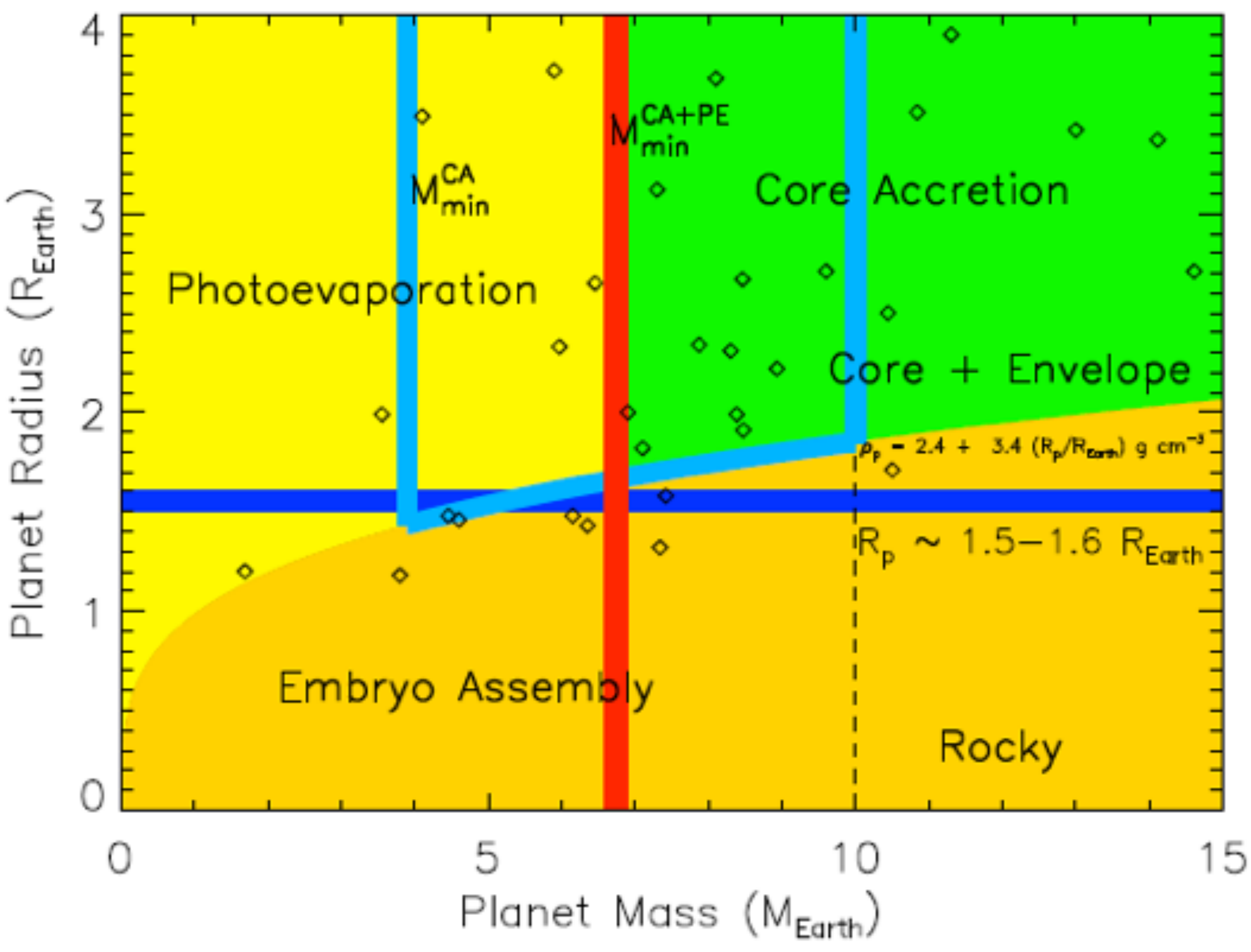
Super-Earths as Failed Cores in Orbital Migration Traps

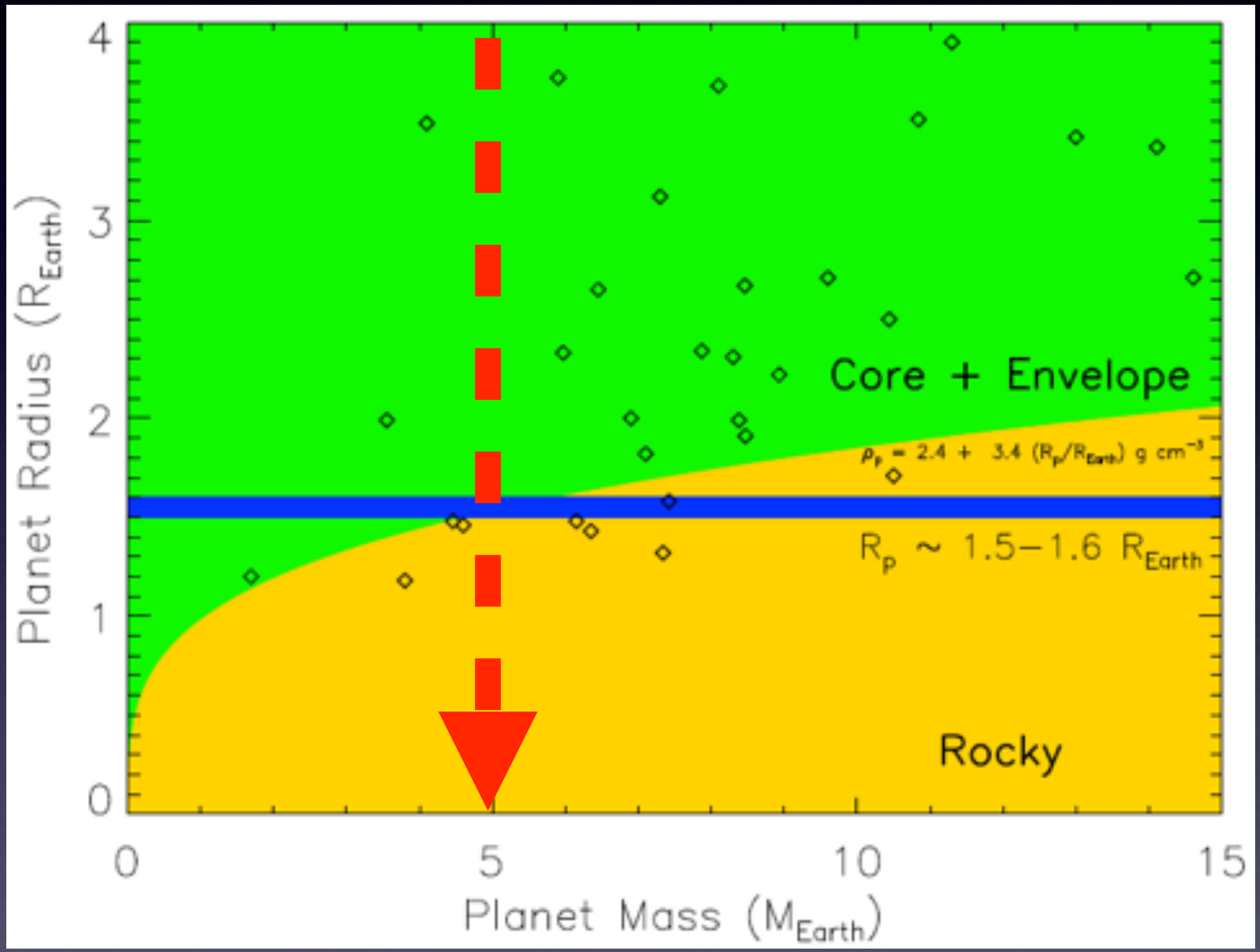


Yasuhiro Hasegawa
(Jet Propulsion Laboratory,
California Institute of Technology)

Hasegawa 2016, ApJ, 832, 83

(Potential) Links to Formation Processes of Planets

e.g., Weiss & Marcy 2014, Marcy et al 2014, Rogers 2015, Wolfgang & Lopez 2014



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

Planets w/ > 1.5 - 1.6 Re

: not purely rocky

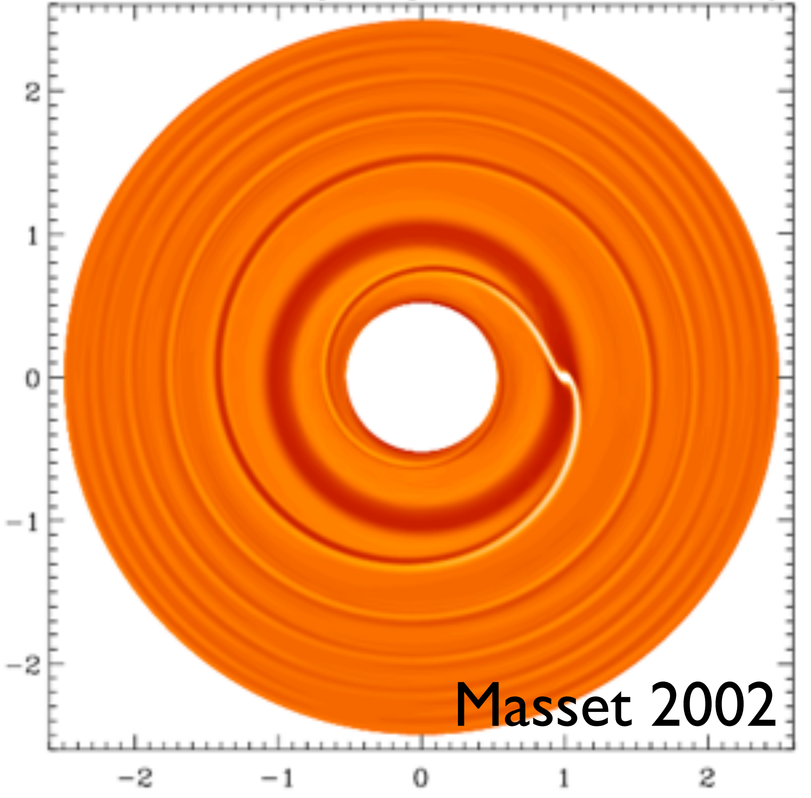
Planets w/ < 1.5 - 1.6 Re

: likely to be purely rocky

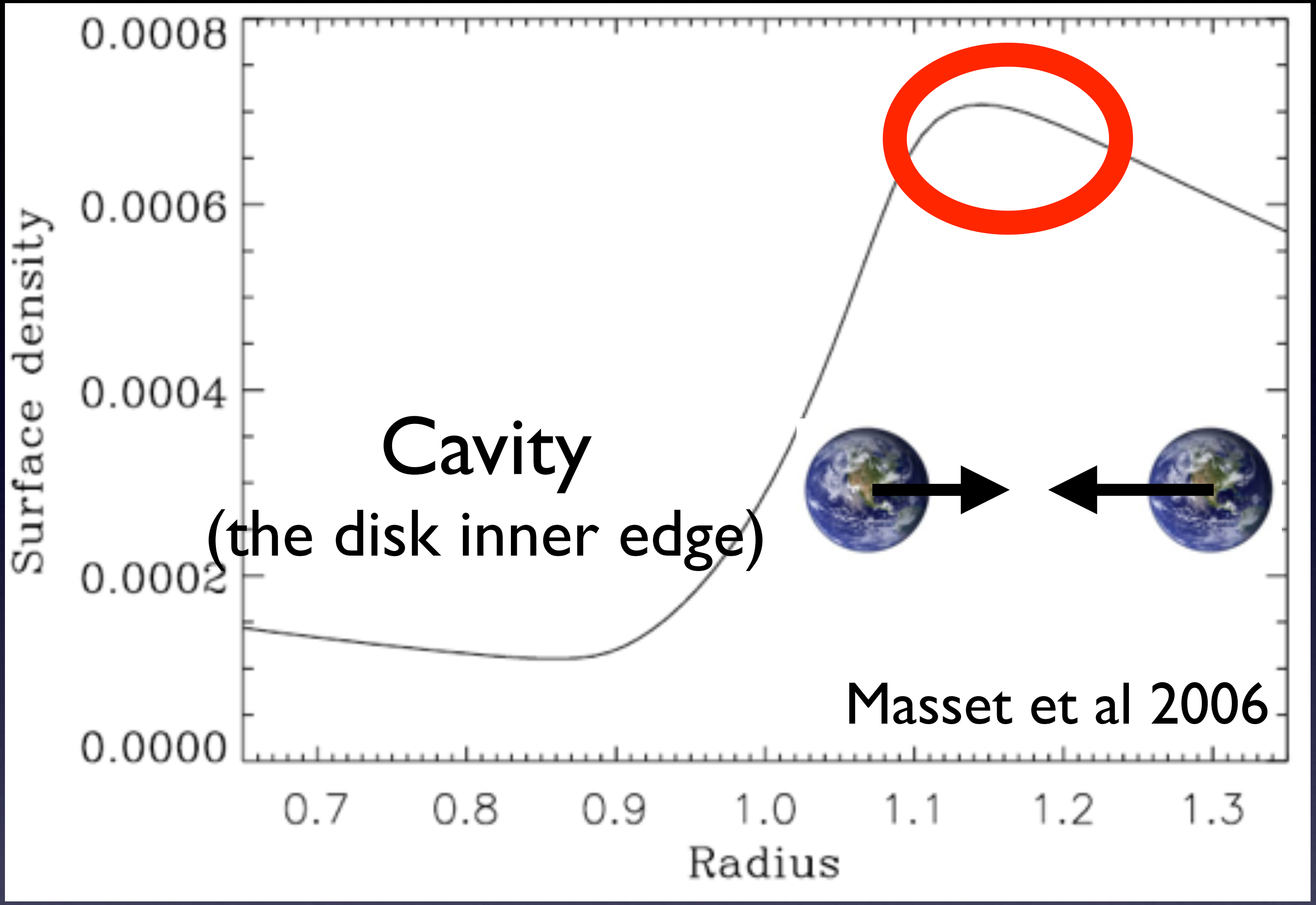
An Implication =>
$M_p \simeq 5 M_\oplus$ may be a
Minimum Mass of Planets
Formed in Gas Disks???

Key Idea: Type I Migration Traps (Planet Traps)

e.g., Masset et al 2006, Hasegawa & Pudritz 2011b



Masset 2002



Cavity

(the disk inner edge)

Masset et al 2006

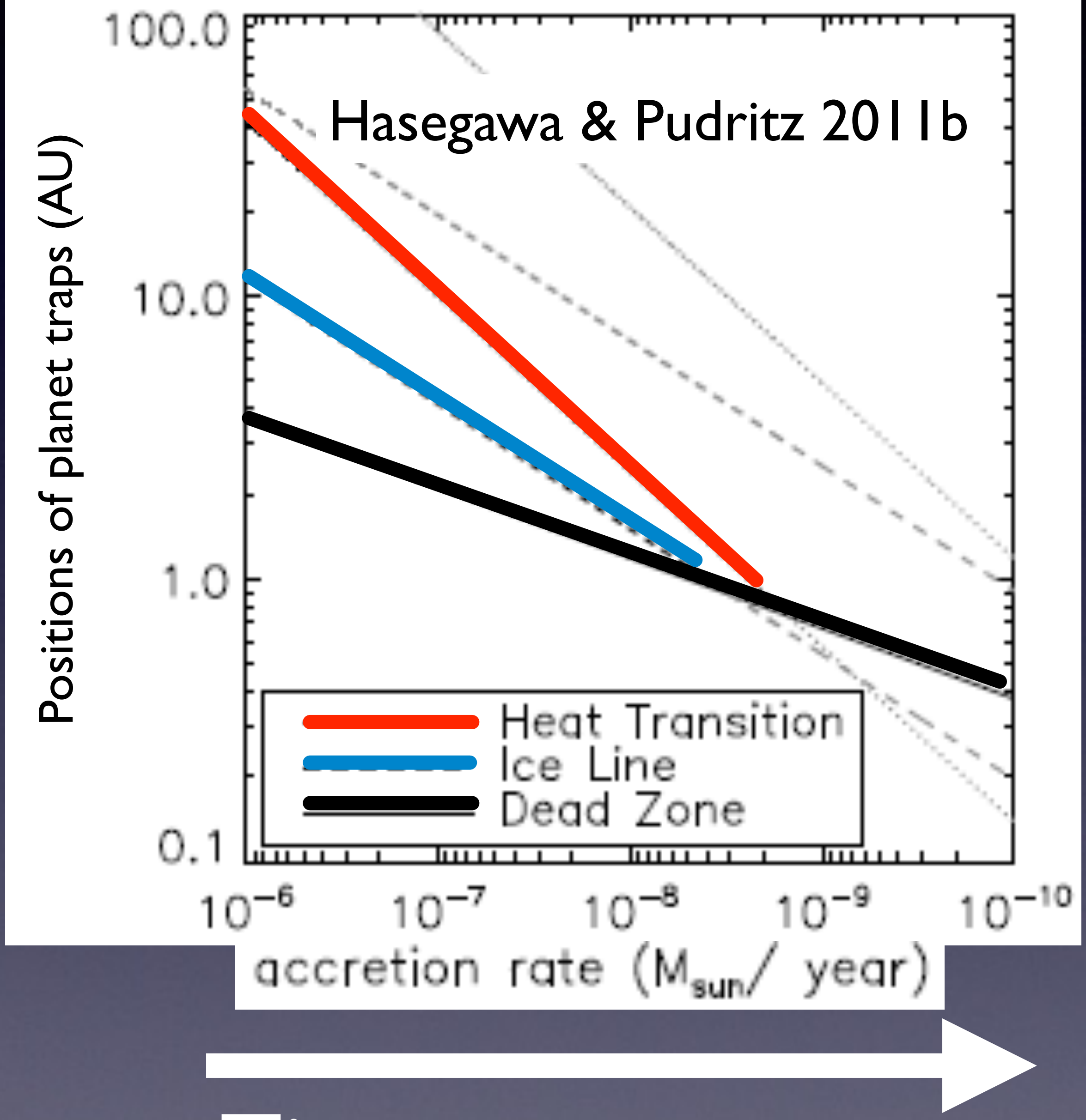
Planetary Migration =
Angular Momentum Transfer
between Planets and Gas Disks

The **Net** of Transferred
Angular Momentum Regulates
the **Direction** of Migration,
which Depends on Disk Structures

Planet Traps = Disk Structures
where the Net Torque
becomes Zero
(i.e. Dead Zones, Ice Lines, etc..)

Fundamental Properties of Planet Traps

e.g., Hasegawa & Pudritz 2011b



Time

Multiple 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

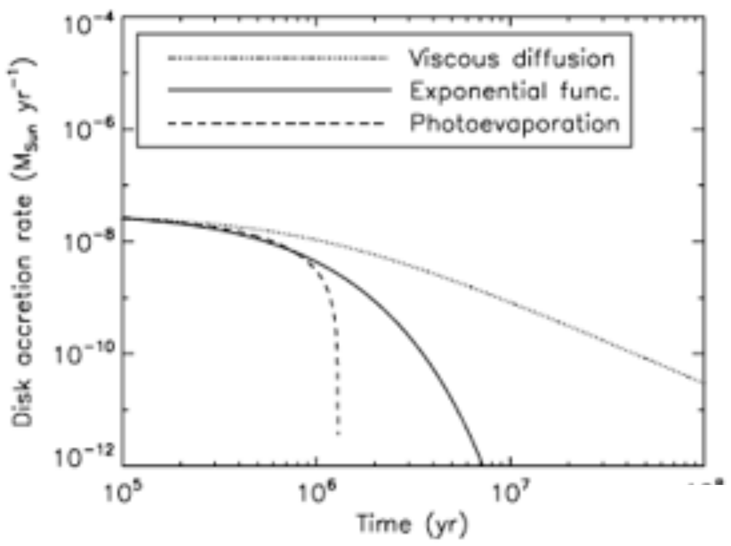
Planets Form Locally at Traps (r > 1 AU) Before Type II Migration

Result 1: Evolutionary Tracks of Trapped Planets

Hasegawa & Pudritz 2012

Disk Evolution

e.g., Hartmann et al 1998

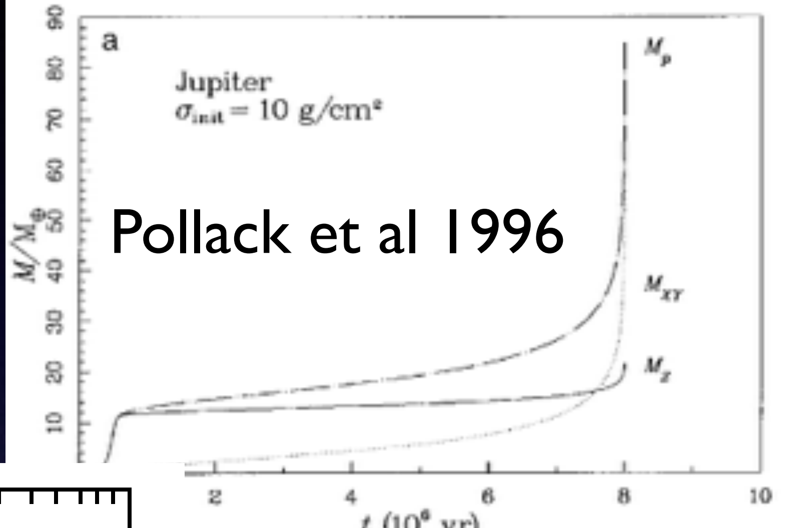


Planetary Migration (Orbital Evolution)

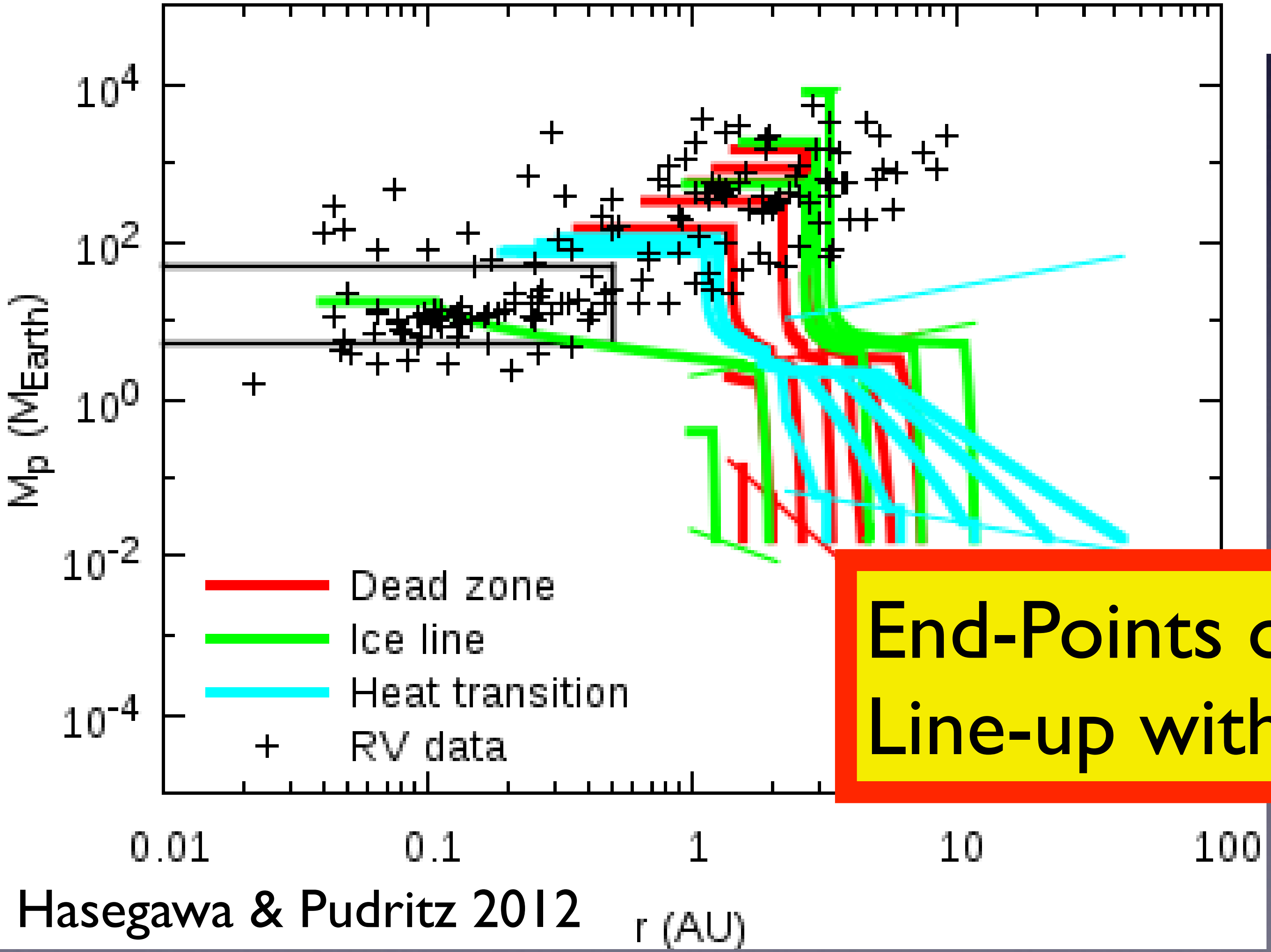
Planet Traps for Low Mass Planets

Type II for Massive Planets (w/ a Gap)

Core Accretion (Mass Growth)



Pollack et al 1996



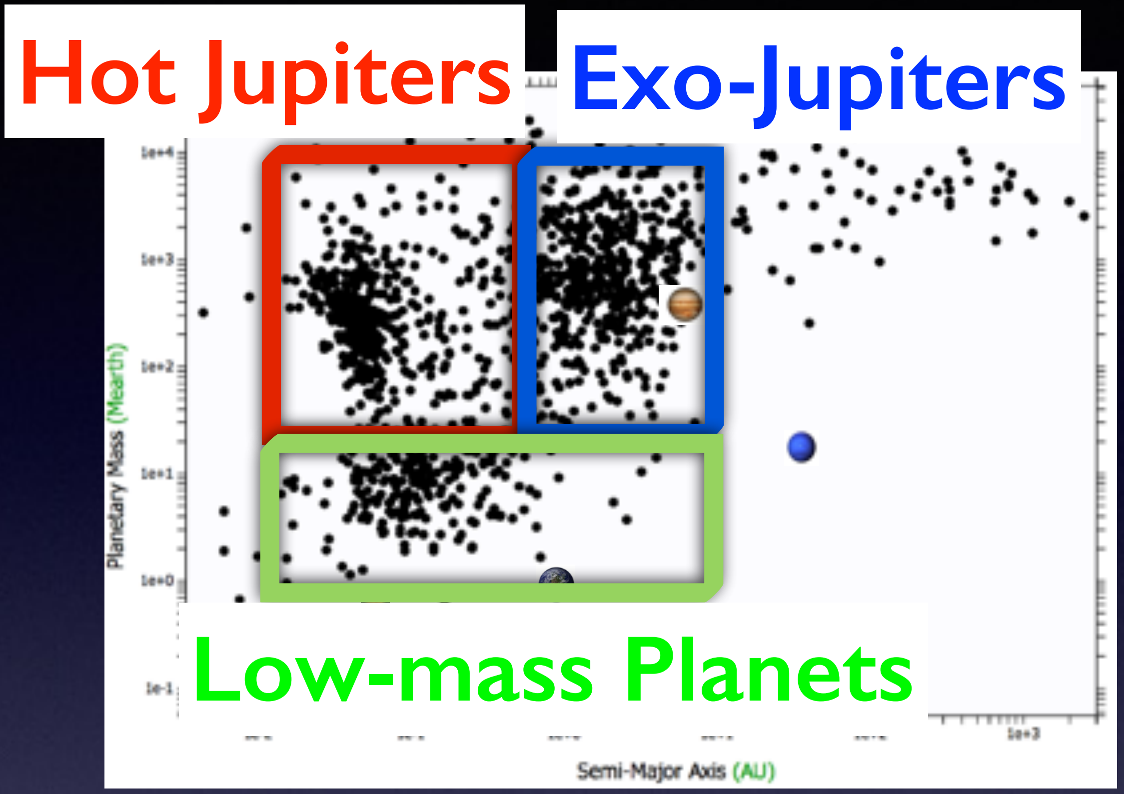
Hasegawa & Pudritz 2012

End-Points of Tracks Line-up with the RV Data

Result 2: Statistical Analysis for Computed Tracks

Hasegawa & Pudritz 2013

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

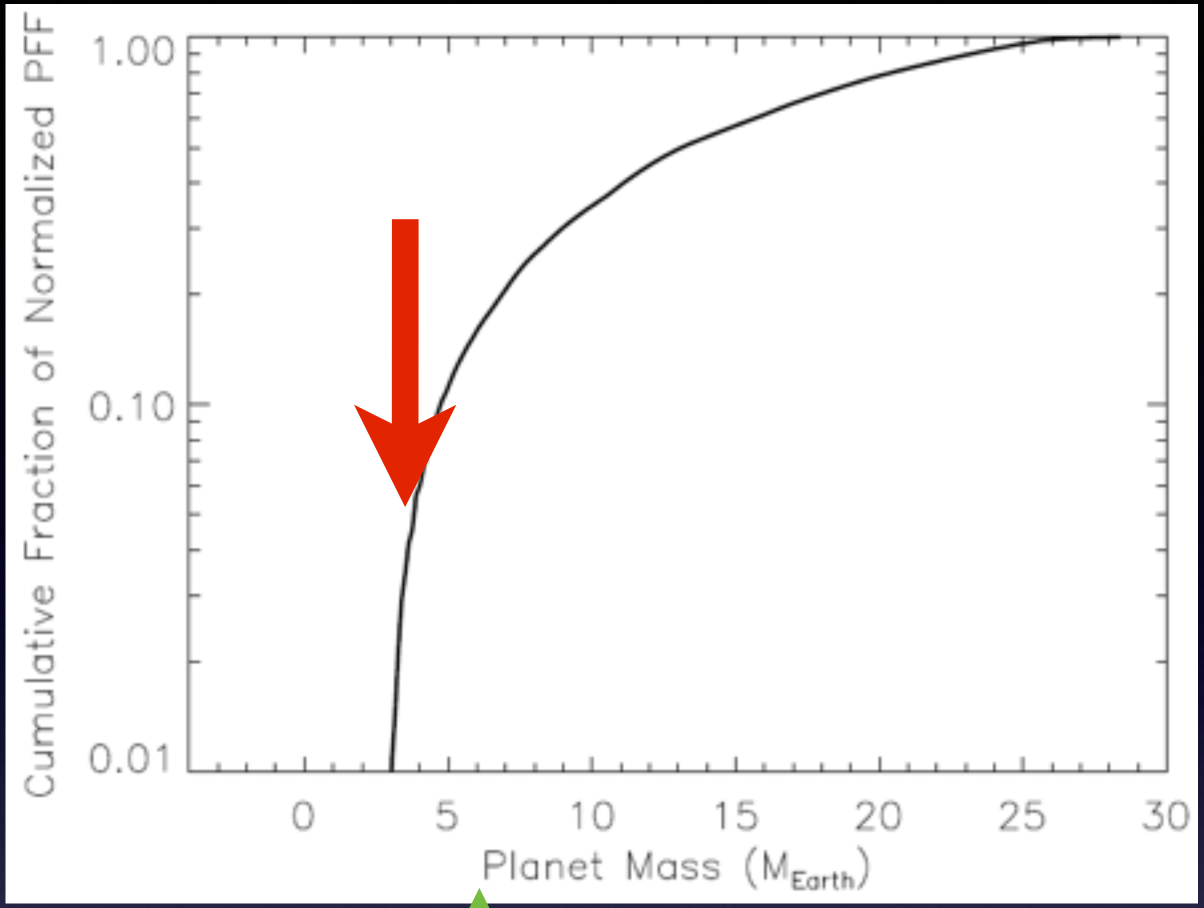
	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	~ 7.6 %	~ 25.3 %	~ 10.2 %	43.1%

The Observational Trend of Massive Planets can be Reproduced

Other Formation Mechanisms are Needed for Super-Earths

The Minimum Mass of Planets Formed by Core Accretion at Planet Traps:

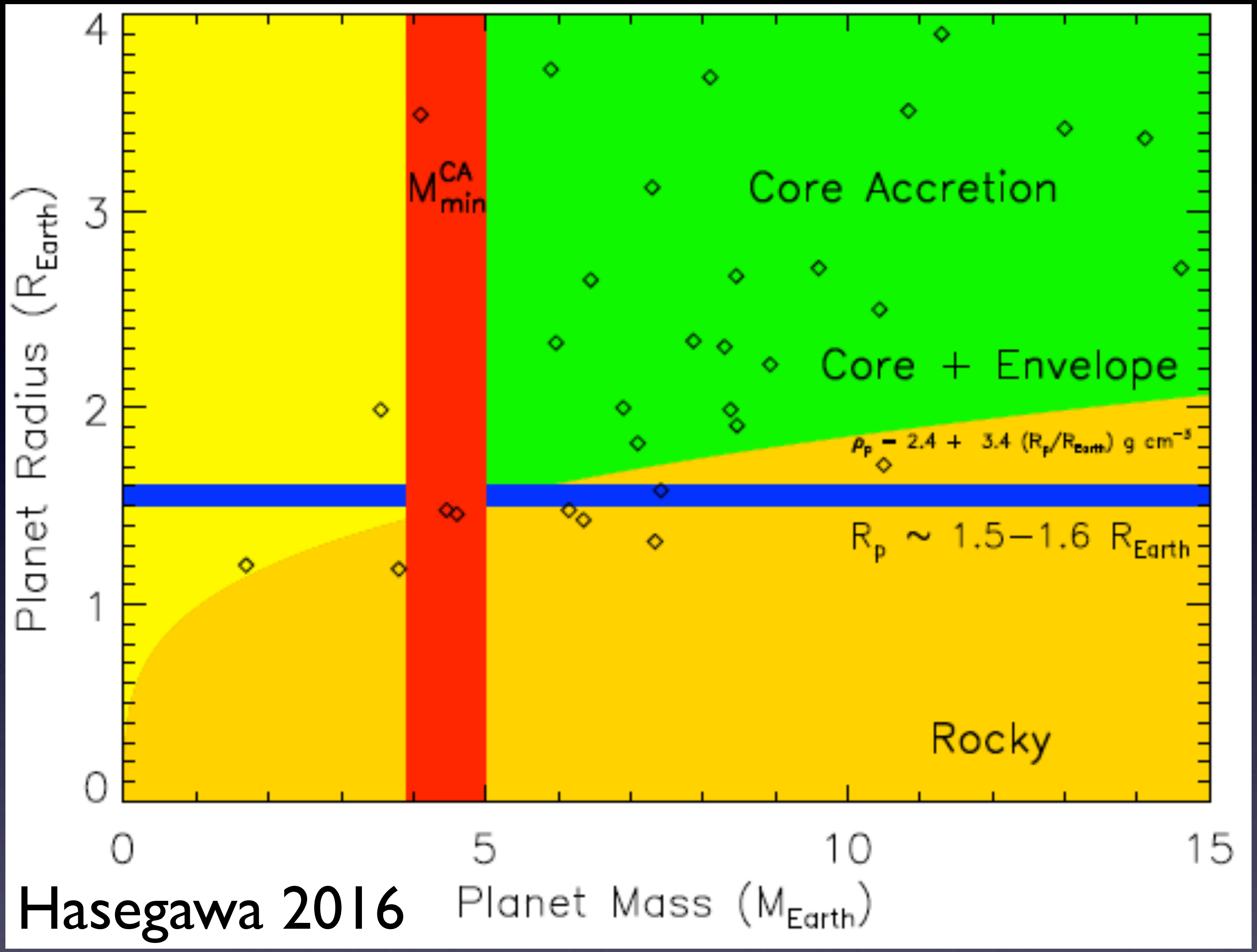
$$M_{min}^{CA} \simeq 4 - 5 M_{\oplus}$$



	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	~ 7.6 %	~ 25.3 %	~ 10.2 %	43.1%

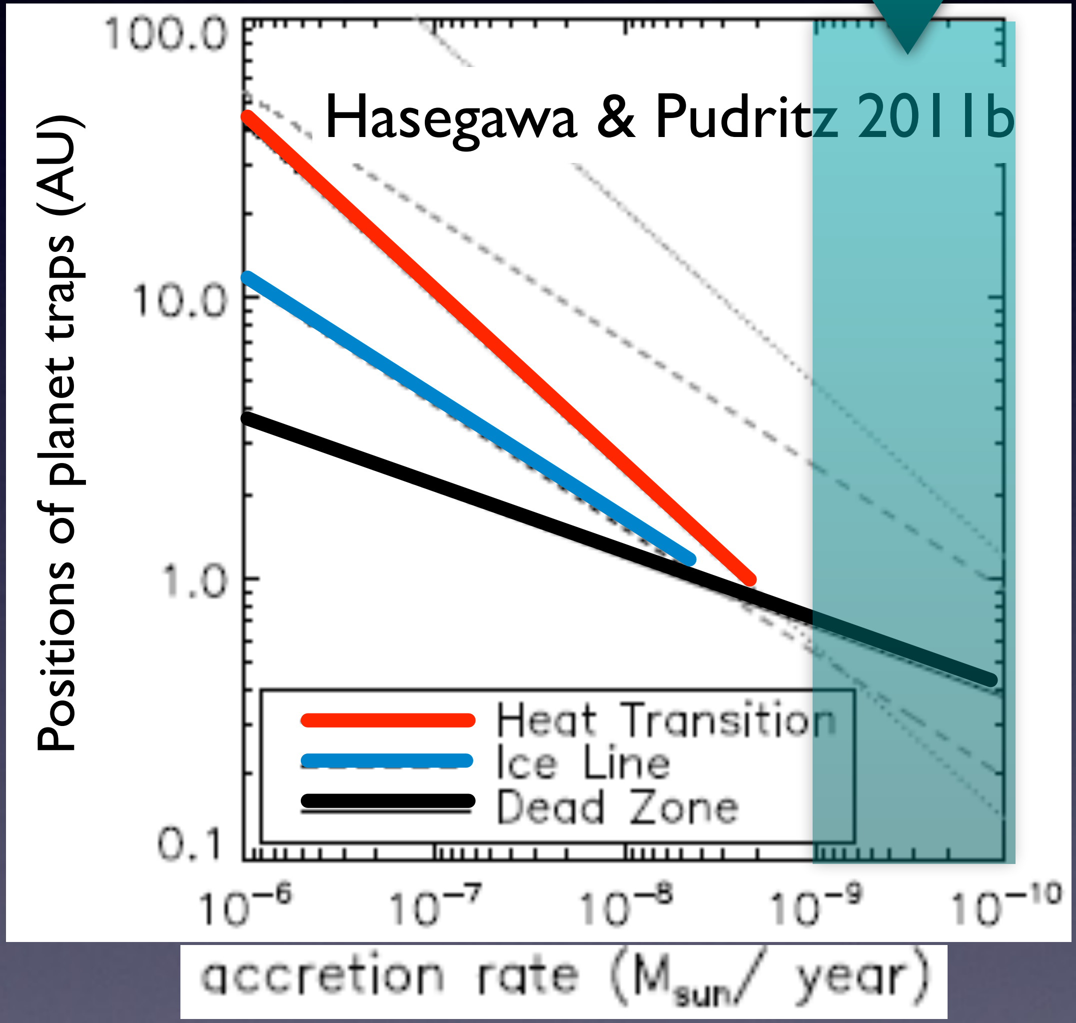
A Considerable Fraction of Close-in Super-Earths can be Formed as Failed Cores of Gas Giants (Mini-Gas Giants)

Switching of Migration Modes at $M_{min}^{CA} \simeq 4-5M_{\oplus}$



Hasegawa 2016

No Gas in Disks
No Planet Traps



Time

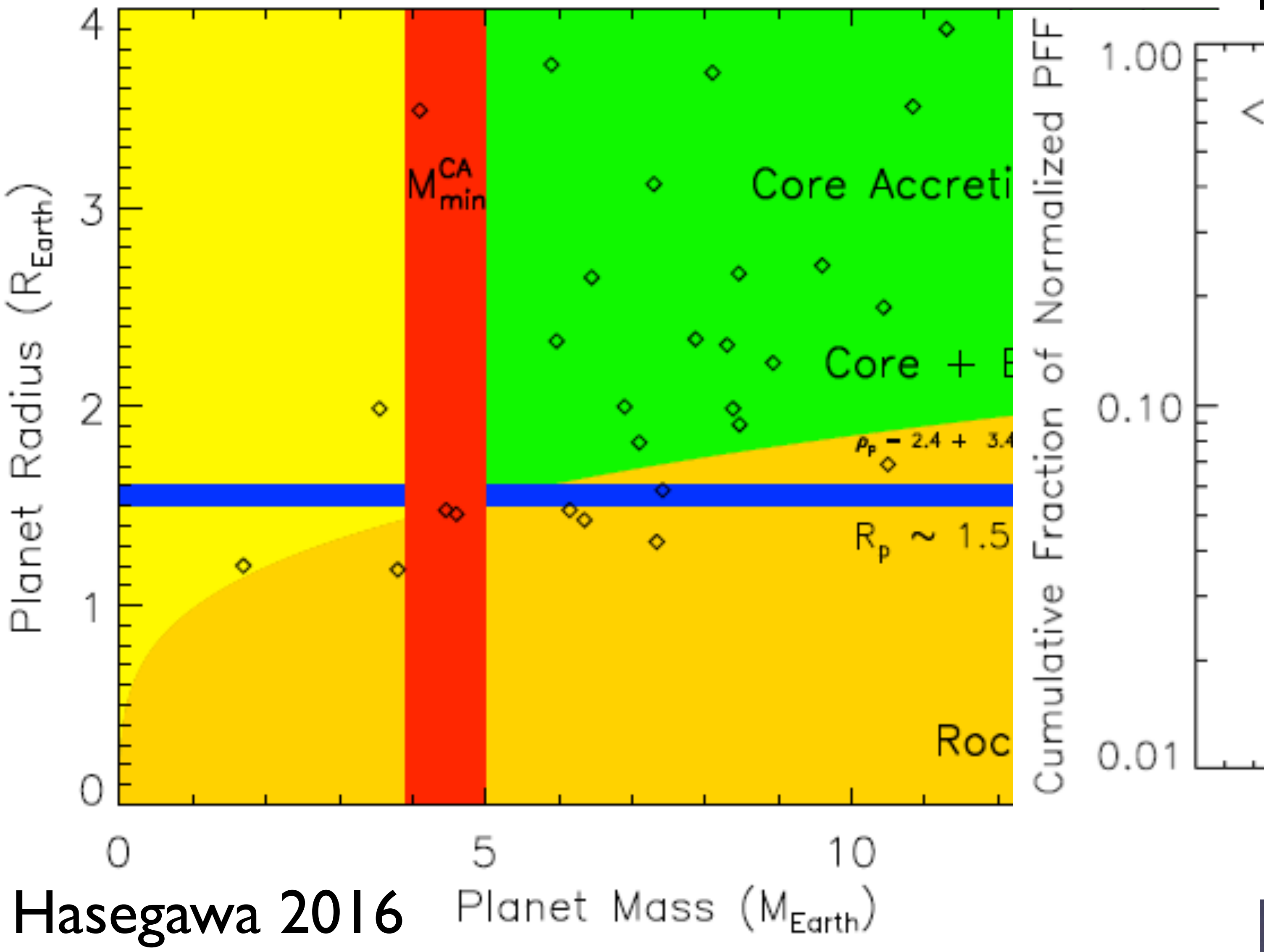
Planet Traps (Type I Migration)

:Transport Forming Planetary Cores
from Large Orbital Radii to >1 AU

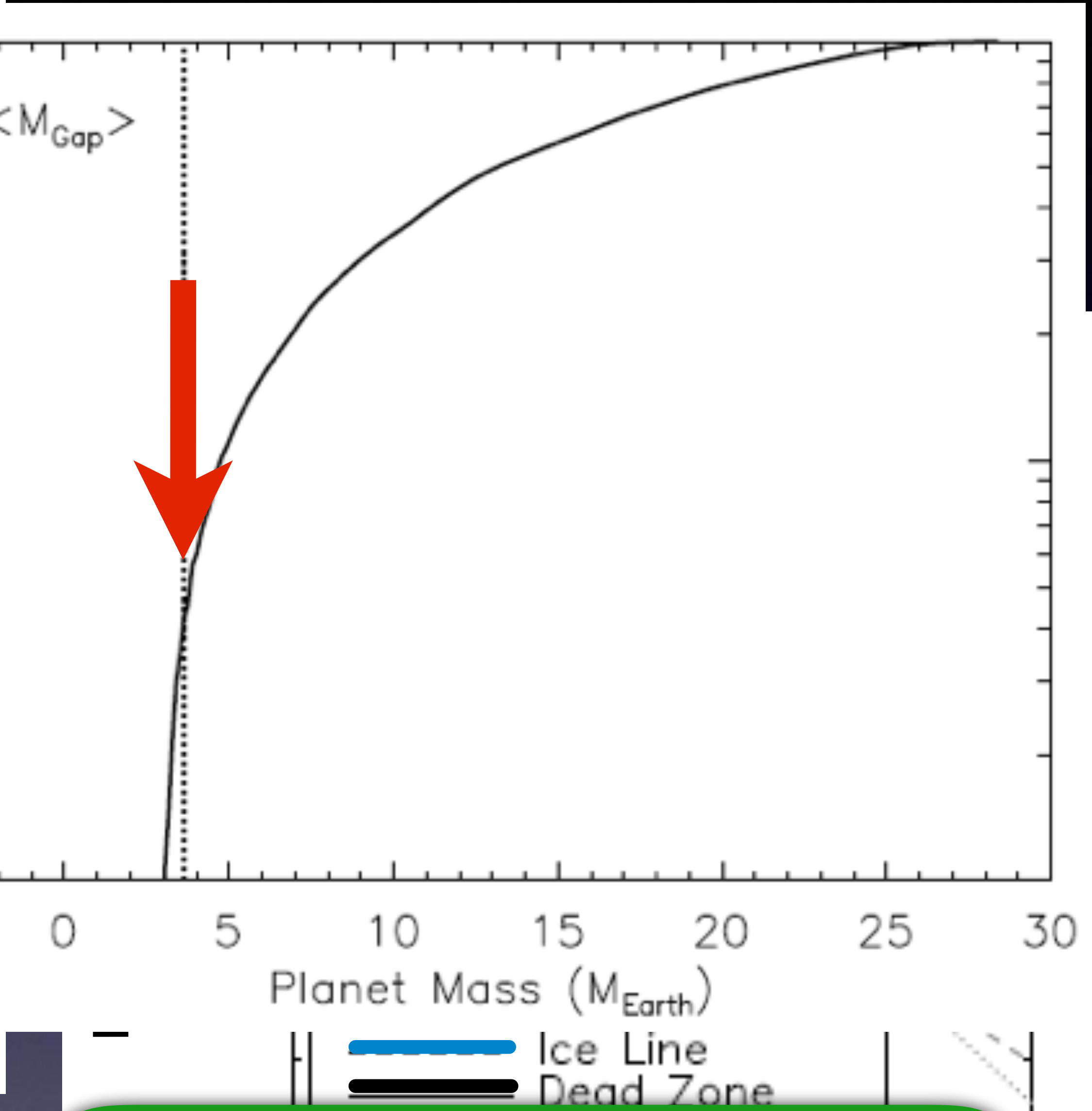
Type II Migration (w/ a Gap)

:Transport the Cores from r > 1 AU to r < 1 AU

Switching of Migration Modes at $M_{min}^{CA} \simeq 4-5M_{\oplus}$



Hasegawa 2016



Planet Traps (Type I Migration)

:Transport Forming Planetary Cores from Large Orbital Radii to >1 AU

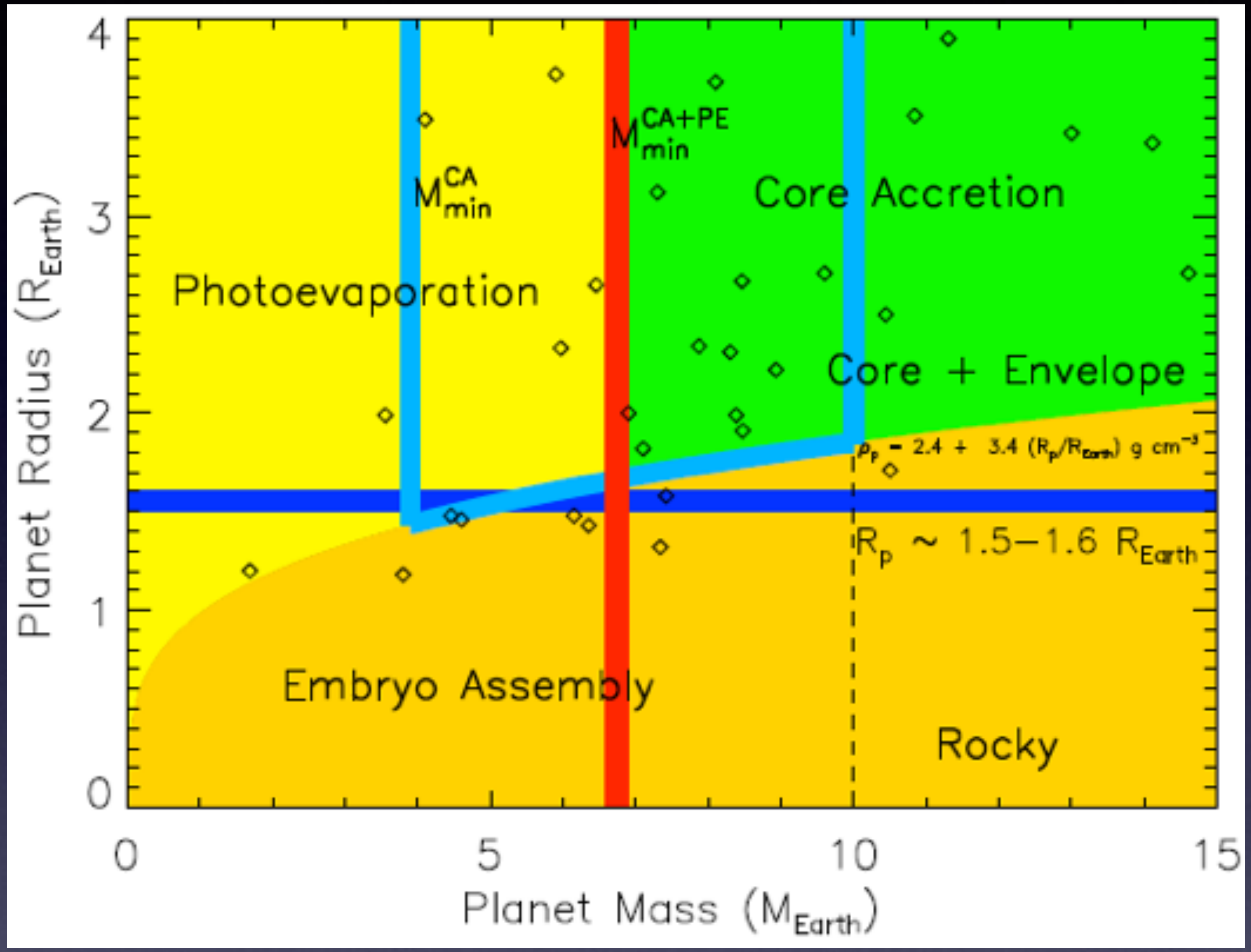
Type II Migration (w/ a Gap)

:Transport the Cores from r > 1 AU to r < 1 AU

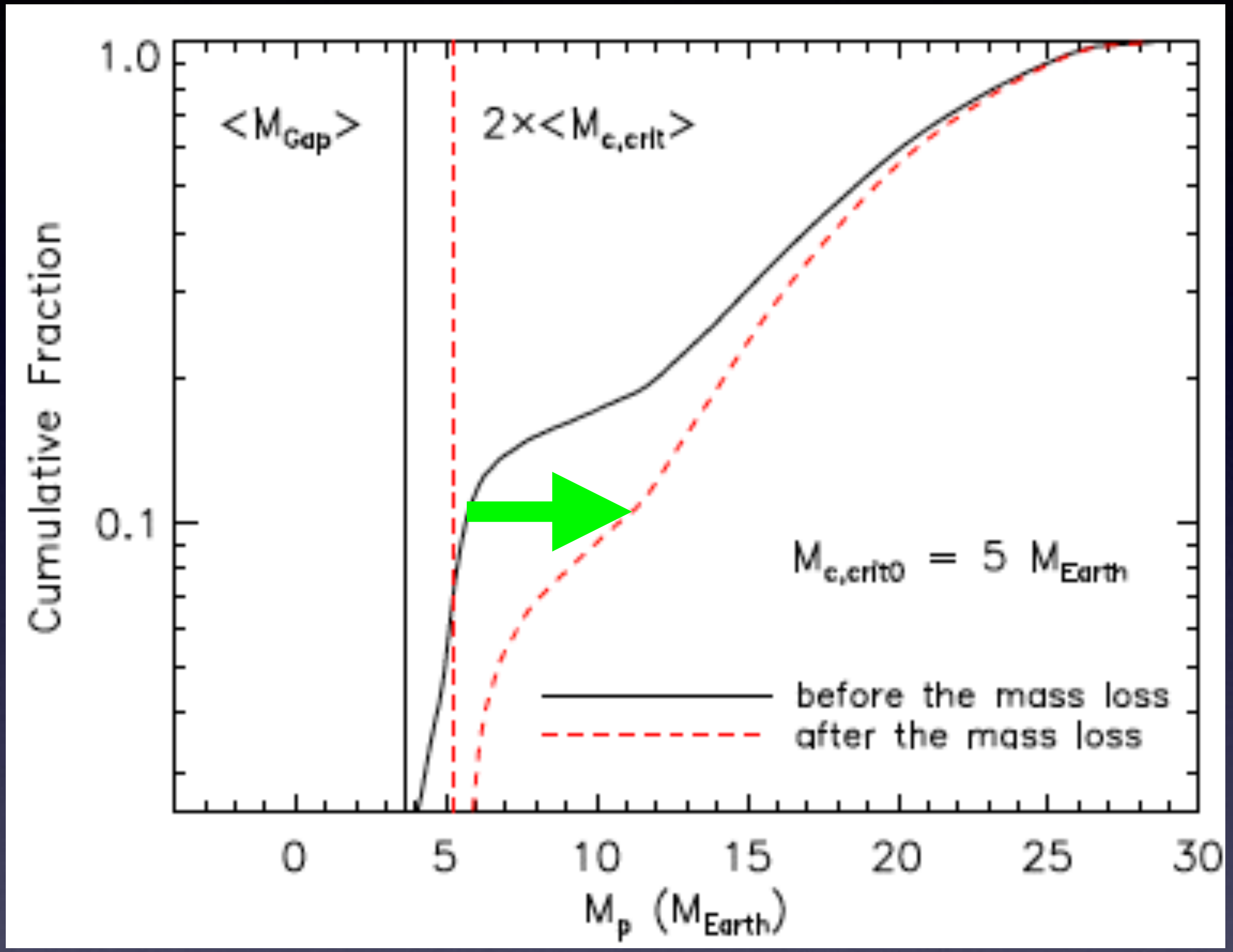
$< M_{Gap} >$ = the Mean Value of the Gap-Opening Mass for Close-in Super-Earths

The Effect of Atmospheric Escape

Hasegawa 2016



The Mass-Radius Diagram Divides into a Number of Regions, and can Specify the Formation Histories of Close-in Super-Earths

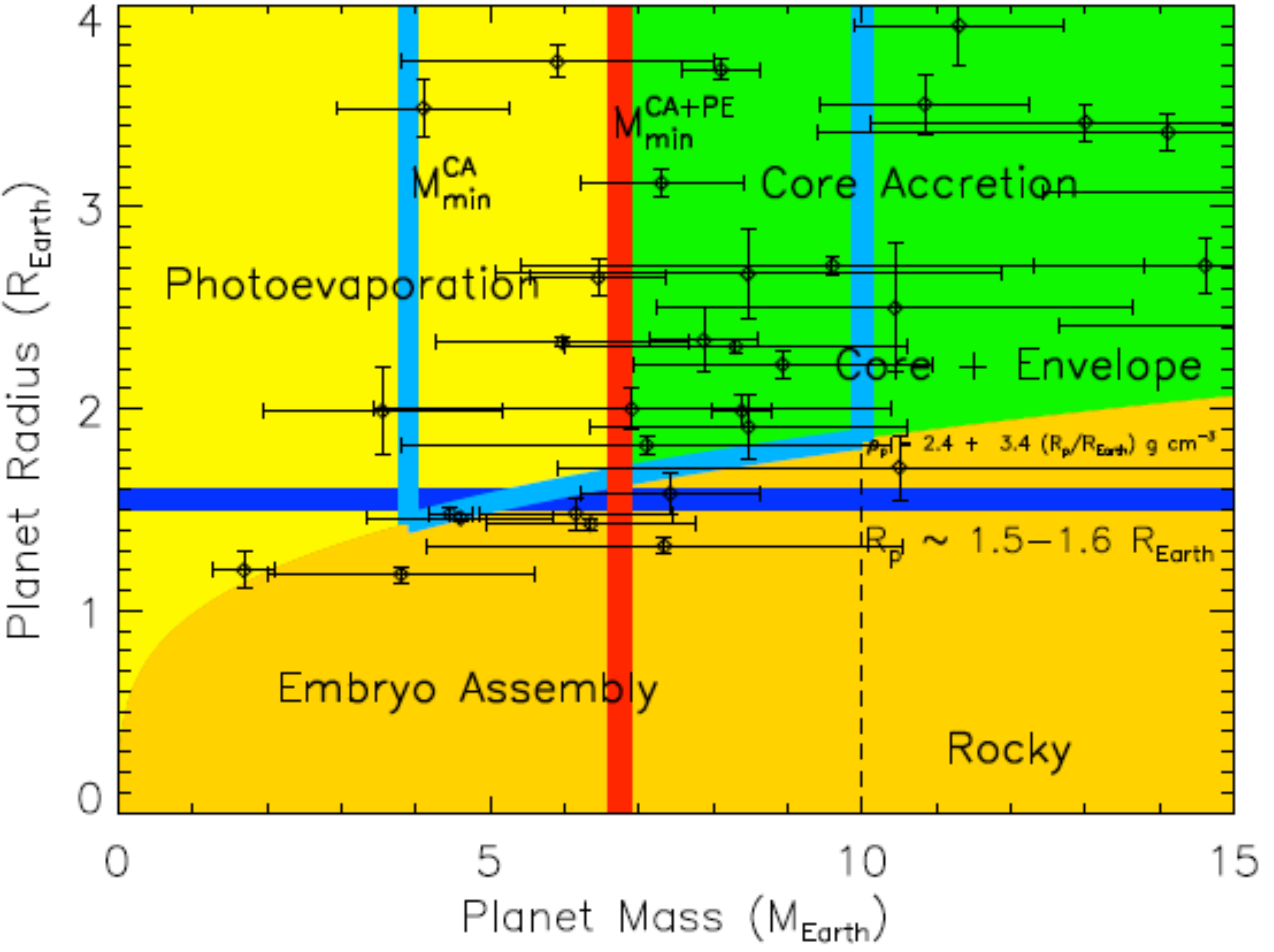


Photoevaporative Mass Loss Increases M_{min}^{CA} of $\sim 5 M_\oplus$ to M_{min}^{CA+PE} of $\sim 7 M_\oplus$ by Stripping the Gas Envelopes

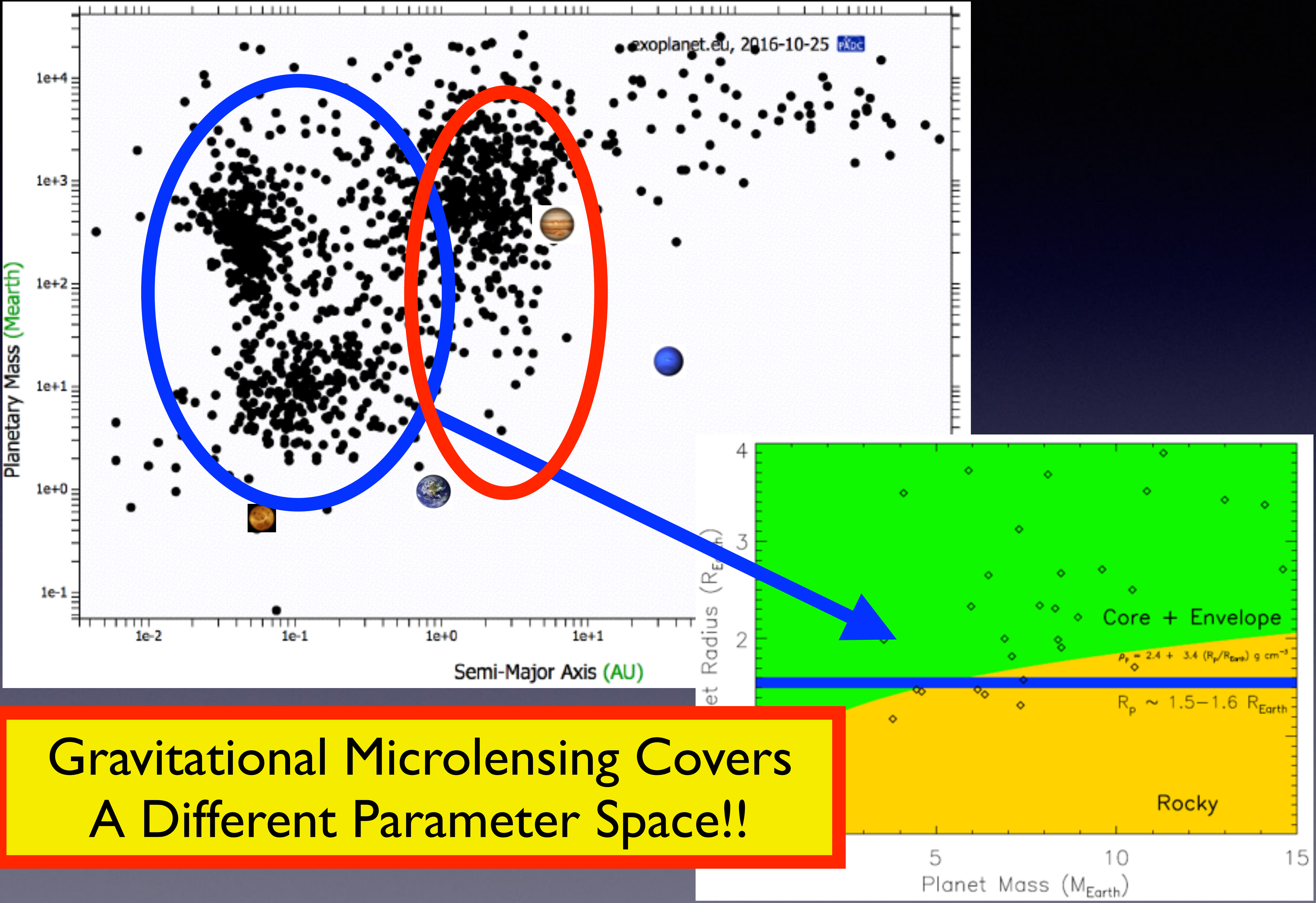
Lopez & Fortney 2013

Exoplanet "Phase" Diagram

Hasegawa 2016



Implications for Gravitational Microlensing



Gravitational Microlensing Covers
A Different Parameter Space!!

Summary

Hasegawa 2016, ApJ, 832, 83

- The currently observed exoplanetary populations are quite useful for deriving some constraints on theory of planet formation
- A population synthesis model is developed, focusing on Type I migration traps (dead zone, ice line, heat transition)
- Planet traps may be important to reproduce the trend of observed massive exoplanets, and for some fractions of observed close-in super-Earths
- Switching of migration modes determines the minimum mass of super-Earths formed by our model, which is M_p > 4-5 M_Earth, & the mass-radius diagram can serve as an exoplanet “phase” diagram
- (Future) gravitational microlensing observations can fill out a different parameter space, and would be useful for drawing a better picture of planet formation

Supplementary

Model: Evolutionary Tracks of Trapped Planets

e.g., Hasegawa & Pudritz 2012

Disk Evolution

+

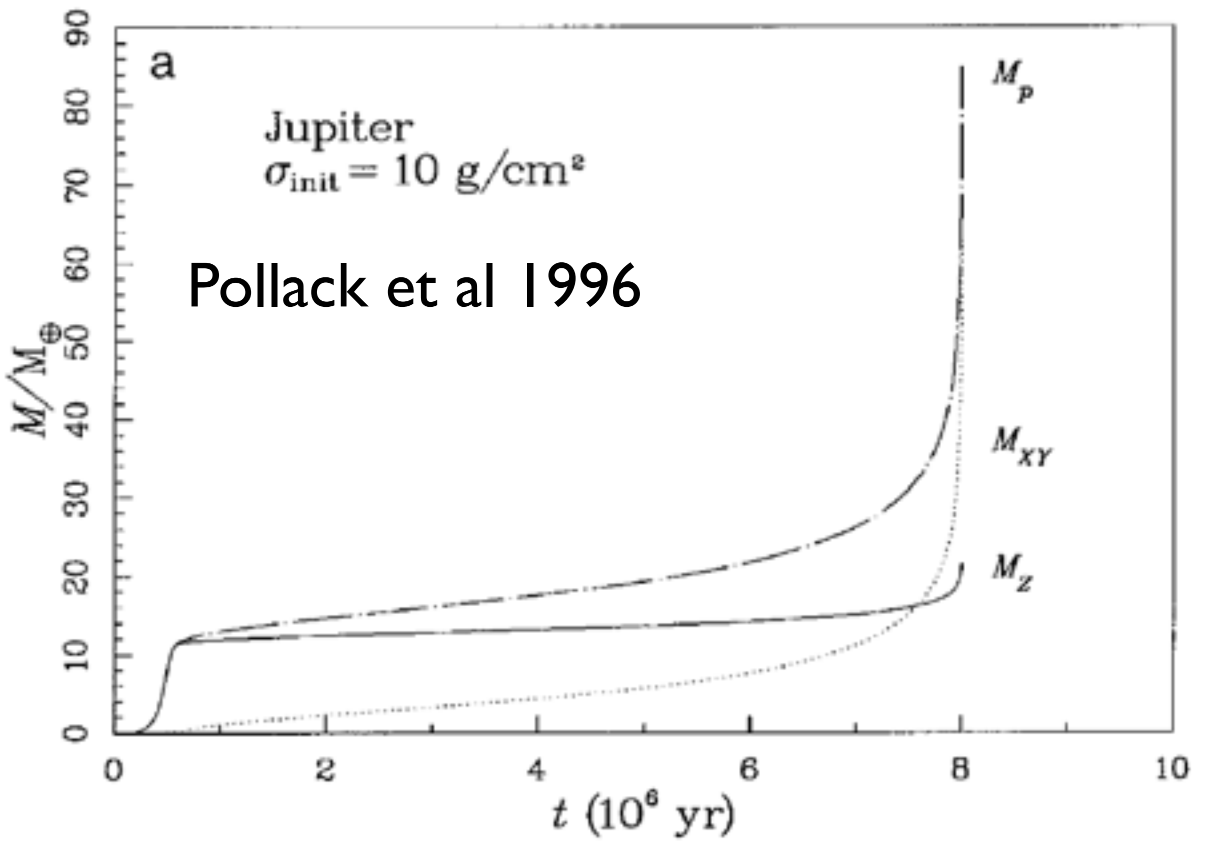
Planetary Migration

(Planet Traps + Type II)

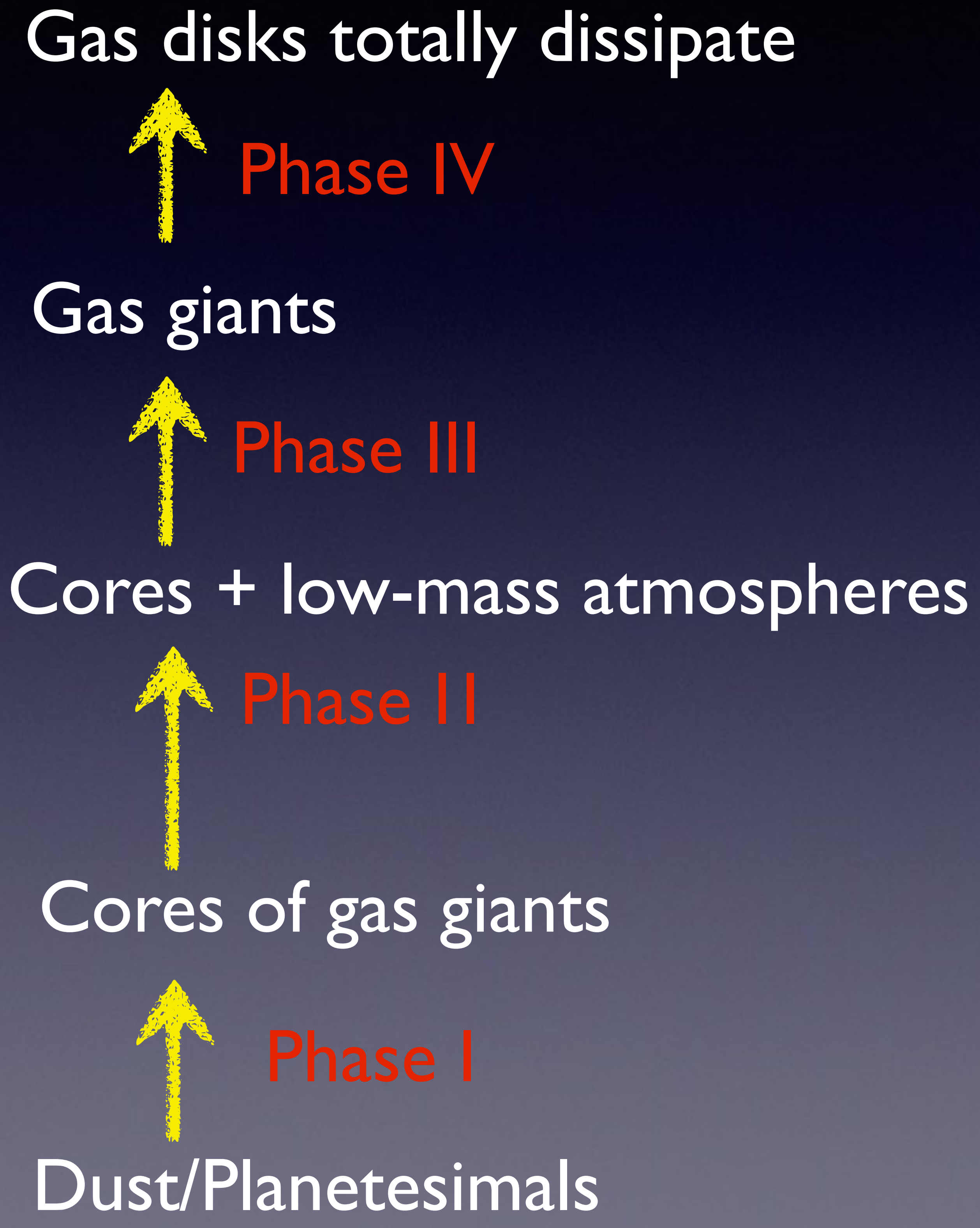
+

Core Accretion

(Mass Growth)



Pollack et al 1996



Gas disks totally dissipate

Phase IV

Gas giants

Phase III

Cores + low-mass atmospheres

Phase II

Cores of gas giants

Phase I

Dust/Planetesimals

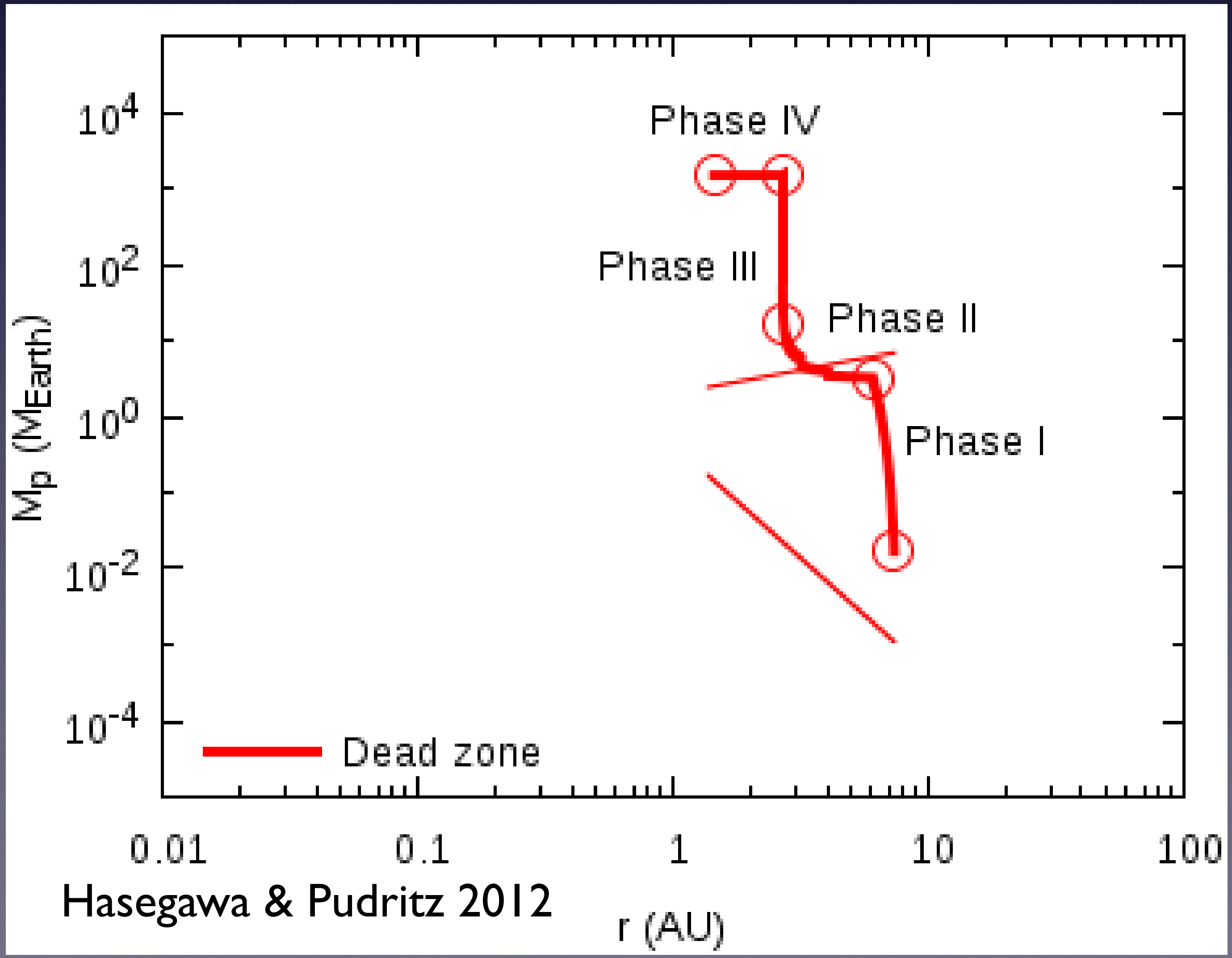
Results: Evolutionary Tracks of Trapped Planets

e.g., 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

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

Results: Evolutionary Tracks of Trapped Planets

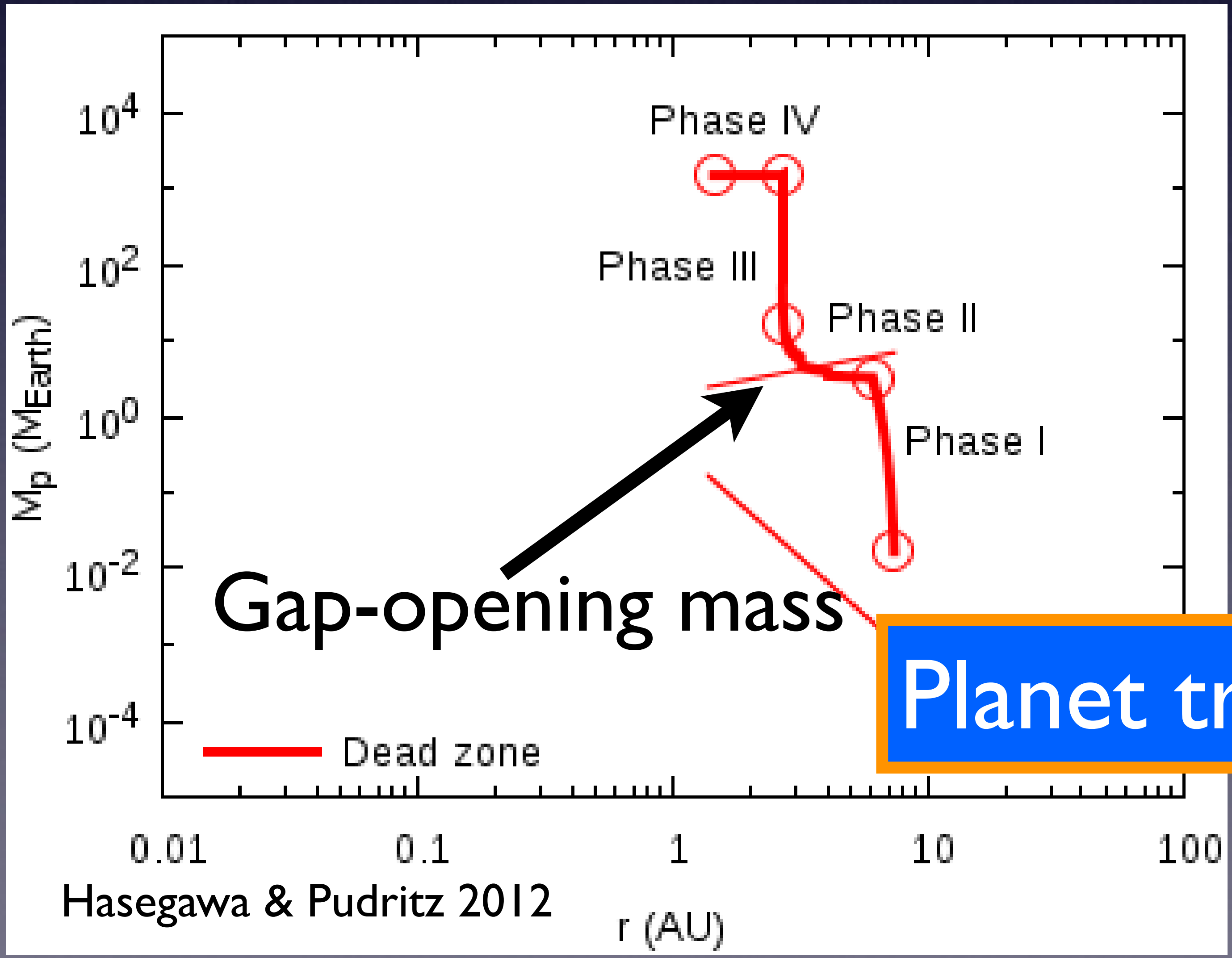
e.g., Hasegawa & Pudritz 2012

A disk around a classical T Tauri star is considered

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

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

Type II migration



Gap-opening mass

Planet traps

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

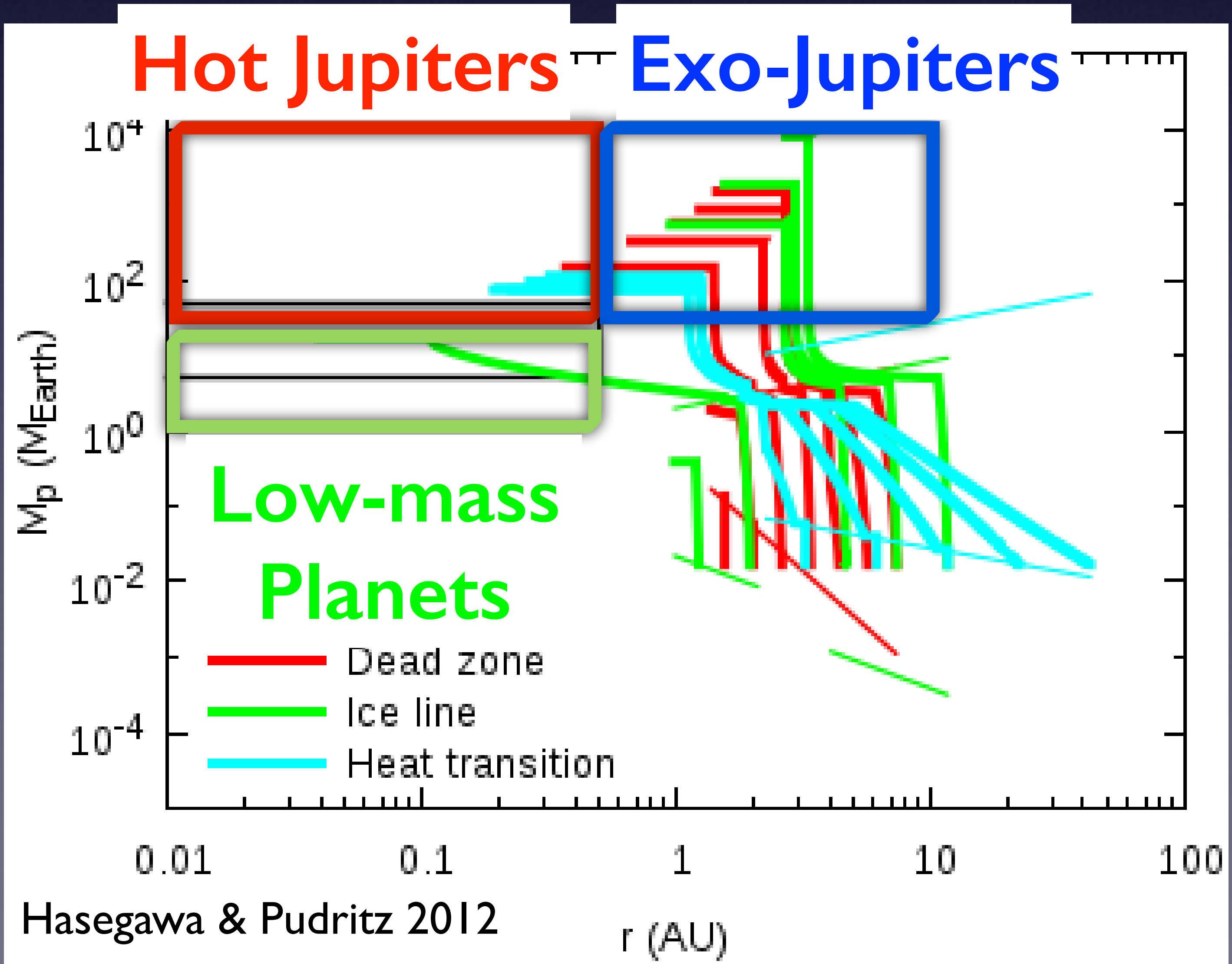
Statistical Analysis for Computed Tracks

e.g., 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)

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

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

↓

Weight functions related to disk observations