# Extrasolar planet taxonomy: implications for the formation of hot planets

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# The planet census

**346 EPs showing large heterogeneity in orbital and physical parameters; plus the 8 planets in our own Solar System.**


1.Formation:

➔two formation theories (CA, DI).

2.Evolution:

➔complex evolution (e.g. migration, evaporation).

3.Environment:

➔very different environments (star multiplicity, clustering, stellar type, metallicity).

# The statistical “quagmire”

Statistical analysis is a necessary tool for studying such a complex planetary sample, with the purpose of unveil underlying physical processes and the relevant parameters for planetary formation and evolution

...but...

the search for trends on the whole sample may be misleading when many processes are at work simultaneously:

**Important information may be smeared out!**

Moreover, several parameters may act simultaneously:

**how to disentangle their effects?**

In order to avoid all this, we decided to break down the planetary “puzzle” into fundamental pieces prior to the statistical analysis.

# Exoplanet taxonomy

**Input variables:**

➔ ***planetary parameters:*** **mass (*Mp*), semi-major axis (*a*) and eccent. (*e*)**
➔ ***environmental parameters:*** **stellar mass (*Ms*) and metallicity (*[Fe/H]*)**

➔ **Multivariate approach: 5-fold space**

**The method:**

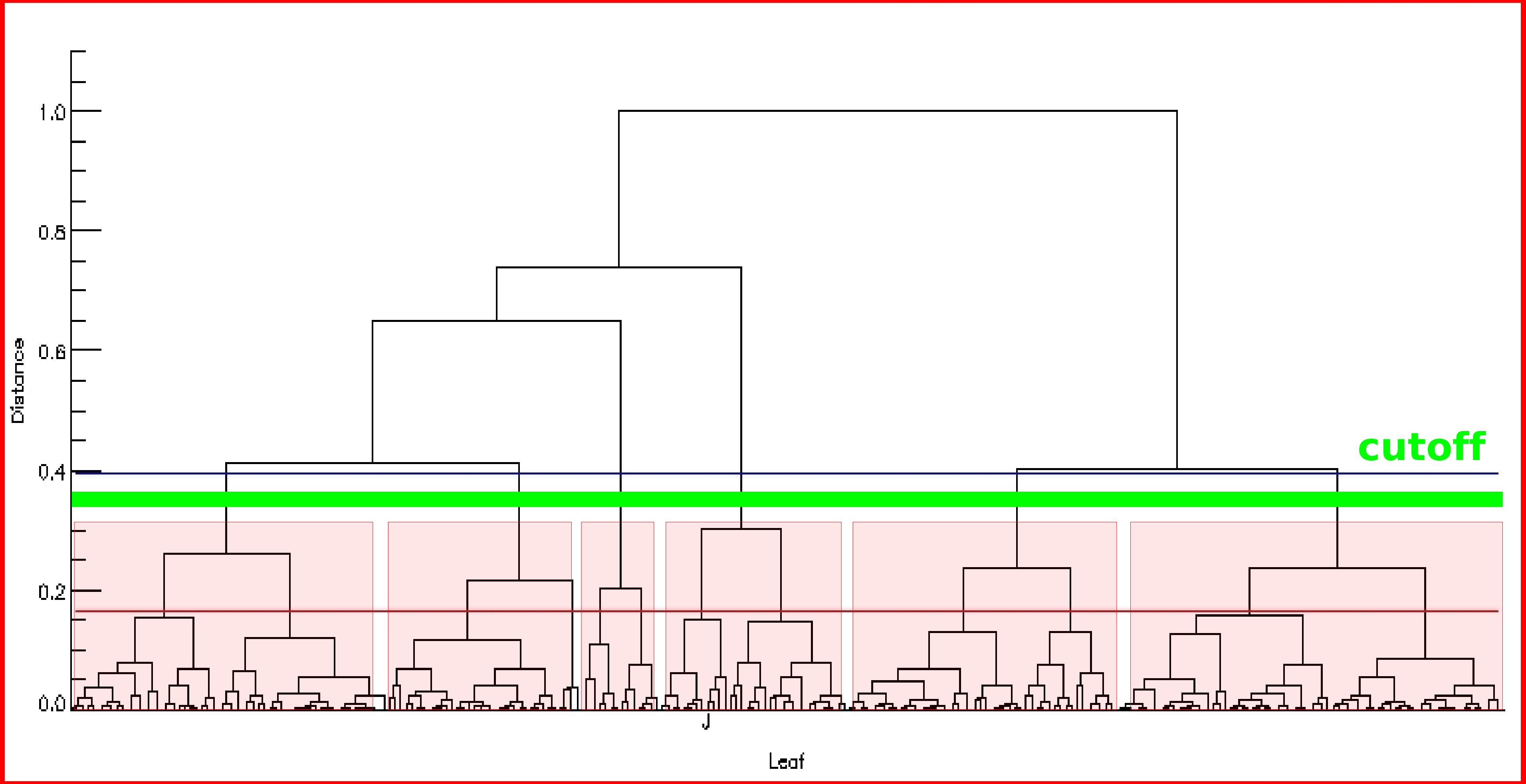
1. **global analysis and dimensional scaling via PCA;**
2. **cluster analysis via hierarchical (bottom-up) algorithms;**

# The best solution

The best solution consists of **6 clusters.**

**Highlights:**

- high significance of PCA;
- high cophenetic coefficient;
- good stability;
- very low Monte Carlo probability.



# Hot planets

Here we define Hot Planets (HPs) those planets having period less than 12 days, however results are not affected much by this choice.

In our sample, we have a total of 69 HPs.

Hot planets within the clusters:

Cluster C1 contains 53.5% of HPs,
Cluster C2 contains 30.4% of HPs,
C3 5.8%, C4 4.3%, C5 4.3%, C6 1.7%

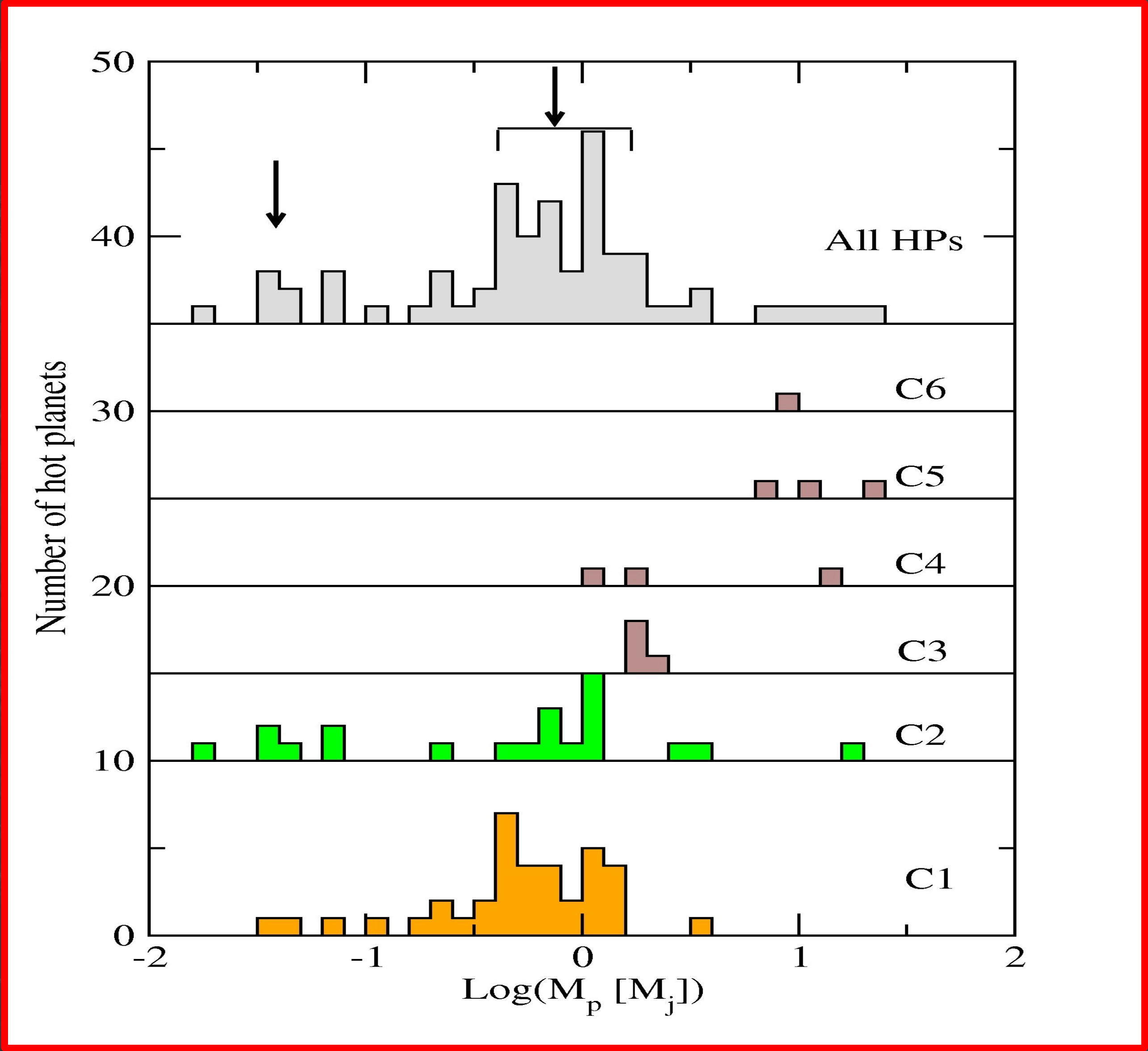
Therefore:

Two groups of HPs are identified, plus some outliers.

The latter maybe due to the clustering algorithm used, or may instead represent peculiar HPs.
We notice that outliers are characterized by very high *Mp*, and supersolar *Ms*.

# Hot planets: *Mp*-distribution

**Hot planets show 2 peaks of *Mp*: taxonomy somehow separates them!**

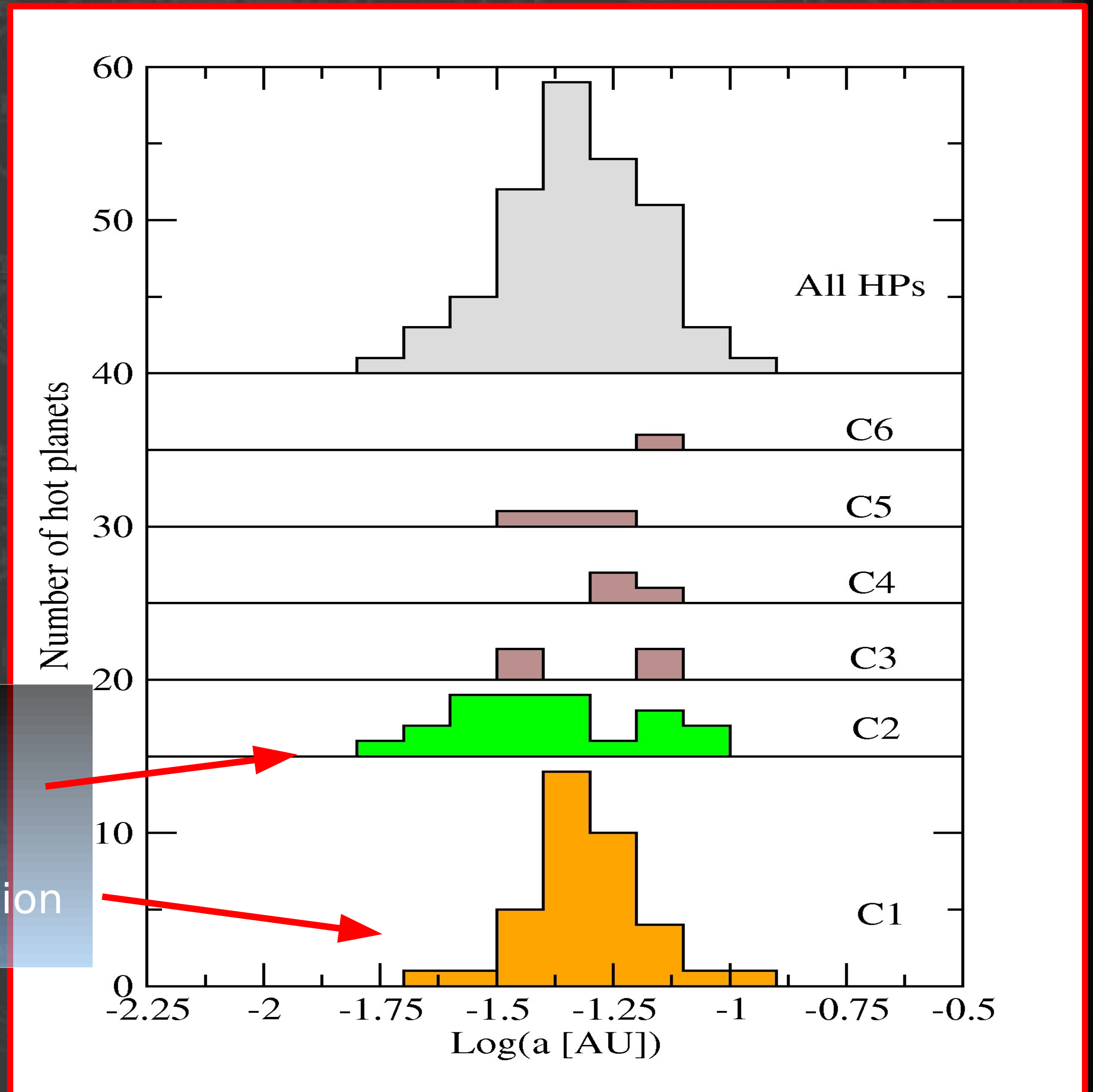


# Hot planets: *a*-distribution

Remarkable difference:

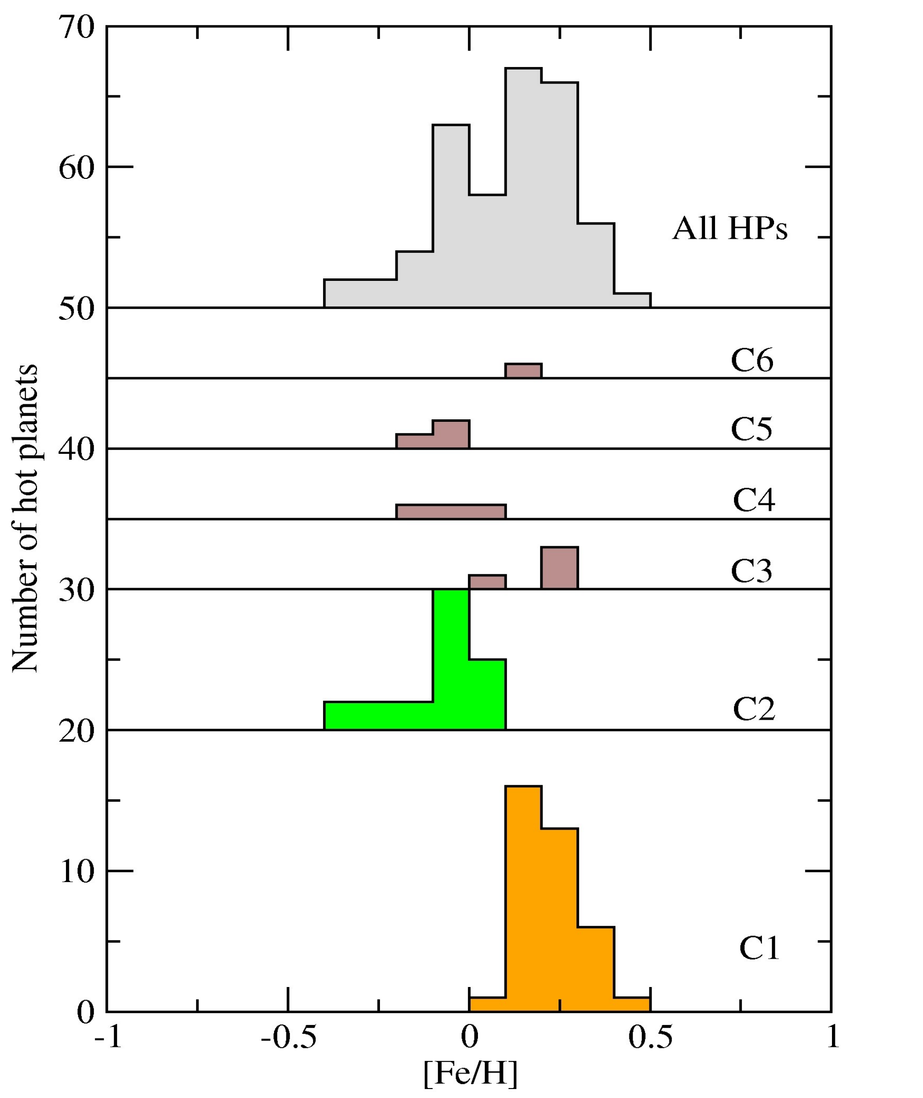
**C2** has a nearly flat distribution in the range 0.02-0.1 AU.

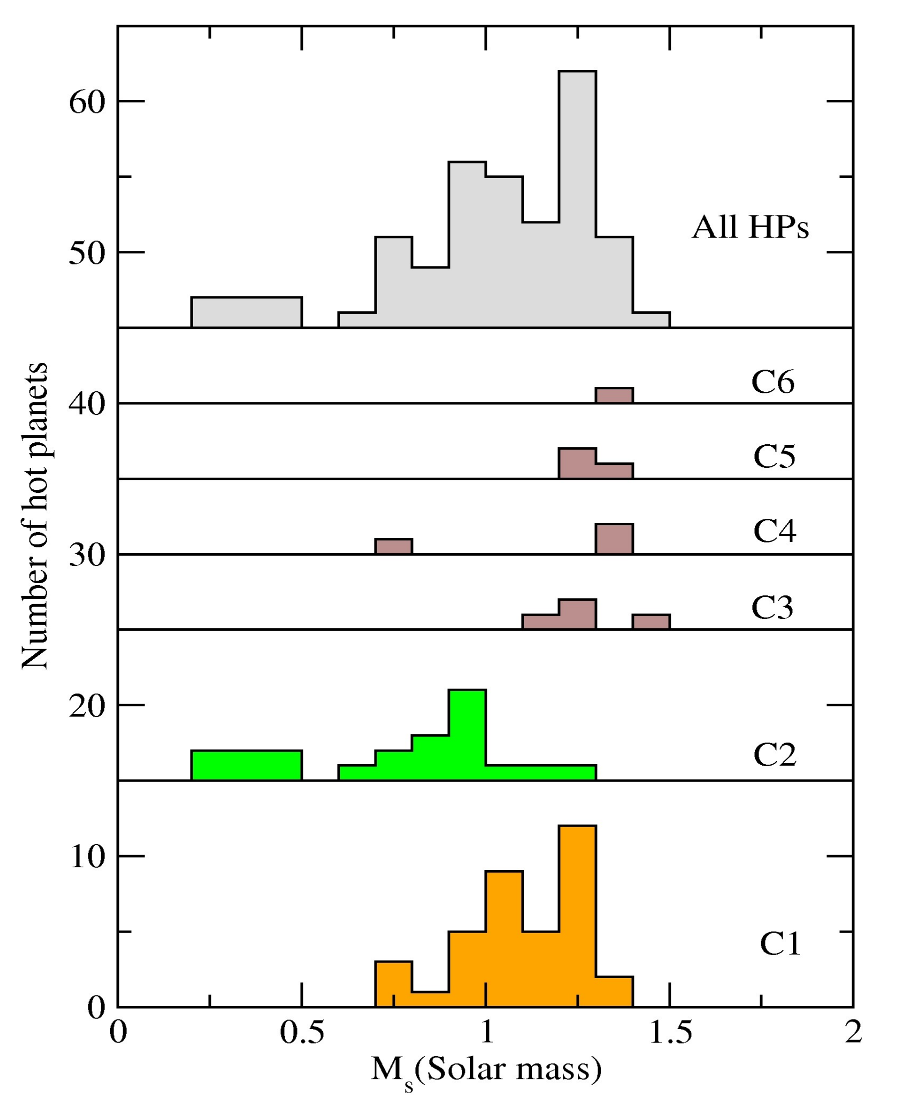
**C1** has semimajor axis distribution peaked at 0.05 AU;



# Hot planets: the environment

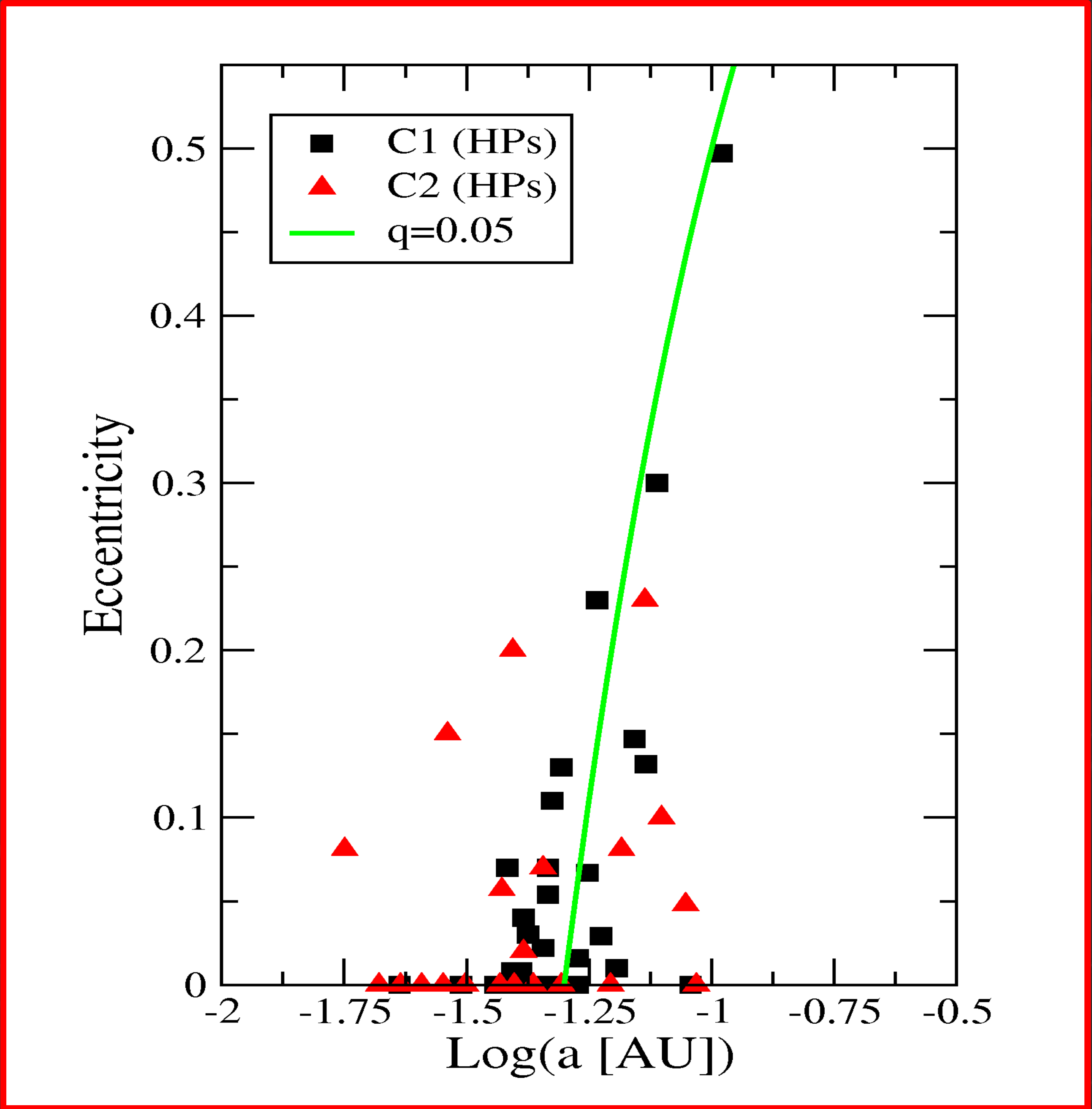
***[Fe/H]*** **is an important parameter that characterize C1 and C2;**
**also *Ms* -to a lesser extend- seems important:**



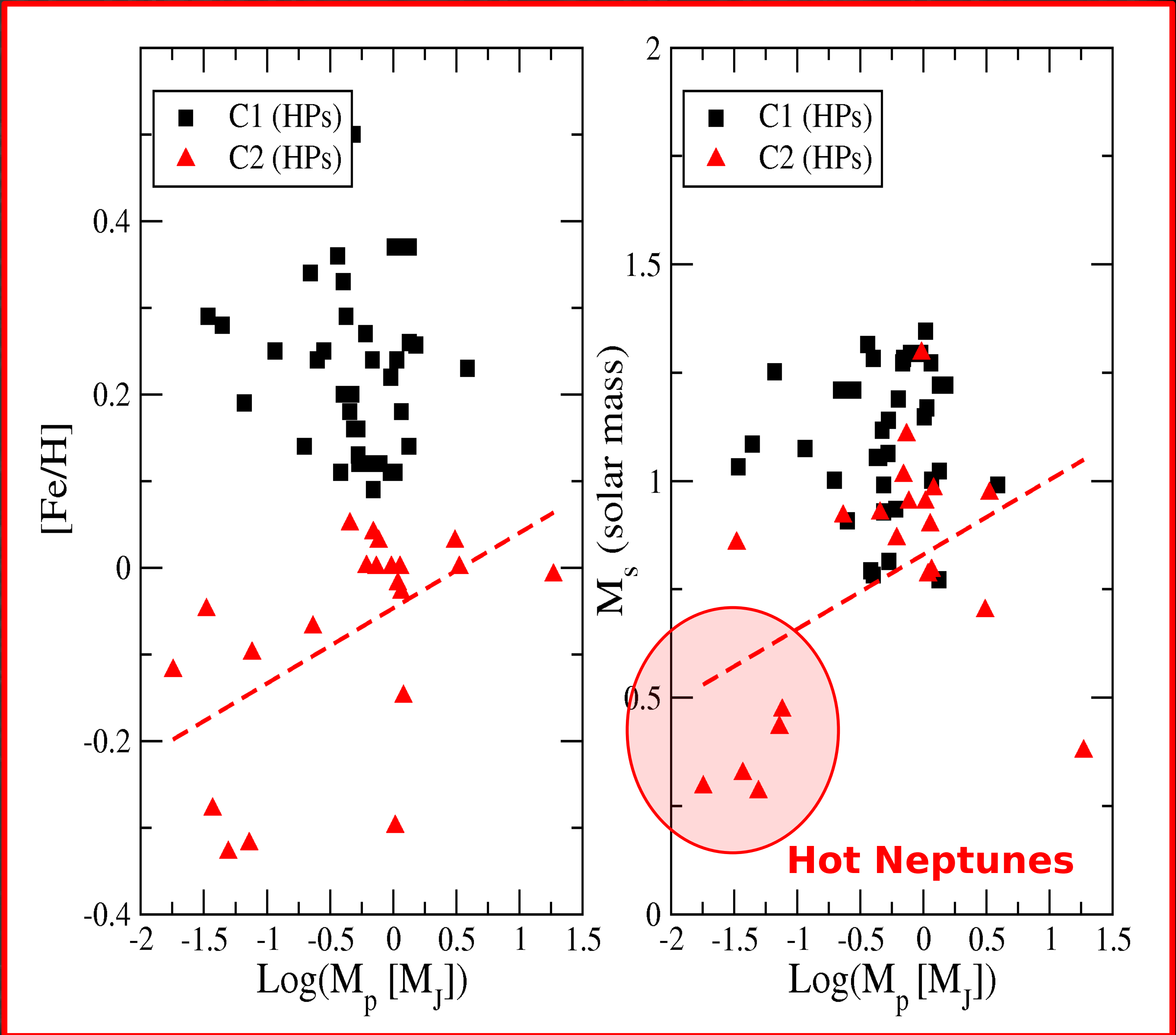
# Hot planets: correlations

**Strong *a-e* correlation holds for C1, no correlation for C2;**



# Hot planets: correlations

other correlations are ***Mp-[Fe/H]*** and ***Mp-Ms*** which hold for C2 and not for C1



# Hot planets: formation

**Two main processes have been proposed:**
**"type II" migration and "scattering"**

**Type II migration: low *e*, *a*-distribution truncated near corotation; post-evolution into the magnetospheric cavity may reduce *a* and increase *e;***

**Scattering: *a*-distribution peaked at ~0.05AU, moderate *e* left**

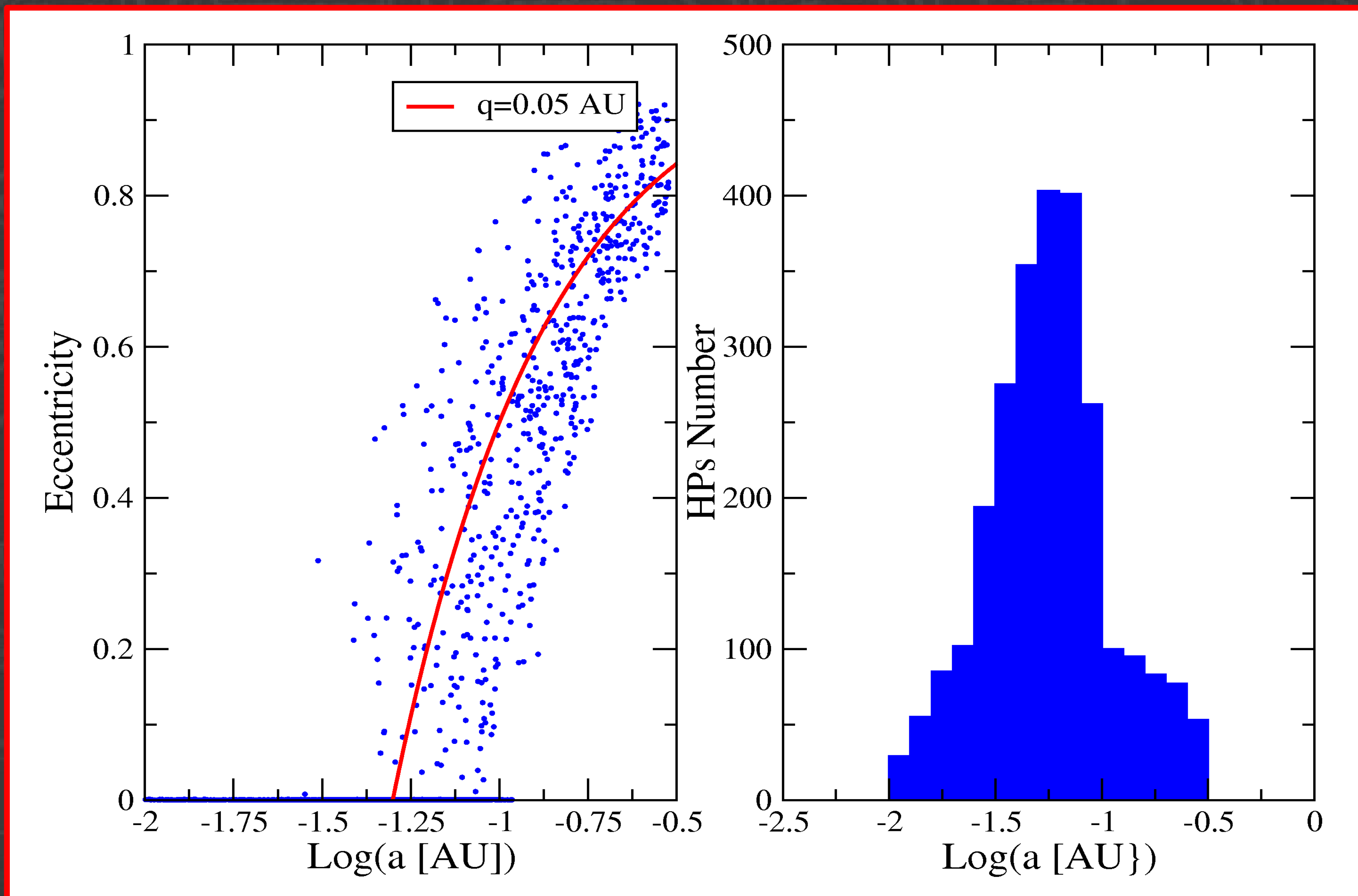
**Scattering, to be efficient, needs more than two massive planets.**
**Type II start operate for single planet with medium-to-large *Mp***

**Scattering is favored in high *Ms* high *[Fe/H]* environments, where more planets are expected to grow**

# Hot planets: scattering

After $10^8$-$10^9$ yr eccentric HPs are present:

Peak at $a$~0.03AU in $10^8$ yr for jupiter-like planets:



# Hot planets: an explanation

**Putting all things together, we may draw the following scenario:**

**HPs of C1 have high *Ms*, high *[Fe/H]* favoring systems with many massive EPs, and therefore high scattering.**

**This is in agreement with the peaked semimajor axis distribution, and the *a-e* correlation.**

**HPs of C2 have moderate *Ms* and low *[Fe/H]* favoring systems with smaller and/or less numerous EPs, and hence evolution by type II migration.**

**This is in agreement with the flat semimajor axis distribution.**

**The outliers HPs may require a combination of these effects or are formed in different ways.**

# Conclusions

**1. Robust taxonomy:**
definition of 6 main clusters of planets;

**2. Physical interpretation of clusters:**
clusters are identified by different properties of input variables, mainly [*Fe/H], Ms, Mp;*

**3. Significant trends for clusters:**
several trends, not visible on whole sample, are present within clusters;

**4. Two types of hot planets:**
characterized by different *Ms* and [*Fe/H];*
C1 has an *a*-distribution peaked at ~0.05AU;
C1 show a striking *a*-*e* correlation;
C2 has a flat *a*-distribution in the range 0.02-0.1AU;
Hot Neptunes belong preferentially to C2;

**5. Type II migration vs scattering:**
30% of HPs seems to form via migration (C2);
50% of HPs seems to form via scattering (C1).

# What is next?

- ➔Testing new input variables;
- ➔refine hierarchical taxonomy with larger sample;
- ➔testing new algorithms;
- ➔Effects of planet formation on star evolution

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*More details on taxonomy:* Marchi S., ApJ 666, 2007.
Marchi & Ortolani, IAUS 249, 2008.
Marchi, Ortolani, Nagasawa, Ida, MNRAS 2009.