

# Exoplanets

## Properties of the host stars

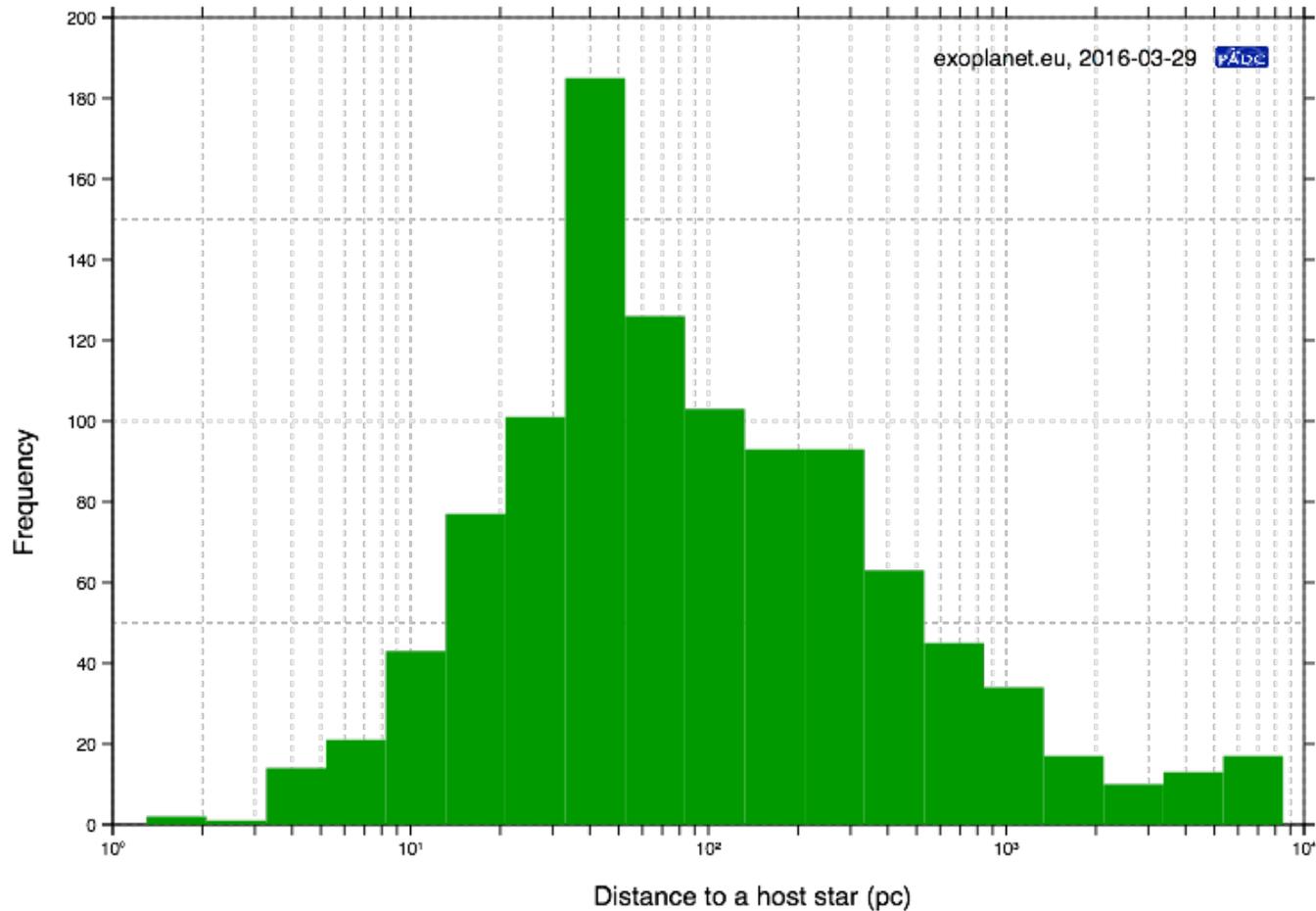
Planets and Astrobiology (2020-2021)  
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# Distances of exoplanets

Most planets found between 10 and 1000 pc

Number of stars increases with sampled volume ( $\sim d^3$ )

Signal-to-noise ratio of stellar data decreases as  $d^{-2}$



# Characterization of the host stars

- **Motivations**

- Accurate determination of stellar masses and radii are required to improve the accuracy of the exoplanet measurements obtained with the Doppler and transit methods
- Accurate measurements of stellar distances are fundamental to calibrate stellar parameters
- Stellar ages indicate the evolutionary state of the hosted planets, since the process of planetary formation takes place over shorter time scales compared to those of stellar evolution
- The space frequency and intrinsic luminosity of stars of different spectral types determines the efficiency of observational surveys with indirect methods

# Characterization of the exoplanet host stars

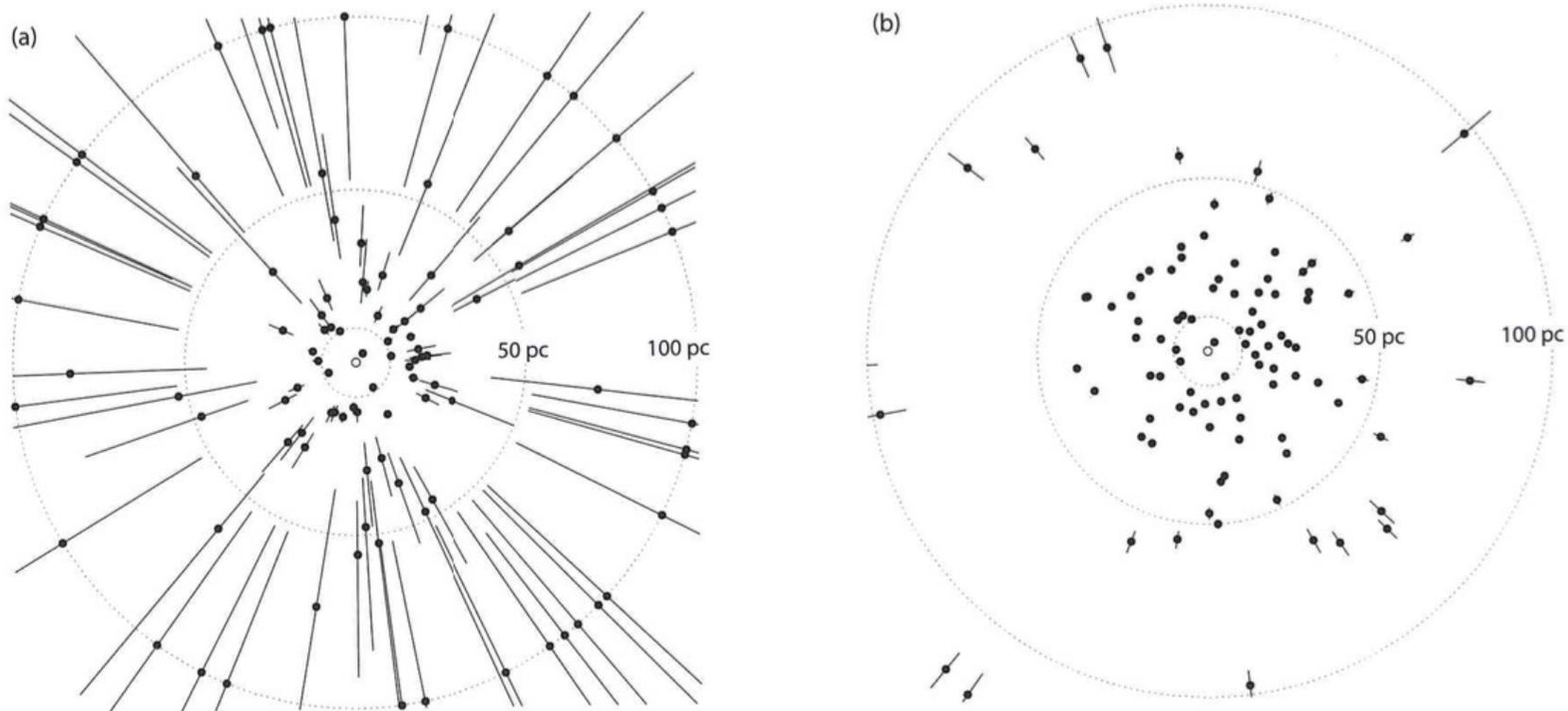
- Properties of the host stars of exoplanets are derived from a combination of astrometric, photometric, and spectroscopic observations, interpreted primarily within the context of stellar evolutionary models



- Exoplanets have been found around stars with different masses, at different stages of evolution, and at different locations in the Galaxy

## Astrometry and stellar distances

- Astrometric measurements provide the database of the most accurate determinations of parallactic angles and stellar distances
- The Hipparcos satellite provided 1 mas accuracy for about  $1.2 \times 10^5$  stars



Improvement in the knowledge of exoplanet host star distances by Hipparcos for the 100 brightest stars with exoplanets known with Doppler method in 2010. Left: ground based compilations of distances. Right: Hipparcos distances.

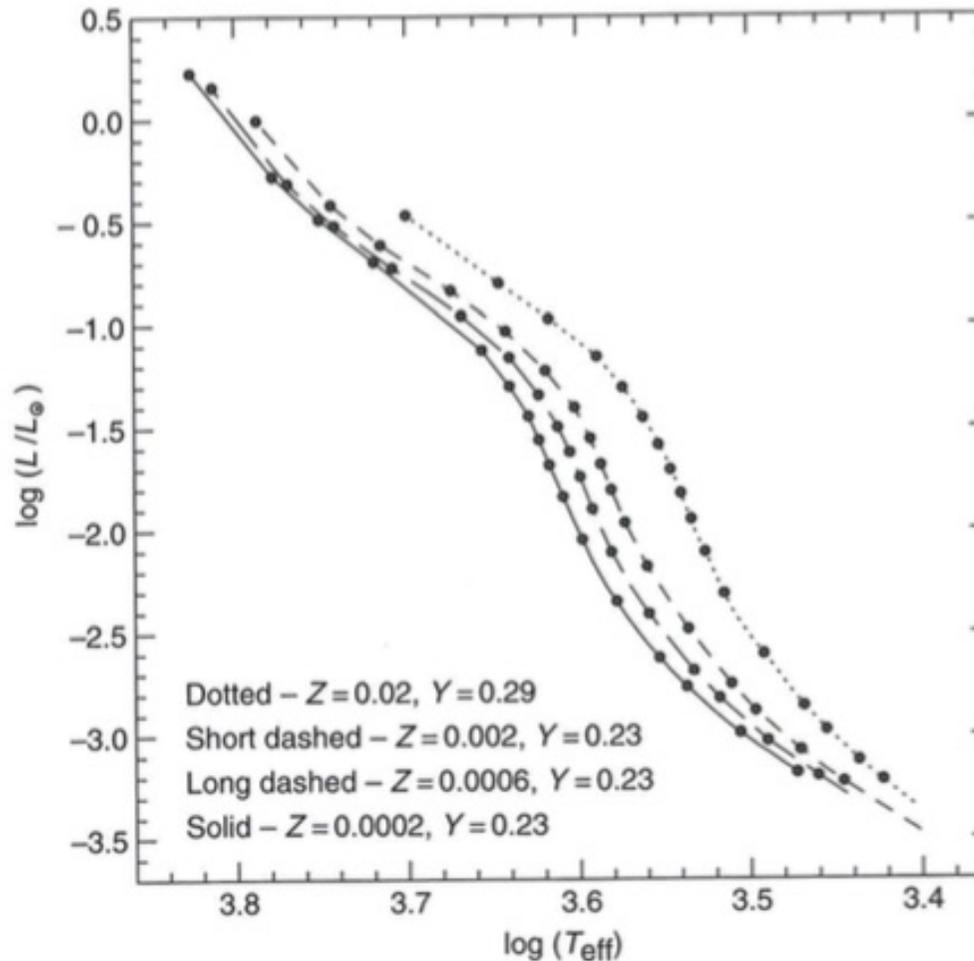
## Astrometry and stellar distances

- The Gaia mission (ESA)
  - <http://gaia.esa.int>
  - Unbiased survey of  $10^9$  point-like Galactic sources (6-20 mag)
  - Astrometric precision, up to 10  $\mu\text{as}$  for the brightest sources, in the range of a few tens  $\mu\text{as}$  for other sources
  - Intermediate resolution spectra for  $\sim 150 \times 10^6$  stars
  - Great increase of the accuracy of exoplanet host-star distances
  - Stars with distances larger than 50-100 pc most greatly benefit with respect to previous measurements based on Hipparcos

# Hertzprung-Russel (HR) diagram

Theoretical diagram:  $L_*$  versus  $T_{\text{eff}}$

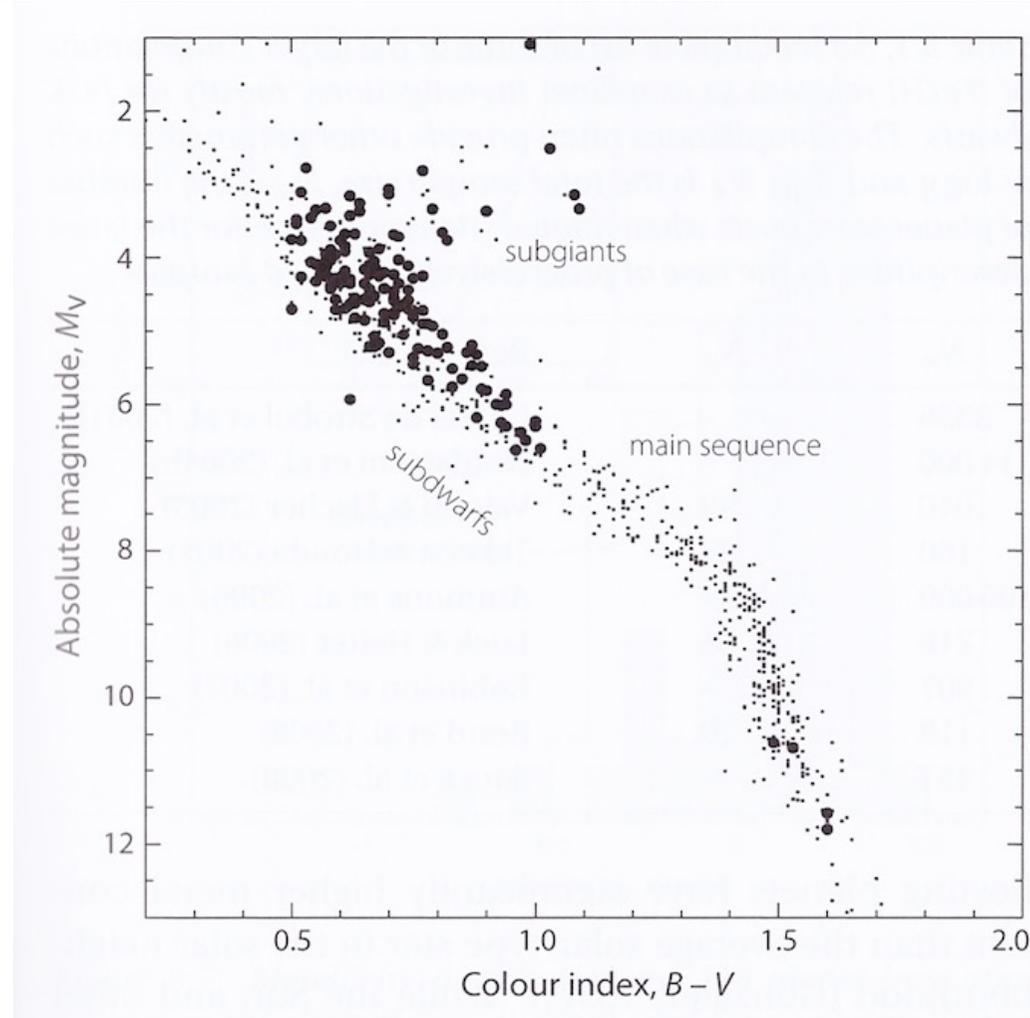
Zero-age main sequences for low-mass stars versus Helium and “metal” abundances ( $Y$  and  $Z$ , respectively)



Evolutionary tracks in HR diagrams are calculated for different masses and metallicities (stellar composition)

# Hertzprung-Russel (HR) diagram

Hipparcos based HR diagram for stars within 25 pc  
Filled circles: stars with planets (2003)

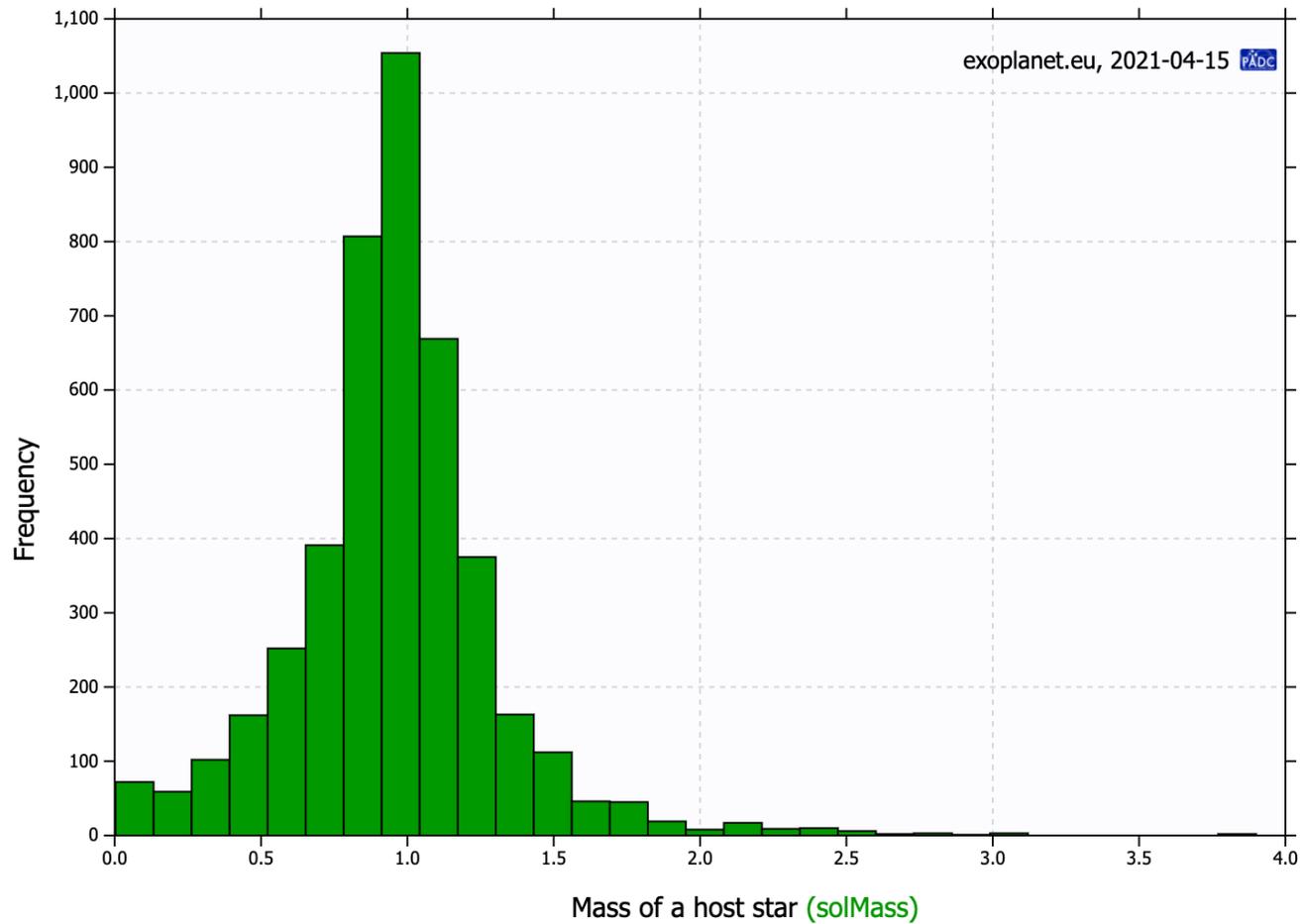


# Statistical properties of exoplanet host stars

- Exoplanet surveys provide the opportunity to search for correlations between the frequency of detected planets and the properties of the host stars
- Trends between stellar and planet properties cast light on the process of planetary formation
- Among the stellar properties investigated, we consider
  - Masses
  - Kinematic properties
  - Metallicities
  - Elemental abundance ratios

# Number of detected exoplanets versus mass of the host star

Stars of lower mass are more numerous and, in addition,  
make easier the indirect detection of planets

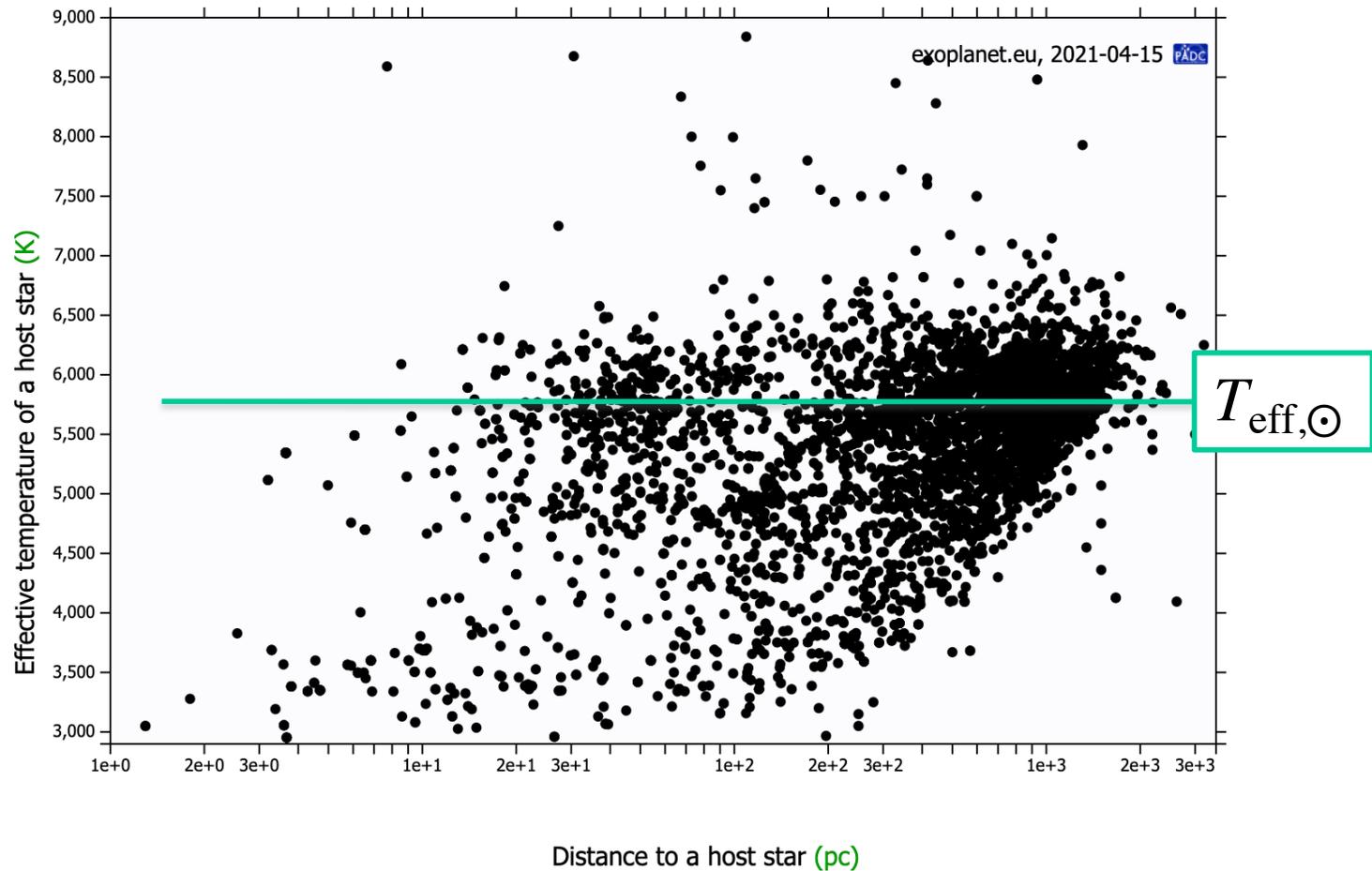


# Effective temperature, $T_{\text{eff}}$ , of the host star

Most planets found in stars colder than the Sun

Planet signal is stronger in stars of low mass (i.e., low effective temperature)

Disadvantage: low-mass stars are fainter and more active than solar-type stars



# Metallicity of the host star

- **Definition**

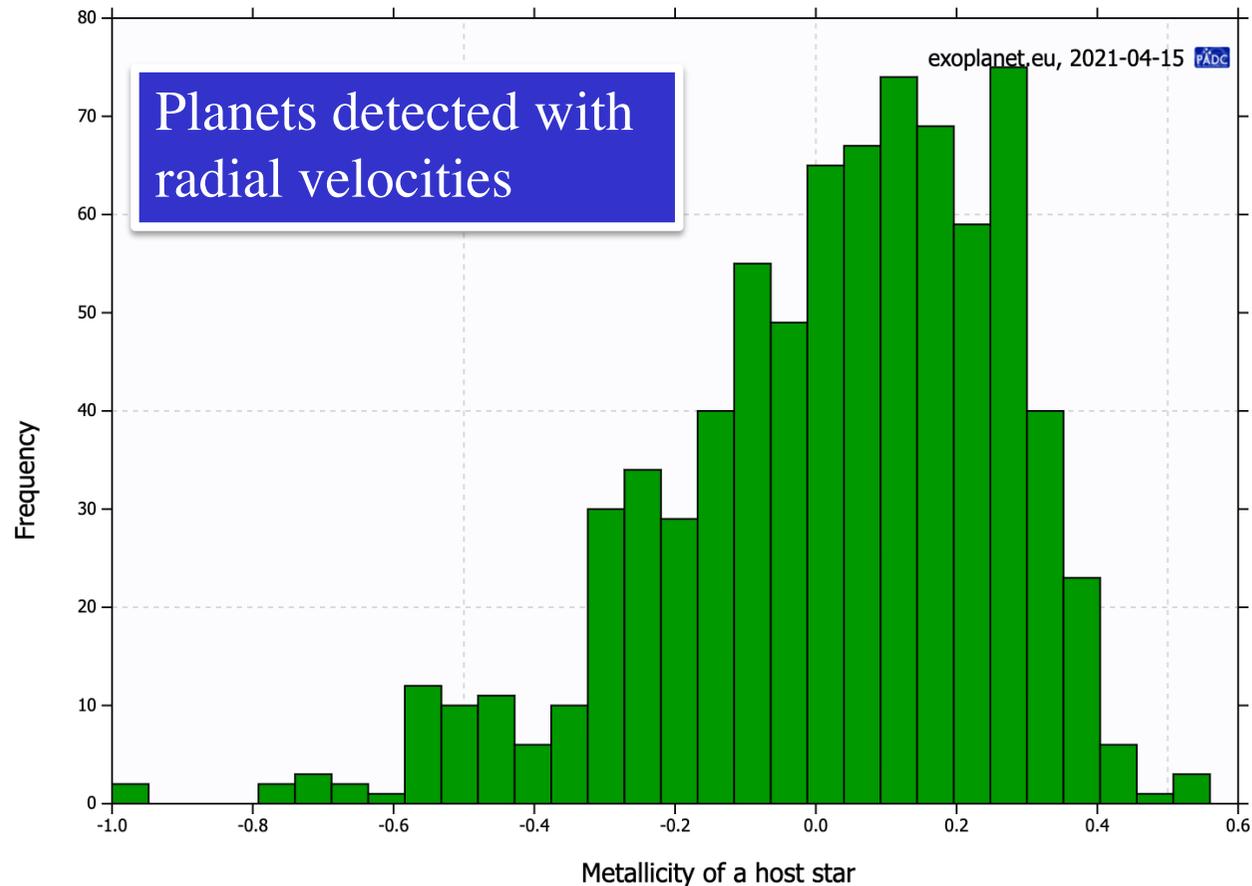
- The abundance by number of an element X relative to hydrogen (also called “absolute abundance”) is usually expressed in logarithmic units, relative to a reference value of solar abundance:

$$[X/H] = \log (N_X/N_H) - \log (N_X/N_H)_\odot$$

- For elements heavier than He, a measurement of stellar [X/H] is an indicator of stellar “metallicity”
  - The most classical indicator is [Fe/H], since iron lines are easy to measure in stellar spectra
- **The metallicity is an indicator of Galactic chemical evolution**
    - Metals are produced by stellar nucleosynthesis and ejected in the interstellar medium
    - Stars born from the interstellar medium previously enriched by metals have a higher metallicity than stars of previous generations

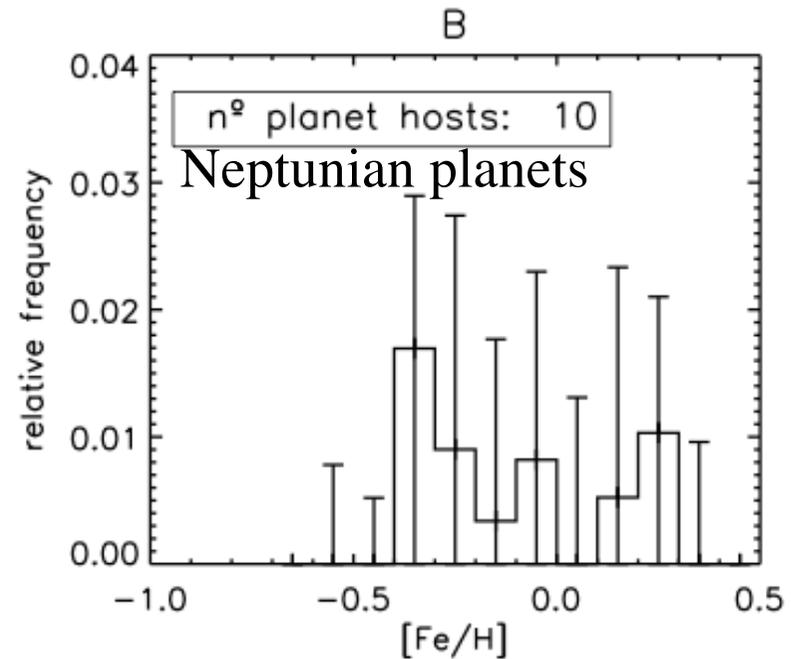
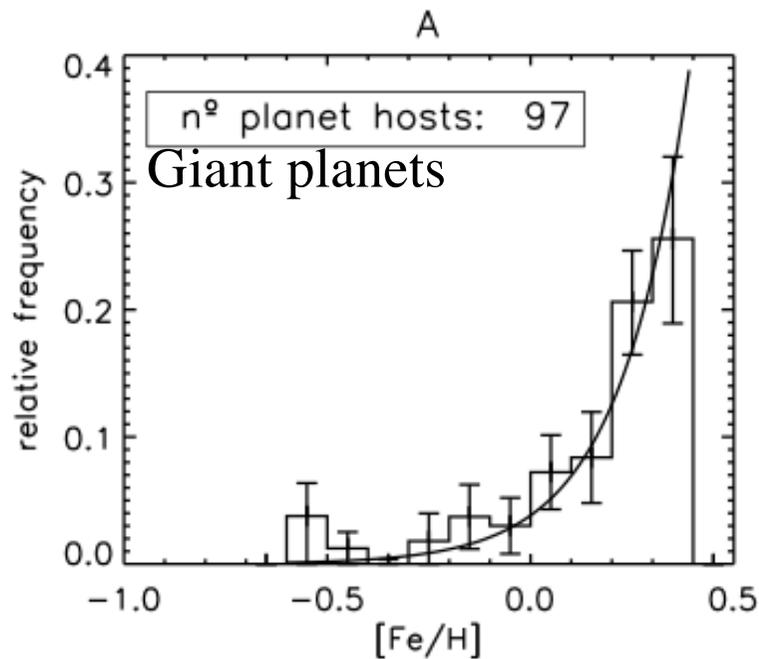
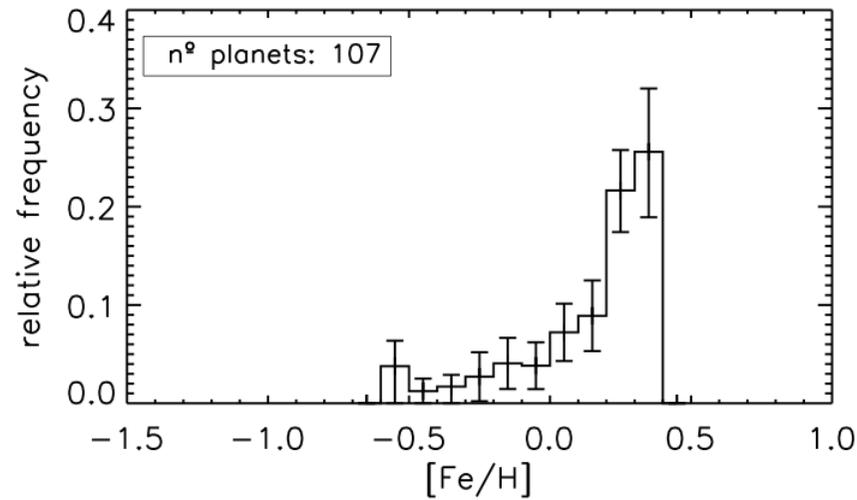
# Metallicity distribution of planet-hosting stars: experimental data

- The frequency of planet-hosting stars increases with metallicity and peaks at abundances higher than solar
- Due to selection effects, the result is dominated by the statistics of giant planets



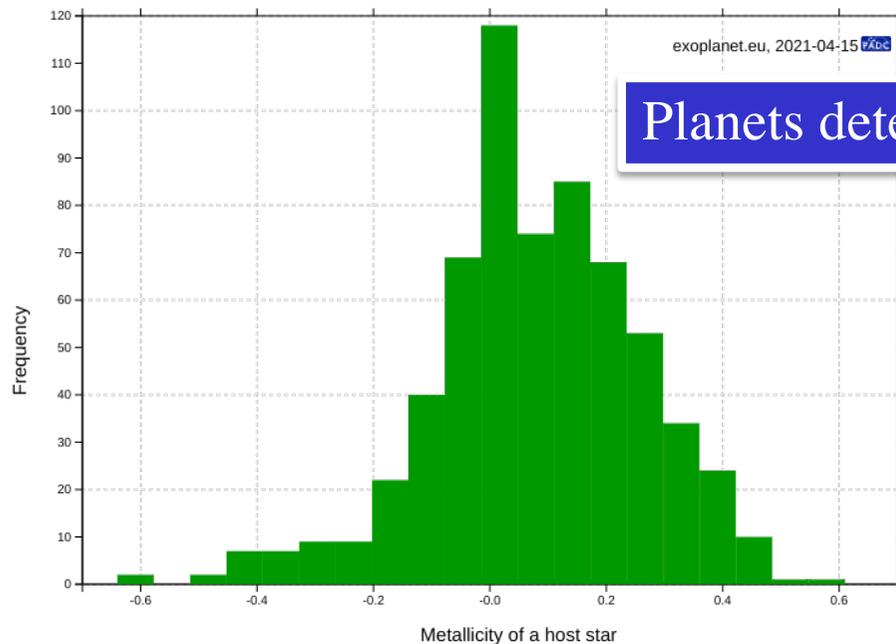
The trend with metallicity is observed for giant planets,  
but not for planets with lower mass

(Sousa et al. 2011)

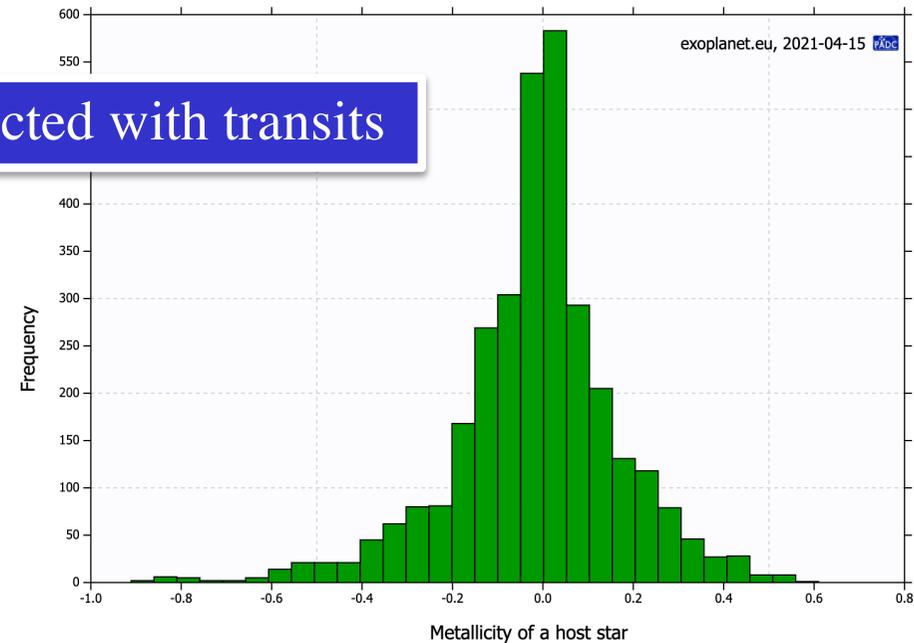


# Metallicity distribution of planet-hosting stars: experimental data

- The asymmetry at high metallicity is also present in planets detected with the transit method
- The effect is evident for large planets
- When the full sample is considered, the effect is diluted because a large number of small planets is detected with the transit method



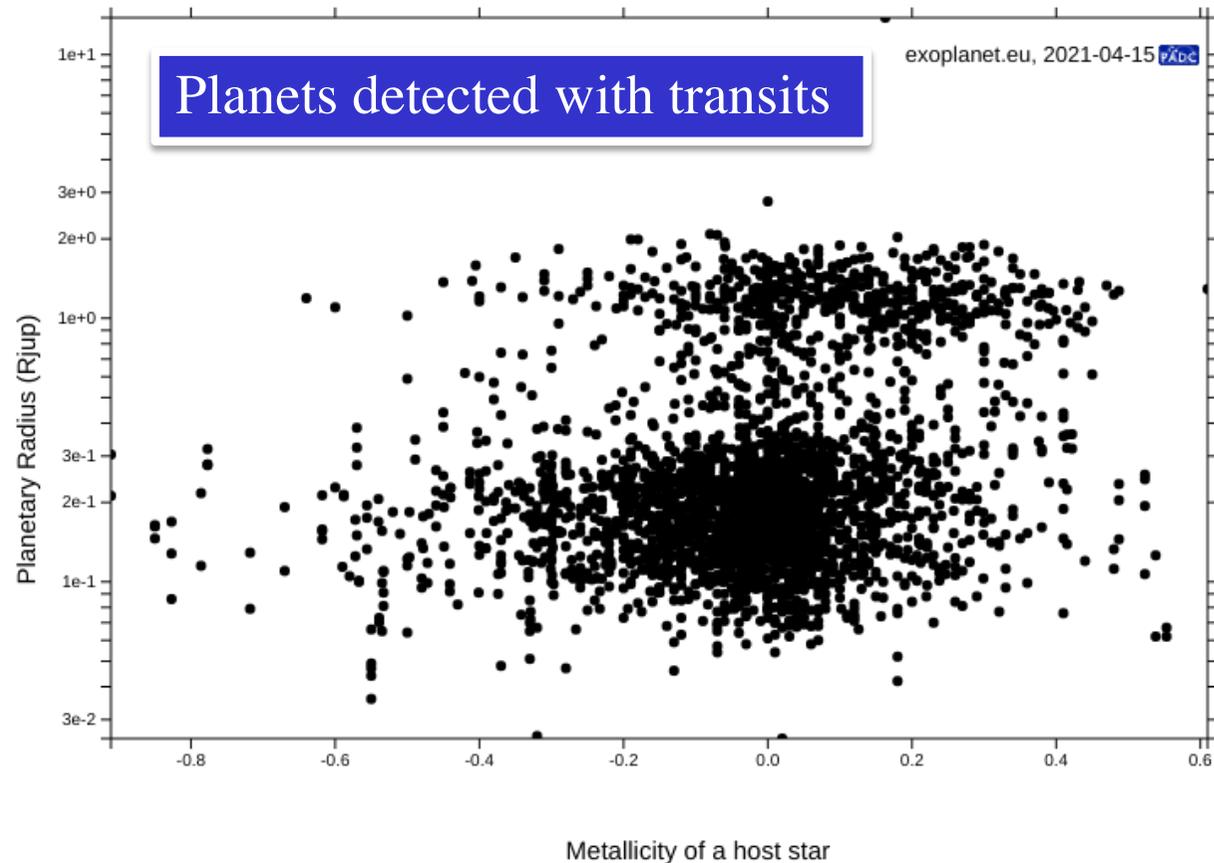
Planets with radius  $> 6 R_{\text{earth}}$



Full sample

## Metallicity distribution of planet-hosting stars: experimental data

- The distribution of planetary radii versus metallicity of the host star shows that giant planets are centered around metallicities larger than solar, whereas small planets are centered at lower metallicities

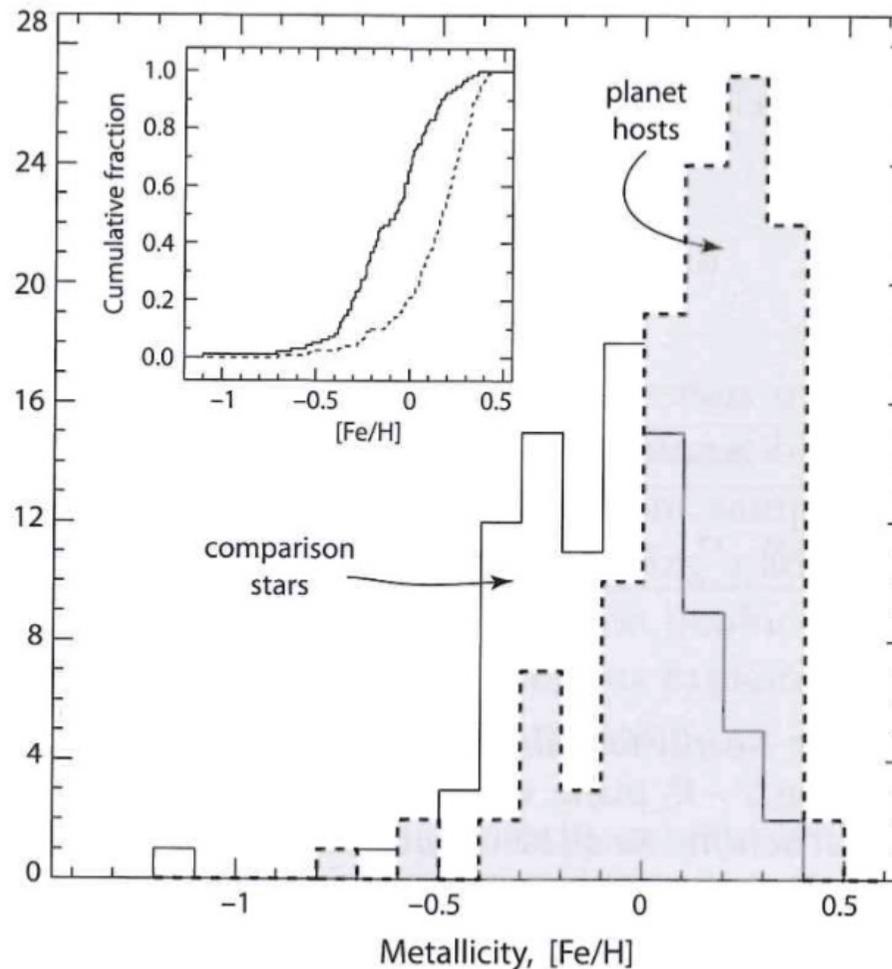


## Metallicity distribution: planet-hosting stars: versus comparison stars

- Statistical comparison between the two samples indicates that stars that host planets have a higher level of metallicity than stars without planets

The selection of a sample of comparison stars is not trivial

Undetected low-mass planets could be present in the comparison sample



## Metallicity distribution of planet-hosting stars: interpretation of the excess of high-metallicity planet hosts

- The role of selection effects is not clear
  - The majority of the sample of detected exoplanets could be representative of a specific subset of the overall exoplanet population
- If the effect is real, the correct interpretation would cast light on the process of planetary formation
  - A larger statistics is required to understand if a trend exists for low-mass planets
- Three types of interpretation have been advanced
  - Primordial occurrence
  - Self-enrichment
  - Different Galactic origins

## Metallicity distribution of planet-hosting stars: interpretation

- **Primordial occurrence**

- Currently this is the most accepted hypothesis
- The metallicity observed in the hosts would represent the original composition out of which the protostellar and protoplanetary disk formed
- In this picture, the higher the metallicity of the primordial cloud, the higher the dust-to-gas ratio in the protoplanetary disk
- A high dust-to-gas ratio facilitates condensation of solids and accelerates protoplanetary accretion before the gas disk is lost
- At low metallicity, the protoplanetary material not used to build up giant planets would become available to accrete low-mass planets
- This could explain why the mechanism is effective for giant planets, but apparently not for low-mass planets

## Metallicity distribution of planet-hosting stars: interpretation of the excess of high-metallicity planet hosts

- **Self-enrichment**

- This hypothesis was advanced when the metallicity-occurrence trend was discovered, but is not supported by observational evidence
- In this interpretation, the high metallicity is a phenomenon restricted to the surface layers of the star, arising from the capture of metal-rich material, and the resulting "pollution" of the outer convective envelope
- The pollution could result from inward migration of rocky planets onto the star as a result of dynamical friction
- Stars with more massive protoplanetary disks (and more planets) would accrete more rocky material and their surface metallicity would rise

## Metallicity distribution of planet-hosting stars: interpretation

- **Stellar migration along Galactocentric distance**
  - According to this hypothesis, the giant planet occurrence-metallicity correlation is related to the radial migration of stars in the Galactic disk
  - The inner Galactic disk has a large reservoirs of  $H_2$  which improve the star formation efficiency, metal production and giant planet formation
  - Giant planet formation would correlate with Galactocentric distance (more giant planets in the inner disk) rather than being primarily linked to metallicity
  - In this scenario, metal-rich stars found in the solar neighbourhood may have migrated from the (more metal-rich) inner Galactic disk

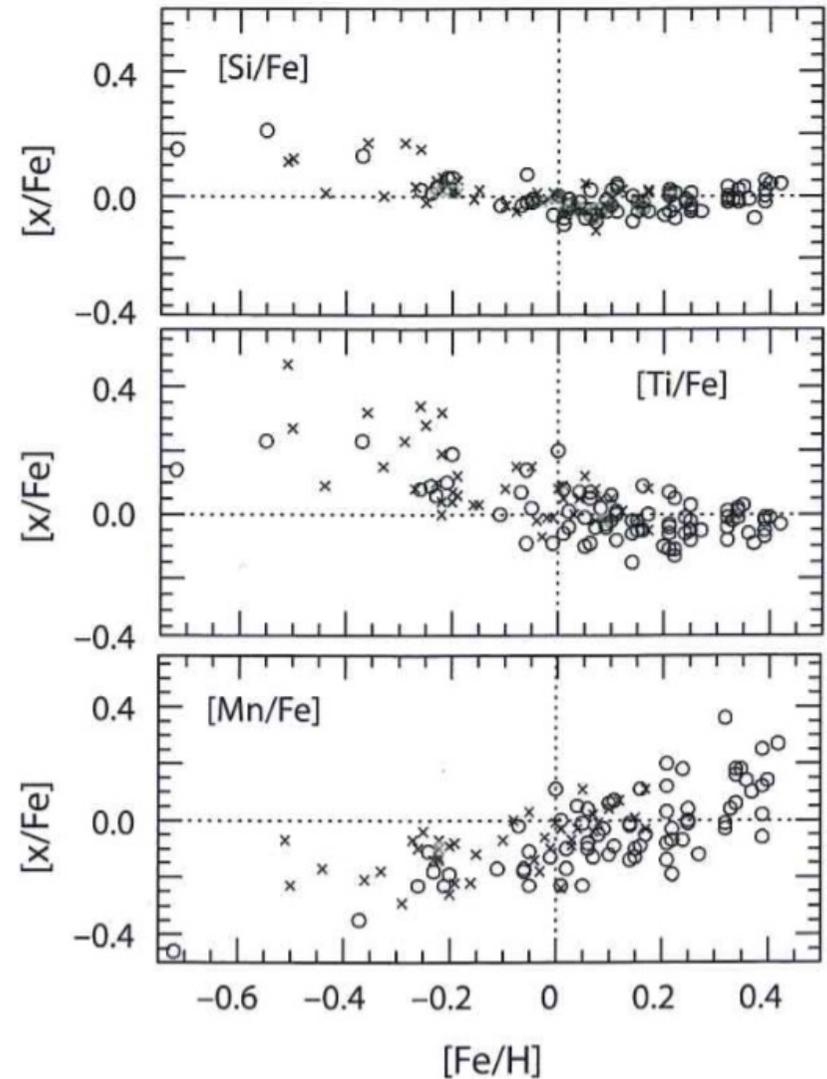
## Abundance ratios in stars with and without planets

- Also element-to-element abundance ratios, such as  $[X/Fe]$ , have been studied, searching for trends that may differentiate samples of stars with or without planets
- The trends of element-to-element abundance ratios versus absolute metallicity, such as  $[Fe/H]$ , provide essential indications on the chemical evolution of galaxies
- Differences in such trends may cast light on the process of planetary formation at different epochs and locations in the Galaxy

## Abundance ratios in stars with and without planets

- Several studies have searched for systematic differences of element-to-element abundance ratios in stars with and without planets
- Most studies indicate that the relative abundances  $[X/Fe]$  are basically similar

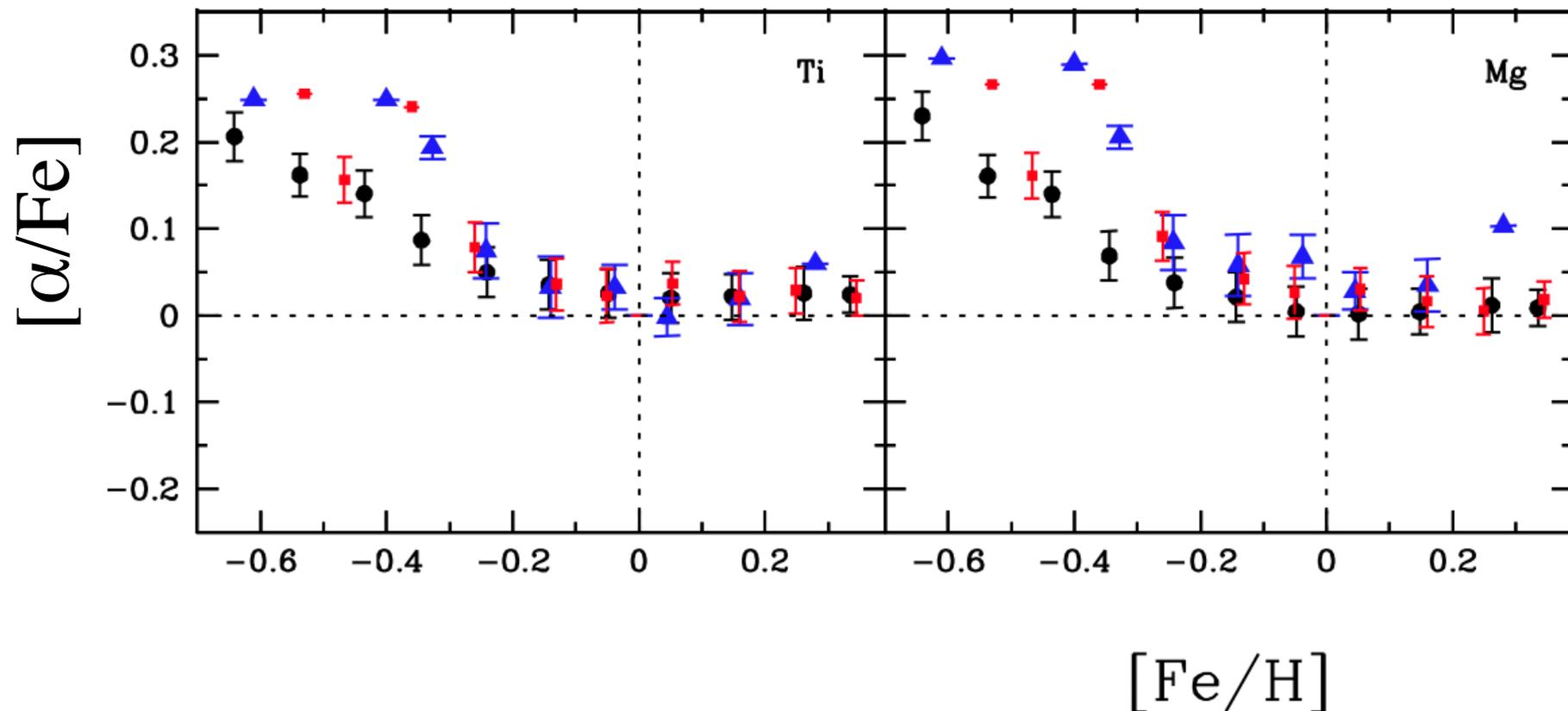
Open circles: planet host stars  
Crosses: comparison stars  
Dashed lines: solar abundances



Tentative evidence for enrichment of  $\alpha$  elements in low-metallicity, planet-hosting stars (Adibekyan et al. 2012)

If confirmed, it would suggest a dependence of planetary formation efficiency on the initial chemical composition of the protoplanetary cloud

The red squares and blue triangles represent stars with Jupiter-mass and Neptunian/super-Earth mass  
Black dots: stars without planetary companion



- The lack of a strong trend between planet occurrence and element-to-element abundance ratios suggests that:
  - the metal enrichment of planet hosting stars is primordial, rather than due to self-enrichment
  - it is not necessary to invoke exceptional events of chemical enrichment (such as the pollution by a nearby supernova) in order to trigger planetary formation
- Minor trends may reveal important details of the planetary formation process
  - E.g., relative importance of refractory and volatile material in the process of planetary formation