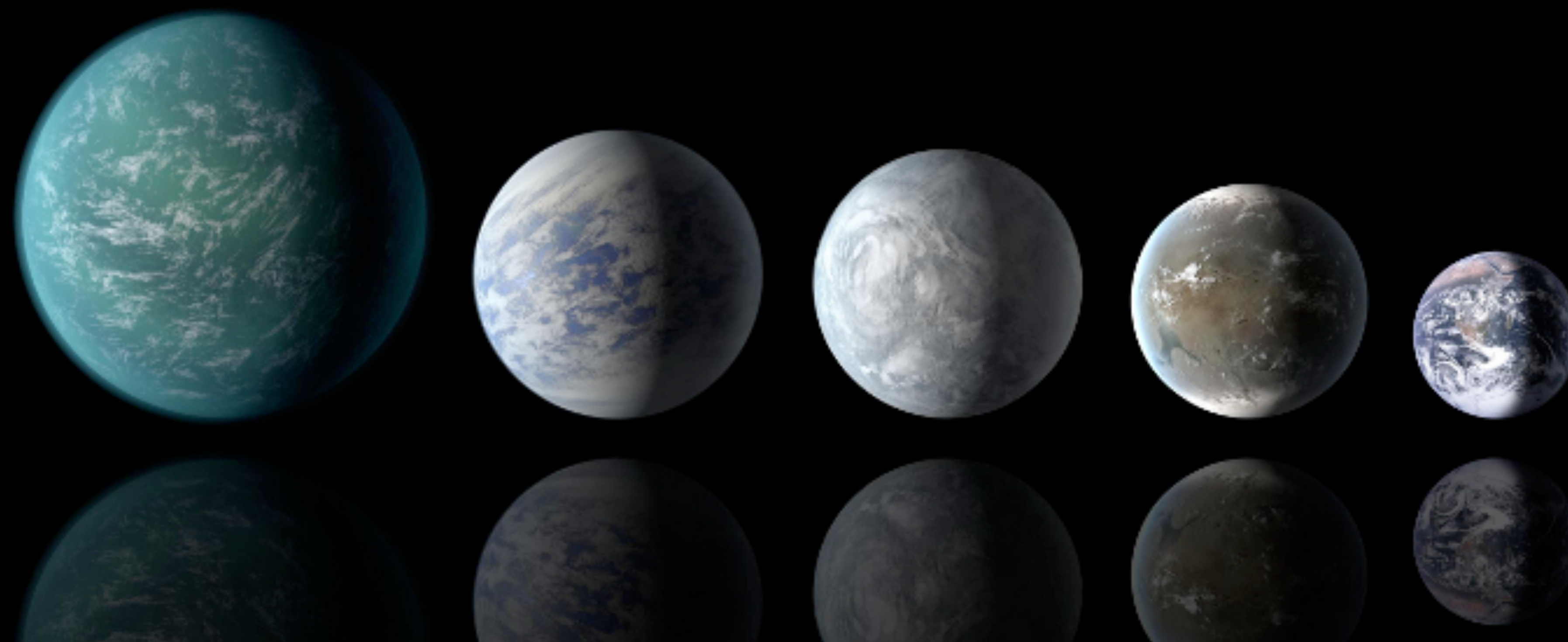
How do systems of hot super-Earths and sub-Neptunes form?

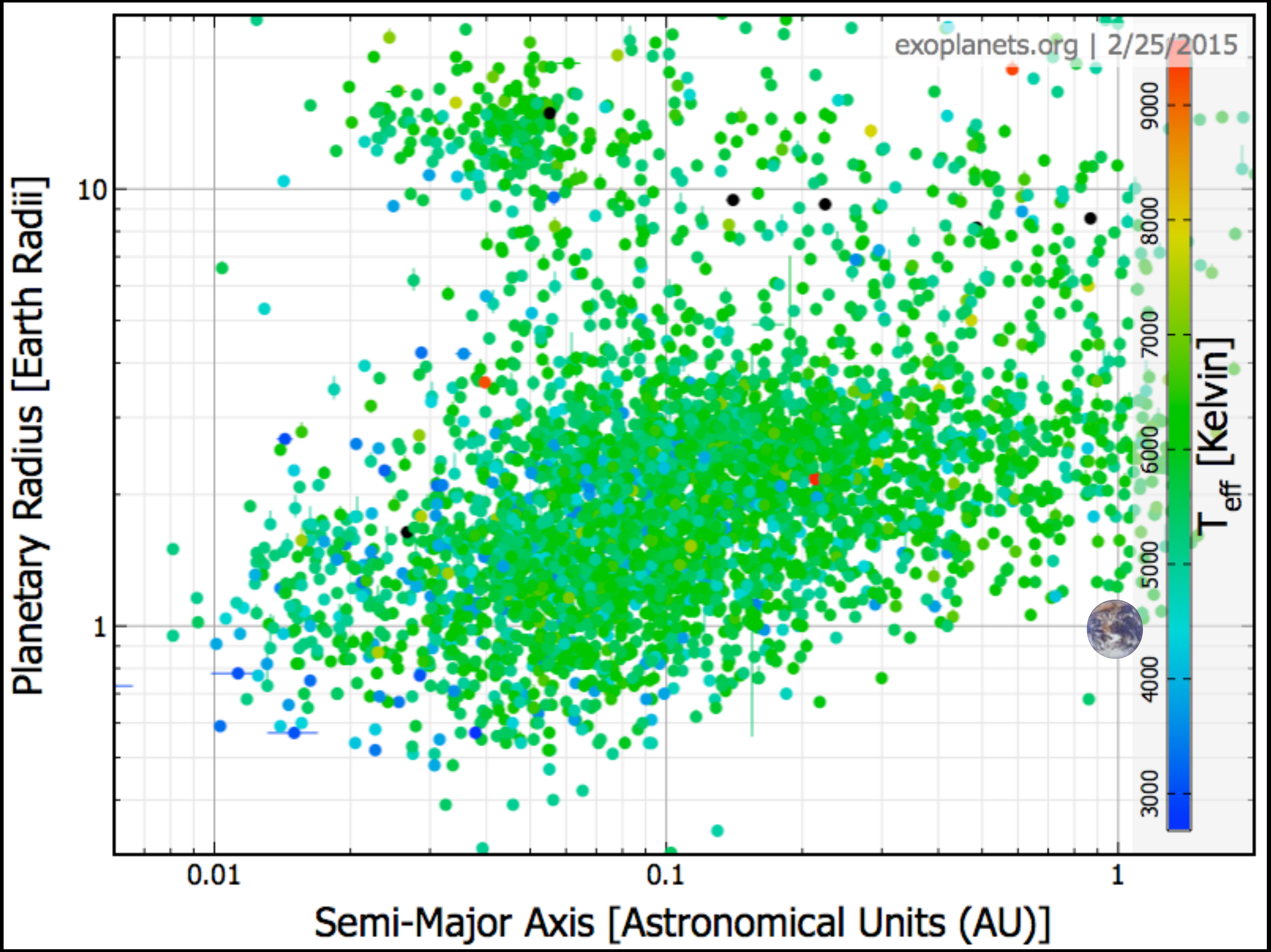


Sean Raymond

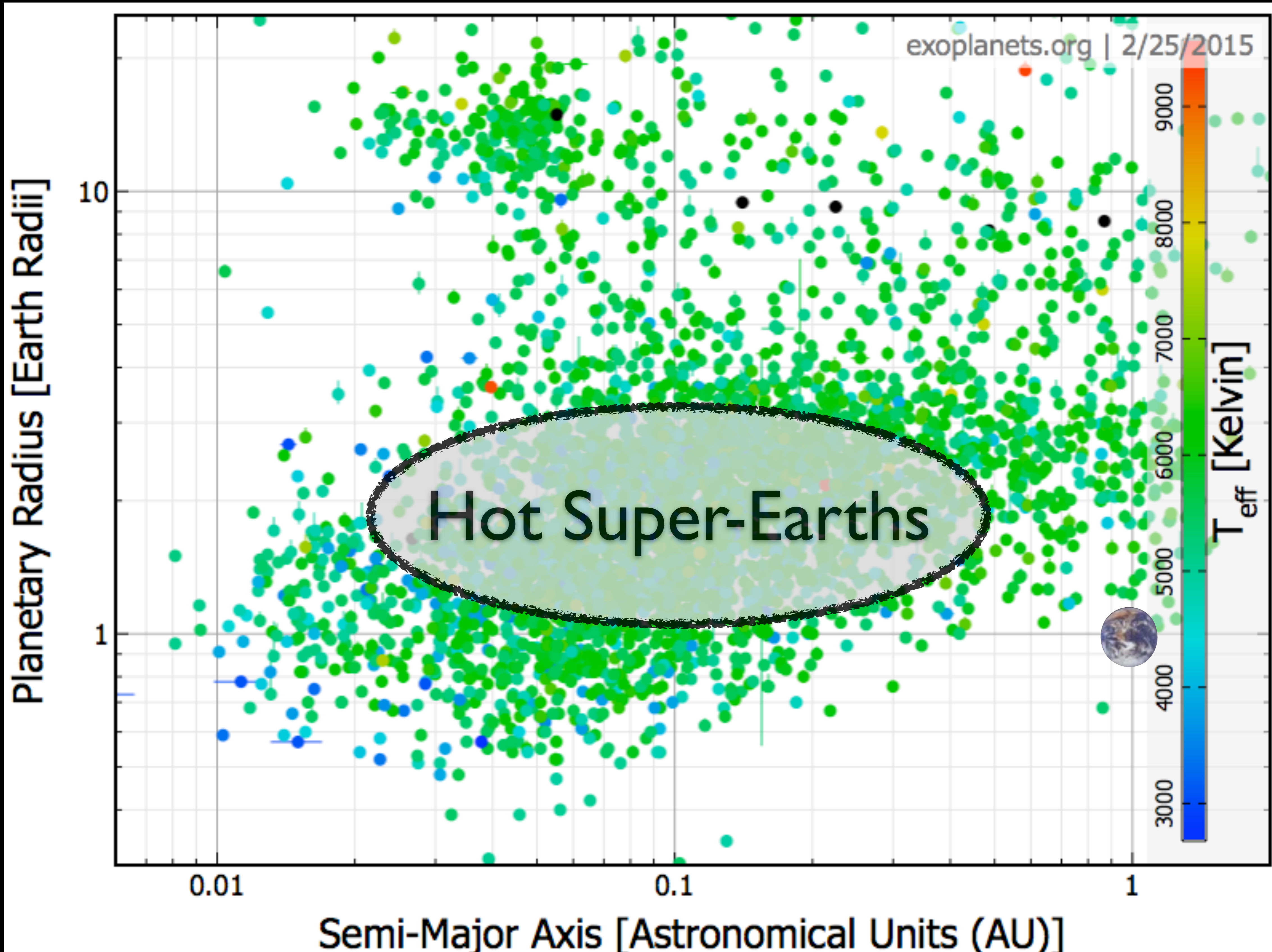
Laboratoire d'Astrophysique de Bordeaux

planetplanet.net

with Christophe Cossou, Andre Izidoro, Alessandro Morbidelli, Arnaud Pierens, Franck Hersant



exoplanets.org | 2/25/2015
Planetary Radius [Earth Radii]
10
1
0.01
0.1
1
Semi-Major Axis [Astronomical Units (AU)]
9000
8000
7000
6000
5000
4000
3000
T_{eff} [Kelvin]



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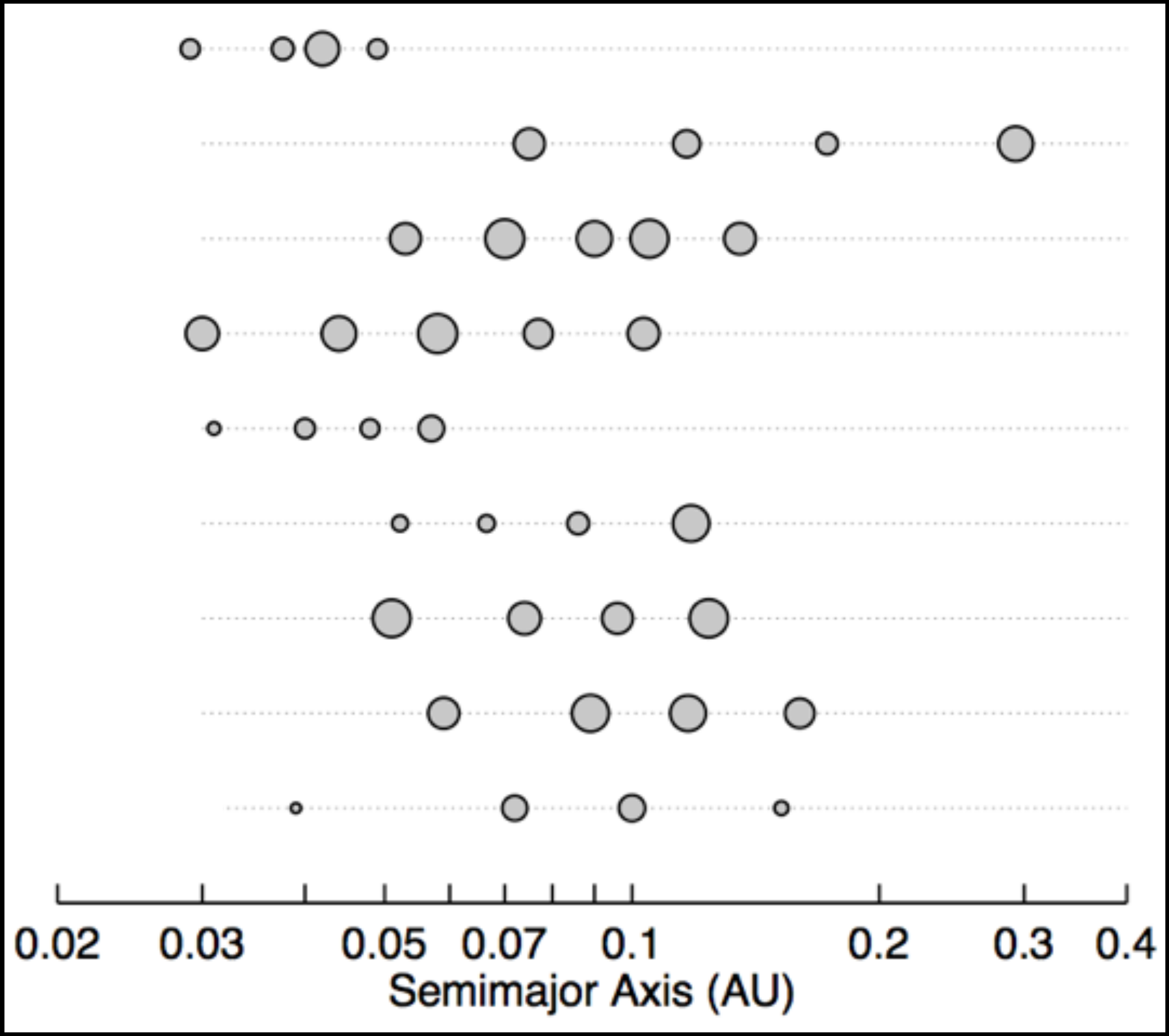
Hot Super Earths

- Exist around 30-50% of main-sequence stars (Mayor et al 2011; Howard et al 2010, 2012; Fressin et al 2013; Petigura et al 2013)
- Multiple systems (e.g., Lovis et al 2011; Lissauer et al 2011a, many more)
- Compact, non-resonant orbits (Lissauer et al 2011b; Fabrycky et al 2014)



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

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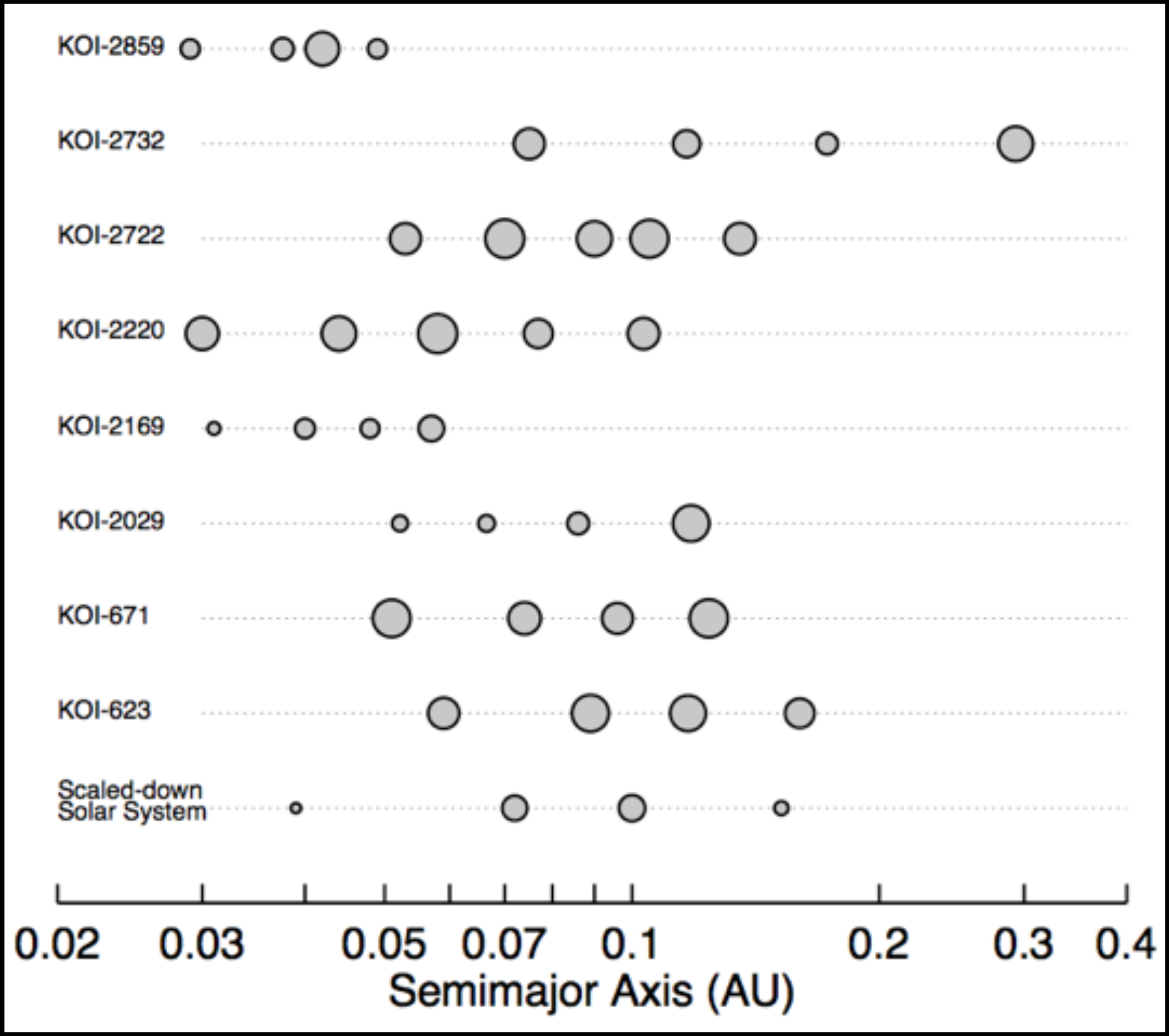
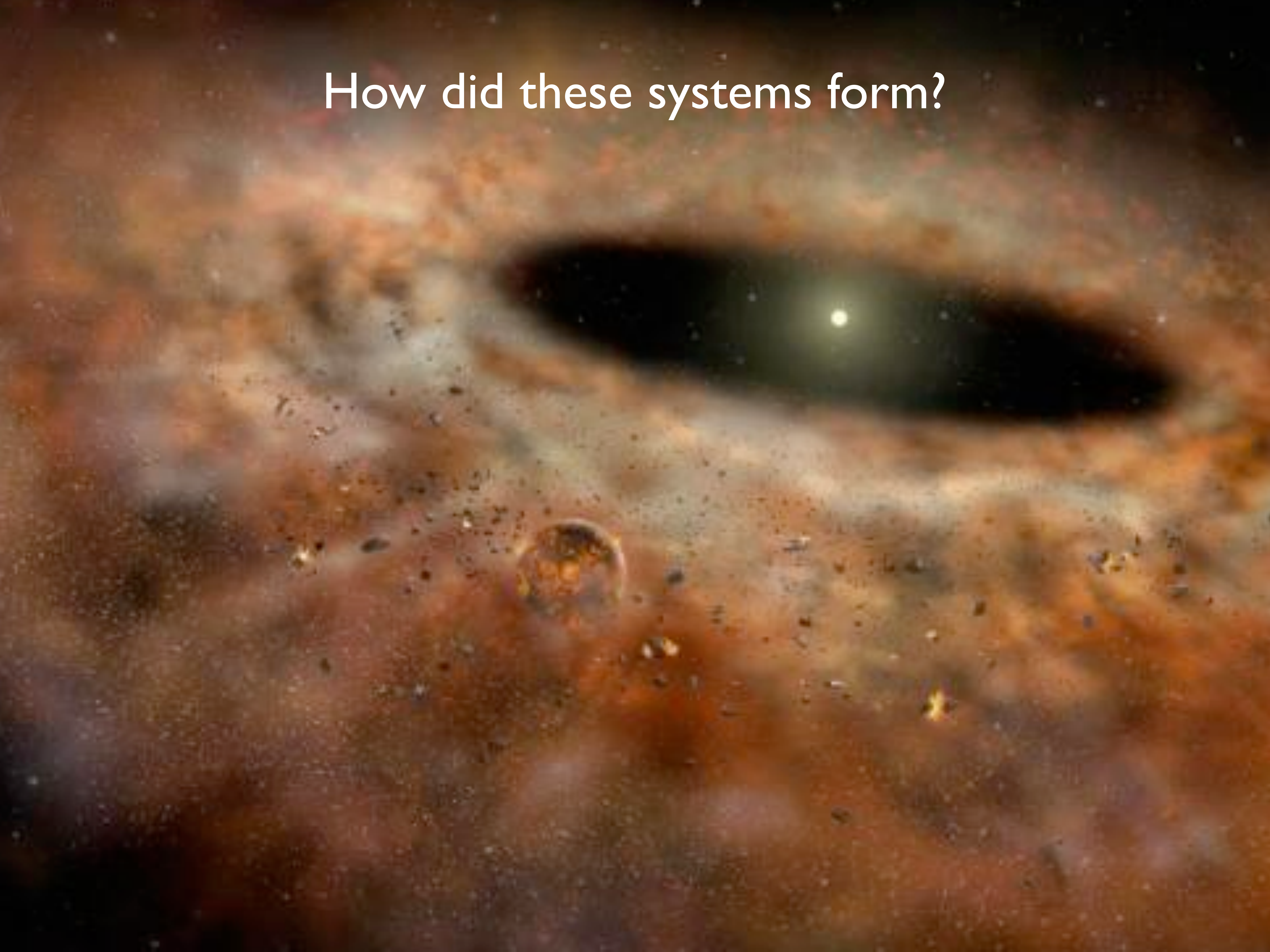
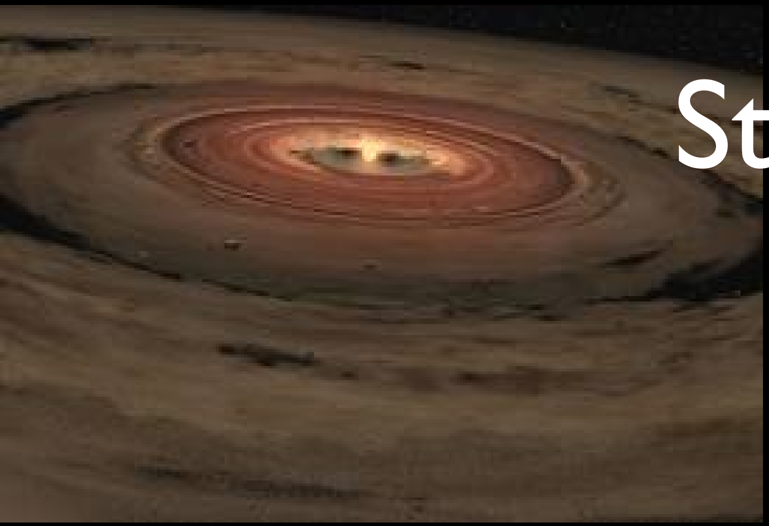


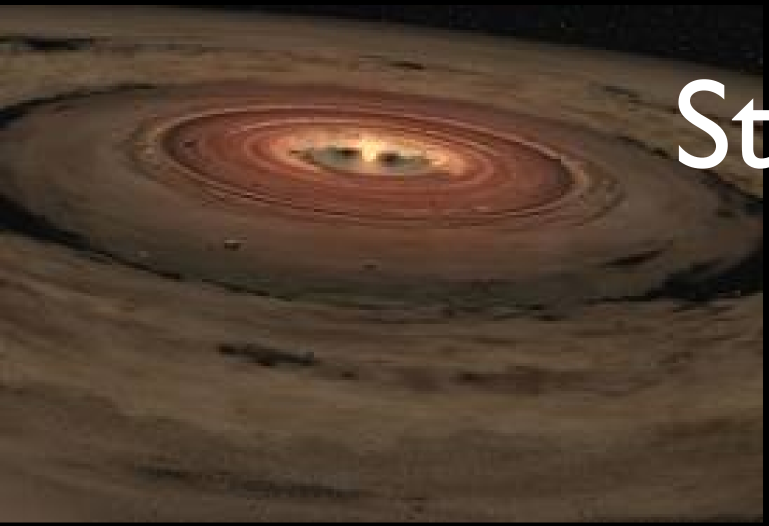
Raymond et al 2014 PP6 chapter; Kepler data from Batalha et al 2013 and Rowe et al 2014

How did these systems form?



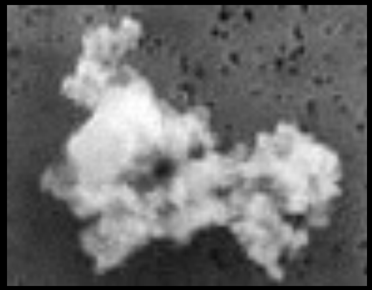
Stages of Planet Formation

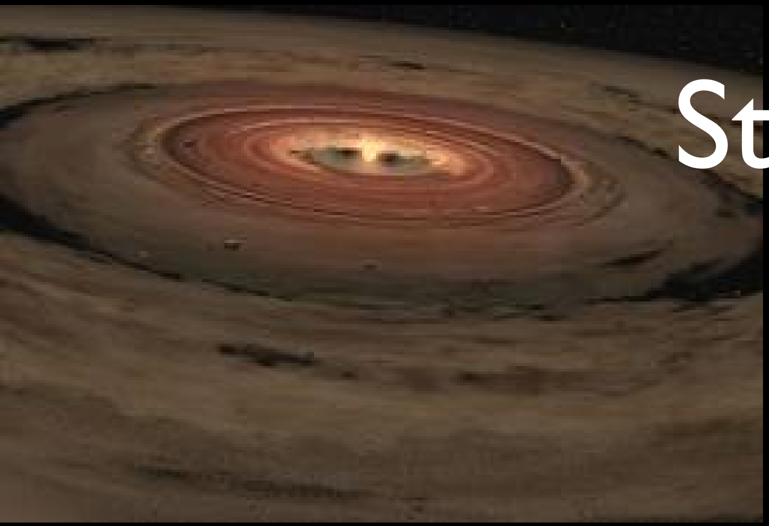




Stages of Planet Formation

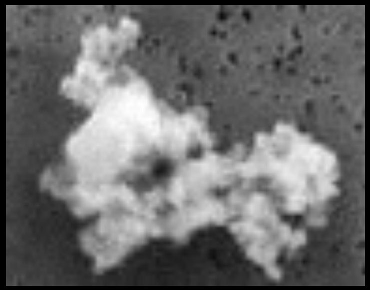
Grains



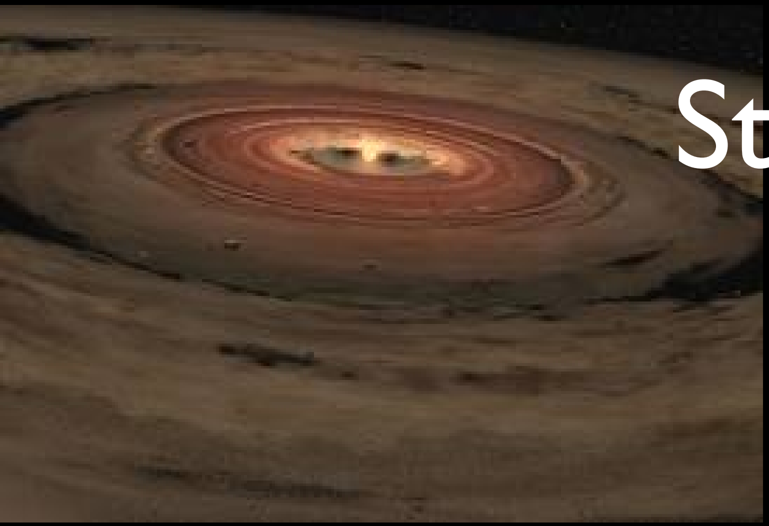


Stages of Planet Formation

Grains

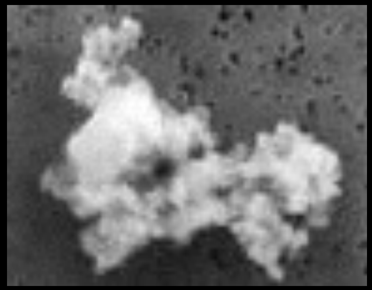


Pebbles



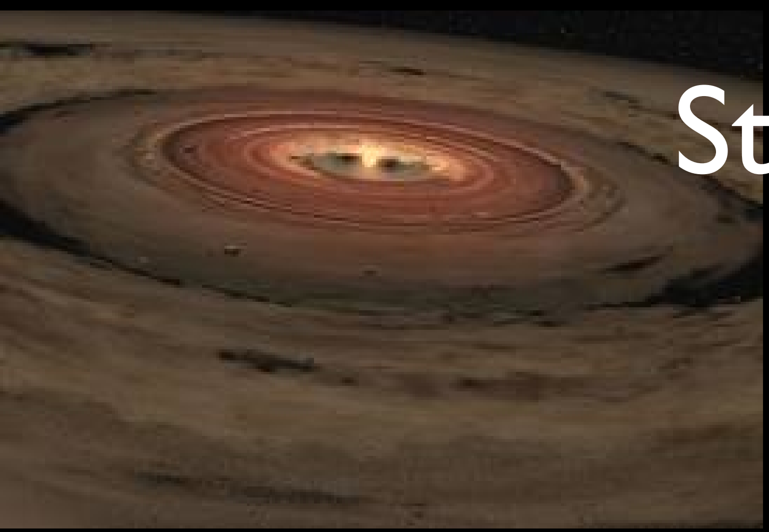
Stages of Planet Formation

Grains



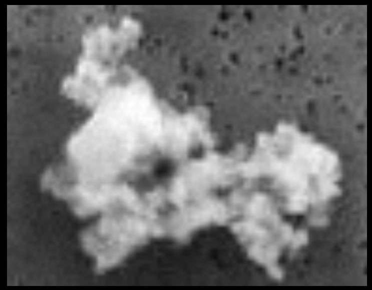
Pebbles

Planetesimals



Stages of Planet Formation

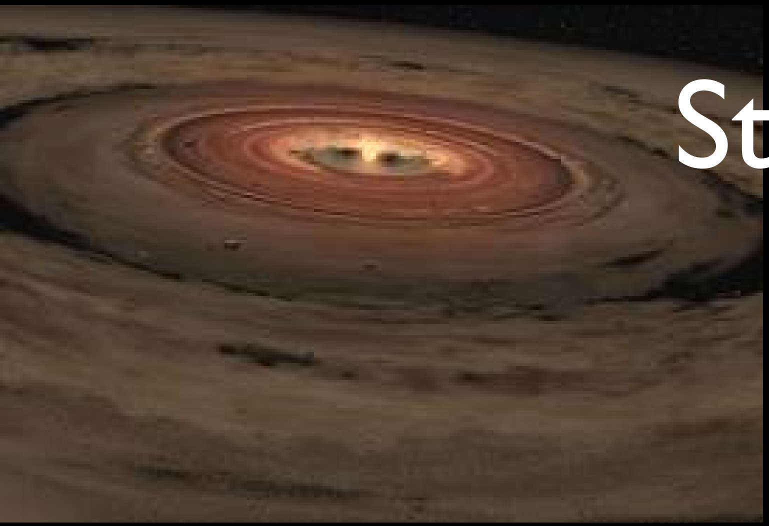
Grains



Pebbles

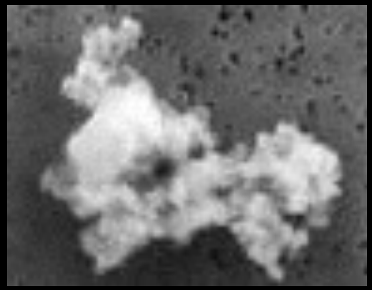
Planetesimals

Planetary Embryos



Stages of Planet Formation

Grains

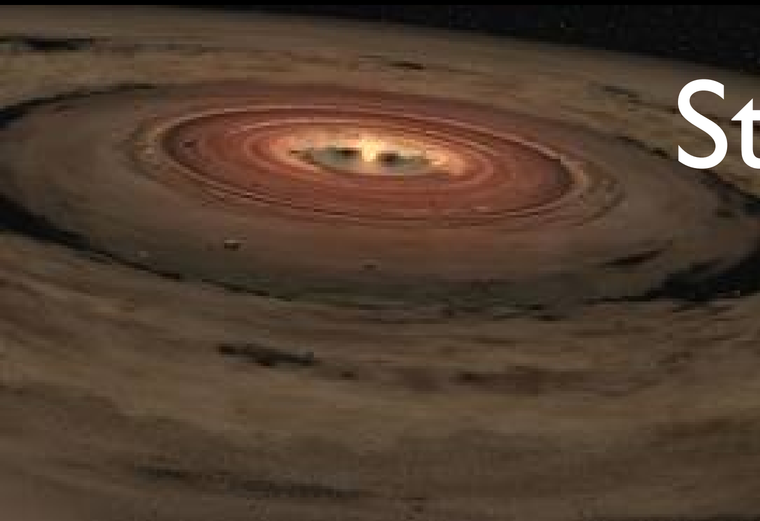


Pebbles

Planetesimals

Planetary Embryos

while gas
remains in disk

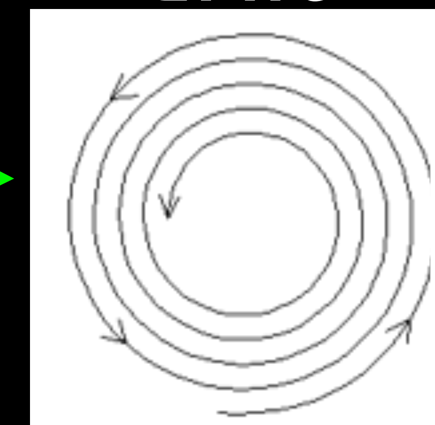


Stages of Planet Formation

Grains

Aerodynamic drift

Pebbles



Planetesimals

Planetary Embryos

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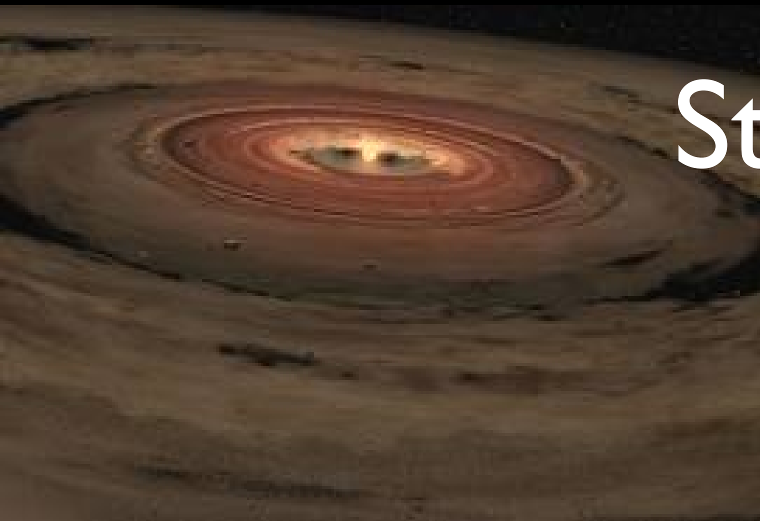
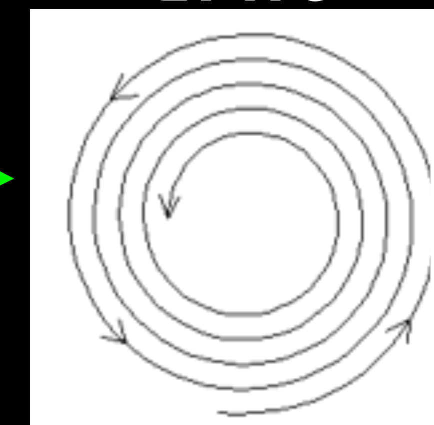


Stages of Planet Formation

Aerodynamic drift

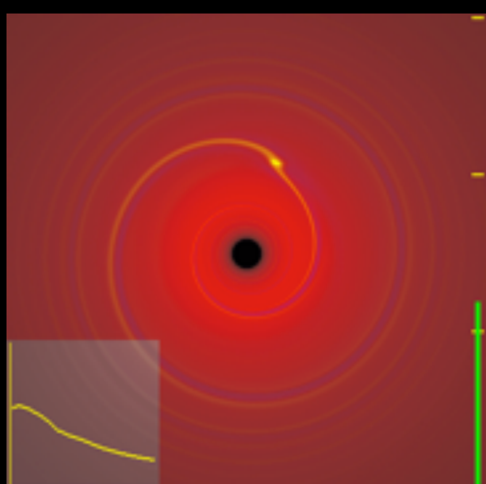
Grains

Pebbles



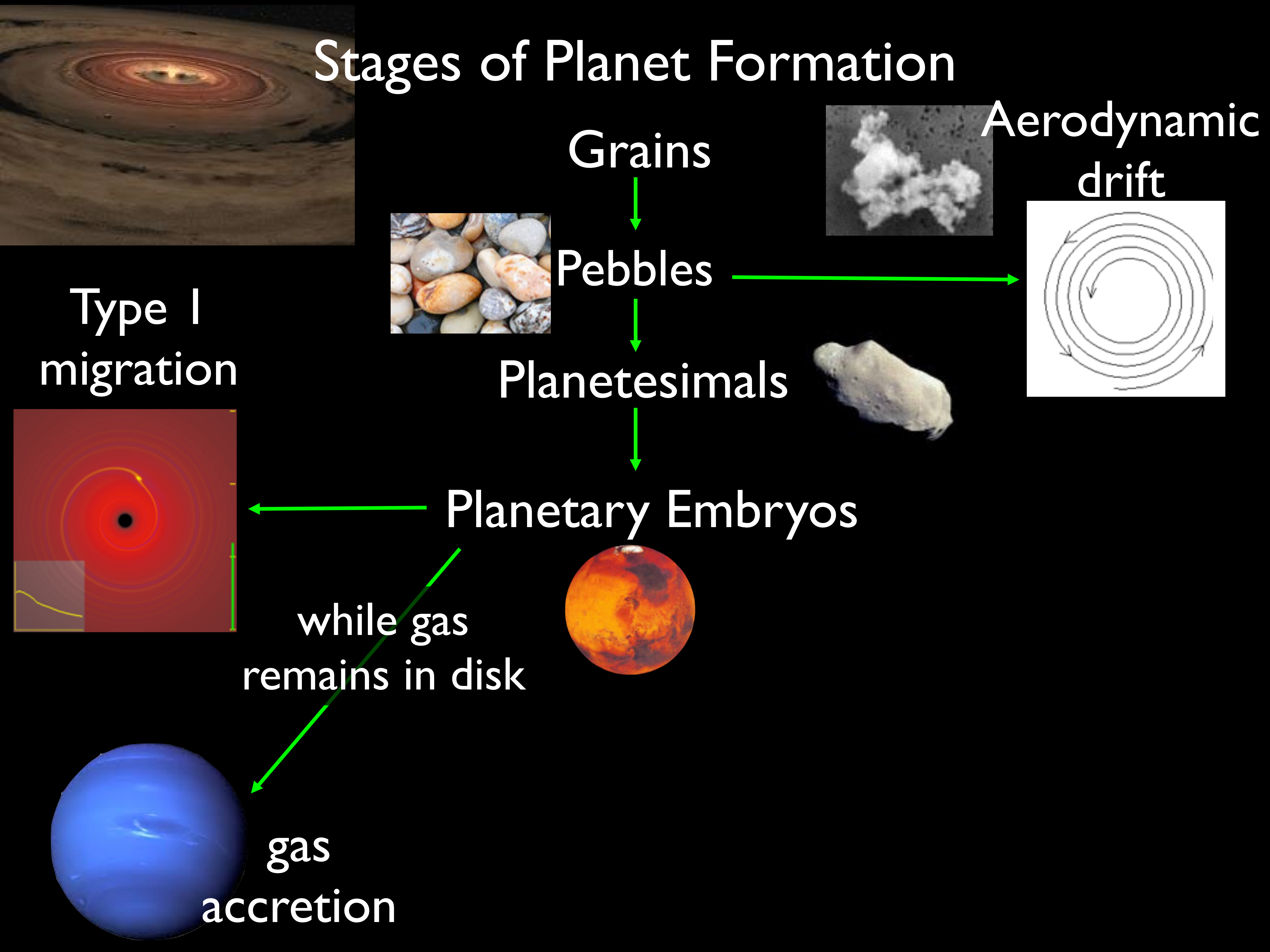
Type I migration

Planetesimals



Planetary Embryos

while gas remains in disk


Stages of Planet Formation
Grains
Pebbles
Planetesimals
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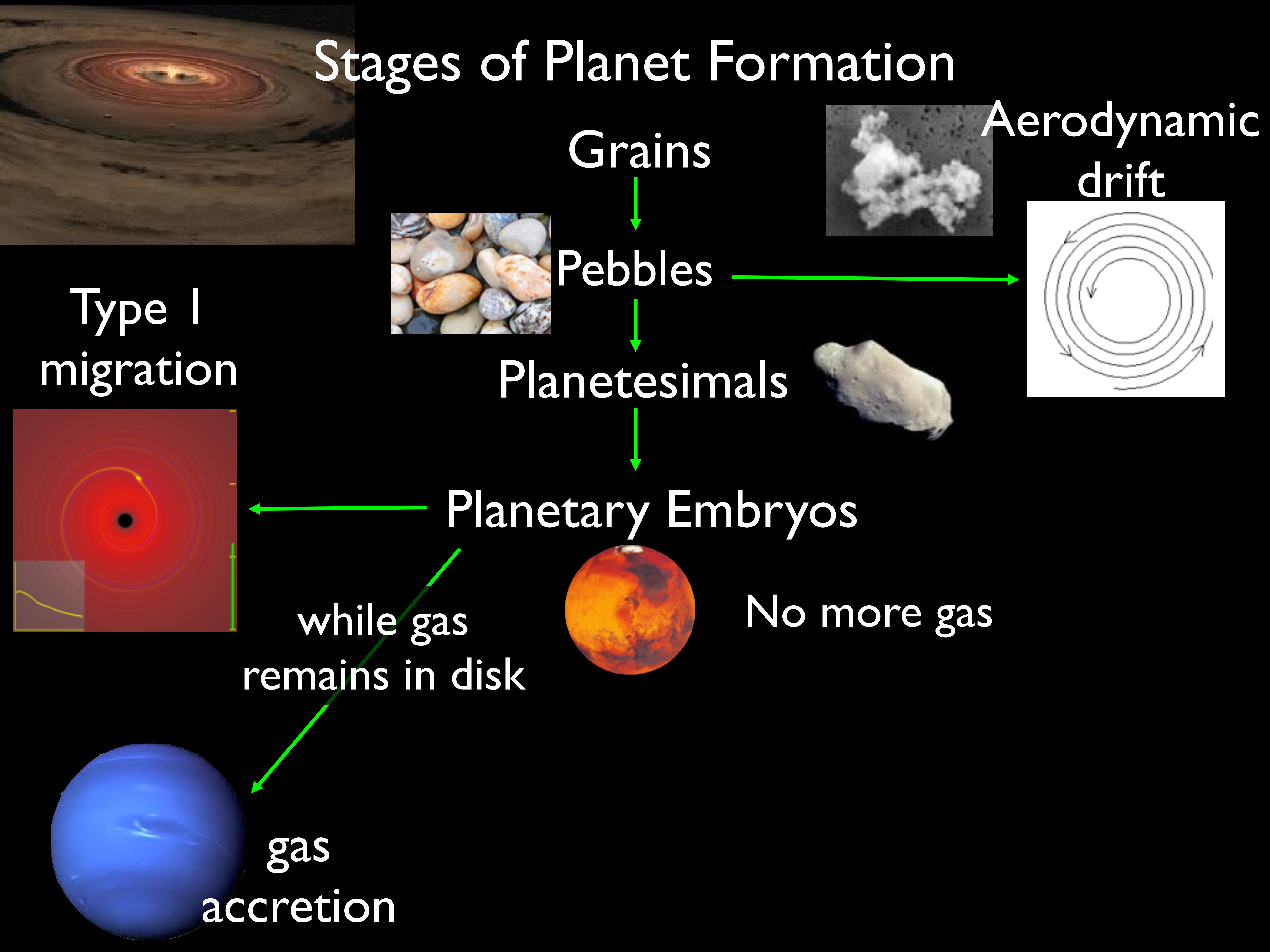
Aerodynamic
drift
Type I
migration
while gas
remains in disk
gas
accretion


Stages of Planet Formation
Grains
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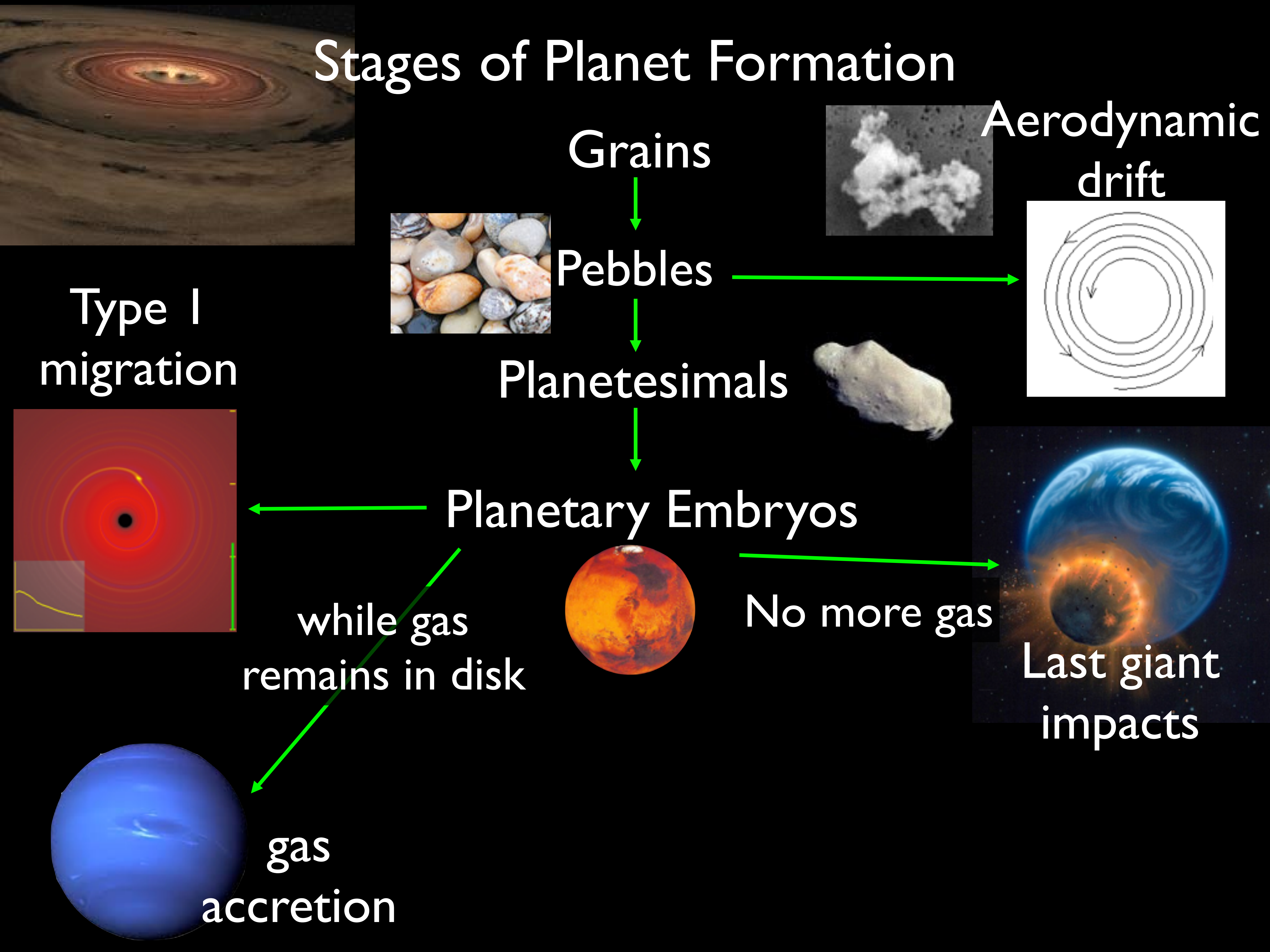
while gas remains in disk
No more gas
gas accretion



Stages of Planet Formation
Grains
Pebbles
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Aerodynamic drift
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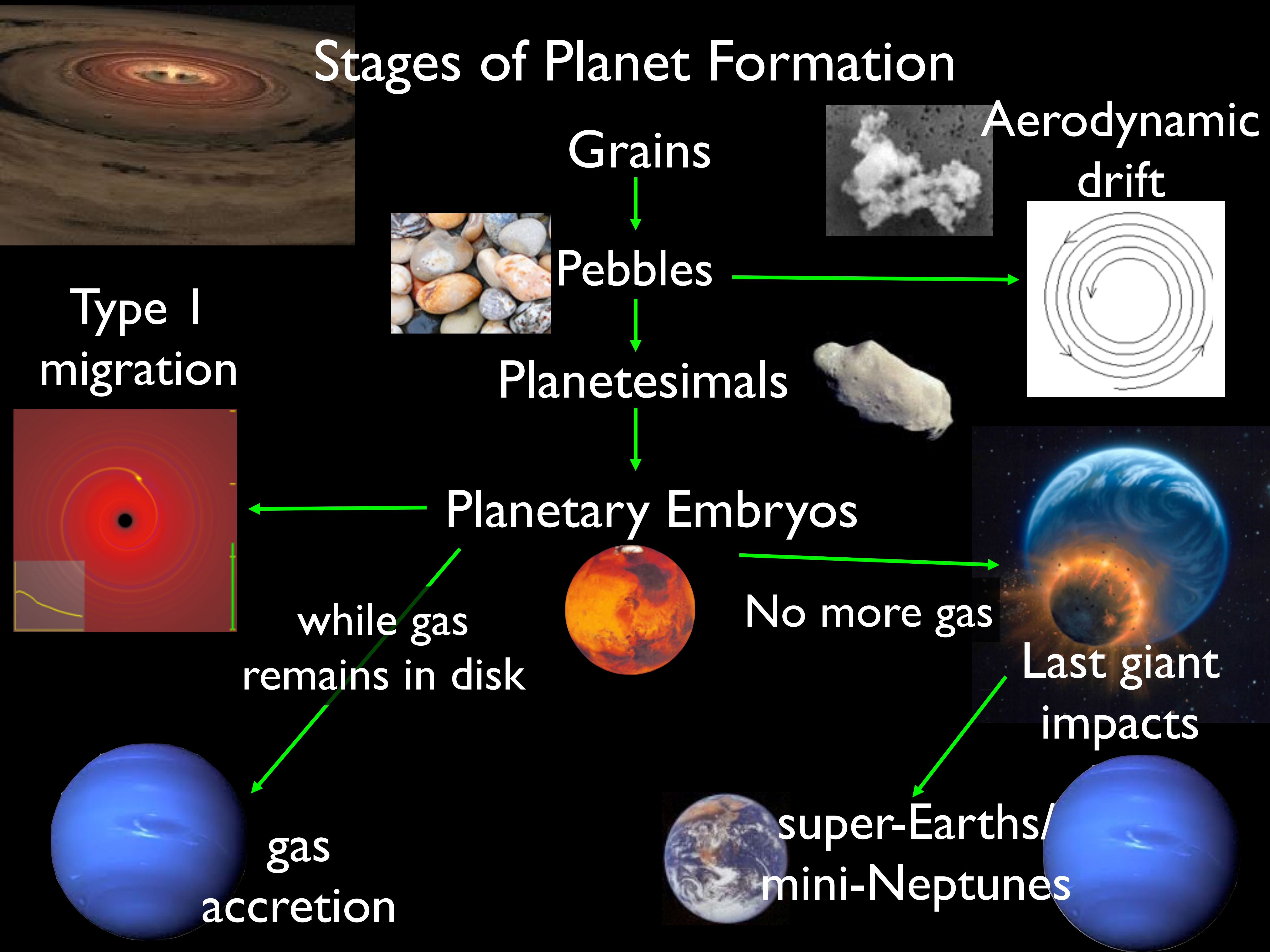
No more gas
Last giant impacts
gas accretion


Stages of Planet Formation
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No more gas
Last giant impacts
super-Earths/ mini-Neptunes

"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
Secular Res. shepherding	Hot Earths with two interacting giants	?
Photo-evaporated gas giant	Correlation with stellar age	Icy (giant planet core)
Tidal Circularization	Isolated hot Earth, eccentricity source	?

Raymond et al 2008, 2014

"Hot Earth" form. model	System Architecture	Hot Earth Composition
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Still viable

Raymond et al 2008, 2014

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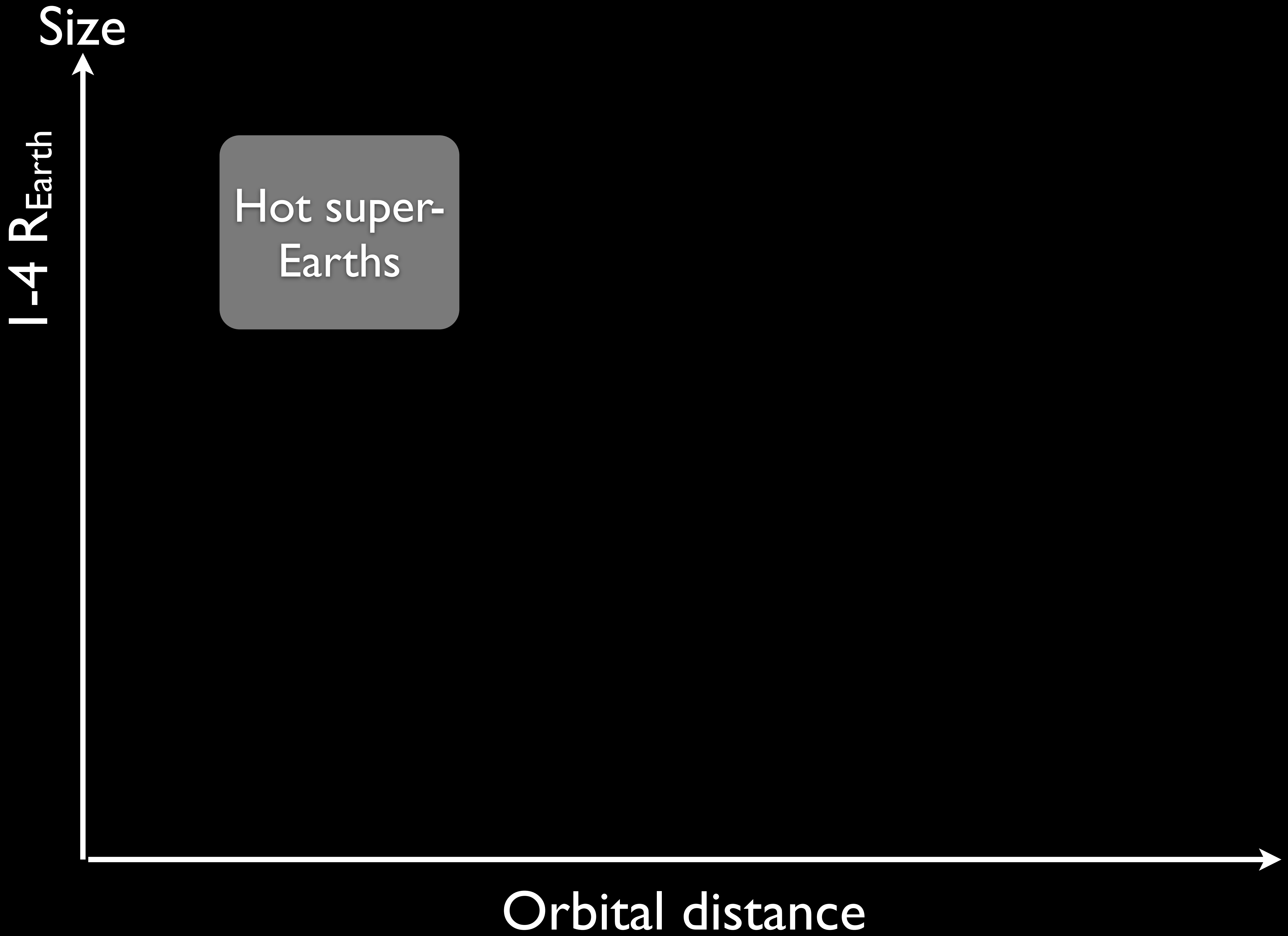
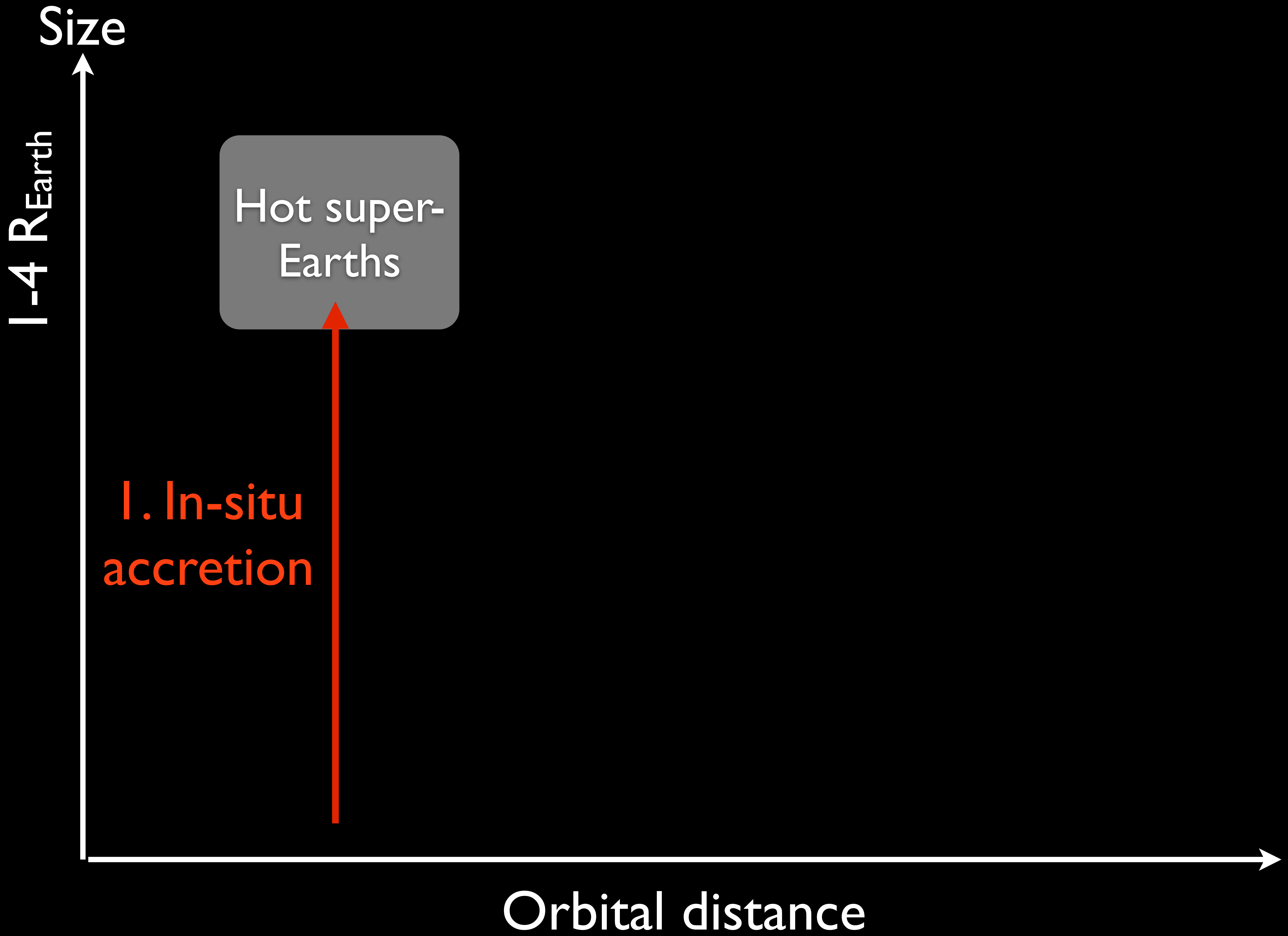


Slide inspired by KITP discussions with Eric Ford,
Geoff Marcy and Jack Lisaeur



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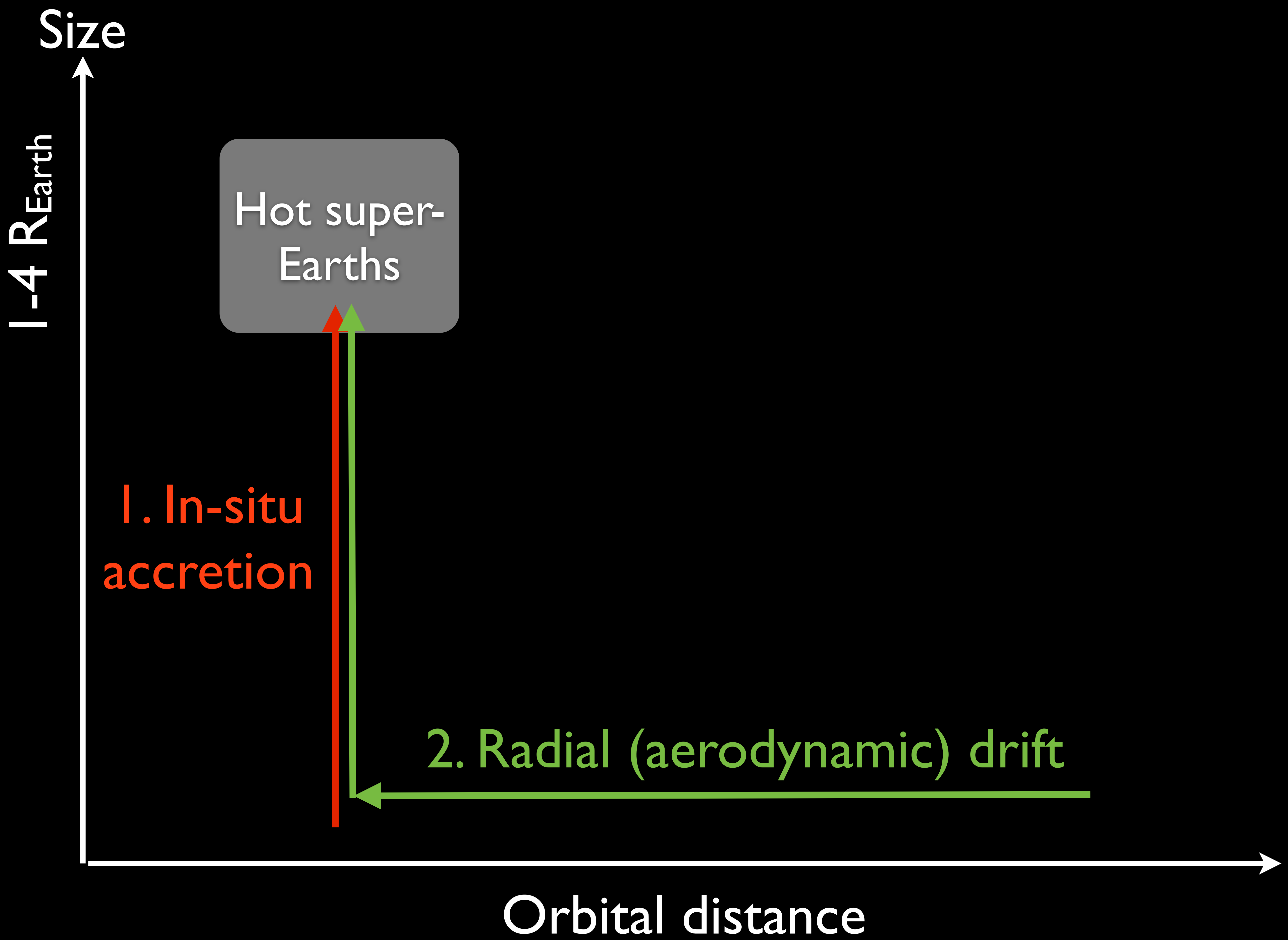

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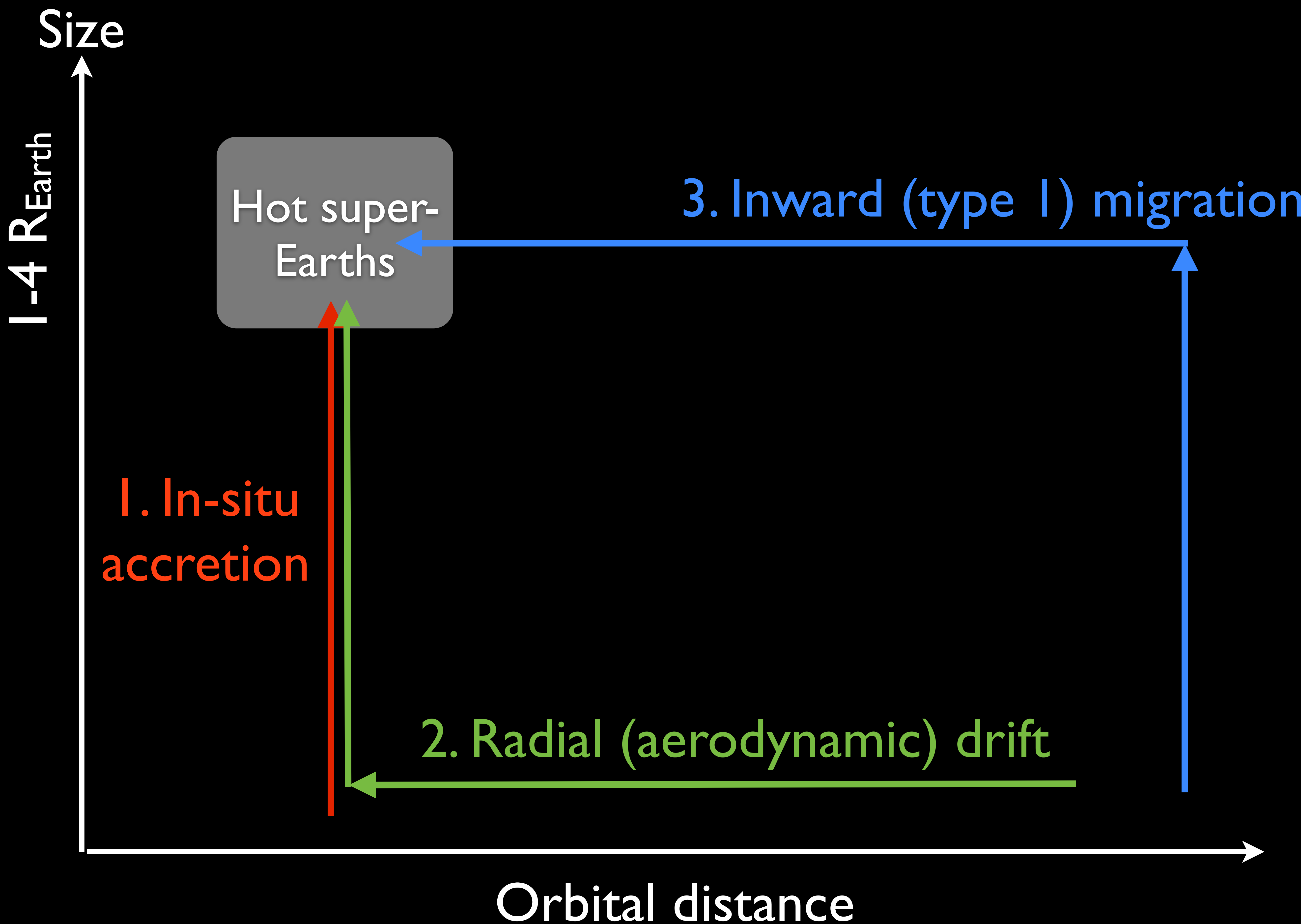

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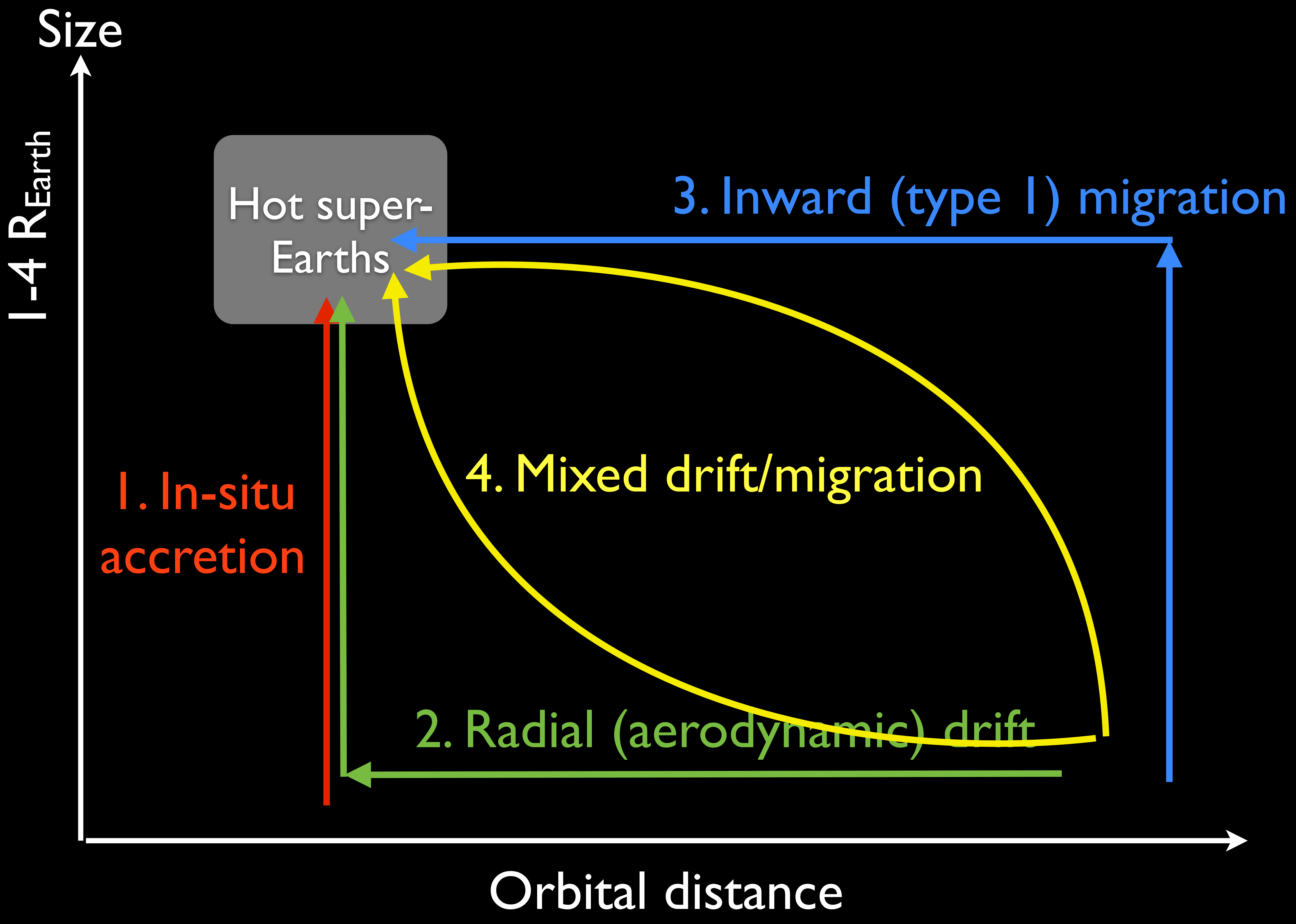

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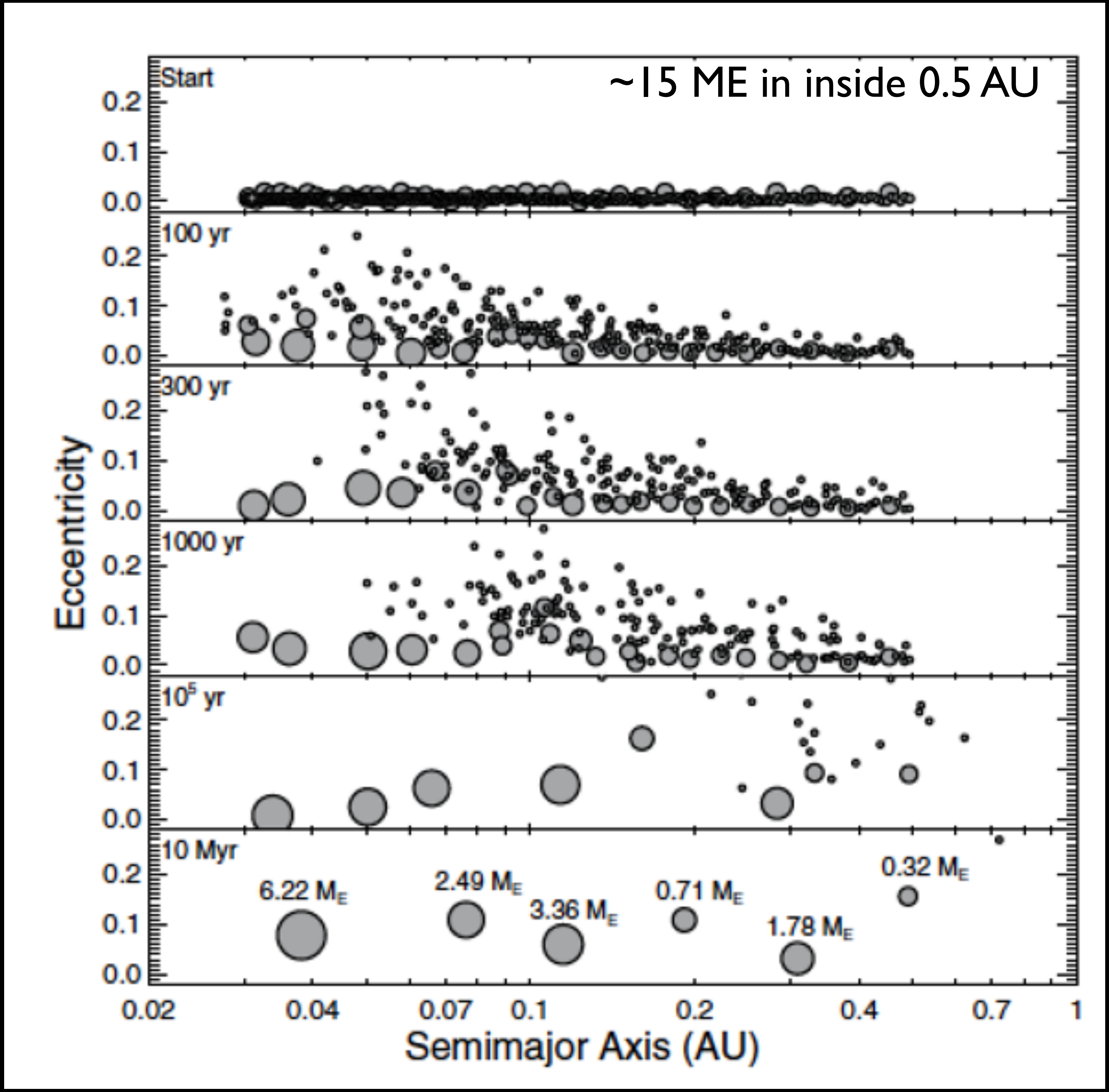
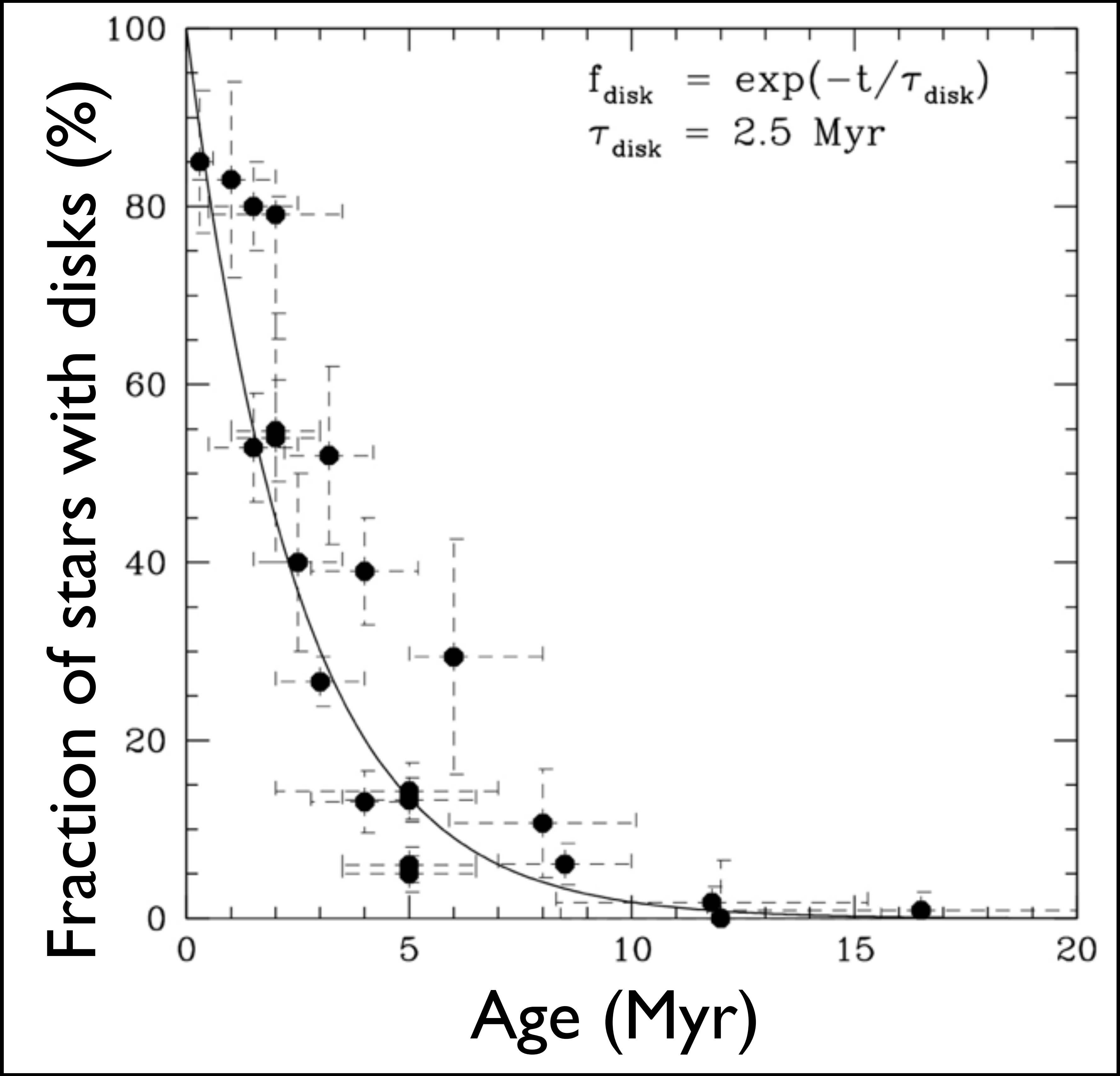
1. In-situ accretion: planets form fast in high-mass disks



Bolmont, Raymond et al 2014

Gaseous protoplanetary disks last a few Myr



Mamajek 2009;
Haisch et al 2001,
Hillenbrand 2008

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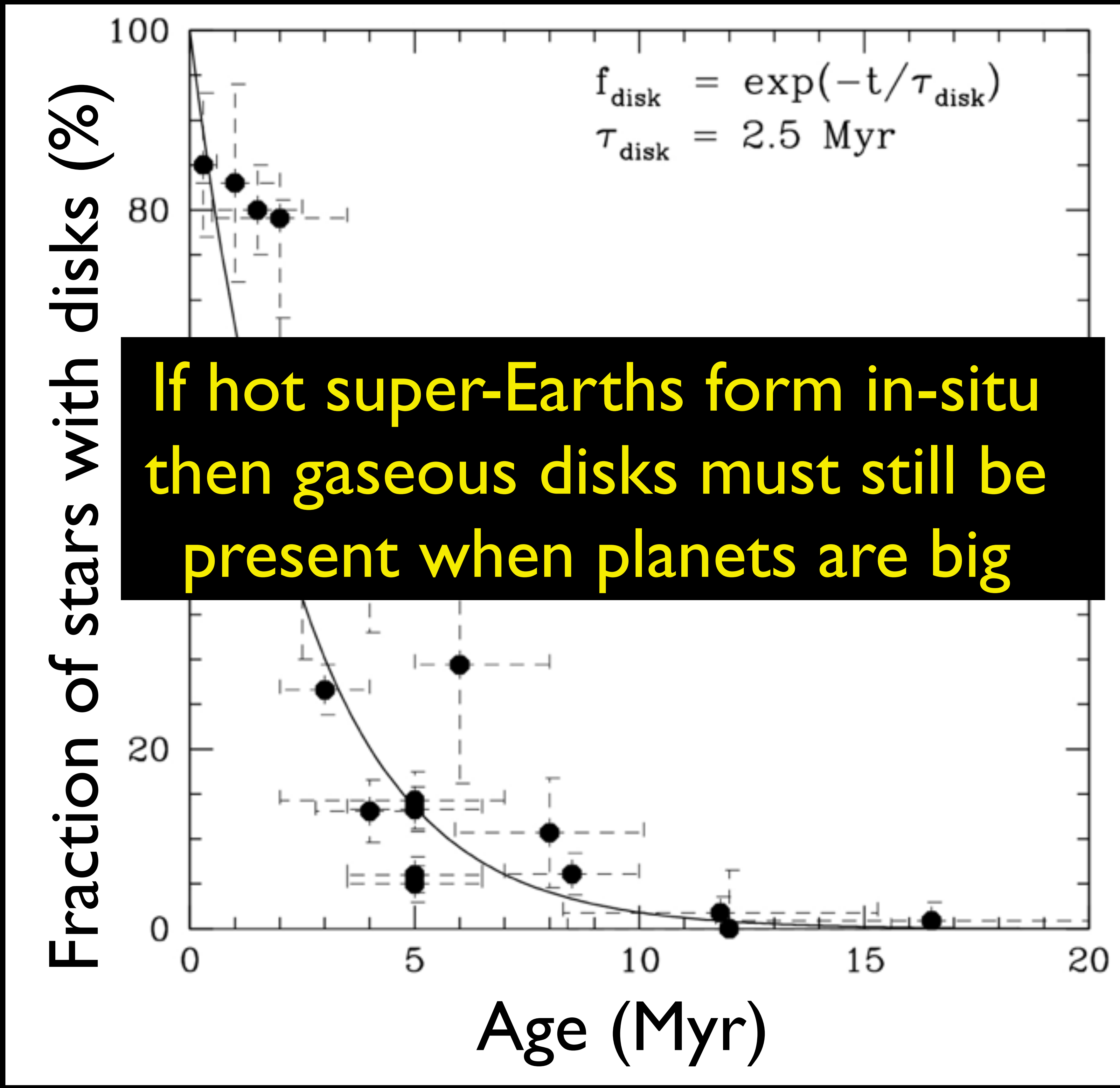


Mamajek 2009; Haisch et al 2001, Hillenbrand 2008

Gaseous disk causes orbital decay

Neptune

Earth

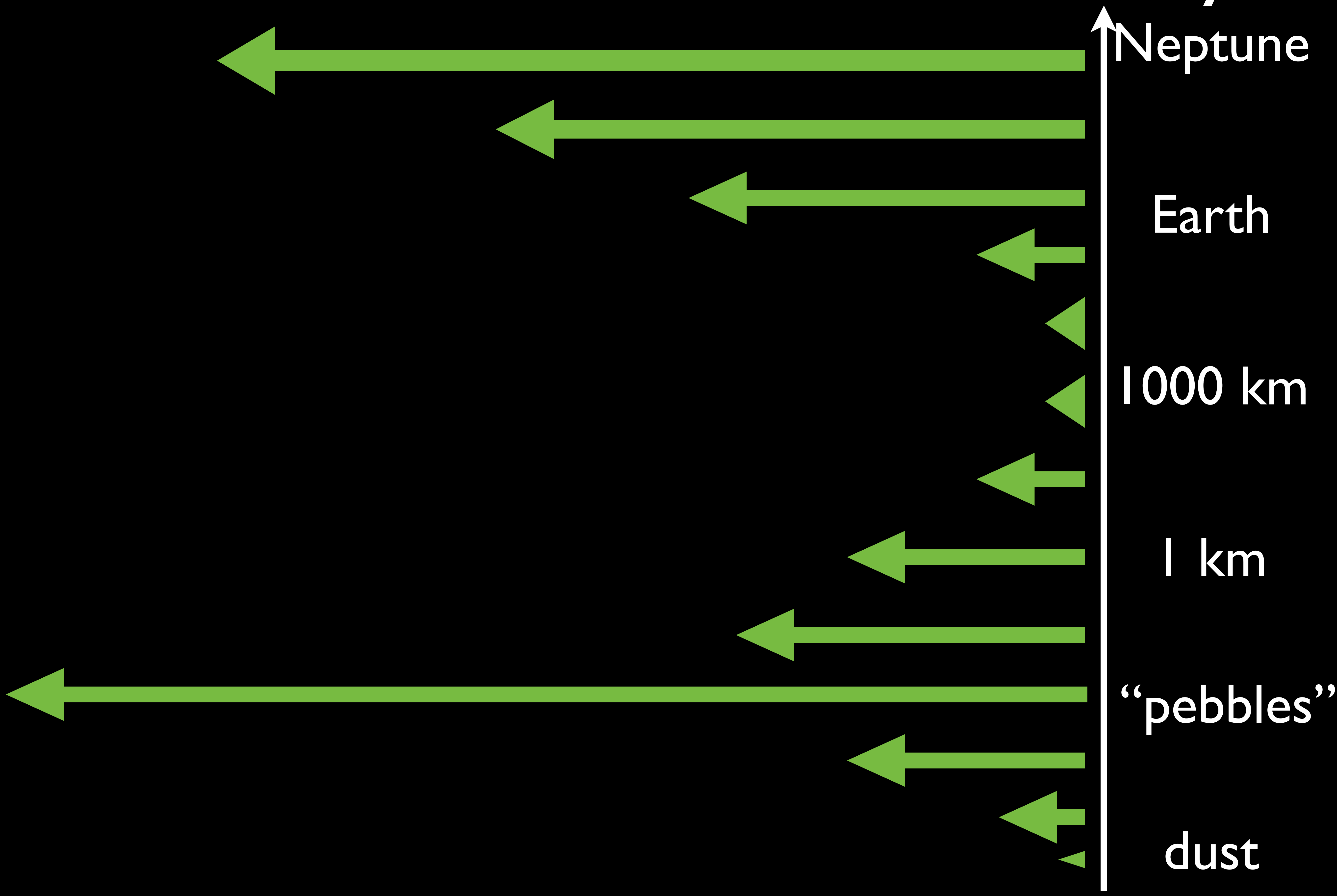
1000 km

1 km

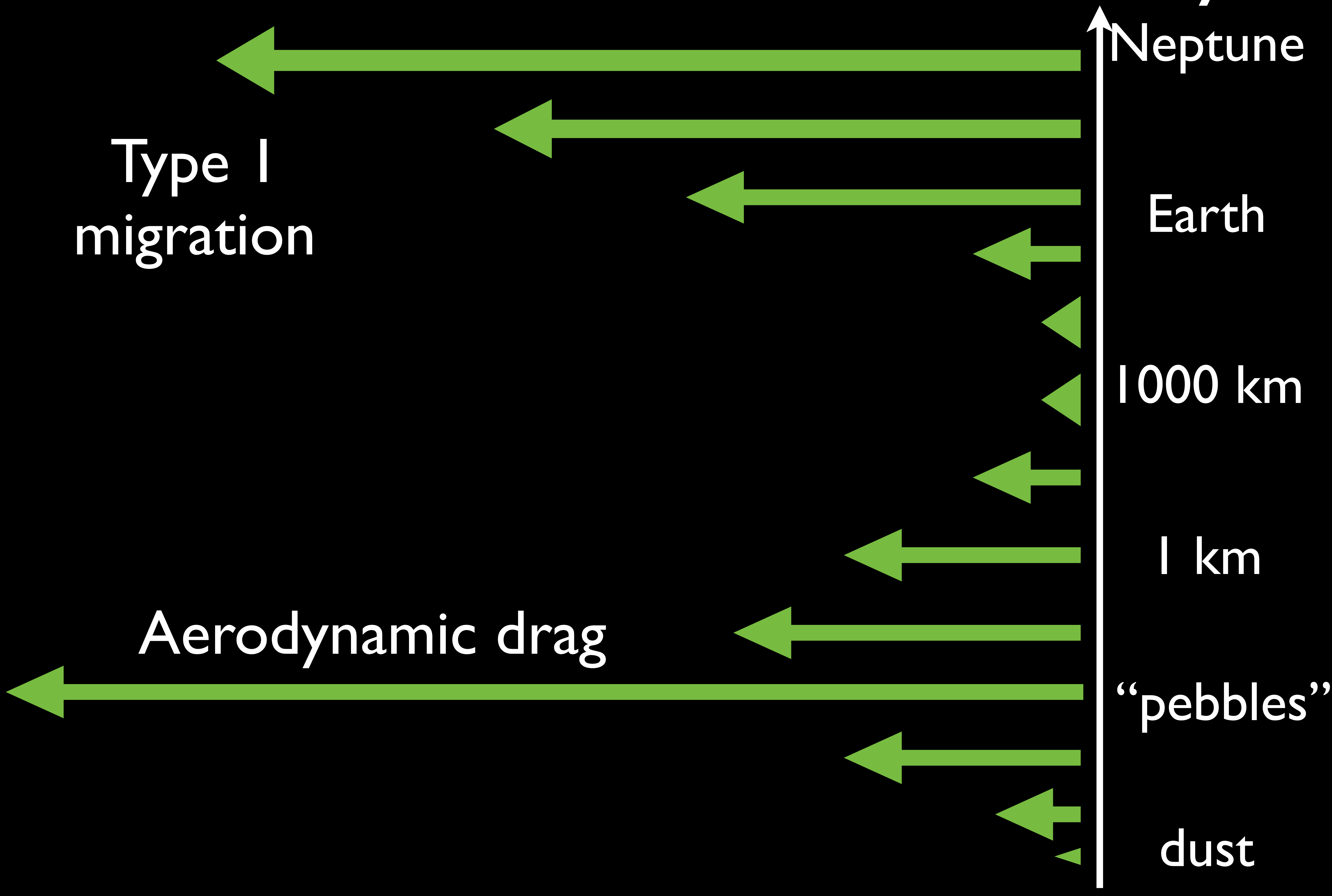
“pebbles”

dust

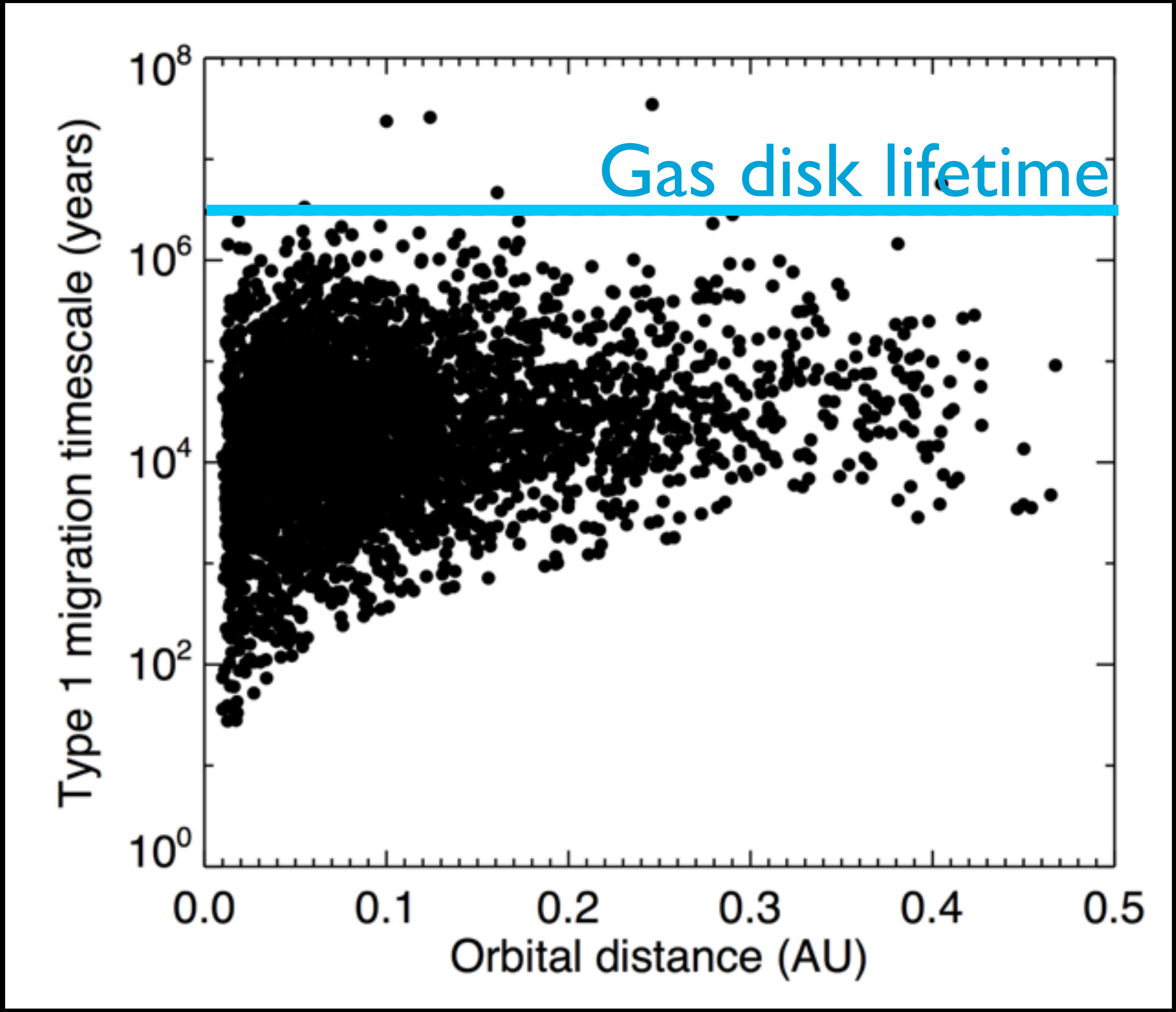
Gaseous disk causes orbital decay



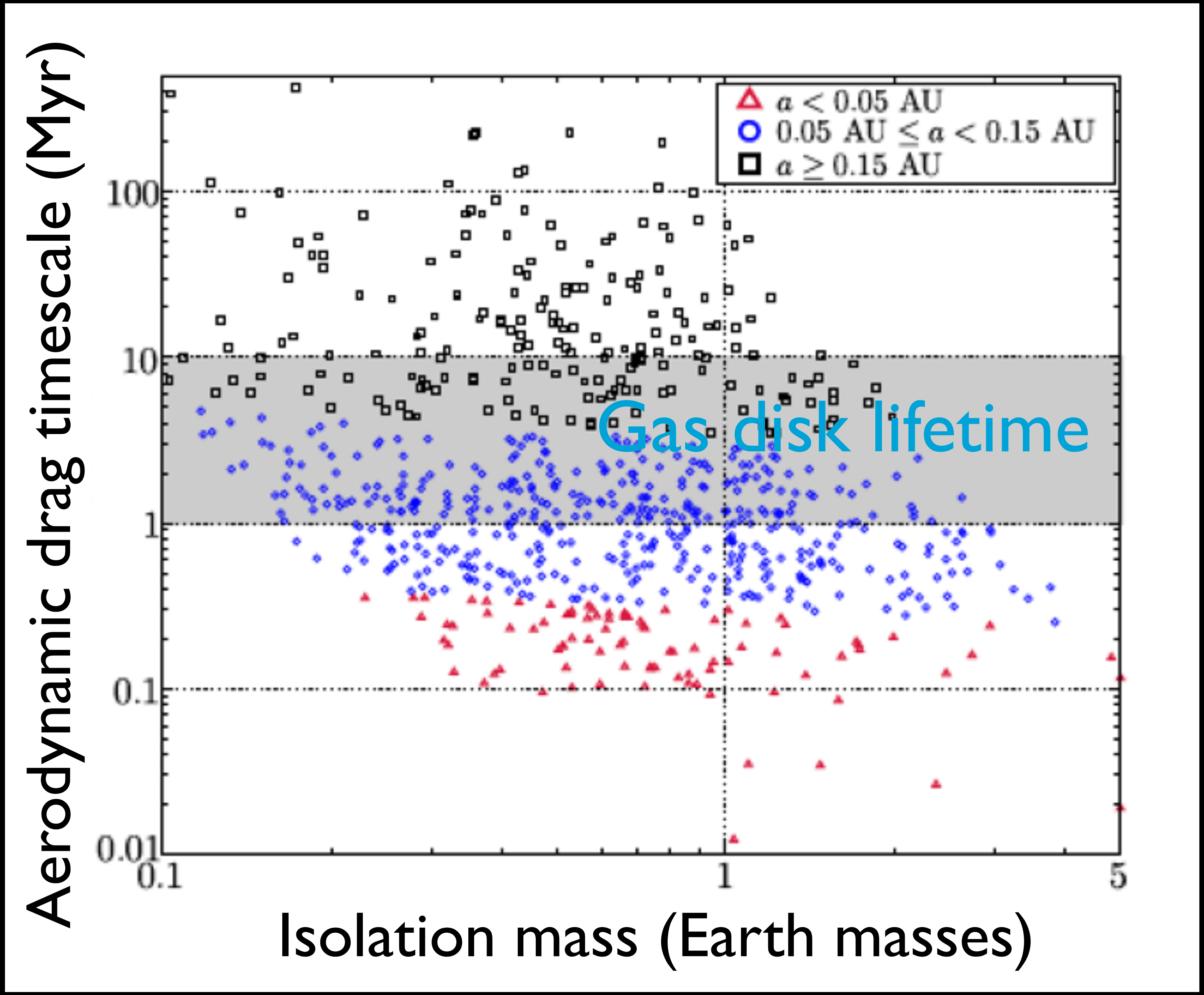
Gaseous disk causes orbital decay



Planets that form in-situ should migrate



Even aerodynamic drag causes planets to drift



Inamdar & Schlichting 2015

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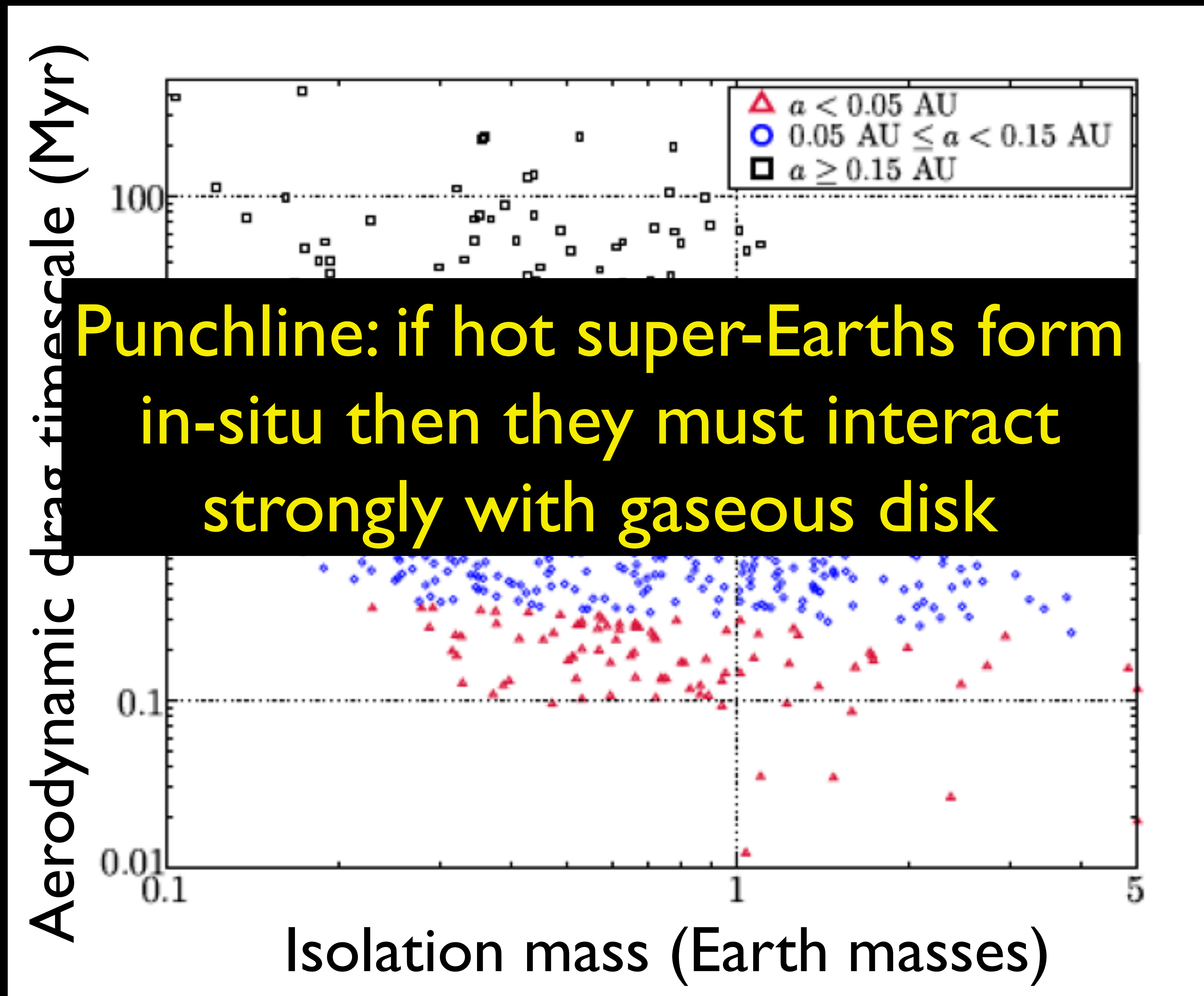
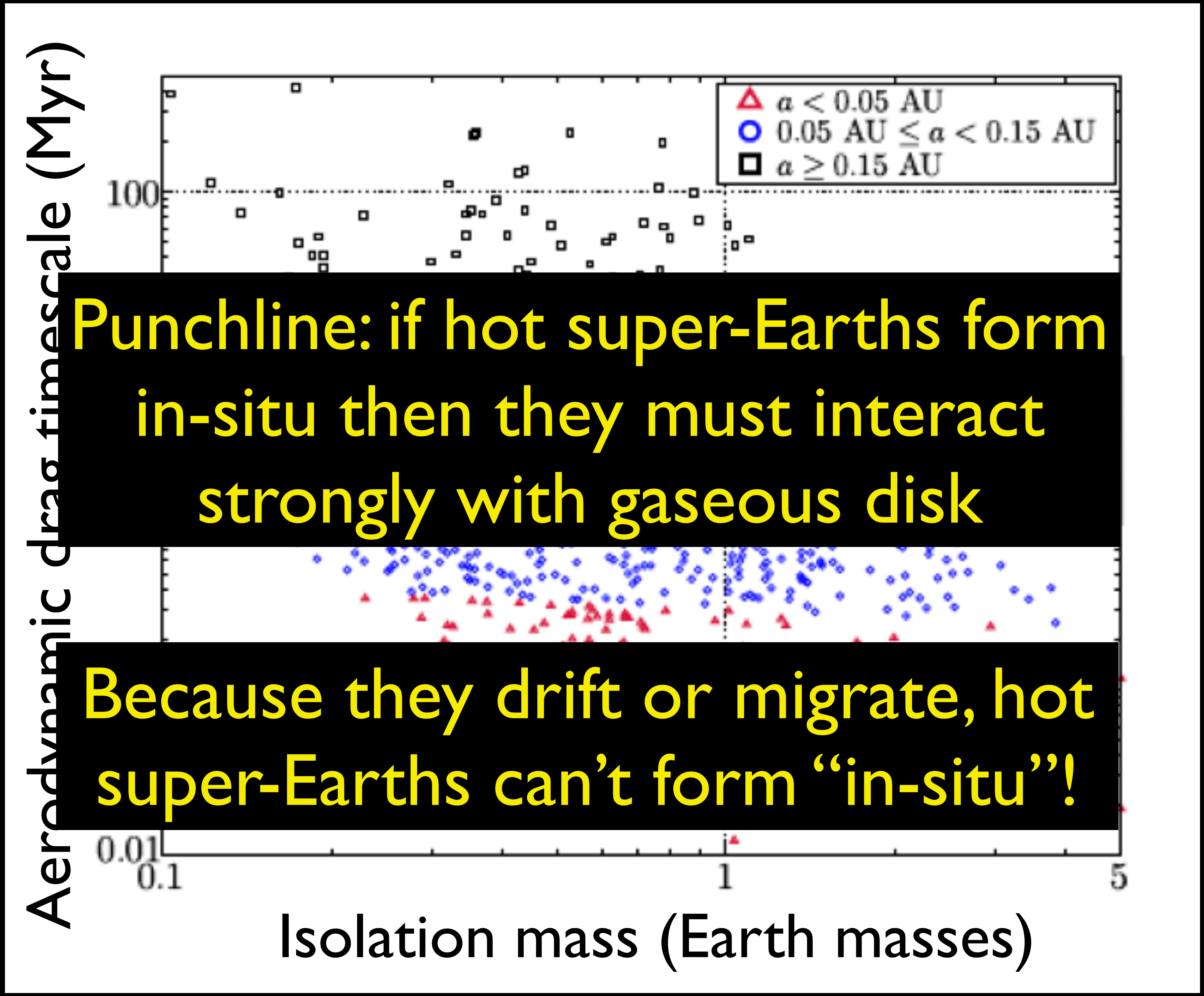


Punchline: if hot super-Earths form in-situ then they must interact strongly with gaseous disk

Inamdar & Schlichting 2015

Even aerodynamic drag causes planets to drift

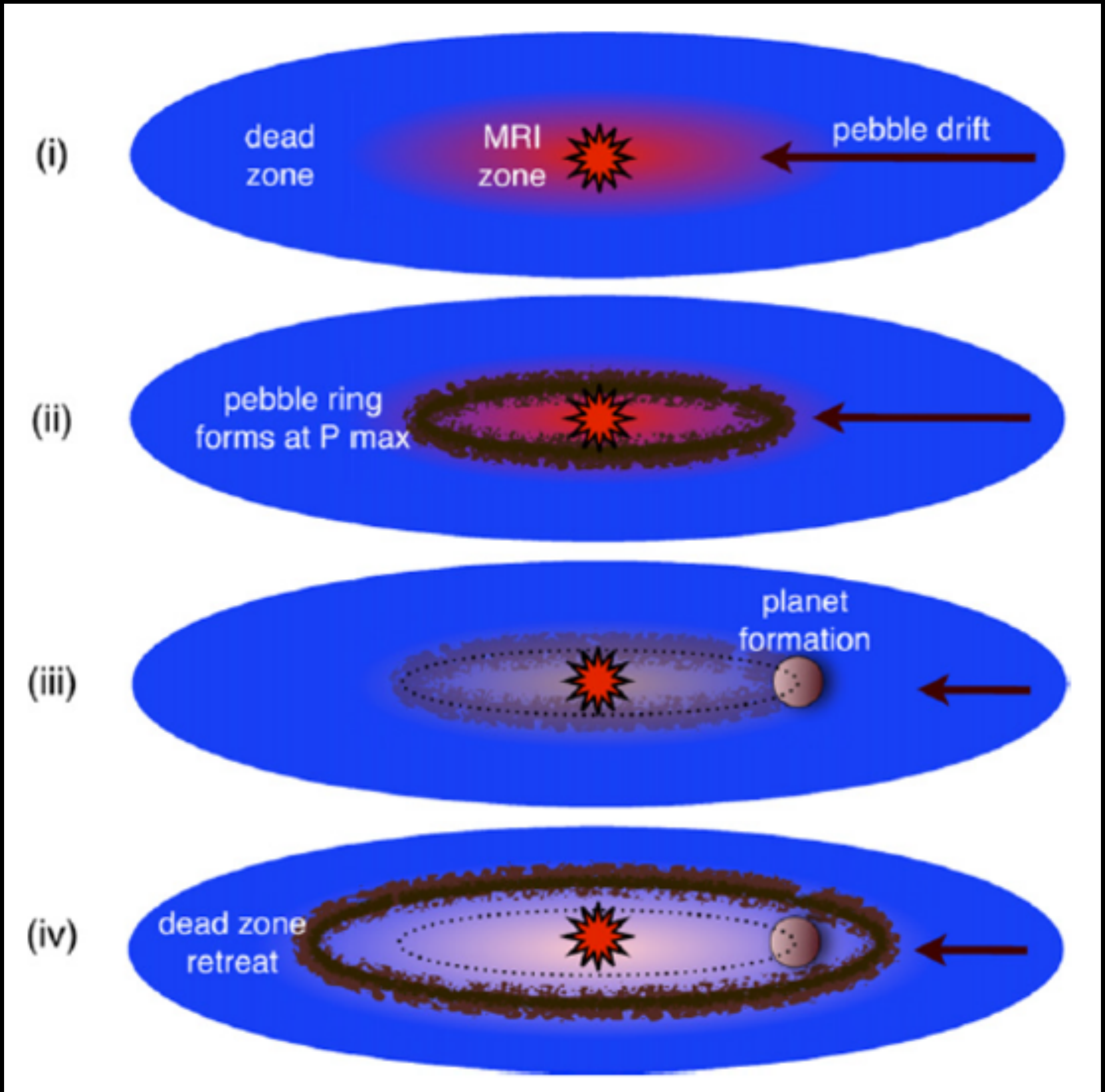


Punchline: if hot super-Earths form in-situ then they must interact strongly with gaseous disk

Because they drift or migrate, hot super-Earths can't form "in-situ"!

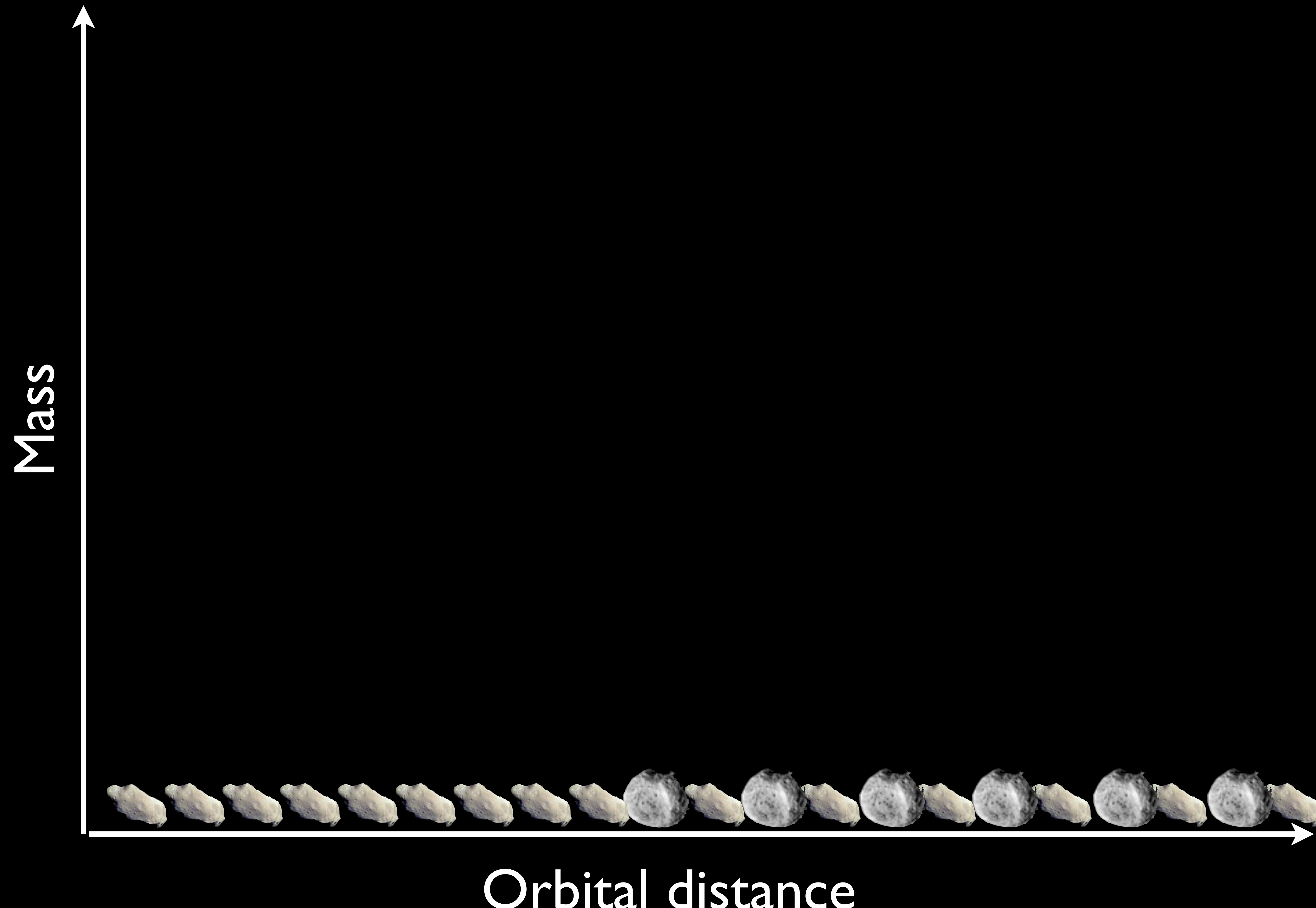
Inamdar & Schlichting 2015

2. Radial drift of small bodies



Chatterjee & Tan 2014, 2015; Hu et al 2014; Boley & Ford 2013; Boley et al 2014

3. Forming hot super-Earths by type 1 migration



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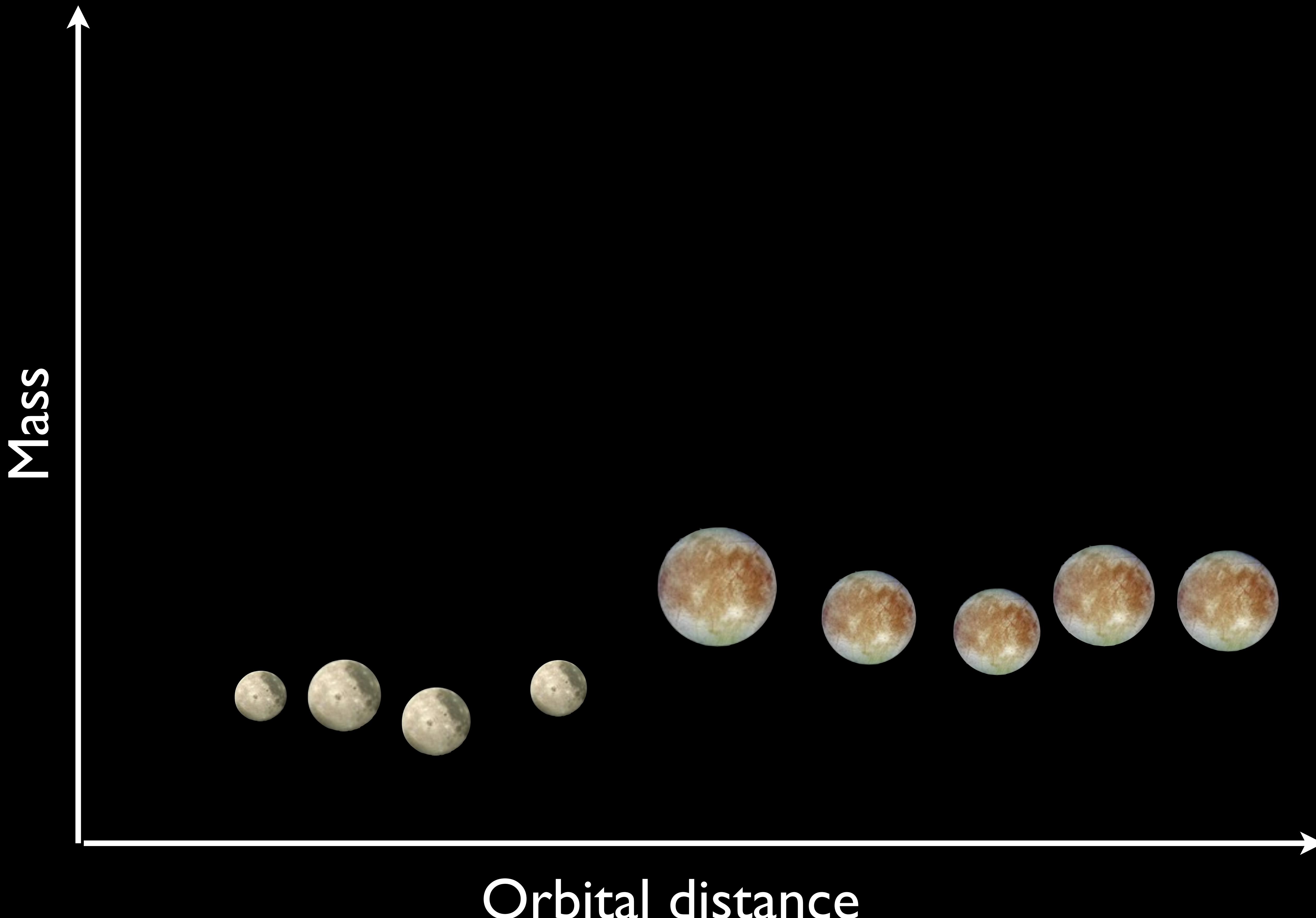

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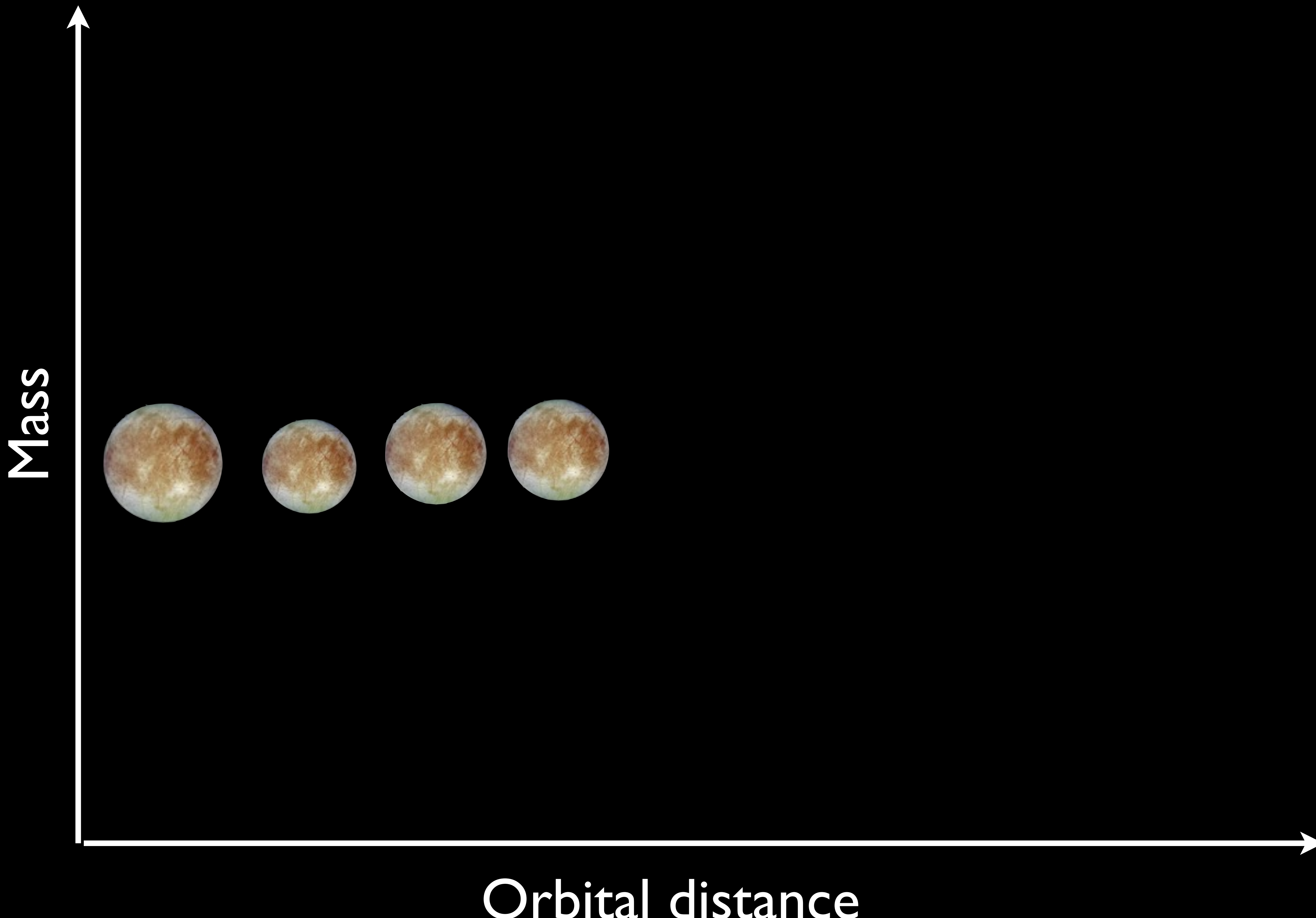
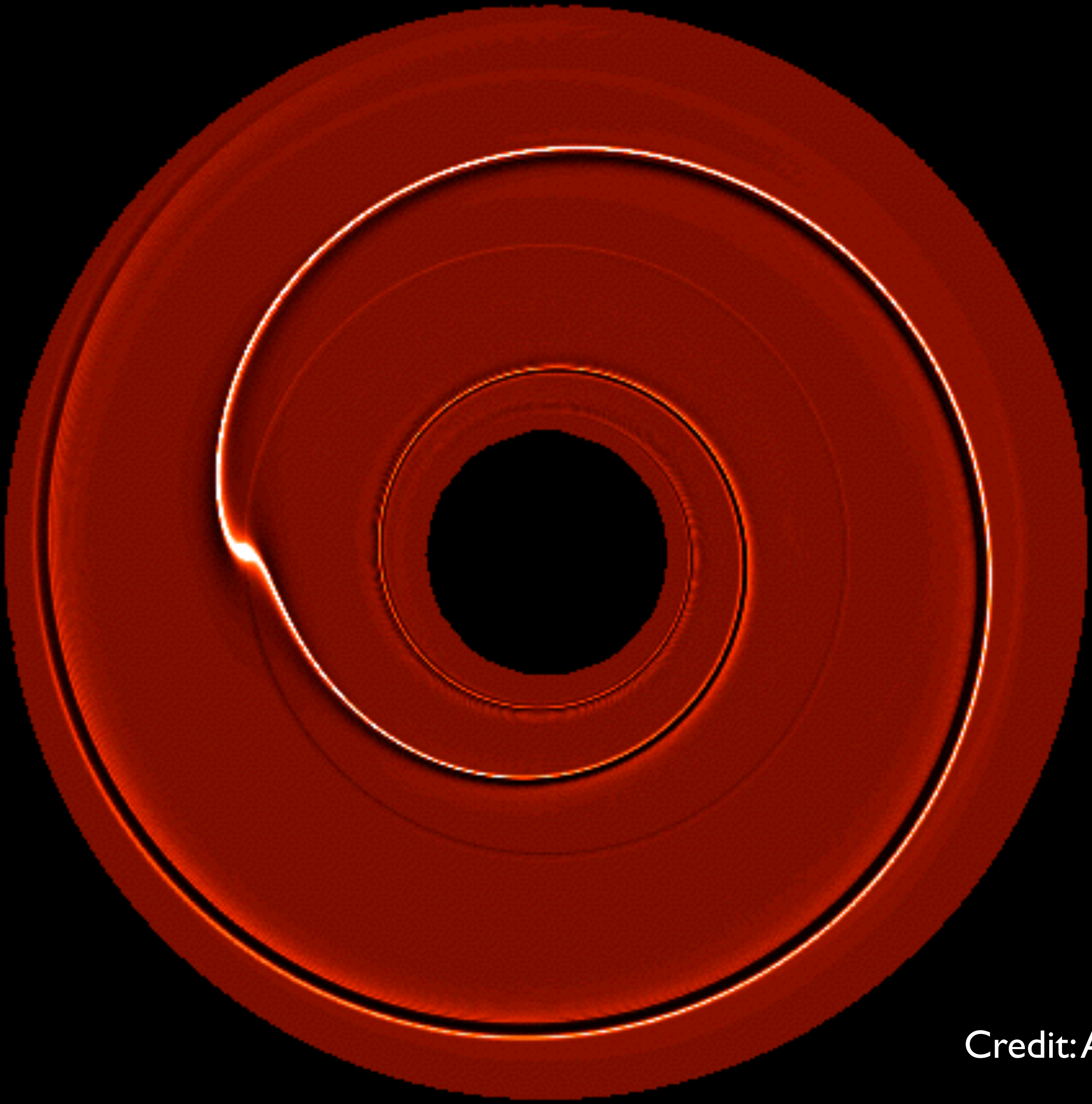


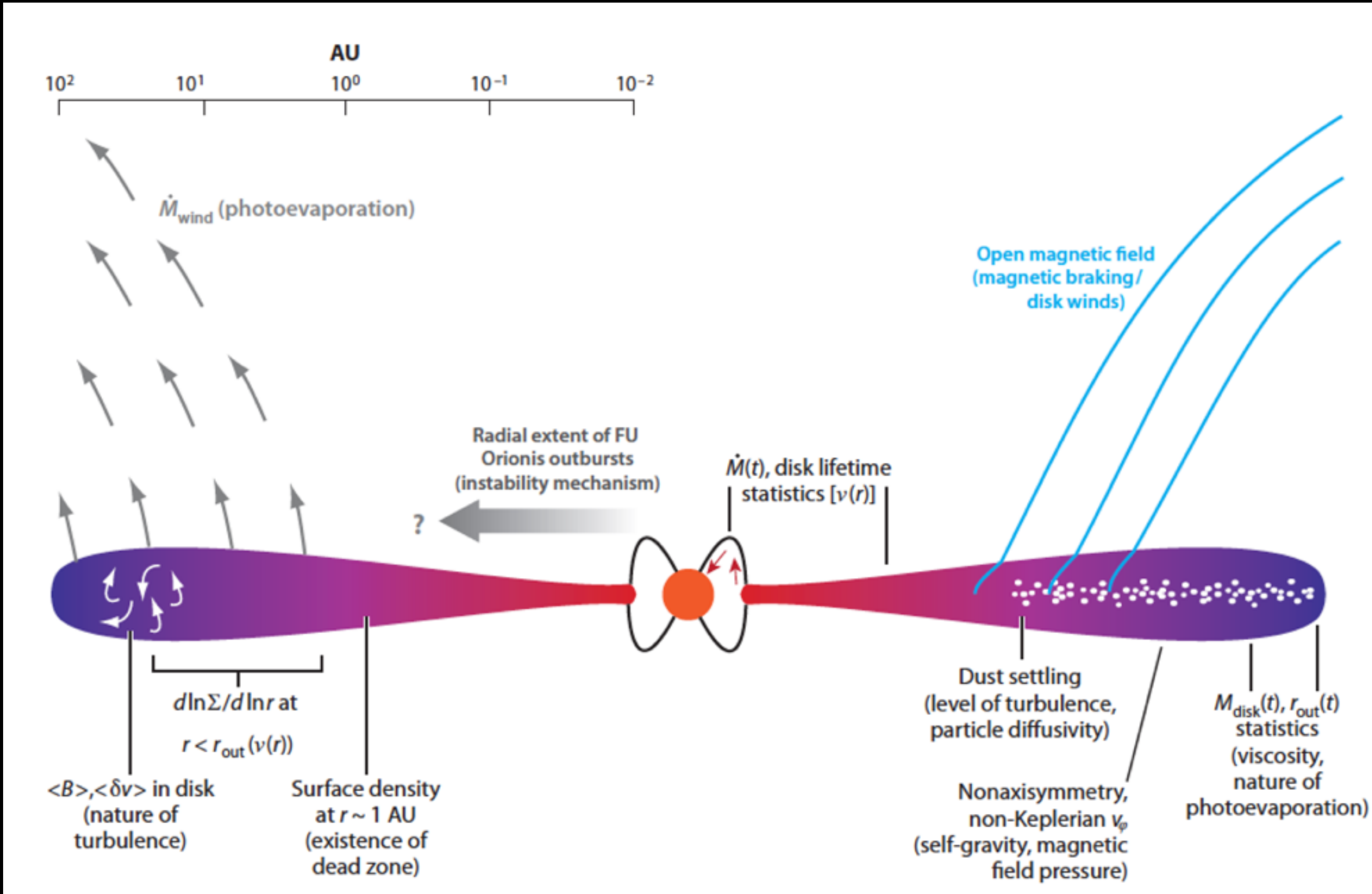
Type I migration

- 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

Migration stops at the inner edge of the disk

Masset et al (2006)

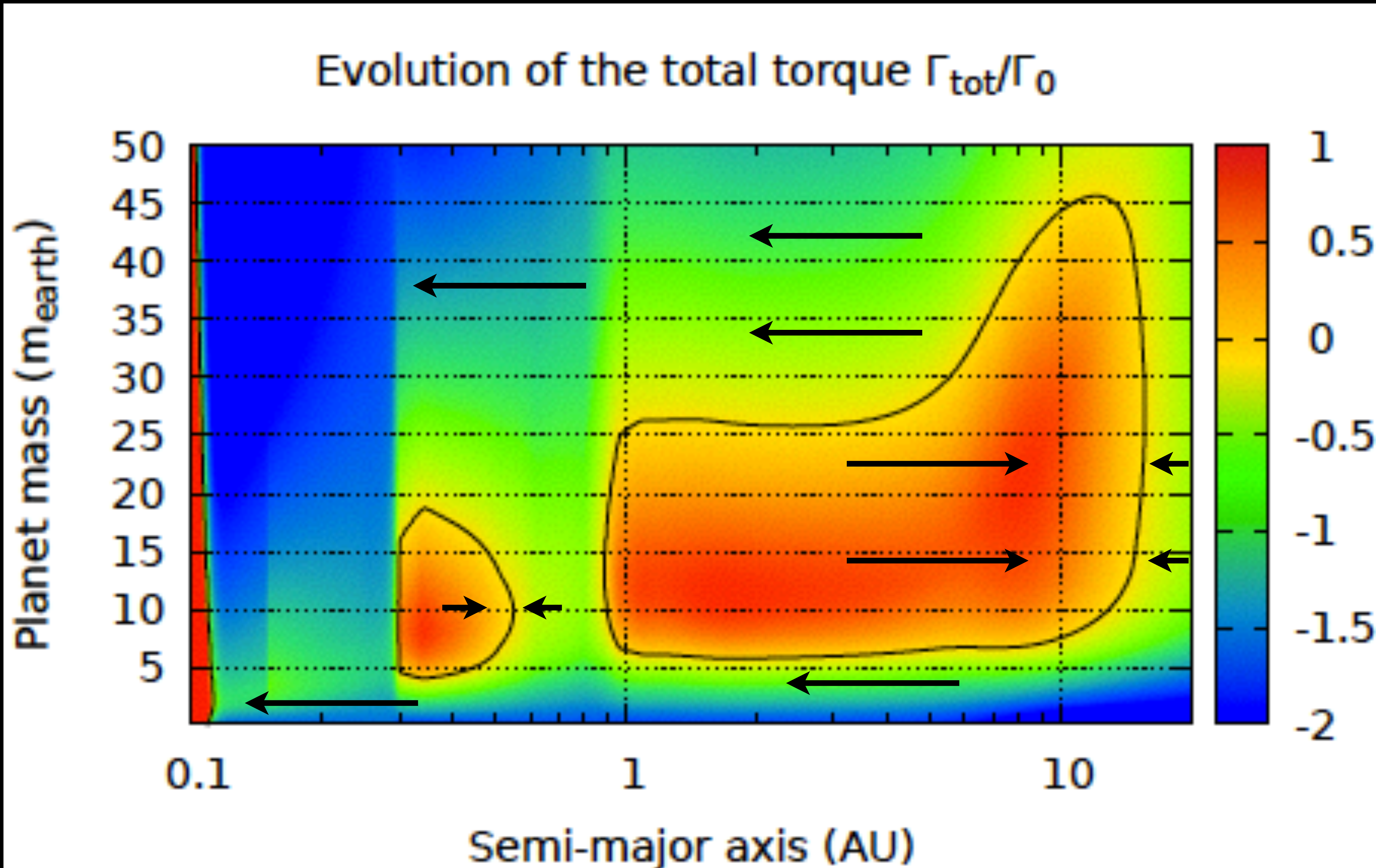
Migration stops at the inner edge of the disk

Masset et al (2006)

Migration stops at the inner edge of the disk

Masset et al (2006)

A type 1 migration map



Cossou et al 2014;
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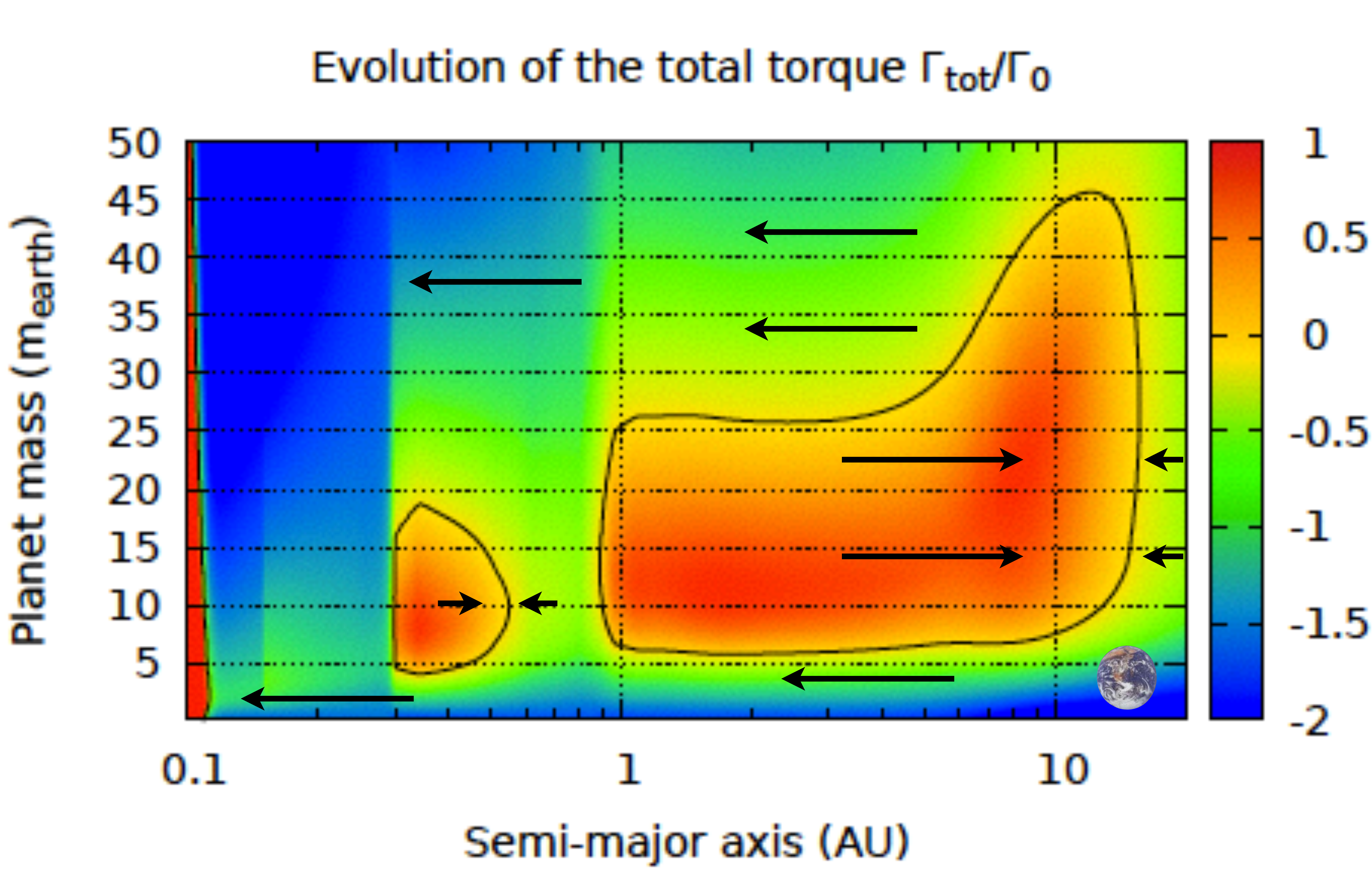

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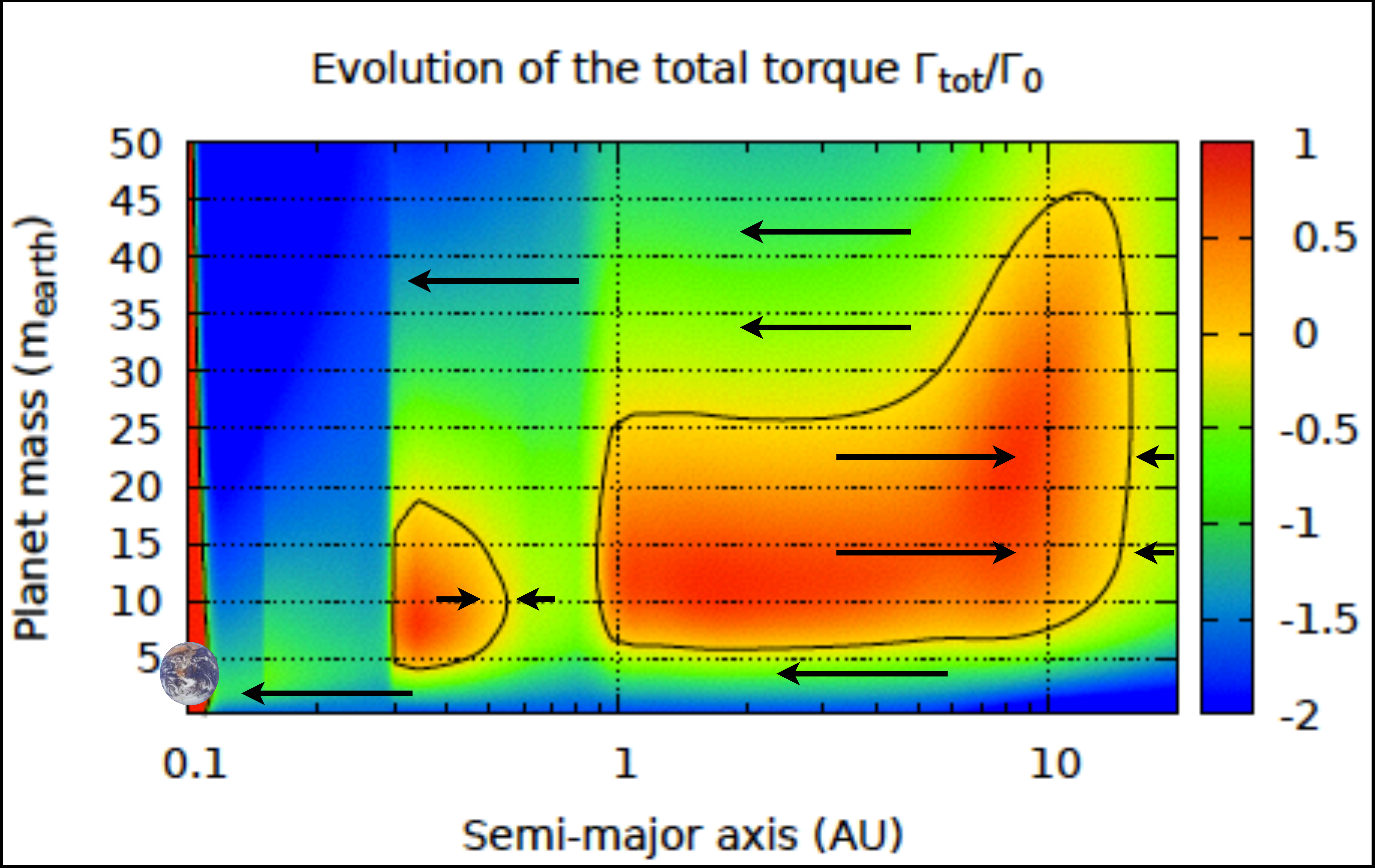

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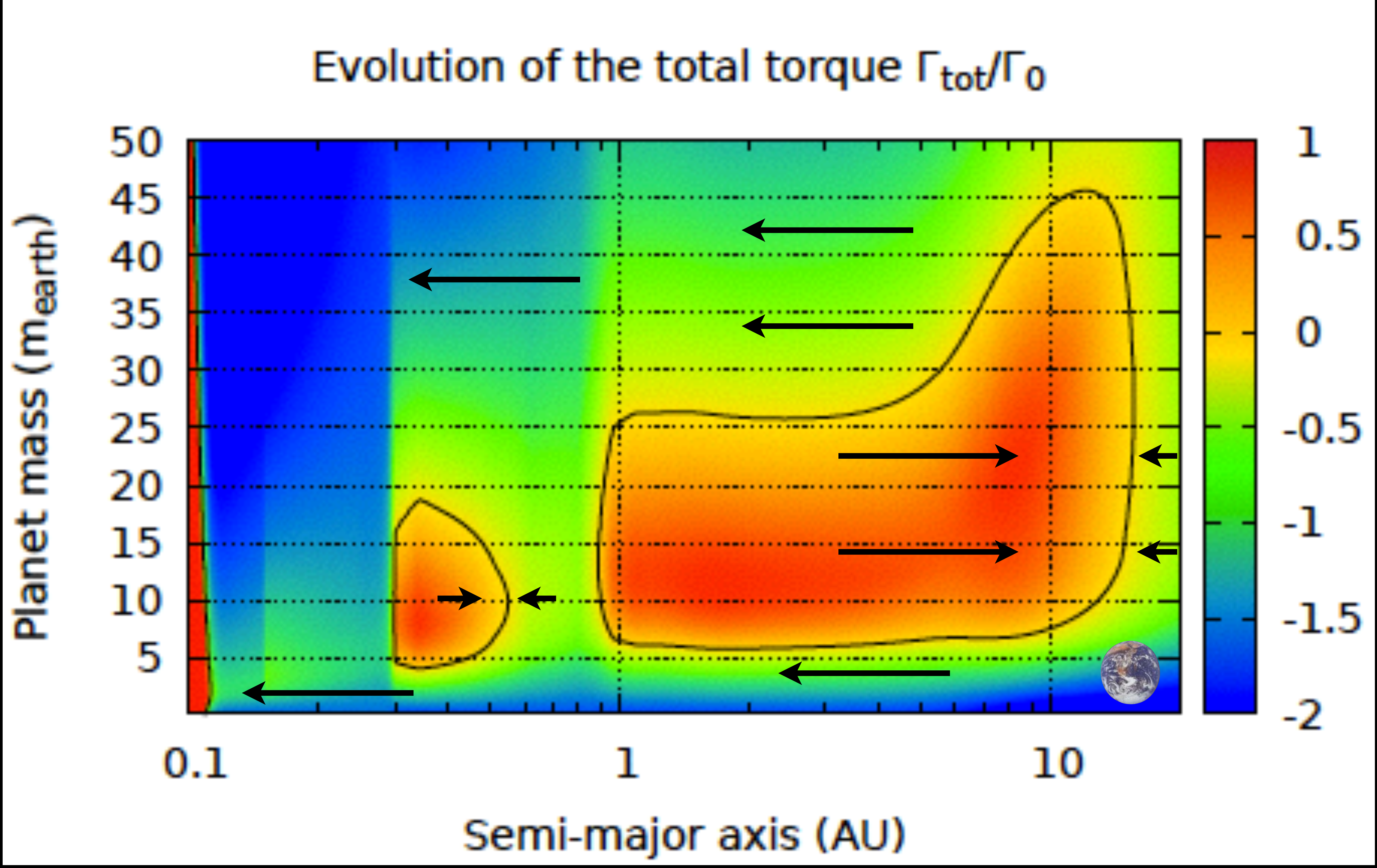

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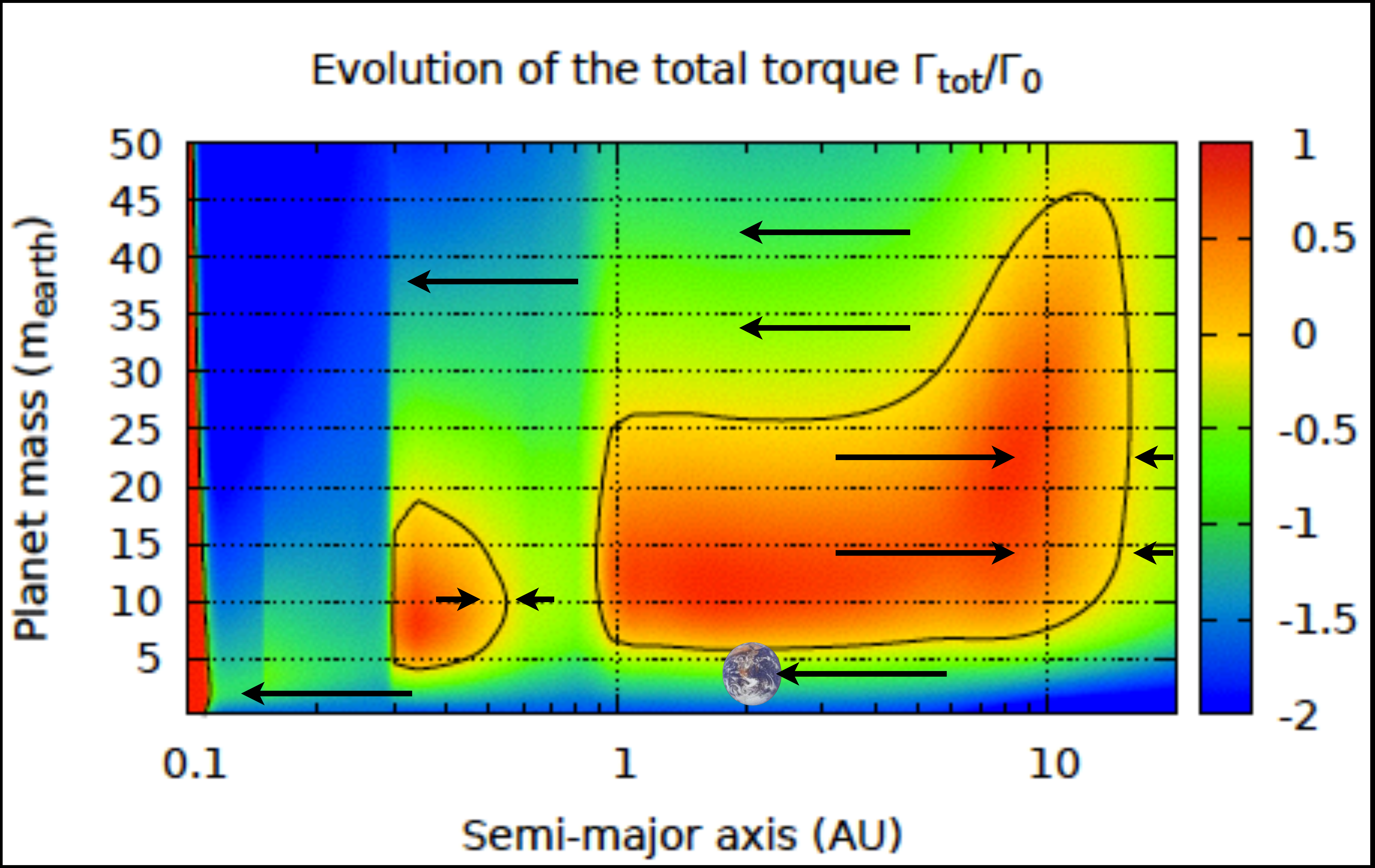

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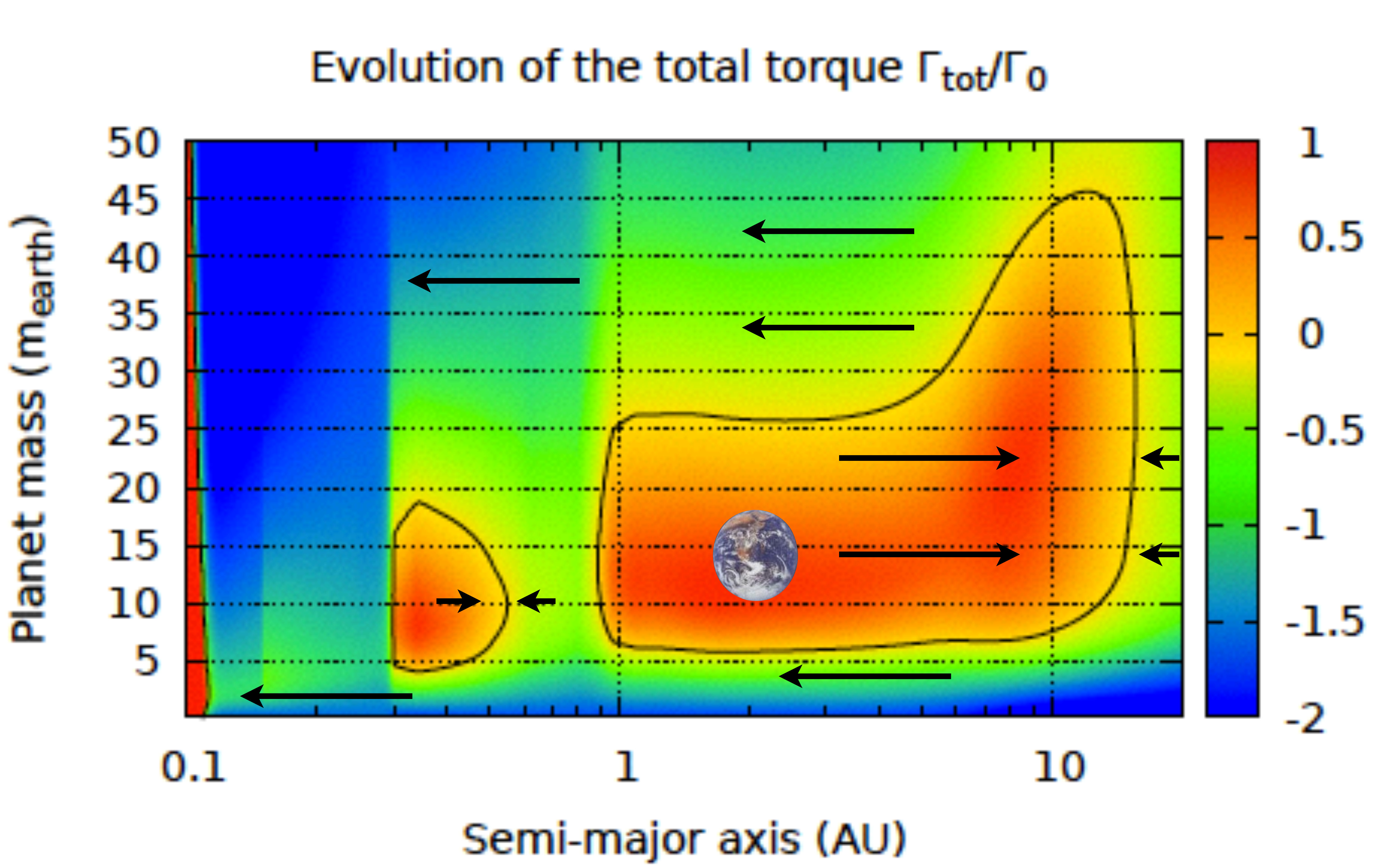

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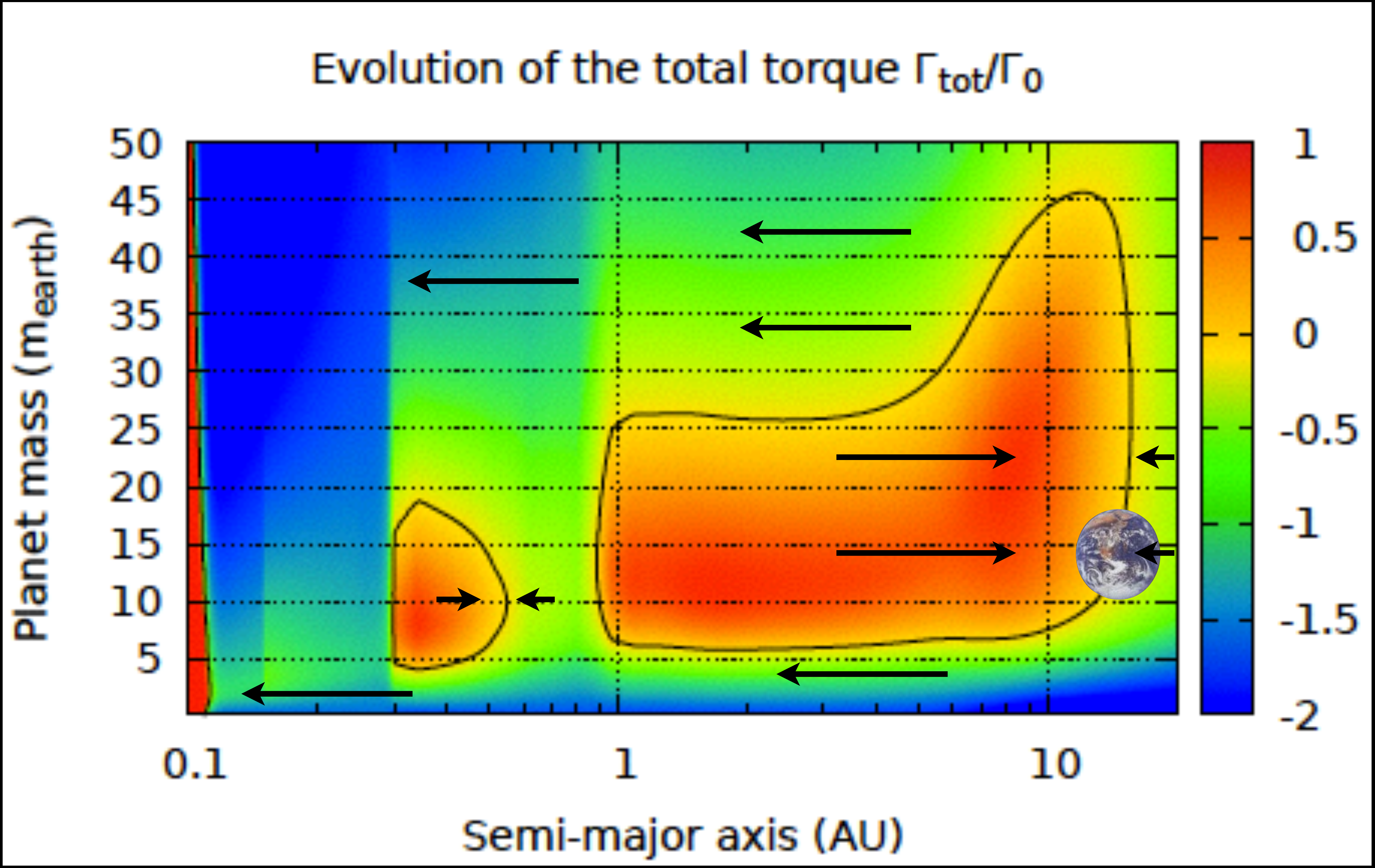

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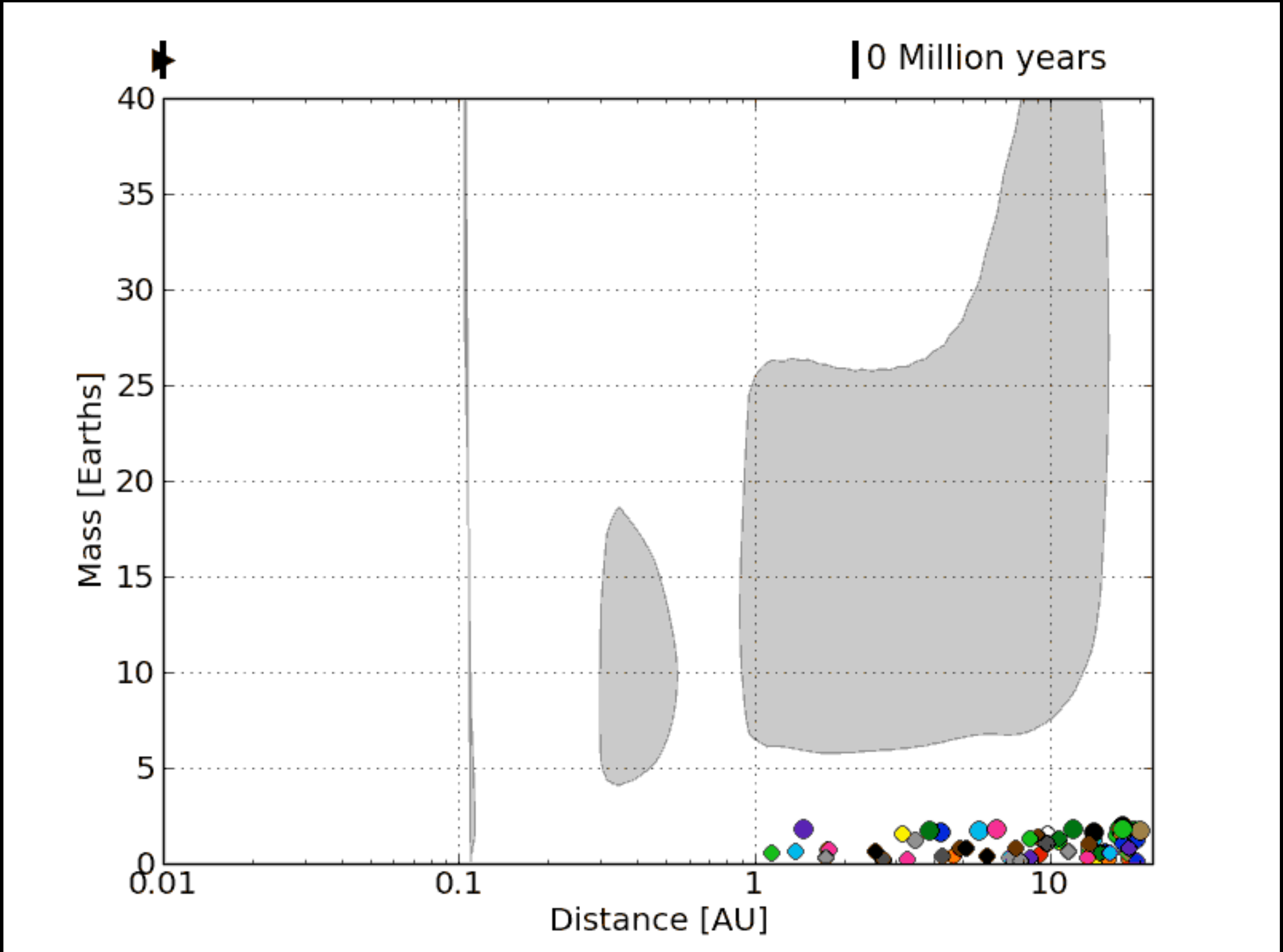
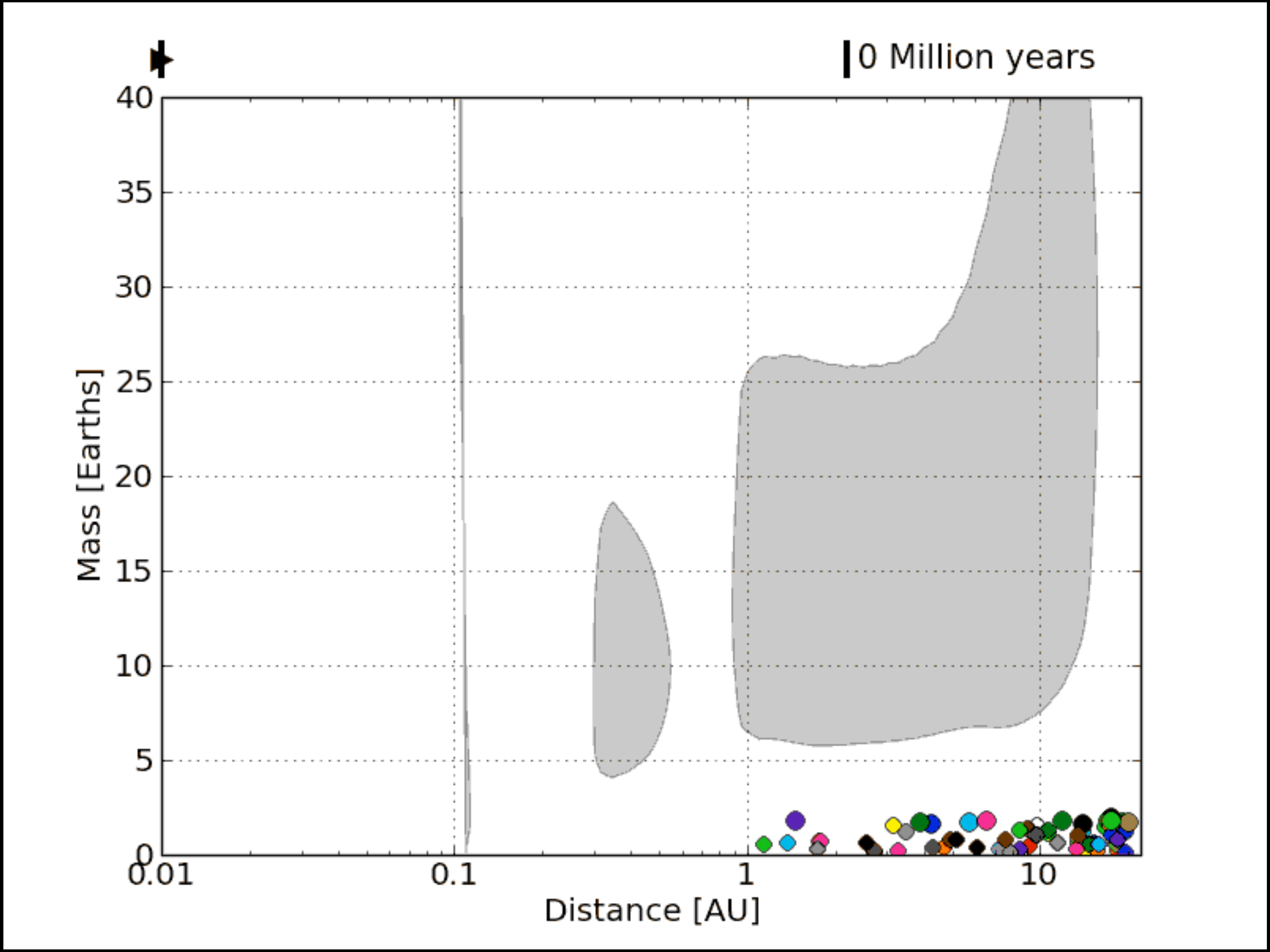
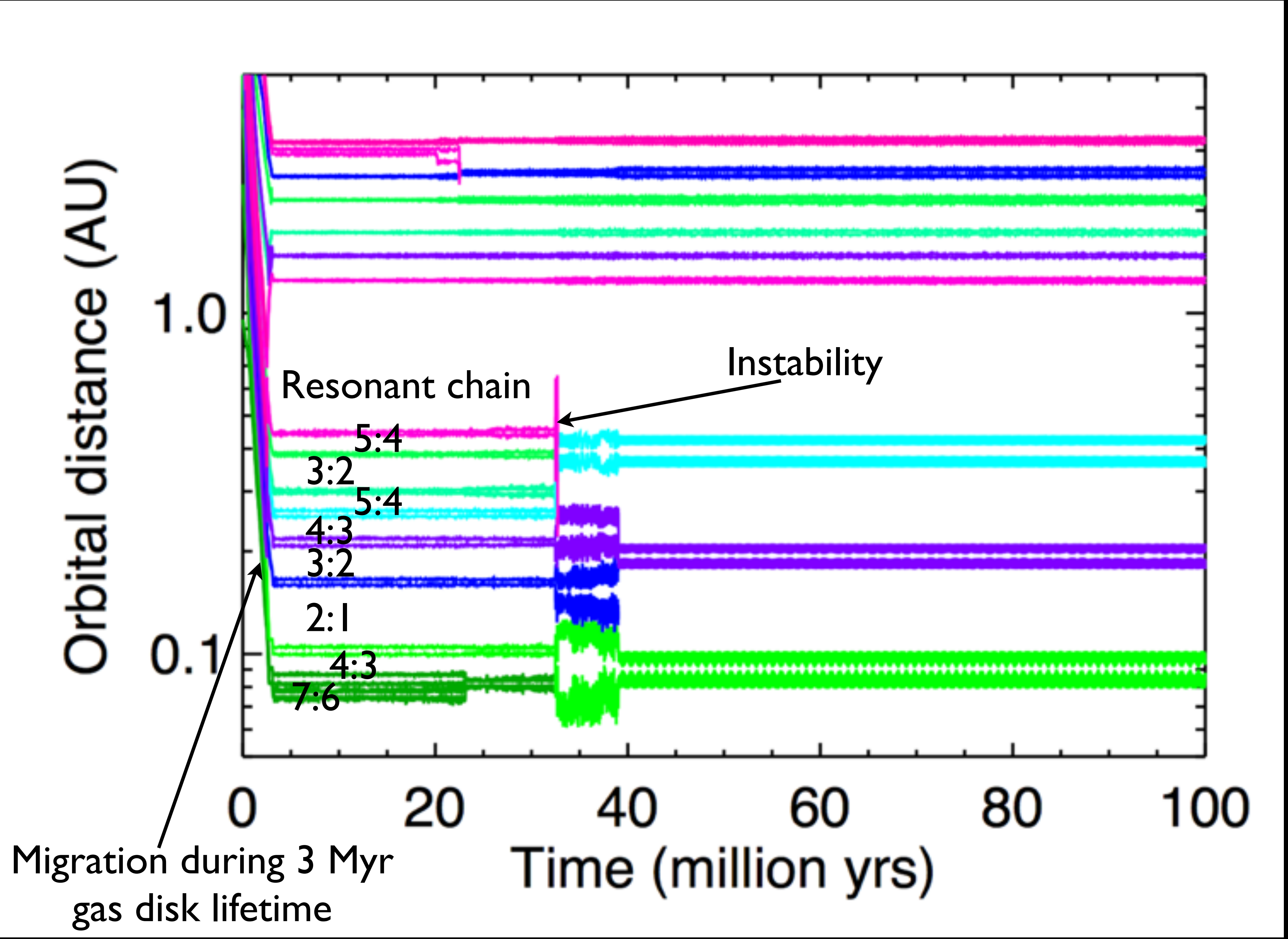


Cossou, Raymond et al 2014



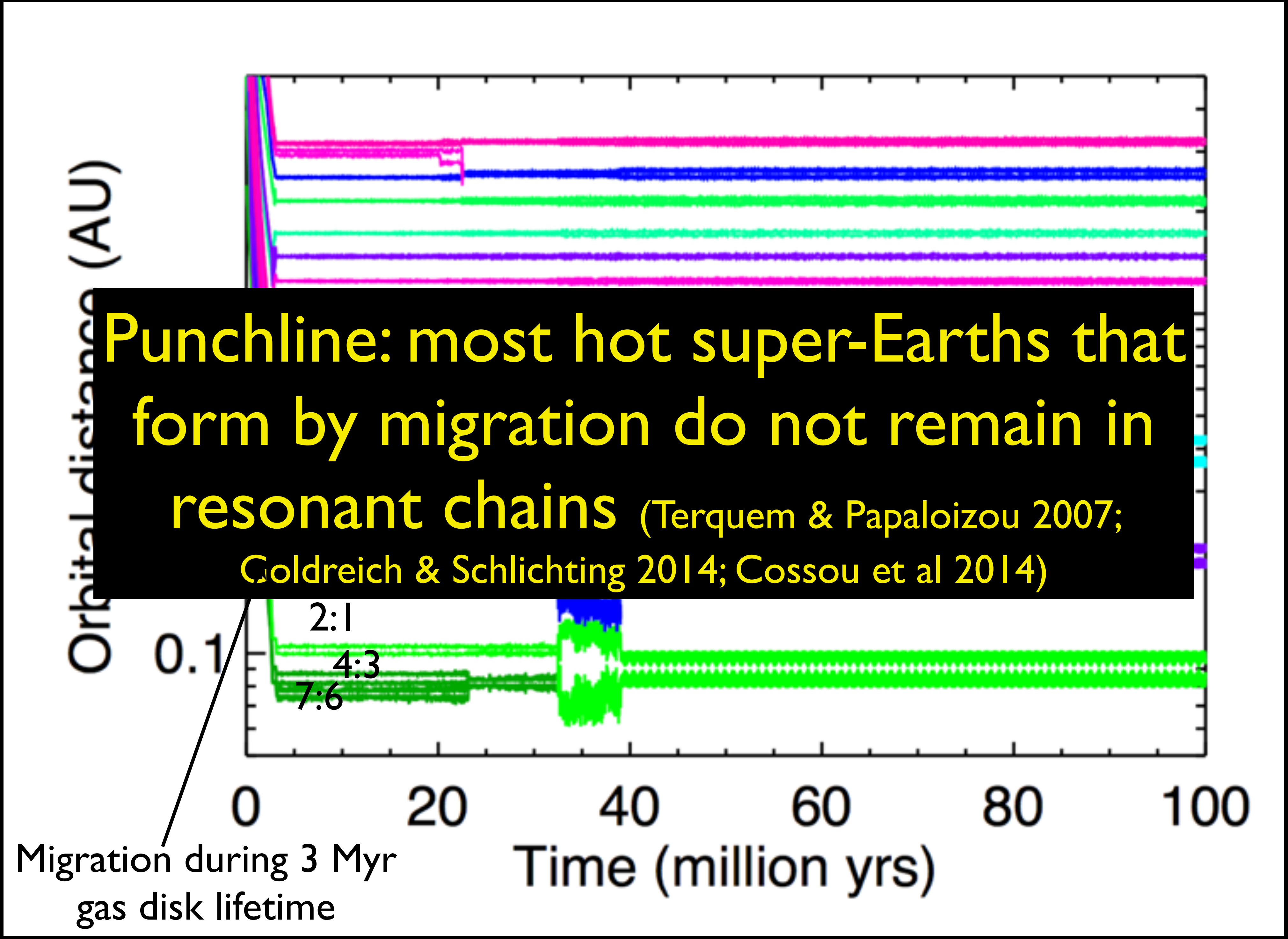
Cossou, Raymond et al 2014

Resonant chains usually go unstable as or after gas disk dissipates



Cossou, Raymond et al 2014

Resonant chains usually go unstable as or after gas disk dissipates



Punchline: most hot super-Earths that form by migration do not remain in resonant chains (Terquem & Papaloizou 2007; Goldreich & Schlichting 2014; Cossou et al 2014)

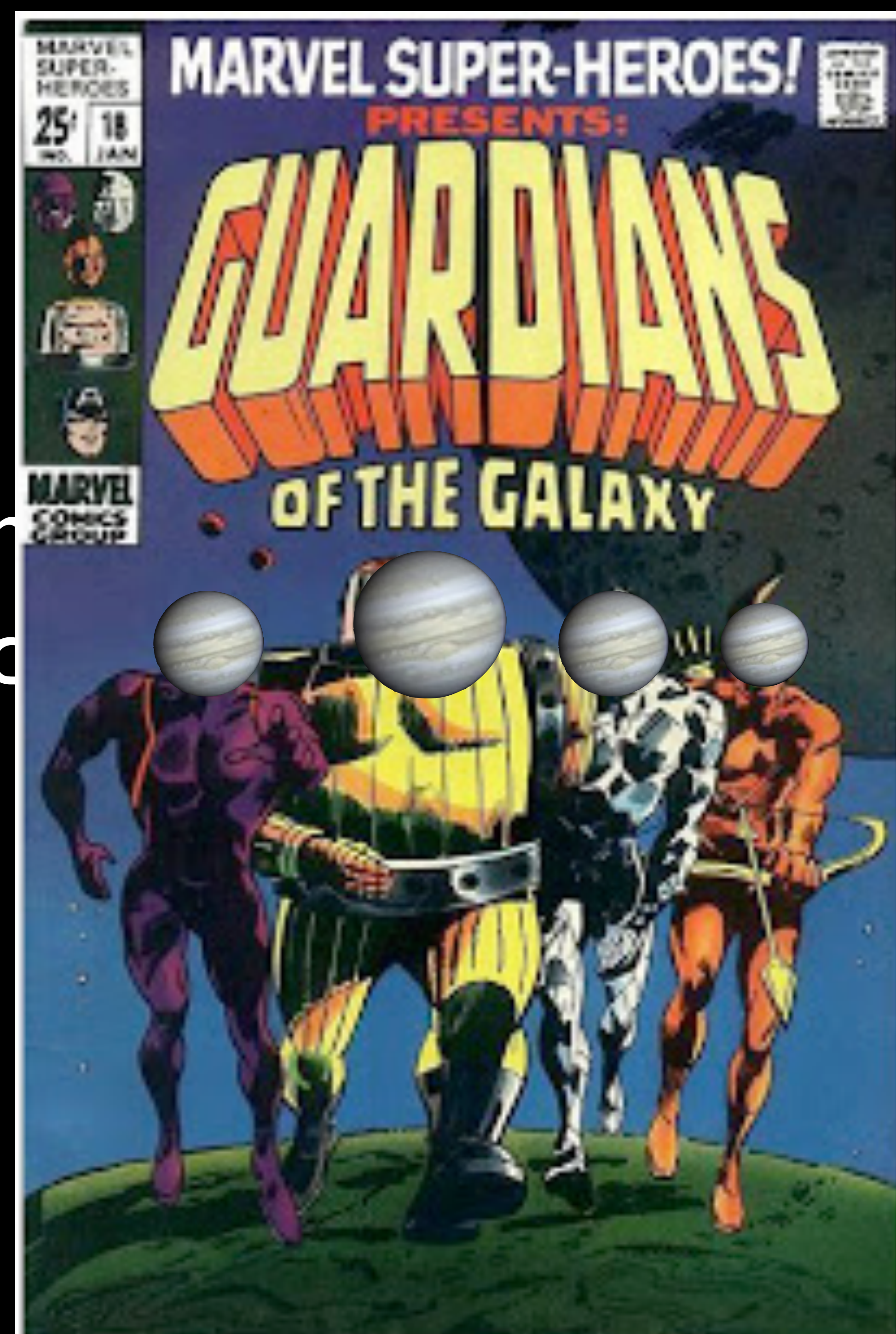
Cossou, Raymond et al 2014

Why no hot super-Earths in Solar System?

Why no hot super-Earths in Solar System?

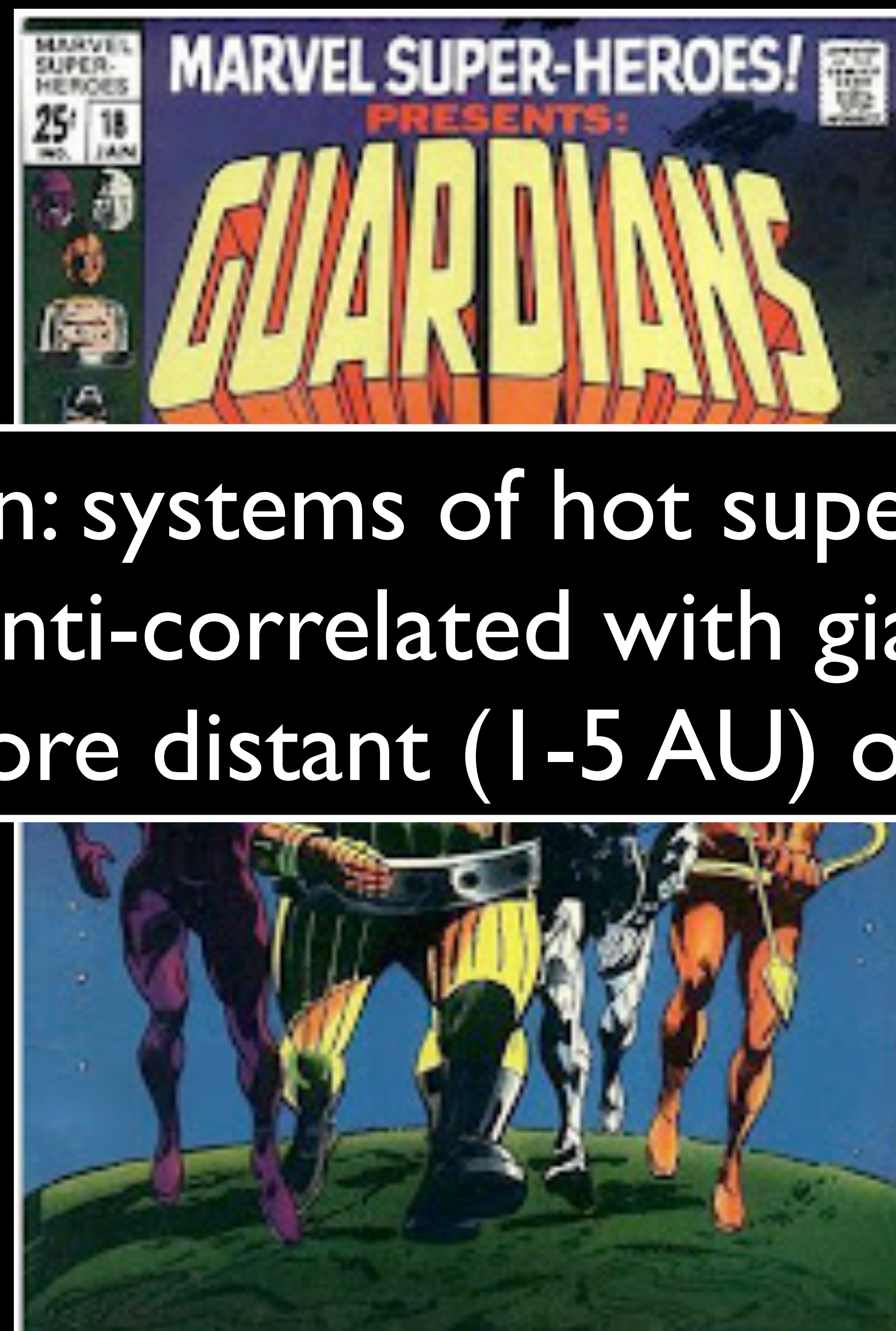
- Fast-forming gas giants can act as a barrier to inward-migrating super-Earths (Izidoro et al 2015)

Why no hot super-Earths in Solar System?

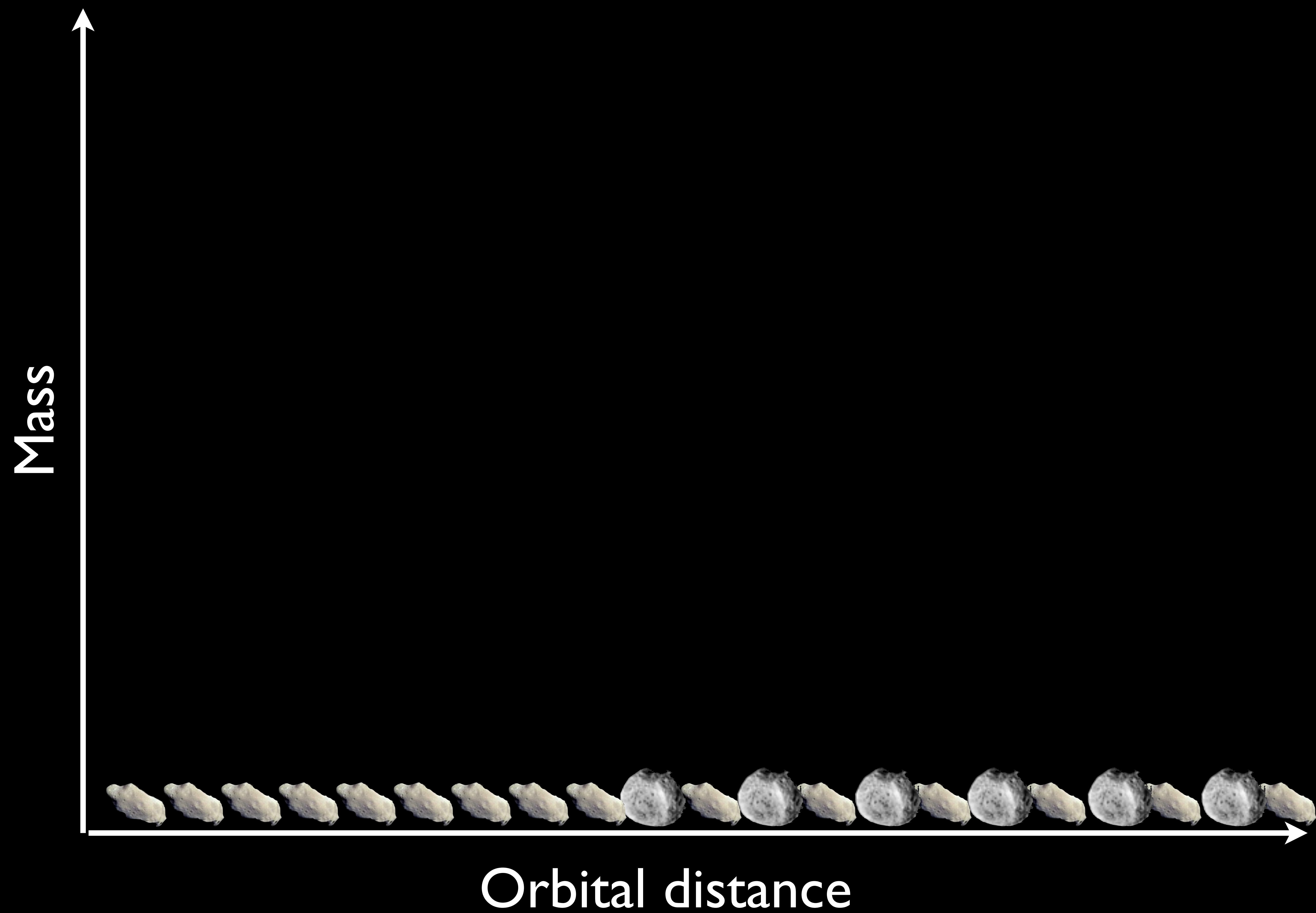


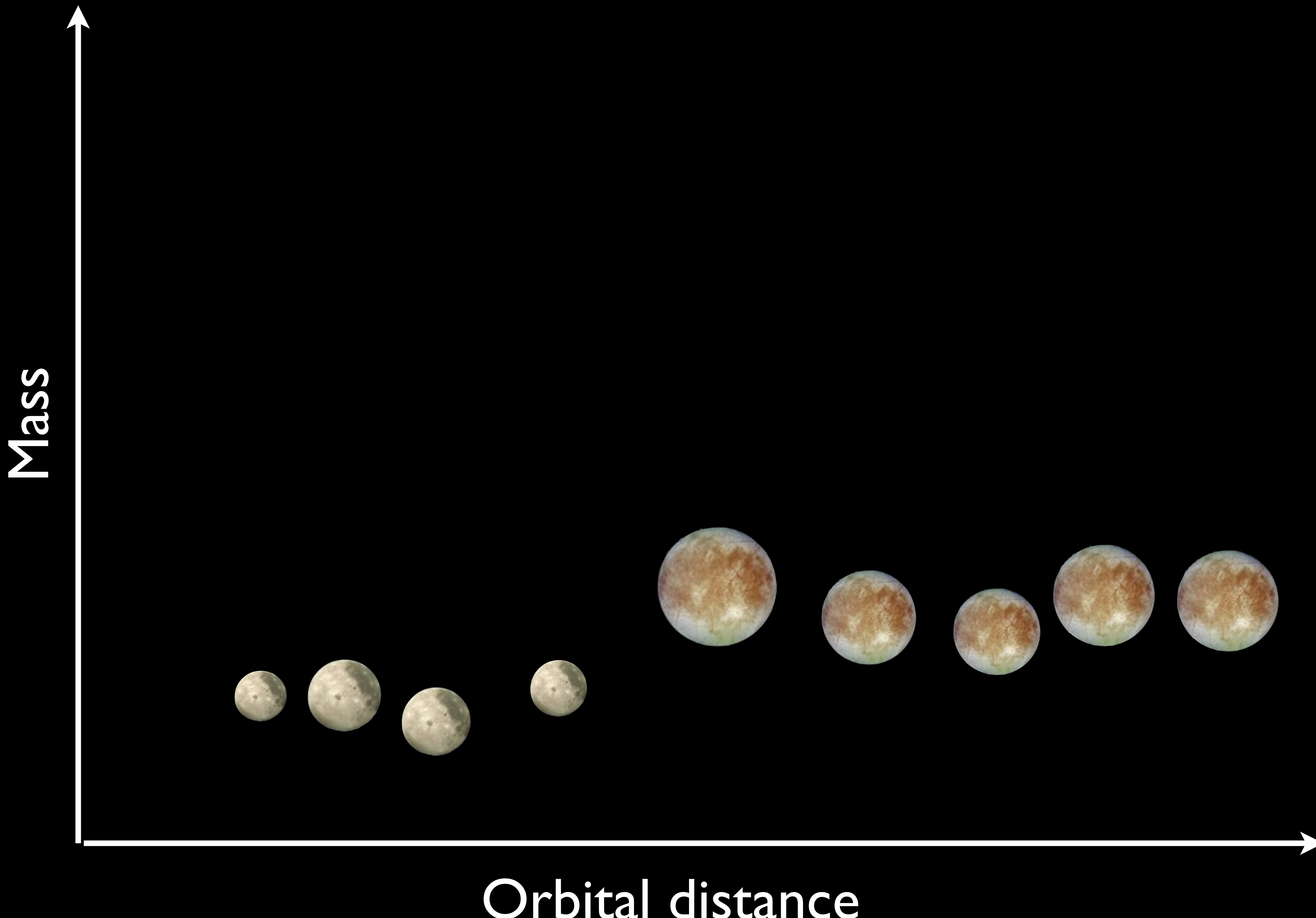
- Fast-form … as a barrier to inwar… ths (Izidoro et al 2015)

Why no hot super-Earths in Solar System?



Prediction: systems of hot super-Earths should be anti-correlated with giant planets on more distant (1-5 AU) orbits


Mass
Orbital distance



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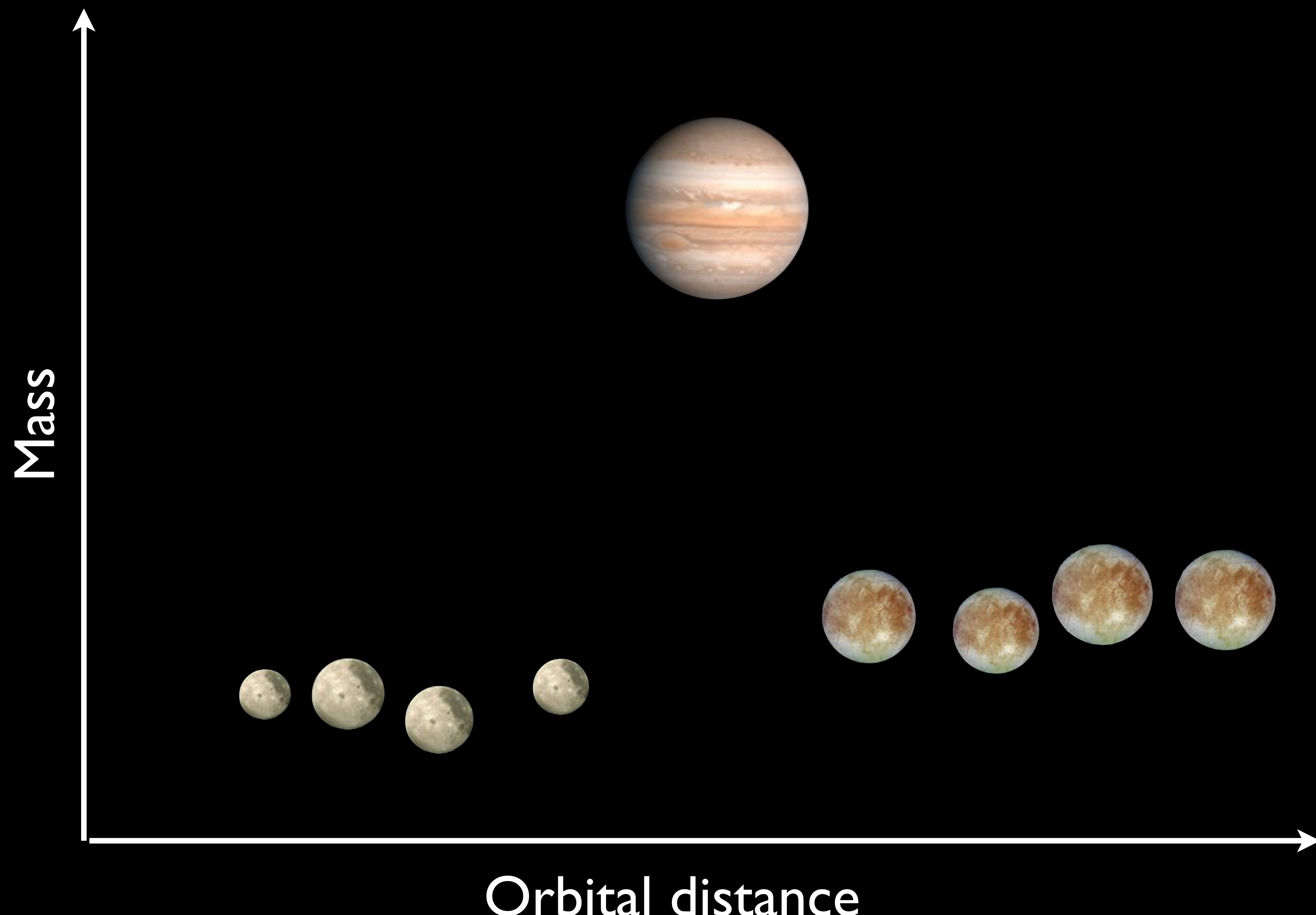
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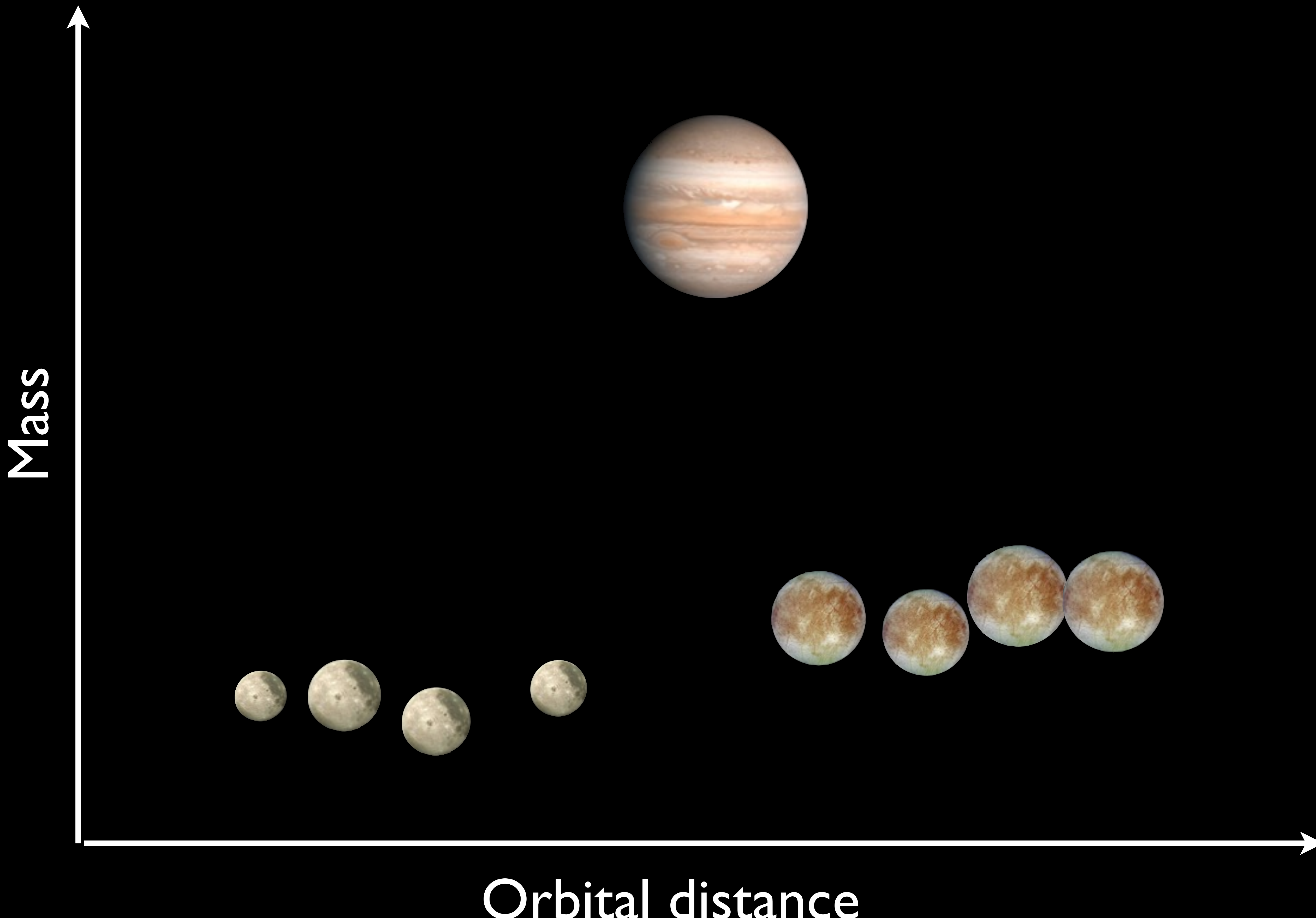
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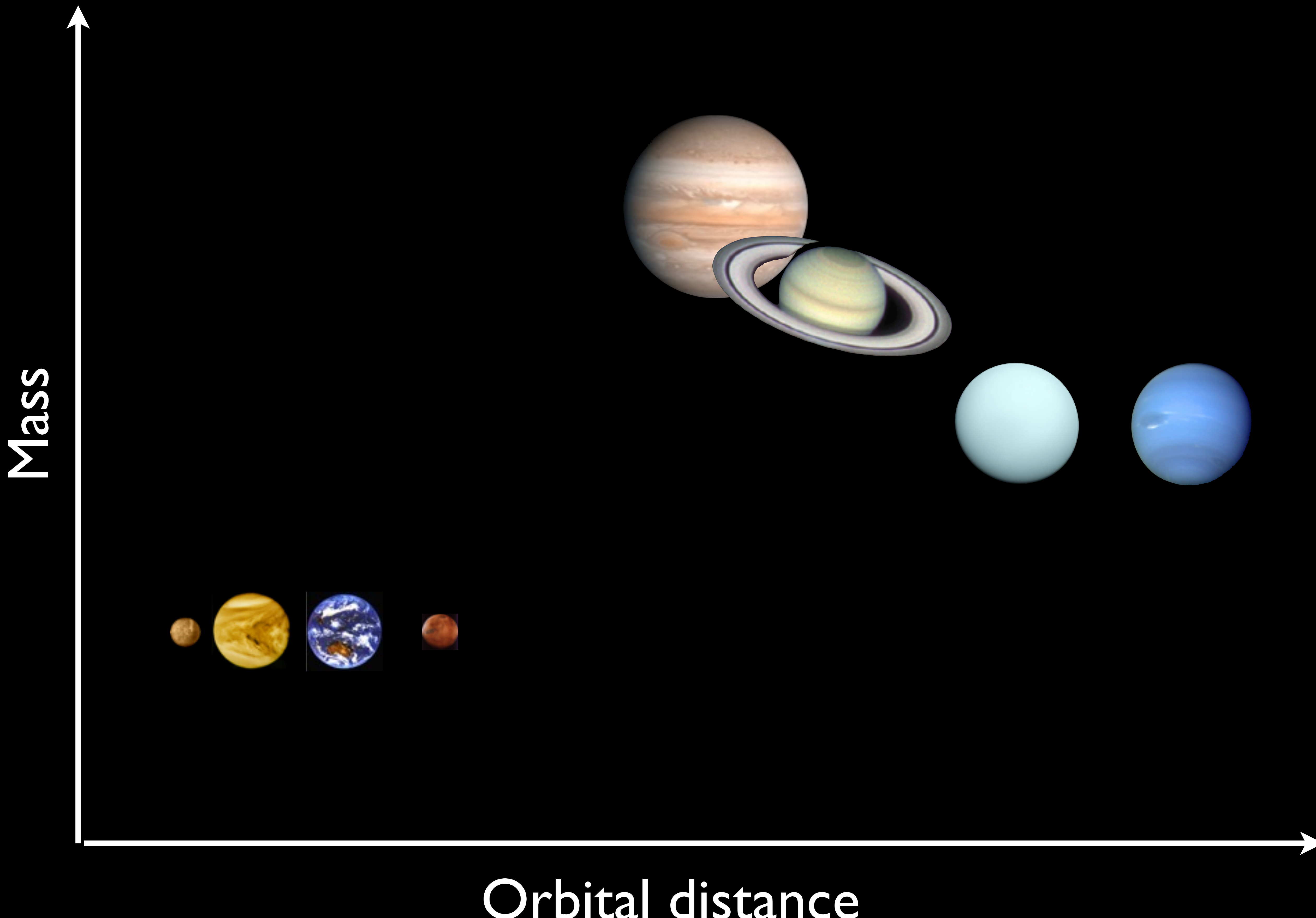
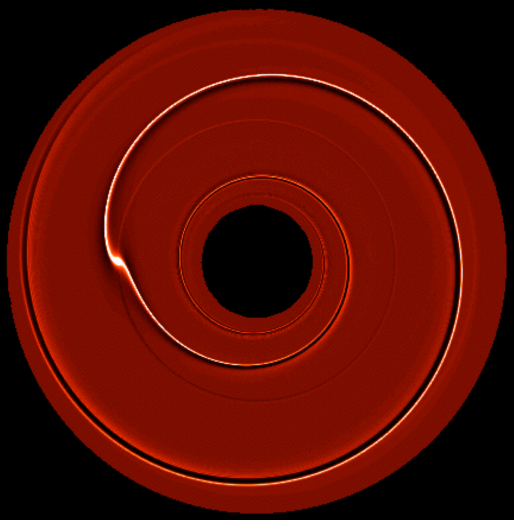
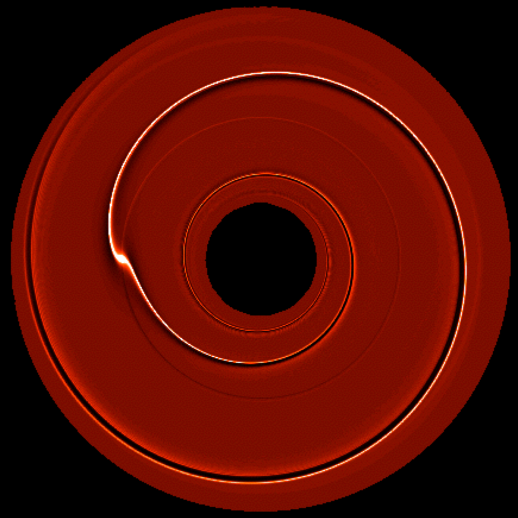

Mass
Orbital distance

Uncertainties in migration model



Uncertainties in migration model

- Initial conditions poorly constrained: how many cores? What sizes? How do they form?



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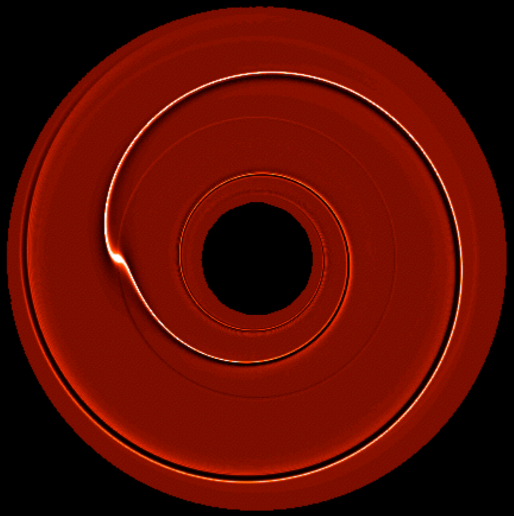
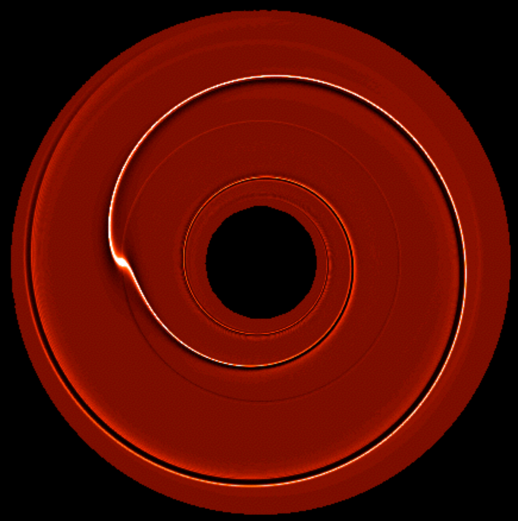


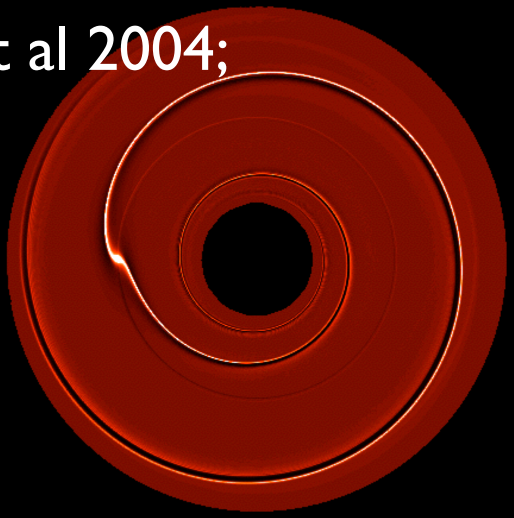
Uncertainties in migration model

- Initial conditions poorly constrained: how many cores? What sizes? How do they form?
- Sensitivity of type I migration to disk conditions
- How efficient is atmospheric accretion during migration?

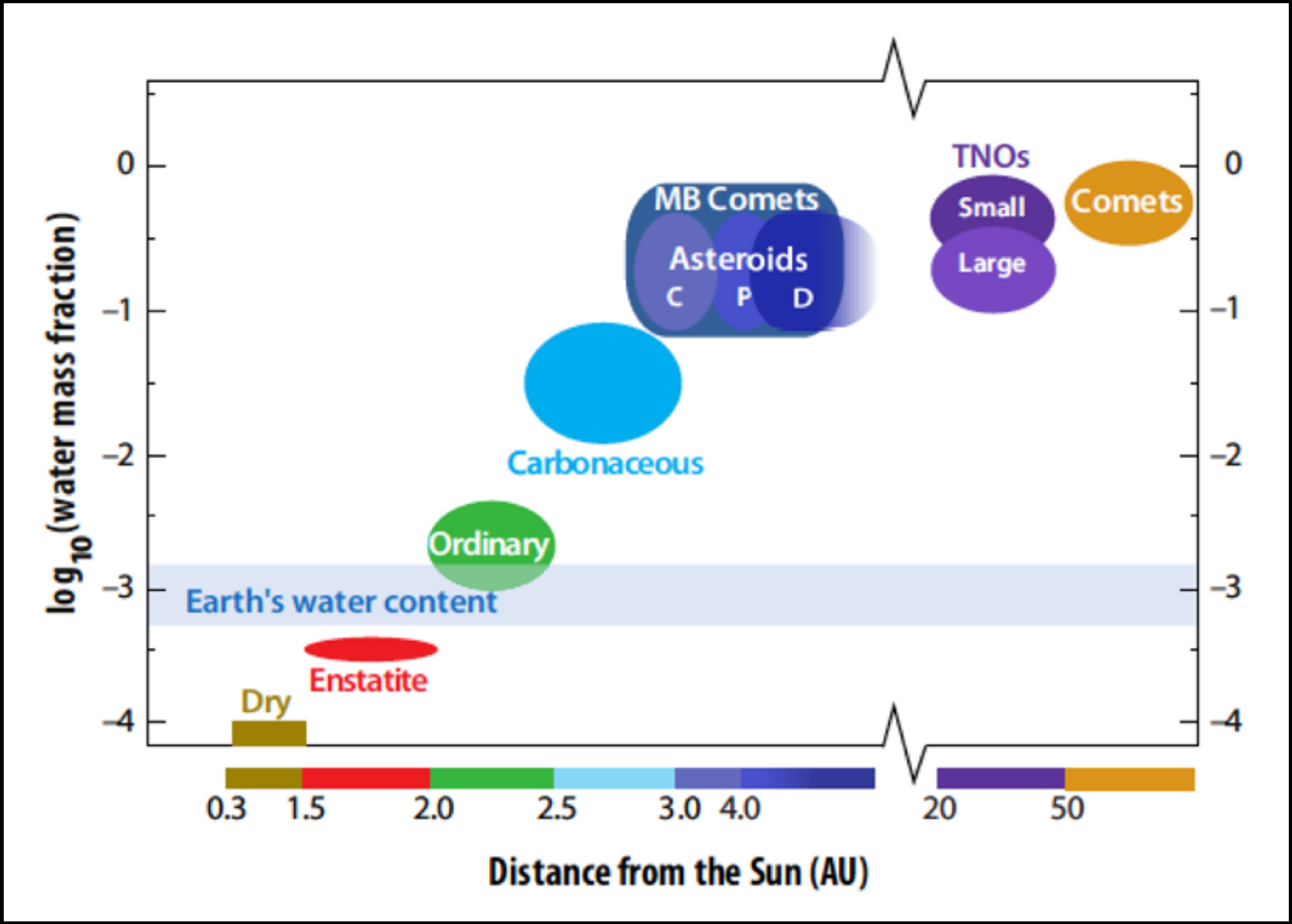


Uncertainties in migration model

- Initial conditions poorly constrained: how many cores? What sizes? How do they form?
- Sensitivity of type I migration to disk conditions
- How efficient is atmospheric accretion during migration?
- Strength and importance of turbulence (Laughlin et al 2004; Nelson 2005; Pierens et al 2012; Rein 2012)



Composition of planetary building blocks



von Dishoeck et al 2014, PP6 chapter; based on Morbidelli et al (2012) and Raymond et al (2004)

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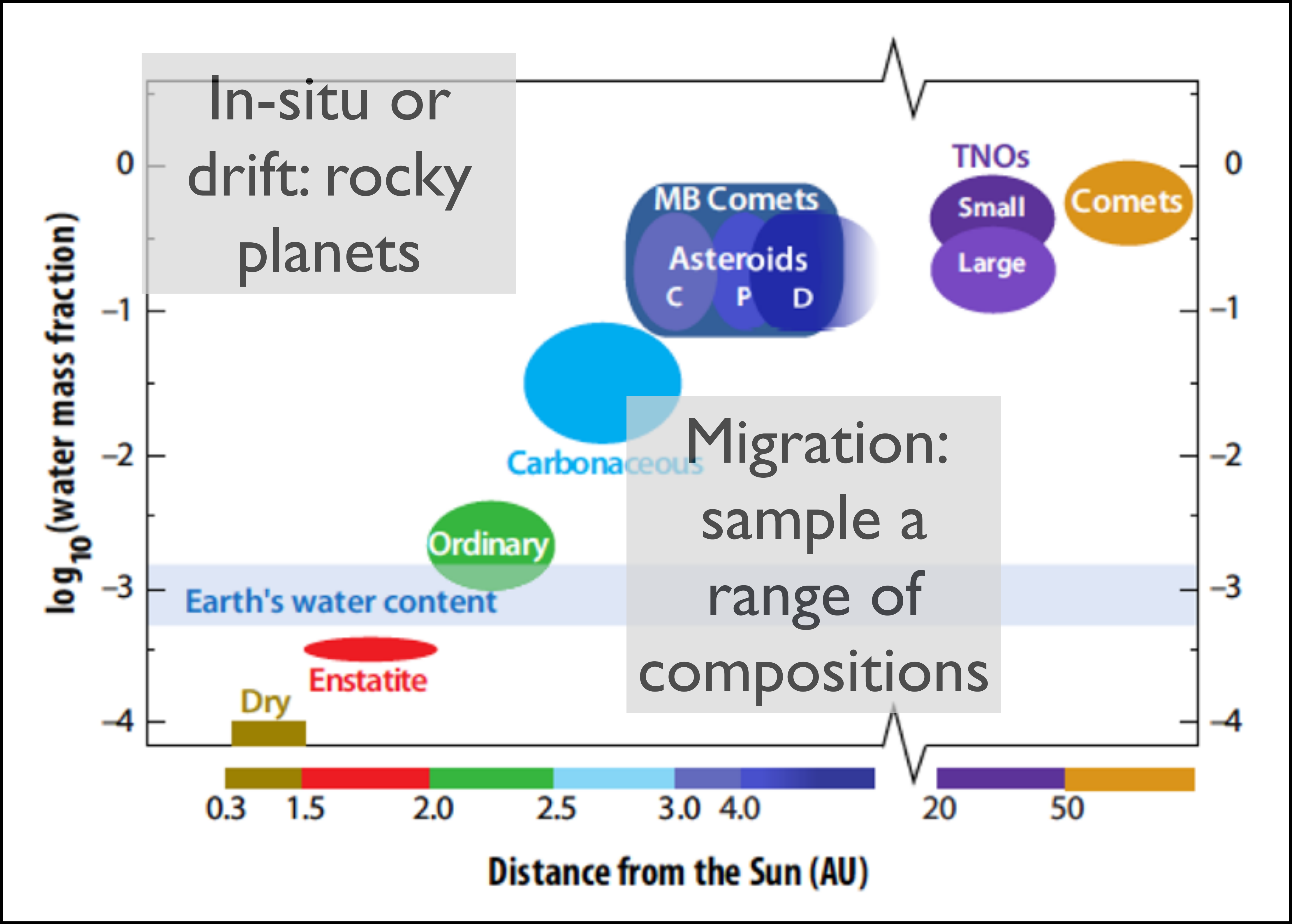

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Conclusions

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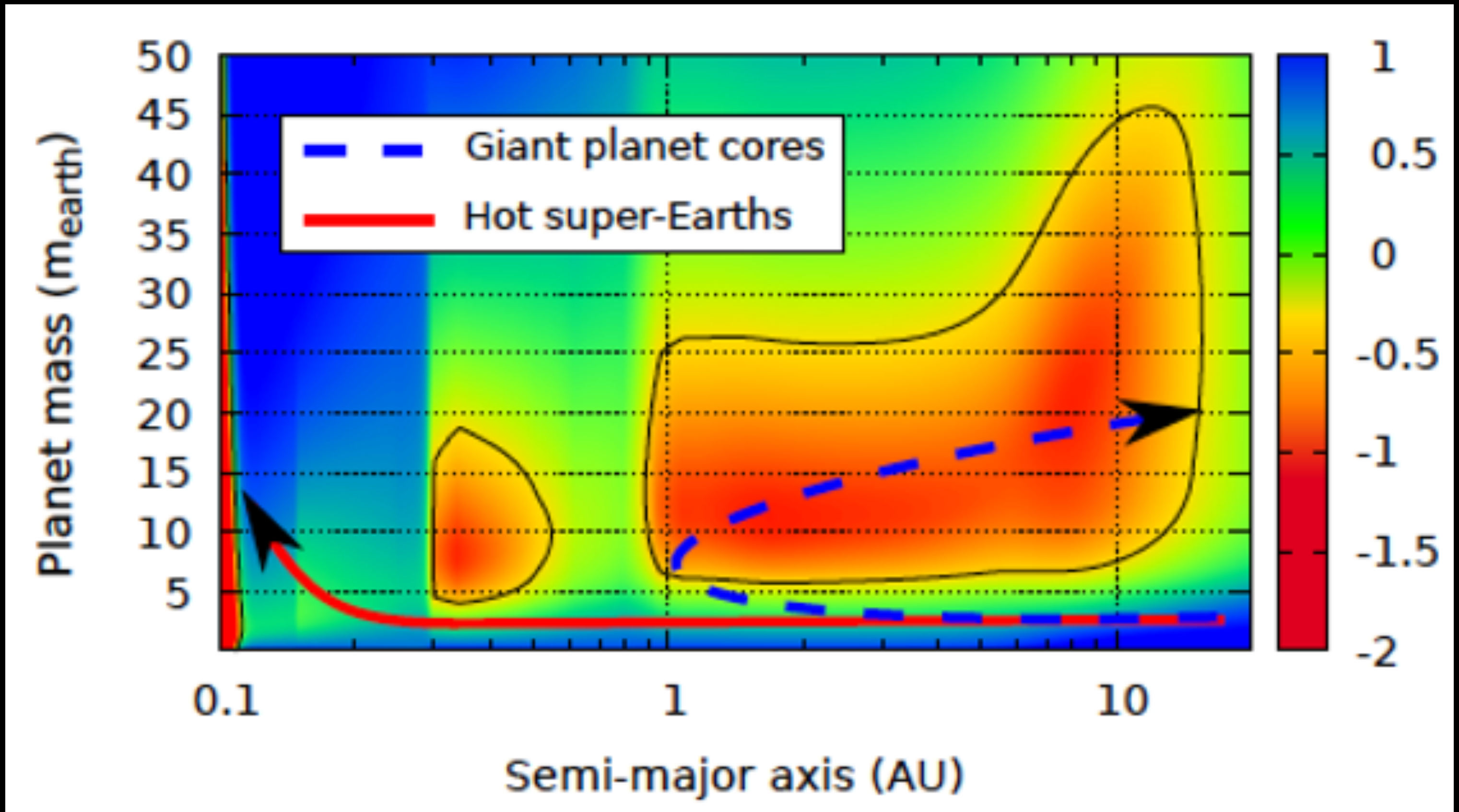
- Pebble drift model: promising but needs further study
- Migration: hot super-Earths and giant planet cores from same model

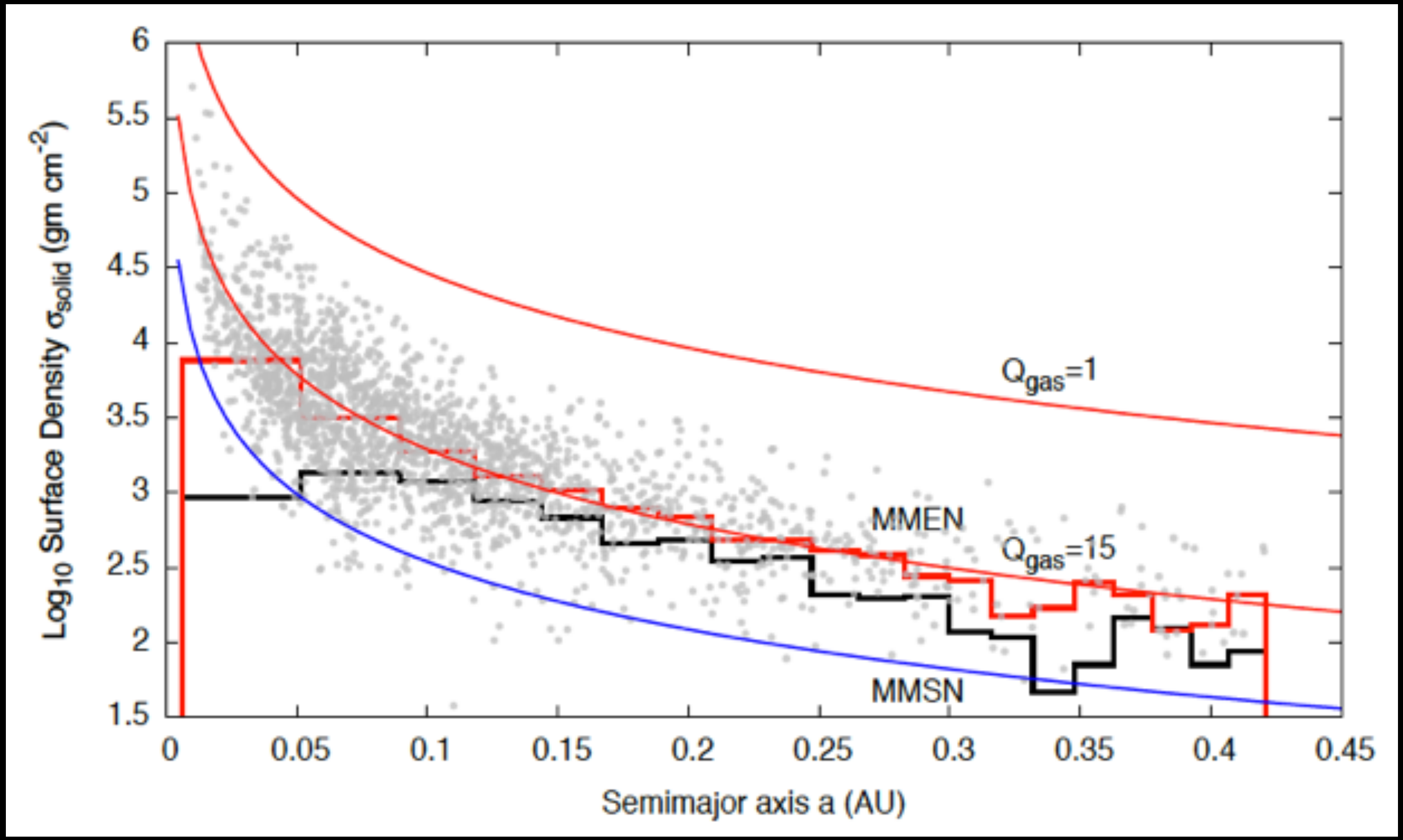


Cossou, Raymond et al 2014

Extra Slides

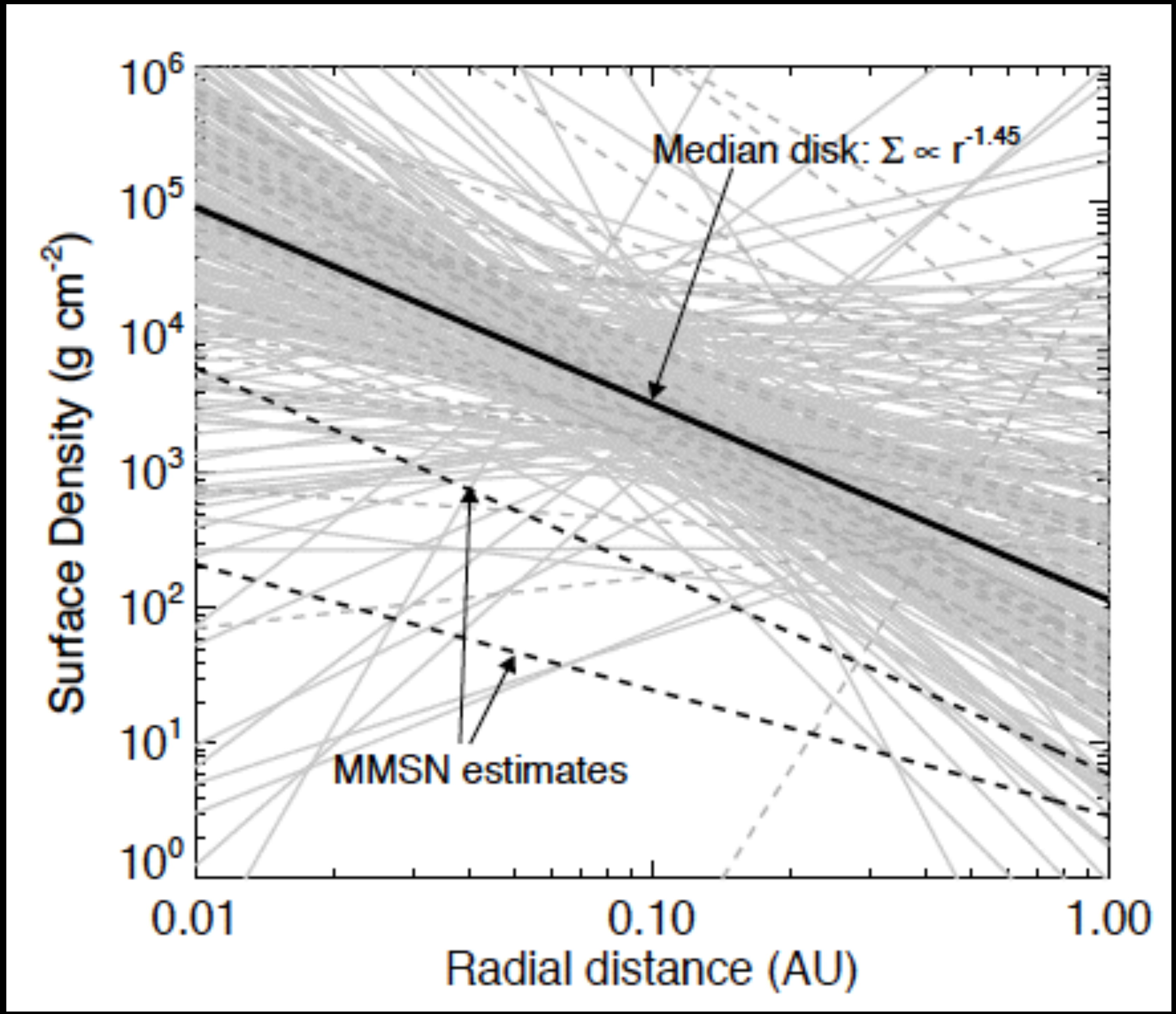
In-situ accretion

- Planets formed where you see them
- Planets remember their initial conditions (minimum-mass nebula model) and this reflects gas disk
- Migration of low-mass planets does not happen



Chiang & Laughlin 2013; see also Kuchner 2004

Minimum-mass disks in multi-planet systems

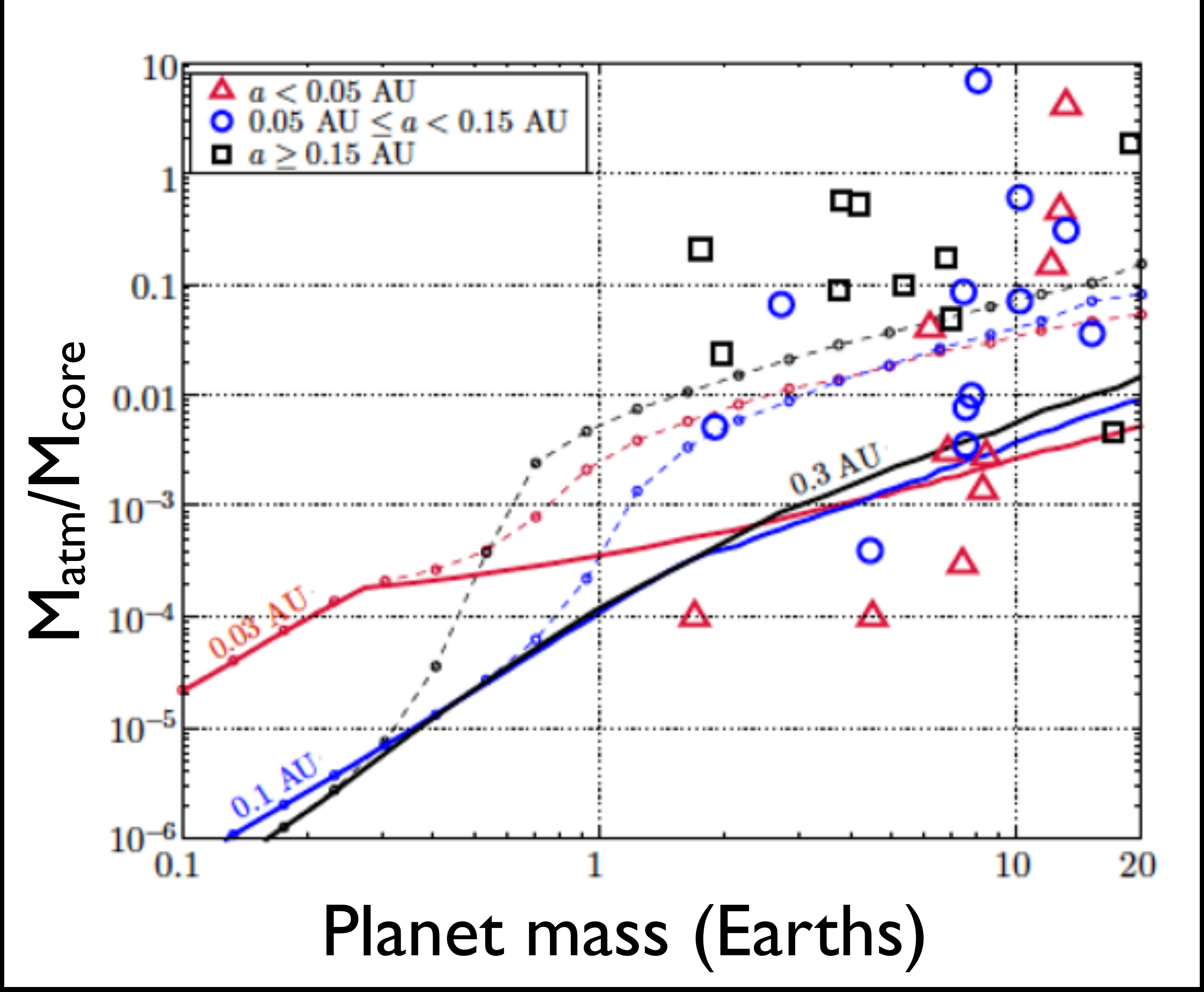


Raymond & Cossou 2014

Atmospheres

In-situ:
thin (~10^{-3}-10^{-2} or less) atmospheres
(Lee et al 2014; Inamdar & Schlichting 2015).

Migration: lose ~half of atmosphere per giant impact



Inamdar & Schlichting 2015

In-situ accretion

Strengths

Weaknesses

Pro: Hansen & Murray 2012, 2013; Chiang & Laughlin 2013; Petrovich et al 2013

Con: Raymond et al 2008, 2014; Schlichting 2014; Raymond & Cossou 2014; Schlaufman 2014; Inamdar & Schlichting 2015; Ogihara et al submitted

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- Some planets closer to stars than dust sublimation radius (Swift et al 2013)
- Cannot produce planets with thick atmospheres (Hori & Ikoma 2012; Inamdar & Schlichting 2015; Lee et al 2014)

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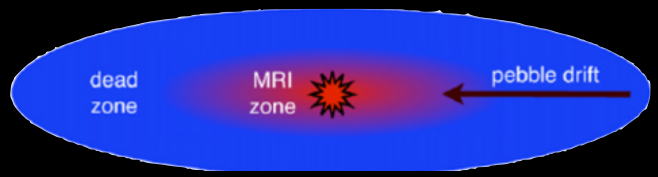
Con: Raymond et al 2008, 2014; Schlichting 2014; Raymond & Cossou 2014; Schlaufman 2014; Inamdar & Schlichting 2015; Ogihara et al submitted

Pebble drift



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Chatterjee & Tan 2014, 2015; Boley & Ford 2013;
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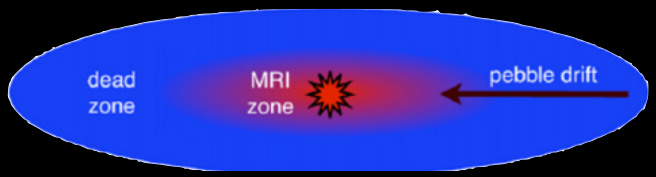

Strengths

- Makes sense in context of sequential growth from small bodies

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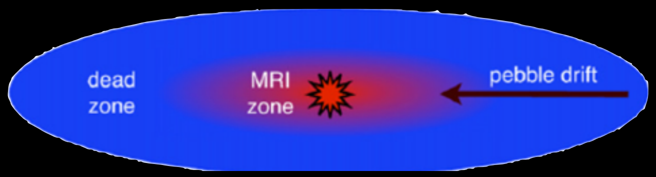

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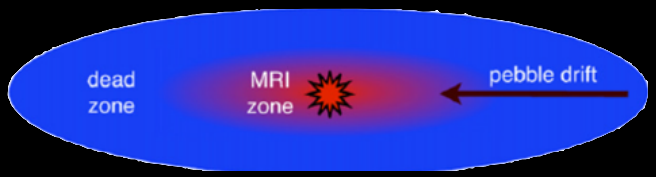

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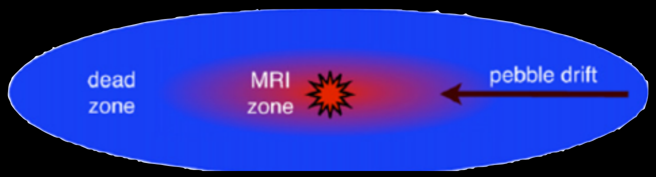

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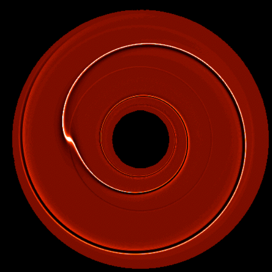
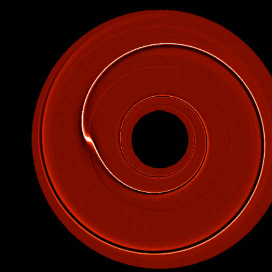


Migration



Strengths

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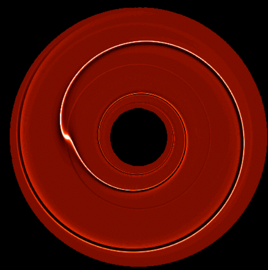

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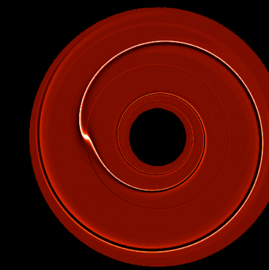

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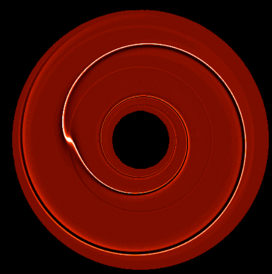

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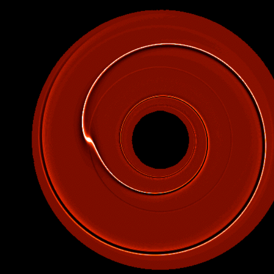

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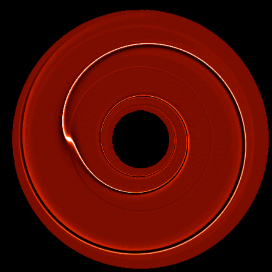

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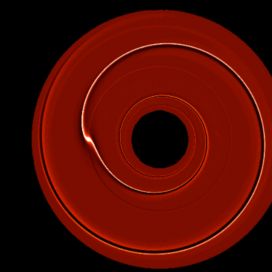

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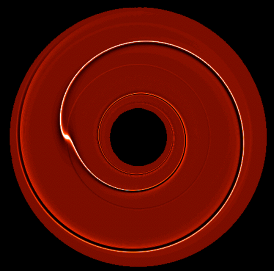

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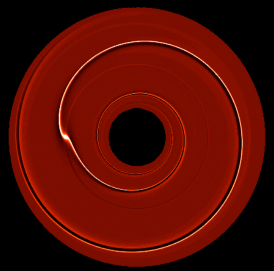

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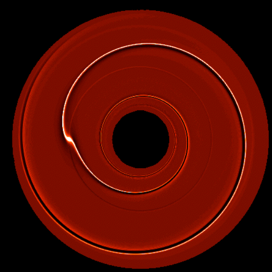

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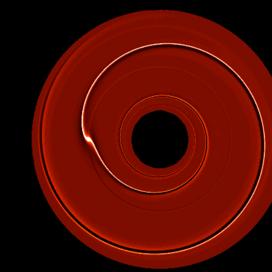

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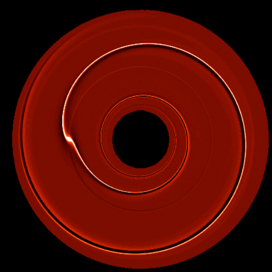

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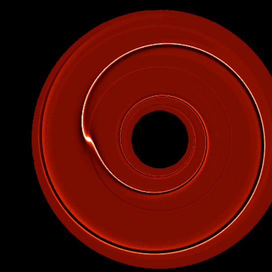

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- Importance of turbulence (studies underway)

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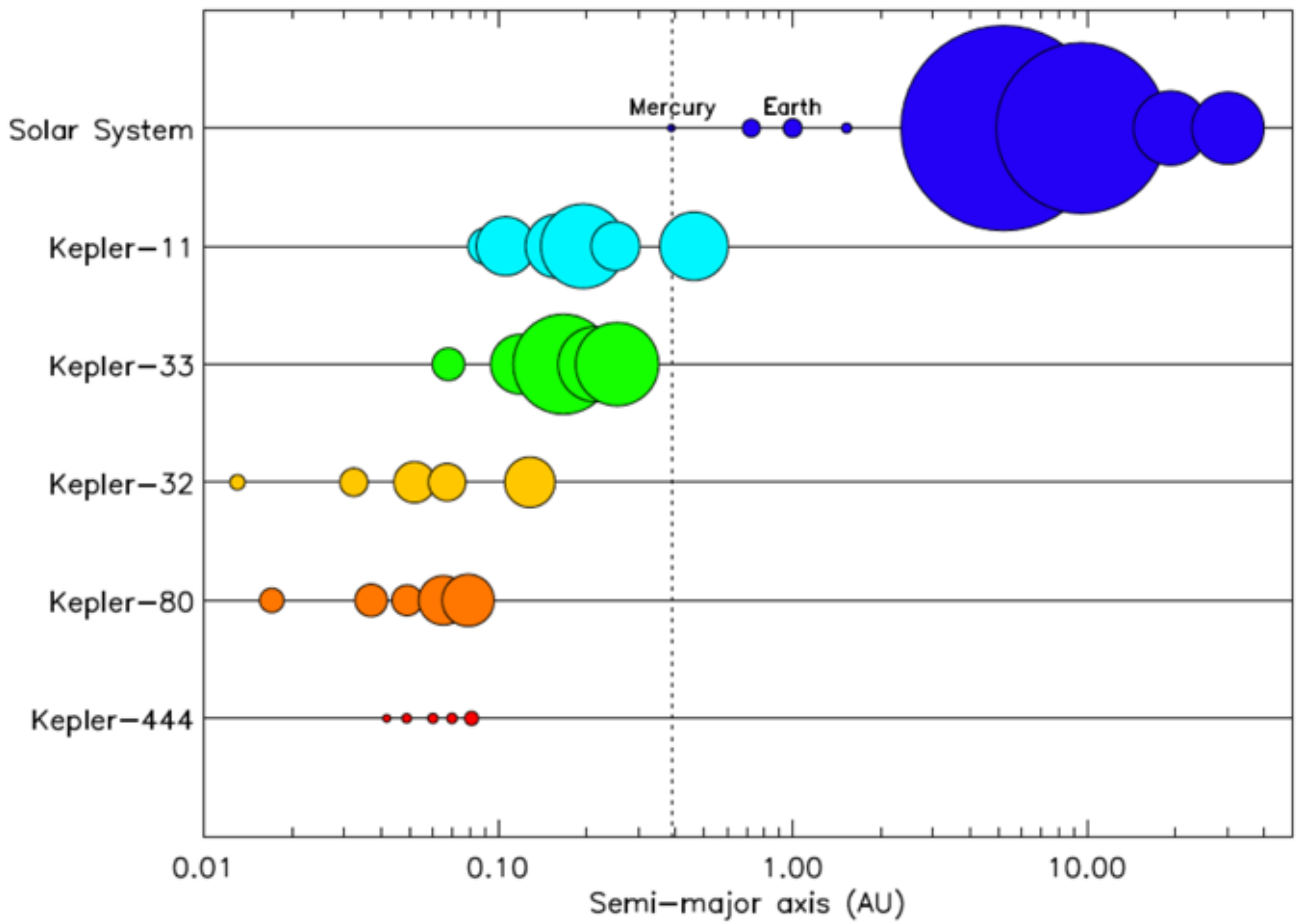
Case study: Kepler-444



Campante et al 2015

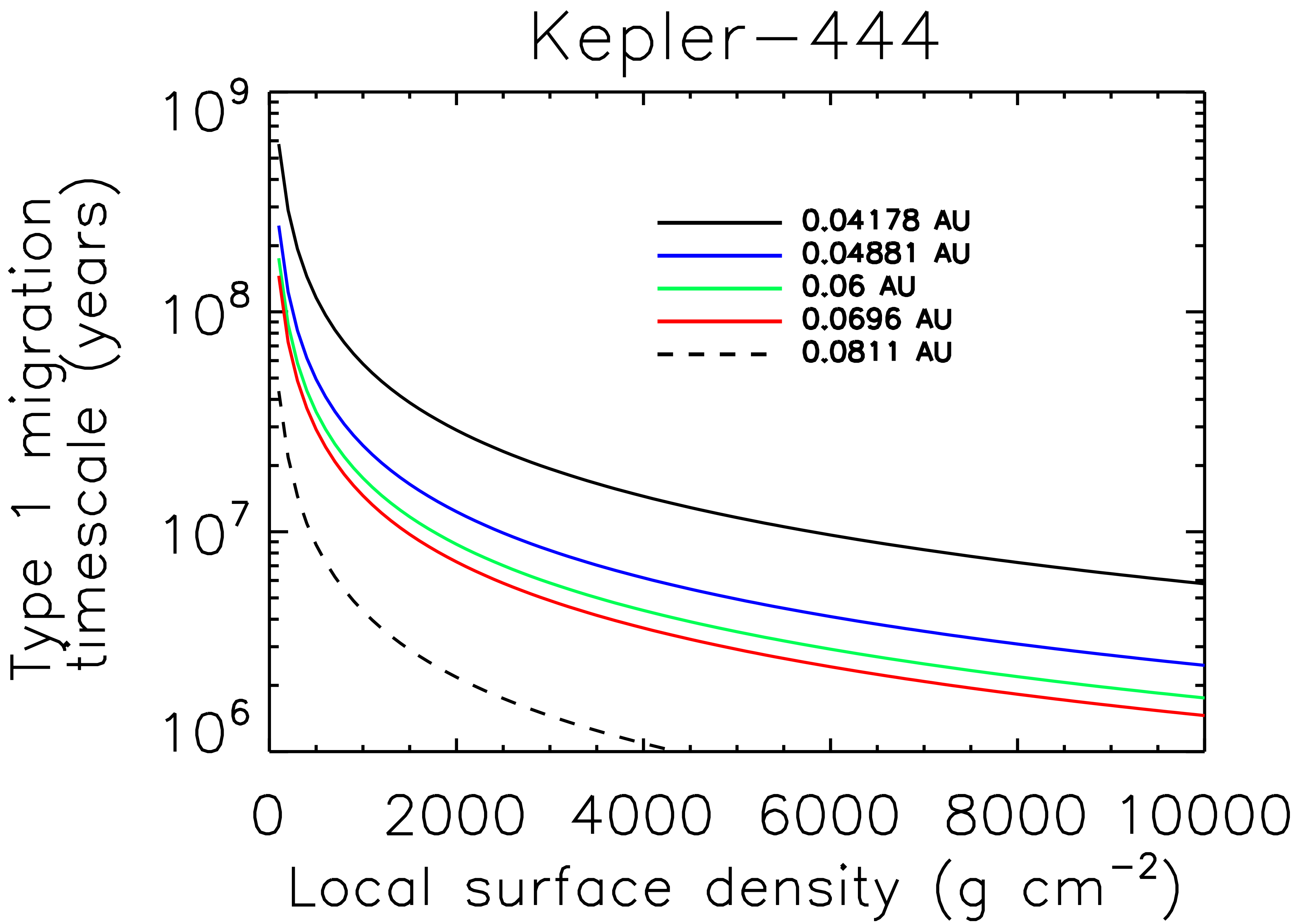
Kepler-444

Table 4. Planetary and orbital parameters.

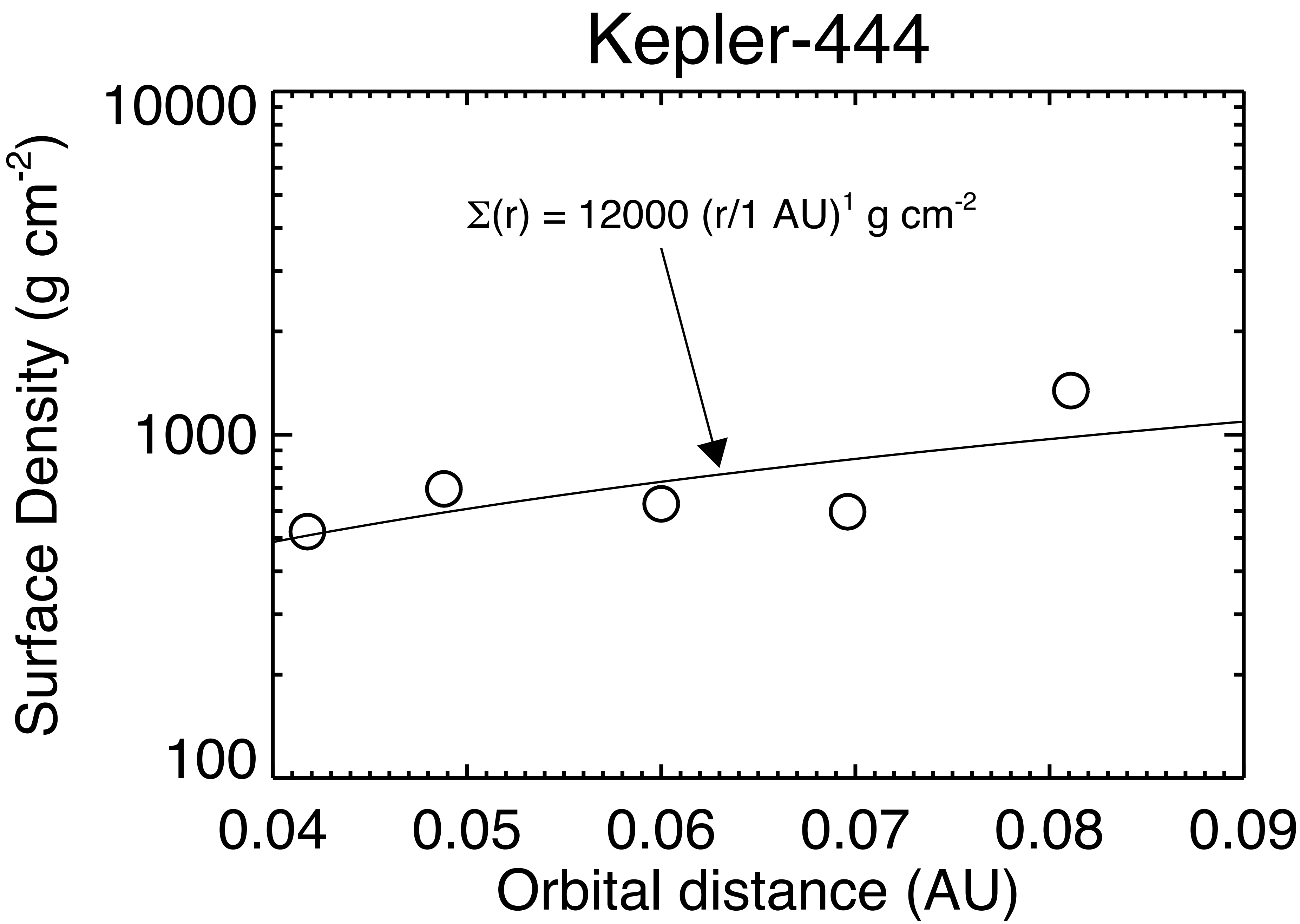
Parameter	Kepler-444b	Kepler-444c	Kepler-444d	Kepler-444e	Kepler-444f
T_0 (BJD−2,454,833)	$133.2599^{+0.0018}_{-0.0018}$	$131.5220^{+0.0013}_{-0.0013}$	$134.7869^{+0.0015}_{-0.0015}$	$135.0927^{+0.0018}_{-0.0018}$	$134.8791^{+0.0011}_{-0.0011}$
P (days)	$3.6001053^{+0.0000083}_{-0.0000080}$	$4.5458841^{+0.0000070}_{-0.0000071}$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

Campante et al 2015

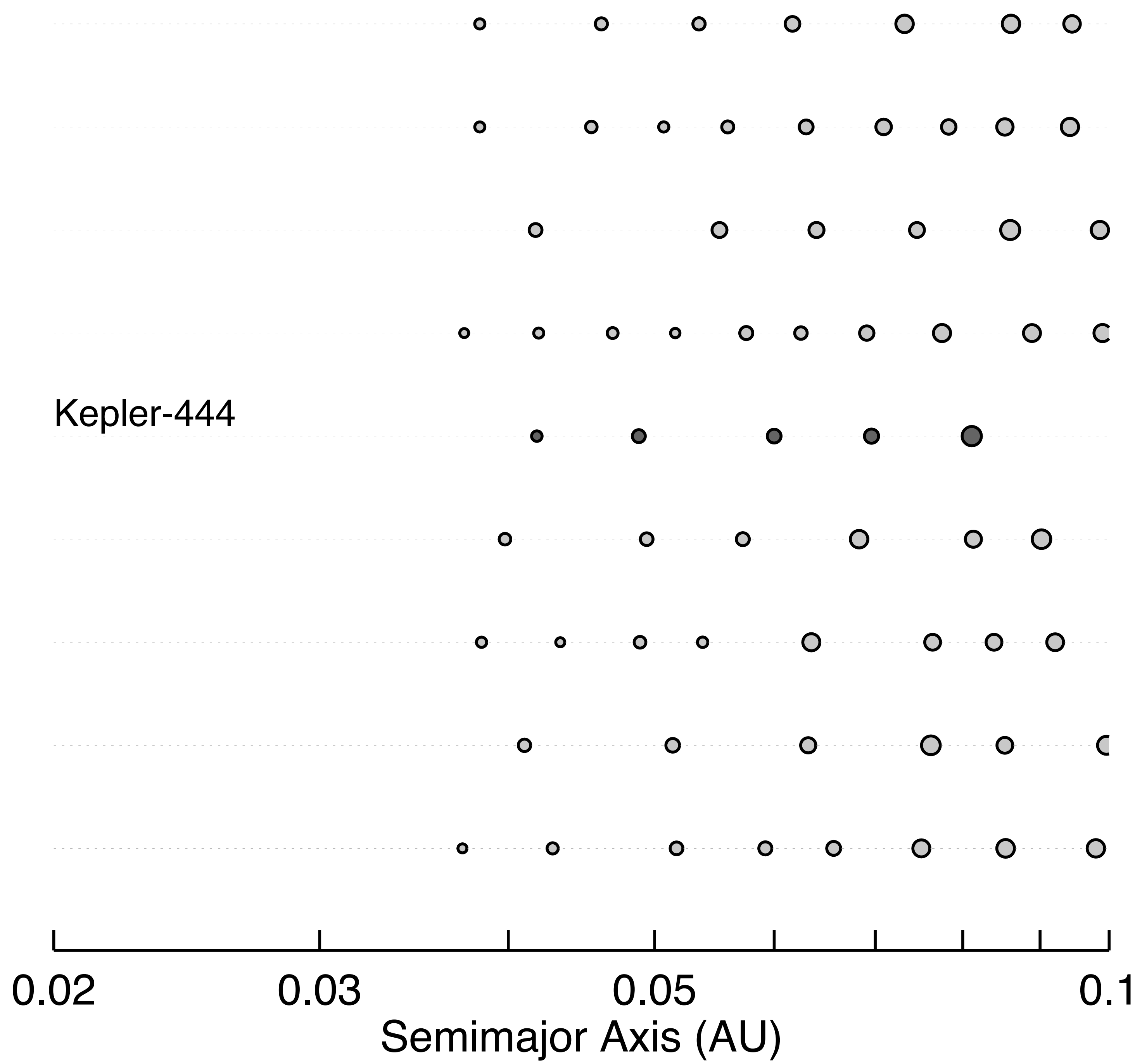
Migration timescales are long



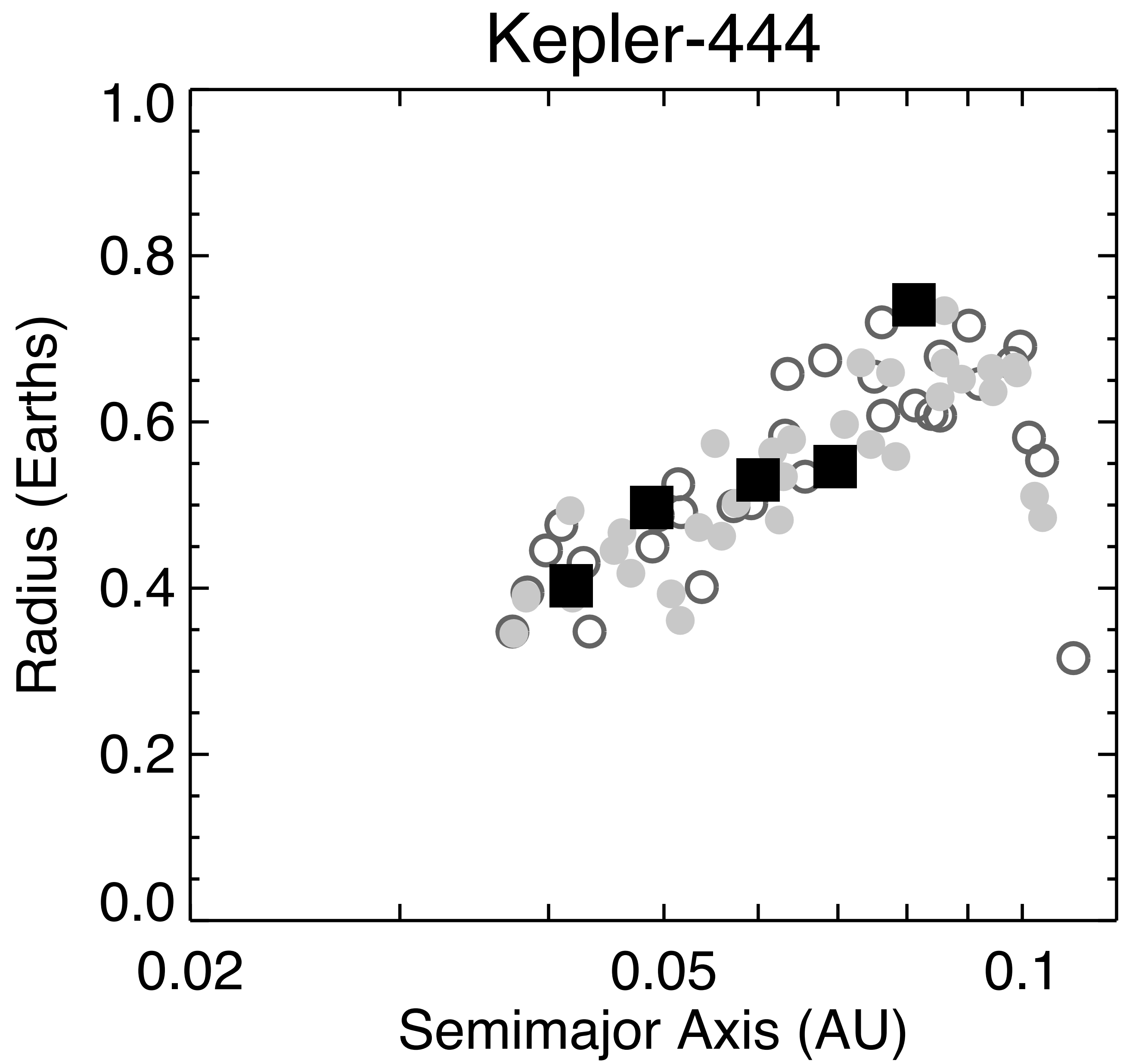
Minimum-mass disk



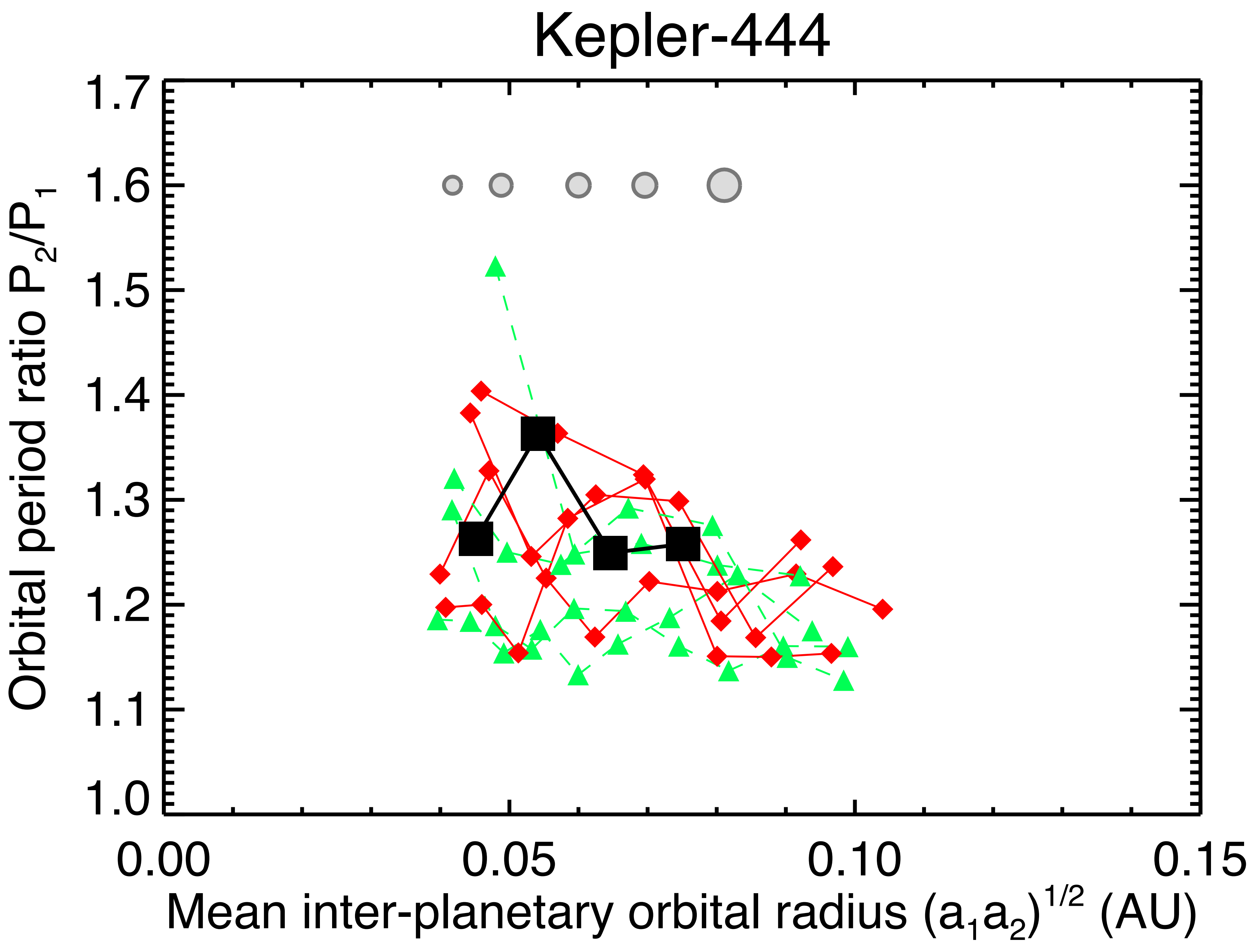
Accretion simulations



Planet size vs orbital distance



Planetary spacing



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- Best candidate: inward drift model