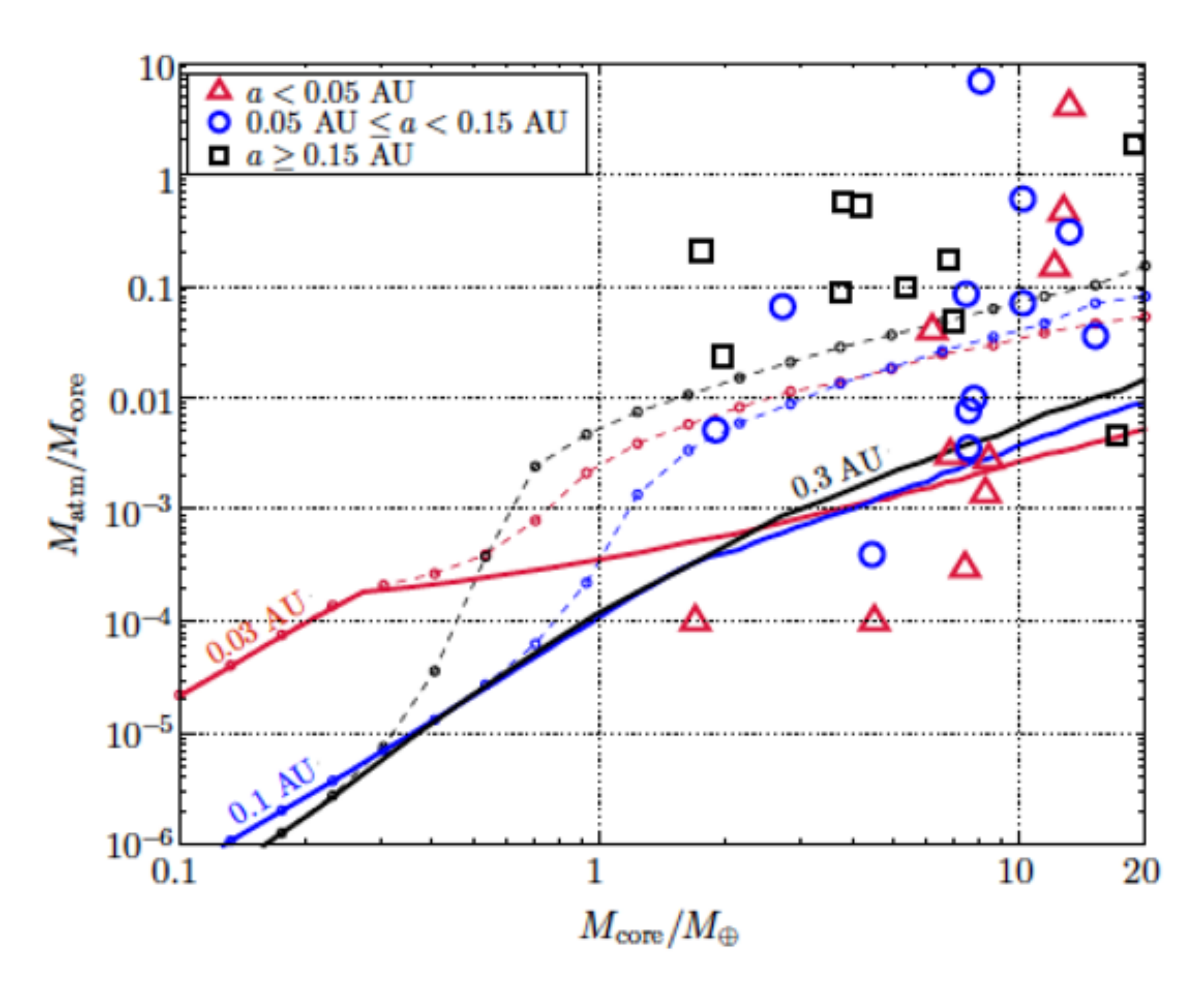


Chatterjee & Tan 2014, 2015; Hu et al 2014; Boley & Ford 2014

Can atmospheres differentiate between drift and migration?

In-situ or drift: thin (~10^{-3} or less) atmospheres.

Migration: a range of possible gas masses. If start from Neptunes and undergo few collisions, expect few percent



Inamdar & Schlichting 2015

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    - How many embryos?
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- Fast-forming gas giants can act as a barrier to inward-migrating super-Earths (Izidoro et al 2015)

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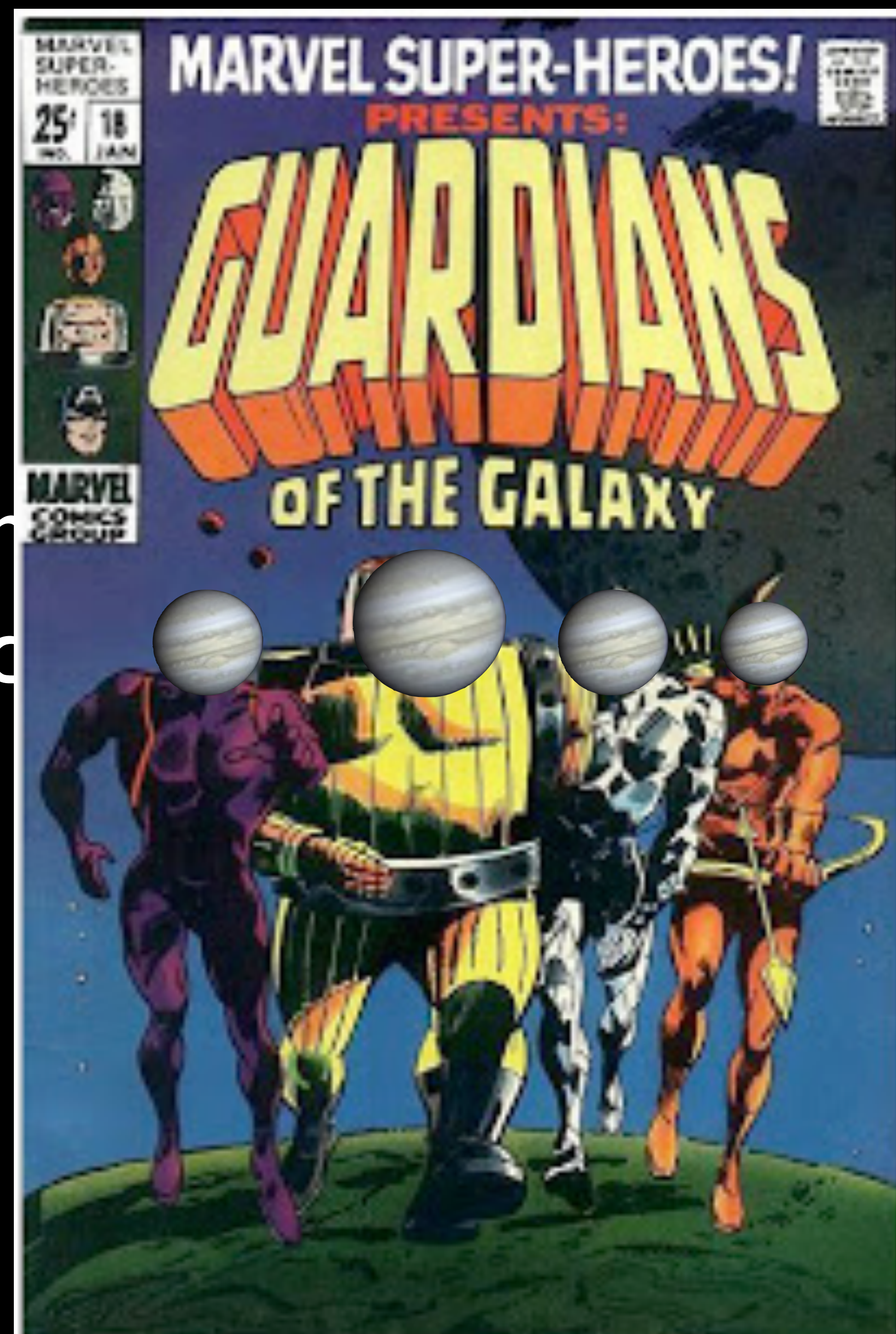

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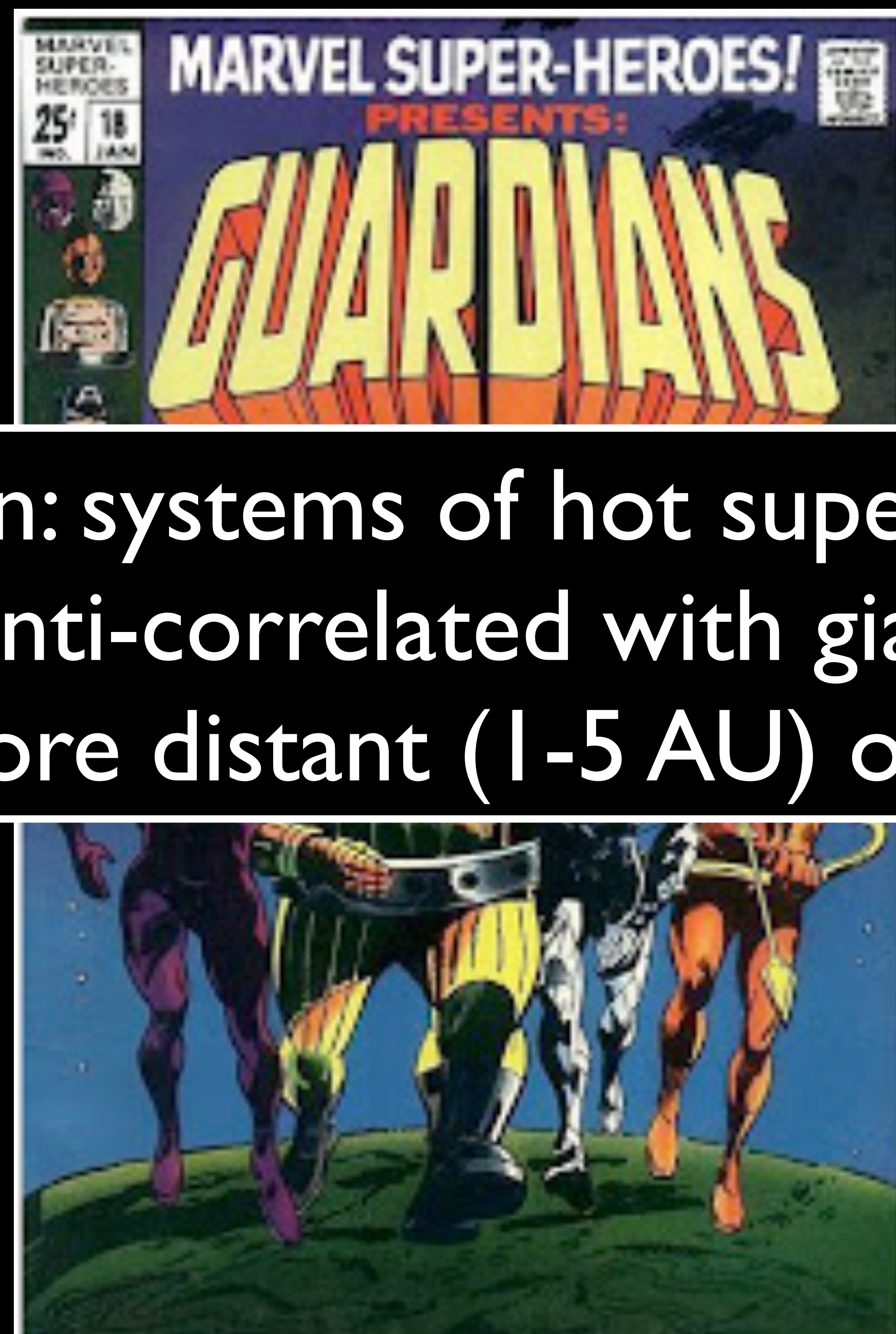
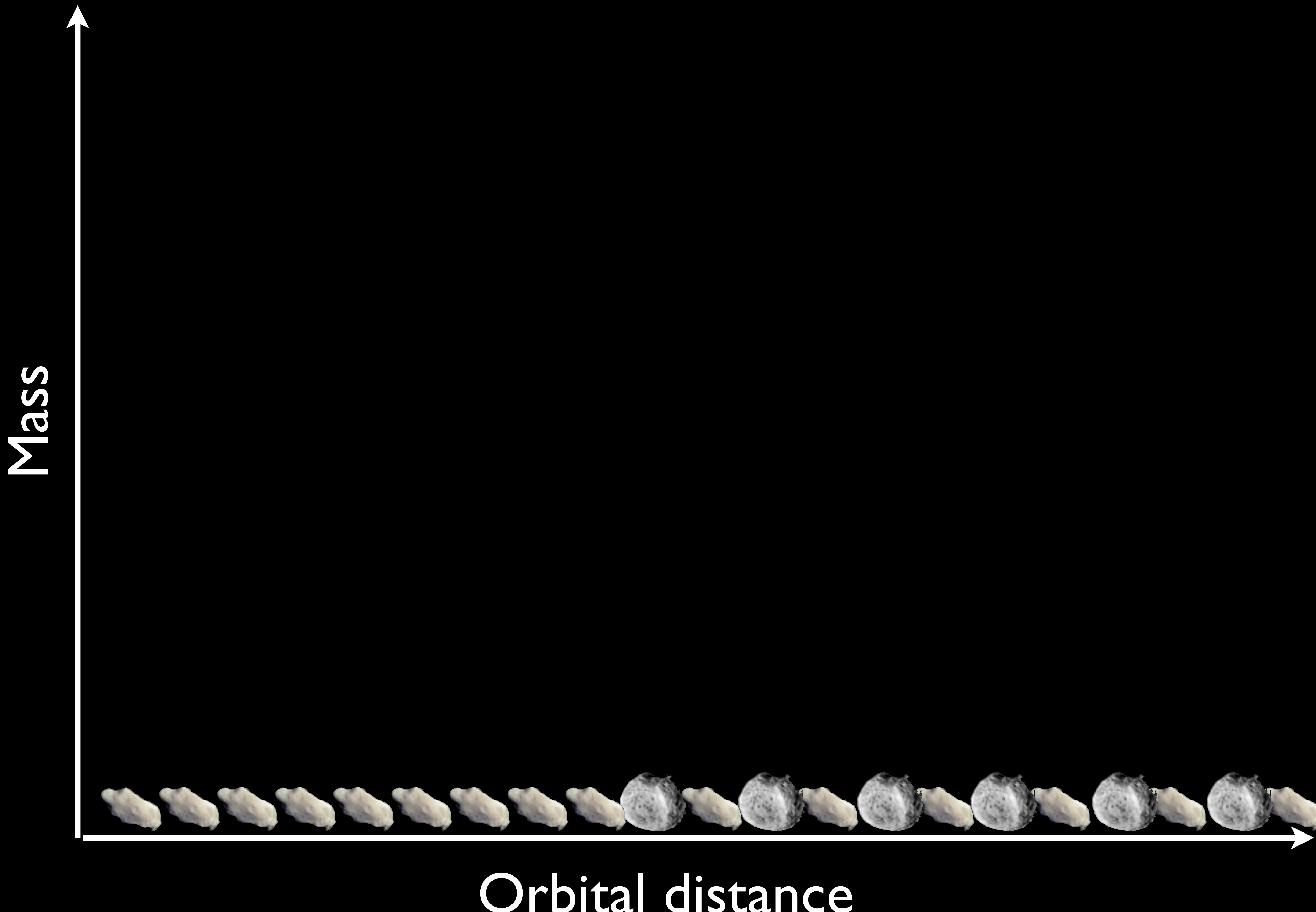


Prediction: systems of hot super-Earths should be anti-correlated with giant planets on more distant (1-5 AU) orbits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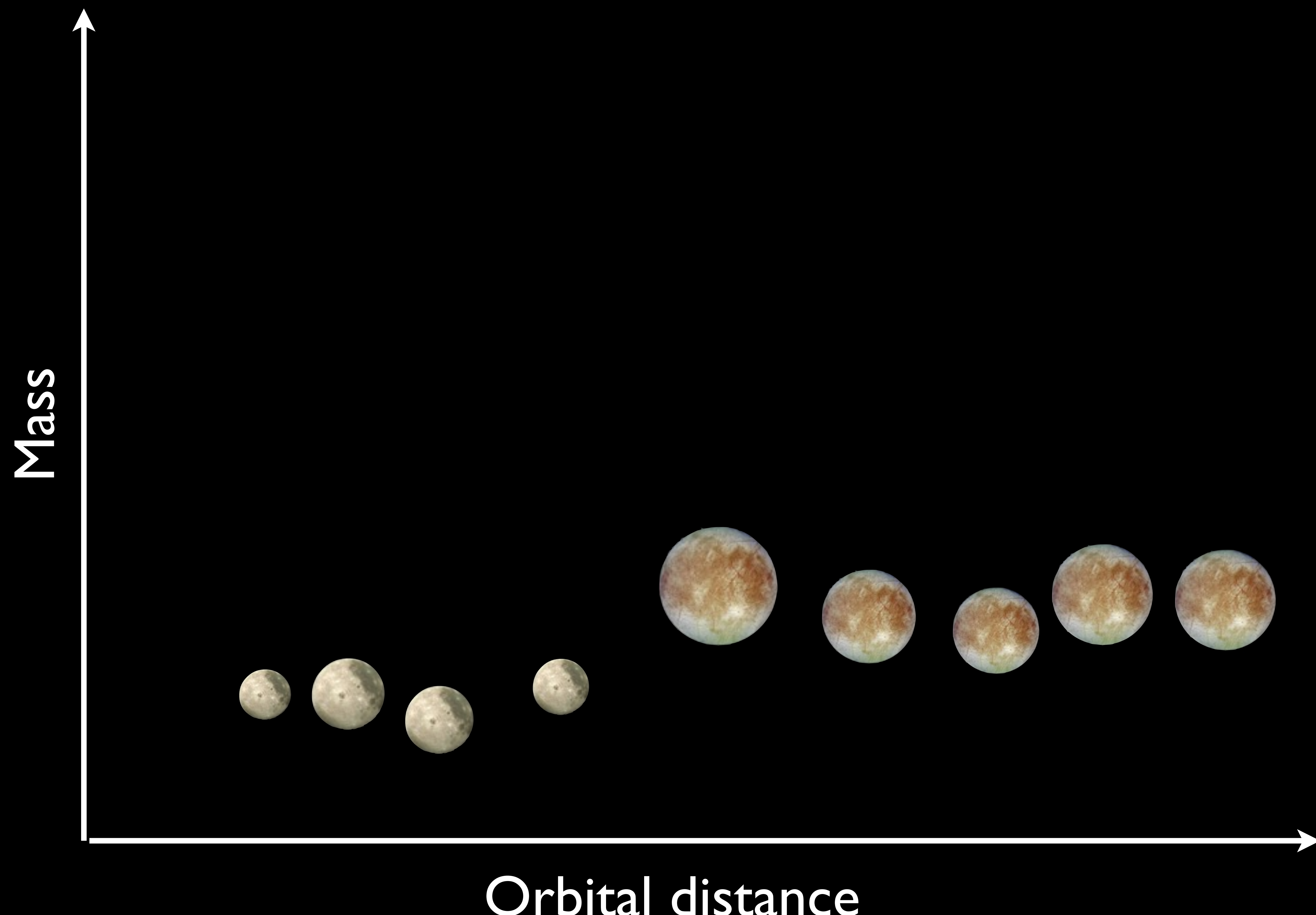
Orbital distance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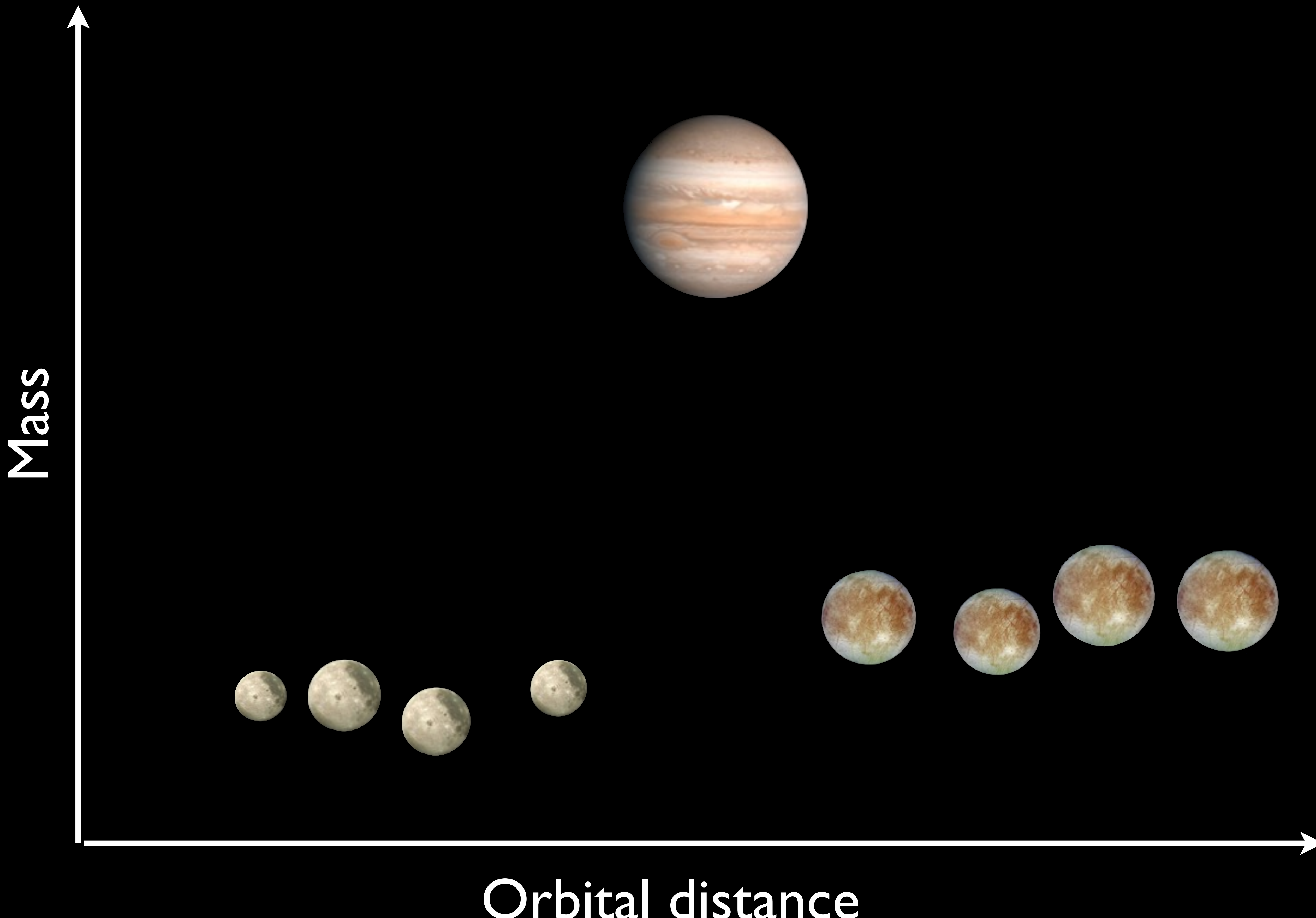
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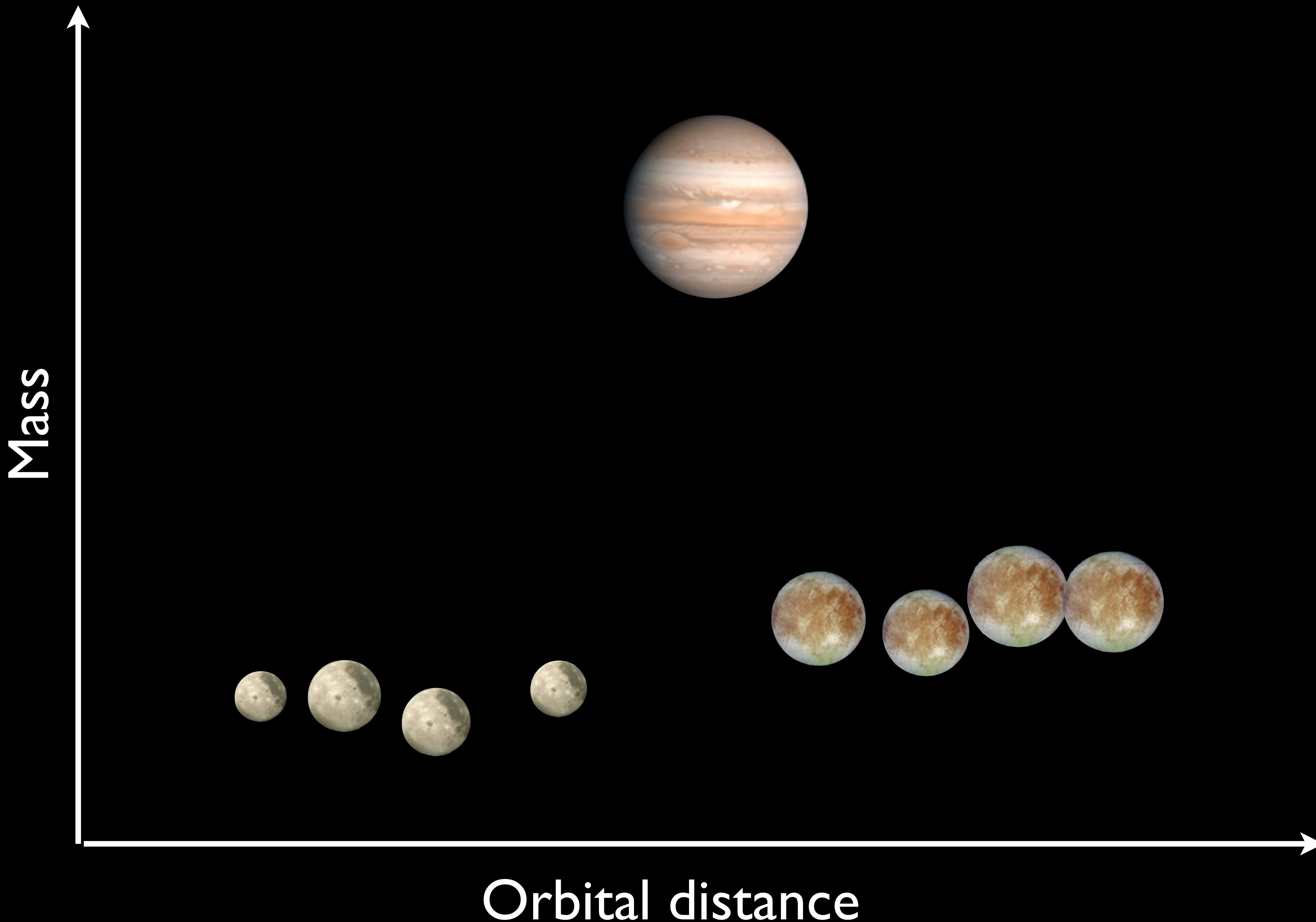
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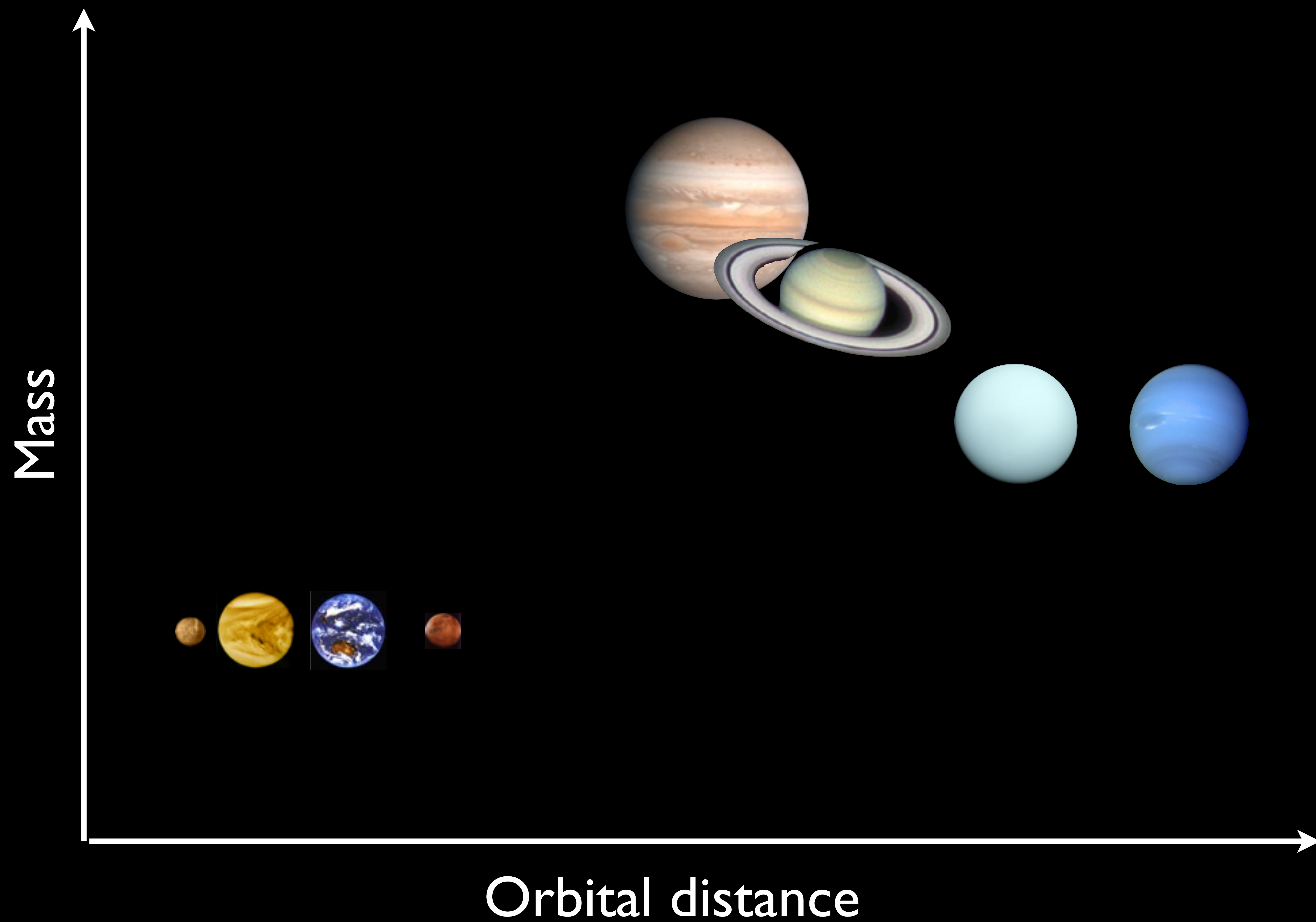
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Other	Type 1 migration cannot exist!	Also explains giant planet cores

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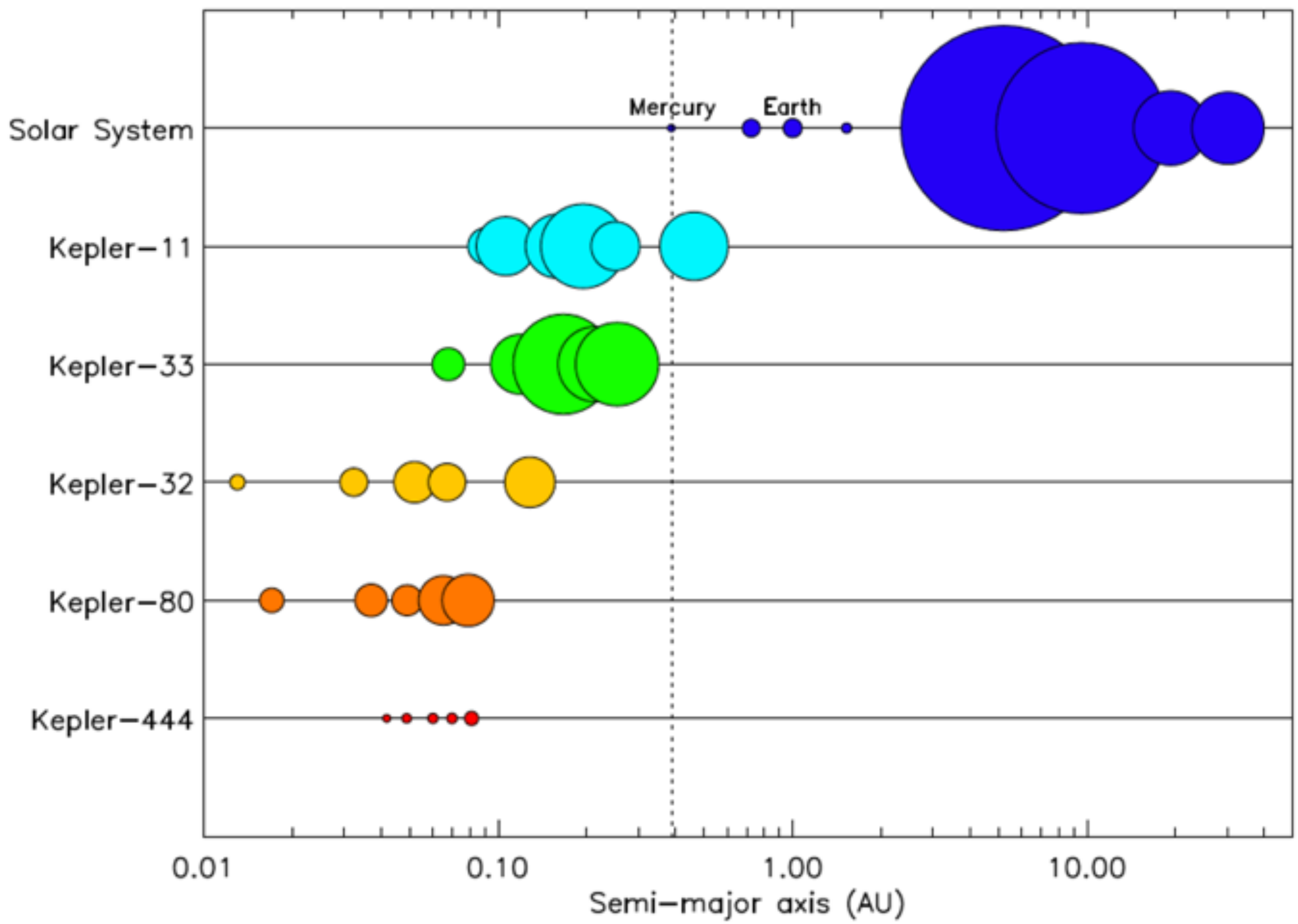
- Inward drift model: promising but needs further study
- Planets with 1+% atmospheres must form by migration model (I think)

Case study: Kepler-444



Campante et al 2015

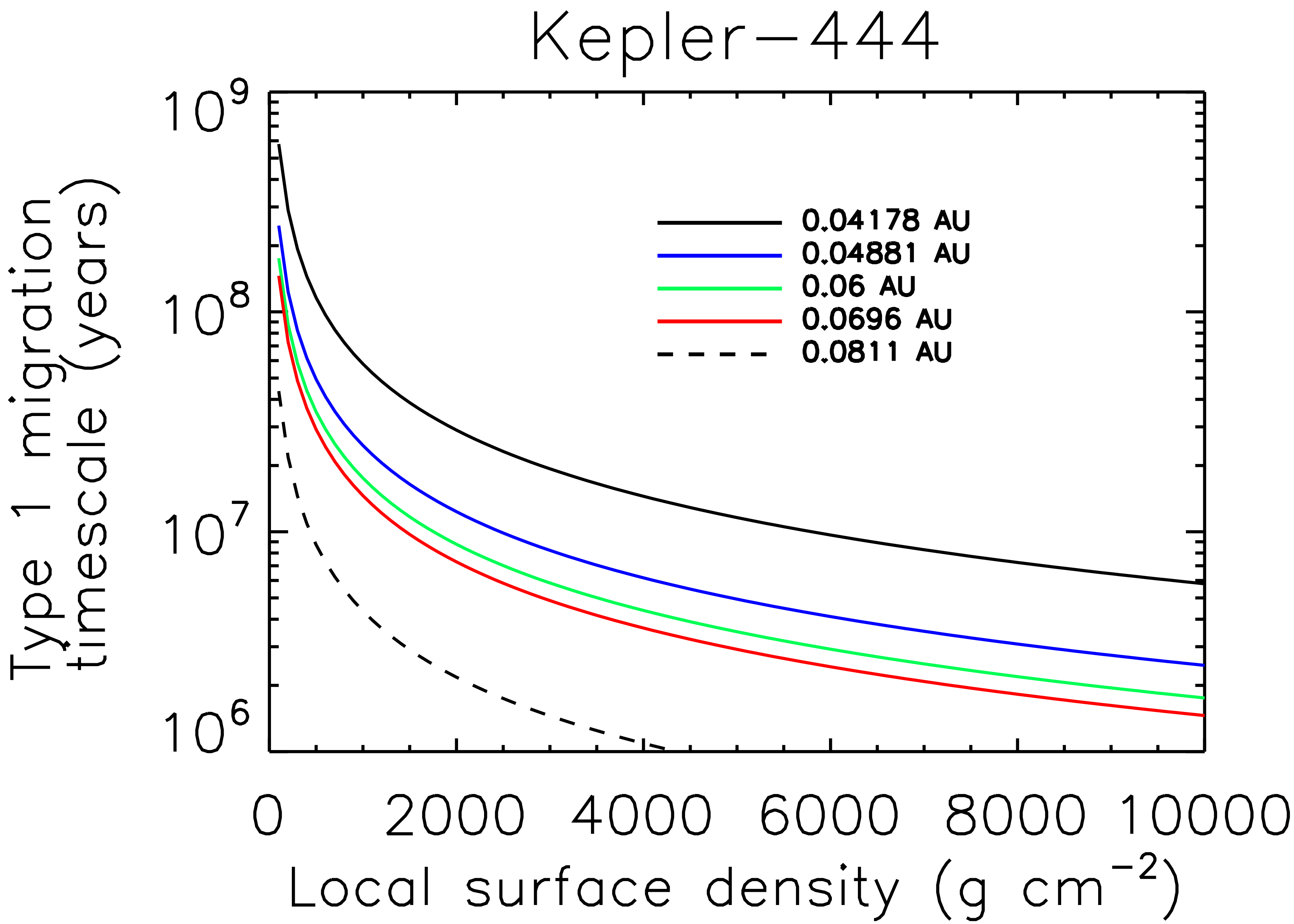
Kepler-444

Table 4. Planetary and orbital parameters.

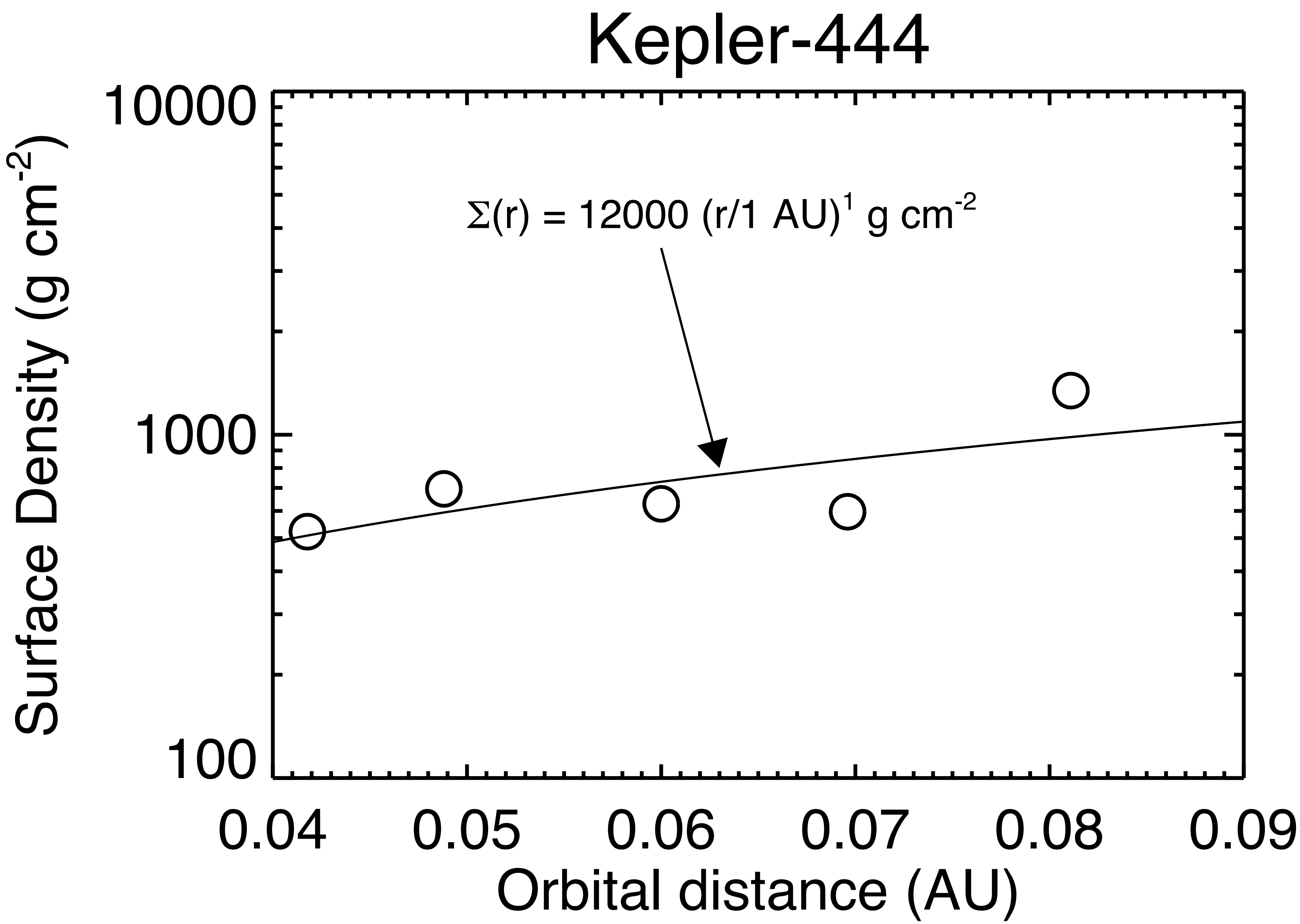
Parameter	Kepler-444b	Kepler-444c	Kepler-444d	Kepler-444e	Kepler-444f
T_0 (BJD−2,454,833)	$133.2599^{+0.0018}_{-0.0018}$	$131.5220^{+0.0013}_{-0.0013}$	$134.7869^{+0.0015}_{-0.0015}$	$135.0927^{+0.0018}_{-0.0018}$	$134.8791^{+0.0011}_{-0.0011}$
P (days)	$3.6001053^{+0.0000083}_{-0.0000080}$	$4.5458841^{+0.0000070}_{-0.0000071}$	$6.189392^{+0.000012}_{-0.000012}$	$7.743493^{+0.000017}_{-0.000016}$	$9.740486^{+0.000013}_{-0.000013}$
$R_p/R_\star$	$0.00491^{+0.00017}_{-0.00014}$	$0.00605^{+0.00025}_{-0.00017}$	$0.00644^{+0.00023}_{-0.00020}$	$0.00664^{+0.00016}_{-0.00014}$	$0.00903^{+0.00046}_{-0.00047}$
$R_p/R_\oplus$	$0.403^{+0.016}_{-0.014}$	$0.497^{+0.021}_{-0.017}$	$0.530^{+0.022}_{-0.019}$	$0.546^{+0.017}_{-0.015}$	$0.741^{+0.041}_{-0.040}$
b	$0.40^{+0.17}_{-0.25}$	$0.42^{+0.22}_{-0.27}$	$0.53^{+0.13}_{-0.23}$	$0.29^{+0.16}_{-0.17}$	$0.79^{+0.07}_{-0.13}$
$e\sin\omega$	$0.01^{+0.08}_{-0.12}$	$0.18^{+0.10}_{-0.15}$	$0.03^{+0.12}_{-0.12}$	$-0.008^{+0.040}_{-0.090}$	$0.09^{+0.20}_{-0.15}$
$e\cos\omega$	$0.00^{+0.20}_{-0.21}$	$0.01^{+0.28}_{-0.25}$	$0.00^{+0.21}_{-0.19}$	$-0.01^{+0.11}_{-0.21}$	$-0.06^{+0.19}_{-0.33}$
e[a]	$0.16^{+0.21}_{-0.10}$	$0.31^{+0.12}_{-0.15}$	$0.18^{+0.16}_{-0.12}$	$0.10^{+0.20}_{-0.07}$	$0.29^{+0.20}_{-0.19}$
$a/R_\star$	$11.951^{+0.046}_{-0.046}$	$13.961^{+0.053}_{-0.053}$	$17.151^{+0.066}_{-0.066}$	$19.913^{+0.076}_{-0.076}$	$23.205^{+0.089}_{-0.089}$
a (AU)	$0.04178^{+0.00079}_{-0.00079}$	$0.04881^{+0.00093}_{-0.00093}$	$0.0600^{+0.0011}_{-0.0011}$	$0.0696^{+0.0013}_{-0.0013}$	$0.0811^{+0.0015}_{-0.0015}$
i (deg)	$88.0^{+1.2}_{-0.6}$	$88.2^{+1.2}_{-1.0}$	$88.16^{+0.81}_{-0.55}$	$89.13^{+0.54}_{-0.52}$	$87.96^{+0.36}_{-0.31}$
Mass (ME) [assuming Earth-like]	0.035	0.075	0.095	0.11	0.33

Campante et al 2015

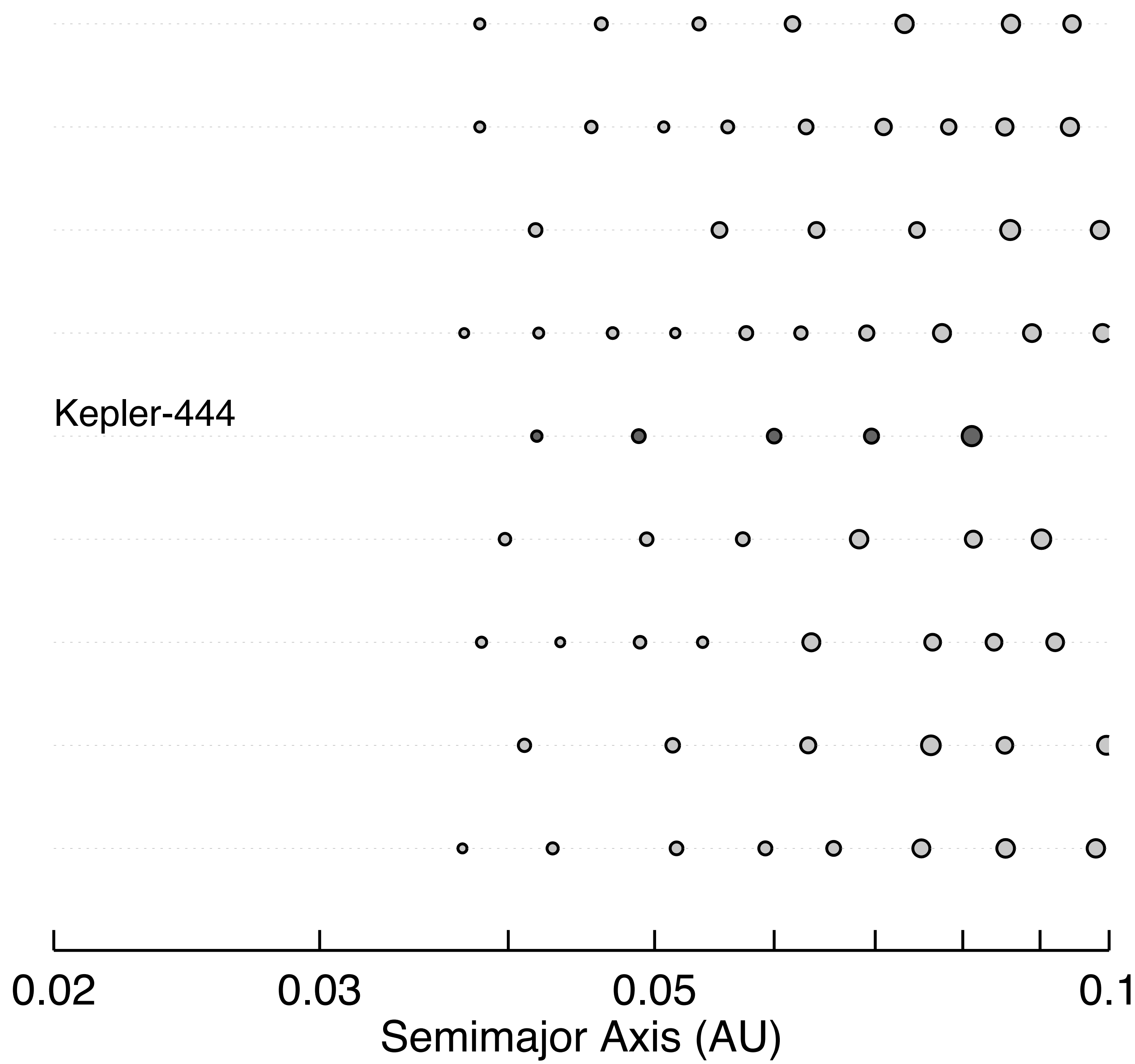
Migration timescales are long



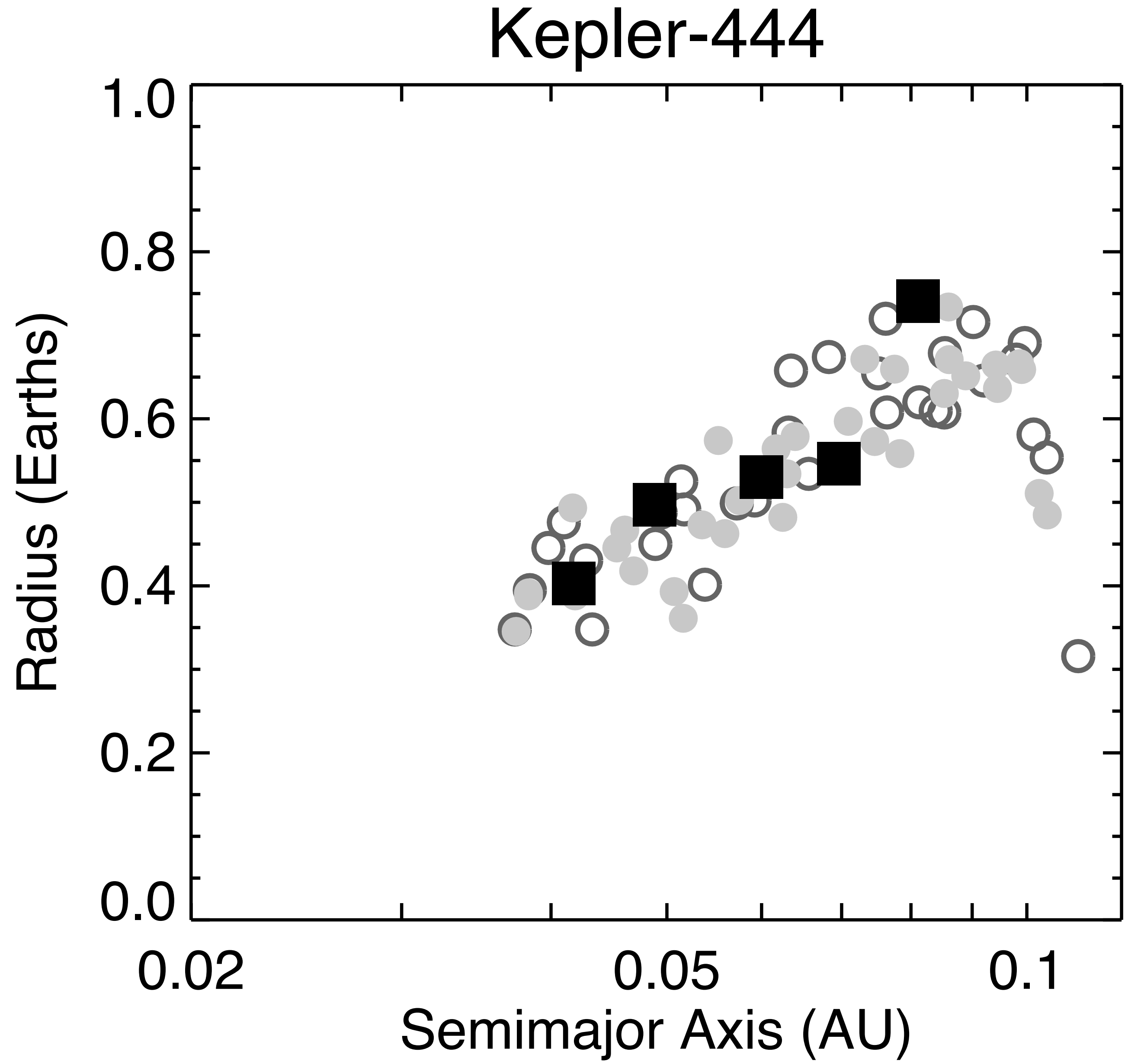
Minimum-mass disk



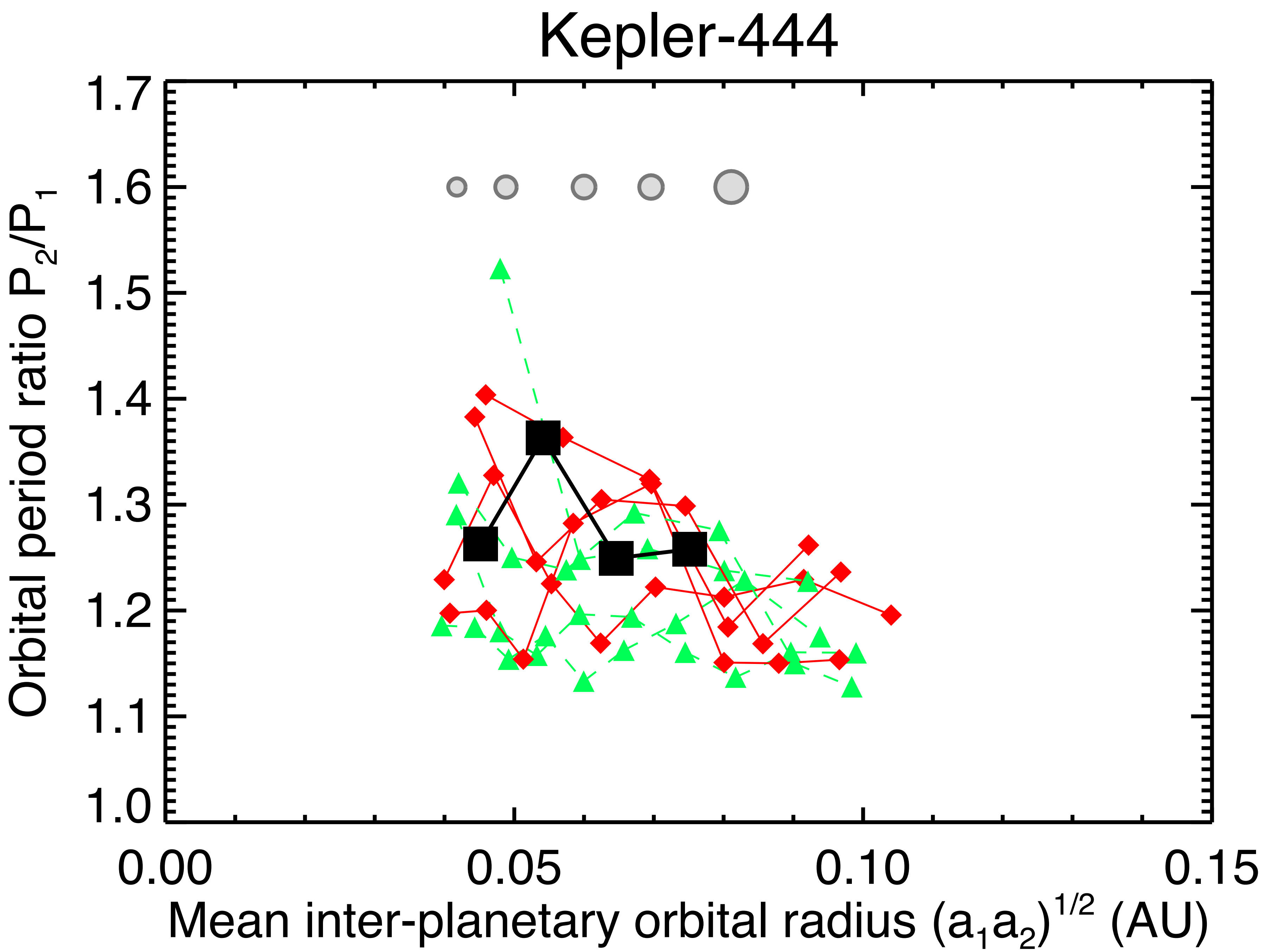
Accretion simulations



Planet size vs orbital distance



Planetary spacing



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- Best candidate: inward drift model