Planet Traps and Exoplanetary Populations

Yasuhiro Hasegawa
(Jet Propulsion Laboratory,
California Institute of Technology)

JPL/Caltech, USA: Neal Turner, Joseph Masiero, Mario Flock
NAOJ, Japan: Eiji Akiyama, Shigeru Wakita, Takaya Nozawa, Yuji Matsumoto, Shouichi Oshino
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ASIAA, Taiwan: Hauyu Baobab Li, Naomi Hirano, Hiroyuki, Hirashita, Li I-Hsiu, Pin-Gao Gu
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Univ. of Dundee, UK: Soko Matsumura
Univ of Delaware: Debanjan Sengupta, Sally Dodson-Robinson

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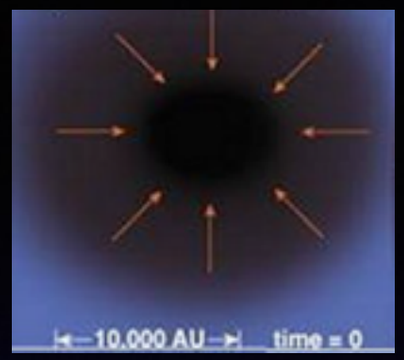
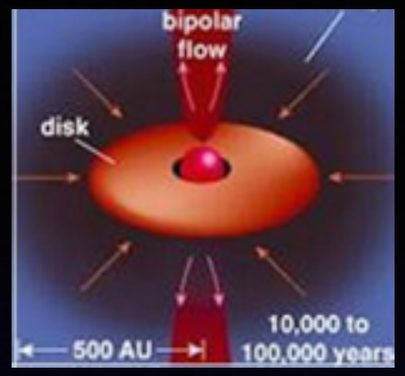
First Stage: Class 0/Class I YSOs

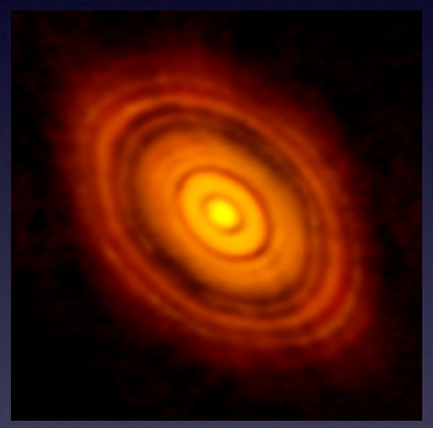




Grain Growth in Class 0/I YSOs

Li et al 2016 in prep, Harada et al 2016, submitted

Second Stage: Class I/Class II Disks



Planet Formation in HL Tau

Akiyama et al 2016, Hasegawa et al 2016 in prep

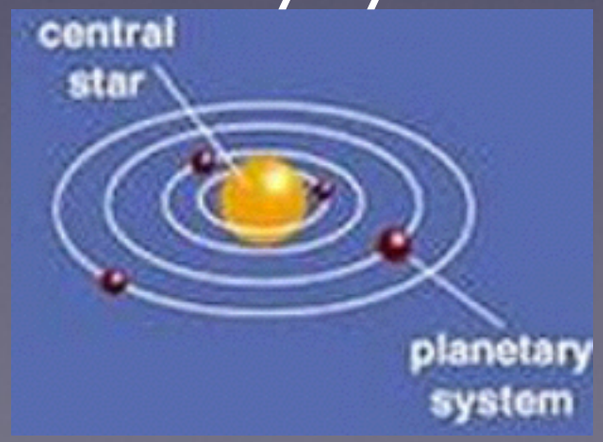
Disks with non-Ideal MHD Effects

Hasegawa & Takeuchi 2015, Hasegawa et al 2016 in prep

Repetitive Outbursts in EX Lupi

Flock et al 2016 in prep

Final Stage: Solar & Extrasolar Planetary Systems



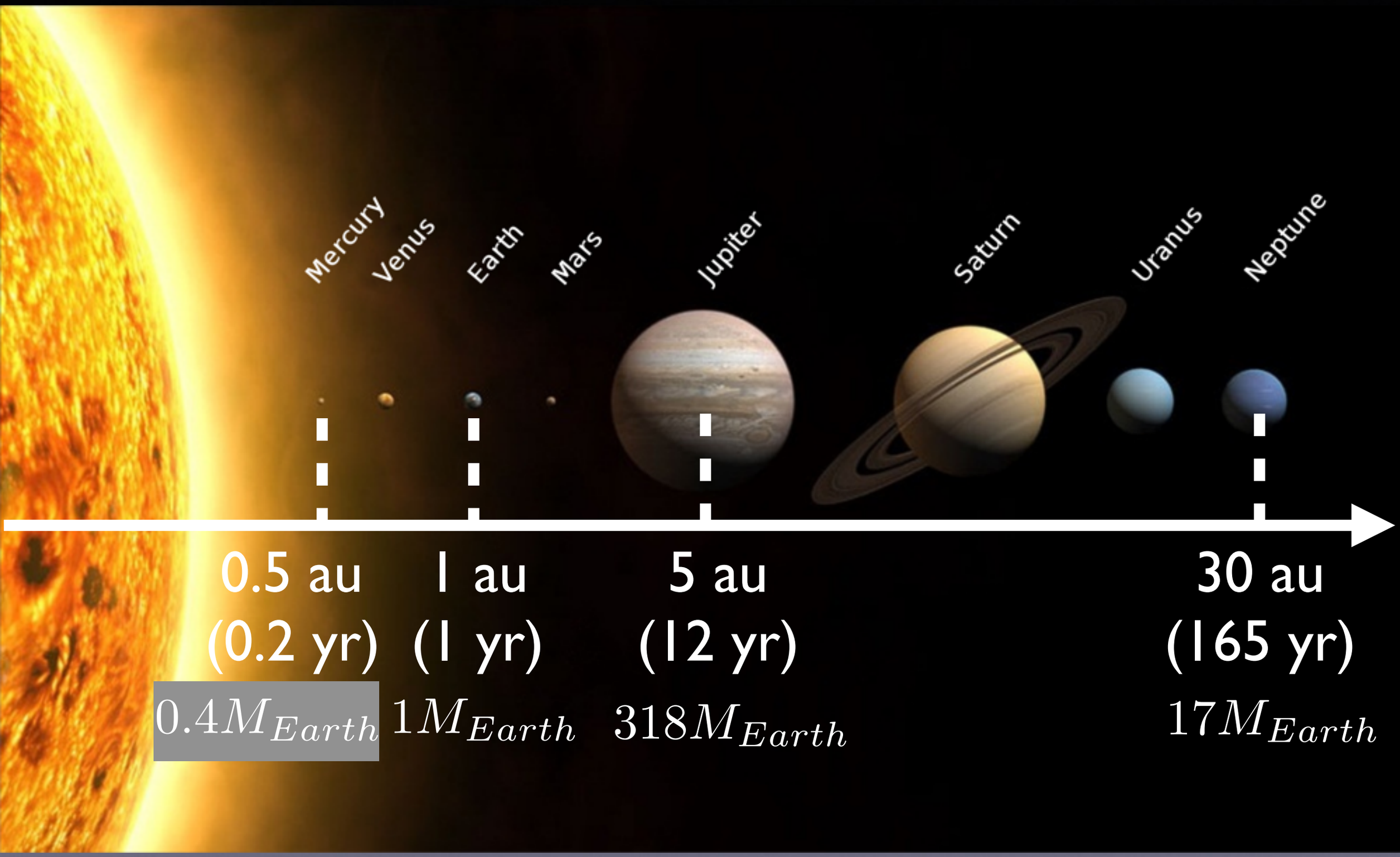
Chondrule Formation & Accretion

Hasegawa et al 2016a,b, Matsumoto et al 2016, submitted
Wakita et al 2016, submitted

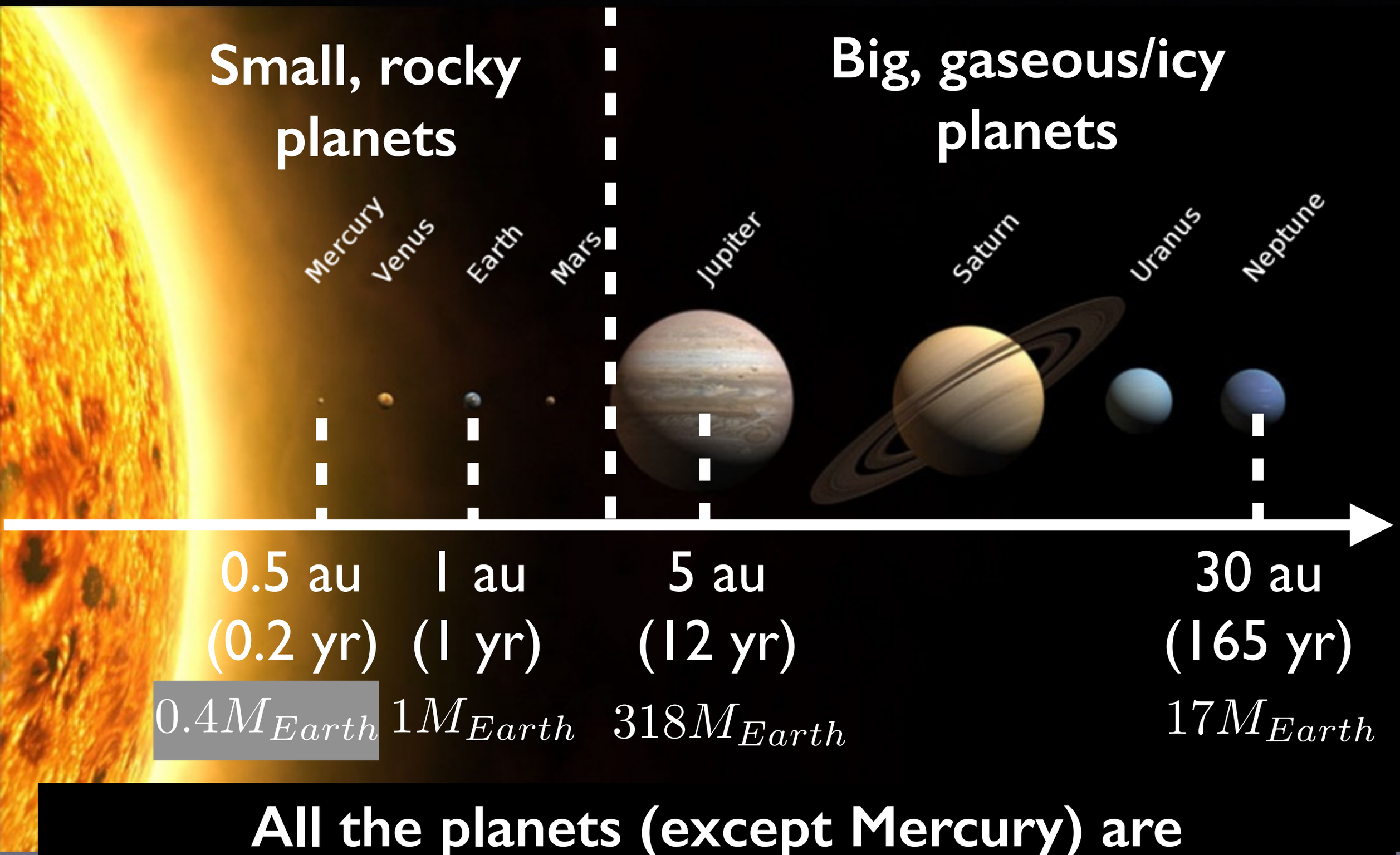
Formation of Presolar Grains

Nozawa et al 2015, Wakita et al 2016, submitted

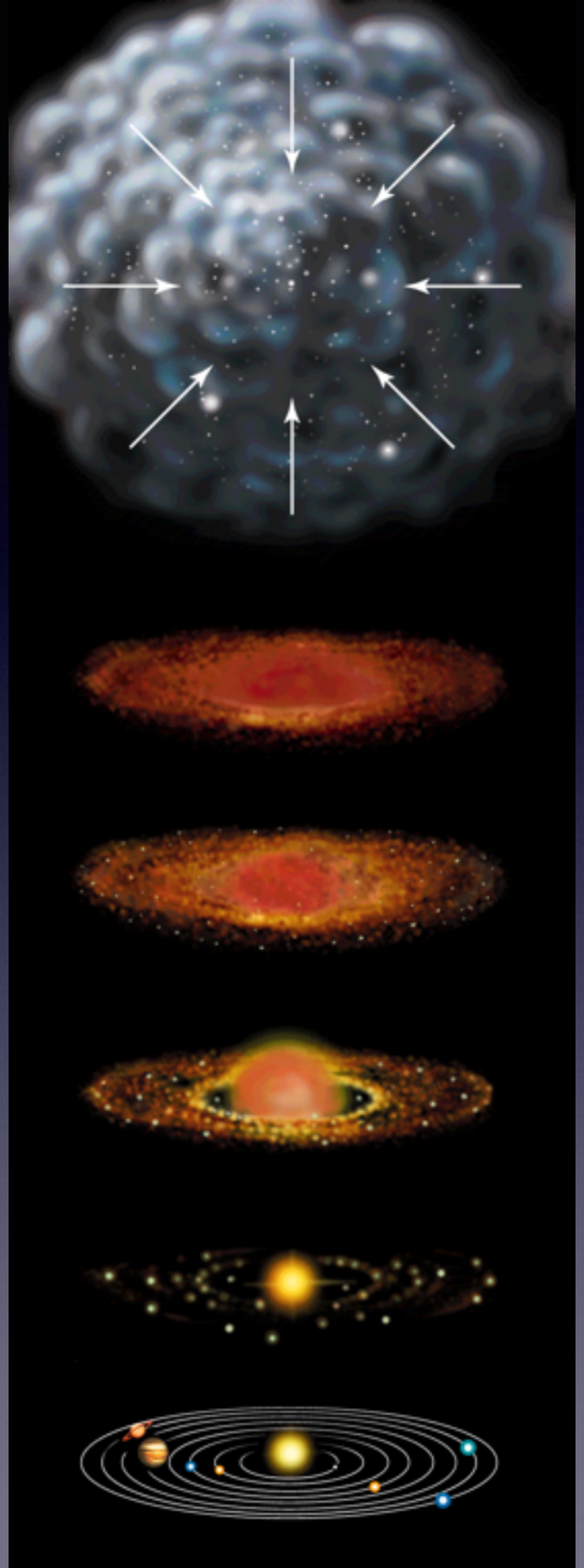
Best Example of Planetary Systems



Best Example of Planetary Systems



All the planets (except Mercury) are in the circular (e < 0.1), coplanar (i ~ 6 degree) orbit



"Classical" Picture of Planet Formation

e.g., Hayashi 1981

All the planets should have formed in a disk around the sun

The natal disk was composed of gas and solid

The composition of planets was determined by their location (**in-situ formation**)

The presence of icy bodies increased the mass of planetary cores and enhanced gas giant formation

the First Detection of an Extra Solar Planet about 20 years ago

nature

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article

Nature **378**, 355 - 359 (23 November 1995); doi:10.1038/378355a0

A Jupiter-mass companion to a solar-type star

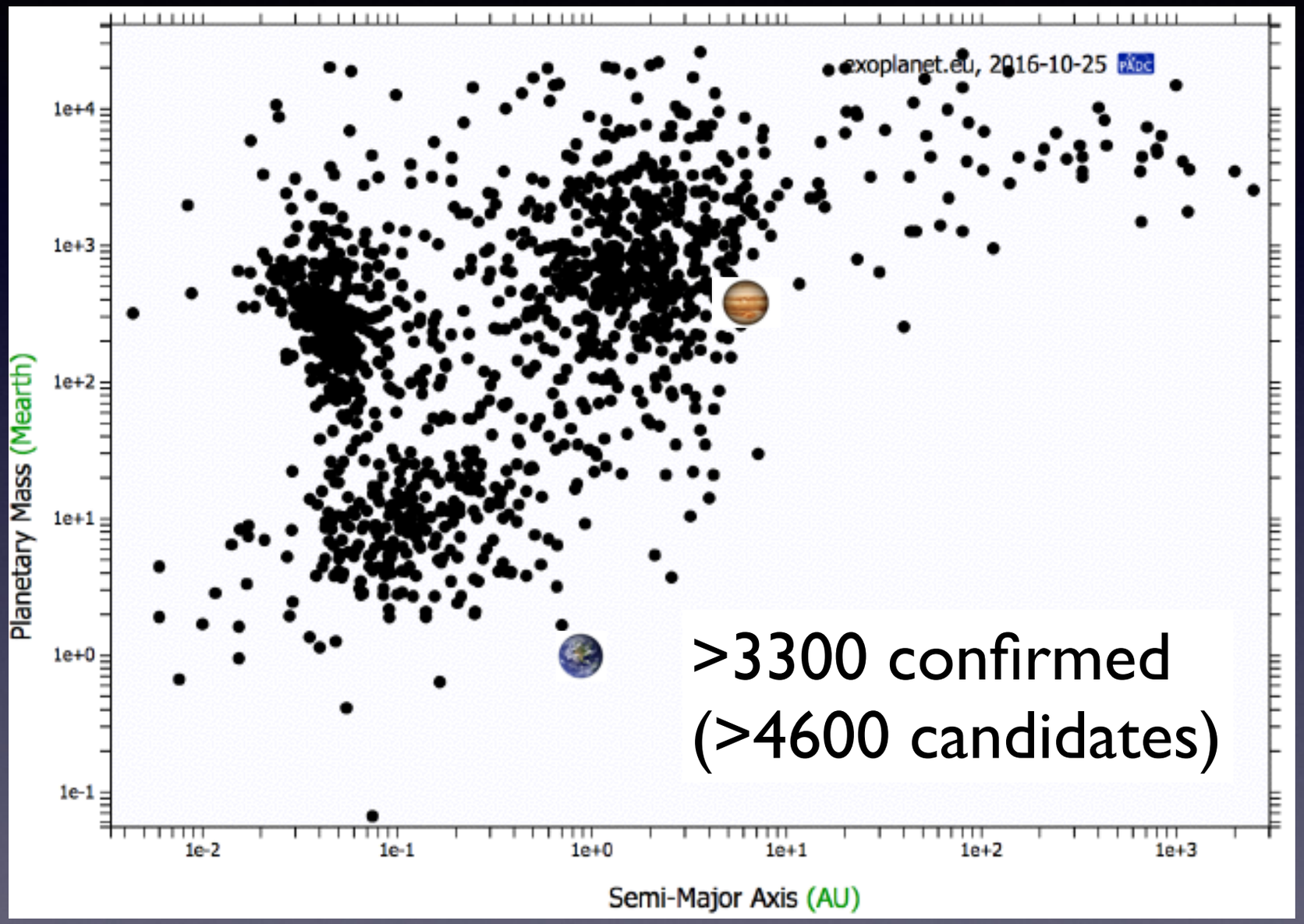
MICHEL MAYOR & DIDIER QUELOZ

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

Exoplanetary Populations

e.g., Mayor et al 2011, Howard et al 2012,
Batalha et al 2013, Holczer et al 2016



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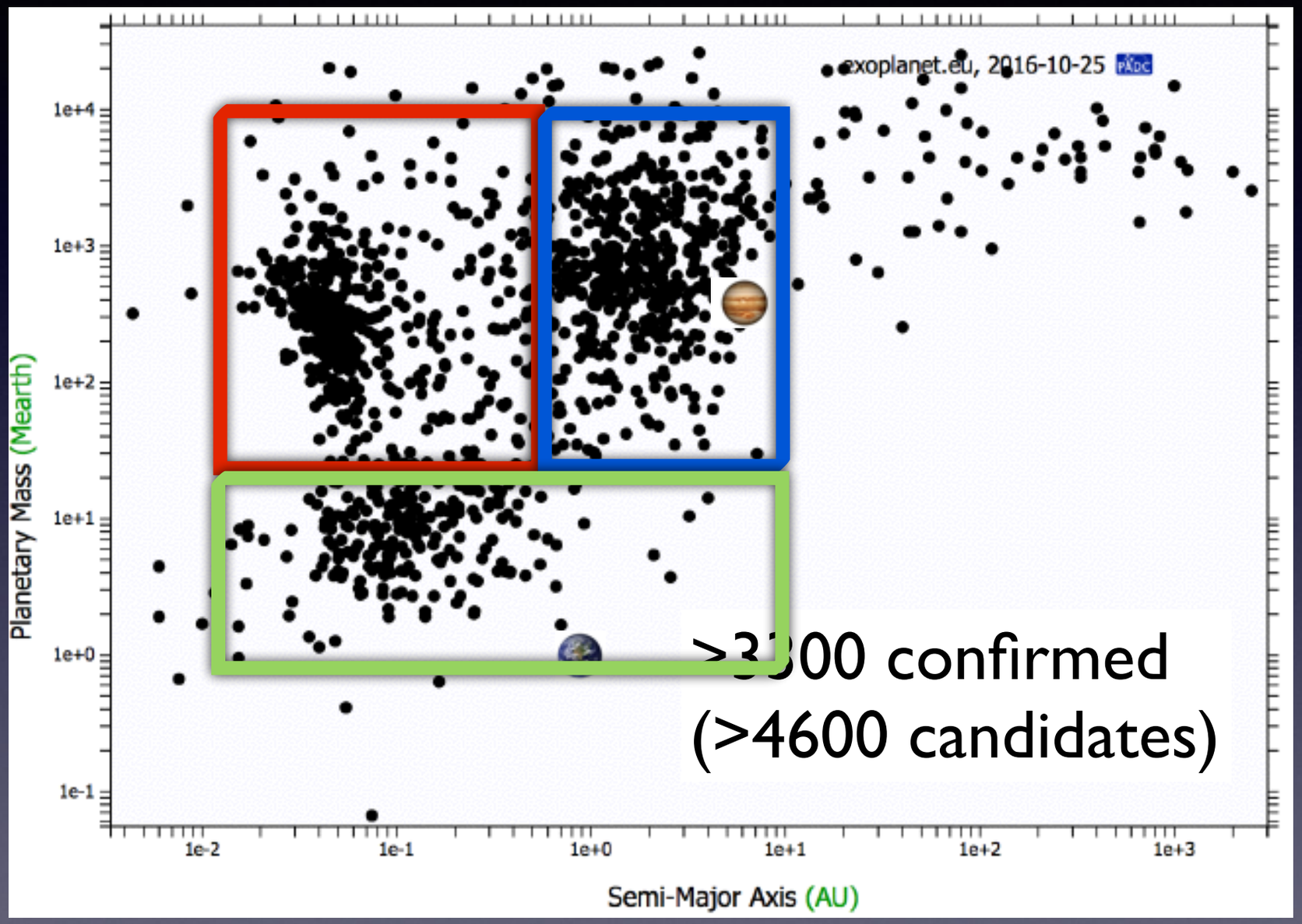


Hot Jupiters

: rare (~ 1 %)

Exo-Jupiters

: more (~ 10 - 20 %)

Low-mass Planets (Super-Earths)

: dominant (> 50 %)

Planet-forming materials or planets should move in protoplanetary disks!!

Exoplanetary populations can be reproduced well by coupling planet traps with core accretion

Key idea: Planet Traps (or Planetary Migration)

Result 1: Orbital Distributions of Planets Formed at Planet Traps

Result 2: the Mass-Radius Diagram for Observed Close-in Super-Earths

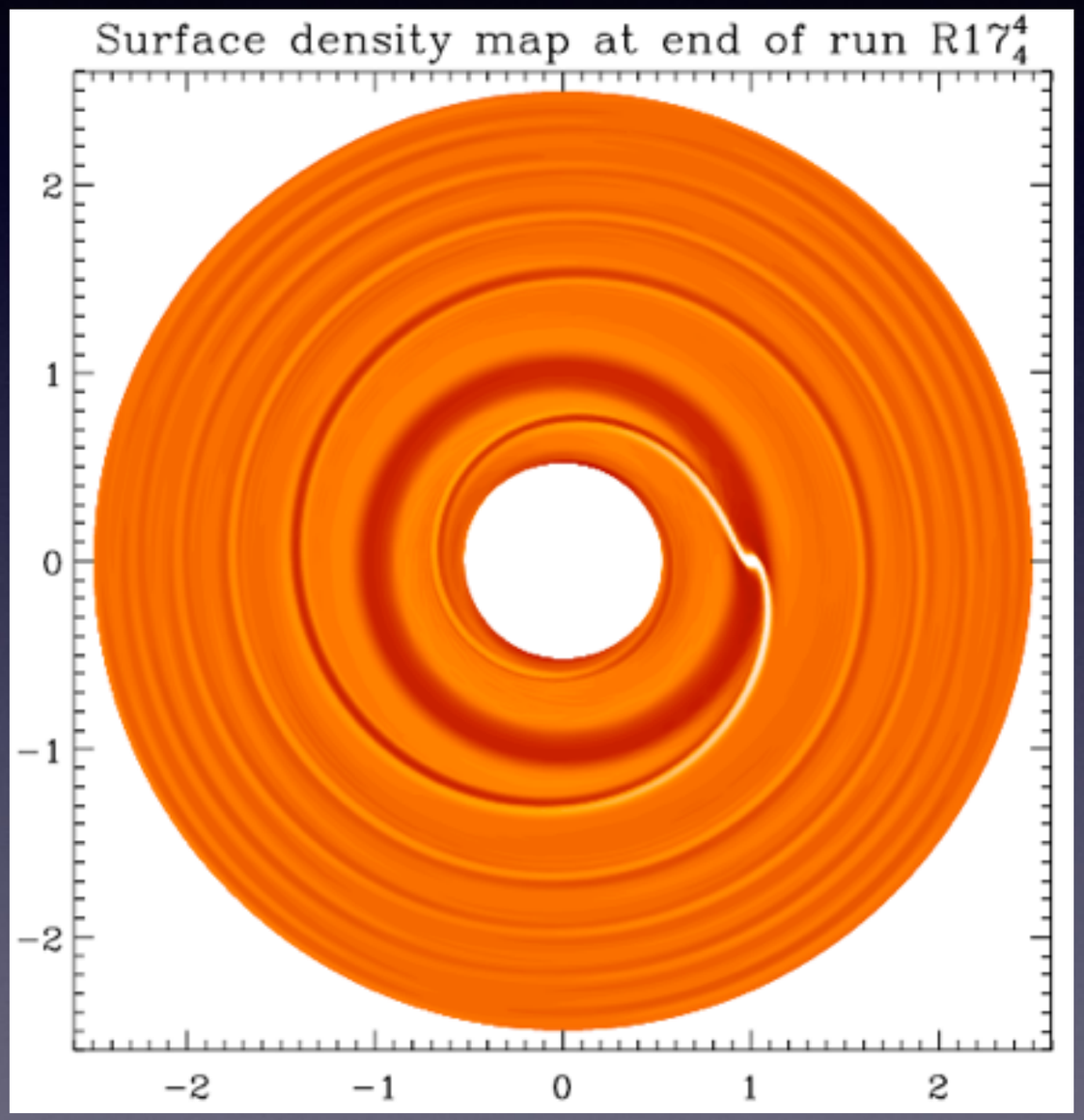
Key Idea:

Planet Traps
(or Planetary Migration)

Hasegawa & Pudritz, 2010b, ApJ, 710, L167
Hasegawa & Pudritz, 2011b, MNRAS, 417, 1236

Planetary Migration

e.g. Goldreich & Tremaine 1980, Ward 1986, Lin & Papaloizou 1986,
Nelson et al 2000, Masset 2001, 2002, Tanaka et al 2002
Baruteau & Masset 2008, Paardekooper et al 2010, 2011



Masset 2002

Angular momentum transfer

Lindblad resonances:
Inner disk => planet => outer disk

Corotation resonances:
Inner disk <= planet <= outer disk

Planetary Migration

e.g. Goldreich & Tremaine 1980, Ward 1986, Lin & Papaloizou 1986,
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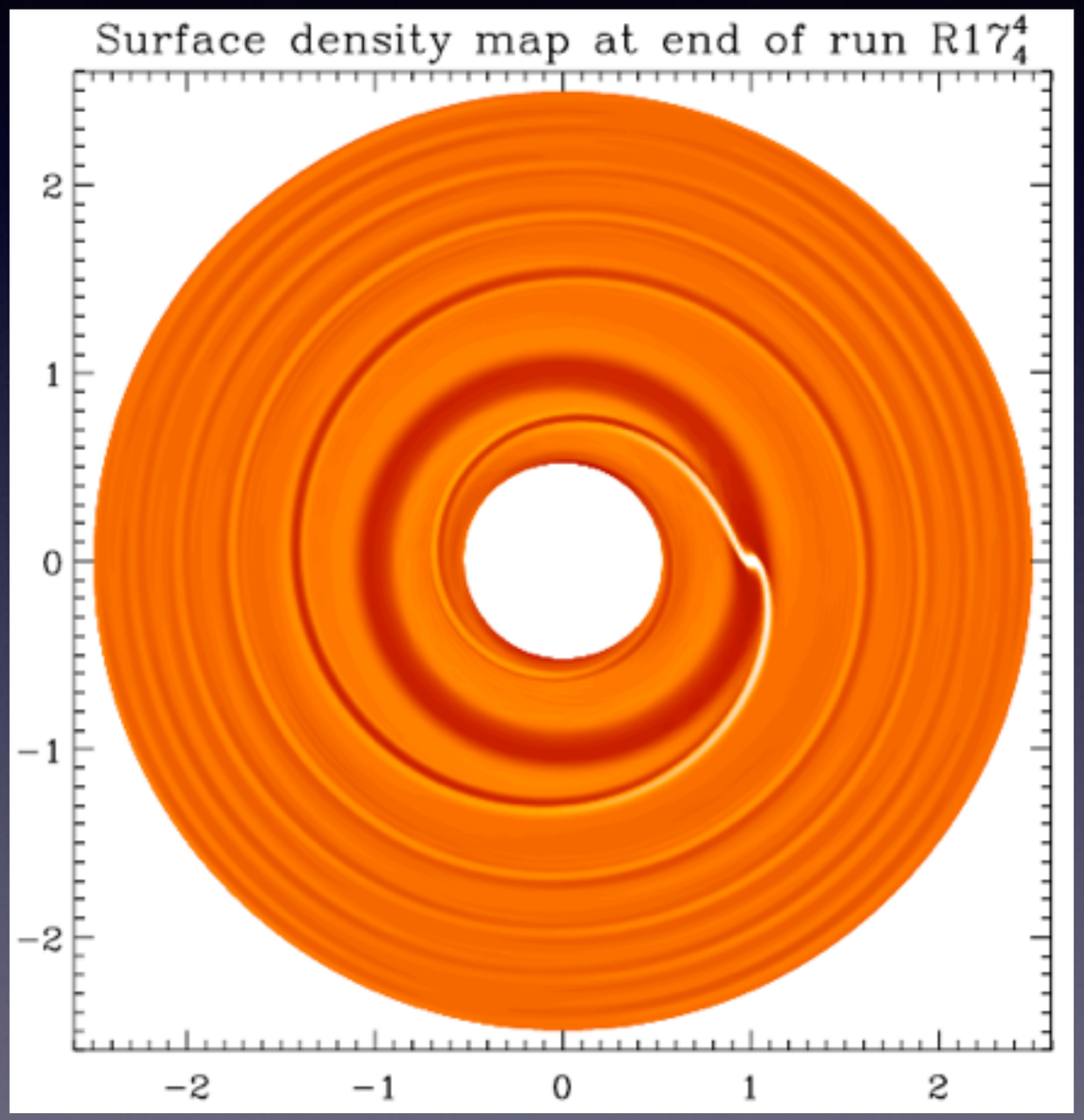


Masset 2002

Angular momentum transfer

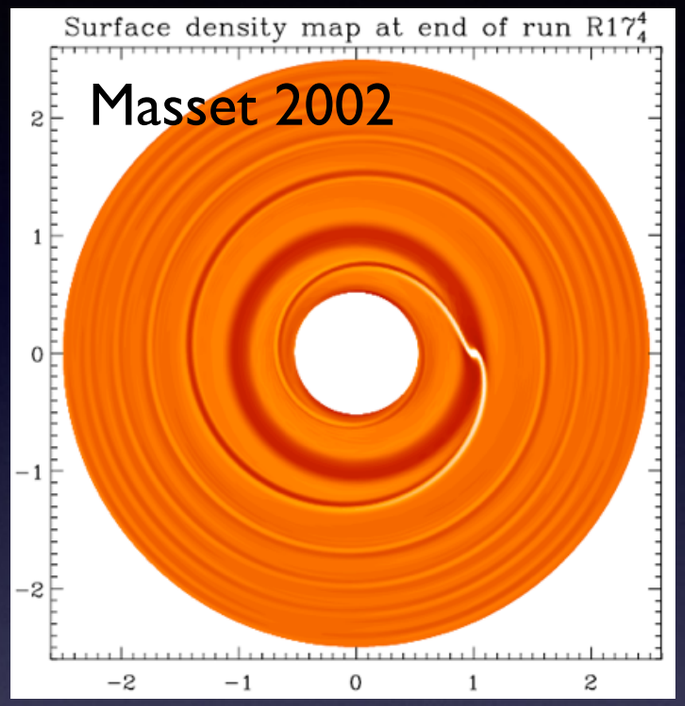
Lindblad resonances:
Inner disk => planet => outer disk

Corotation resonances:
Inner disk <= planet <= outer disk

The net of transferred angular momentum regulates migration

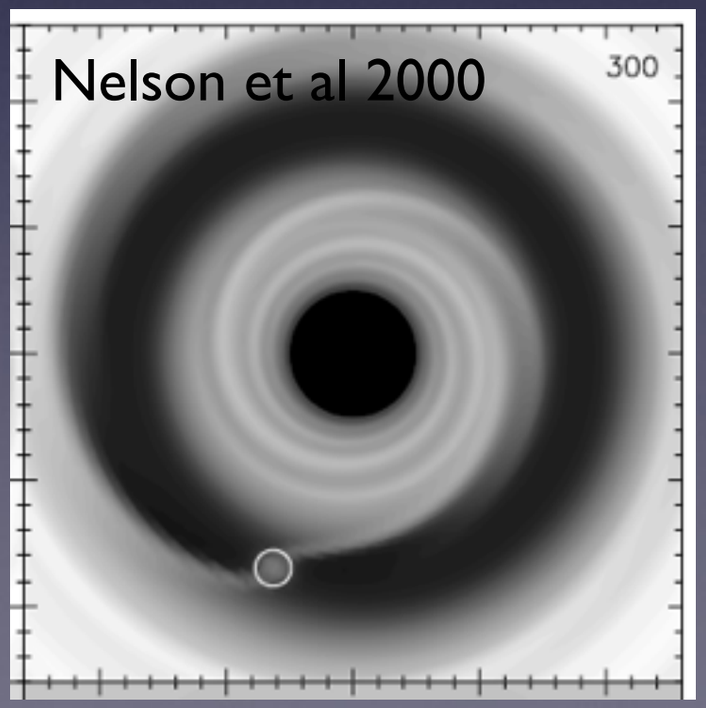
2 Modes of Migration

e.g. Goldreich & Tremaine 1980, Ward 1986, Lin & Papaloizou 1986,
Nelson et al 2000, Masset 2001, 2002, Tanaka et al 2002
Baruteau & Masset 2008, Paardekooper et al 2010, 2011



Type I migration (no gap)

: effective for low mass planets such as terrestrial planets & cores of gas giants

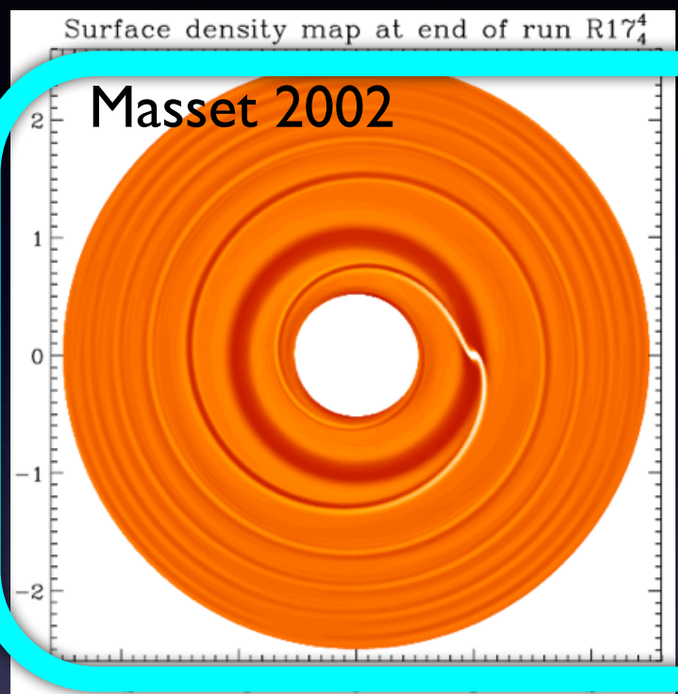


Type II migration (gaps)

: effective for massive planets such as Jovian planets

Planet Traps

e.g. Goldreich & Tremaine 1980, Ward 1986, Lin & Papaloizou 1986,
Nelson et al 2000, Masset 2001, 2002, Tanaka et al 2002
Baruteau & Masset 2008, Paardekooper et al 2010, 2011



Type I migration (no gap)

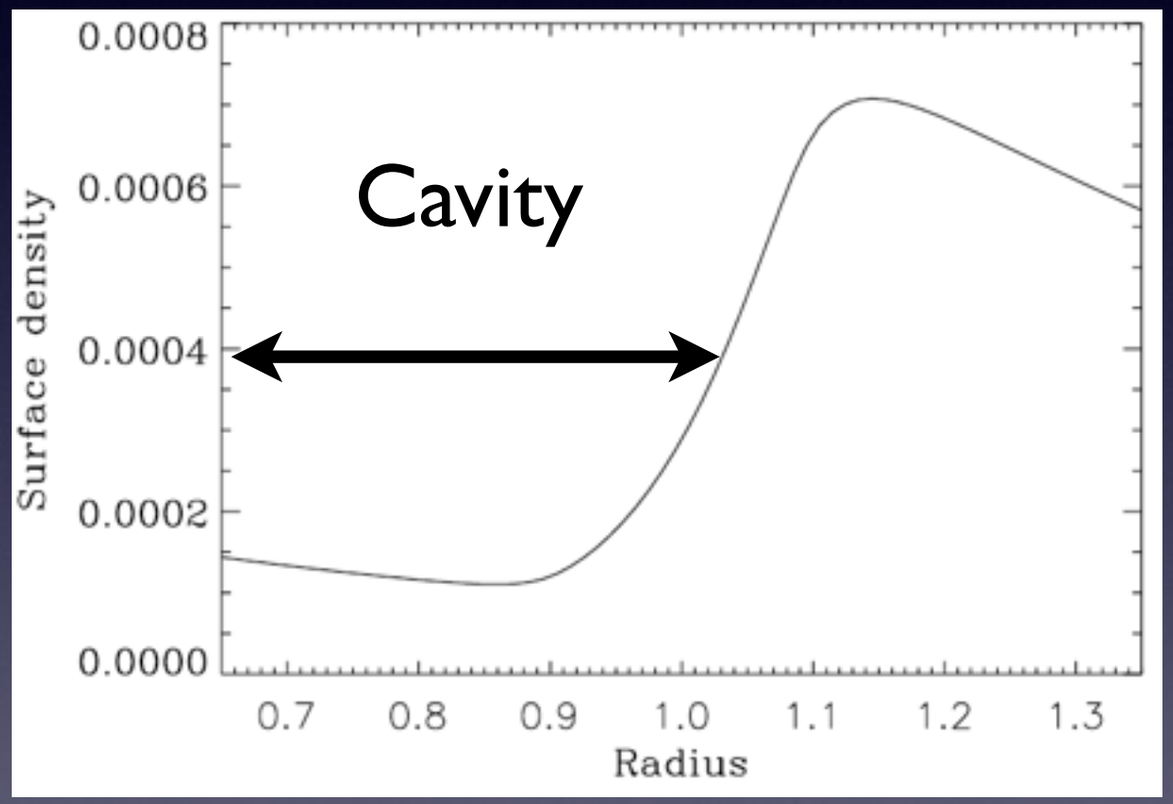
: effective for low mass planets such as terrestrial planets & cores of gas giants

The direction and the speed of migration depend on disk properties such the surface density & the disk temperature

Planet traps = disk structures
at which the net torque is zero

Planet Traps

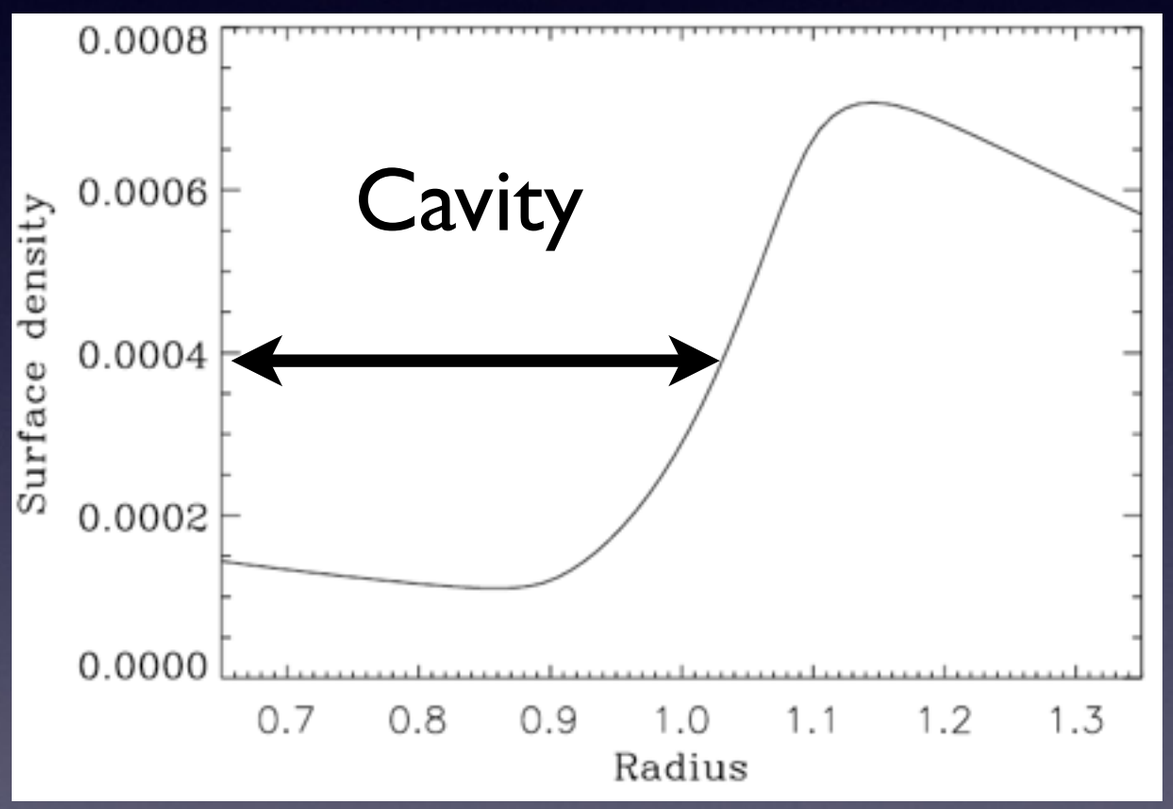
Masset et al 2006



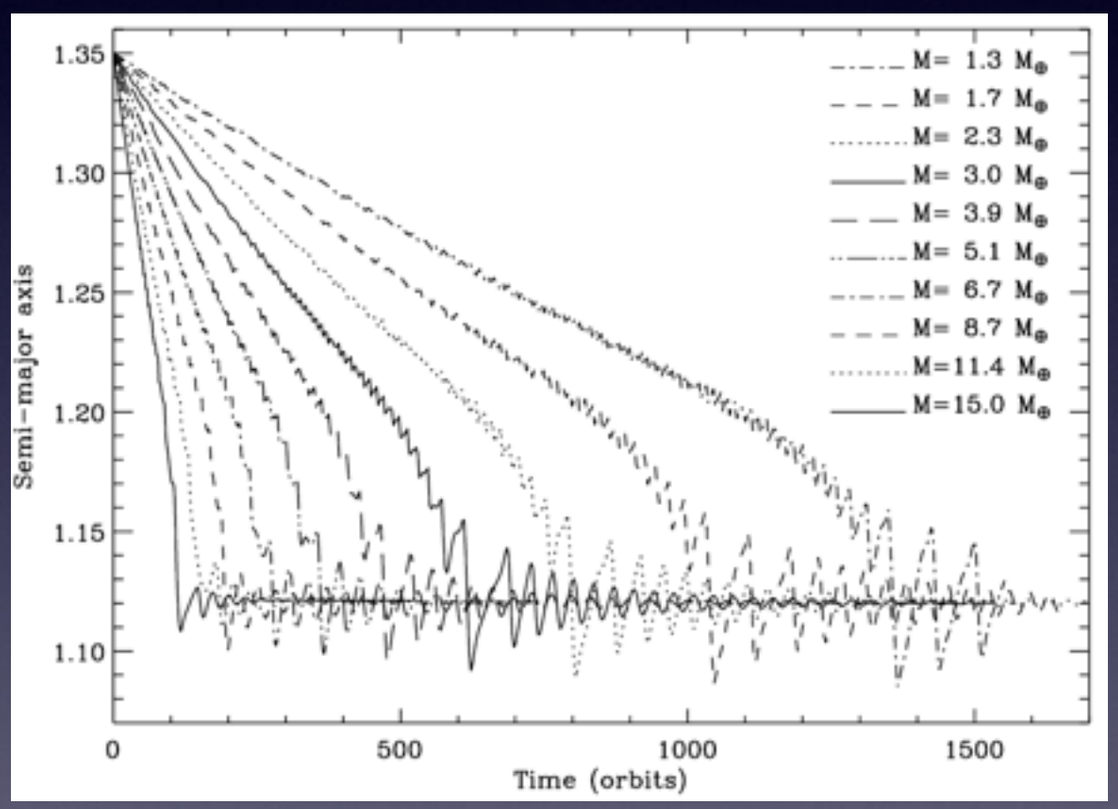
Inner edge of disks

Planet Traps

Masset et al 2006



Inner edge of disks



Planets are trapped at the inner edge

Planet Traps

Masset et al 2006 **Matsumura, Pudritz, & Thommes 2007, 2009**

Ida & Lin 2008, Morbidelli et al 2008

Hasegawa & Pudritz 2010b, Lyra et al 2010

Hasegawa & Pudritz 2011b, Bitsch & Kley 2011

Hellary & Nelson 2012, Kretke & Lin 2012, Mordasini et al 2012

Pierens et al 2013, Bitsch et al 2013, etc...

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Planet Traps

Masset et al 2006 **Matsumura, Pudritz, & Thommes 2007, 2009**

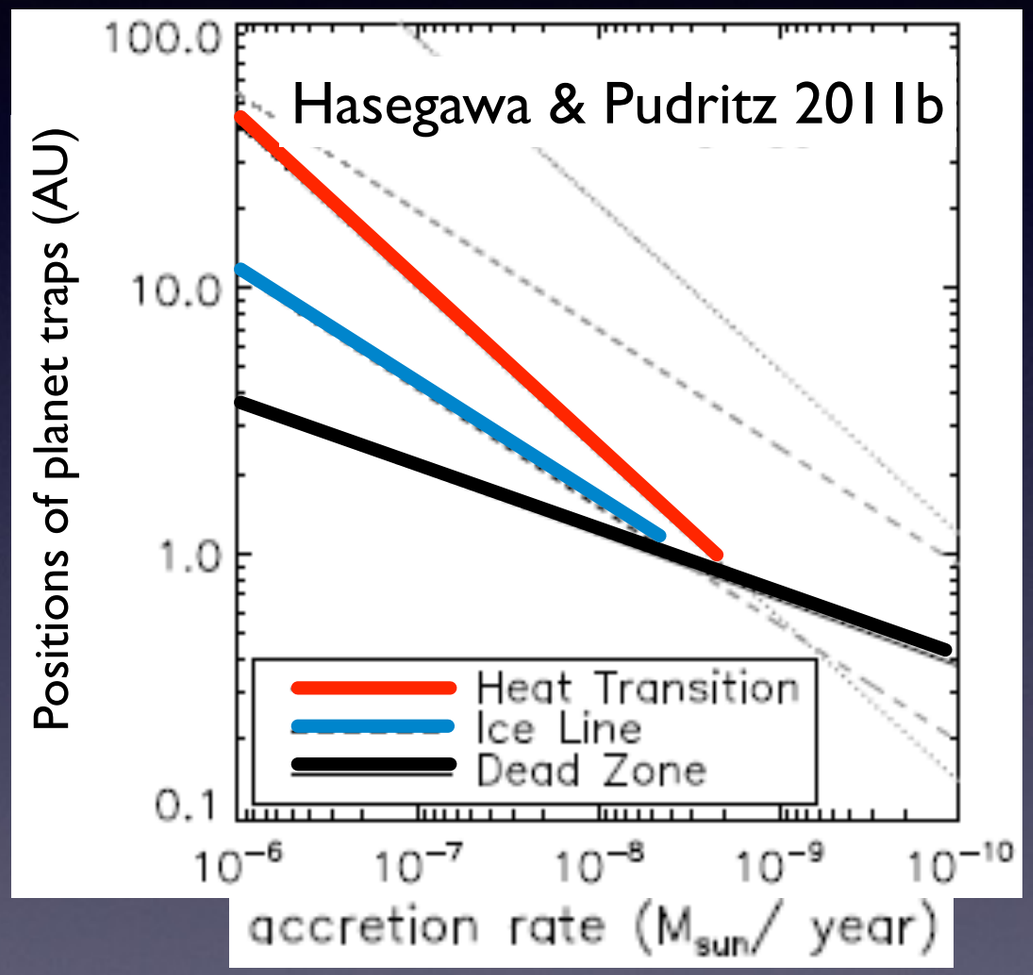
Acceptable conclusion may be...

some kinds of traps are very likely to be present in protoplanetary disks

Planet Traps

3 types of traps in single disks

: the outer edge of dead zones, ice lines, heat transitions



Planet Traps

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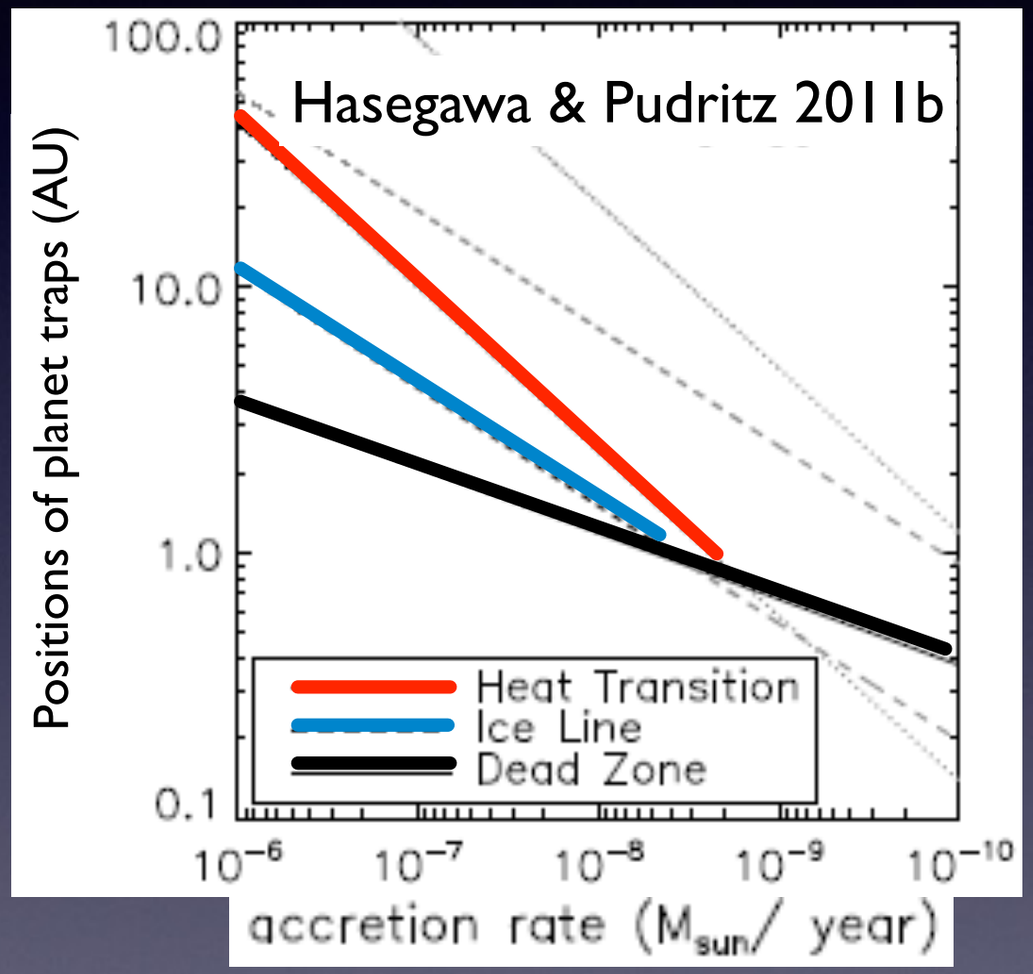
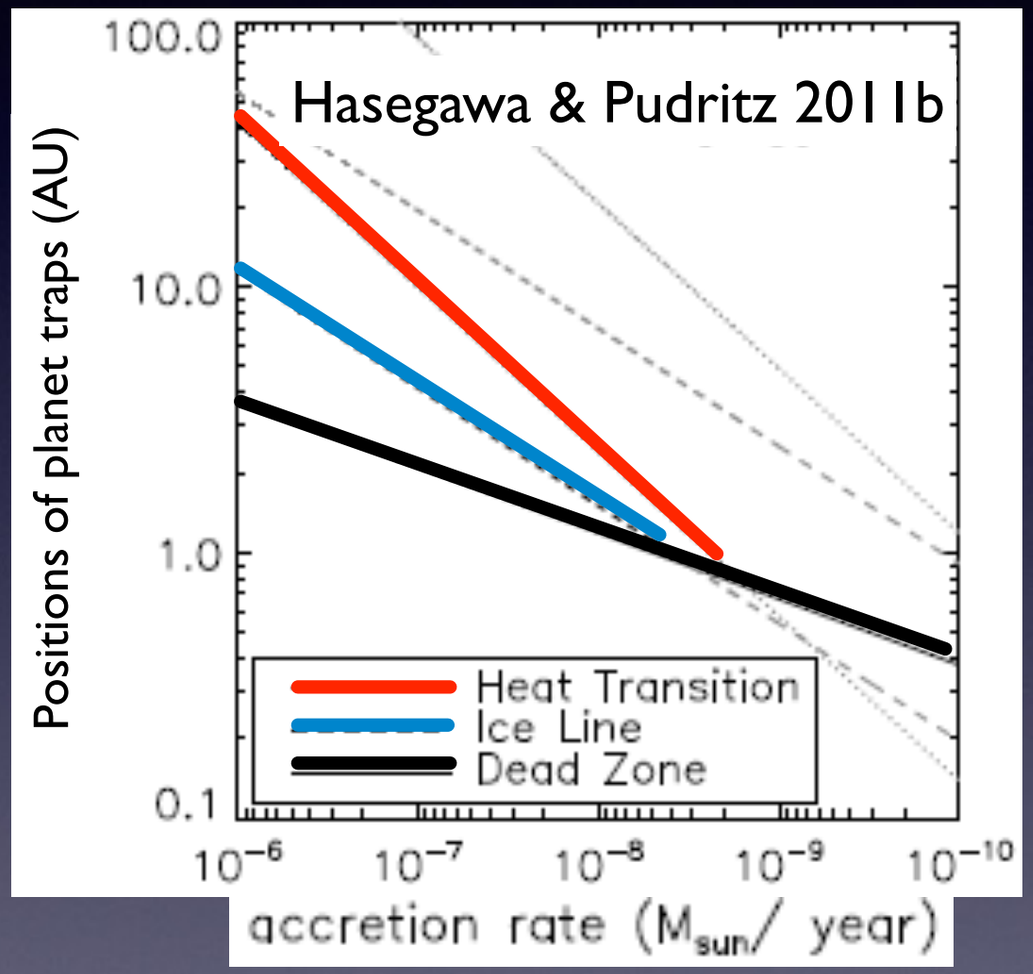


Locations of traps are specified by disk evolution

Planet Traps

3 types of traps in single disks

: the outer edge of dead zones, ice lines, heat transitions

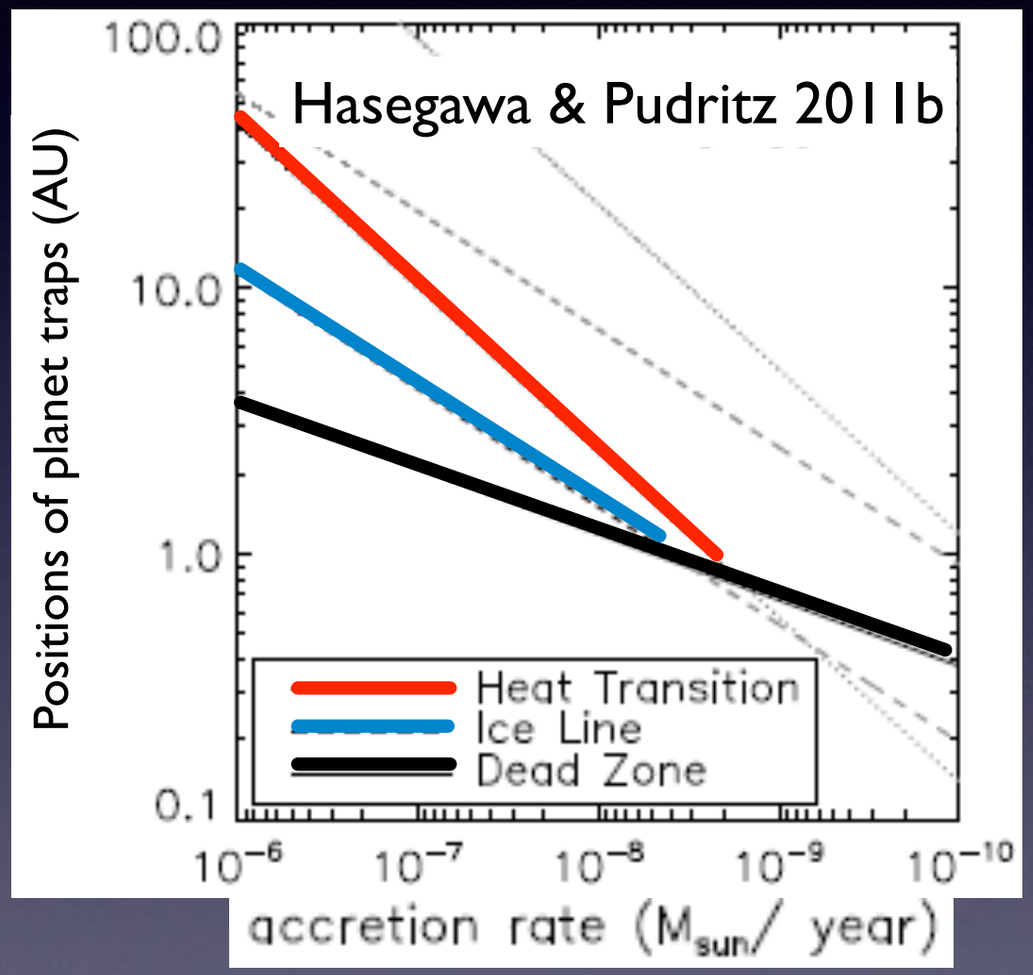


Locations of traps are specified by disk evolution

Mass dependence of traps

: planet traps are effective until protoplanets obtain the gap-opening mass & undergo type II migration

Planet Traps



3 types of traps in single disks

: the outer edge of dead zones, ice lines, heat transitions

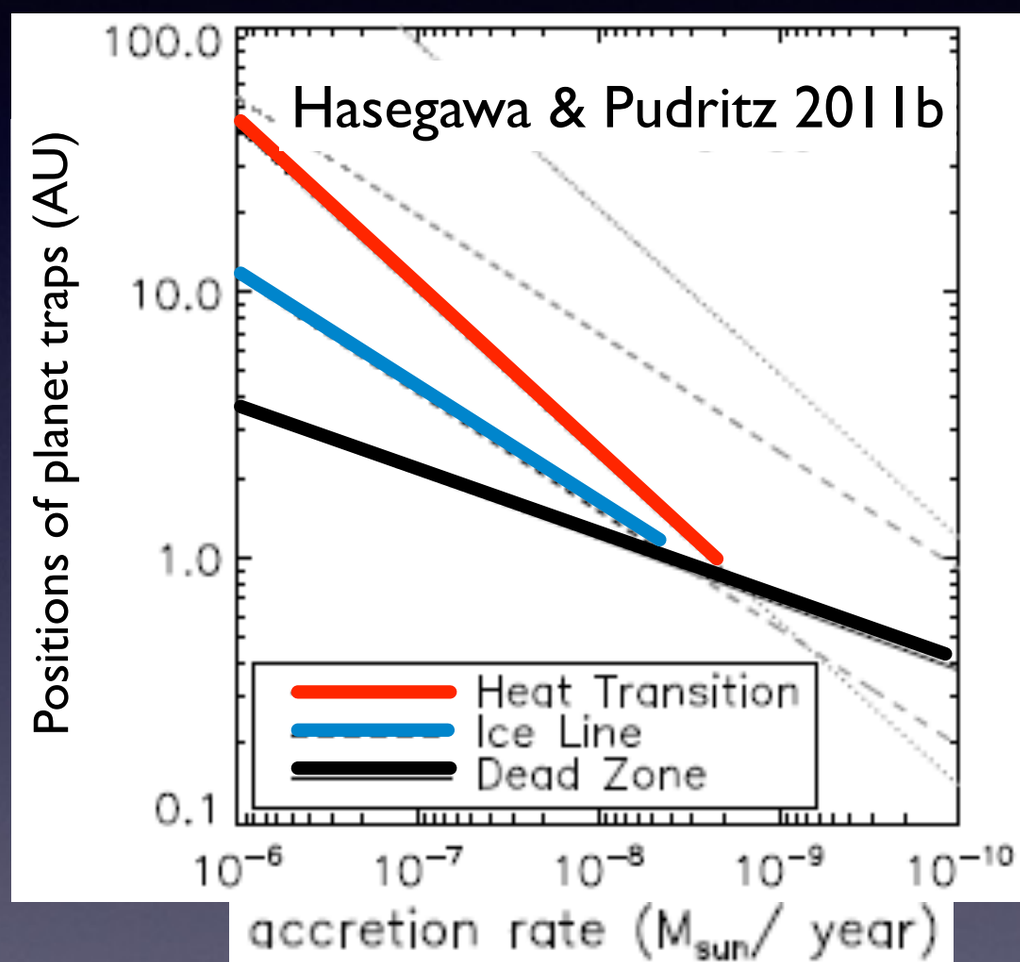
Locations of traps are specified by disk evolution

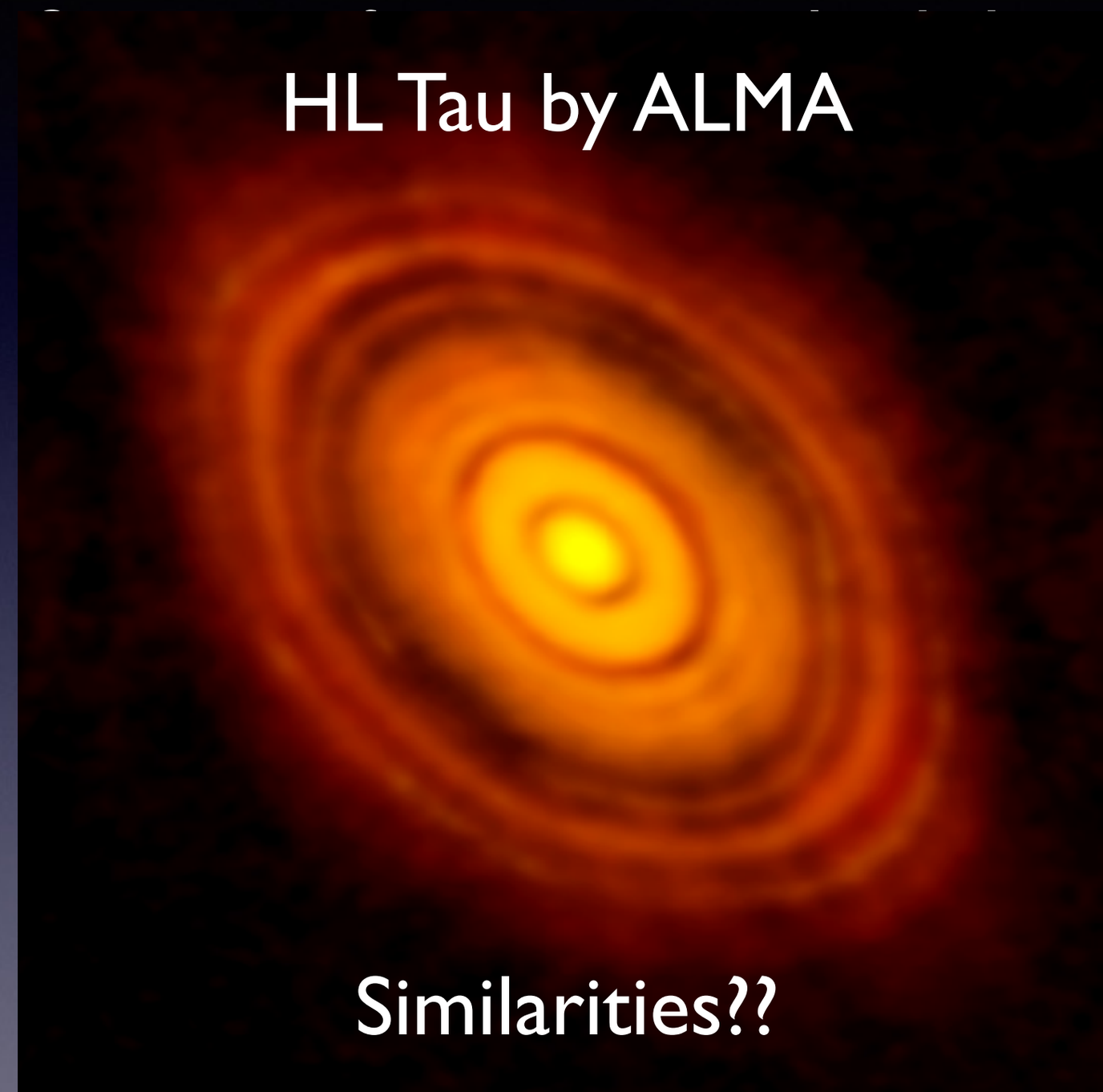
Mass dependence of traps

: planet traps are effective until protoplanets obtain the gap-opening mass & undergo type II migration

Planets form locally at traps before type II migration

Planet Traps



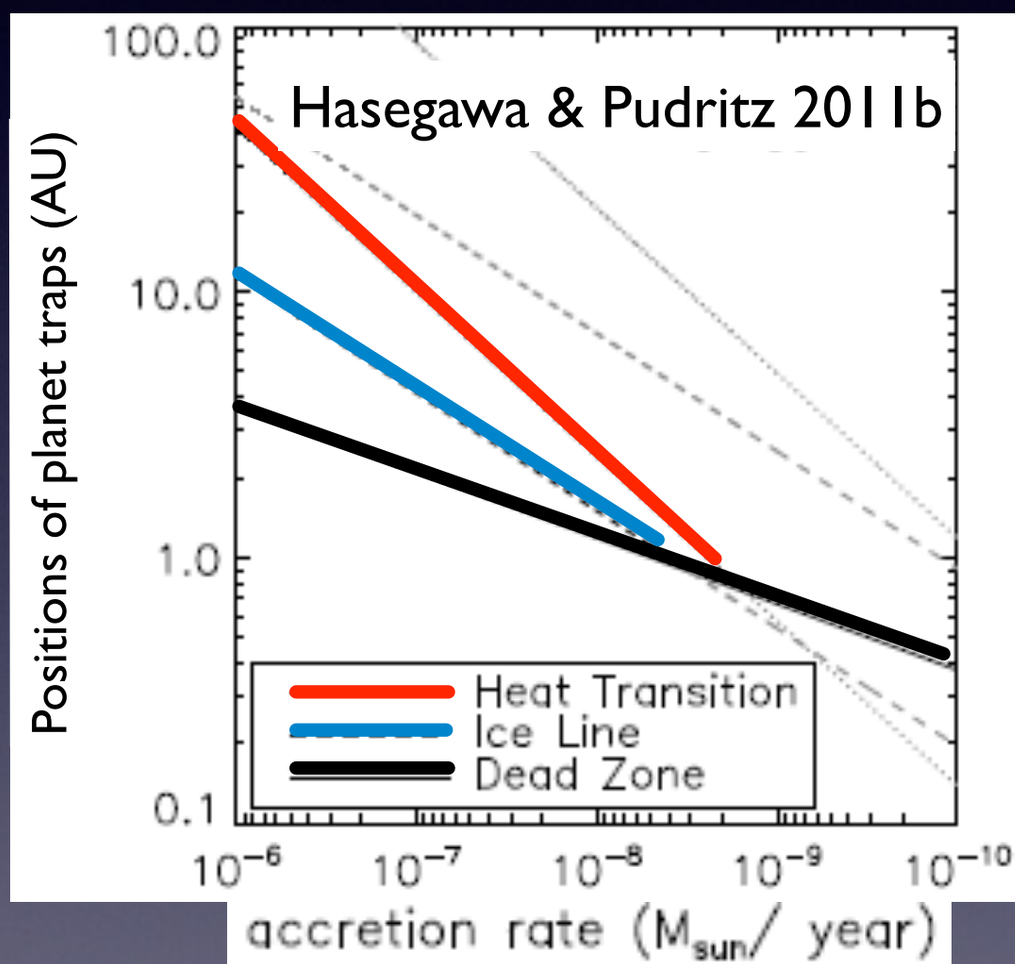


Result 1:

Orbital Distributions of Planets Formed at Planet Traps

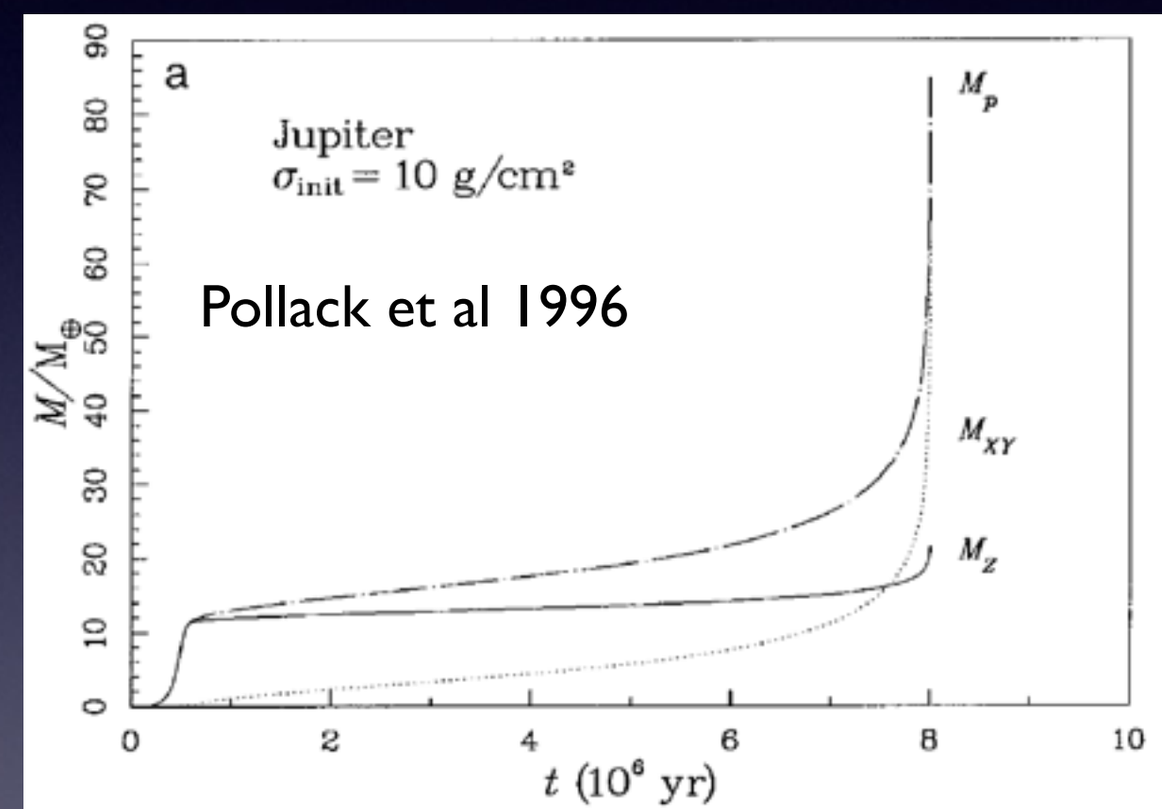
Hasegawa & Pudritz, 2012, ApJ, 760, 117
Hasegawa & Pudritz, 2013, ApJ, 778, 78

Planet Traps (Orbital Evolution)



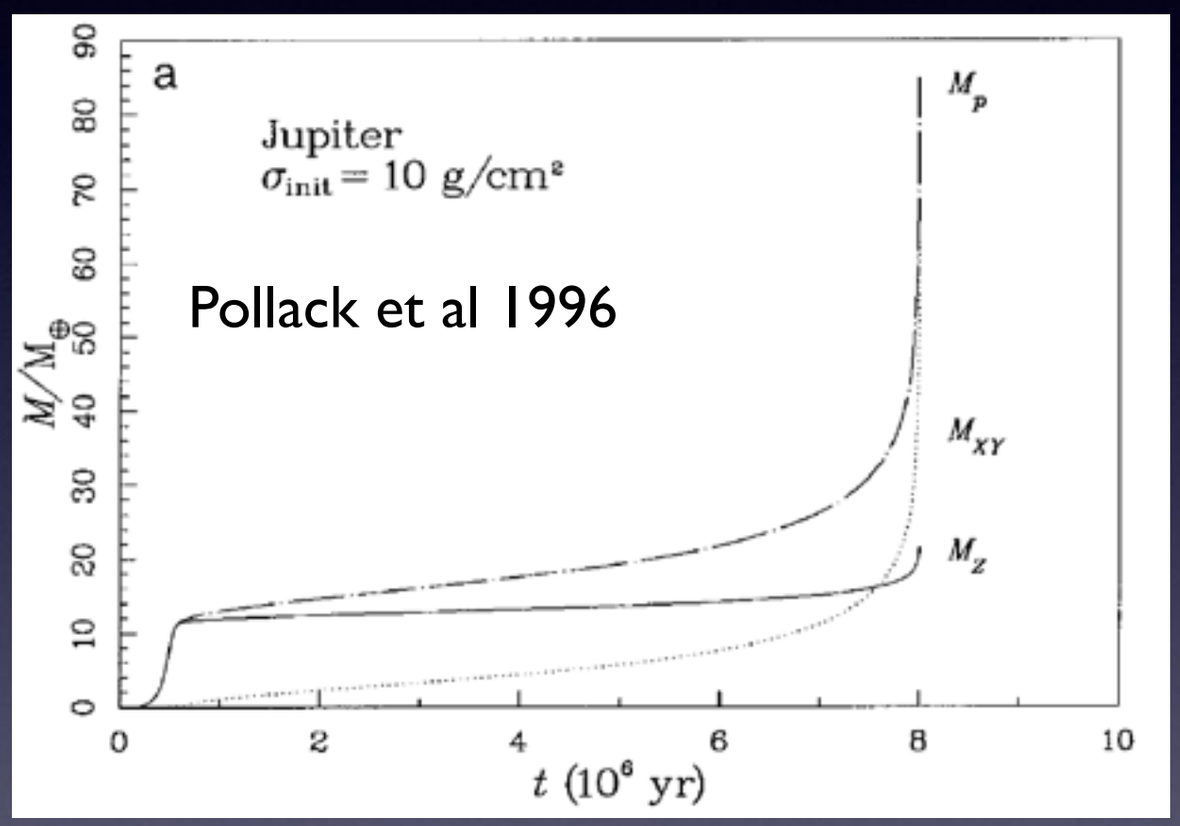
+

Core Accretion (Mass Growth)



Core Accretion: Mass Growth of Planets

e.g., Mizuno 1980, Stevenson 1982, Bodenheimer & Pollack 1986, Pollack et al 1996, Ikoma et al 2000, Hubickyj et al 2005, Lissauer et al 2009, Movshovitz et al 2010



Gas giants

↑

Cores +
low-mass atmospheres

↑

Cores of gas giants

↑

Dust/Planetesimals

Core Accretion: Mass Growth of Planets

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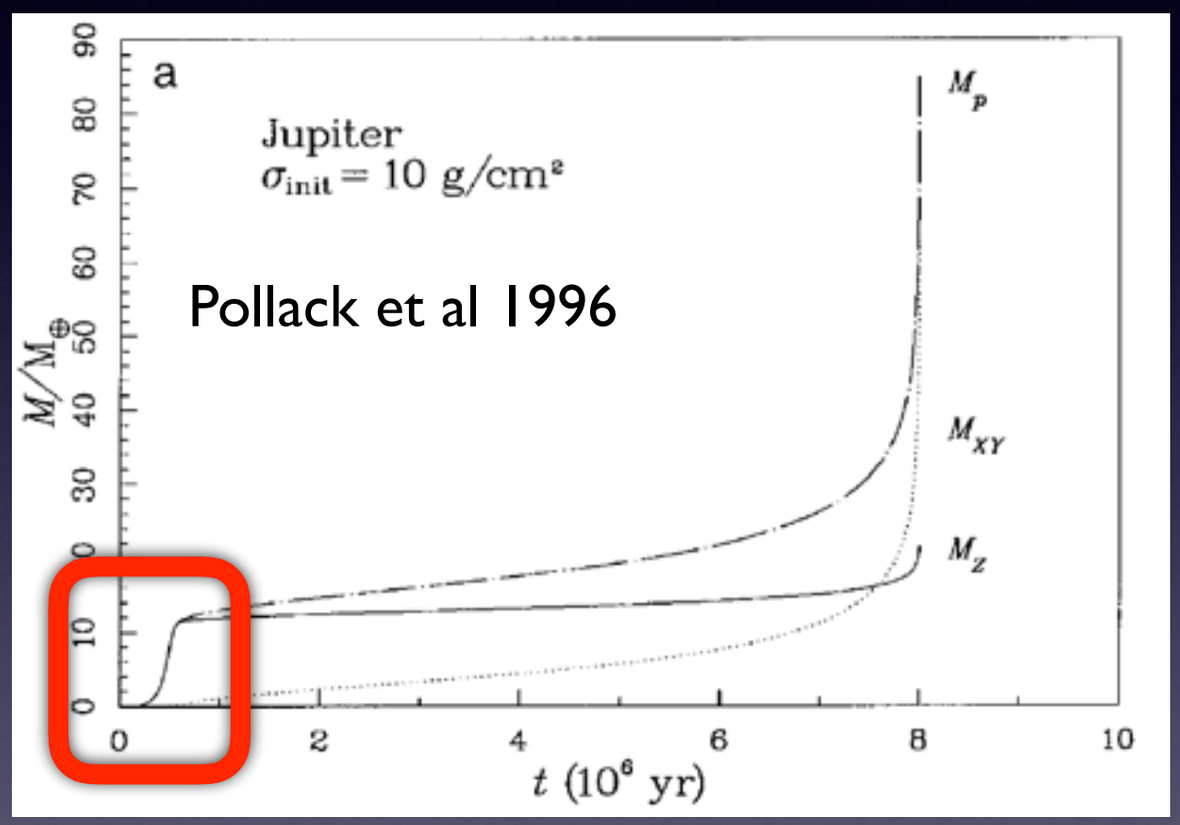

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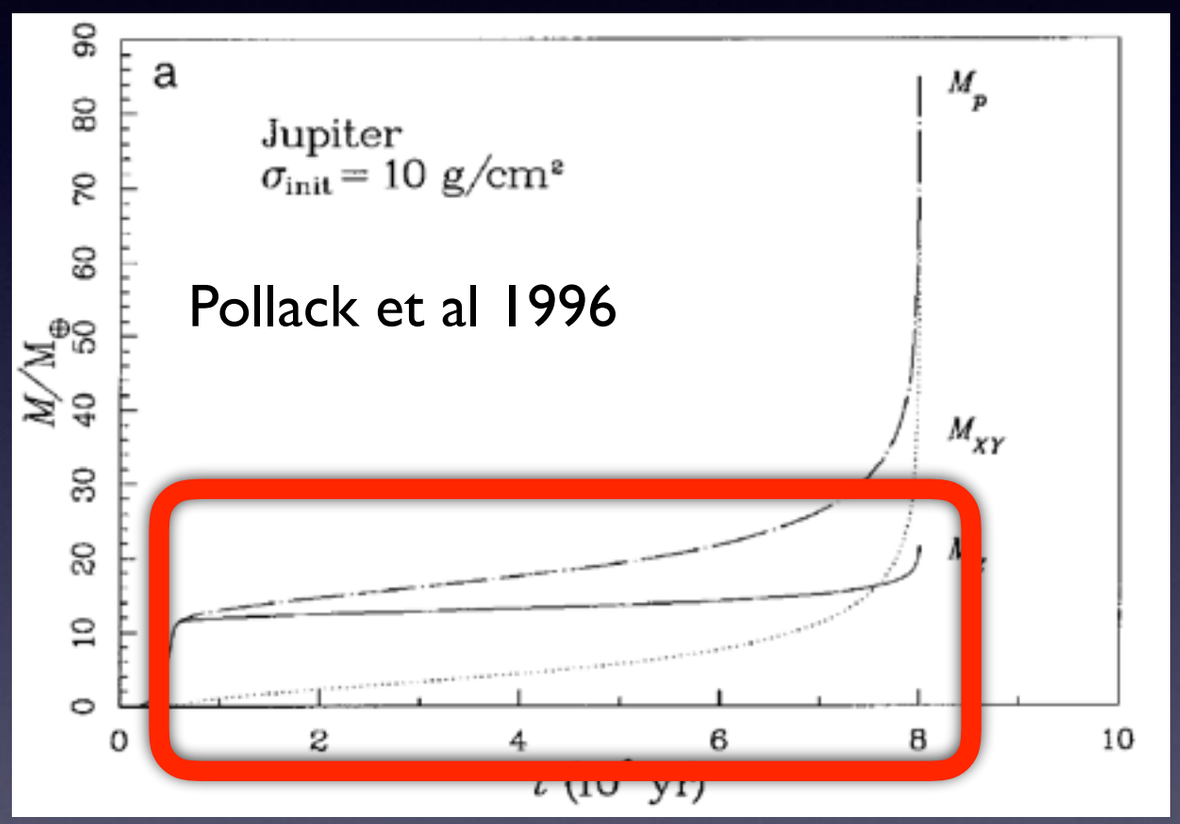

Gas giants

Cores + low-mass atmospheres

Cores of gas giants

Dust/Planetesimals

Core Accretion: Mass Growth of Planets

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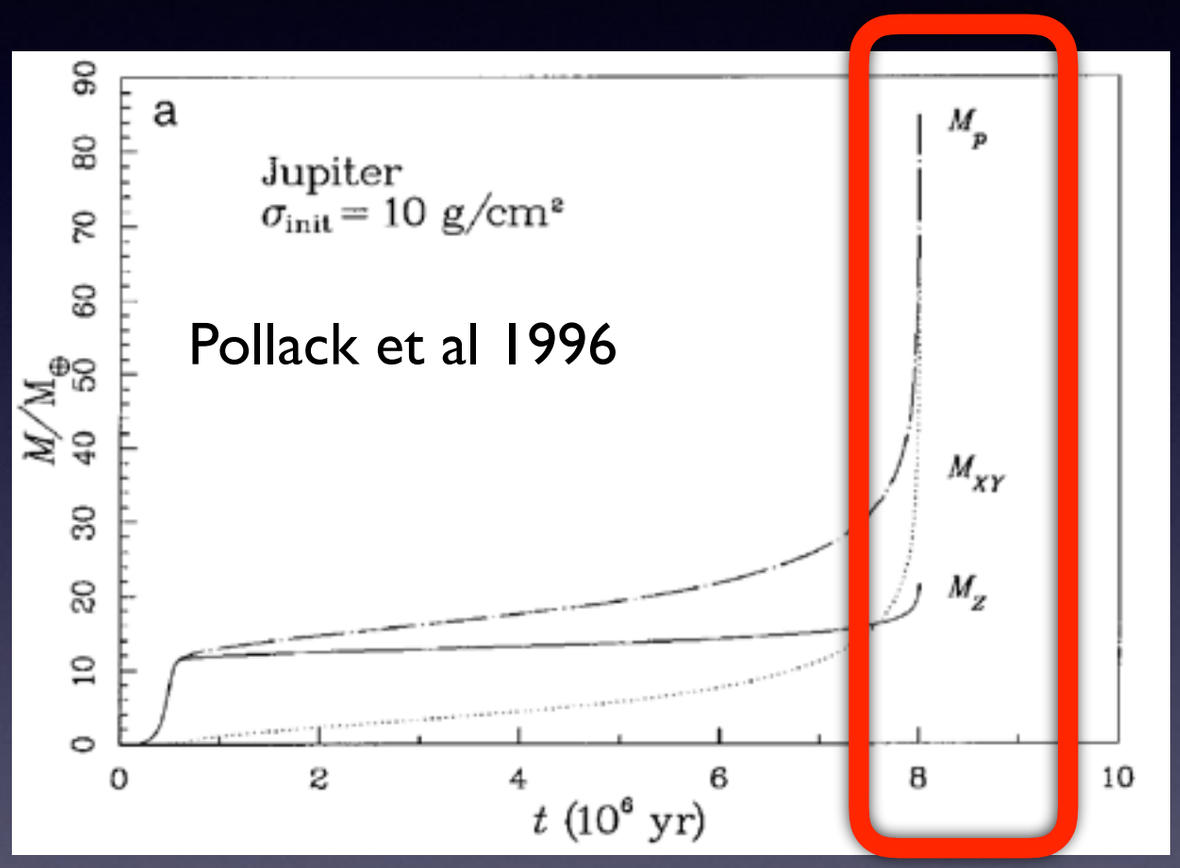


Gas giants

Cores + low-mass atmospheres

Cores of gas giants

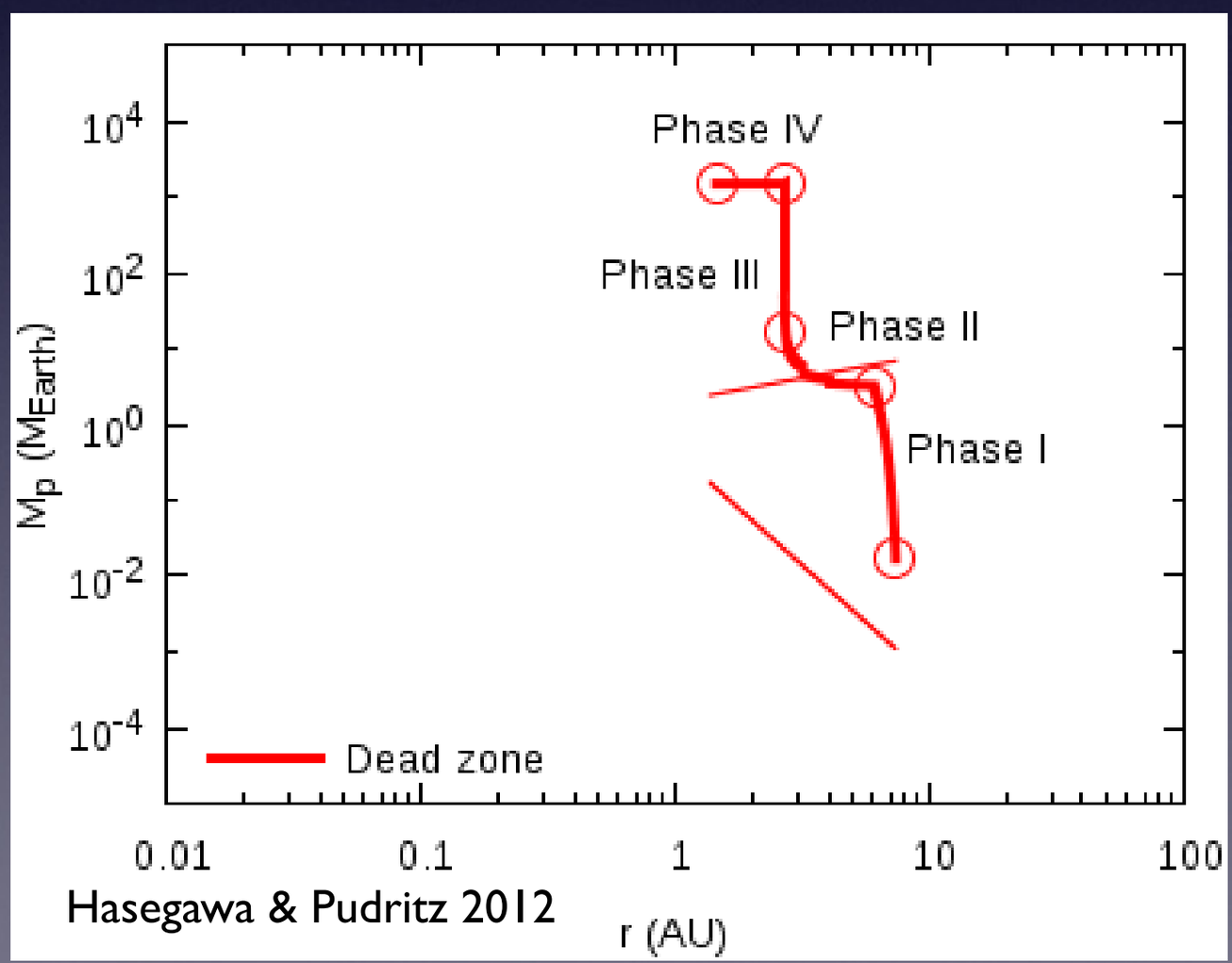
Dust/Planetesimals

Evolutionary Tracks

A disk around a classical T Tauri star is considered

$$M_{disk} \sim 0.03 M_{\odot}$$

$$\tau_{disk} \sim 8.8 \times 10^{6} years$$



Hasegawa & Pudritz 2012

Evolutionary Tracks

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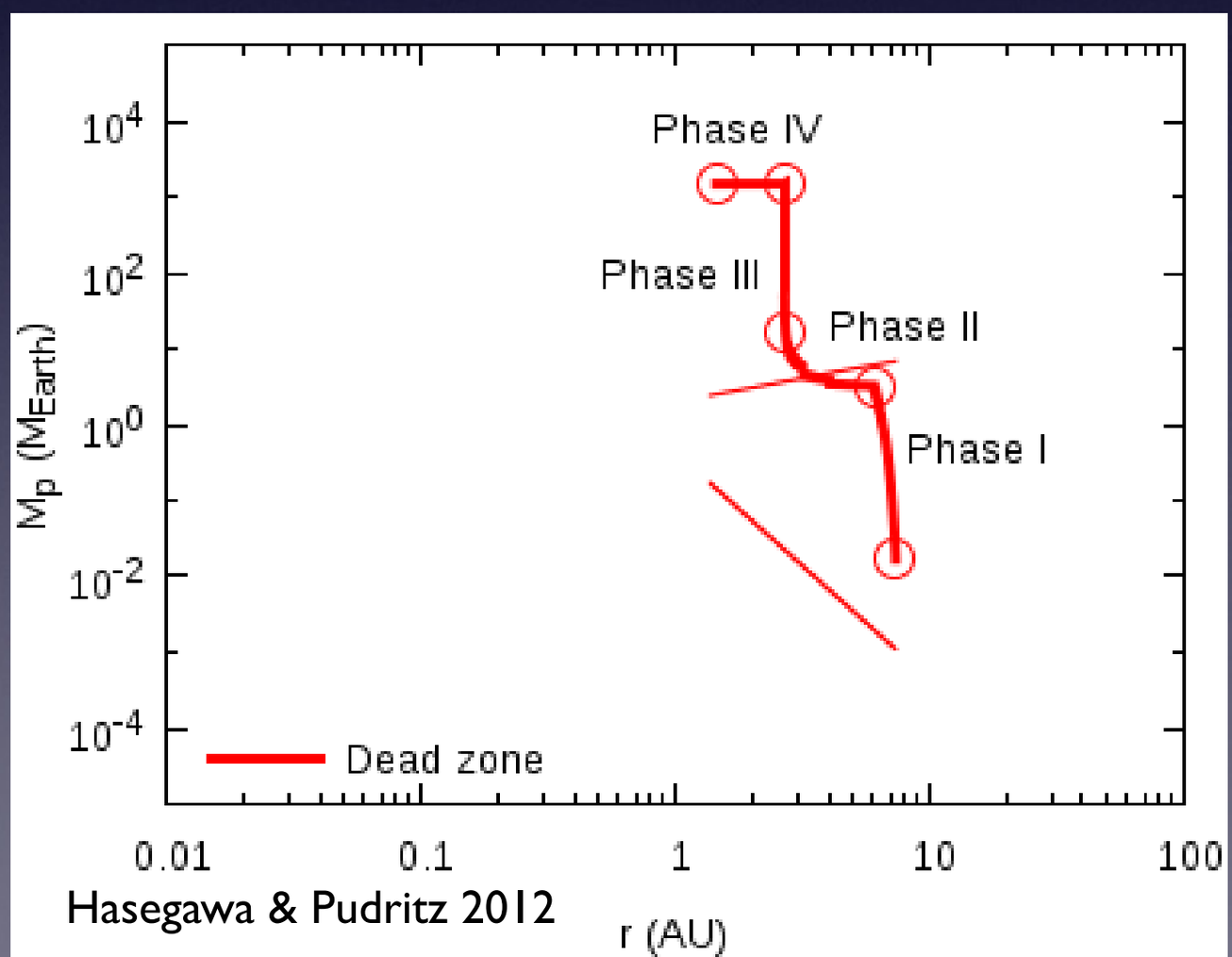


Hasegawa & Pudritz 2012

Gas disks totally dissipate

Phase IV $(> 10^{6} years)$

Gas giants

Phase III $(< 10^{5} years)$

Cores + low-mass atmospheres

Phase II

$(\sim 2 \times 10^{6} years)$

Cores of gas giants

Phase I $(< 10^{6} years)$

Dust/Planetesimals

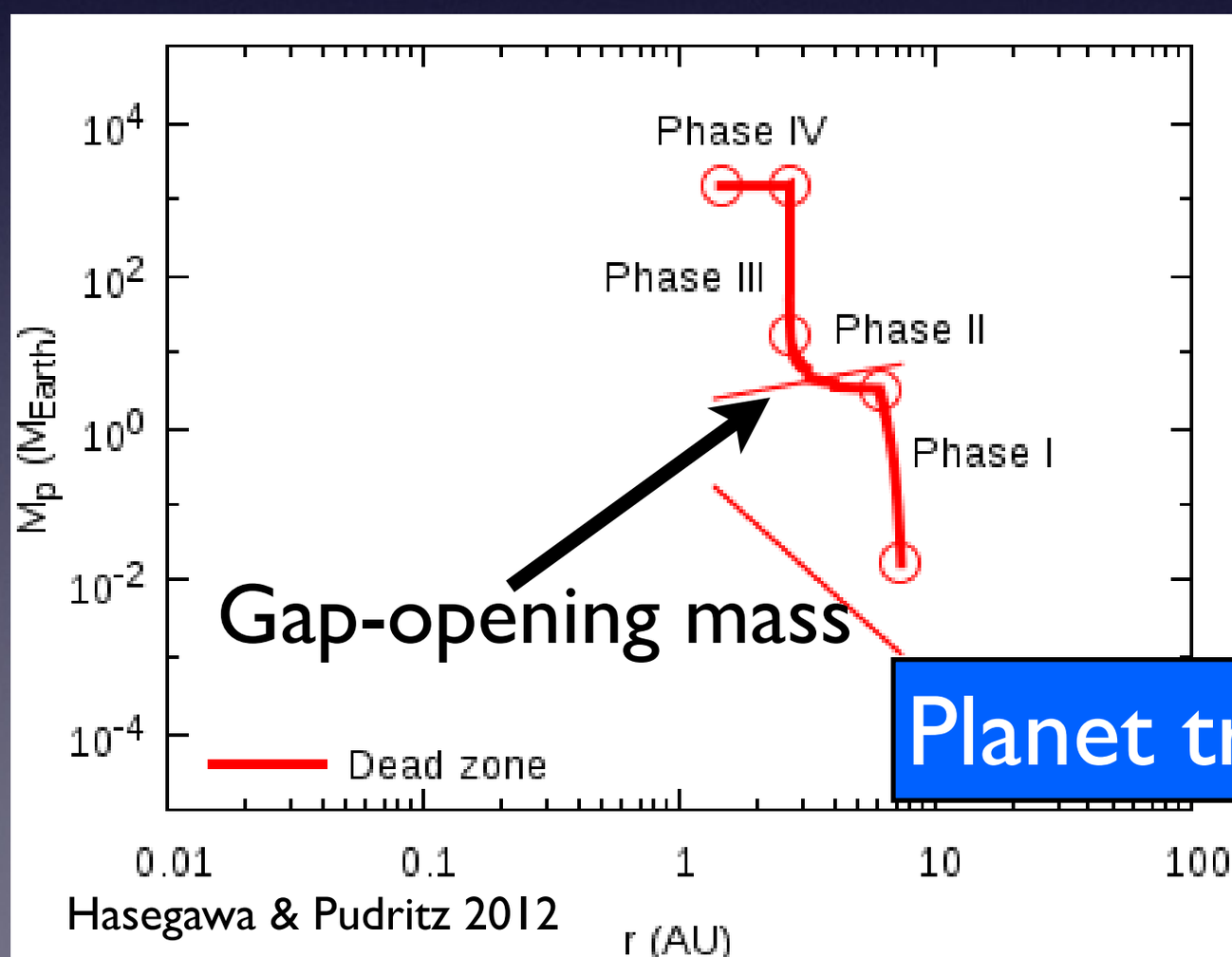
Evolutionary Tracks

A disk around a classical T Tauri star is considered

$M_{disk} \sim 0.03$

$\tau_{disk} \sim 8.8 \times 10^6 years$

Type II migration



Hasegawa & Pudritz 2012

Planet traps

Gas disks totally dissipate

Phase IV $(> 10^6 years)$

Gas giants

Phase III $(< 10^5 years)$

Cores + low-mass atmospheres

Phase II

$(\sim 2 \times 10^6 years)$

Cores of gas giants

Phase I $(< 10^6 years)$

Dust/Planetesimals

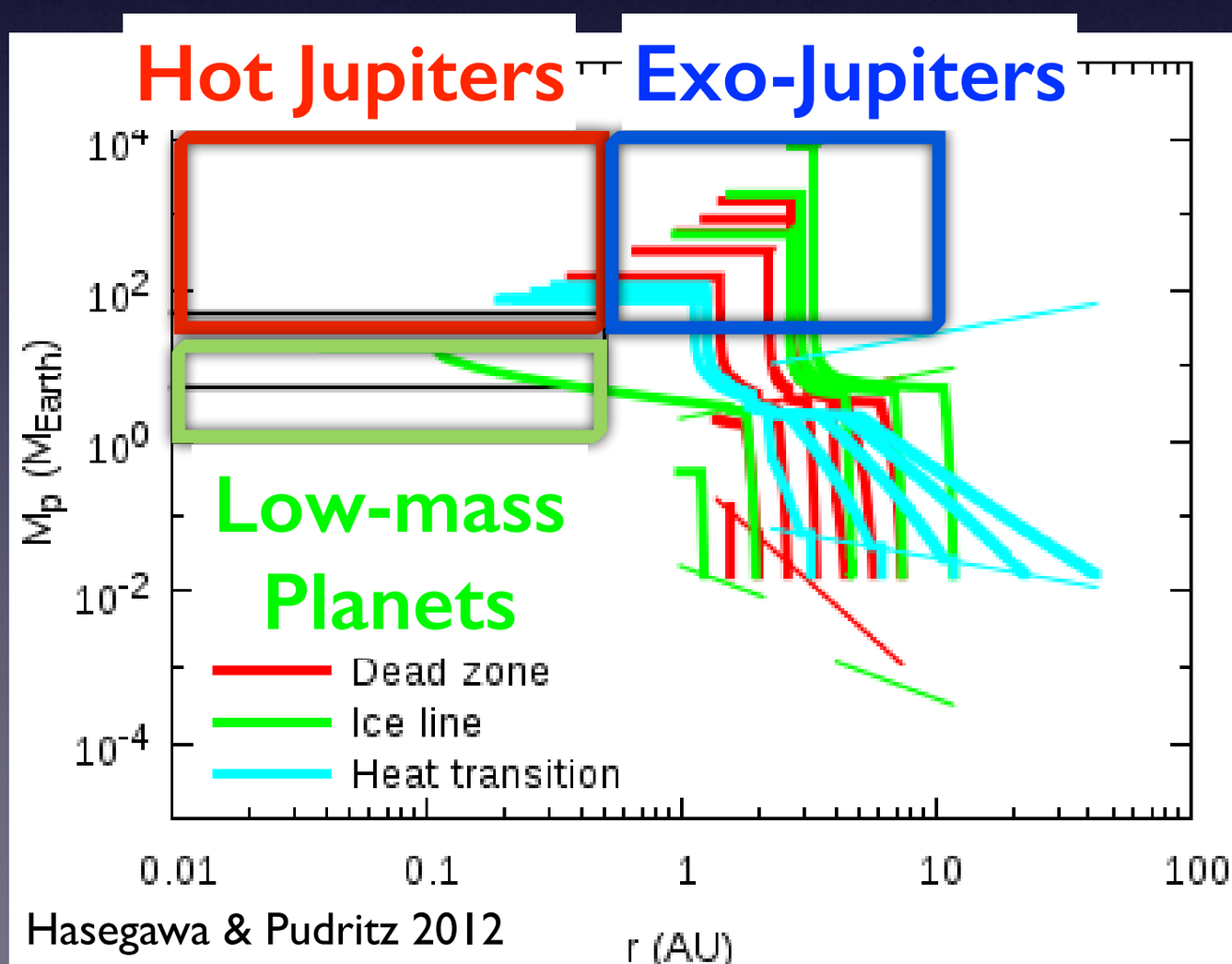
Planet Formation Frequencies (PFFs)

Hasegawa & Pudritz 2013

A disk around a classical T Tauri star is considered

$$M_{disk} \sim 0.03 M_{\odot}$$

$$\tau_{disk} \sim 8.8 \times 10^{6} years$$



Hasegawa & Pudritz 2012

Compute lots of tracks

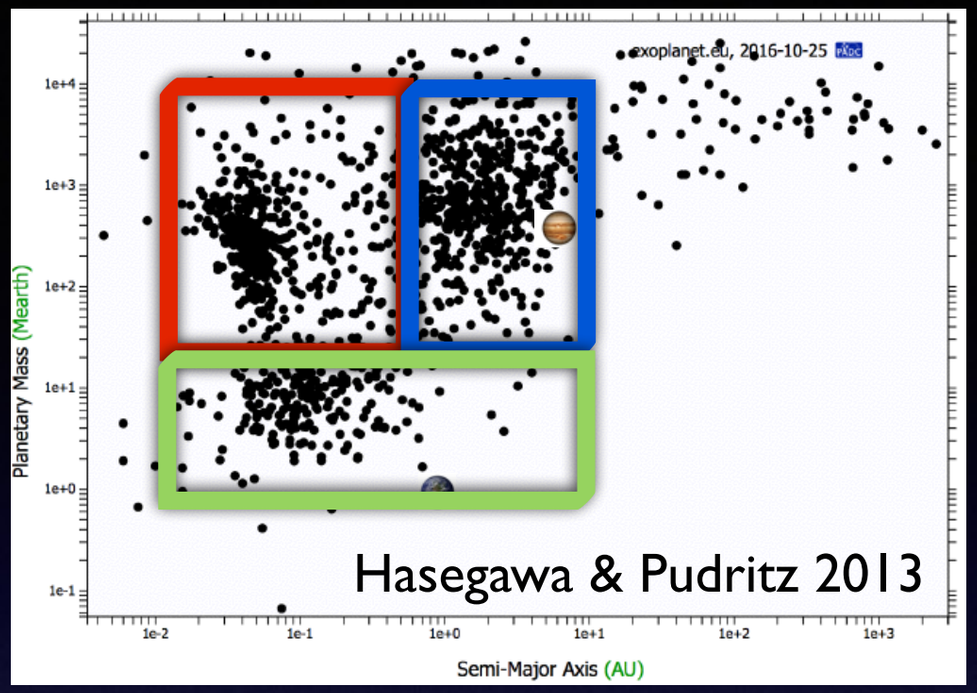
Partition the diagram

Calculate planet formation frequencies (PFFs)

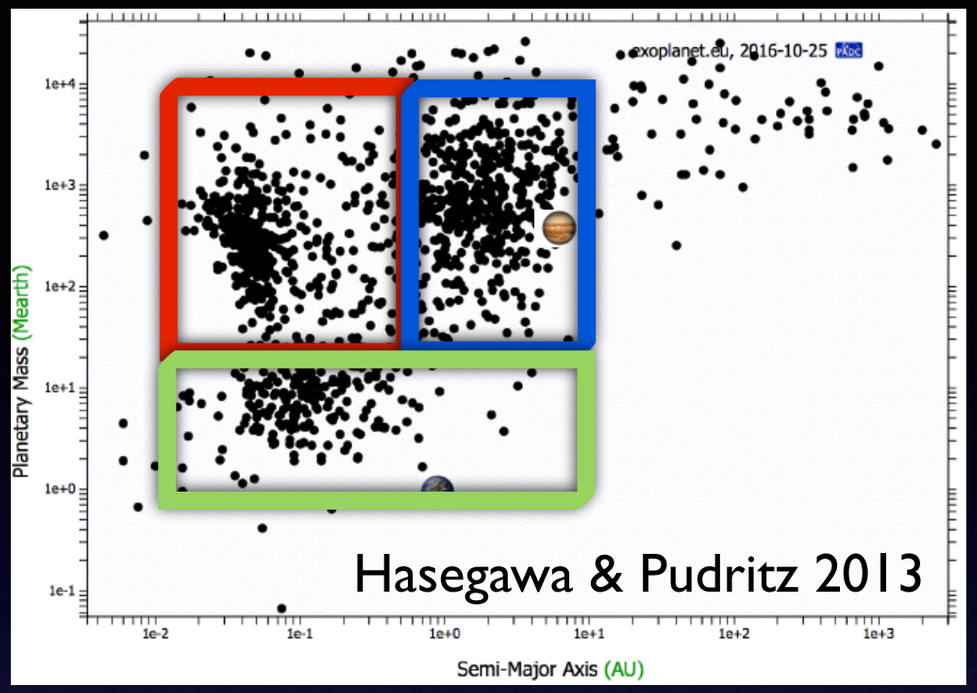
$$PFFs \equiv \sum_{\eta_{acc}} \sum_{\eta_{dep}} \frac{N(\eta_{acc}, \eta_{dep})}{N_{int}}$$

$$\times w_{mass}(\eta_{acc}) w_{lifetime}(\eta_{dep})$$

Weight functions related to disk observations



	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	~ 10.6 %	~ 24 .4%	~ 14.2 %	49.2%
Dead zone	~ 5.5 %	~ 12 %	~ 7.1 %	24.6%
Ice line	~ 4.9 %	~ 11 %	~ 0.5%	16.4%
Heat transition	~ 0.2 %	~ 1.4 %	~ 6.6%	8.2%



reproduce the trend of massive planets

	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
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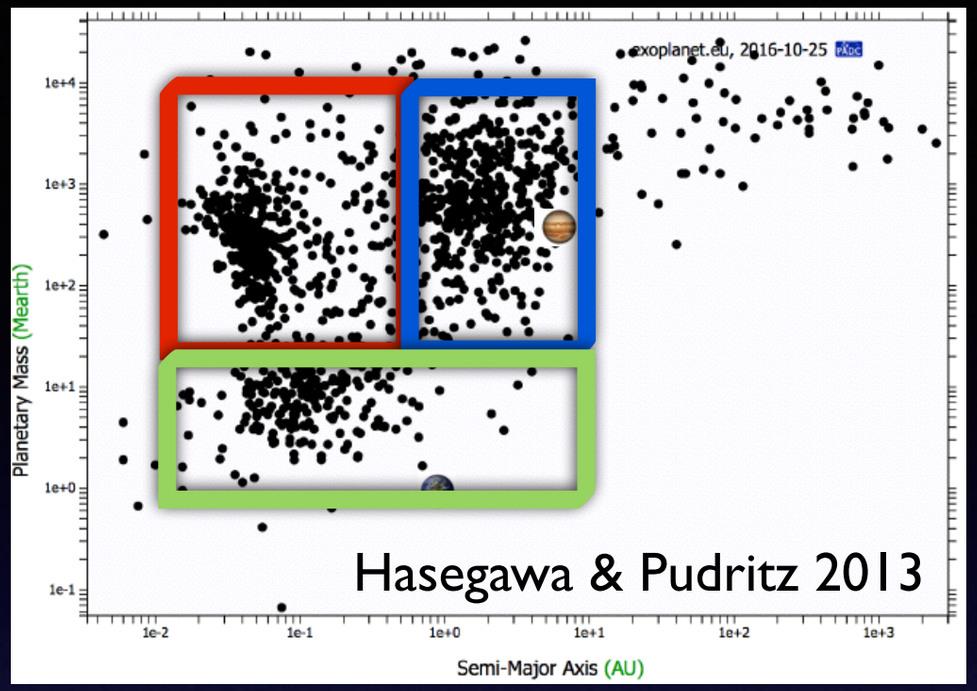

reproduce the trend of massive planets

Hot Jupiters form equally at dead zone & ice line traps

	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	~ 10.6 %	~ 24 .4%	~ 14.2 %	49.2%
Dead zone	~ 5.5 %	~ 12 %	~ 7.1 %	24.6%
Ice line	~ 4.9 %	~ 11 %	~ 0.5%	16.4%
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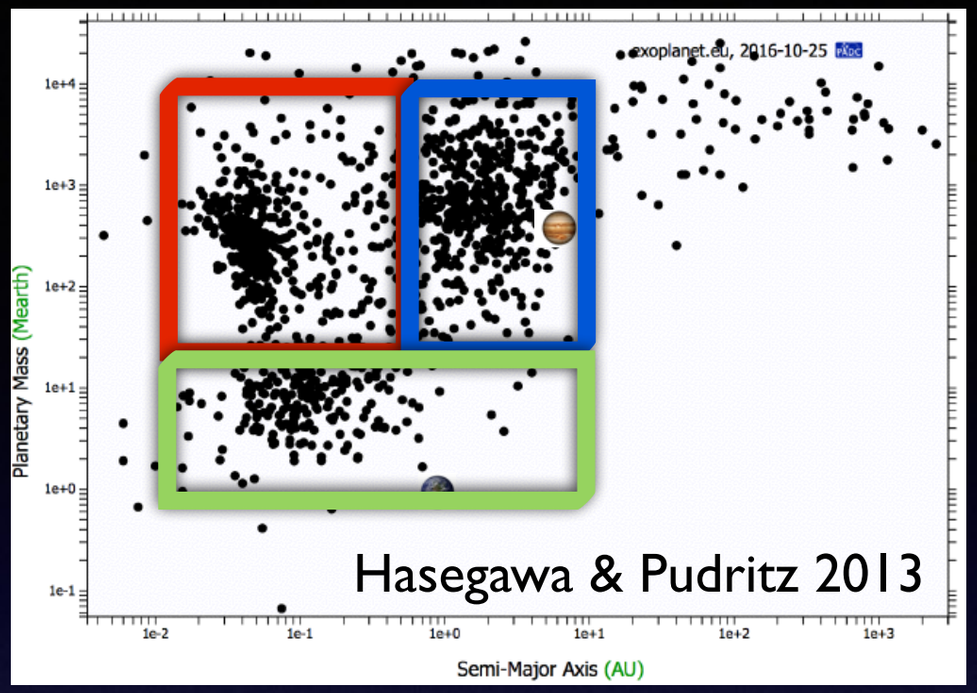

reproduce the trend of massive planets

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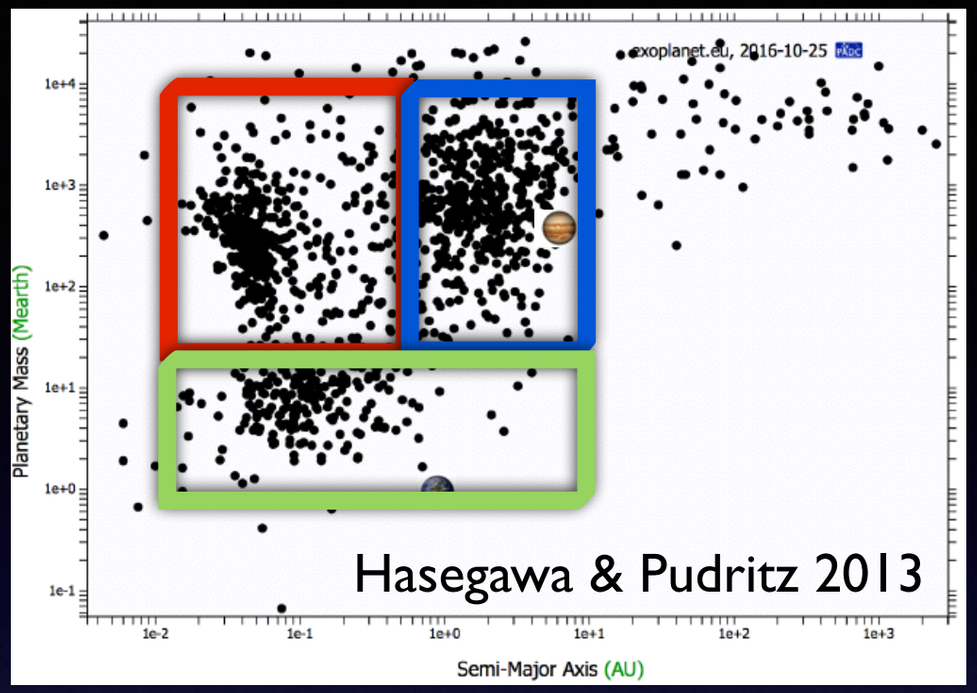

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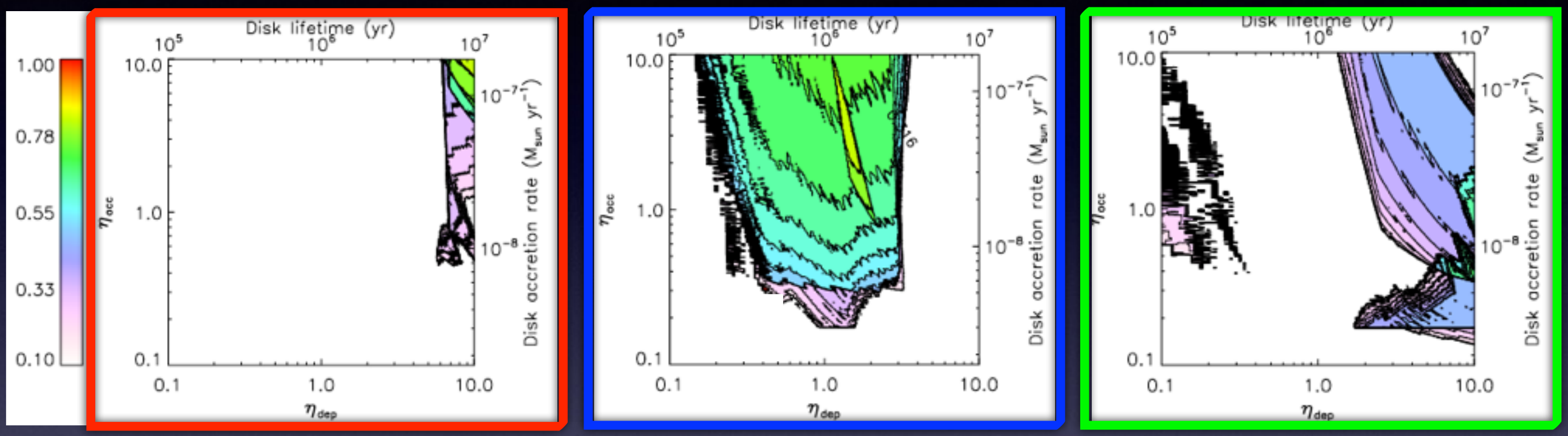


Long-lived, massive disks are needed for **Hot Jupiters**

A wide range of disk parameters end up with **Exo-Jupiters**

Long-lived disks generate **Super-Earths**

The general trends are the same for a wide range of parameters

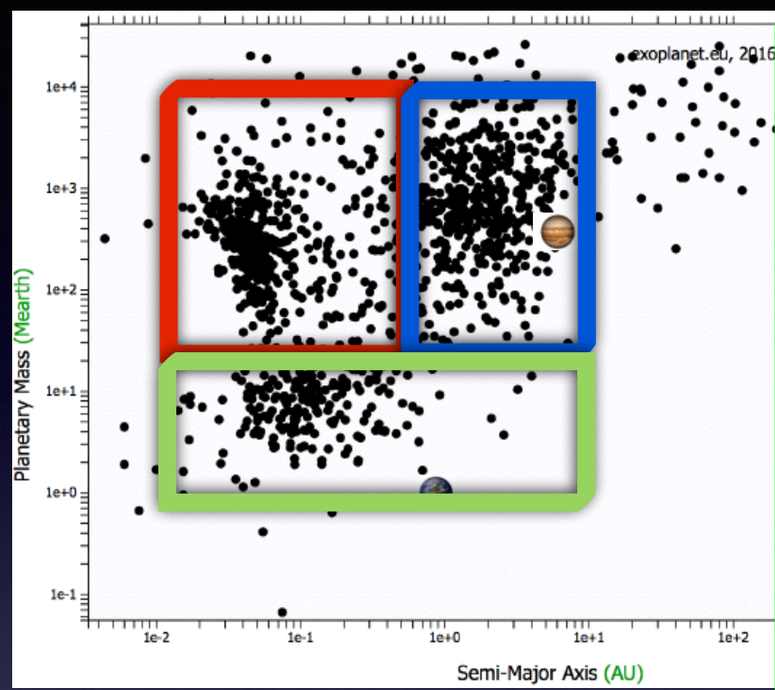
Hasegawa & Pudritz 2013

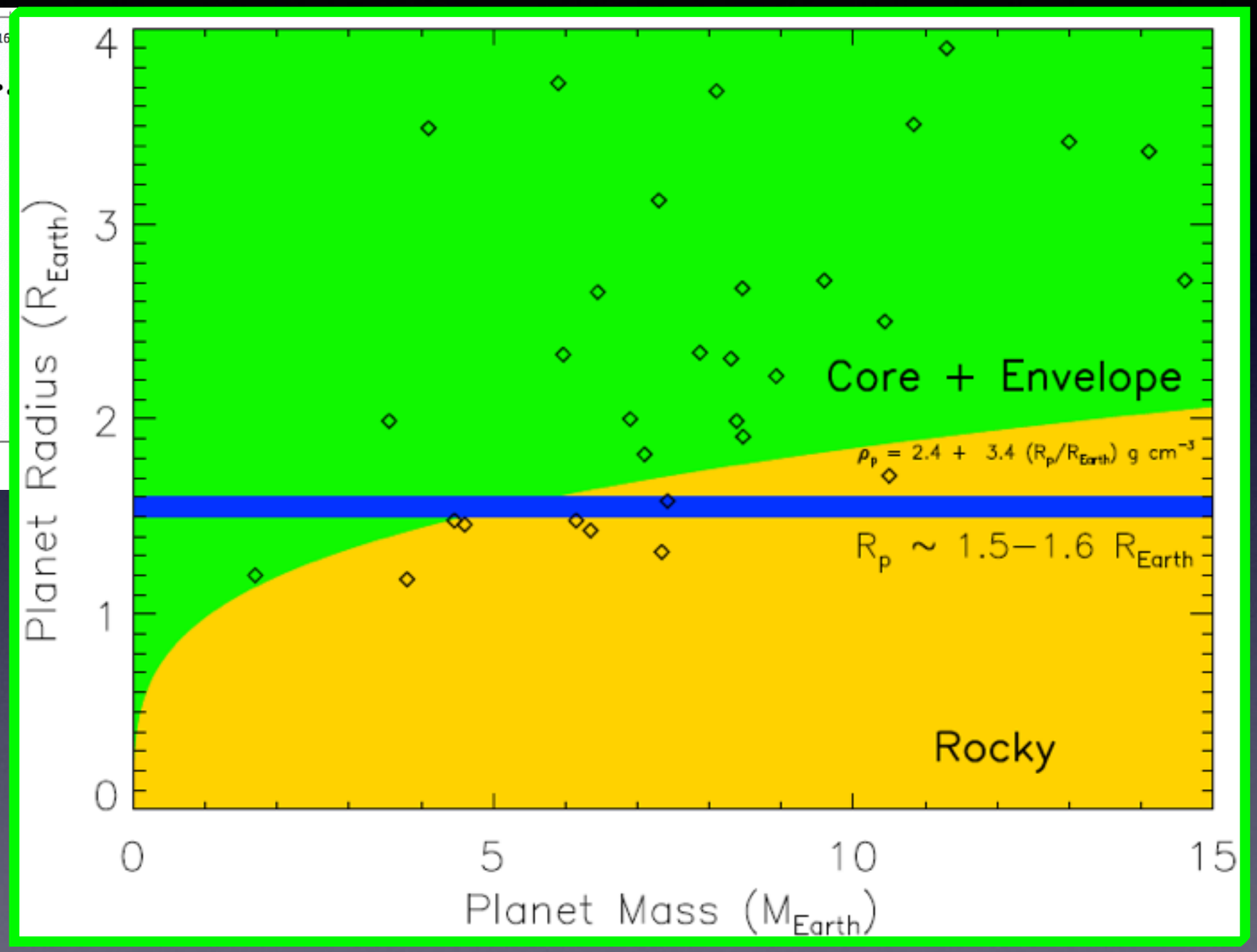
Result 2:

the Mass-Radius Diagram for Observed Close-in Super-Earths

Hasegawa 2016, ApJ (accepted; arXiv:1609.04798)

The Mass-Radius Diagram for observed close-in super-Earths





Planets w/ > 1.5 - 1.6 Re

: not purely rocky

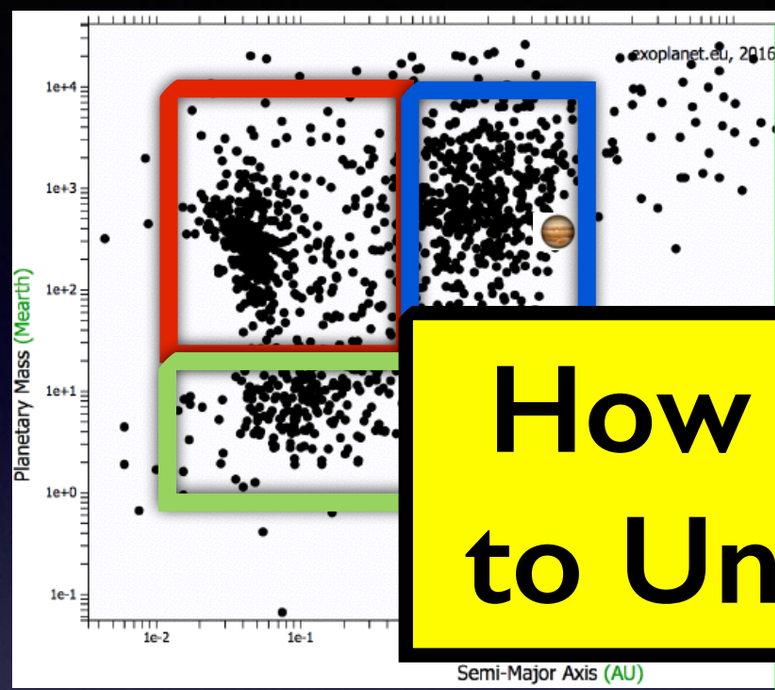
Planets w/ < 1.5 - 1.6 Re

: likely to be purely rocky

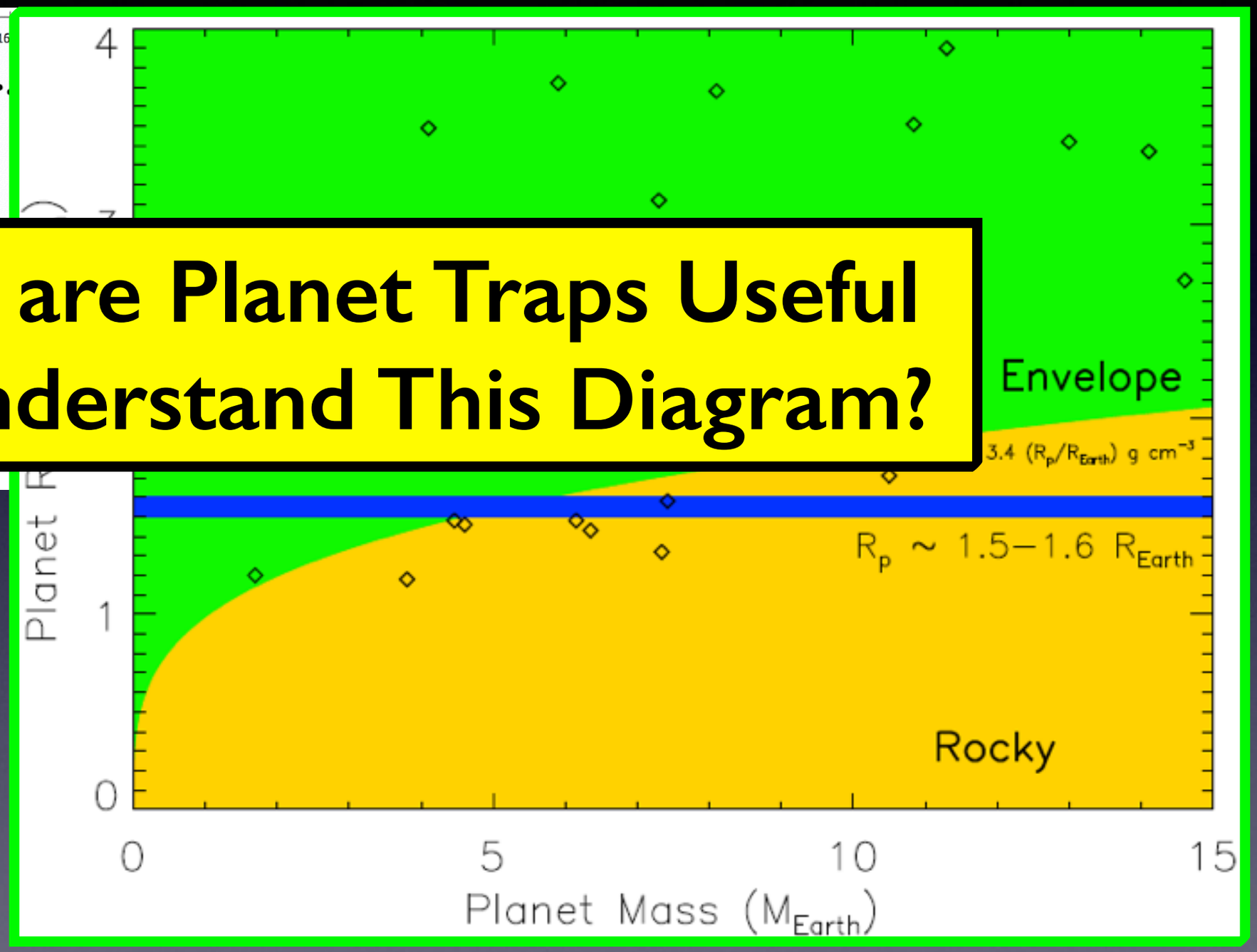
Sub-set of samples from Weiss & Marcy 2014 (mass measurements better than 2-sigma)

e.g., Weiss & Marcy 2014, Marcy et al 2014, Rogers 2014, Wolfgang & Lopez 2014

The Mass-Radius Diagram for observed close-in super-Earths



How are Planet Traps Useful to Understand This Diagram?



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Hasegawa 2016

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A considerable fraction of observed super-Earths may be formed as failed cores of gas giants (mini-gas giants)

Hasegawa 2016

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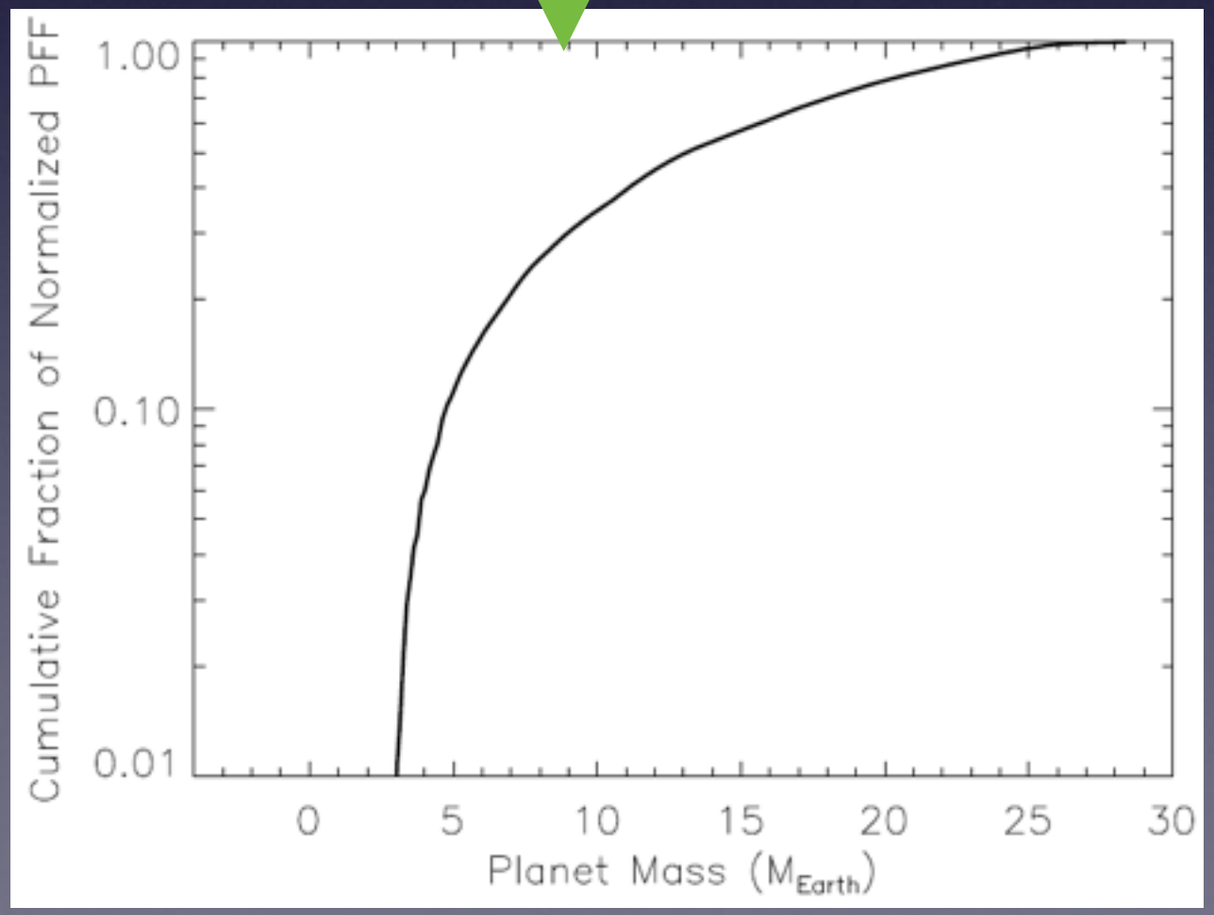

Hasegawa 2016

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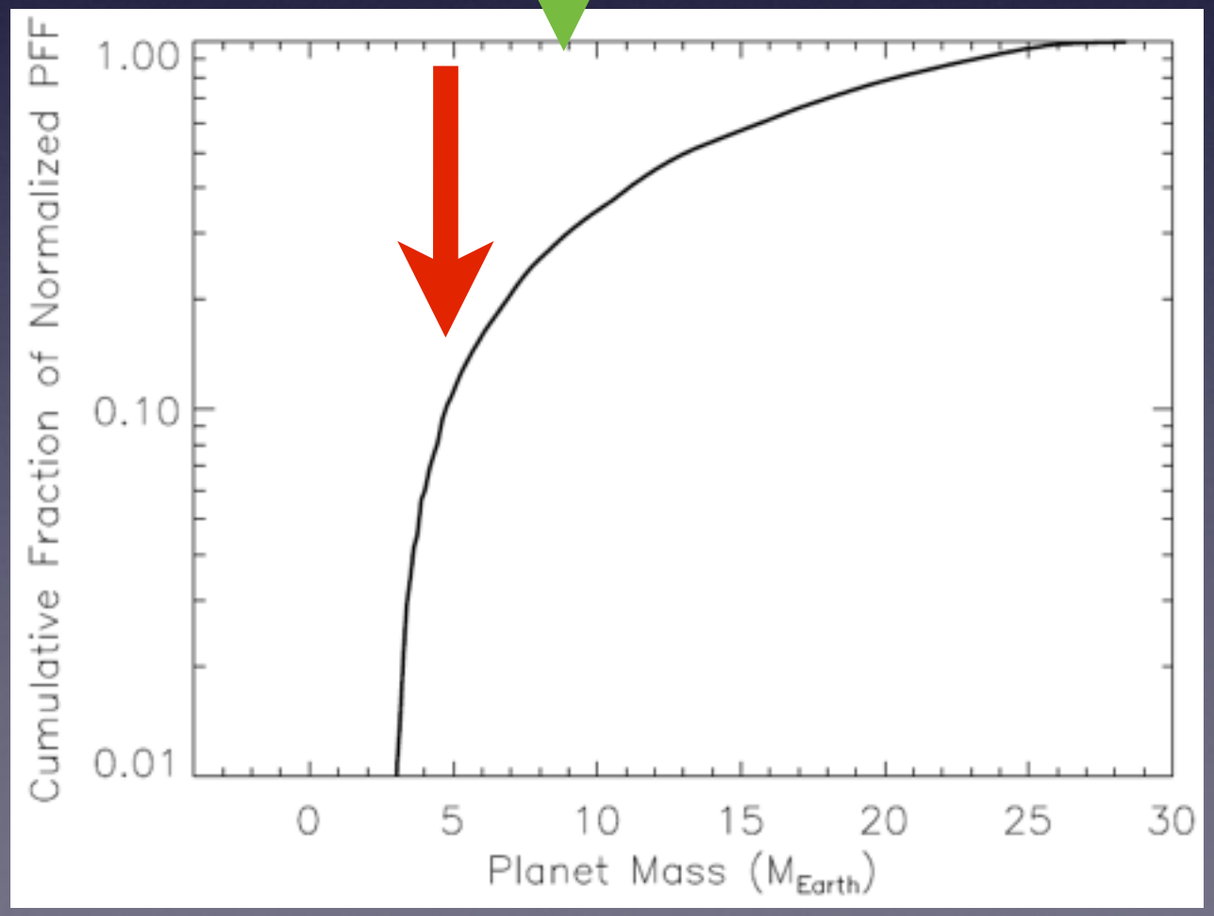
The minimum mass of planets formed by core accretion at planet traps:

$$M_{min}^{CA} \simeq 4 - 5 M_\oplus$$



Why $M_{min}^{CA} \simeq 4 - 5 M_{\oplus}$??

Hasegawa 2016

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Hasegawa 2016

1) photoevaporative mass loss of planets

Why $M_{min}^{CA} \simeq 4 - 5 M_{\oplus}$??

Hasegawa 2016

1) photoevaporative mass loss of planets

=> No, for our model, since it is NOT included yet

Why $M_{min}^{CA} \simeq 4 - 5 M_{\oplus}$??

Hasegawa 2016

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

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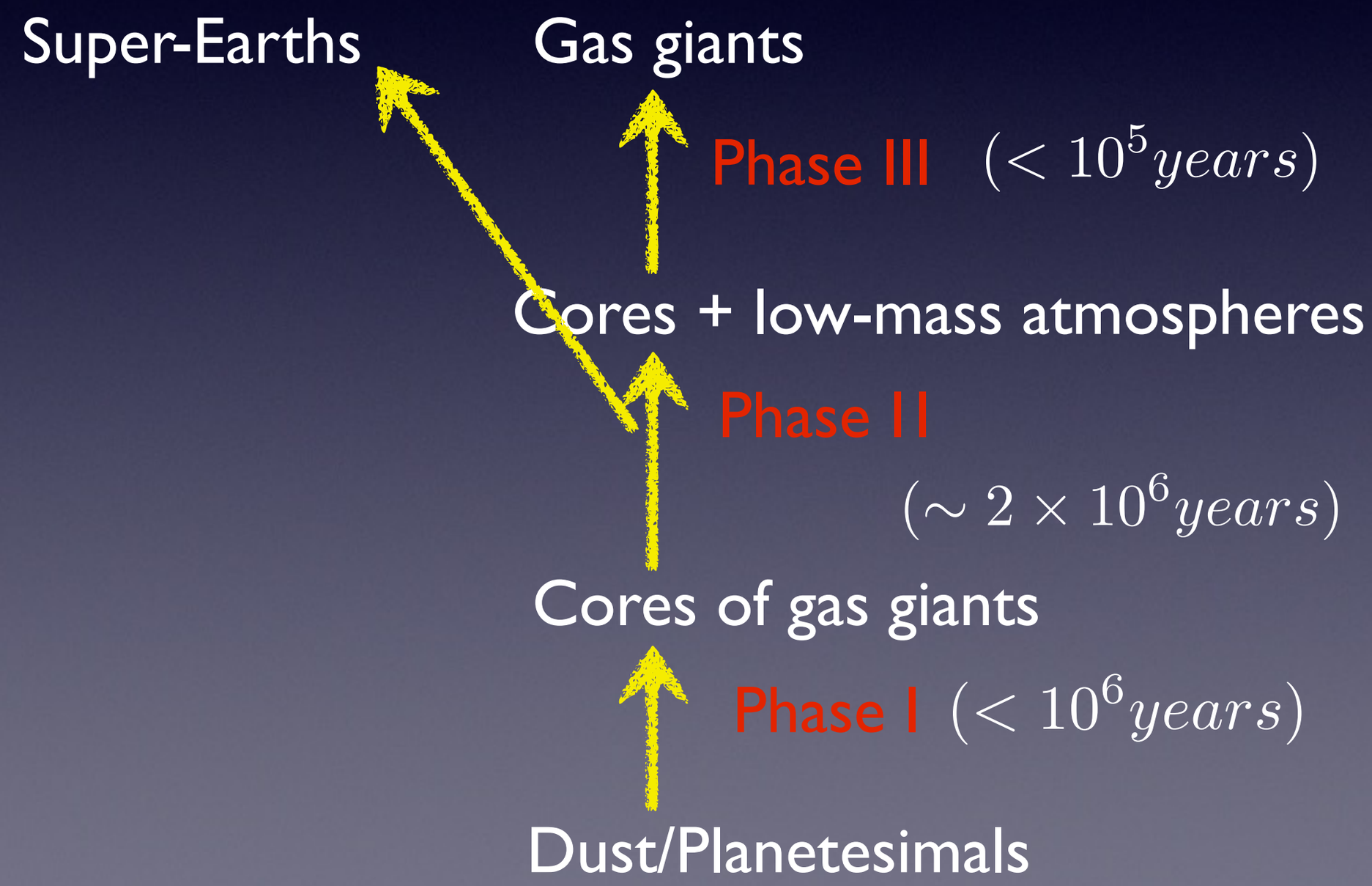

Why $M_{min}^{CA} \simeq 4 - 5 M_\oplus$??

Hasegawa 2016

1) photoevaporative mass loss of planets

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Super-Earths Gas giants

$$M_c > M_{c,crit0} \left(\frac{\dot{M}_c}{10^{-6} M_\oplus yr^{-1}} \right)^{1/4}$$

$M_{c,crit0}$: Parameter

$\sim 10 M_\oplus$ for the canonical case

$< 10 M_\oplus$ when dust grains grow in atmospheres

Phase III $(< 10^5 years)$

Cores + low-mass atmospheres

Phase II

$(\sim 2 \times 10^6 years)$

Cores of gas giants

Phase I $(< 10^6 years)$

Dust/Planetesimals

Why $M_{min}^{CA} \simeq 4 - 5M_\oplus$??

Hasegawa 2016

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

$M_{c,crit0}$	$3M_\oplus$	$5M_\oplus$	$10M_\oplus$
M_{min}^{CA}			

Why $M_{min}^{CA} \simeq 4 - 5M_\oplus$??

Hasegawa 2016

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

$M_{c,crit0}$	$3M_\oplus$	$5M_\oplus$	$10M_\oplus$
M_{min}^{CA}	$3.9M_\oplus$	$5M_\oplus$	$4.6M_\oplus$

=> No, M_{min}^{CA} is very insensitive to the critical core mass

Why $M_{min}^{CA} \simeq 4 - 5 M_{\oplus}$??

Hasegawa 2016

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

3) planetary migration in gas disks

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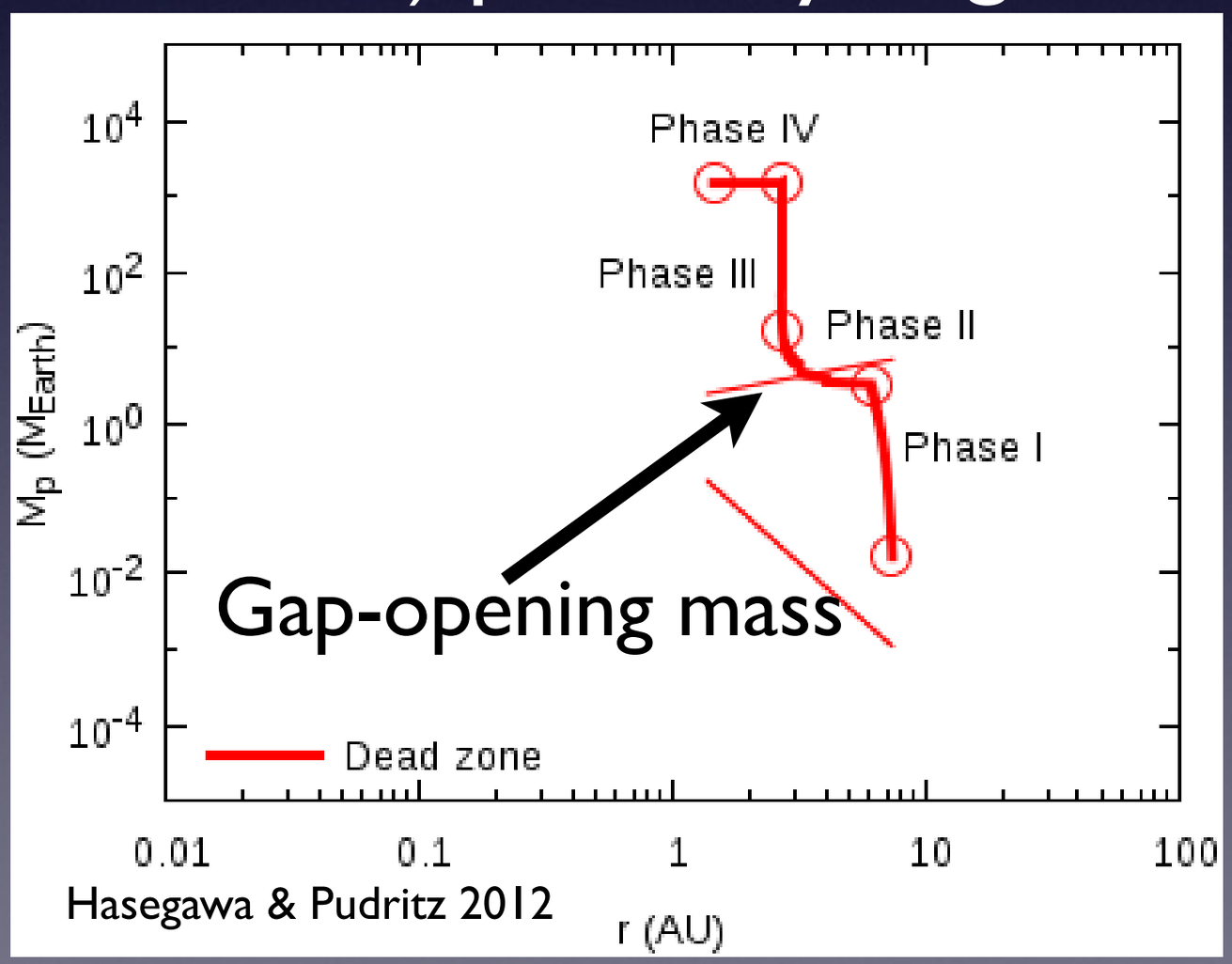

Hasegawa & Pudritz 2012

Two kinds of migration in our model

Planet traps

: transport forming cores from large radii to >1 AU

Type II migration

: transport cores with atmospheres from > 1 AU to < 1 AU

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Hasegawa 2016

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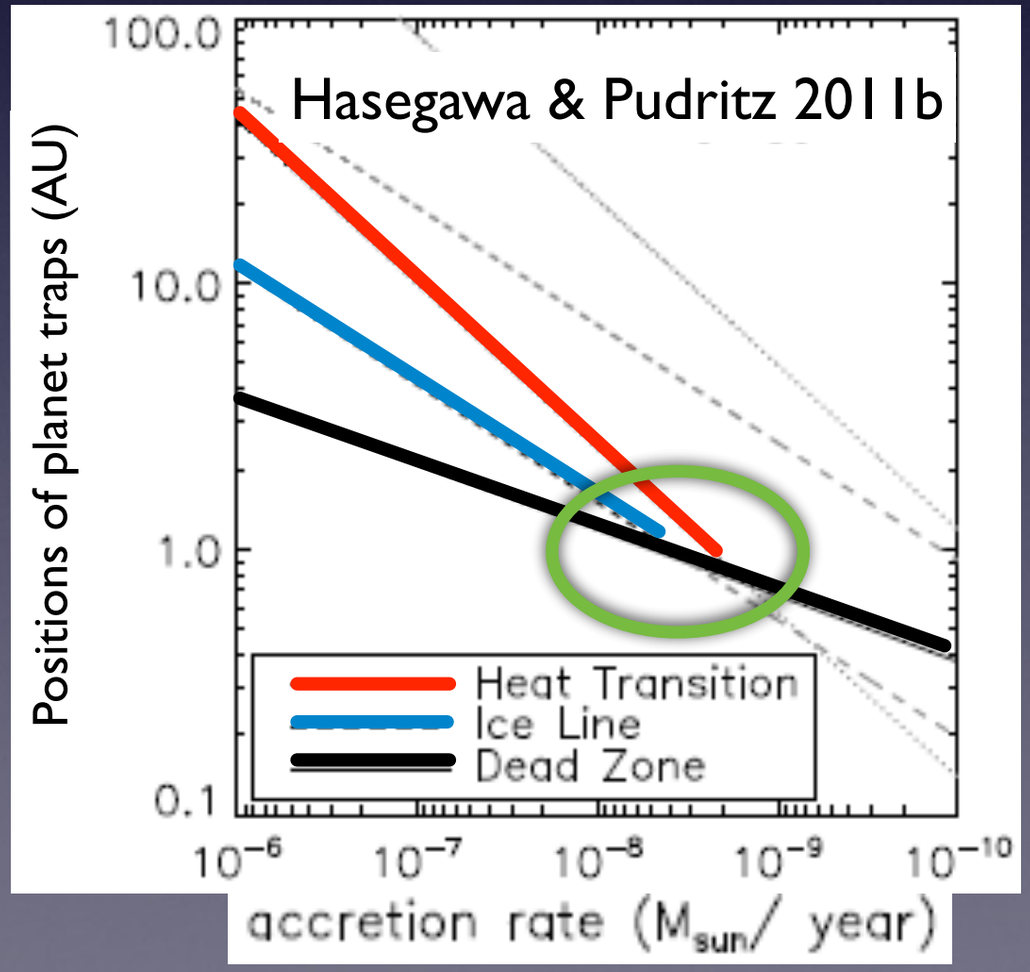

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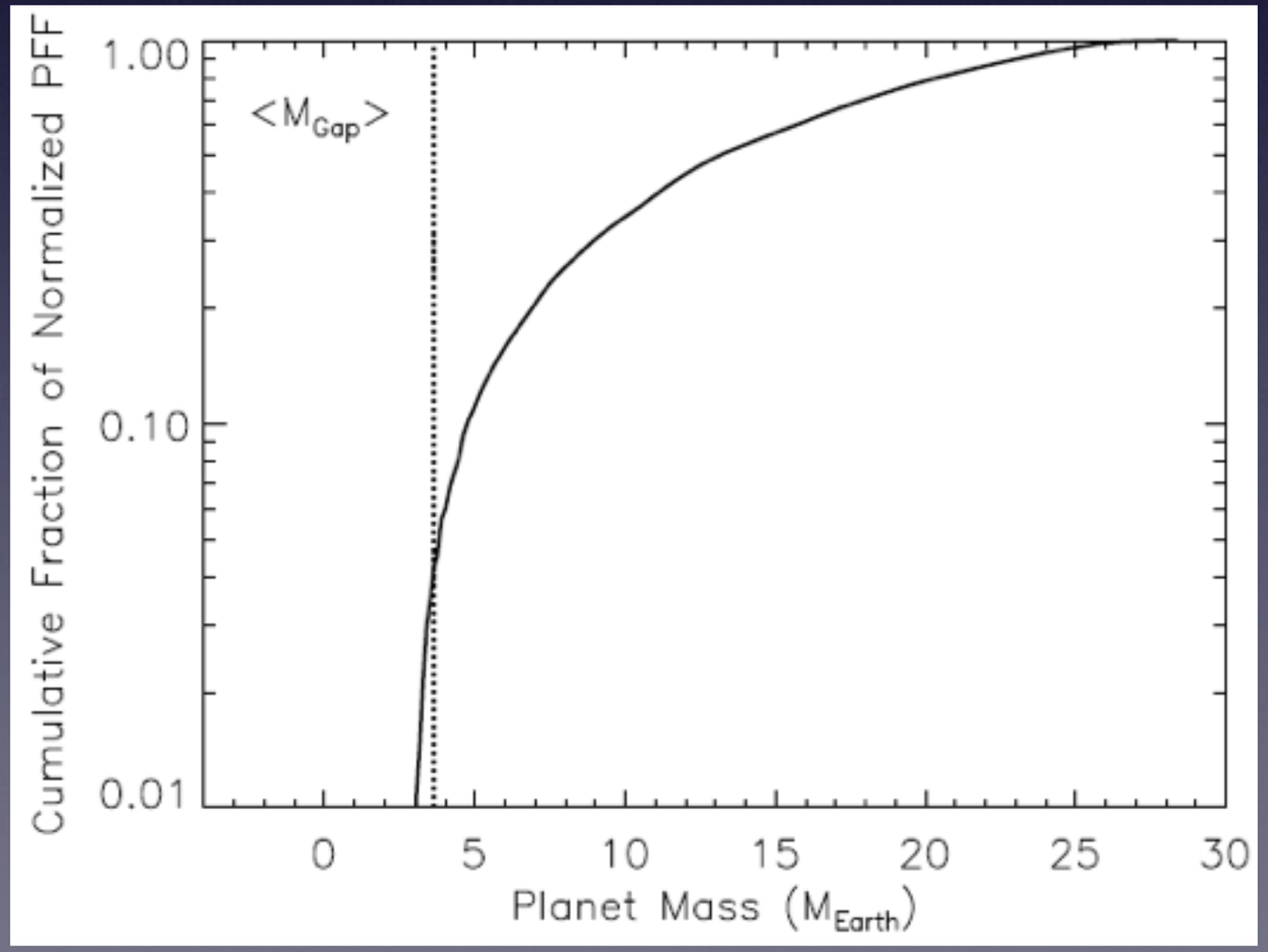
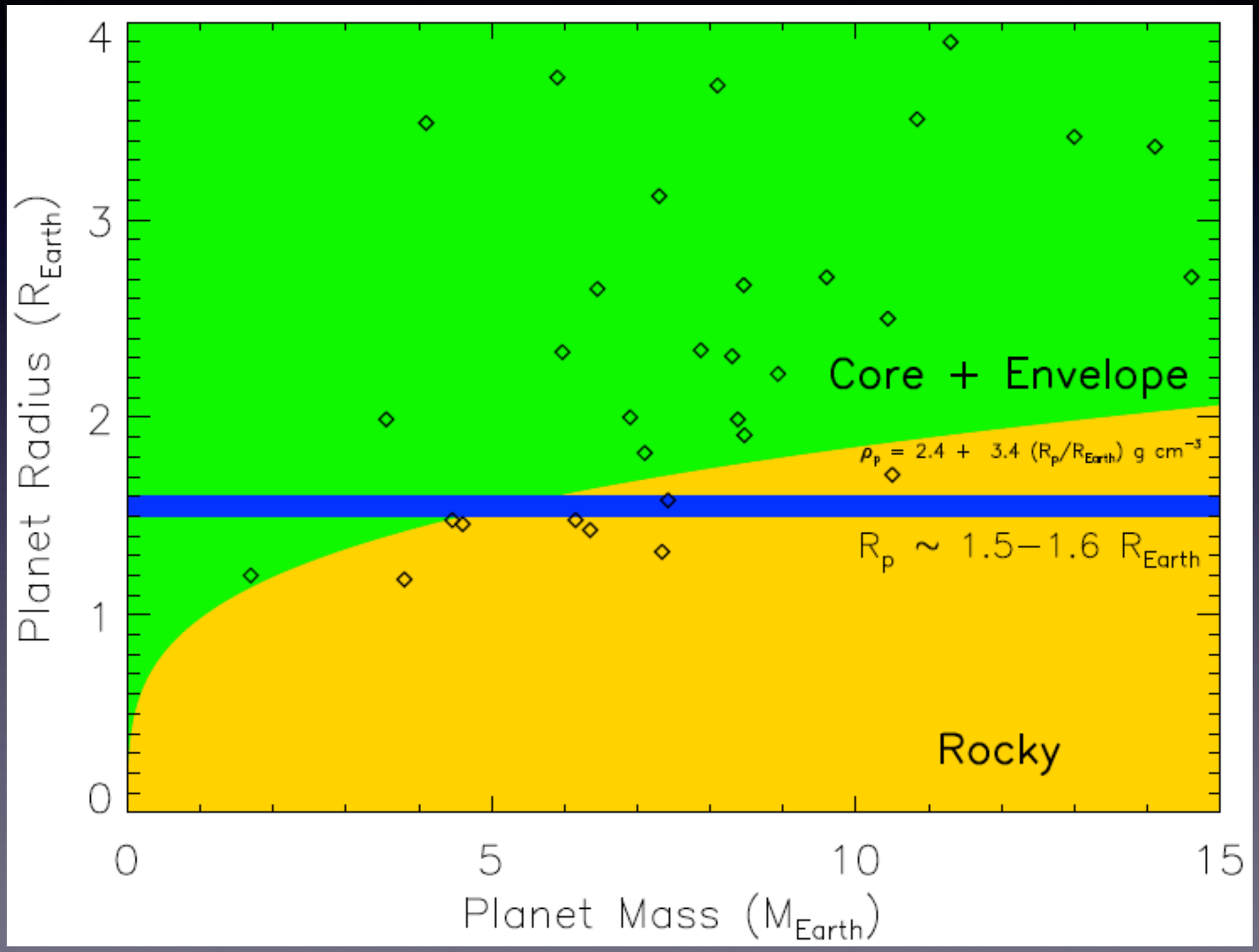
$< M_{Gap} >$

= the mean value of the gap-opening mass of planets which end up in the low-mass regime



Implication for the Mass-Radius Diagram

Hasegawa 2016



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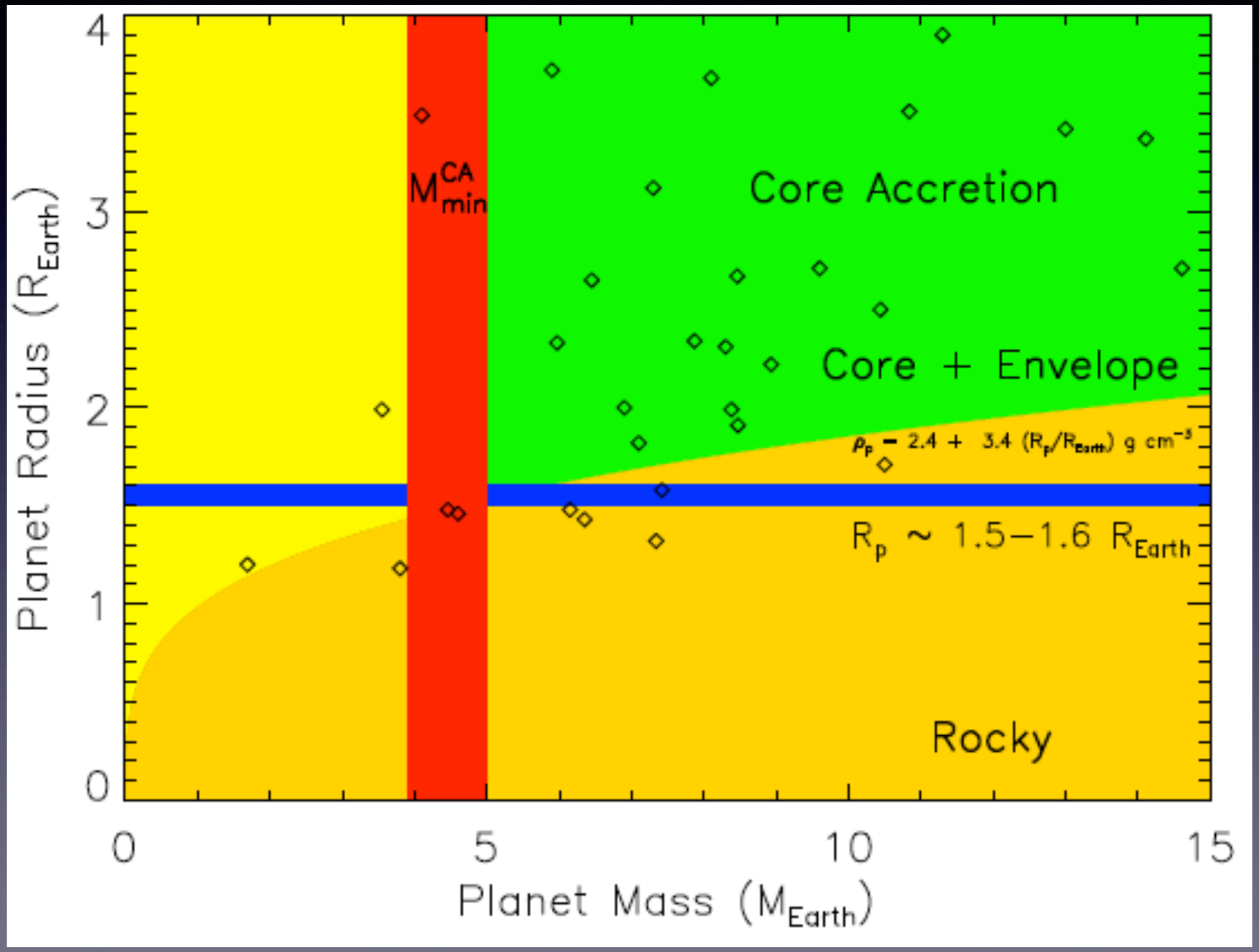

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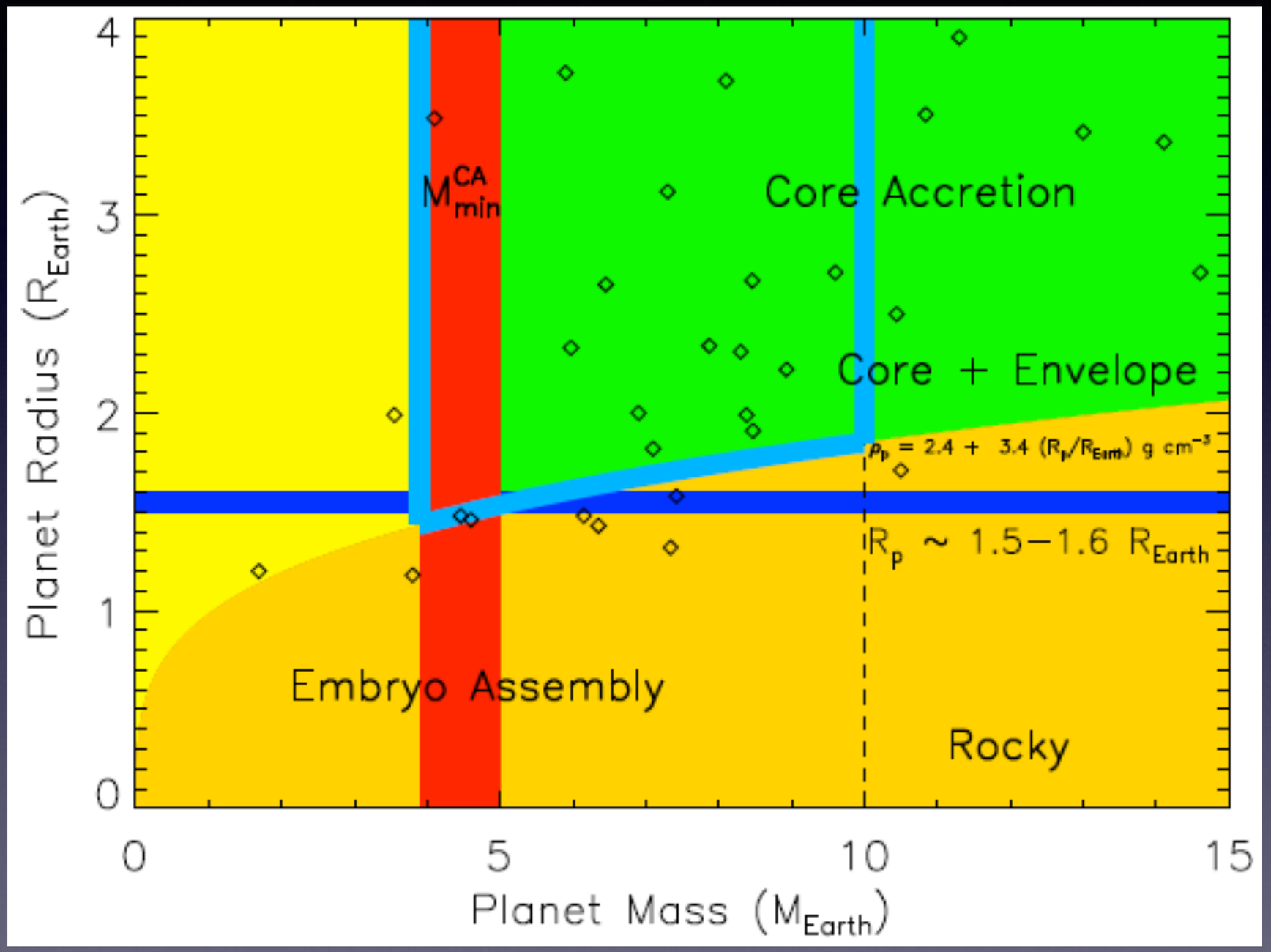
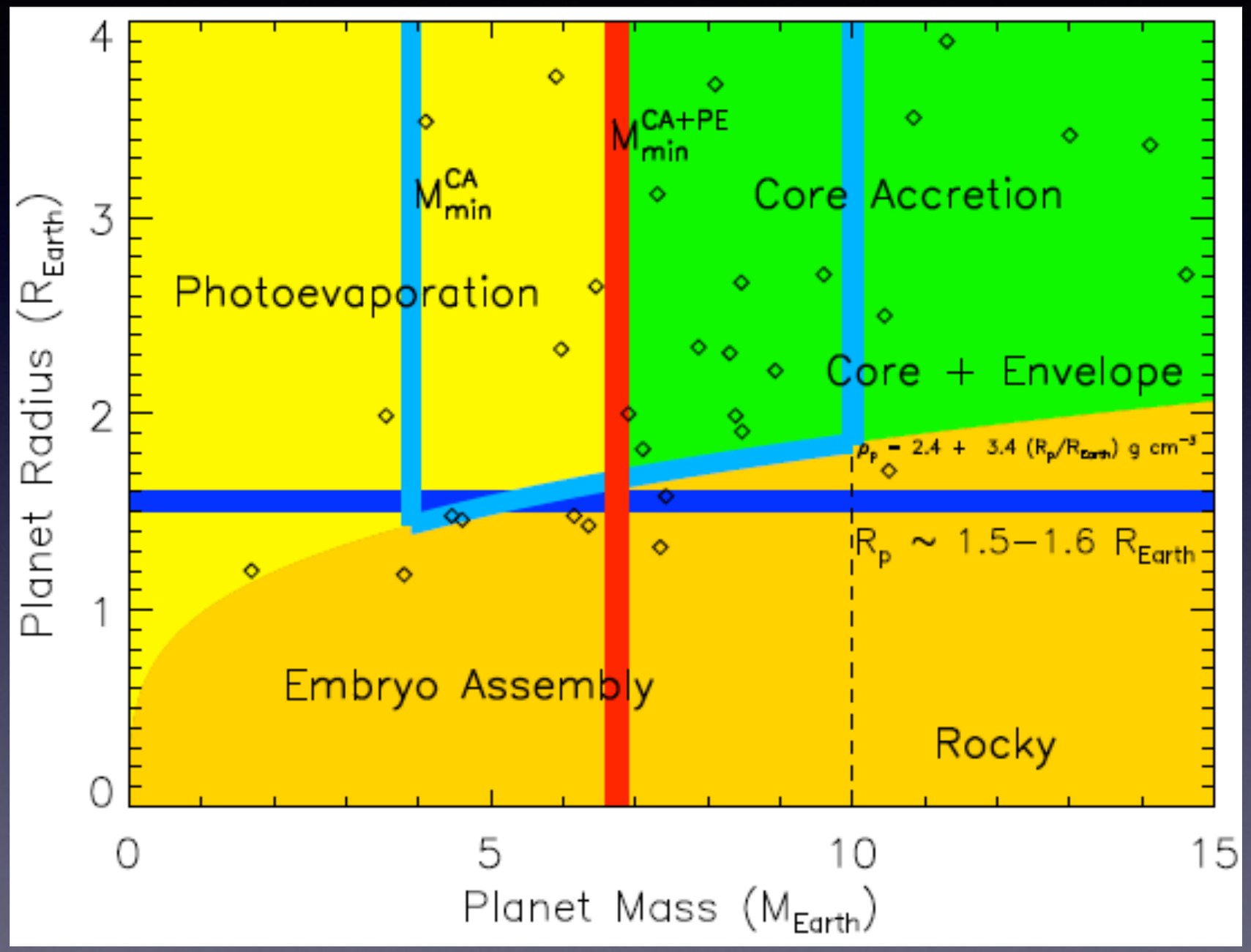


Embryo assembly scenario (in situ formation) can form planets with < 10 M_Earth

e.g., Ogihara & Ida 2009, Hansen & Murray 2013

Implication for the Mass-Radius Diagram

Hasegawa 2016

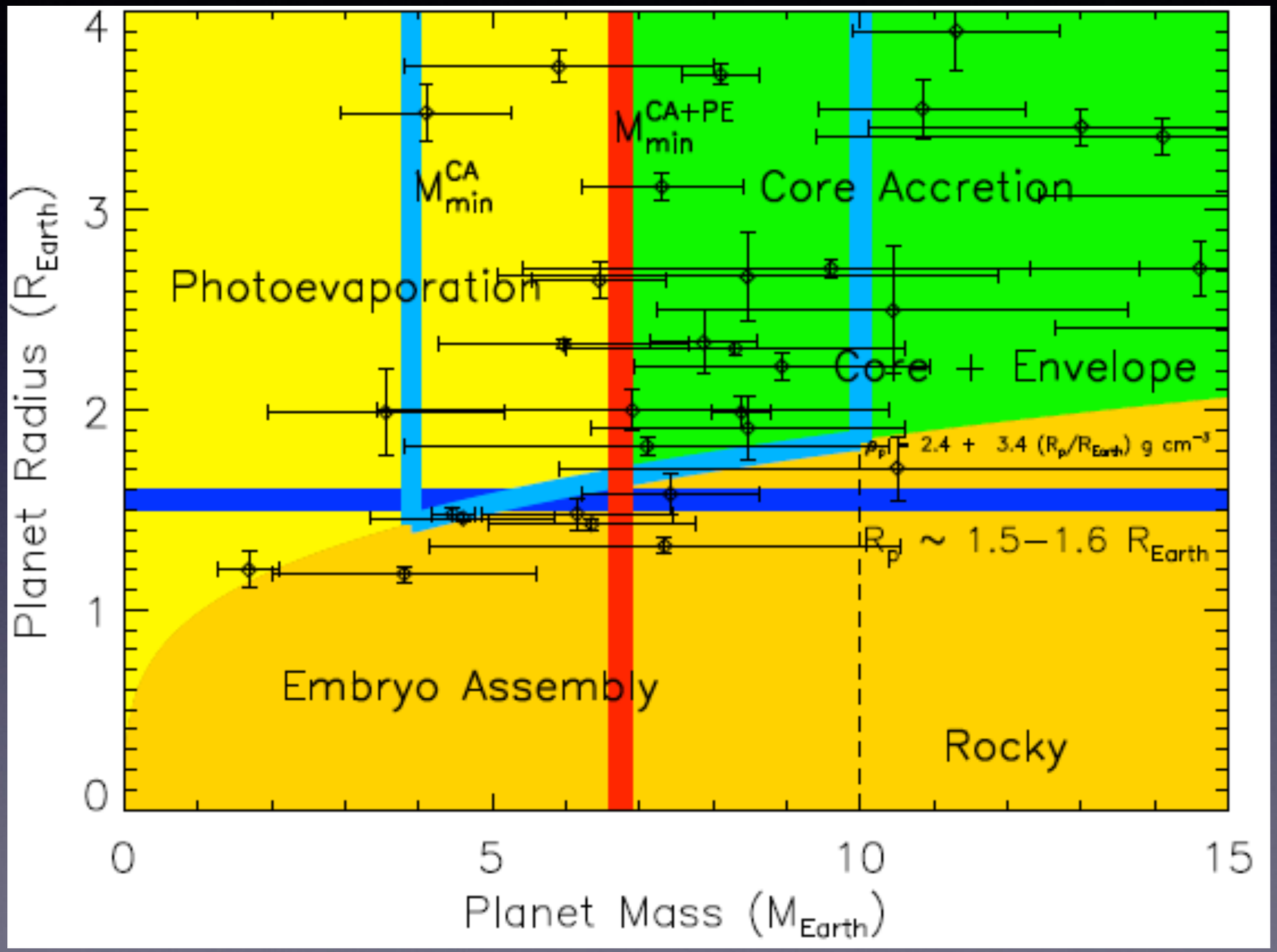


Inclusion of photoevaporative mass loss from planets

Lopez & Fortney 2013

Exoplanet "Phase" Diagram

Hasegawa 2016



Summary

- The currently observed exoplanetary populations are quite different from that of the solar system
- Planetary migration or the resultant planet traps can play an important role in regulating the orbital distribution of planets
- computed the position of 3 types of traps (dead zone, ice line, heat transition) that evolves with time
- calculated evolutionary tracks of planets formed at these traps & investigated the resultant orbital distribution of planets - the trend of observed massive exoplanets is well reproduced
- switching of migration modes determines the minimum mass of super-Earths formed by our model, which is $M_p > 4\text{-}5\ M_{Earth}$, & the mass-radius diagram can serve as an Exoplanet "phase" diagram