Planet Traps & Planetary Cores

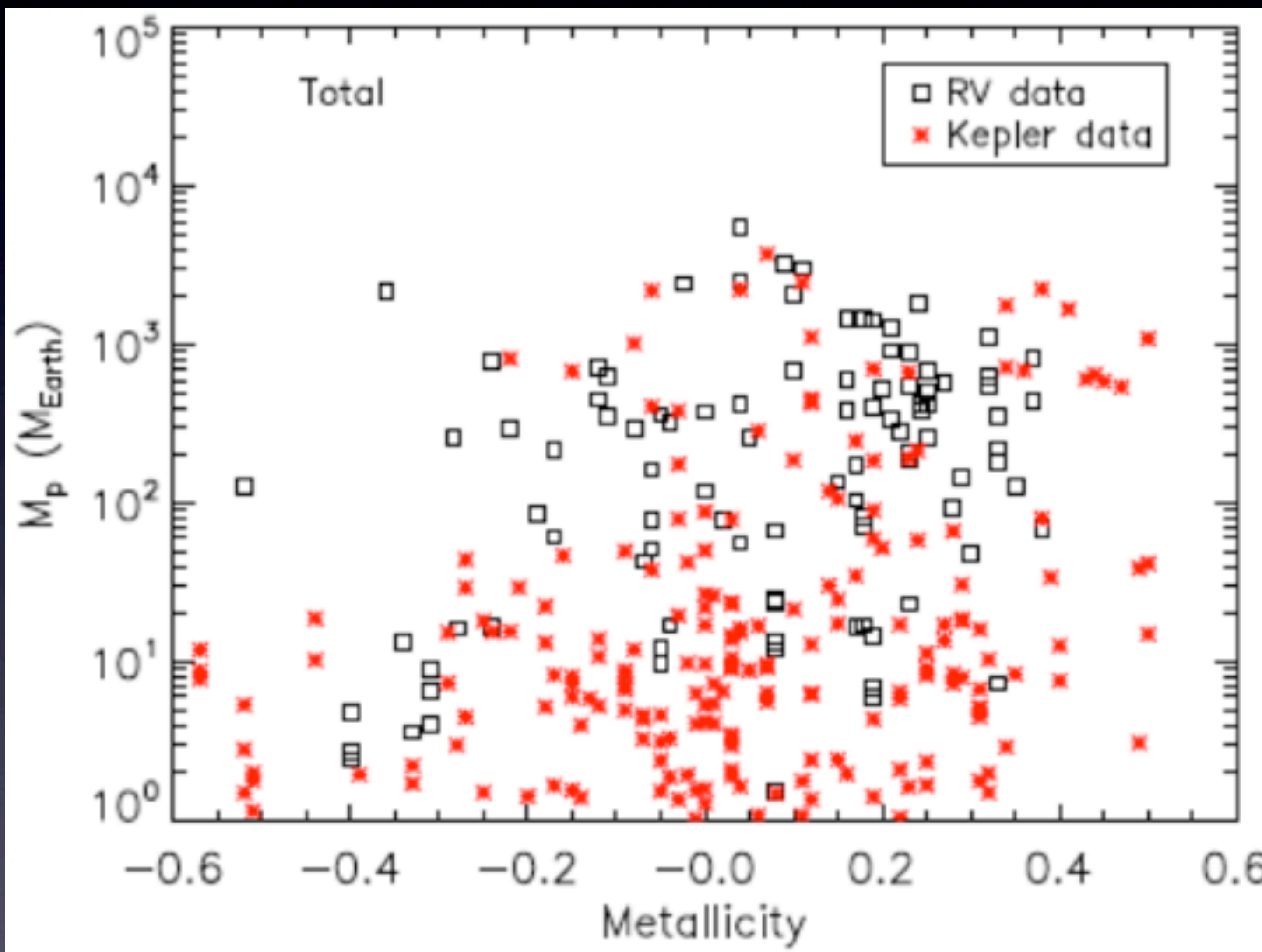
: Origins of the Planet-Metallicity Correlation

Yasuhiro Hasegawa (EACOA fellow @ ASIAA)

Ralph Pudritz (McMaster Univ.)

Planet-Metallicity correlation

e.g. Santos et al 2004, Udry & Santos 2007, Mayor et al 2011, Schlaufman & Laughlin 2011, Buchhave et al 2012



Massive planets

: higher detectability for stars with higher metallicities

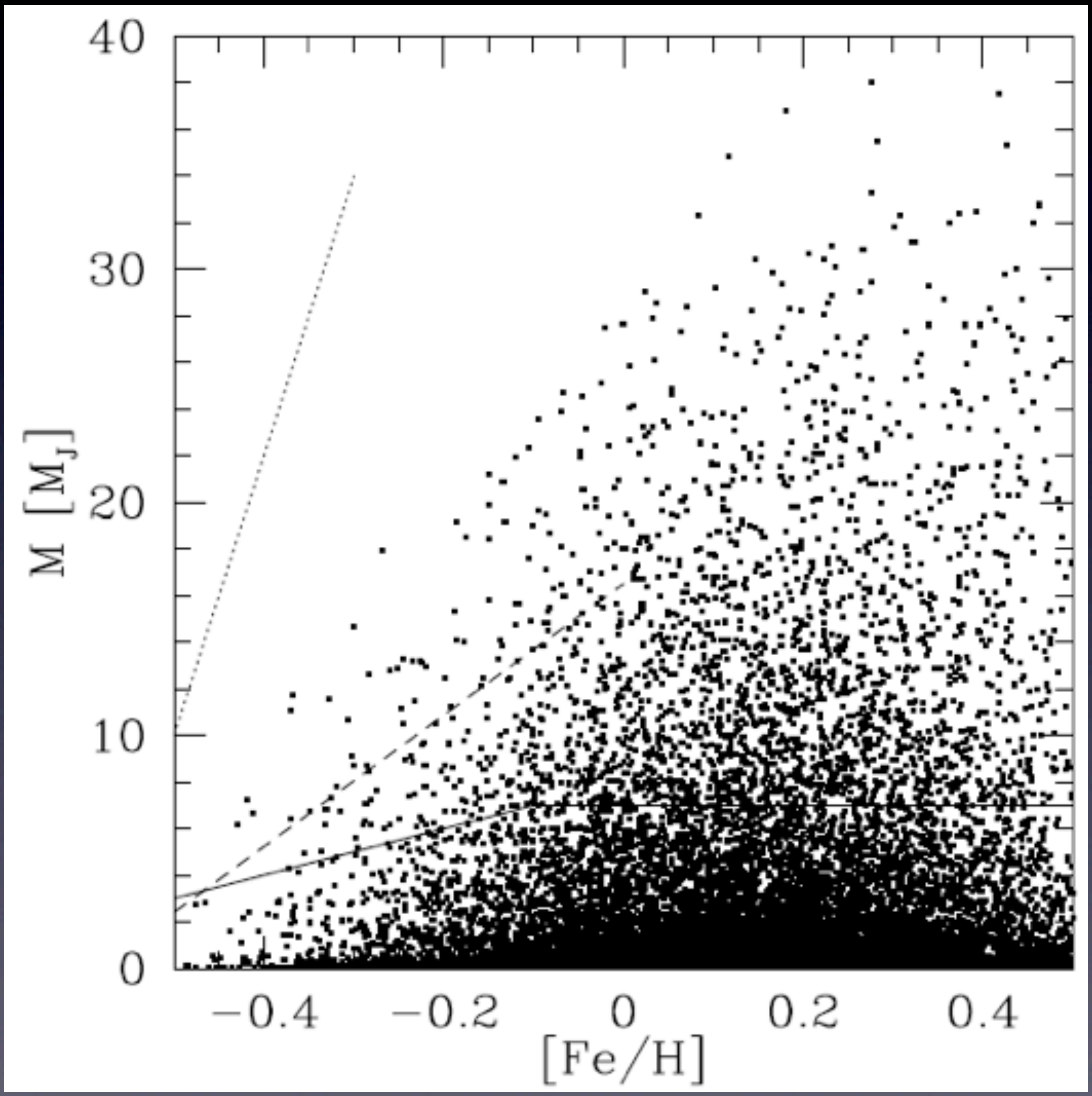
Low-mass planets

:no such a trend

RV data from Mayor et al 2011
Kepler data from Buchhave et al 2012

Population Synthesis Calculations

e.g. Ida & Lin 2004a,b, 2005, 2008a,b, 2010,
Mordasini et al 2009a,b, 2012, Alibert, Mordasini, & Benz 2011



Mordasini et al 2012

Core accretion scenario

: dust/planetesimals
=> cores of gas giants
=> gas giants

Monte Carlo methods

: the initial conditions
(stellar/disk parameters)
are randomly selected

Population Synthesis Calculations

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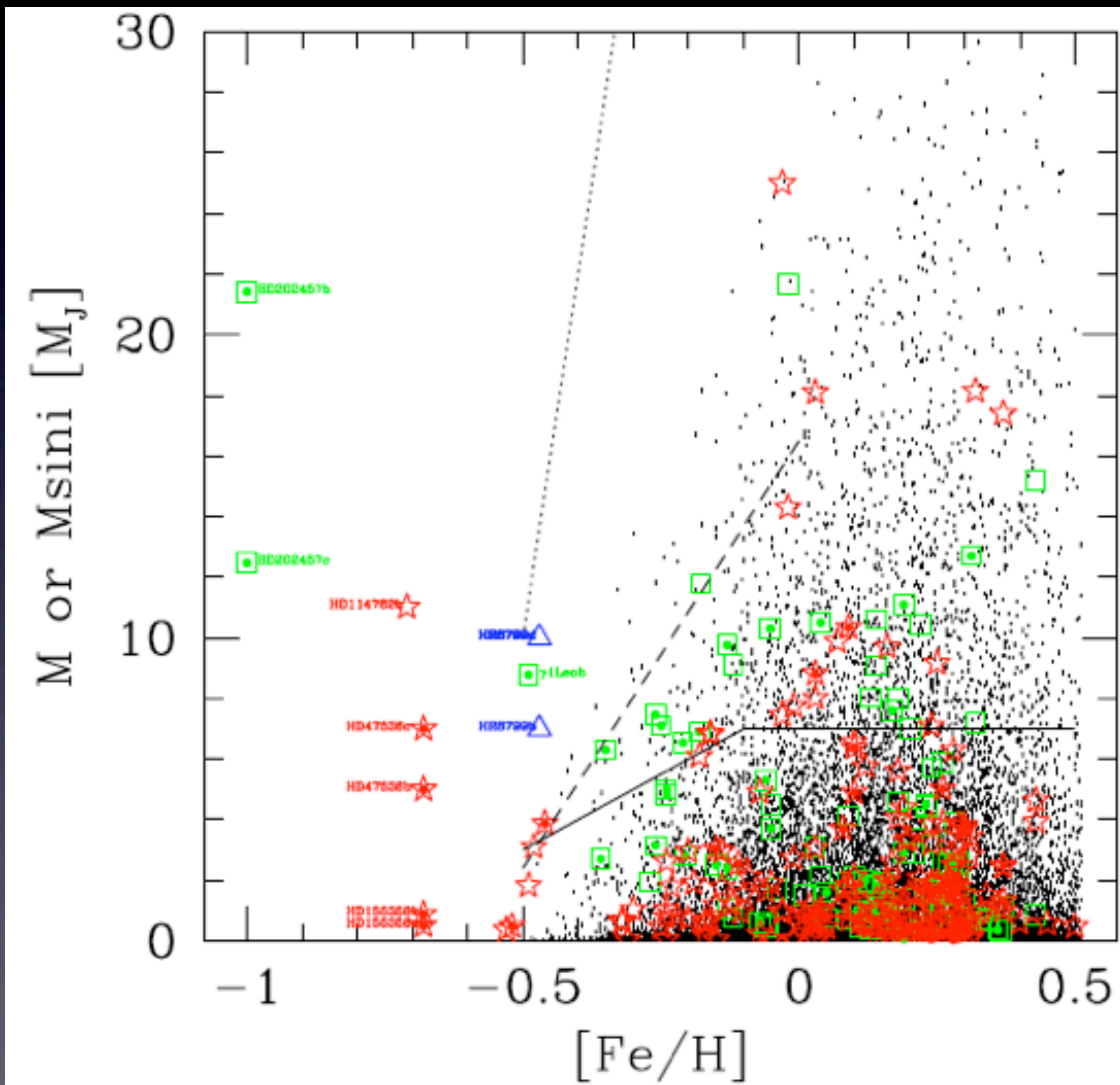

Mordasini et al 2012

Comparison with the observations

Population Synthesis Calculations

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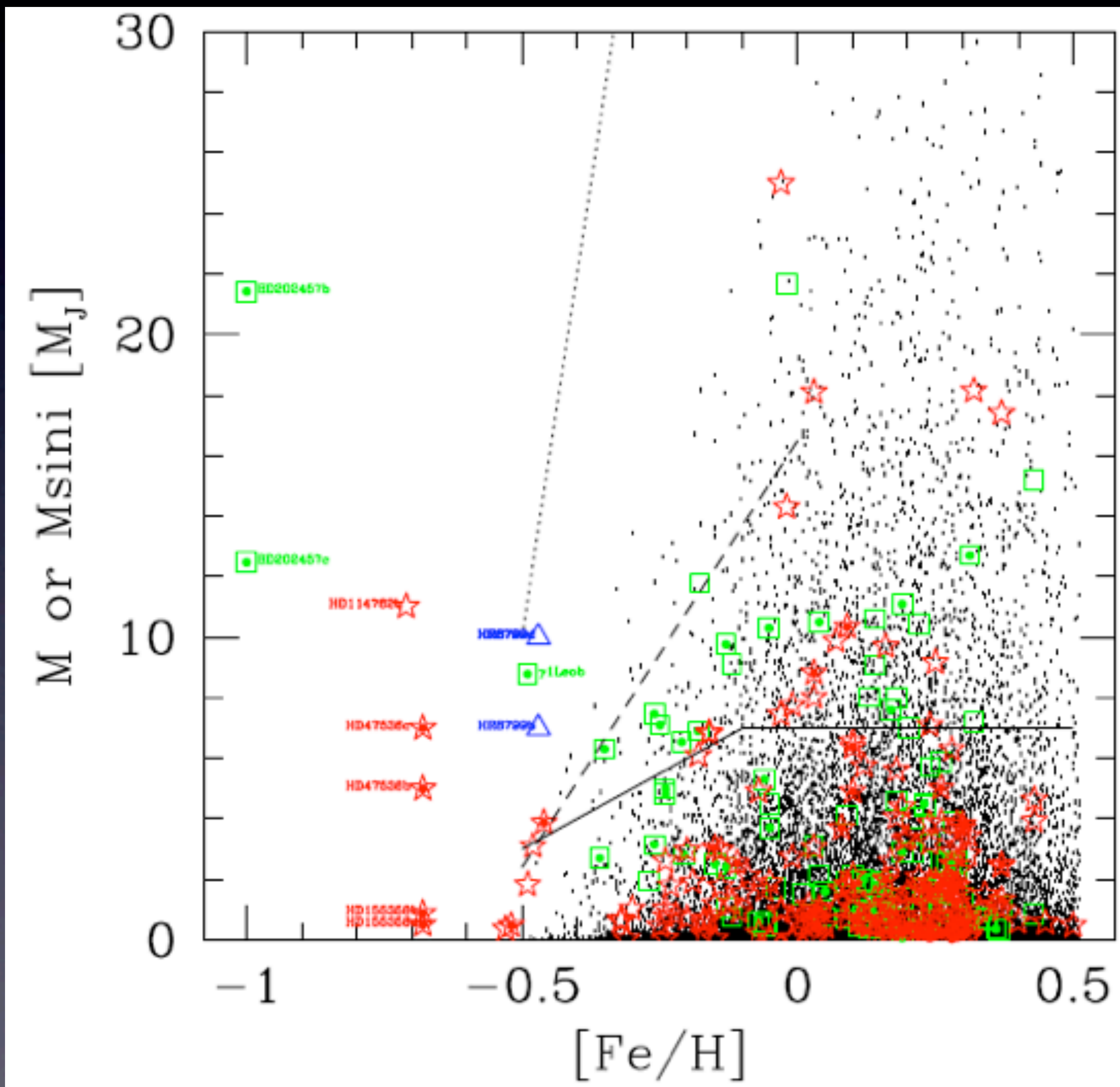

Mordasini et al 2012

Comparison with the observations

Problem 1

: **fine tuning** of many physical processes

Problem 2

: **loss of direct connection** with theories

Population Synthesis Calculations

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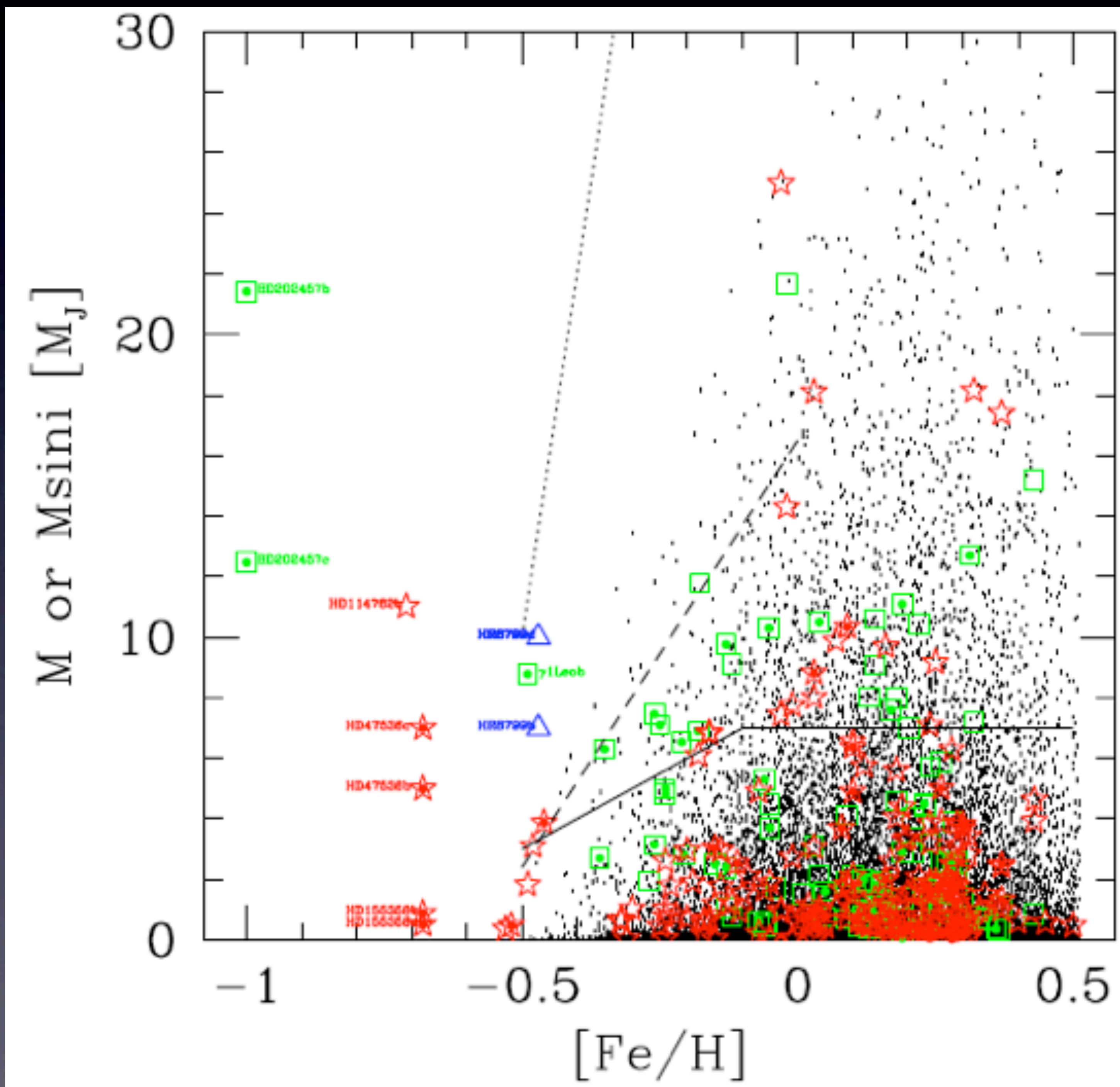


Mordasini et al 2012

Comparison with the observations

~~Problem 1~~ Concern 1

: **fine tuning** of many physical processes

~~Problem 2~~ Concern 2

: **loss of direct connection** with theories

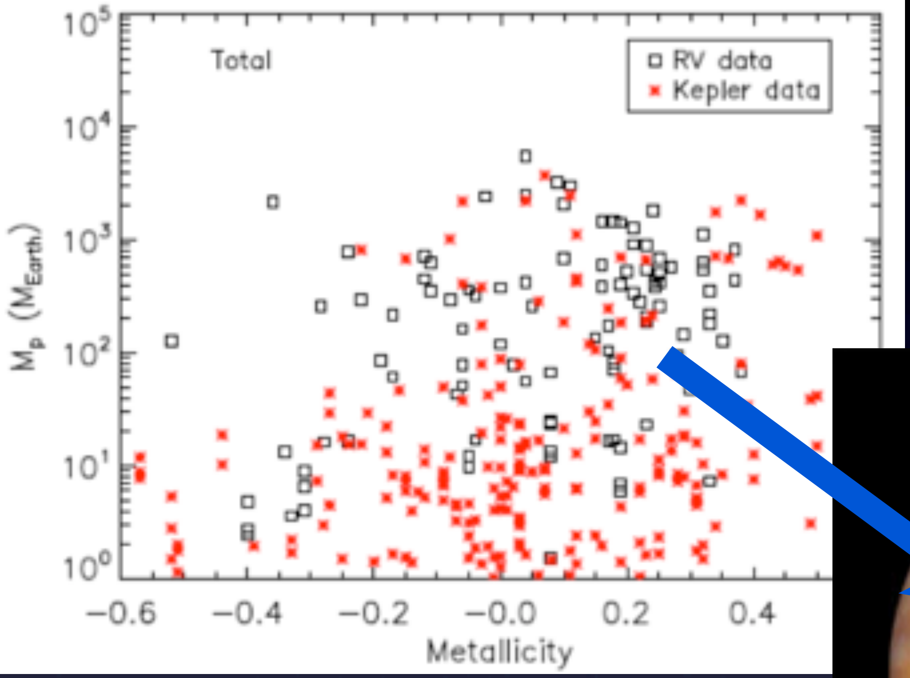
A method to derive invaluable information from observations easily

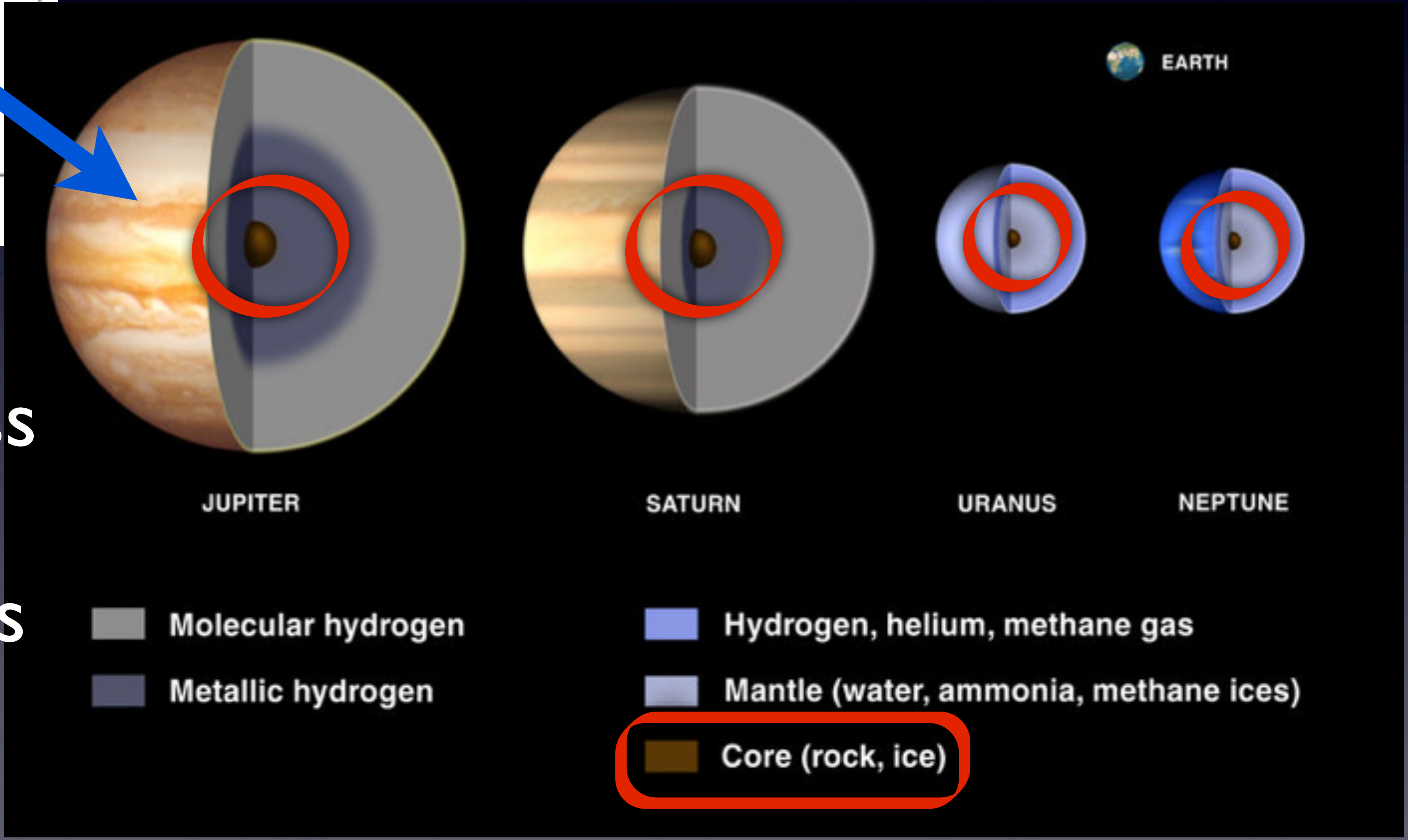
Step 1: the presence of distinct populations
in the observed exoplanets

Step 2: planet traps - direct connection with
disk evolution

Step 3: evolutionary tracks of growing planets at
traps & the statistical treatment of them

A method to derive invaluable information from observations easily

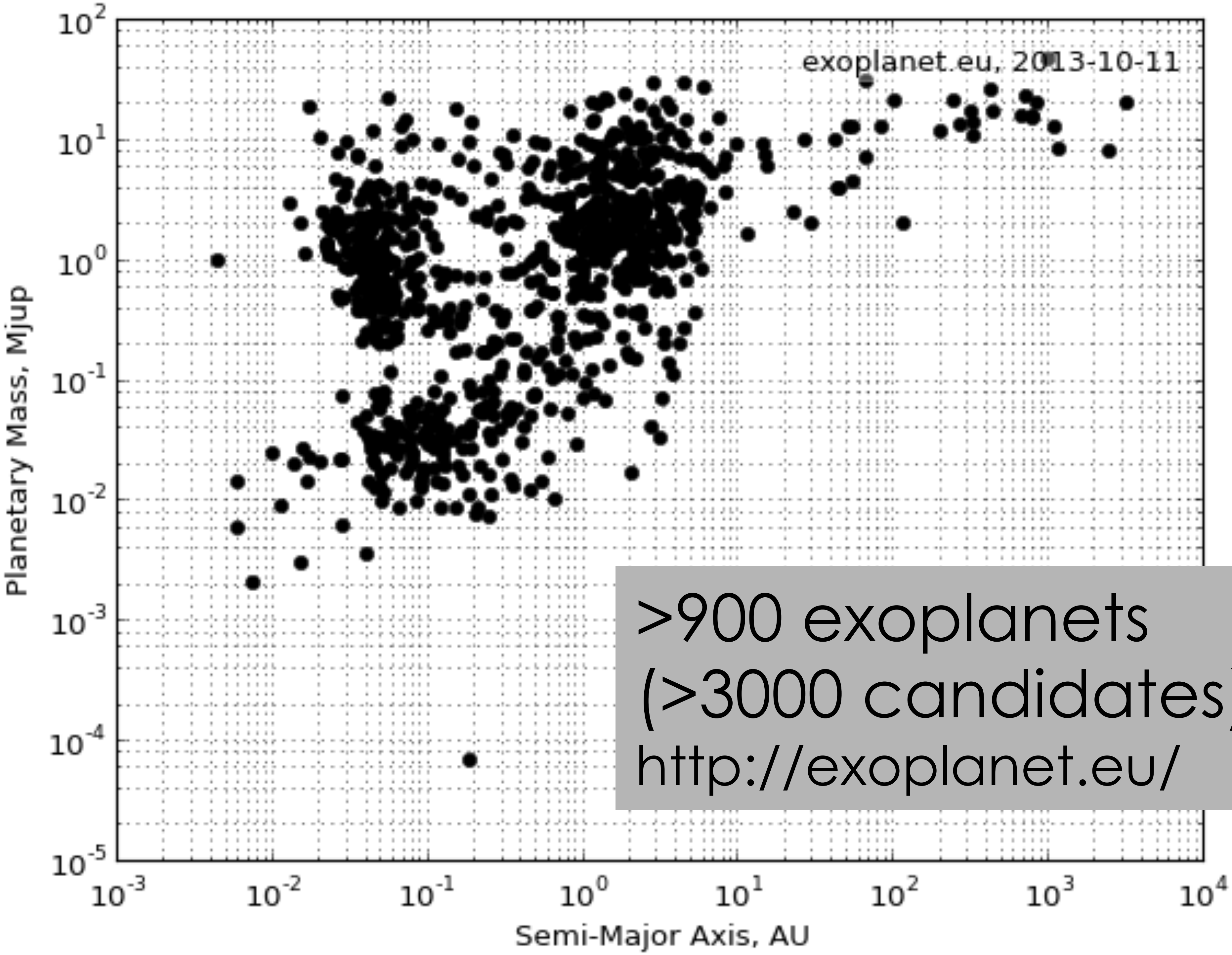




Calibrate the mass
of cores
of massive planets

Step 1: Distinct populations

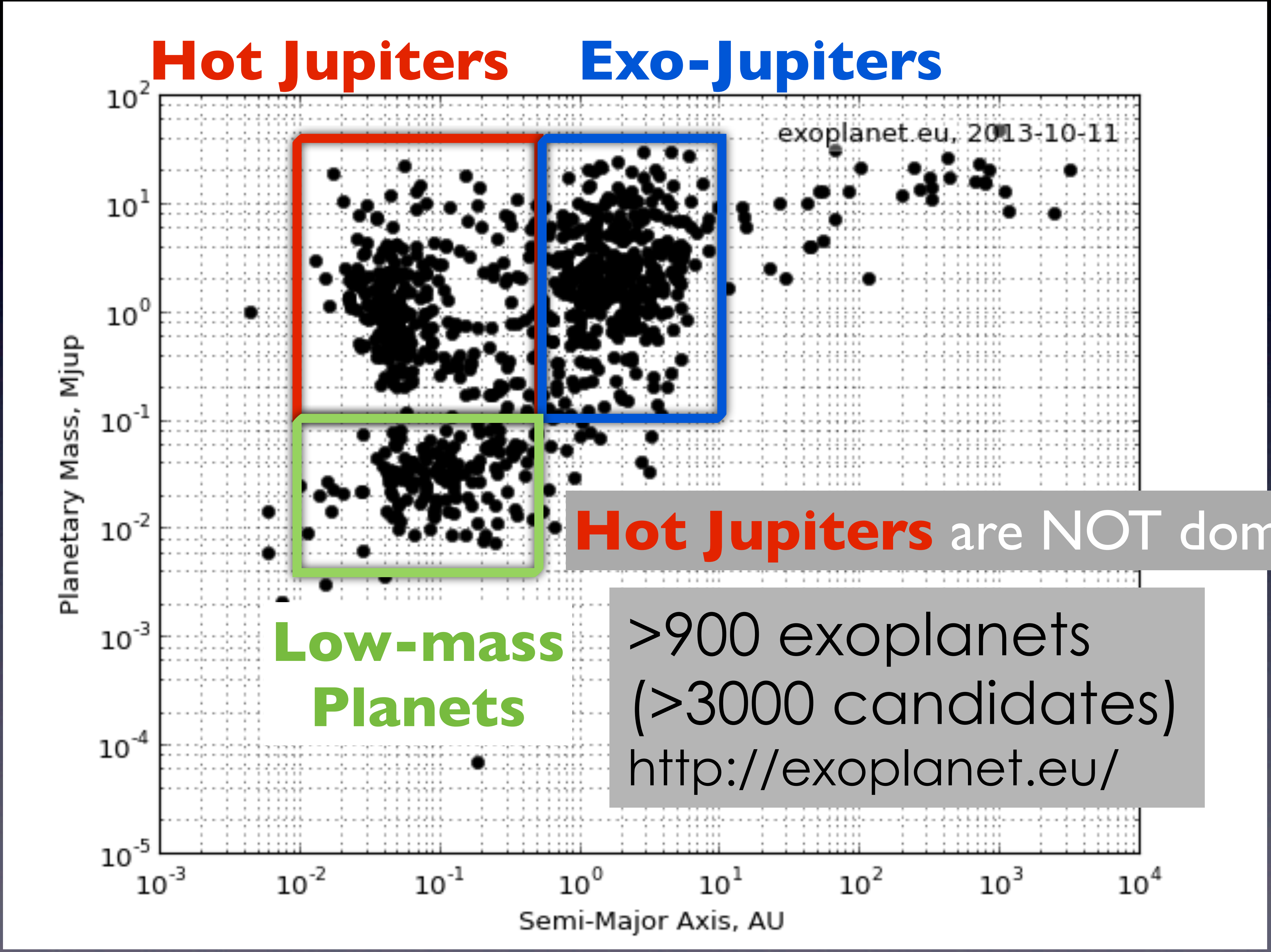
Chiang & Laughlin 2013, Hasegawa & Pudritz 2013



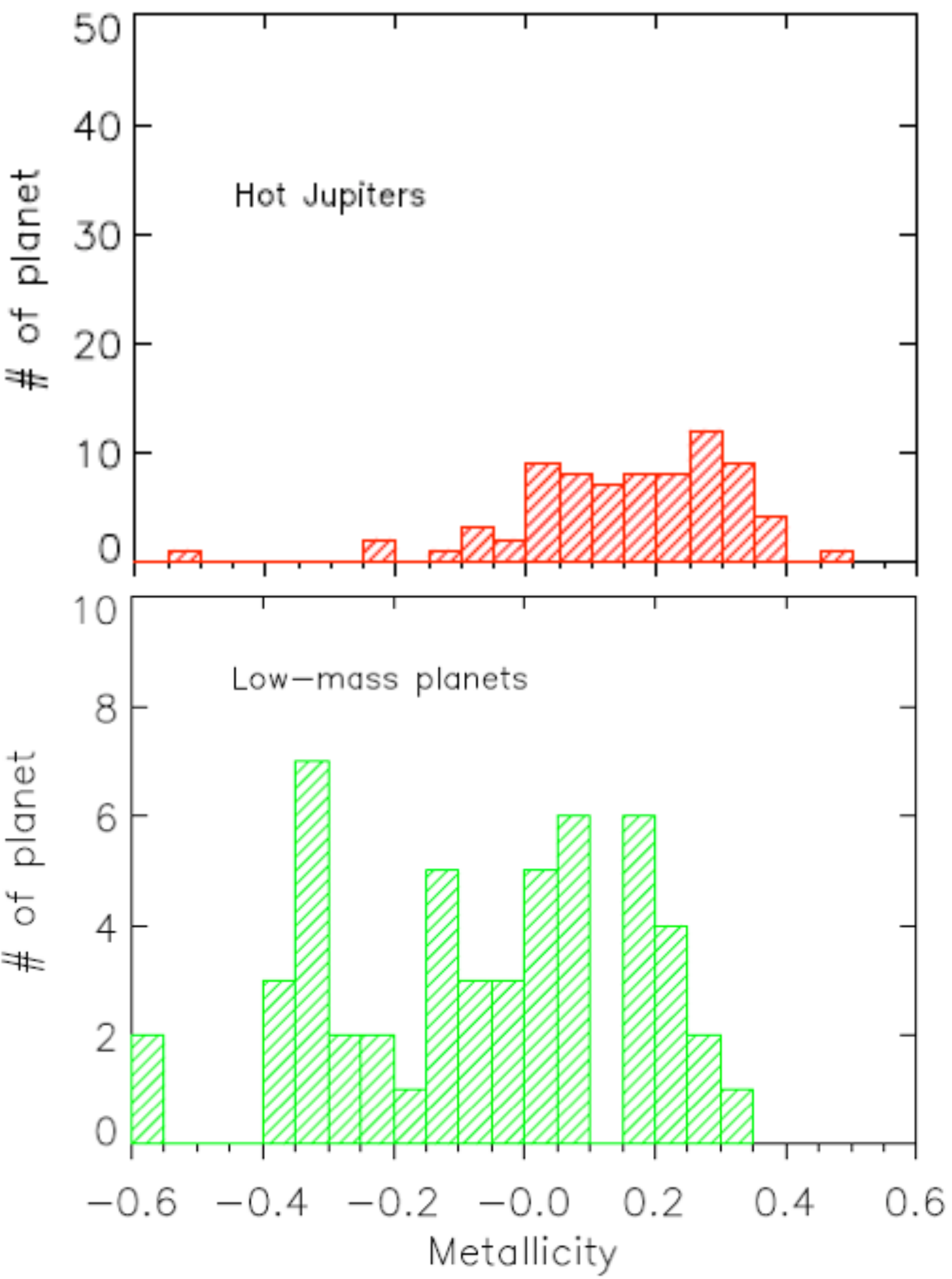
>900 exoplanets
(>3000 candidates)
http://exoplanet.eu/

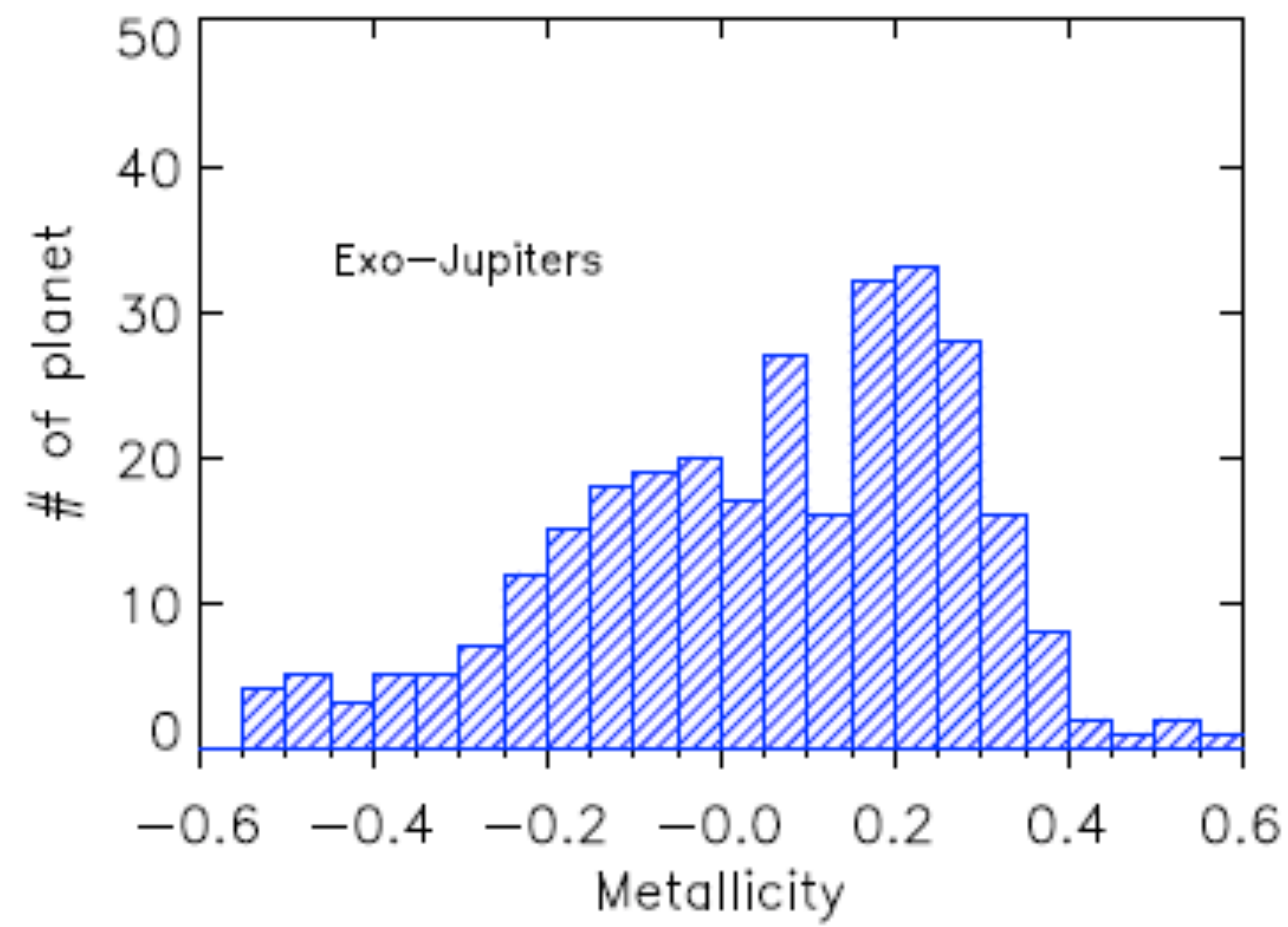
Step 1: Distinct populations

Chiang & Laughlin 2013, Hasegawa & Pudritz 2013



Planet-Metallicity correlation (again!!)





Hot Jupiters may be more sensitive to metallicities than **Exo-Jupiters**

Step 2: Planet traps

e.g. Masset et al 2006, Matsumura, Pudritz, & Thommes 2007, Lyra et al 2010, Hasegawa & Pudritz 2010, 2011

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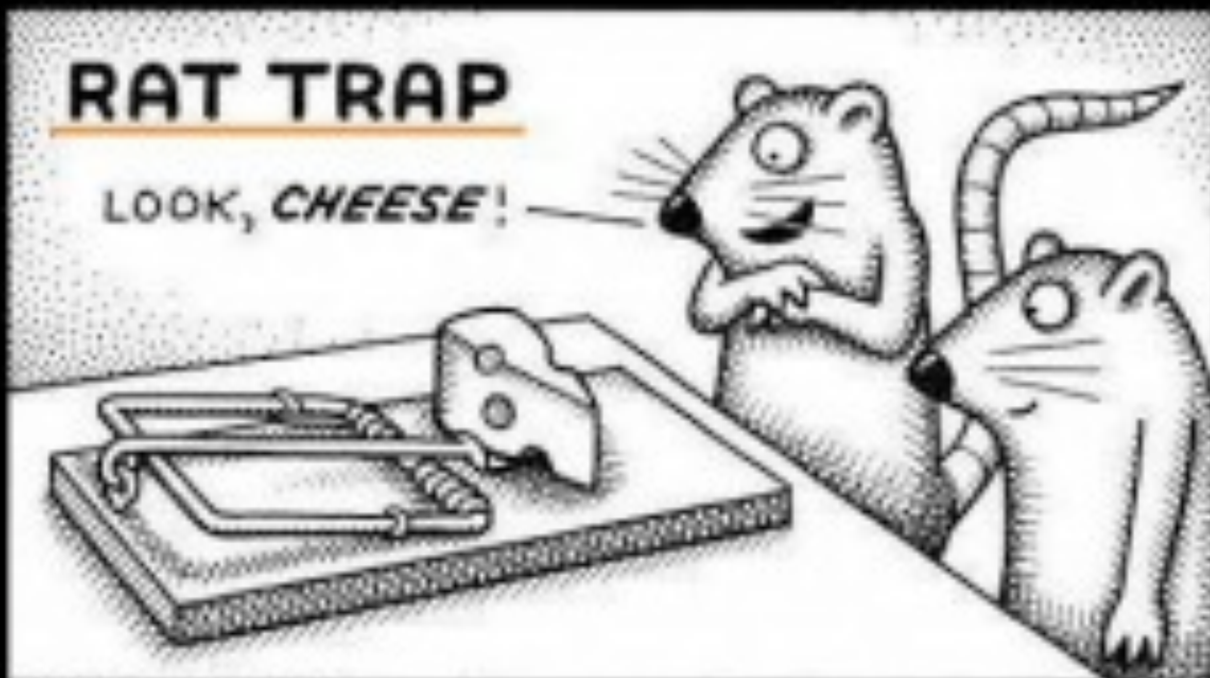

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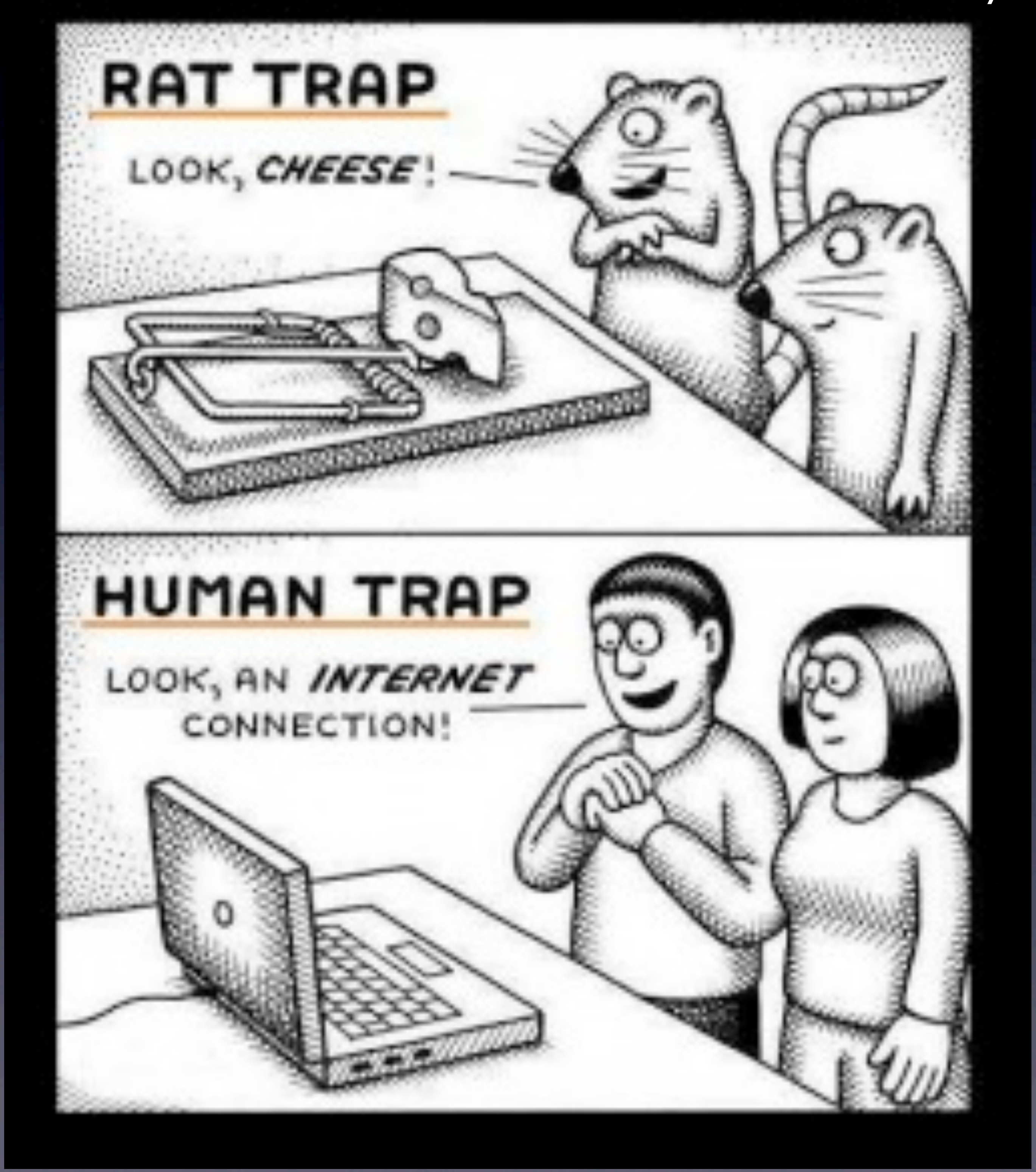

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Put appropriate traps
at appropriate locations !!

Step 2: Planet traps

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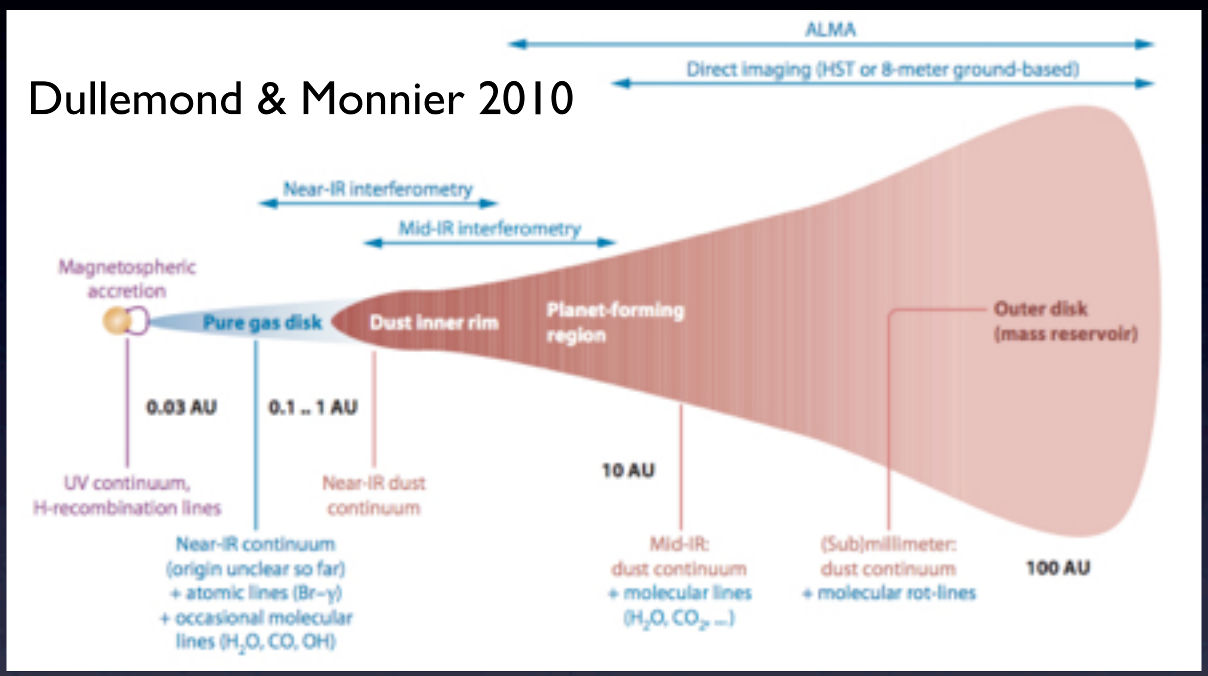

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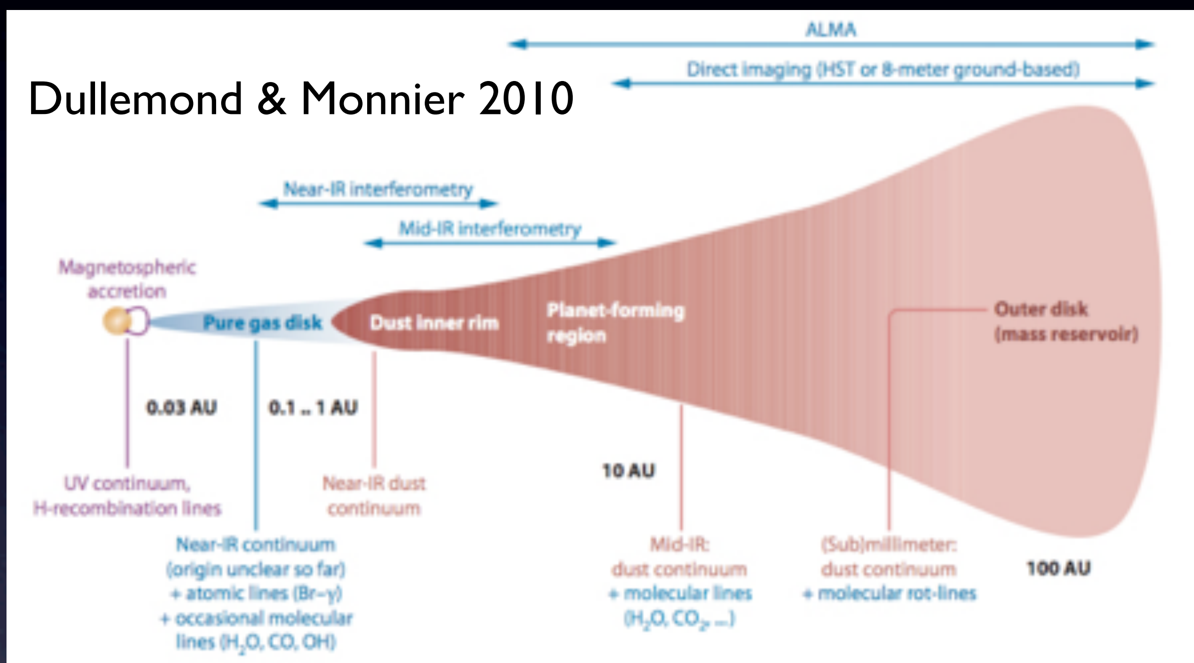
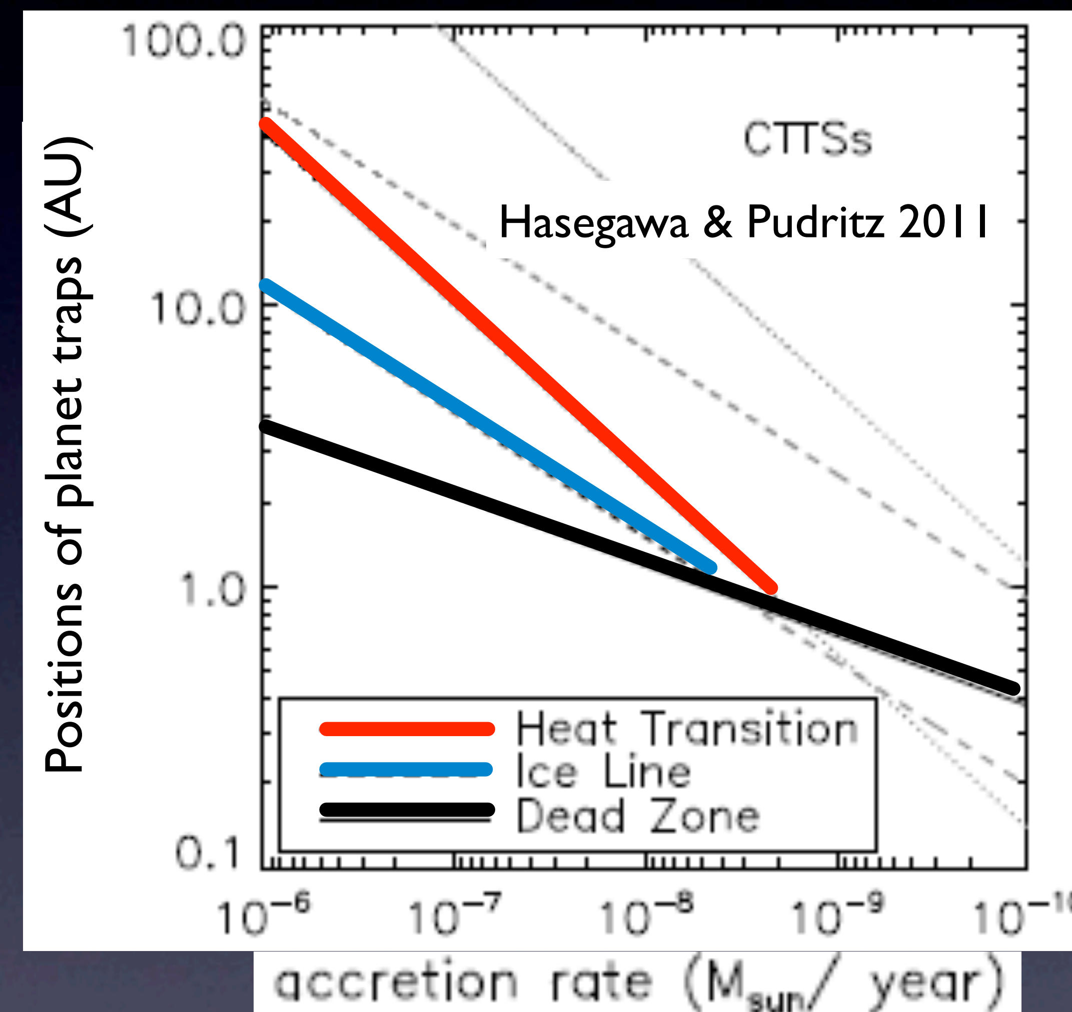




3 types of traps in single disks
: dead zones, ice lines, heat transitions

Planets form locally at traps

Traps move inward slowly, following disk evolution

Step 3: Tracks & Statistics

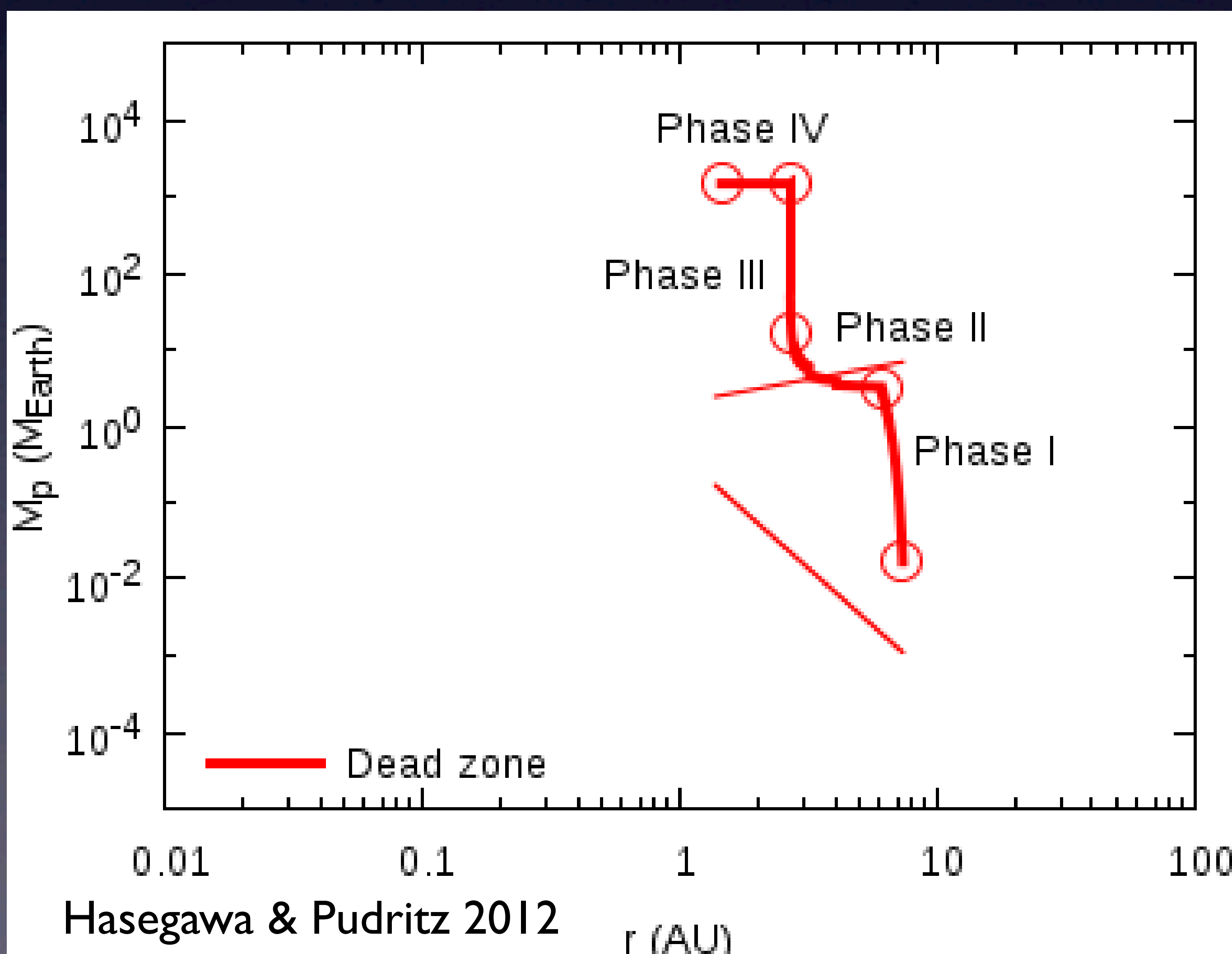
e.g. Hasegawa & Pudritz 2012, 2013

Step 3: Tracks & 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 2012

e.g. Hasegawa & Pudritz 2012, 2013

Gas giants

Phase III $(< 10^5 years)$

Cores + low-mass atmospheres

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

Cores move inward, following moving traps

Cores of gas giants

Phase I $(< 10^6 years)$

Dust/Planetesimals

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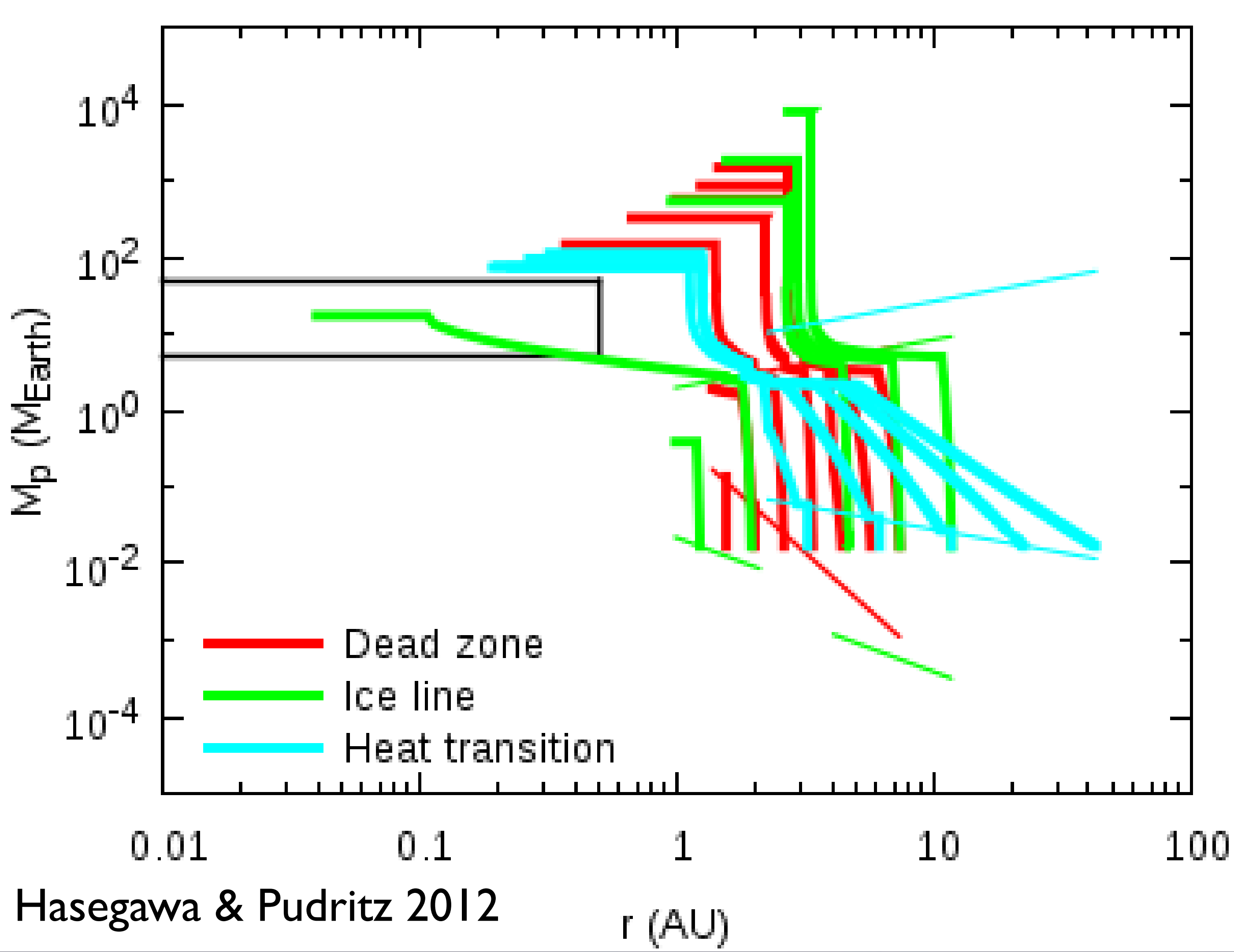
Compute lots of tracks



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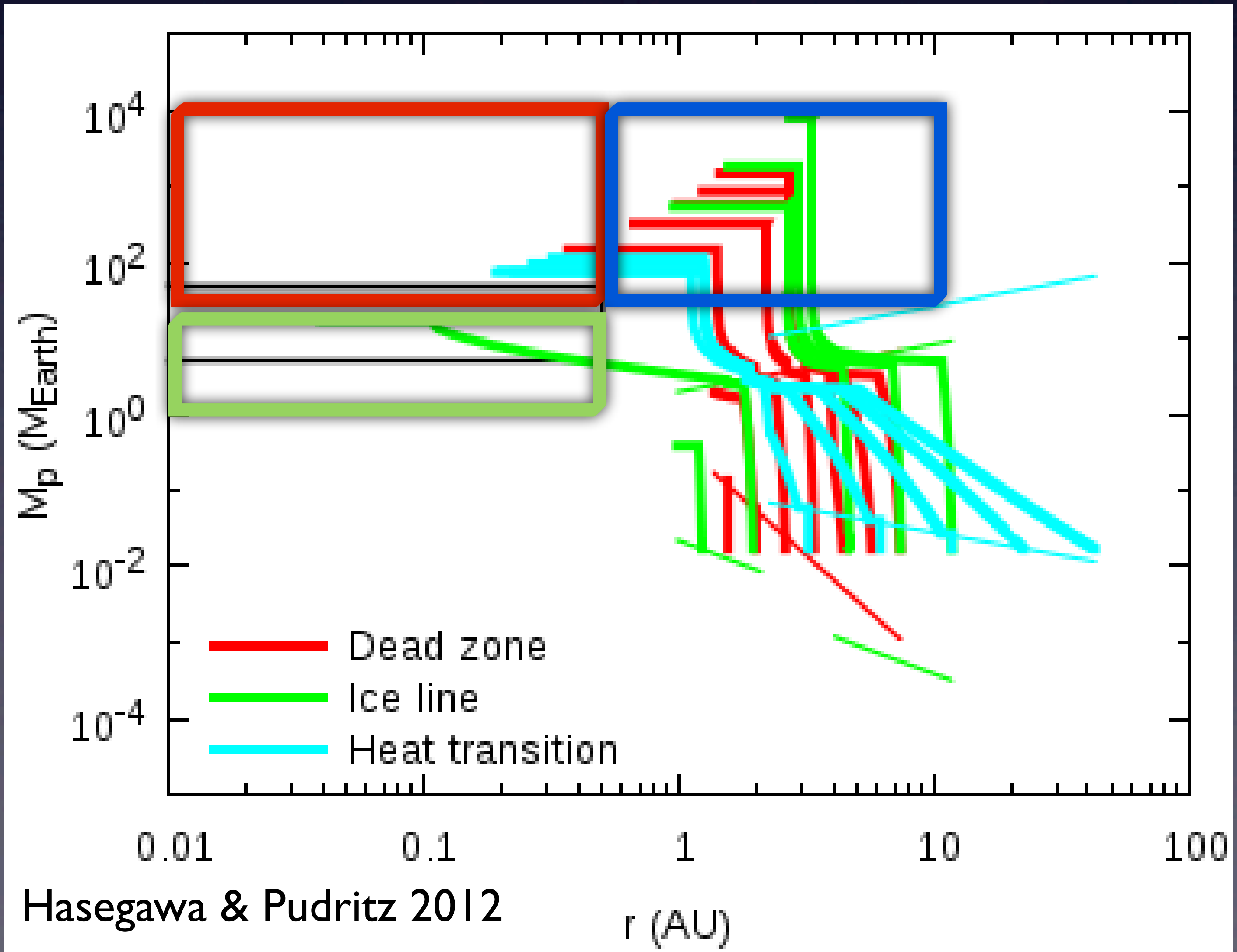
Compute lots of tracks

Partition the diagram



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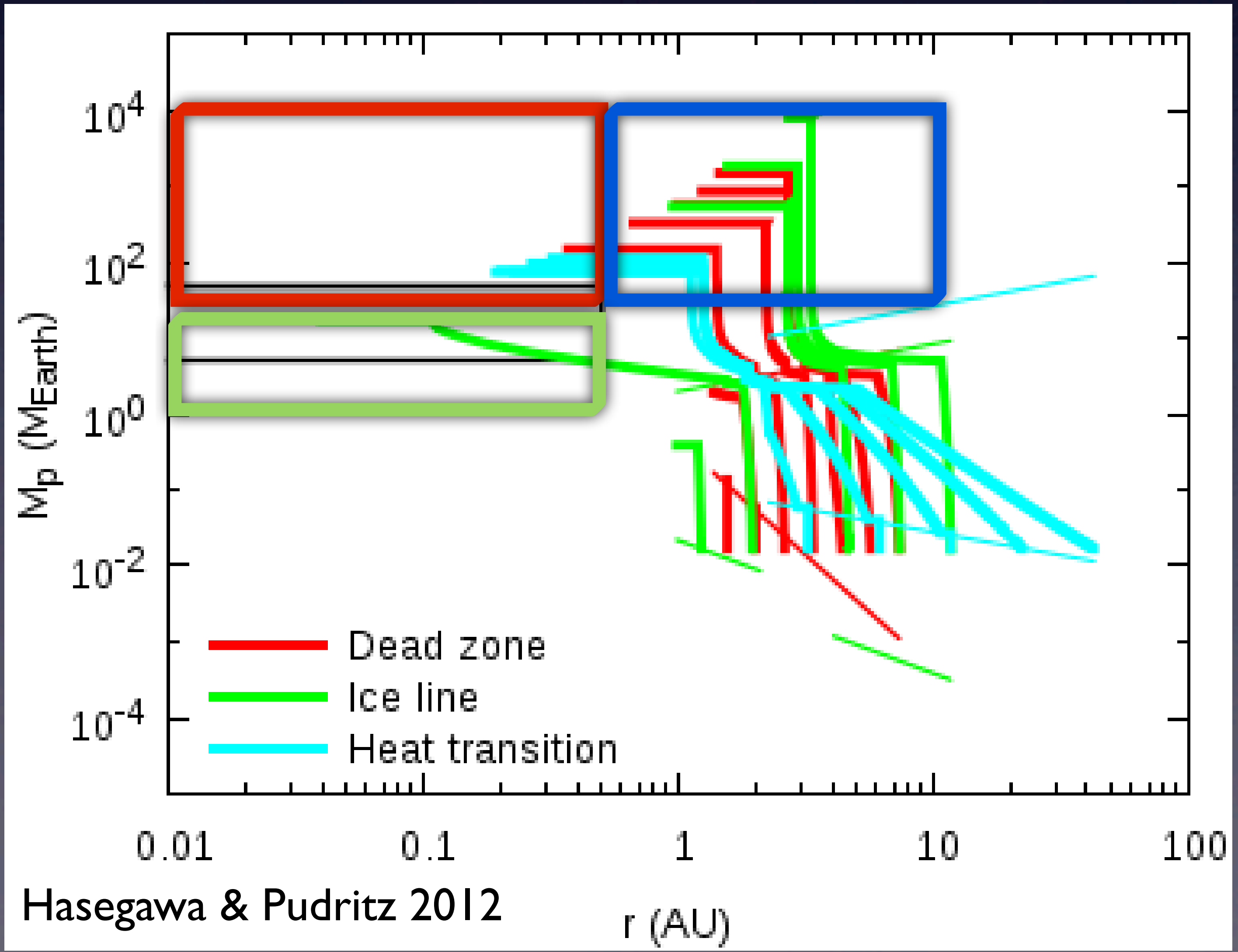


Hasegawa & Pudritz 2012

e.g. Hasegawa & Pudritz 2012, 2013

Compute lots of tracks

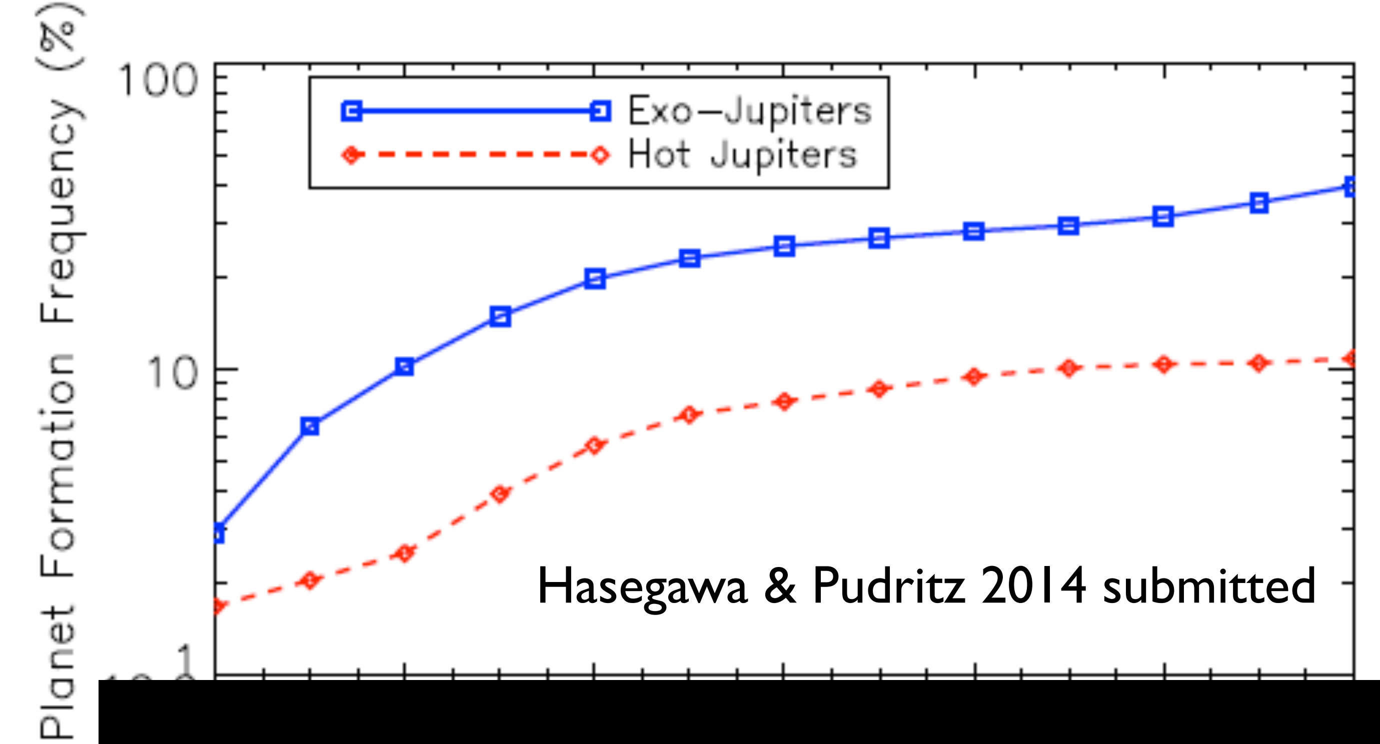
Partition the diagram

Calculate planet formation frequencies (PFFs)

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

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

Weight functions related to disk observations



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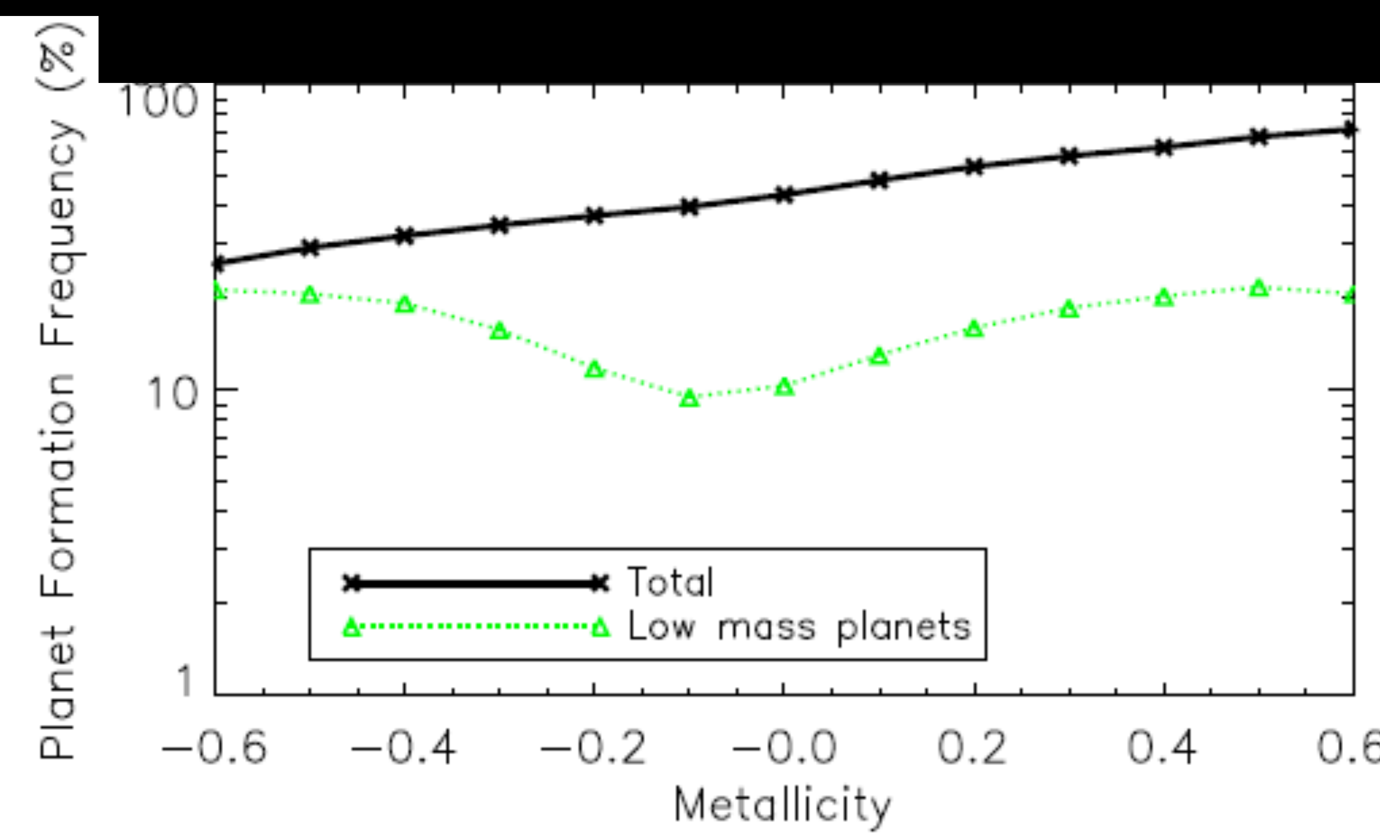


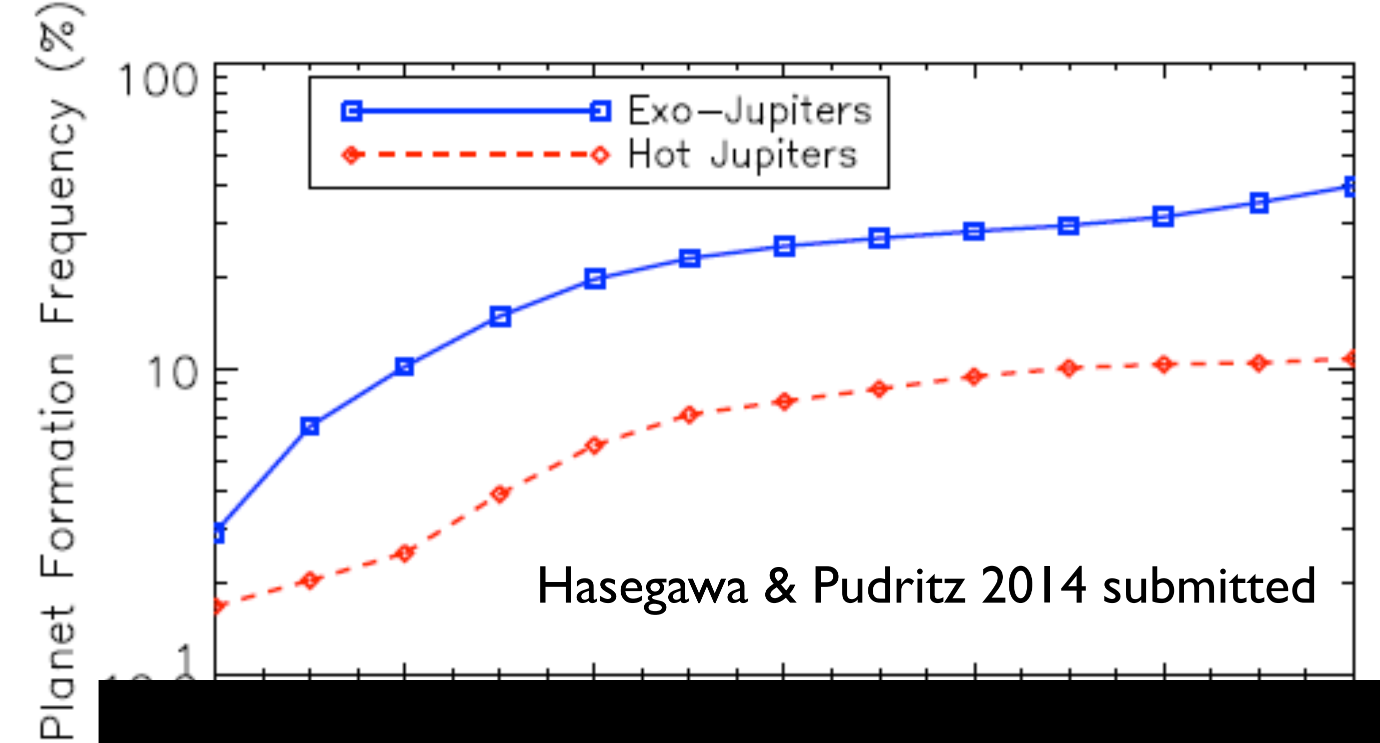
Total

: PFFs are steadily increasing with metallicities

Low mass planets

: PFFs are insensitive to metallicity

: formed as “failed” gas giants



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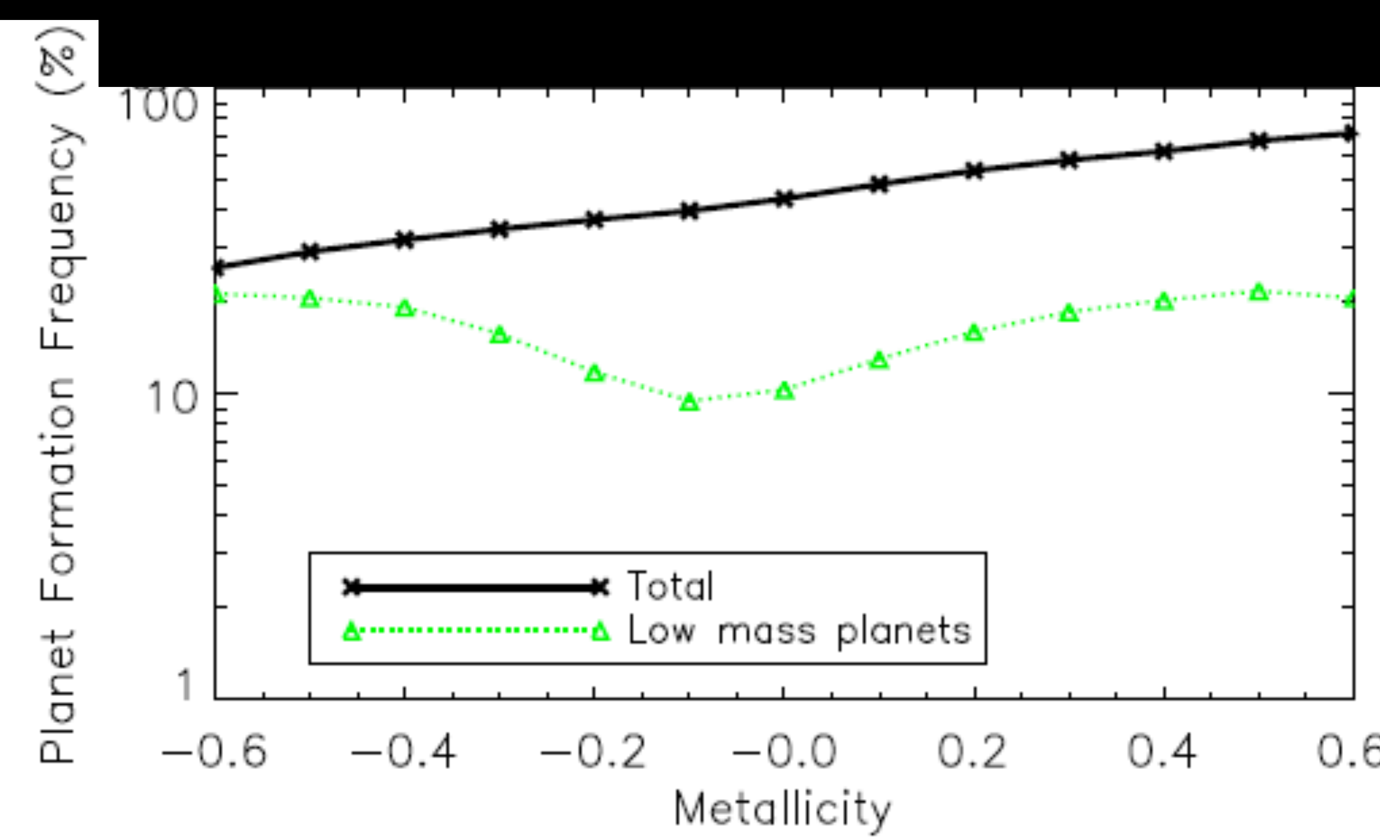


Massive planets

: PFFs are high for high metallicities

: PFFs of **exo-Jupiters** are higher than **hot Jupiters**

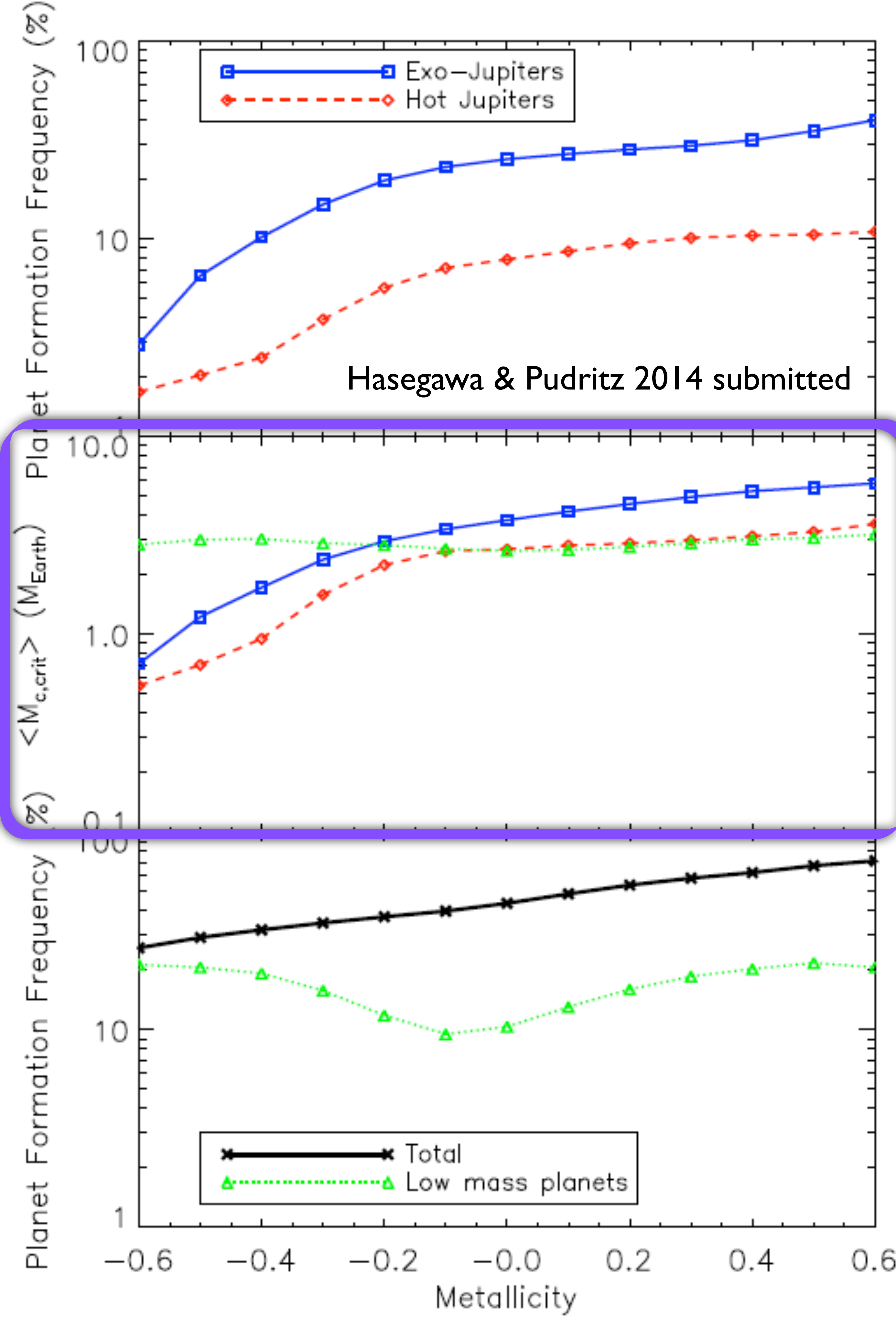
Total

: PFFs are steadily increasing with metallicities

Low mass planets

: PFFs are insensitive to metallicity

: formed as “failed” gas giants



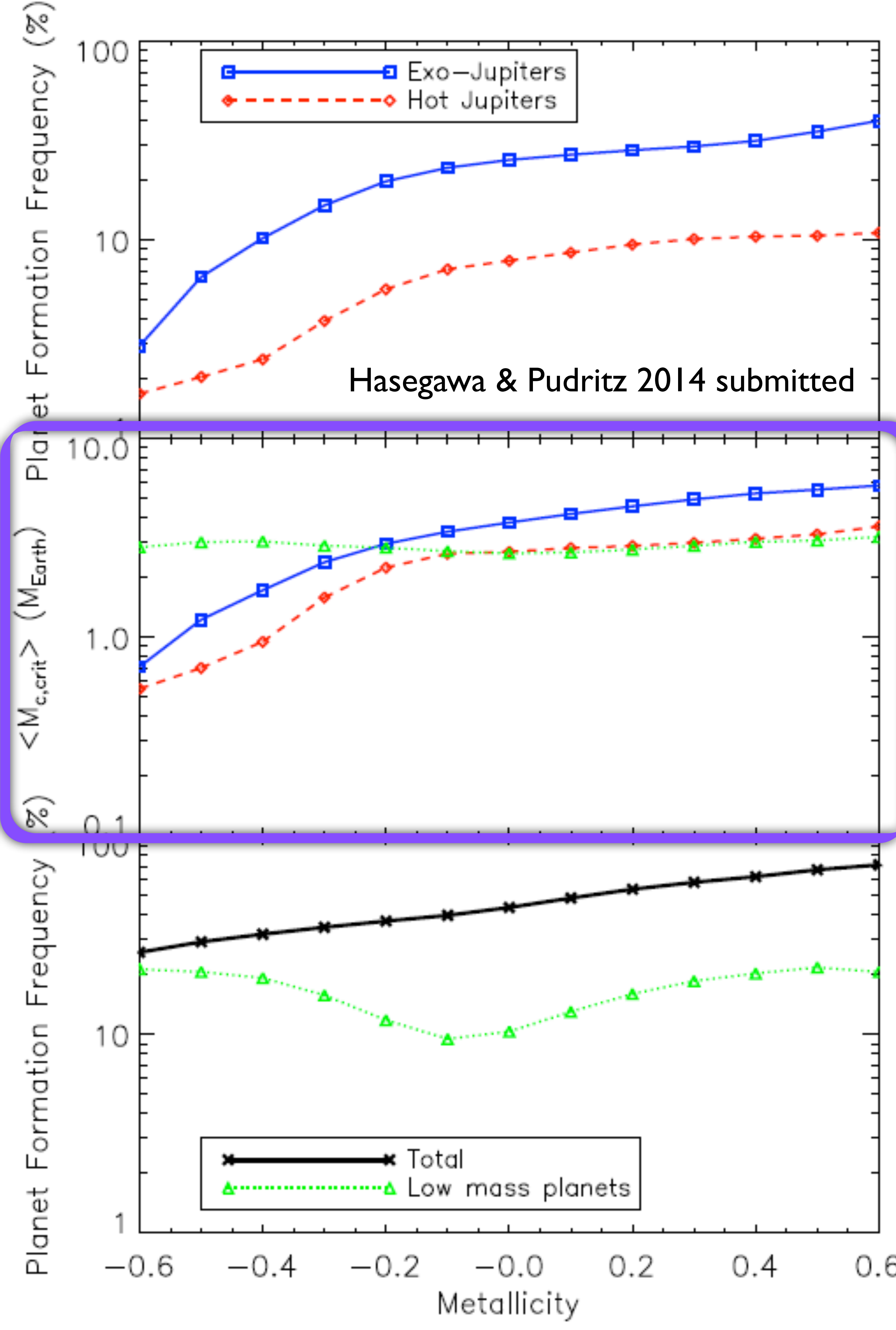
$$< M_{c,crit} >$$

= the mean mass of cores just before gas accretion

Massive planets

: $< M_{c,crit} >$ of **exo-Jupiters** is higher than **hot Jupiters**

=> higher PFFs for **exo-Jupiters**



$< M_{c,crit} >$

= the mean mass of cores just before gas accretion

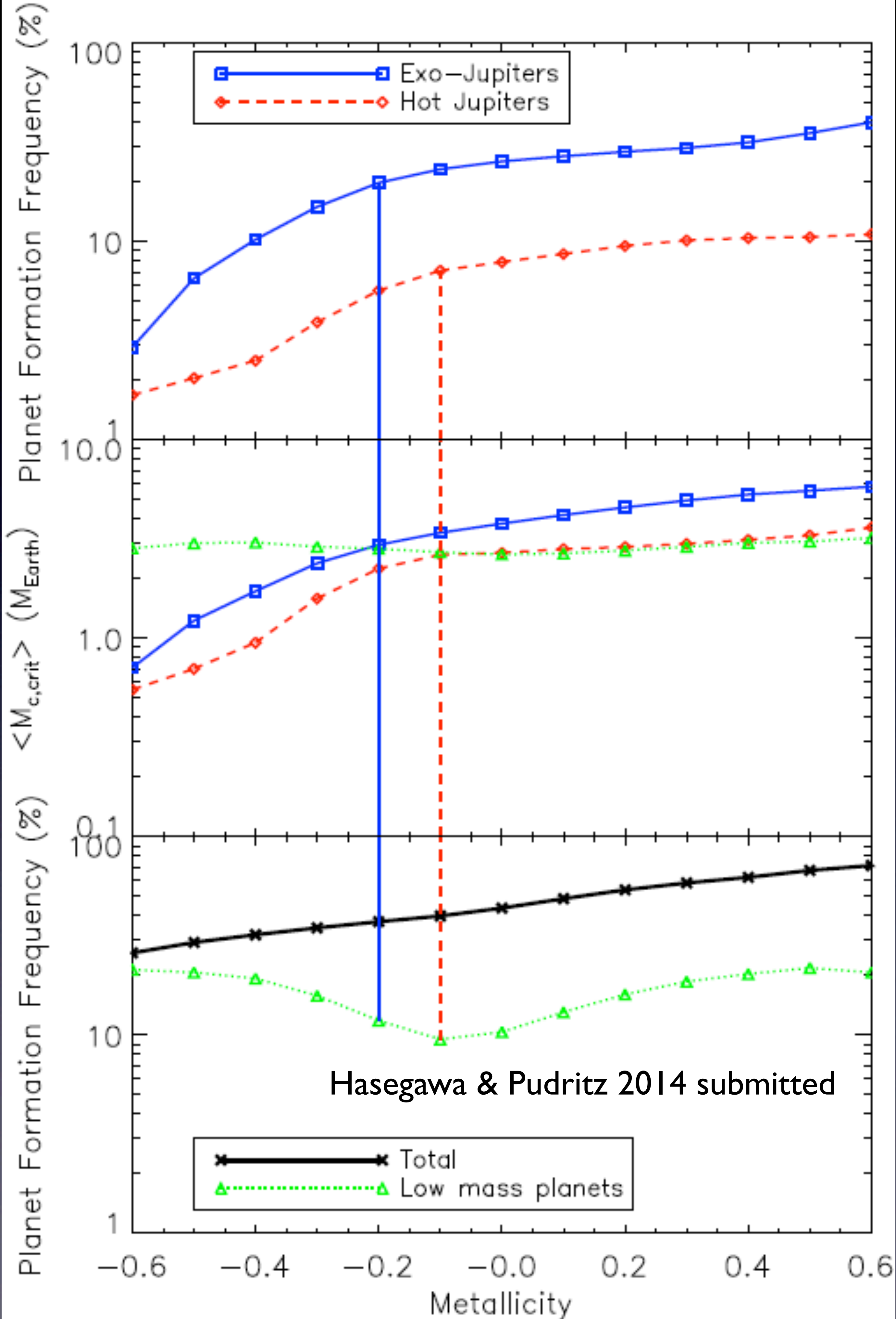
Massive planets

: $< M_{c,crit} >$ of **exo-Jupiters** is higher than **hot Jupiters**

=> higher PFFs for **exo-Jupiters**

Low mass planets

: $< M_{c,crit} >$ = the threshold mass of cores that start gas accretion



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Massive planets

: $< M_{c,crit} >$ of **exo-Jupiters** is higher than **hot Jupiters**

=> higher PFFs for **exo-Jupiters**

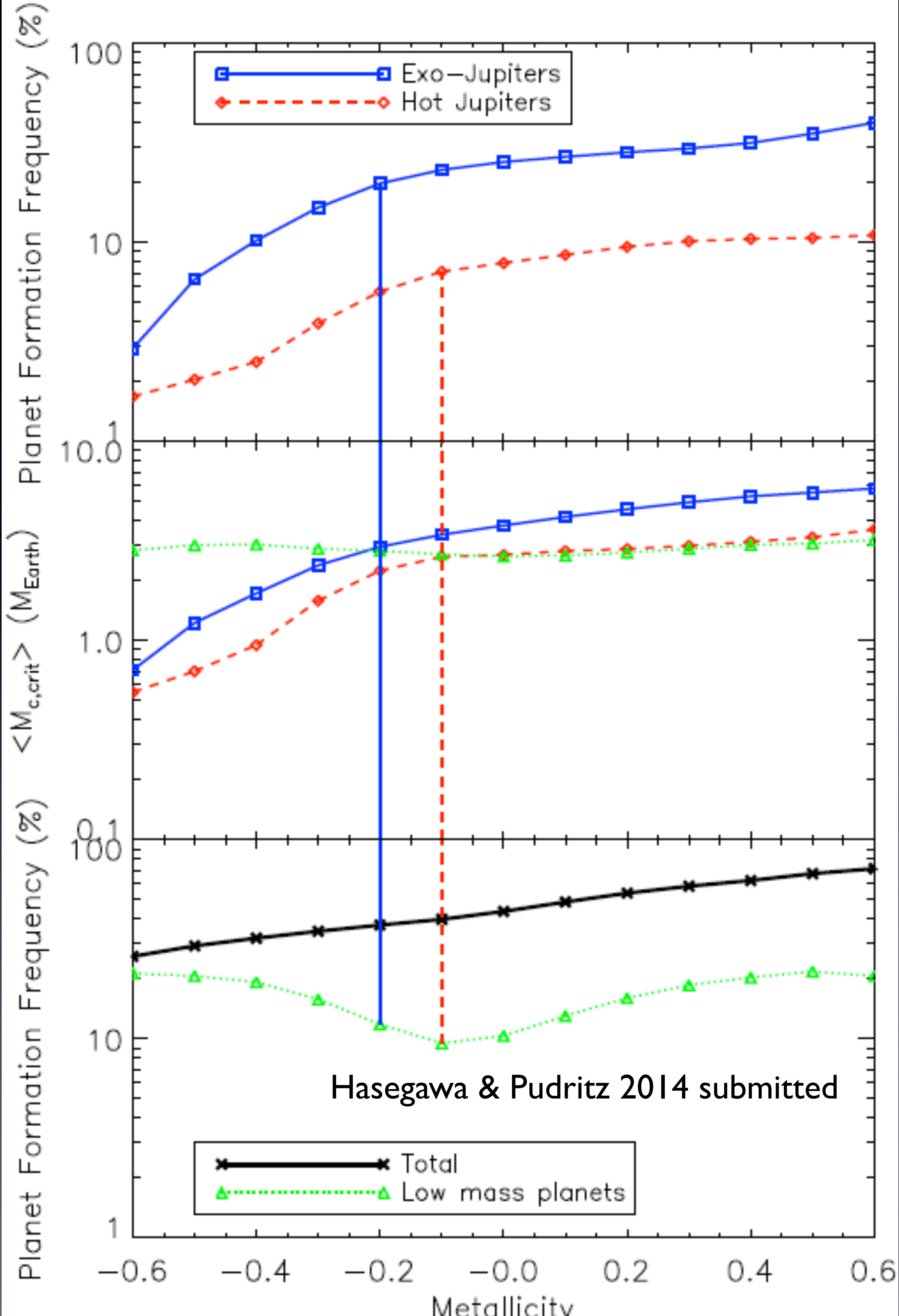
Low mass planets

: $< M_{c,crit} >$

= the threshold mass of cores that start gas accretion

intersections

=> the critical metallicities for forming gas giants

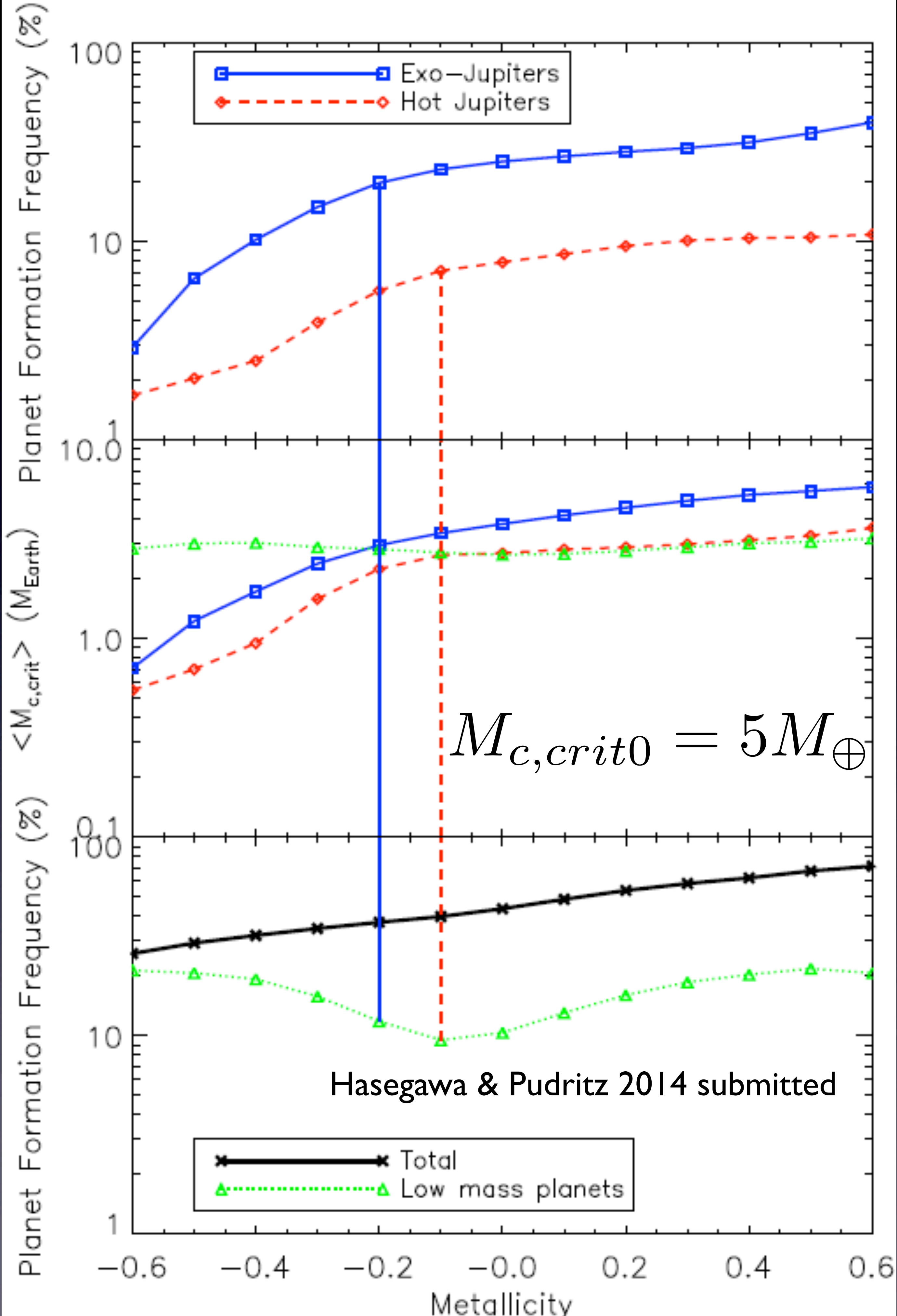


Gas giants

Cores +
low-mass atmospheres

Cores of gas giants

Dust/Planetesimals



Gas giants

Cores +
low-mass atmospheres

Yes

No

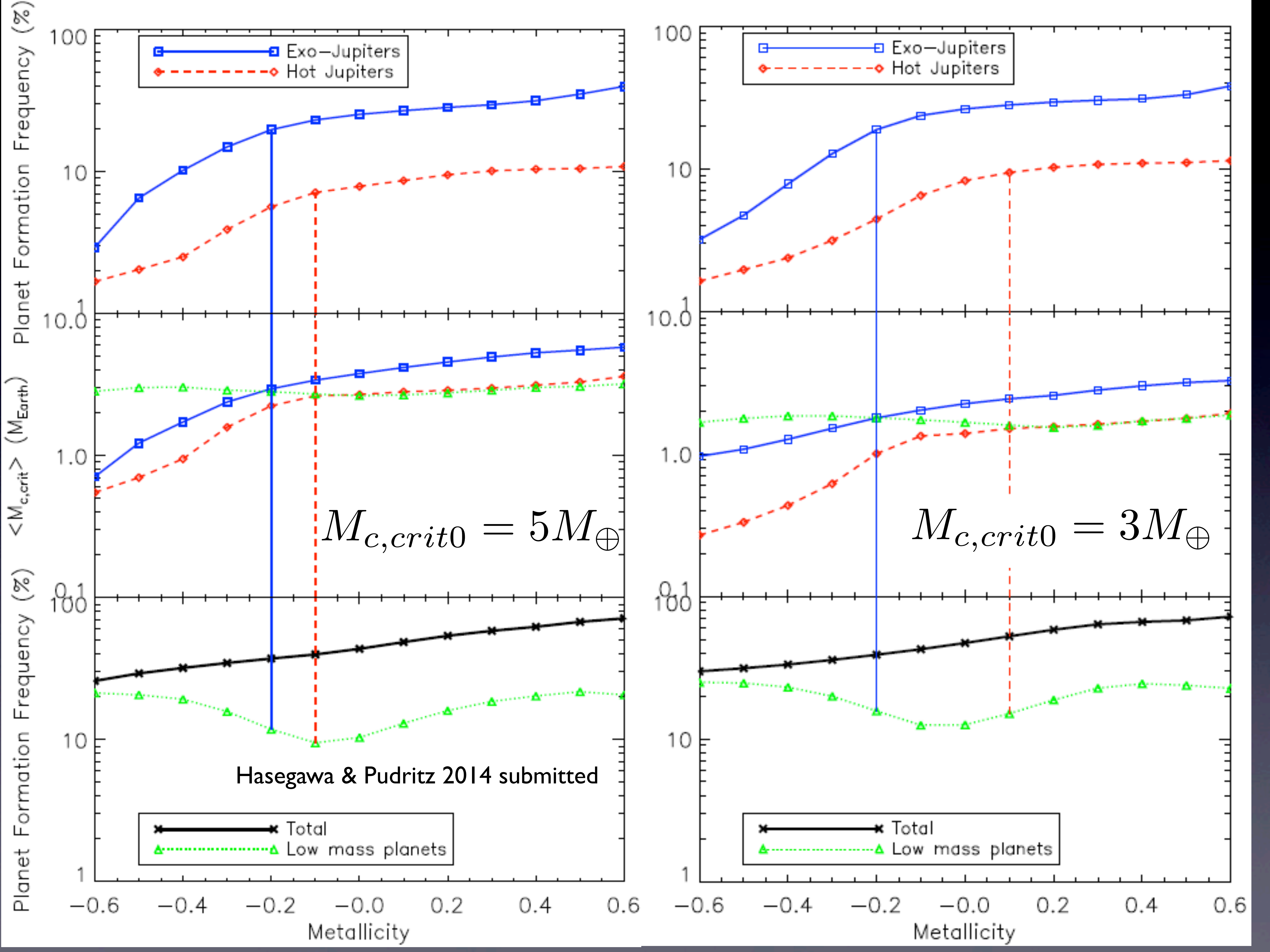
$$M_p > M_{c,crit}$$

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

Ikoma et al 2000, Ida & Lin 2004

Cores of gas giants

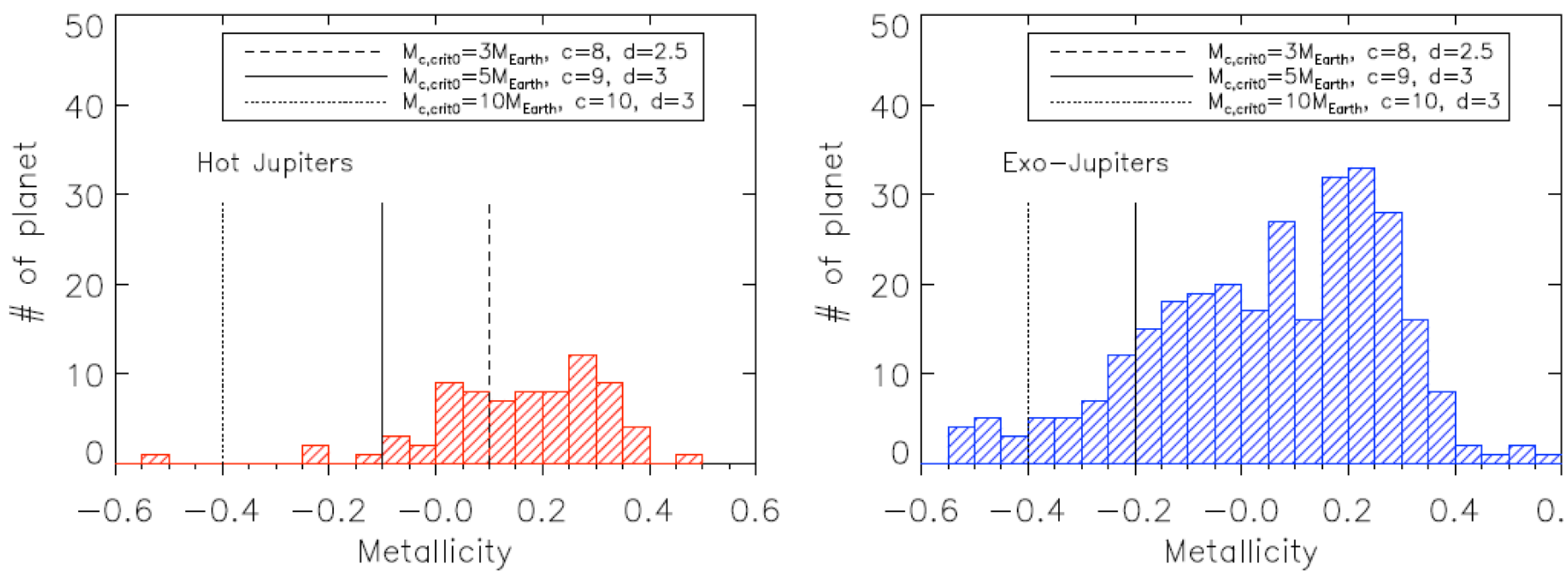
Dust/Planetesimals



Exo−Jupiters
Hot Jupiters
Planet Formation Frequency (%)
$\langle M_{c,crit} \rangle$ (M_{Earth})
$M_{c,crit0} = 5M_{\oplus}$
$M_{c,crit0} = 3M_{\oplus}$
Hasegawa & Pudritz 2014 submitted
Total
Low mass planets
Metallicity

Comparison with observations

Hasegawa & Pudritz 2014 submitted



$M_{c,crit0} = 5M_\oplus (< 10M_\oplus)$ is the most likely value of the critical mass of planetary cores to reproduce the current observations

Opacity effects

$$M_{c,crit0} = 10M_{\oplus}\left(\frac{\kappa}{1cm^2g^{-1}}\right)^{0.2-0.3}$$

κ : grain opacity in the atmosphere

Ikoma et al 2000, Ida & Lin 2004, Hori & Ikoma 2010

Our results ($M_{c,crit0} \simeq 5M_{\oplus}, \kappa \simeq 0.1cm^2g^{-1}$) imply that grain growth in the atmosphere of observed exoplanets may commonly occur during the formation process

Caveats

The effectiveness of planet traps

: effects of planetary mass & orbital periods as well as disk evolution

Planet-planet interactions

: effects on the final architecture of planetary systems

Gas accretion onto cores & the final mass of planets

: effects on the PFFs for low-mass planets

A wide range of stellar masses

: effects on comparison with observations

Summary

- the Planet-Metallicity correlation is one of the most prominent features in exoplanet observations
- Developed a brand-new statistical approach: (1) partition of the mass-semimajor axis diagram, (2) planet traps (3) tracks & statistics
- The critical mass of planetary cores is very likely to be $M_{c,crit0} = 5M_{\oplus} (< 10 M_{\oplus})$ to account for the current observations of exoplanets
- This would suggest that grain growth may occur in the atmosphere of observed exoplanets