Planet Traps
& Super-Earths

: Origins of the Planet-Metallicity Relation

& Implications for the Mass-Radius Diagram

Yasuhiro Hasegawa (EACOA fellow @ ASIAA / NAOJ)

Ralph Pudritz (McMaster Univ.)

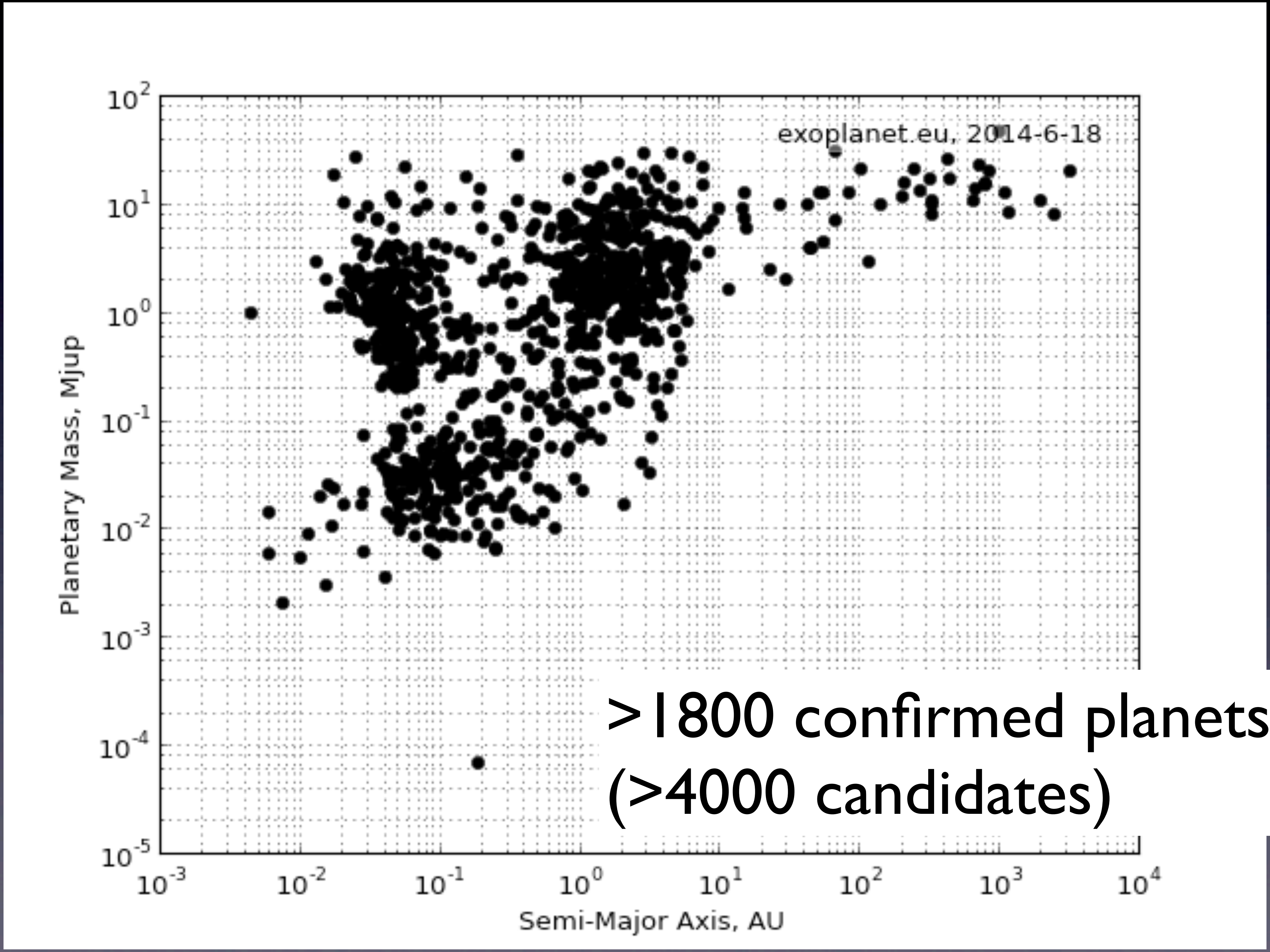
Planet Traps & Super-Earths

: Origins of the Planet-Metallicity Relation
=> see arXiv:1408.1841 (accepted by ApJ)

& Implications for the Mass-Radius Diagram

Yasuhiro Hasegawa (EACOA fellow @ ASIAA / NAOJ)

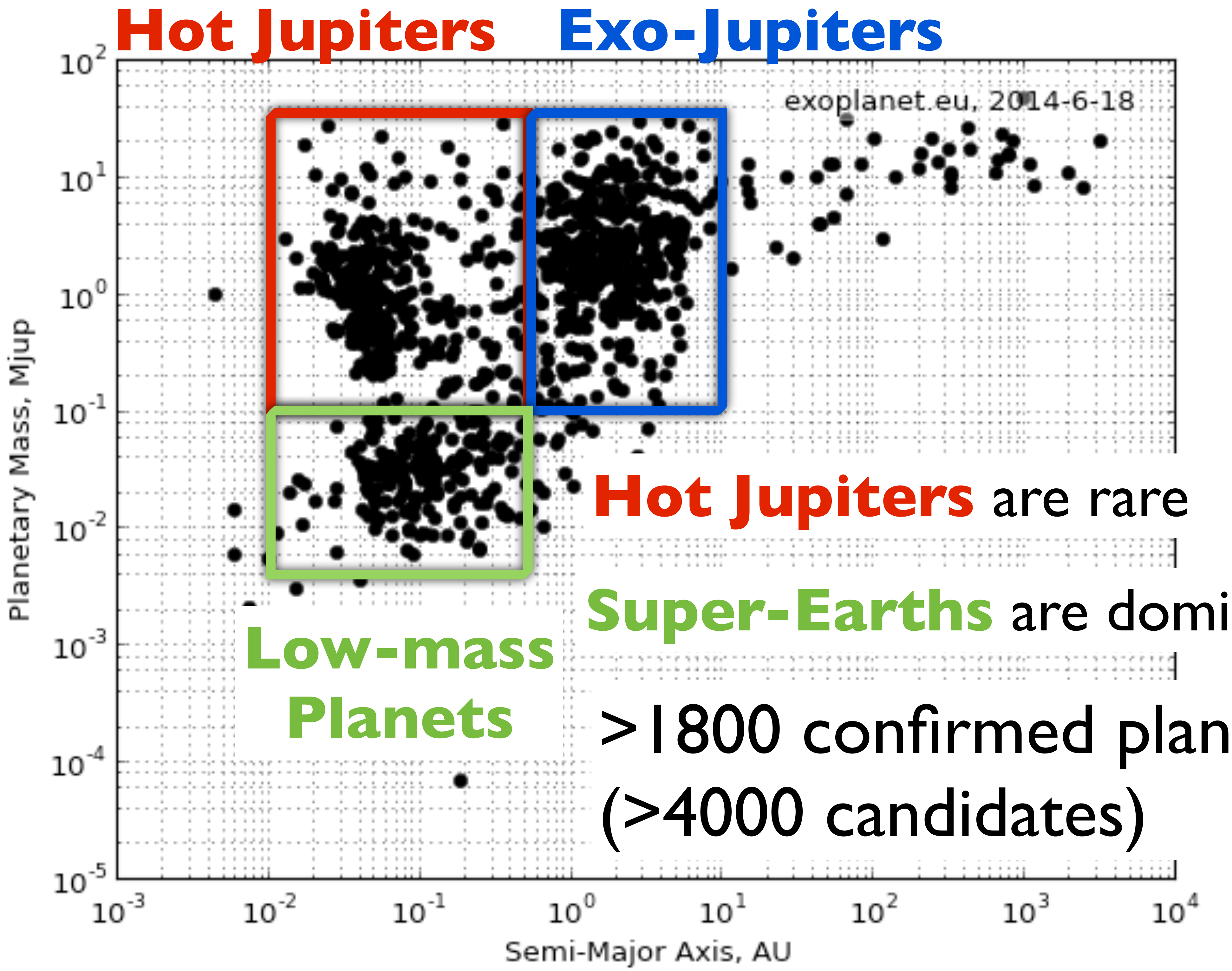
Mass-Semimajor Axis Diagram



>1800 confirmed planets
(>4000 candidates)

Distinct Populations

Chiang & Laughlin 2013, Hasegawa & Pudritz 2013, 2014



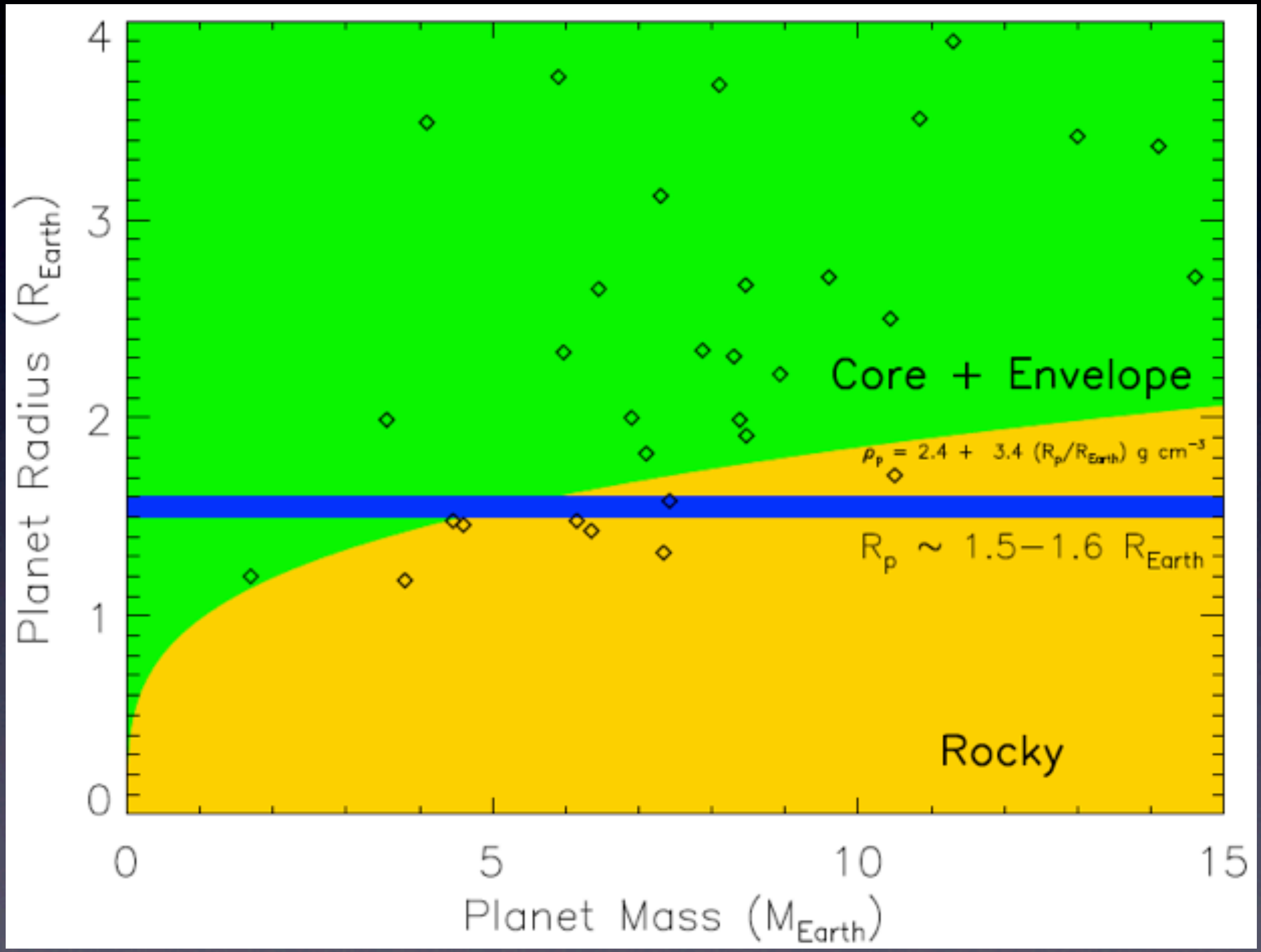
Hot Jupiters are rare

Super-Earths are dominant

>1800 confirmed planets
(>4000 candidates)

Mass-Radius Diagram

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



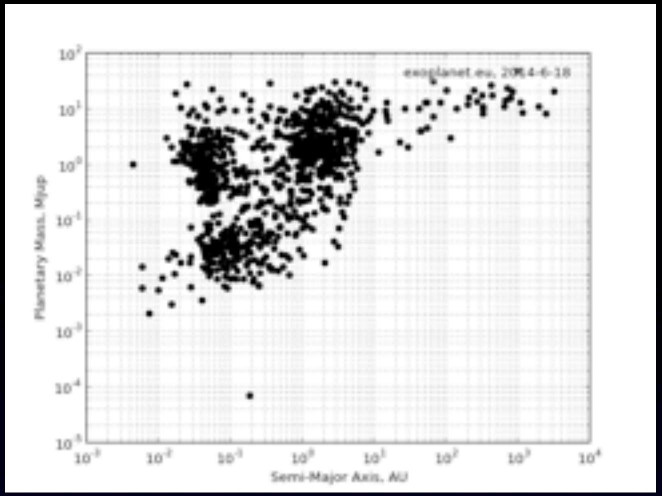
Planets w/
> 1.5 - 1.6 Re

: not purely rocky

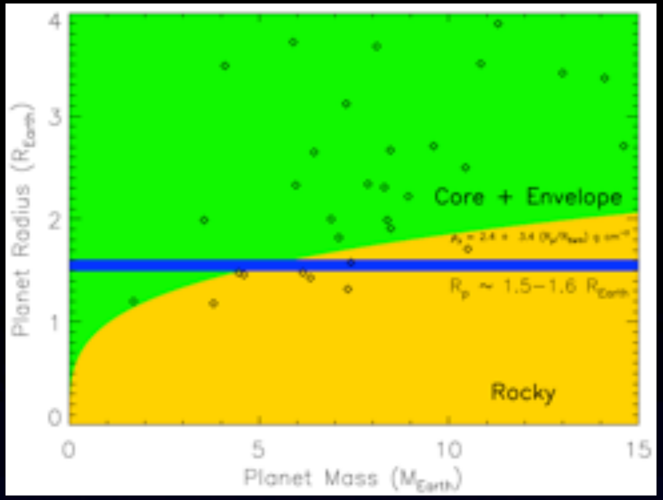
Planets w/
< 1.5 - 1.6 Re

: likely to be purely rocky

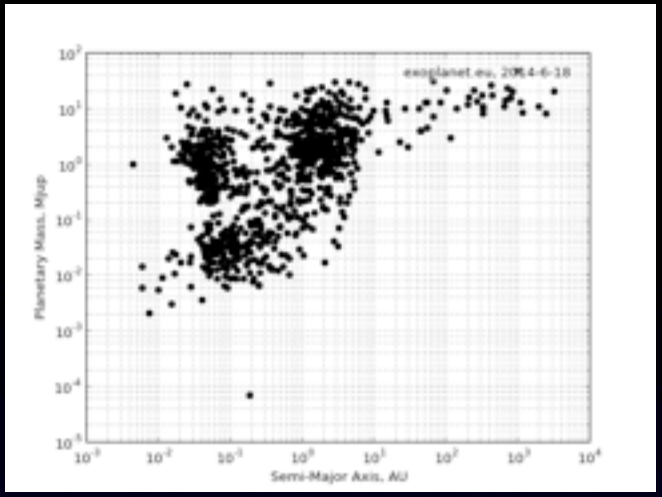
Sub-set of samples from Weiss & Marcy 2014
(mass measurements better than 2-sigma)



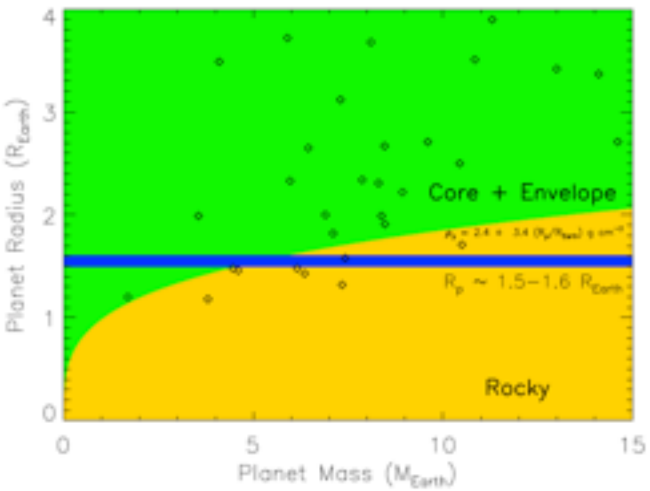
+



Derived invaluable constraints on
the formation and evolution of planetary systems



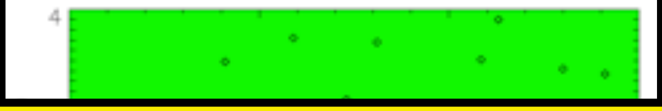
+



Derived invaluable constraints on the formation and evolution of planetary systems

↑

Provide a physical explanation, using theoretical models



In reality, it is still difficult...

e.g., Mordasini et al 2012, Ida et al 2013, Hansen & Murray 2013, Chiang & Laughlin 2013

1) many processes are involved:

formation, migration, disk evolution, dynamics,
photoevaporative mass loss, & etc...

1) unclear formation mechanisms:

a scaled-up version of rocky planet formation
vs
a scaled-down version of gas giant formation

Planet traps + core accretion can simplify a picture of planet formation in gas disks

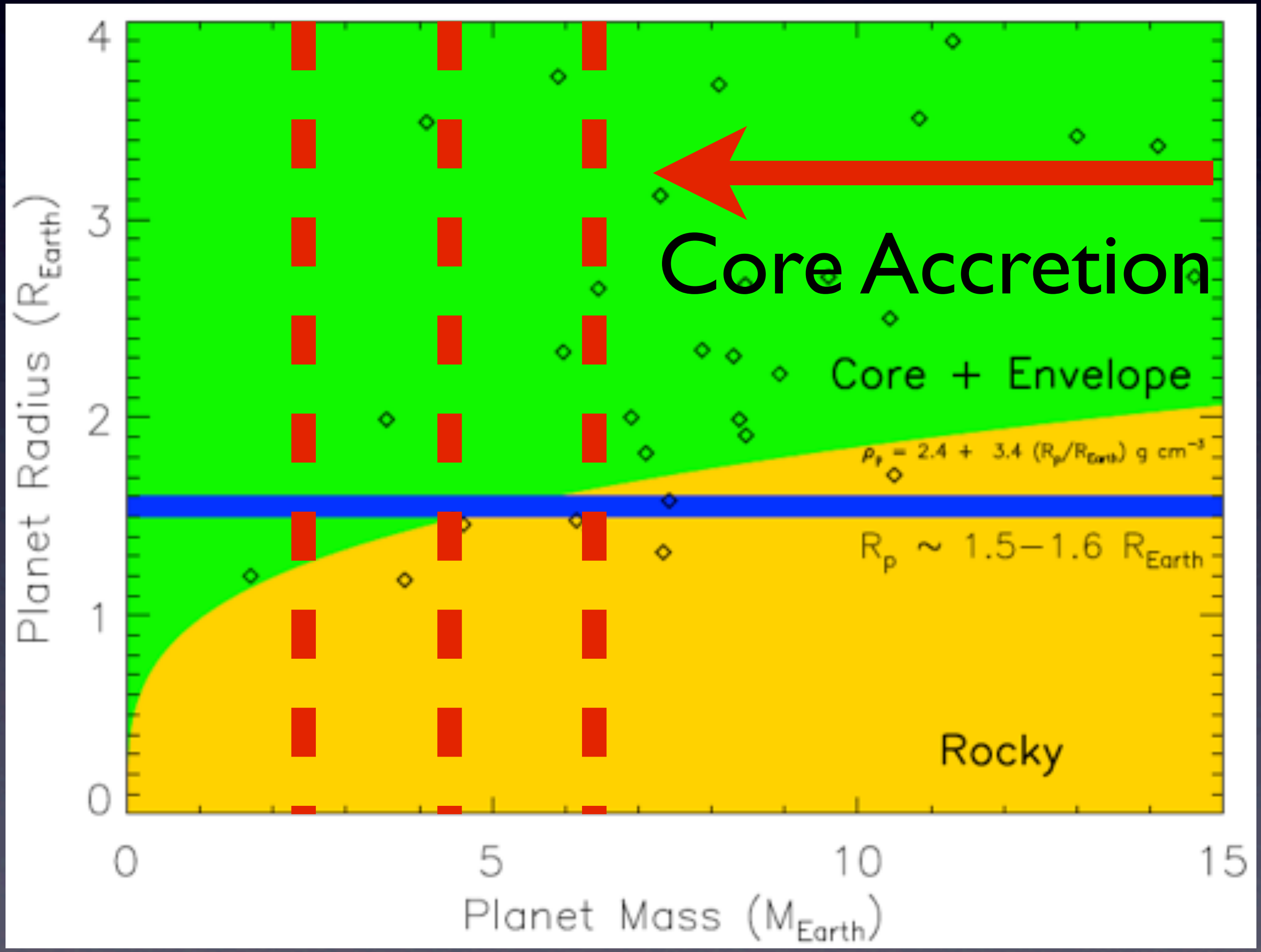
Step 1: planet traps - direct connection with
disk evolution

Step 2: evolutionary tracks of forming planets
at planet traps

Step 3: planet formation frequencies (PFFs) -
our version of population synthesis calculations

Failed Core Scenario:

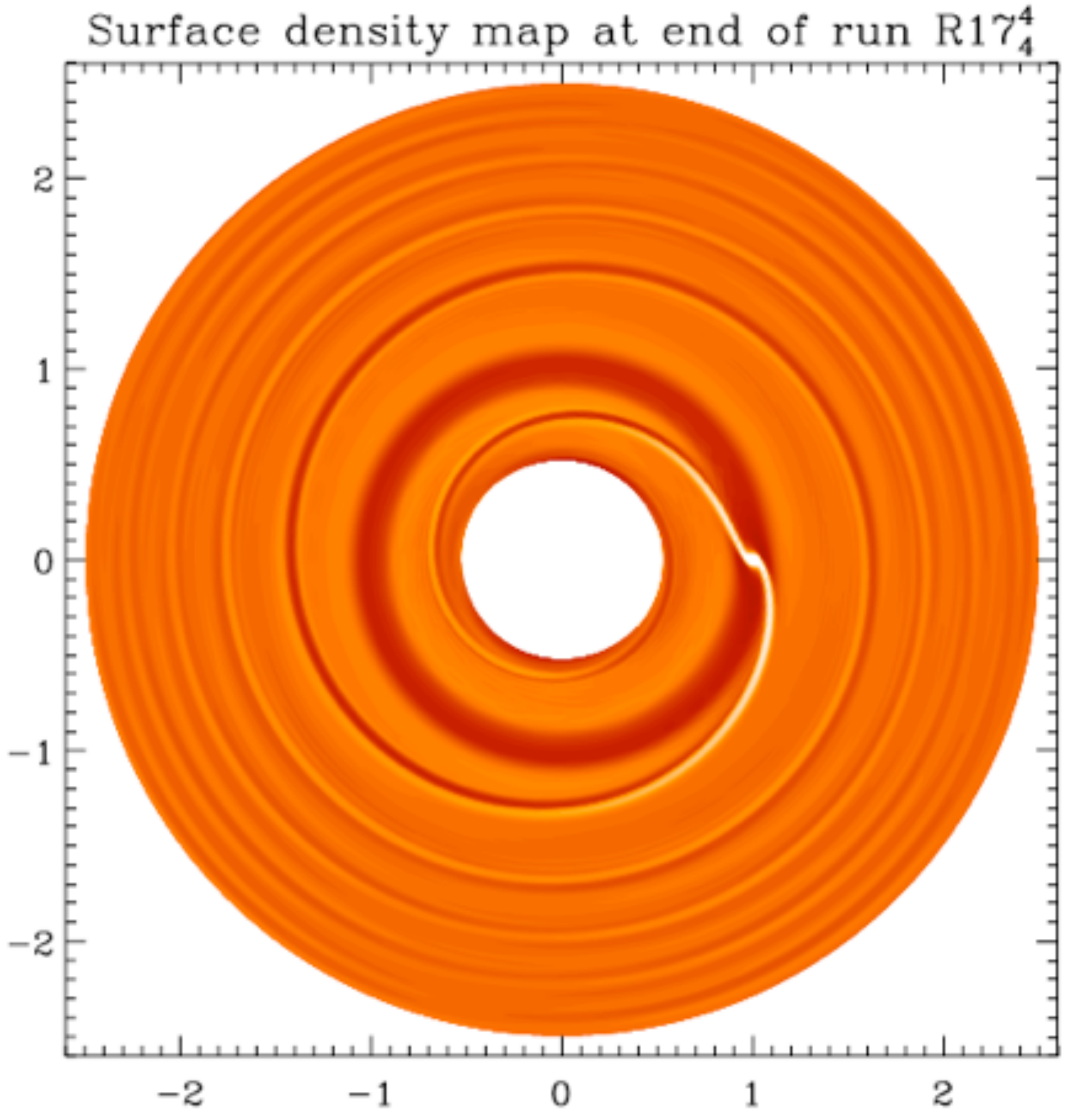
Planet traps + Core accretion



What is the minimum mass of planets formed at planet trap by core accretion??

Step 1: Planet Traps

Step 1: Planet Traps



Masset 2002

Rapid type I migration

e.g. Goldreich & Tremaine 1980, Ward 1986, 1997,
Masset 2001, 2002, Tanaka et al 2002, Baruteau & Masset 2008,
Paardekooper et al 2010, 2011, Hasegawa & Pudritz 2011a

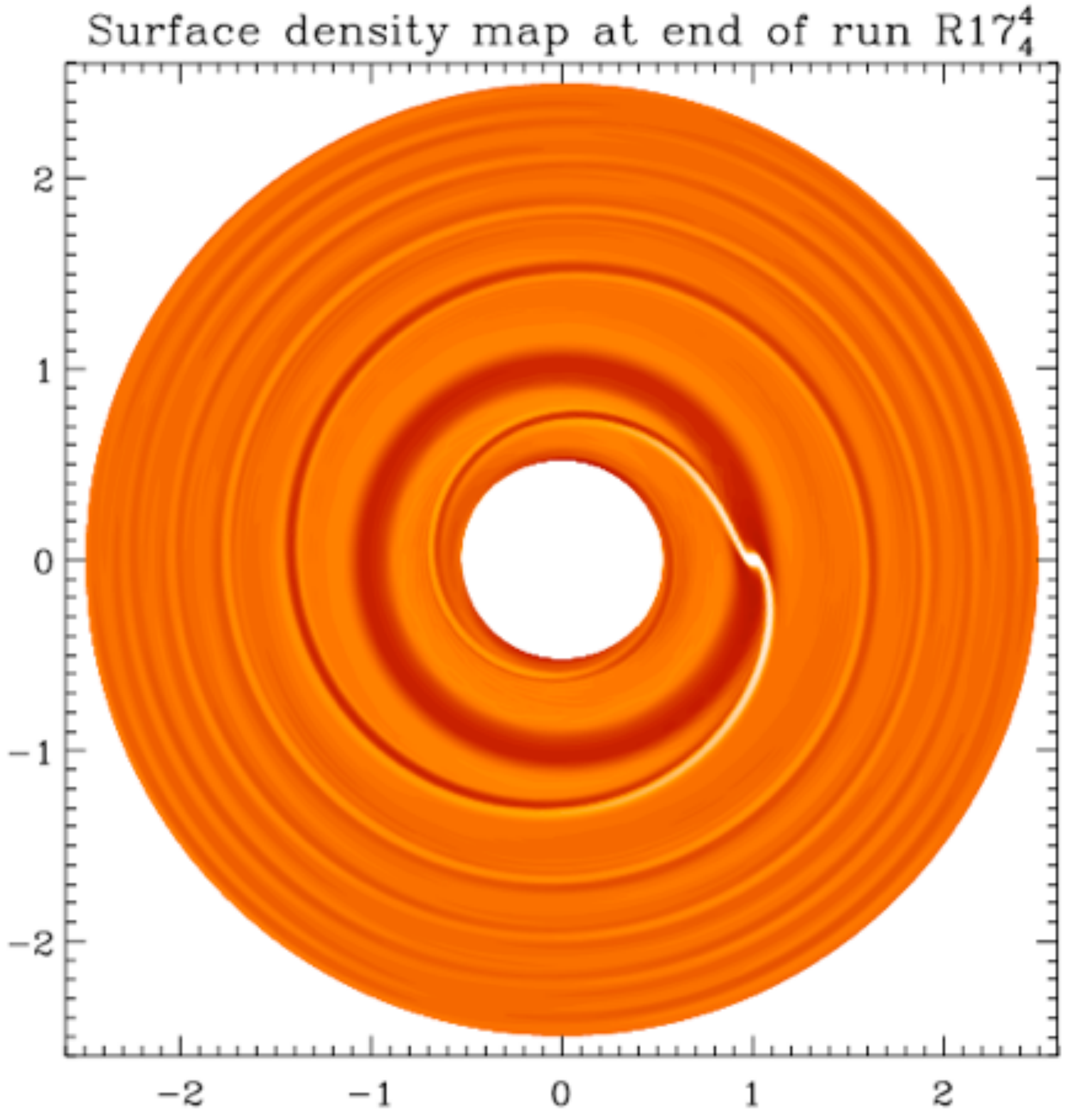
Angular momentum transfer

: Lindblad & corotation resonances

The direct of migration

: depends sensitively on disk properties such as
the surface density, disk temperature, & opacity

Step 1: Planet Traps



Masset 2002

Rapid type I migration

e.g. Goldreich & Tremaine 1980, Ward 1986, 1997,
Masset 2001, 2002, Tanaka et al 2002, Baruteau & Masset 2008,
Paardekooper et al 2010, 2011, Hasegawa & Pudritz 2011a

Angular momentum transfer

: Lindblad & corotation resonances

The direct of migration

: depends sensitively on disk properties such as
the surface density, disk temperature, & opacity

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

Step 1: 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...

.

.

.

Step 1: 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

Step 1: Planet Traps

Hasegawa & Pudritz 2011b

3 types of traps in single disks

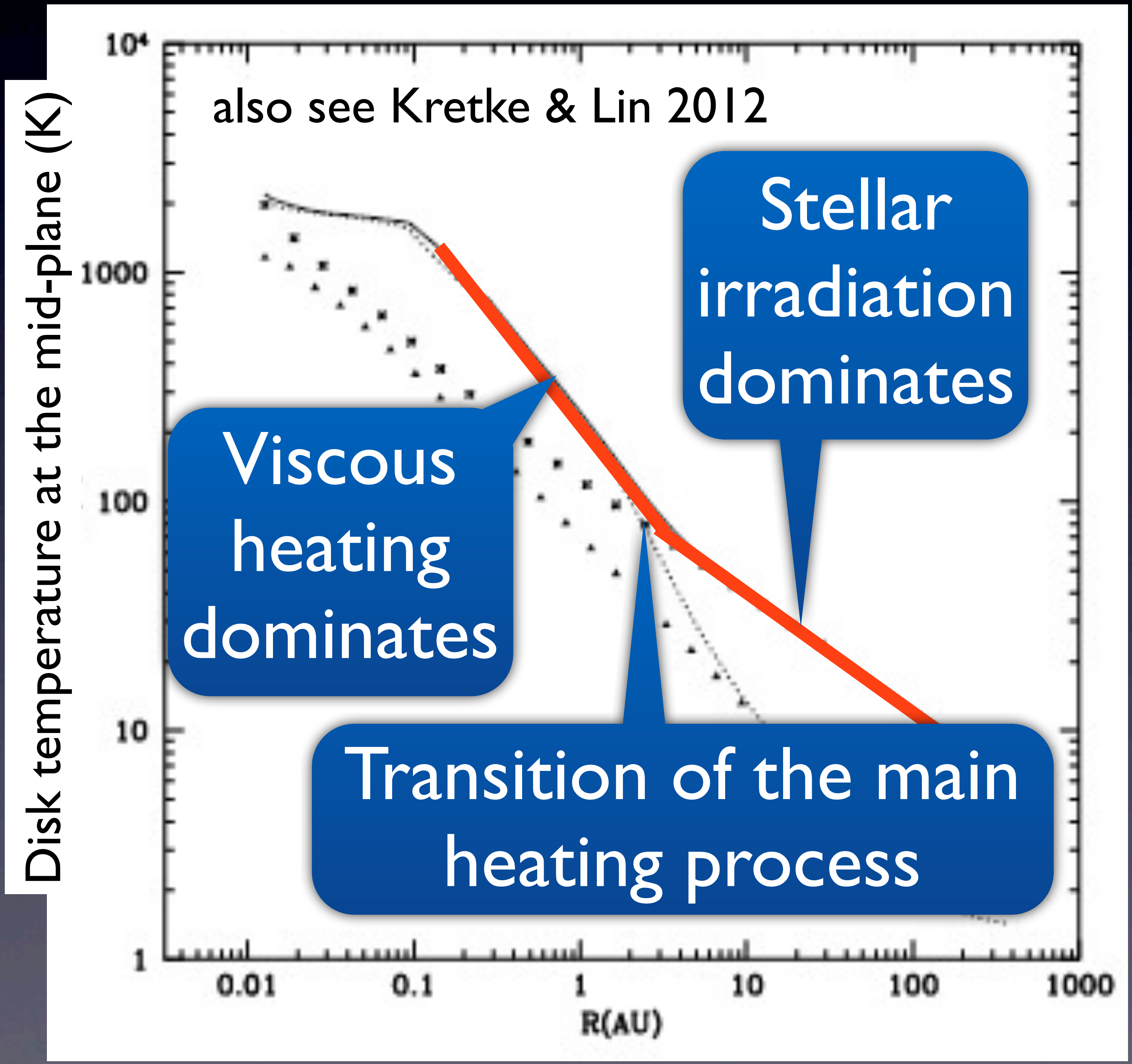
: the outer edge of dead zones, ice lines, heat transitions

Step 1: Planet Traps

Hasegawa & Pudritz 2011b

3 types of traps in single disks

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



also see Kretke & Lin 2012

Stellar irradiation dominates

Viscous heating dominates

Transition of the main heating process

D'Alessio et al 1998

Step 1: Planet Traps

Hasegawa & Pudritz 2011b

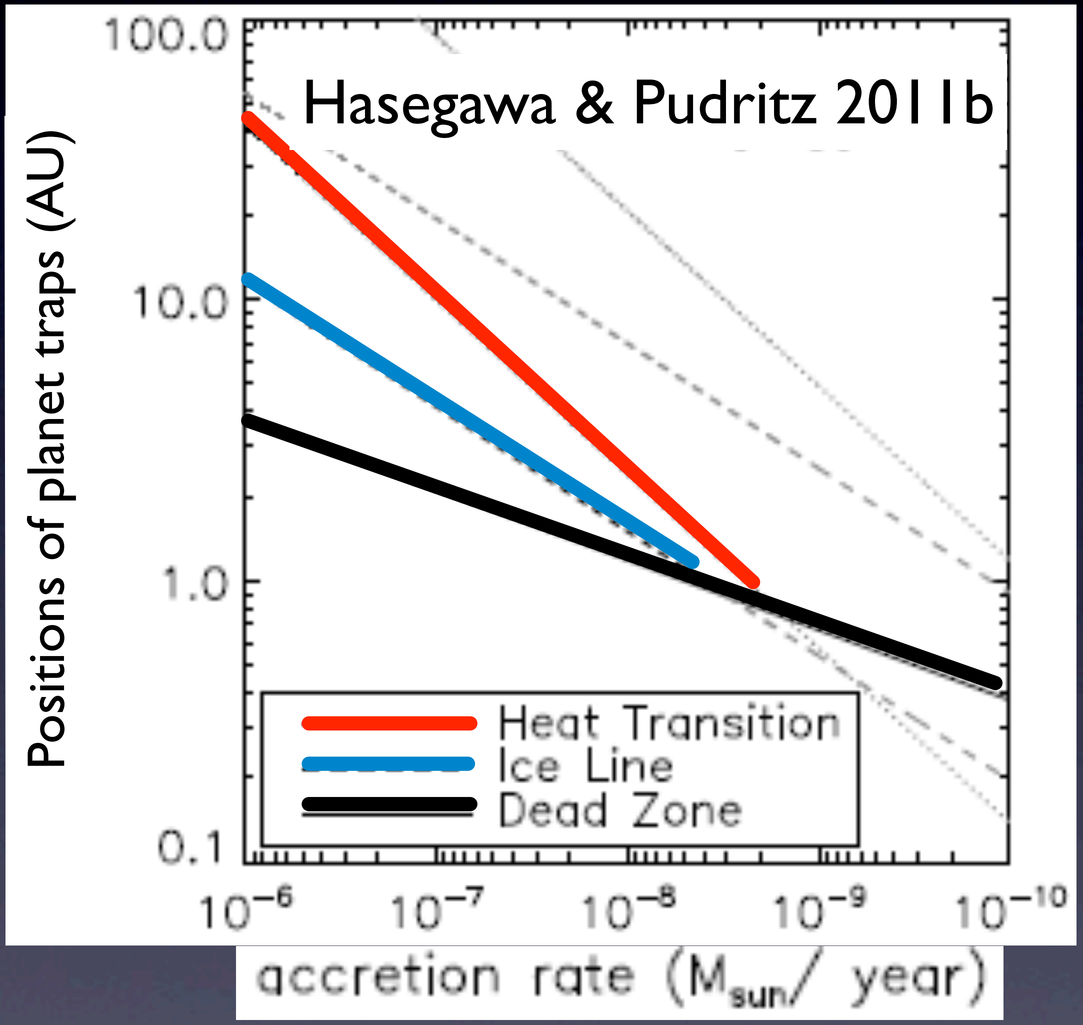
3 types of traps in single disks

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

Step 1: Planet Traps

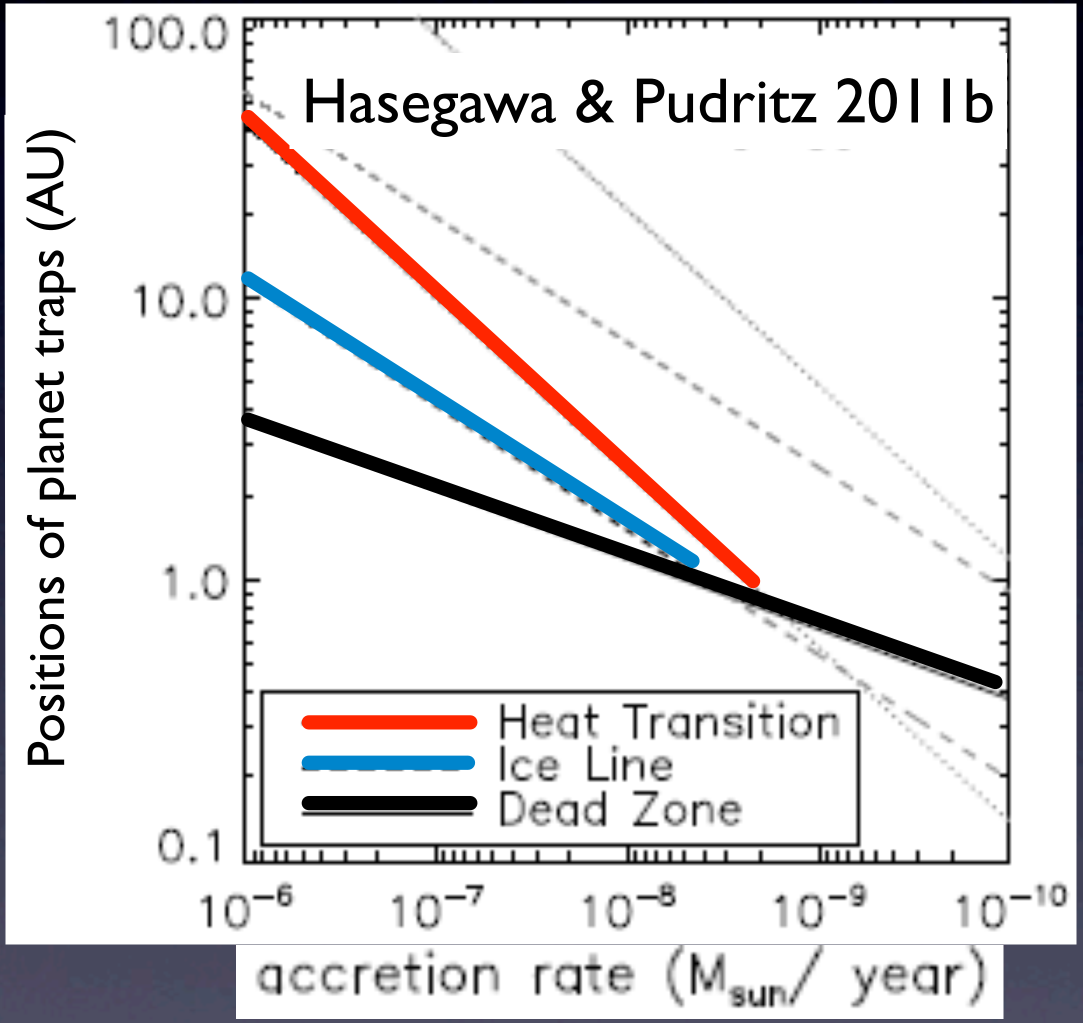
3 types of traps in single disks

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



Locations of traps are specified by disk evolution

Step 1: Planet Traps



3 types of traps in single disks

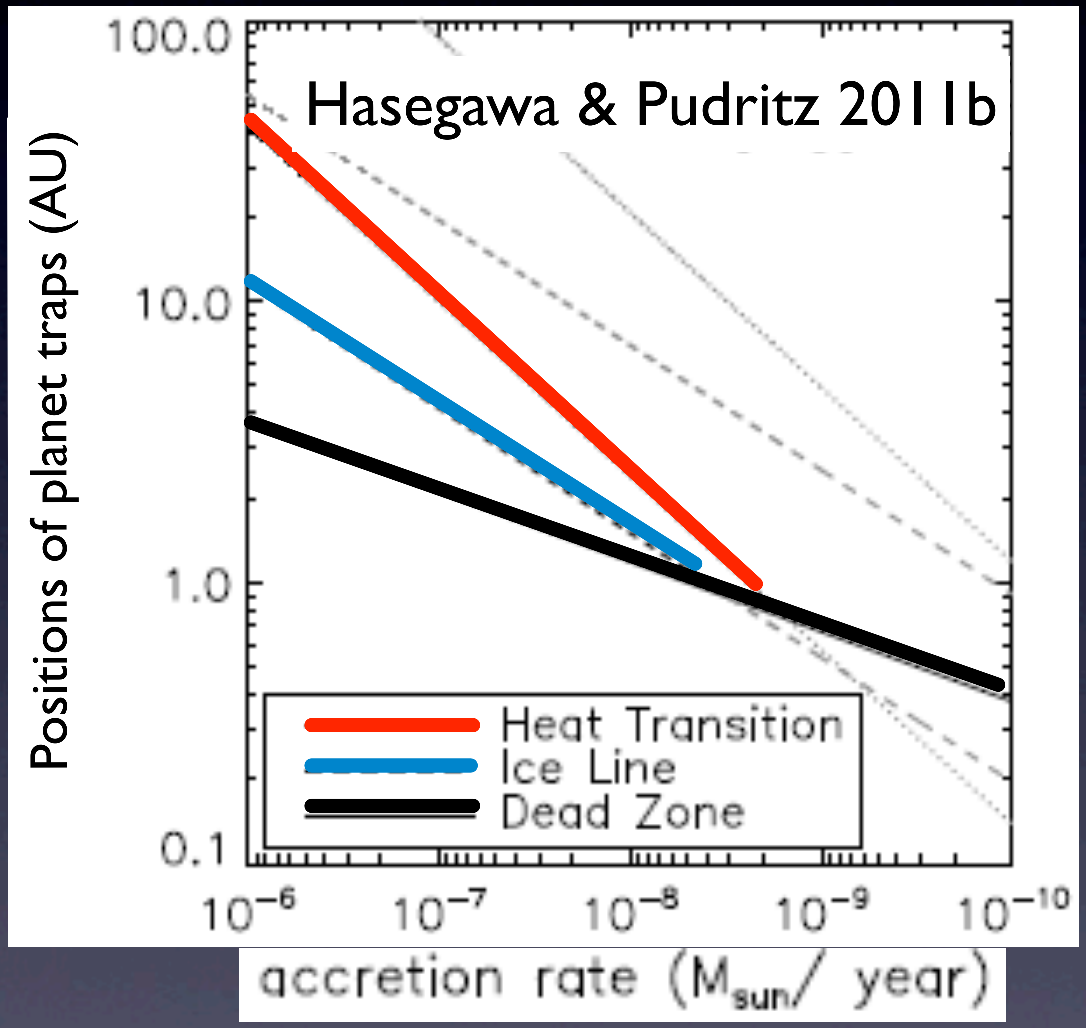
: the outer edge of dead zones, ice lines, heat transitions

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

Step 1: 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

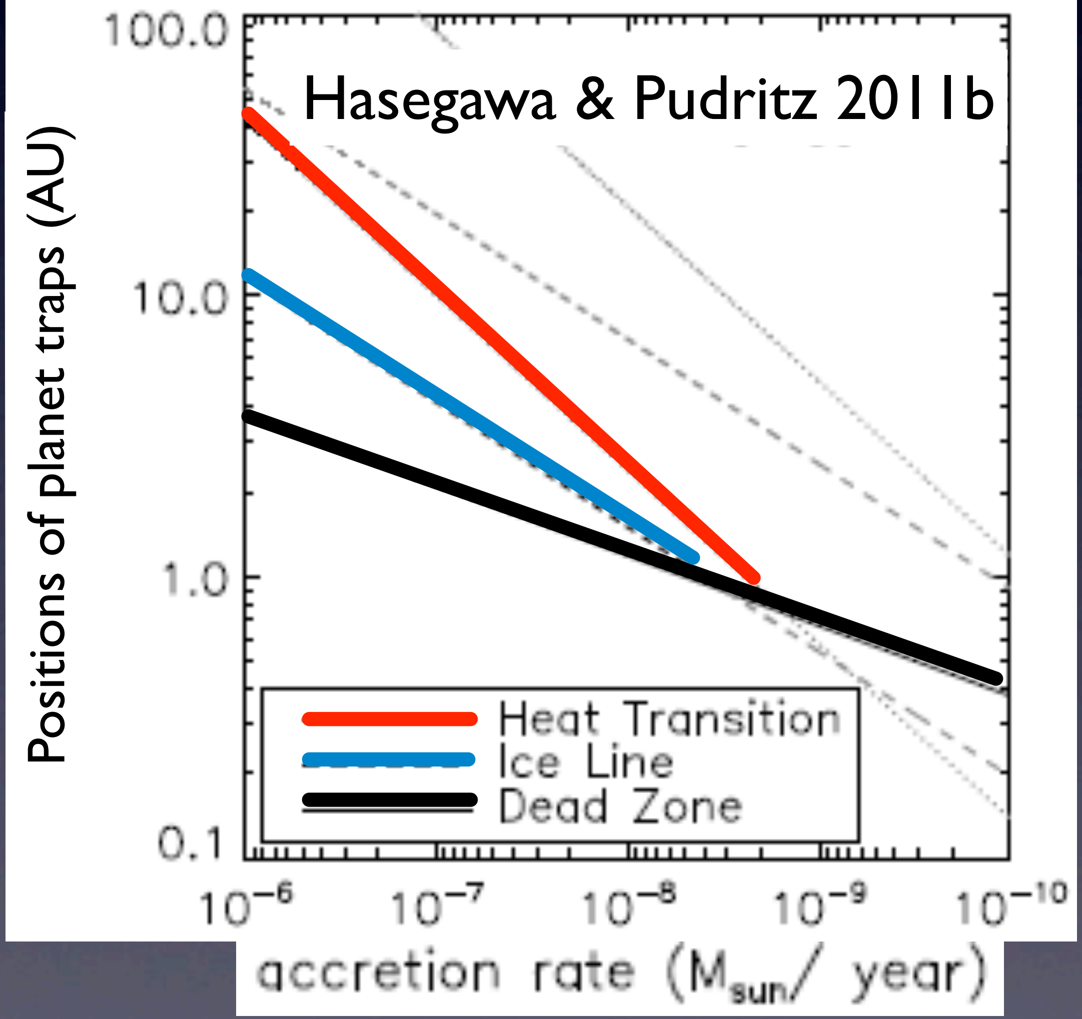
: planet traps are effective until protoplanets obtain the gap-opening mass & undergo type II migration

Planets form locally at traps before type II migration

Step 2: Evolutionary Tracks

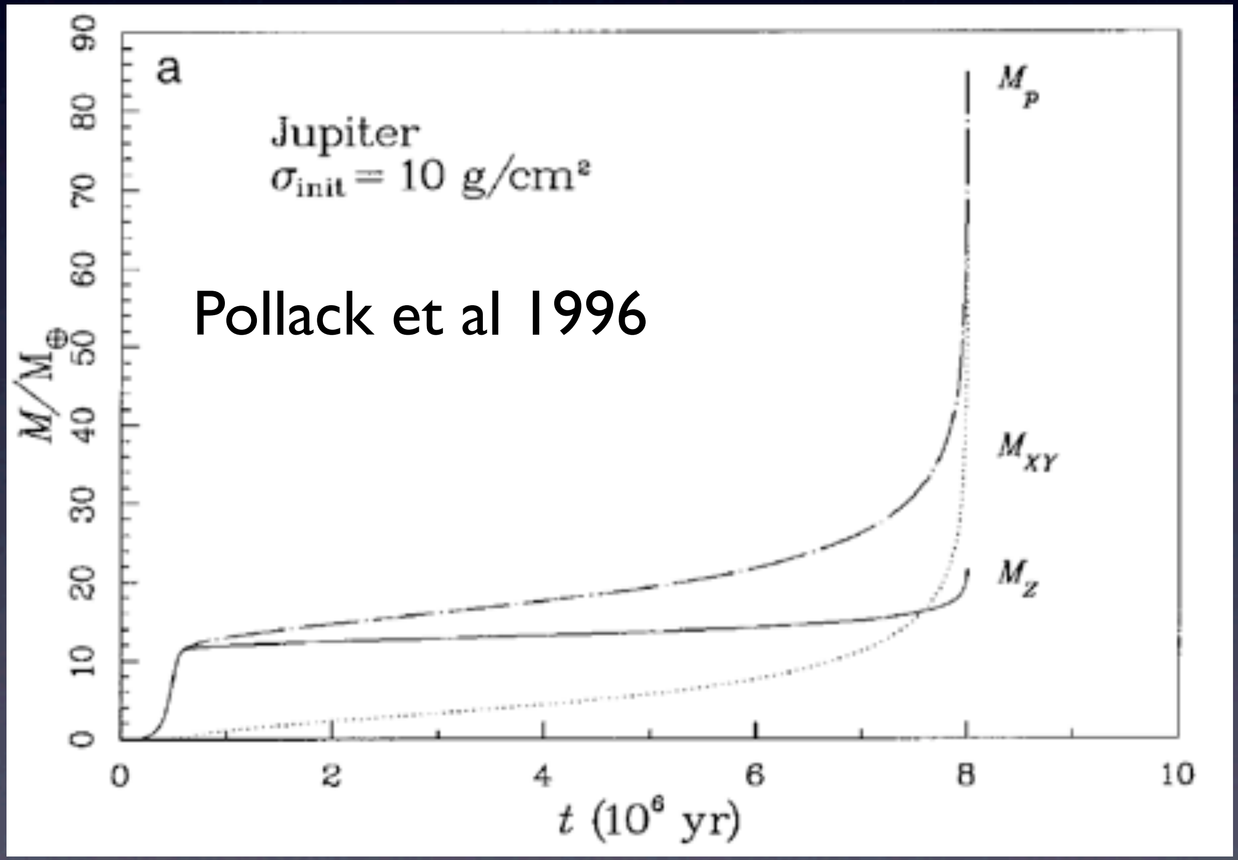
Planet traps

Core accretion



Hasegawa & Pudritz 2011b

+



Pollack et al 1996

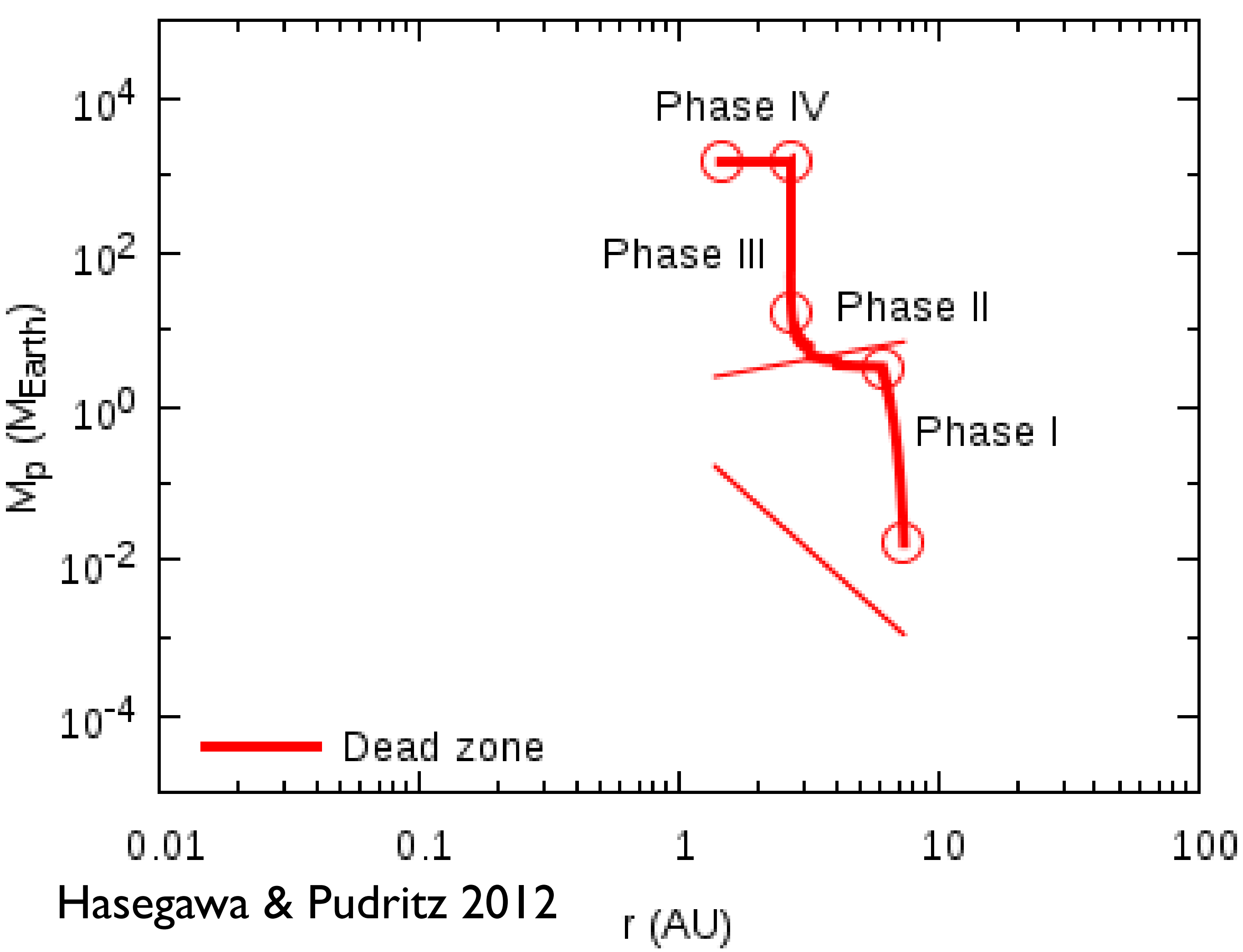
Step 2: Evolutionary Tracks

Hasegawa & Pudritz 2012

A disk around a classical T Tauri star is considered

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

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



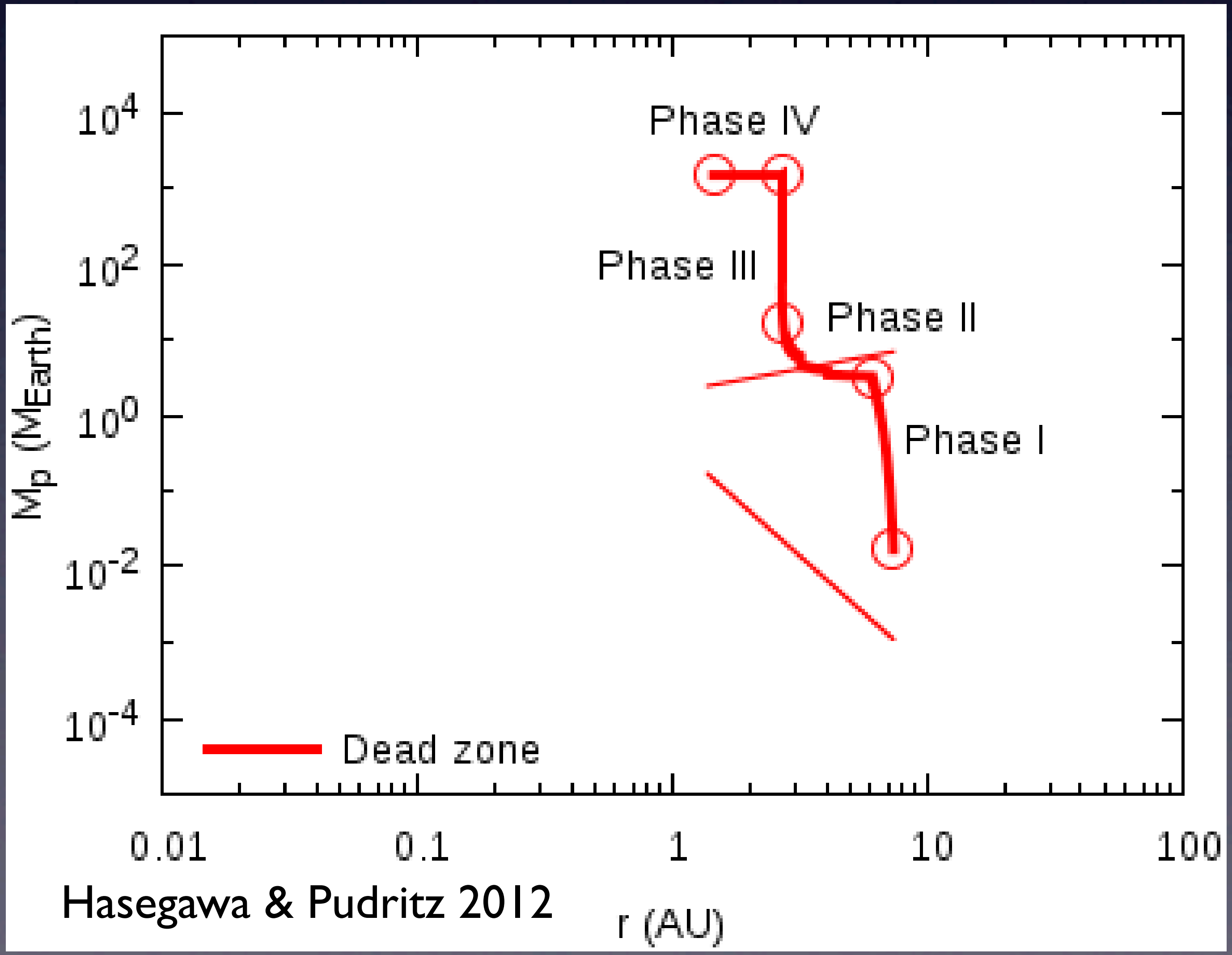
Hasegawa & Pudritz 2012

Step 2: 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

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 $(< 10^{6} years)$

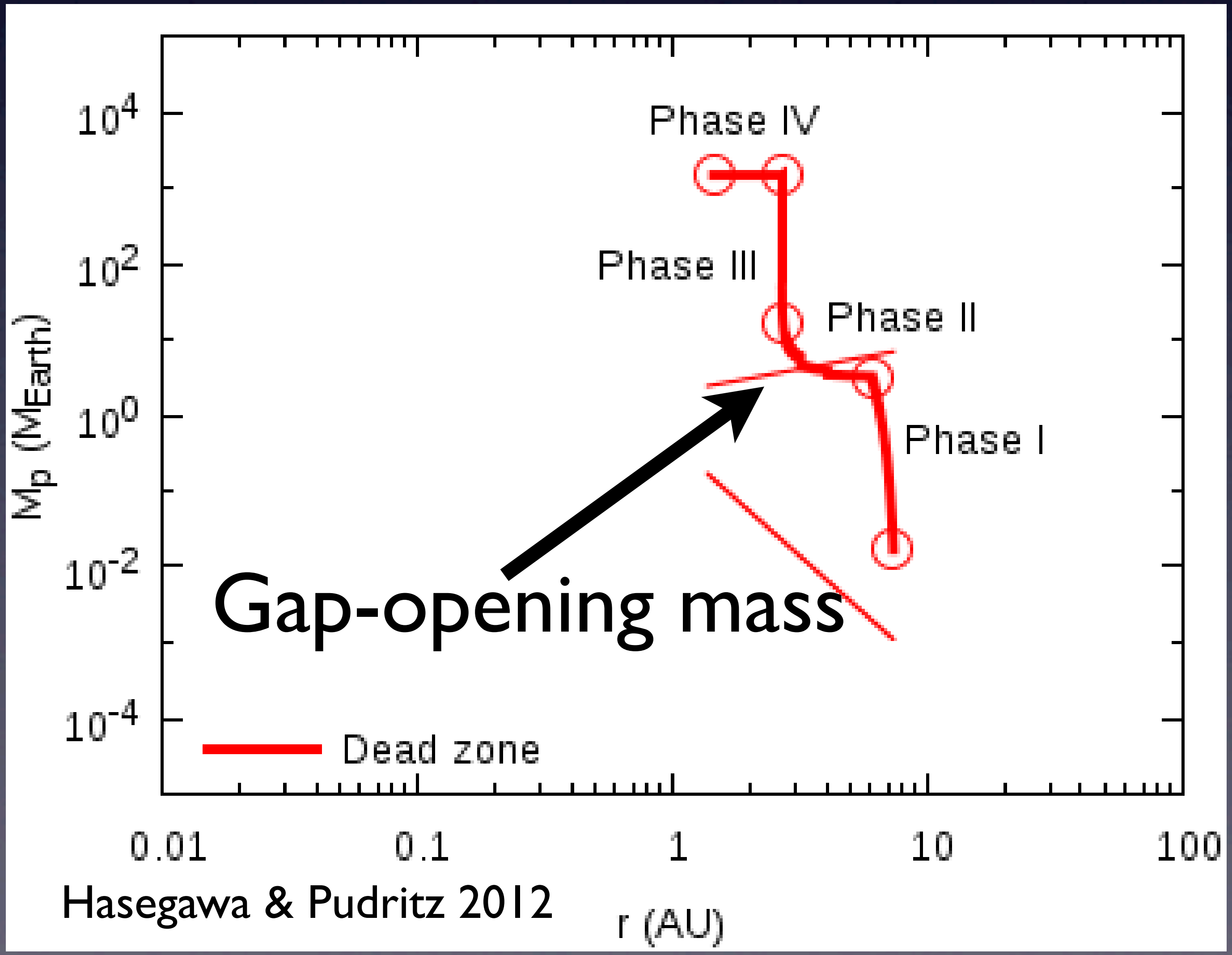
Dust/Planetesimals

Step 2: 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

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

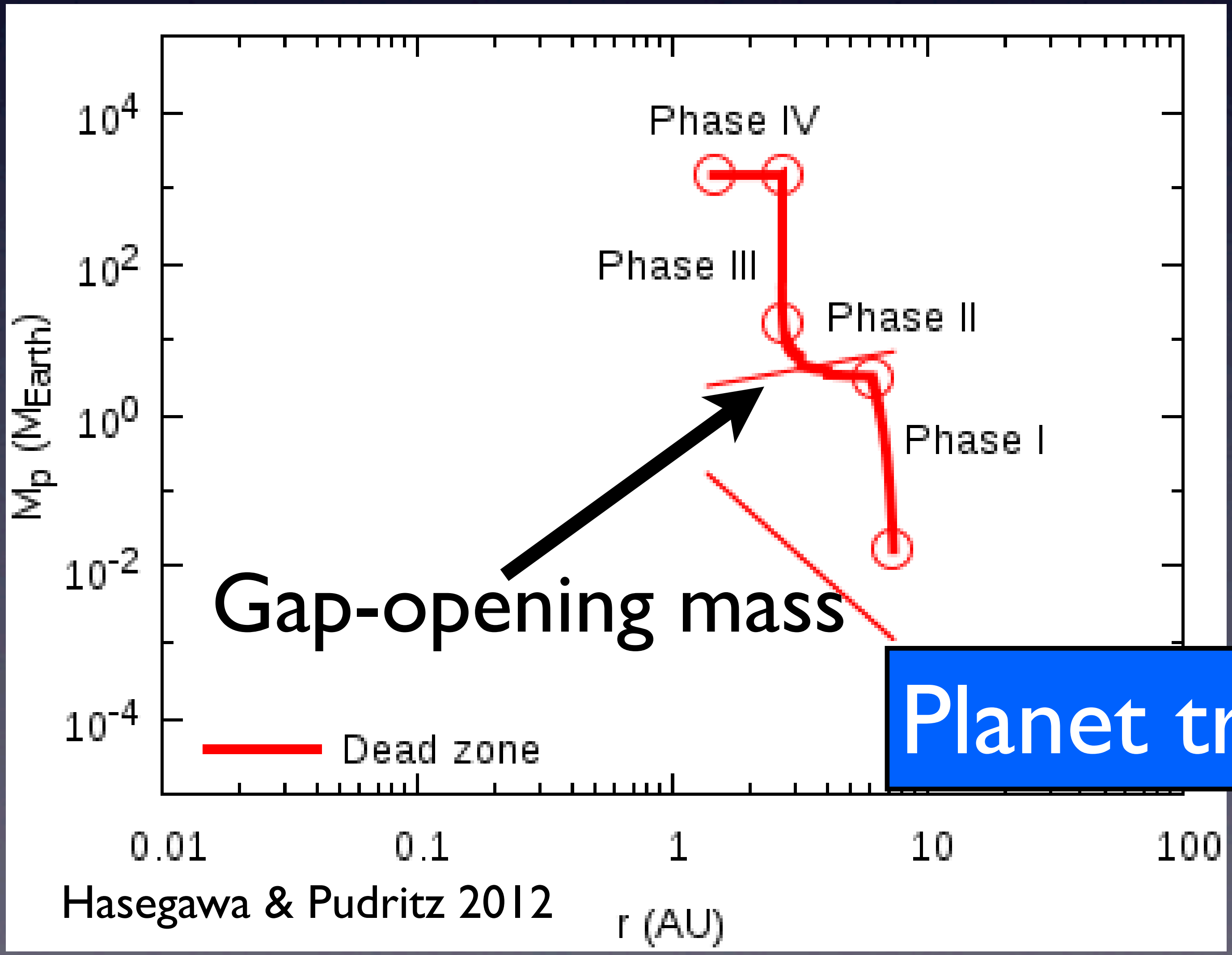
Step 2: Evolutionary Tracks

A disk around a classical T Tauri star is considered

$M_{disk} \sim 0.03$

Type II migration

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

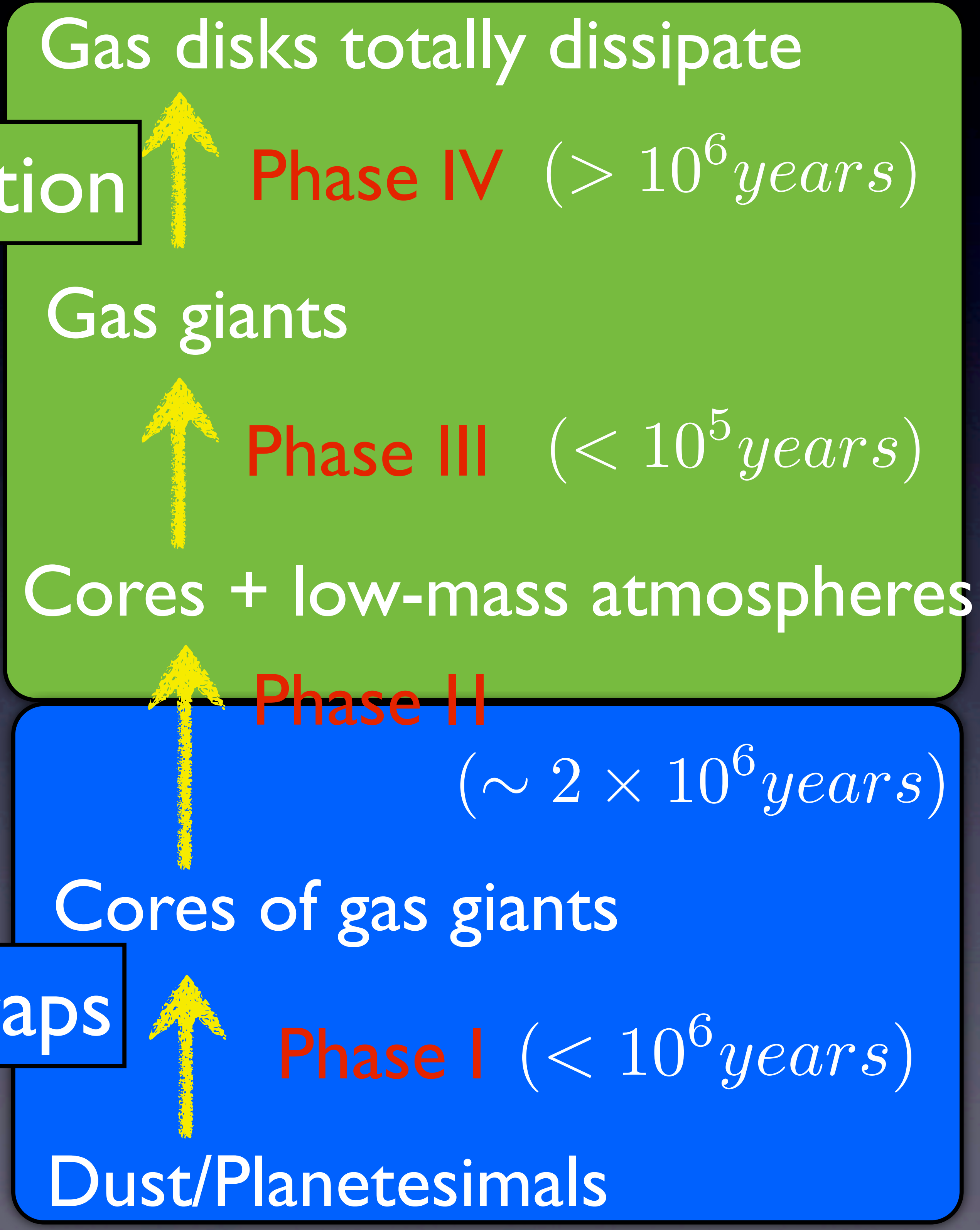


Gap-opening mass

Planet traps

Hasegawa & Pudritz 2012

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

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

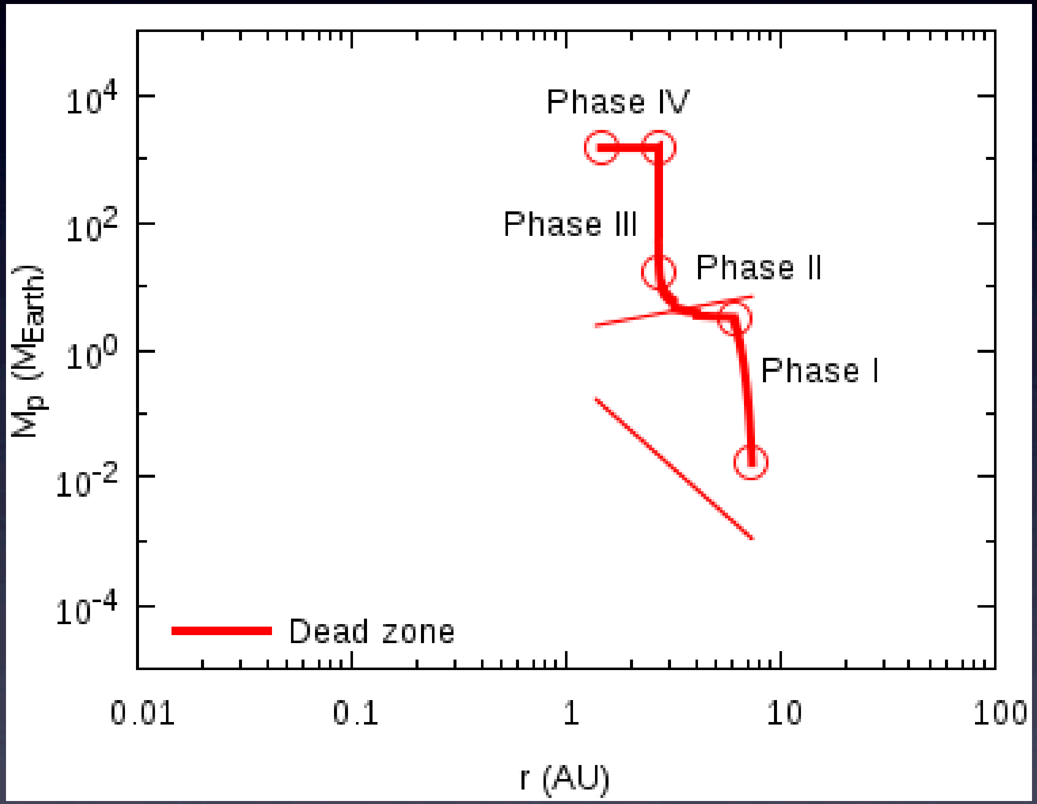
Cores of gas giants

Phase I $(< 10^6 years)$

Dust/Planetesimals

Step 3: Statistics

Hasegawa & Pudritz 2013



→

Statistical quantities

Step 3: Statistics

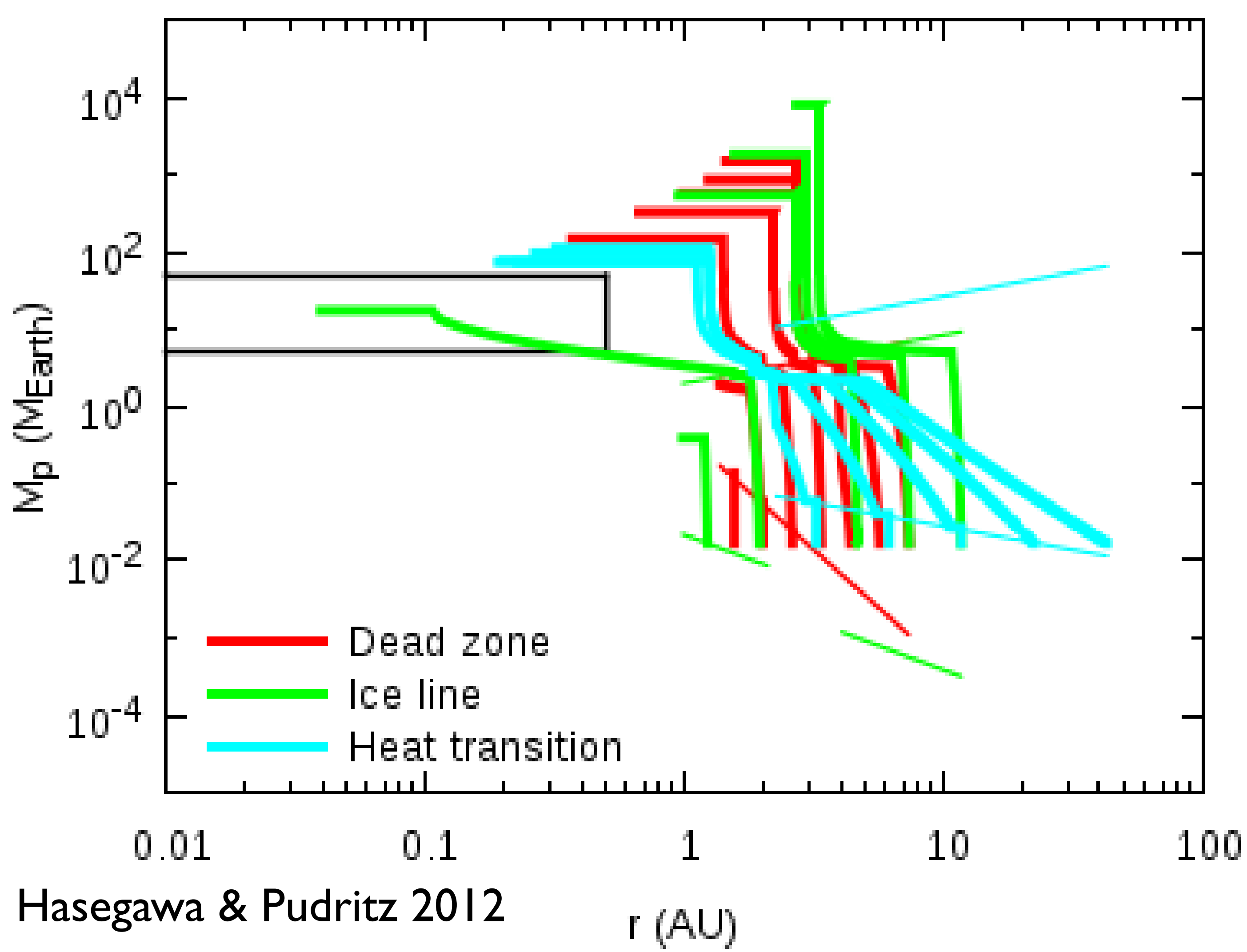
A disk around a classical T Tauri star is considered

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

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

Hasegawa & Pudritz 2013

Compute lots of tracks



Hasegawa & Pudritz 2012

Step 3: Statistics

A disk around a classical T Tauri star is considered

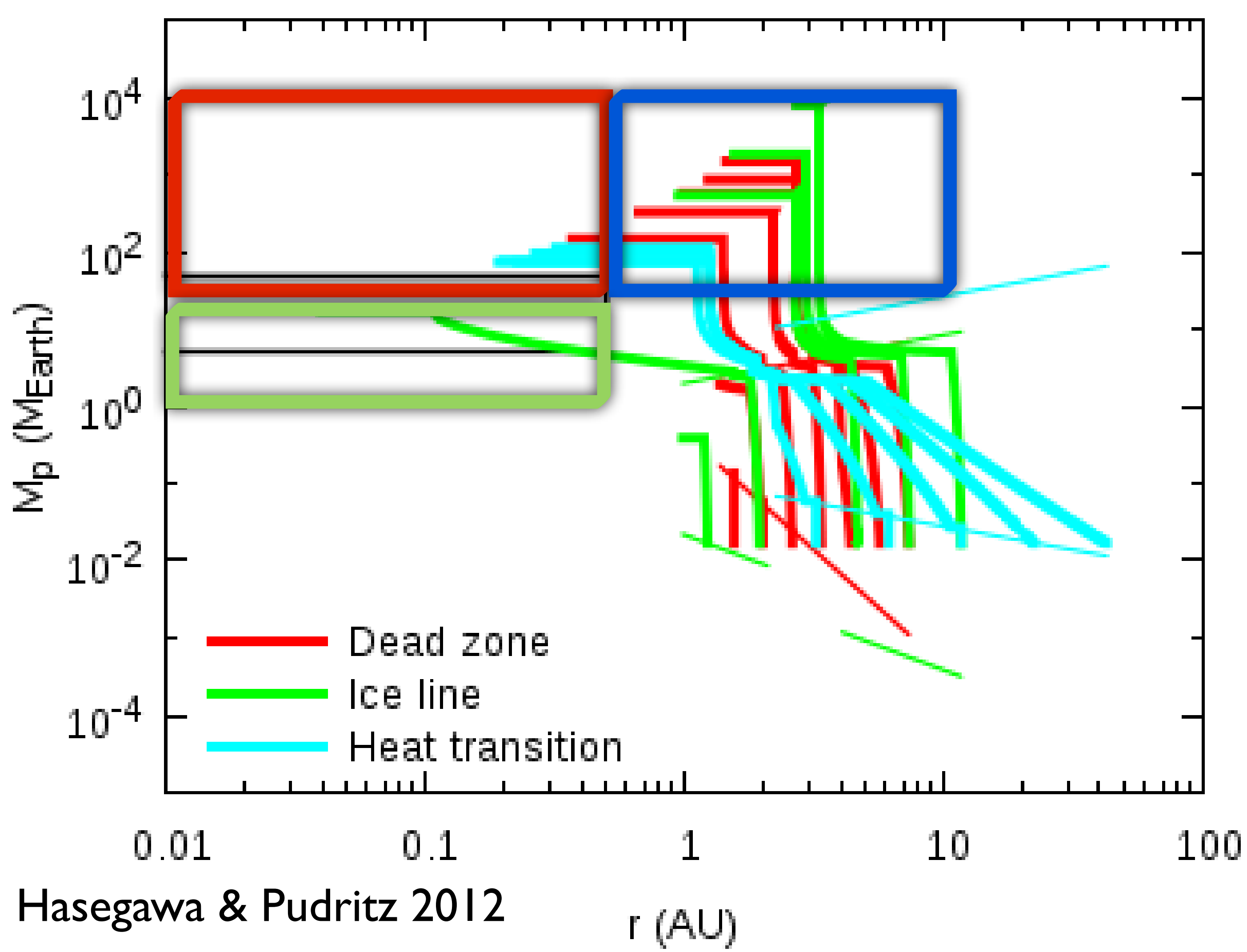
$$M_{disk} \sim 0.03 M_{\odot}$$

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

Hasegawa & Pudritz 2013

Compute lots of tracks

Partition the diagram



Hasegawa & Pudritz 2012

Step 3: Statistics

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 2013

Compute lots of tracks

Partition the diagram

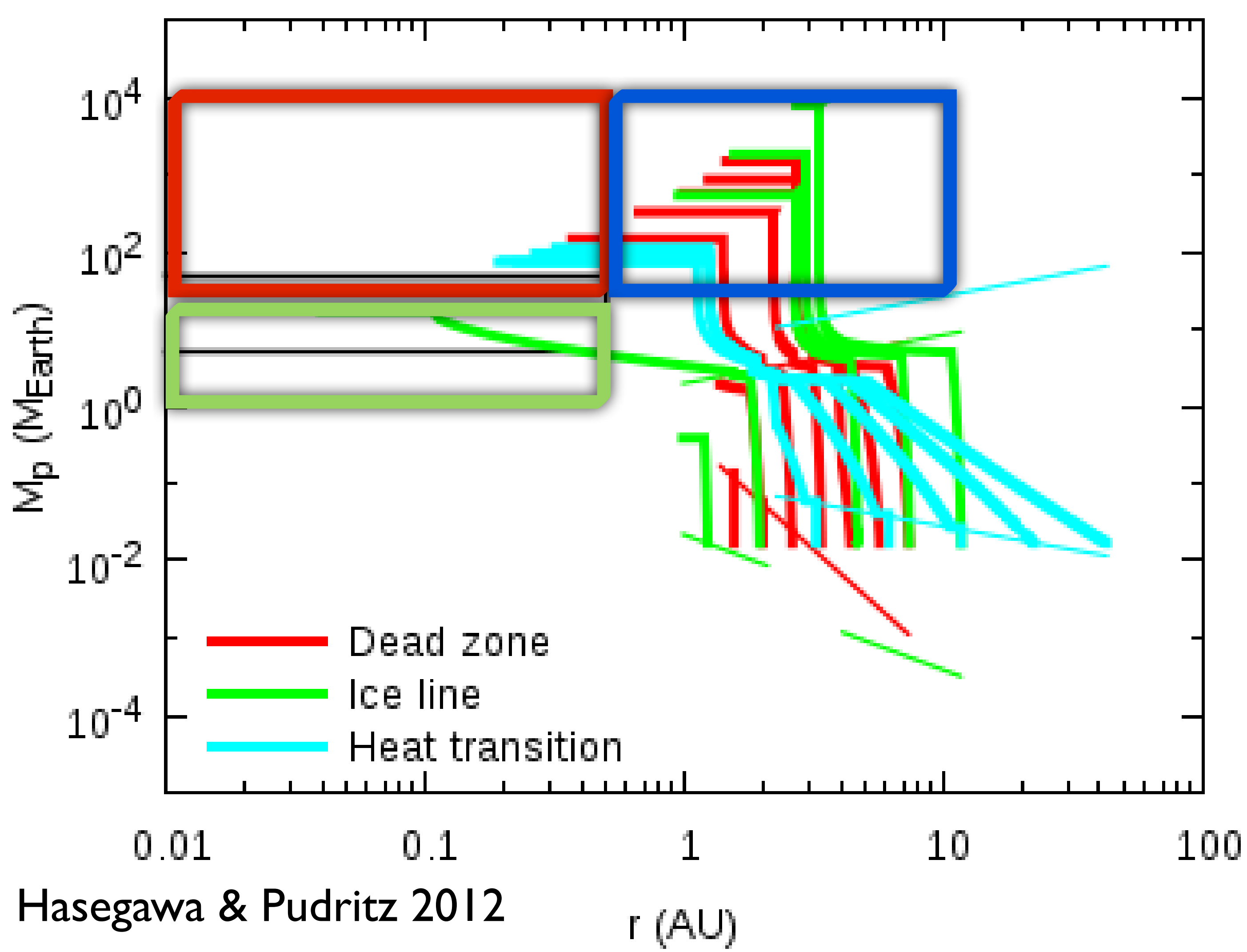
Calculate planet formation frequencies (PFFs)

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

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

↓

Weight functions related to disk observations



Hasegawa & Pudritz 2012

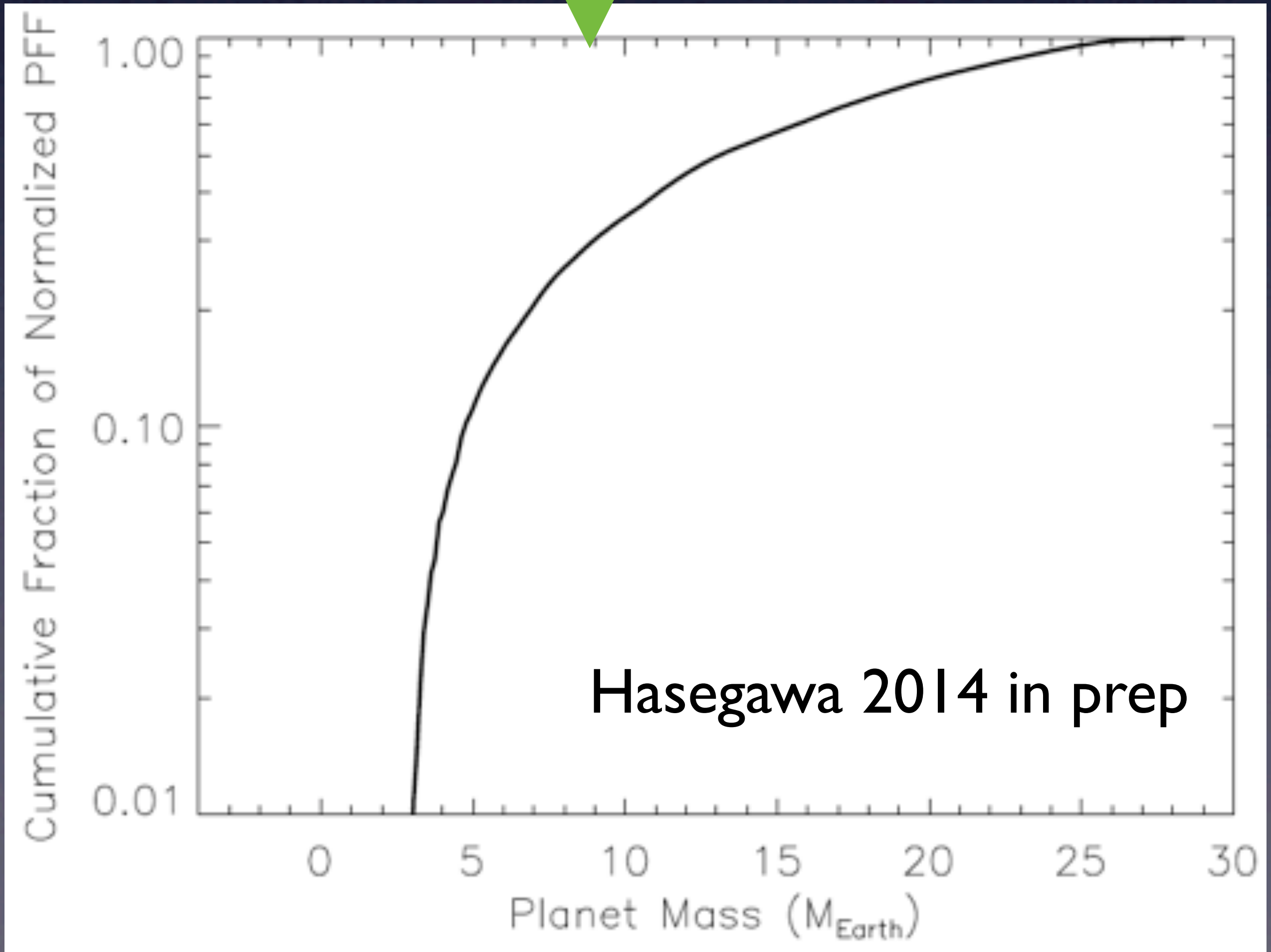
$1M_\odot$	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF				

$1M_\odot$	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	~ 7.6 %	~ 25.3 %	~ 10.2 %	43.1%

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

$1M_\odot$	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	~ 7.6 %	~ 25.3 %	~ 10.2 %	43.1%

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



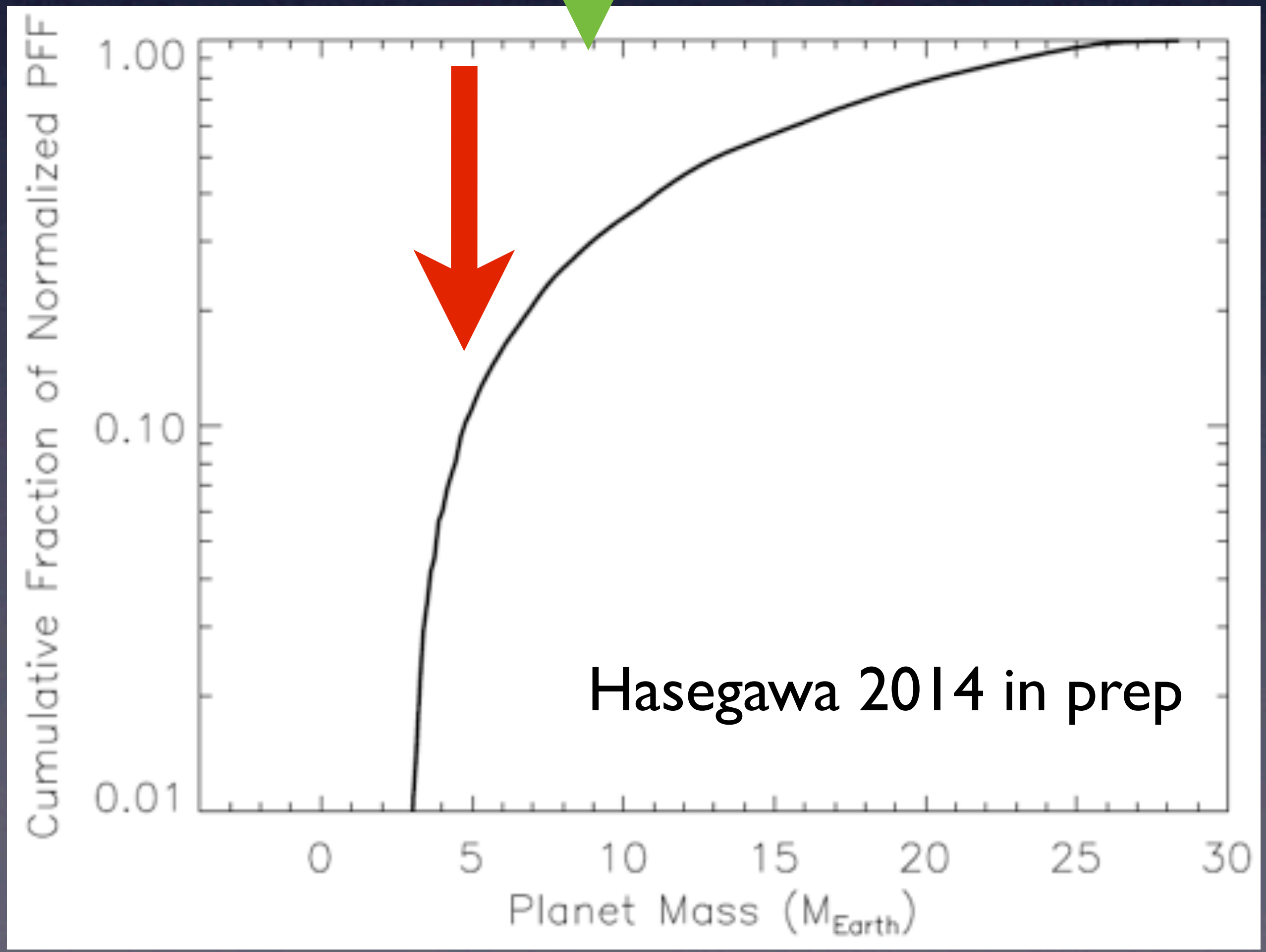
Hasegawa 2014 in prep

$1M_\odot$	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	~ 7.6 %	~ 25.3 %	~ 10.2 %	43.1%

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

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

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



Hasegawa 2014 in prep

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

Hasegawa 2014 in prep

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

Hasegawa 2014 in prep

1) photoevaporative mass loss of planets

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

Hasegawa 2014 in prep

1) photoevaporative mass loss of planets

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

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

Hasegawa 2014 in prep

1) photoevaporative mass loss of planets

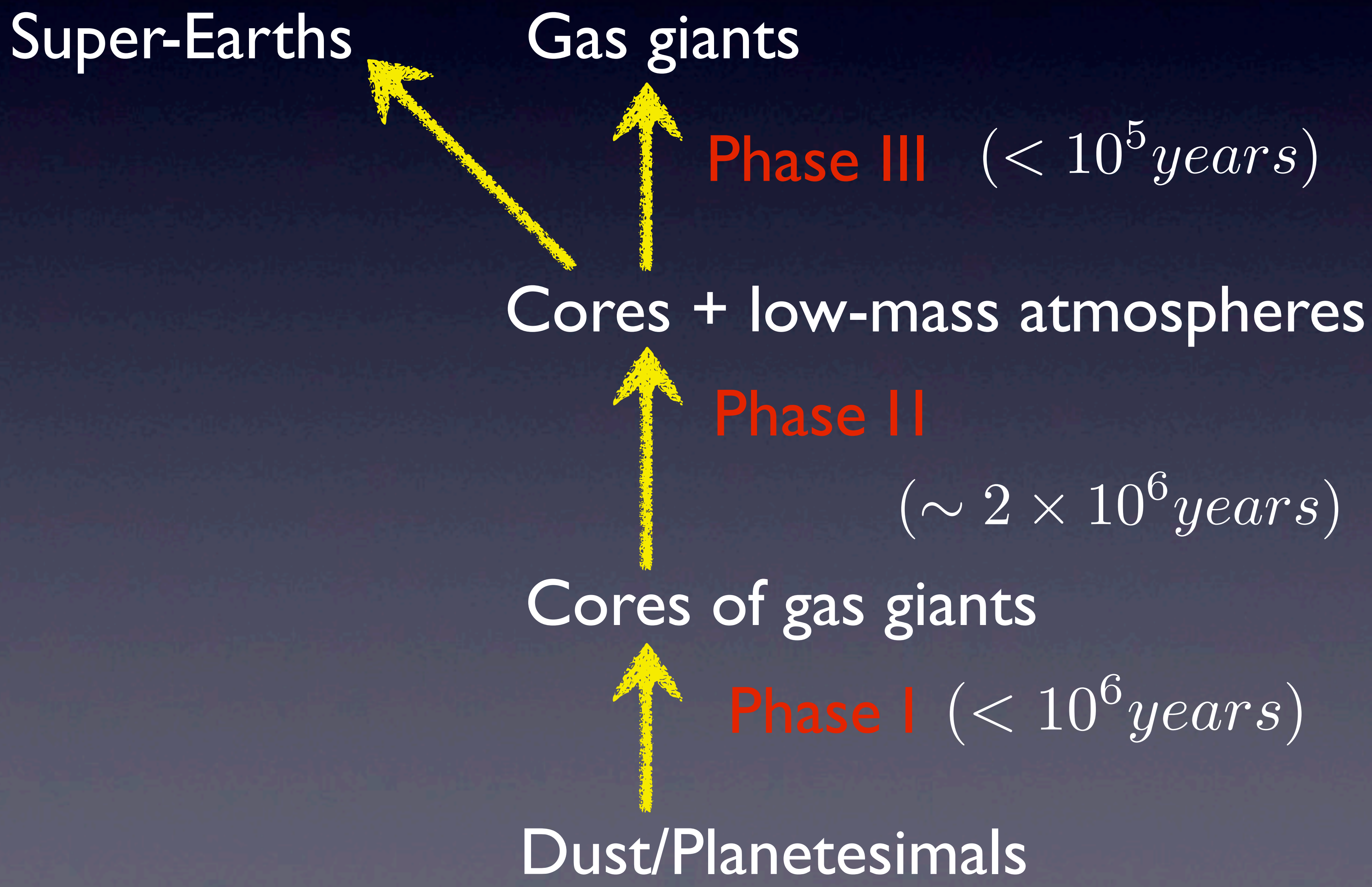
2) the critical core mass to start gas accretion

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

Hasegawa 2014 in prep

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion



Super-Earths

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 $(< 10^6 years)$

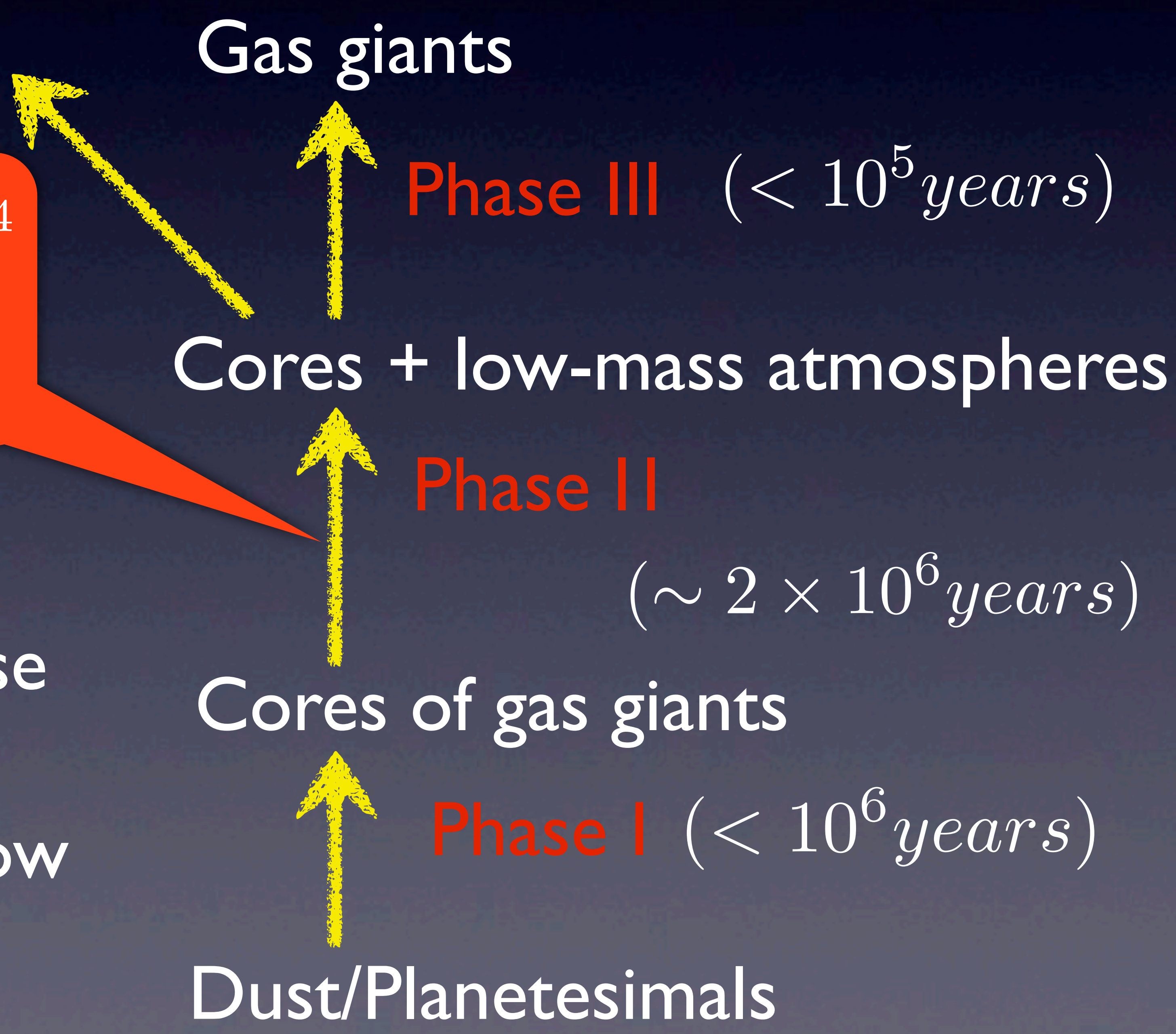
Dust/Planetesimals

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

Hasegawa 2014 in prep

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion



Super-Earths

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

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

$M_{c,crit}$: Parameter

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

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

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

Hasegawa 2014 in prep

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

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

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

Hasegawa 2014 in prep

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

$M_{c,crit}$	$3M_\oplus$	$5M_\oplus$	$10M_\oplus$
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 2014 in prep

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

3) planetary migration in gas disks

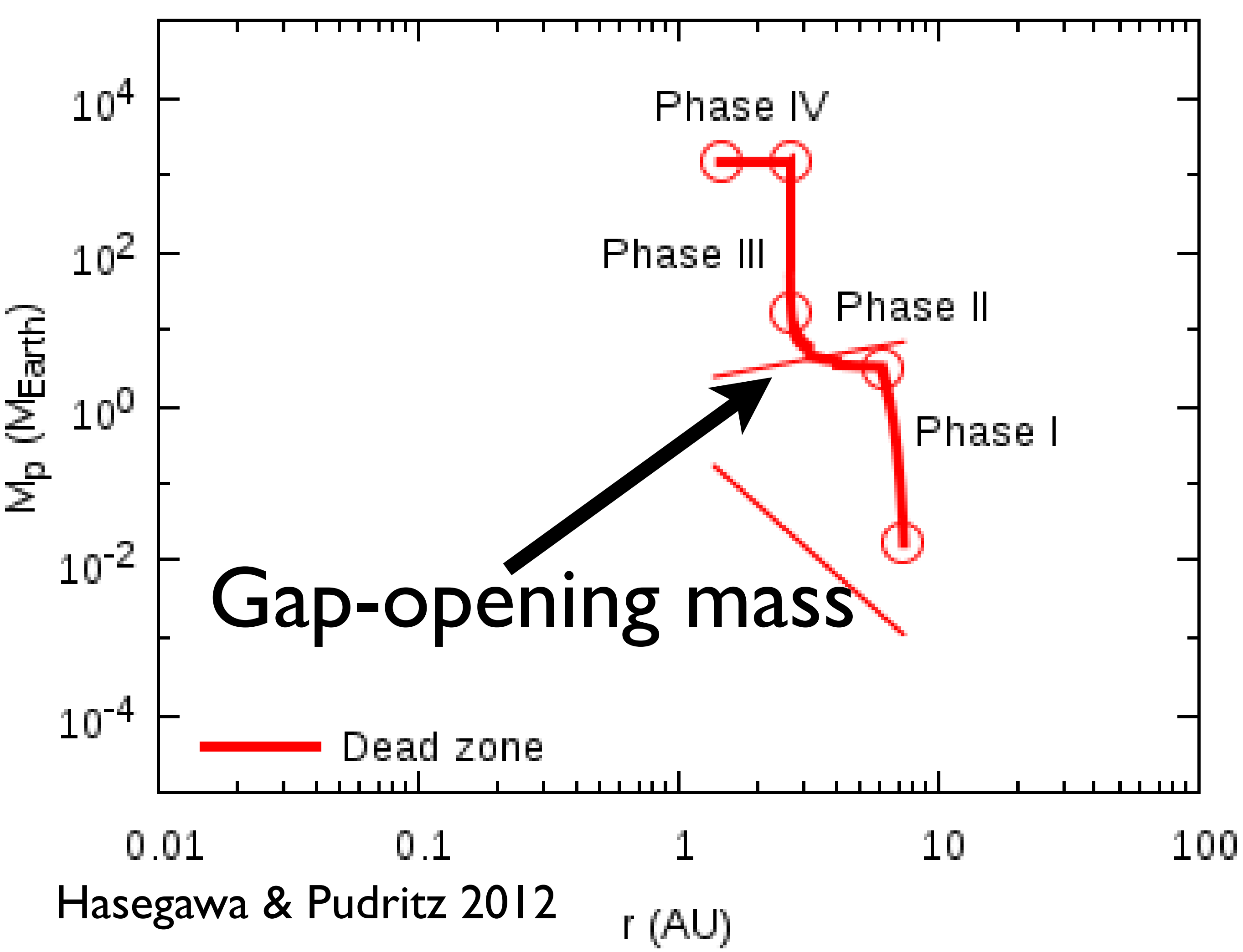
Why $M_{min}^{CA} \simeq 4-5M_{\oplus}$??

Hasegawa 2014 in prep

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

3) planetary migration in gas disks



Gap-opening mass

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

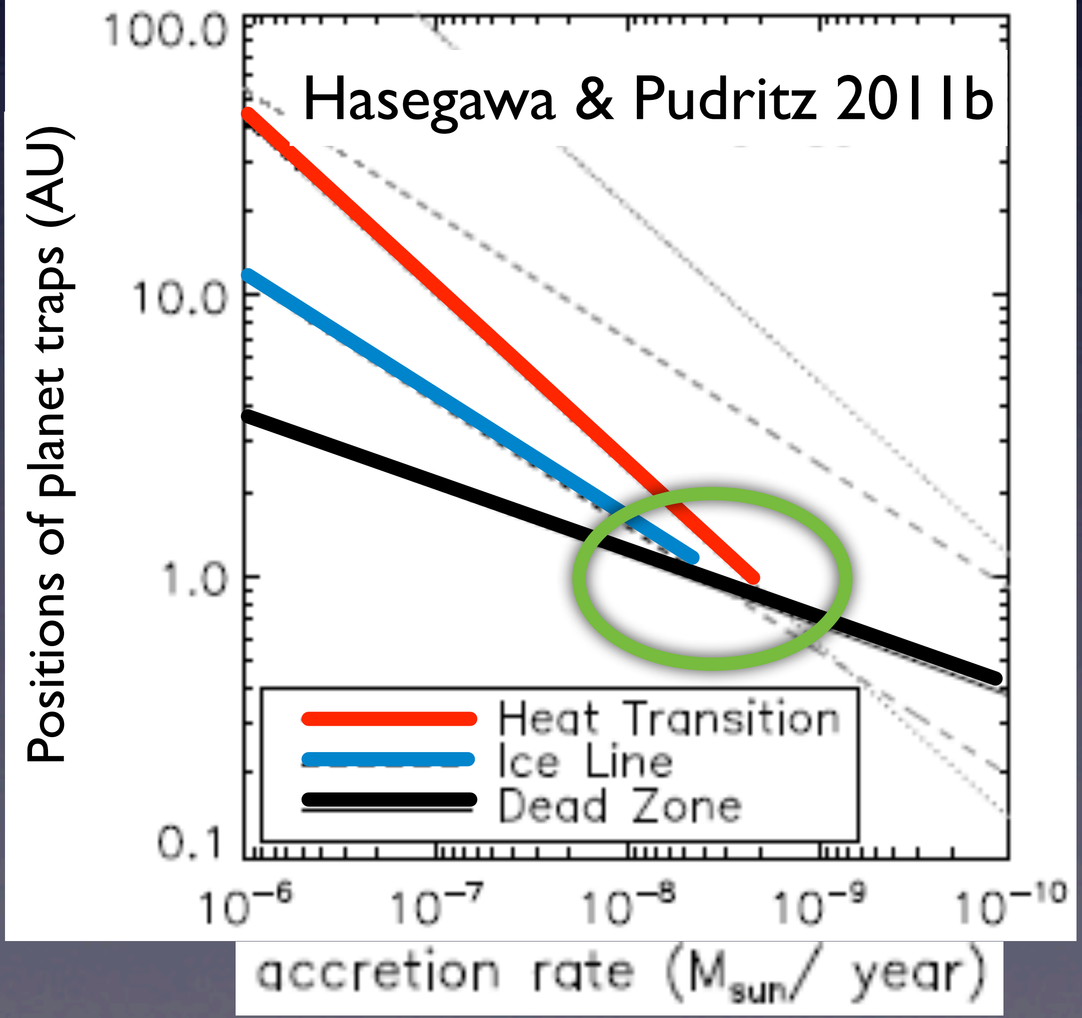
Why $M_{min}^{CA} \simeq 4-5M_{\oplus}$??

Hasegawa 2014 in prep

1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

3) planetary migration in gas disks



Hasegawa & Pudritz 2011b

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

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

Hasegawa 2014 in prep

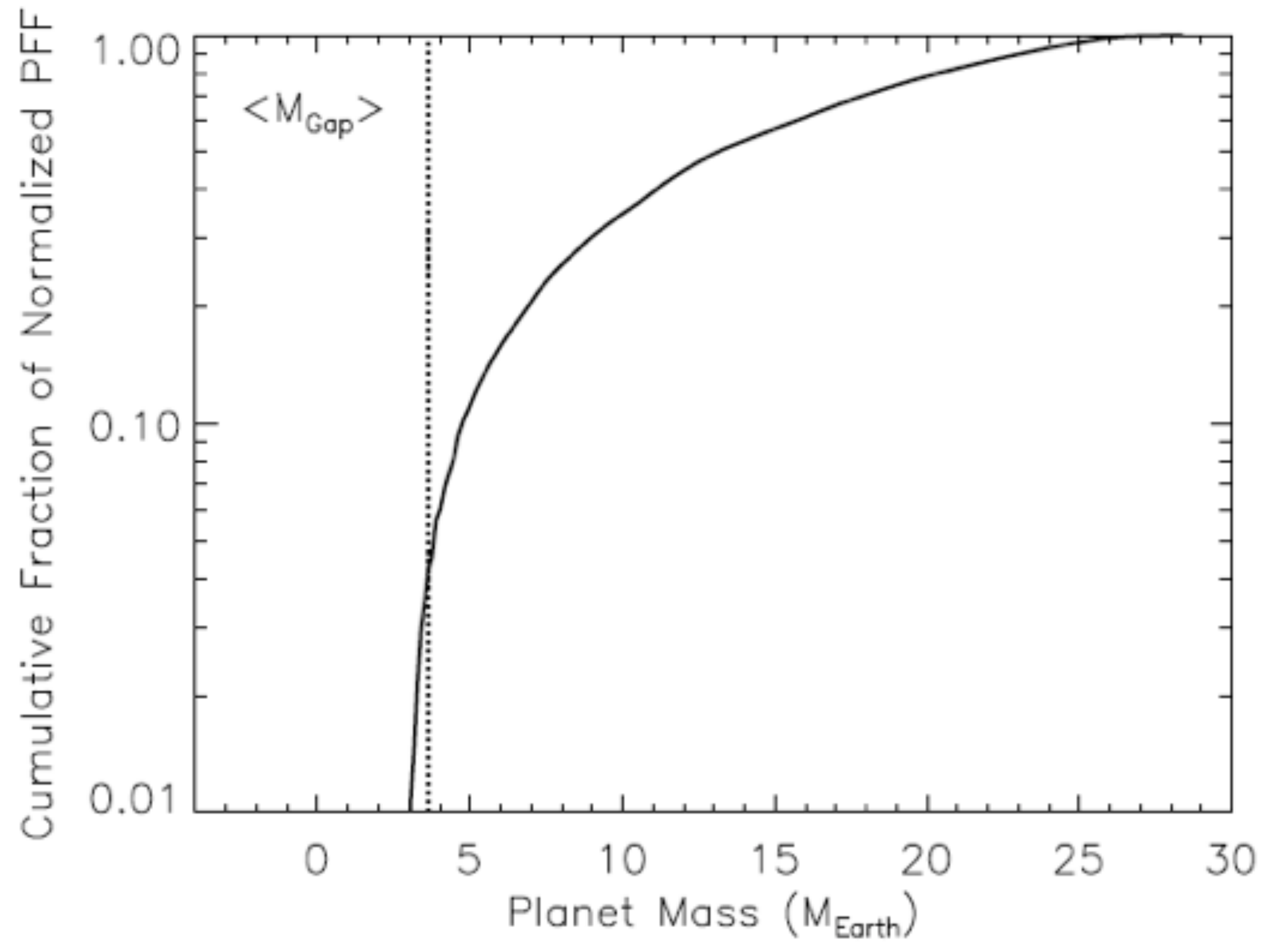
1) photoevaporative mass loss of planets

2) the critical core mass to start gas accretion

3) planetary migration in gas disks

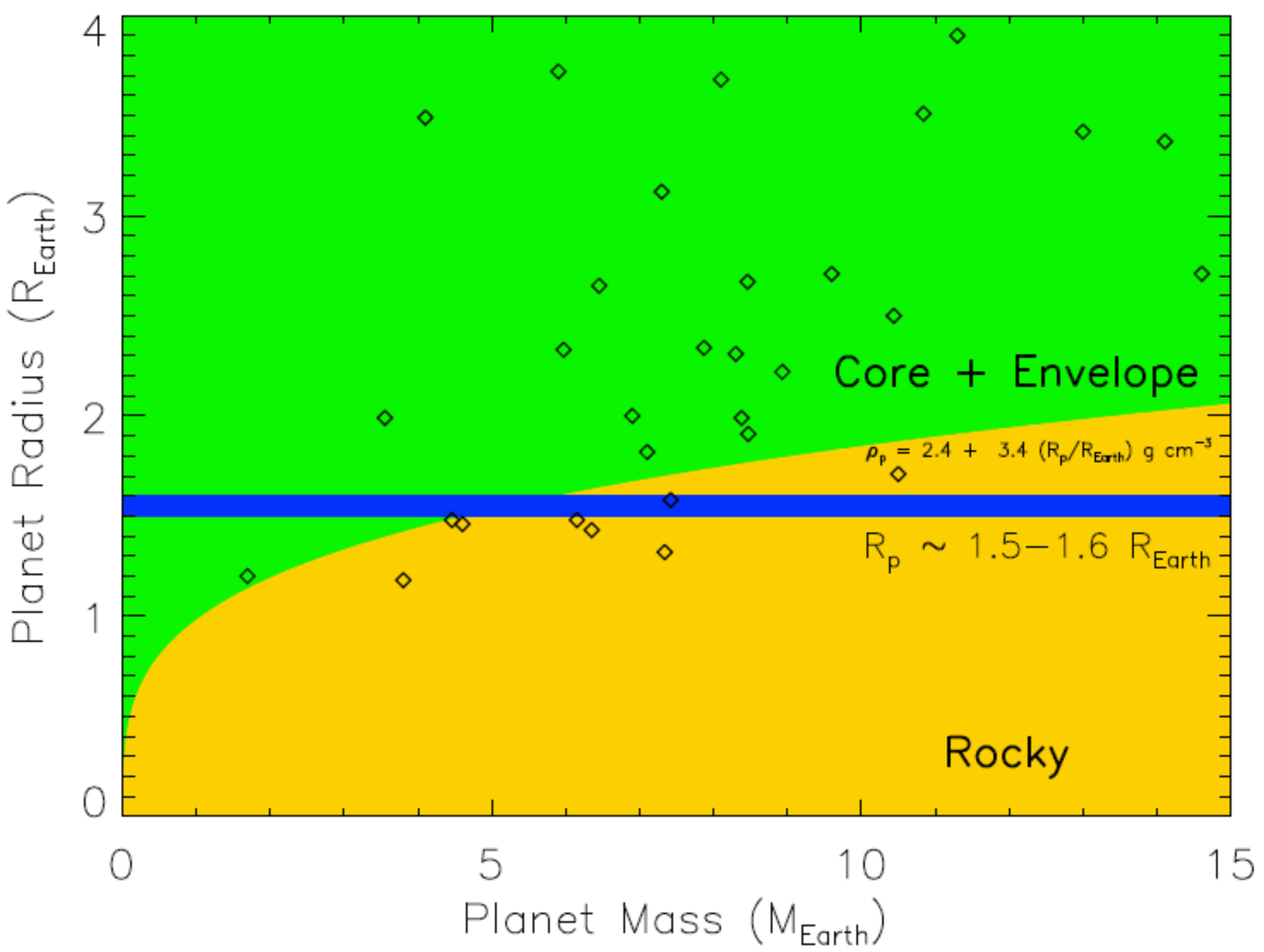
$< M_{Gap} >$

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



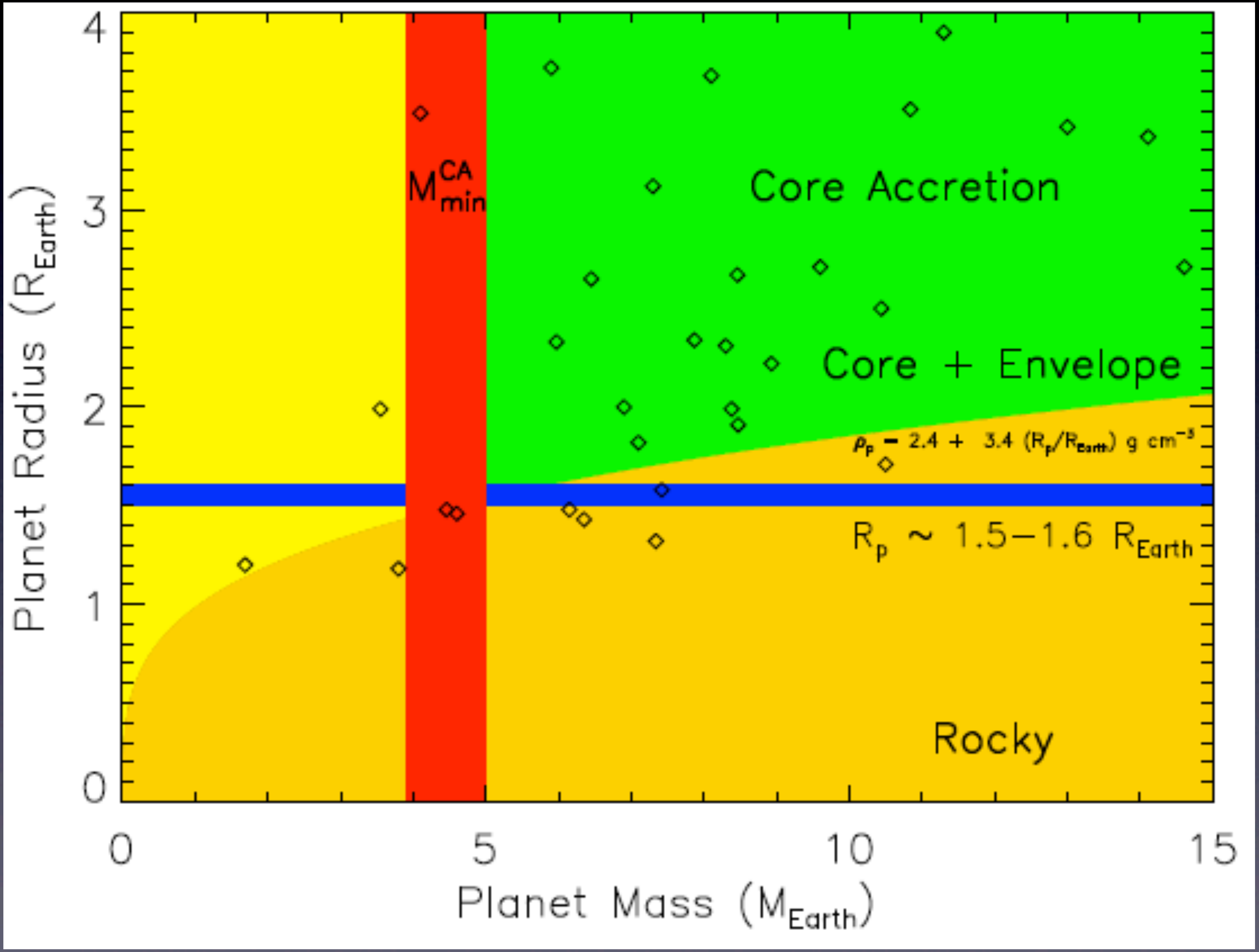
Implication for the Mass-Radius Diagram

Hasegawa 2014 in prep



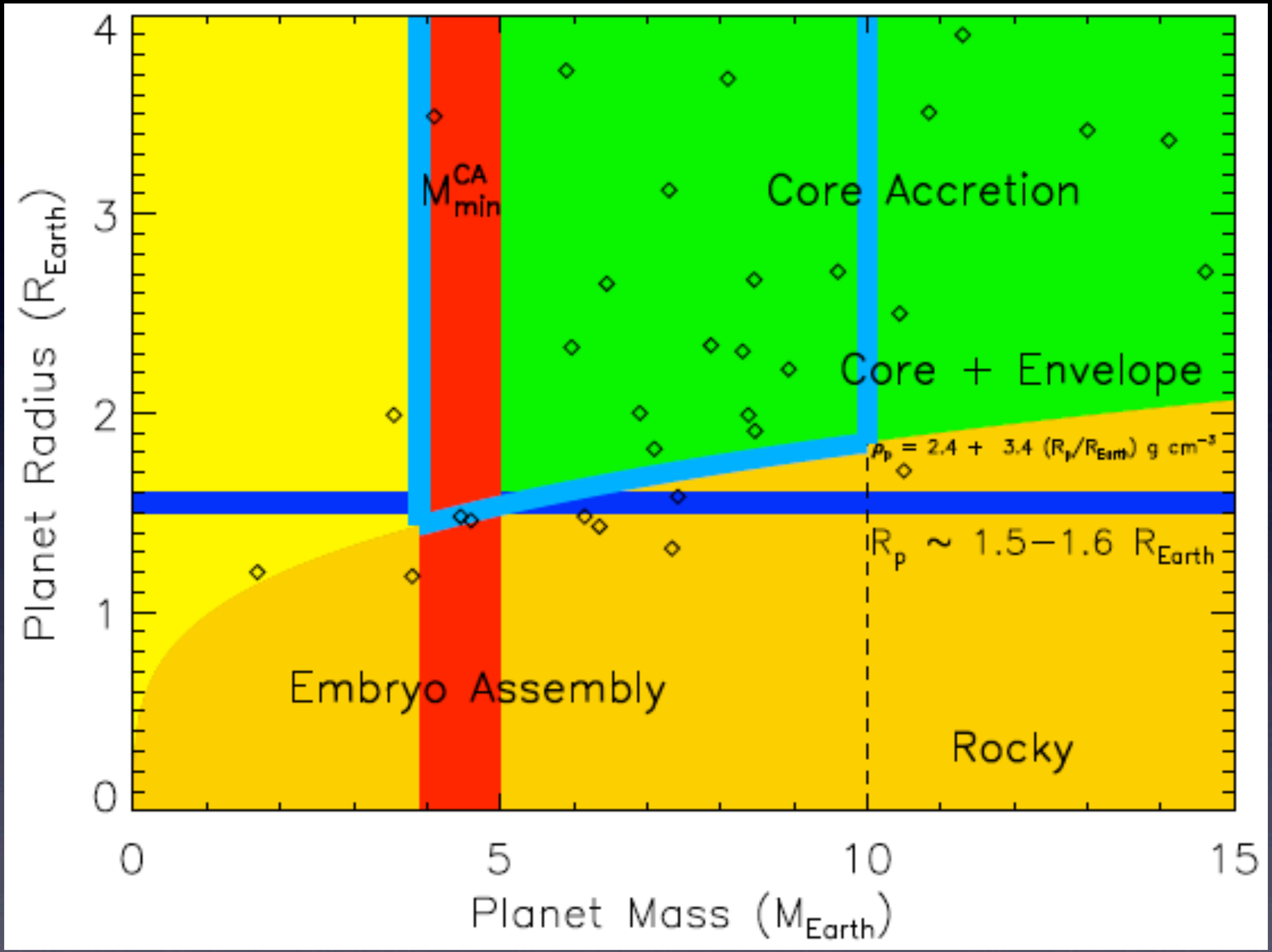
Implication for the Mass-Radius Diagram

Hasegawa 2014 in prep



Implication for the Mass-Radius Diagram

Hasegawa 2014 in prep

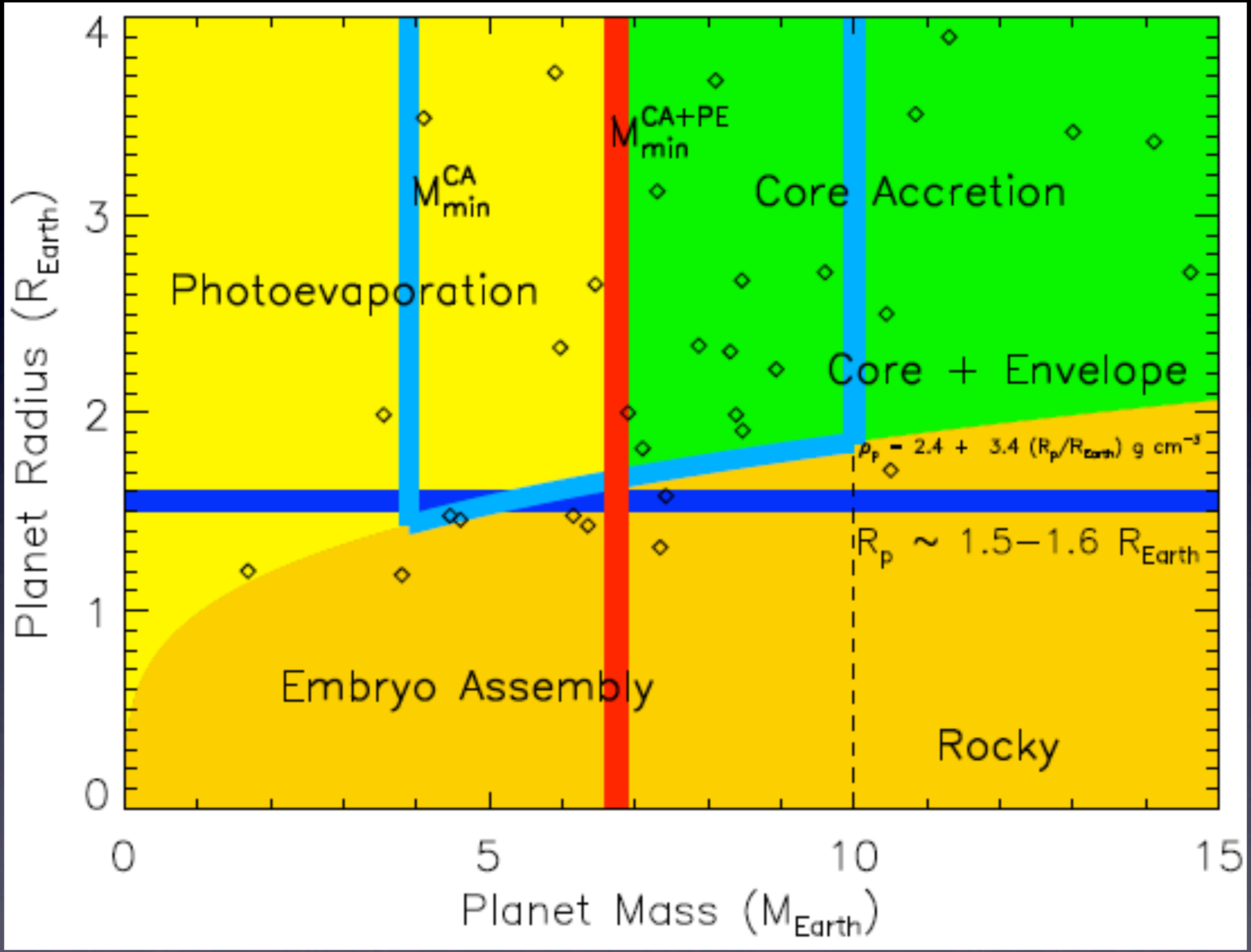


Embryo assembly scenario (in situ formation) can form planets with < 10 M_Earth

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

Implication for the Mass-Radius Diagram

Hasegawa 2014 in prep

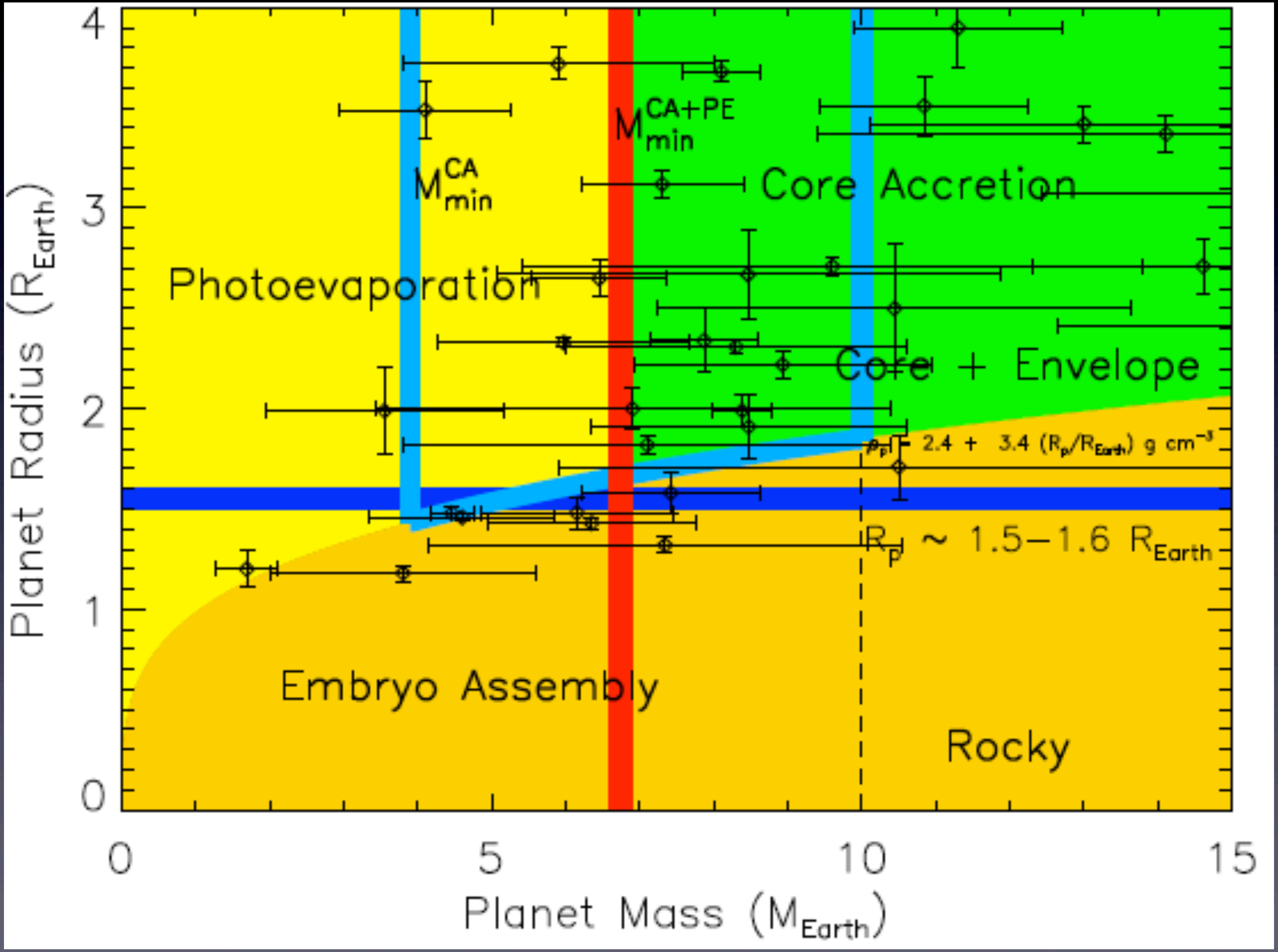


Inclusion of photoevaporative mass loss from planets

Lopez & Fortney 2013

Exoplanet "Phase" Diagram

Hasegawa 2014 in prep



Summary

- Super-Earths are very interesting populations
- The composition of super-Earths may change significantly around R_p = 1.5 R_Earth (M_p = 4-5 M_Earth)
- Discussed a new statistical approach - PFF by combining planet traps with core accretion
- Our model suggests that the minimum mass of planets formed by our model is M_p > 4-5 M_Earth
- The results do not change very much for a certain range of parameters involved with planet formation
- Our results can be understood by intimate coupling of planet formation and migration (especially by type II)