Exoplanets
Properties of the host stars

Planets and Astrobiology (2022-2023)
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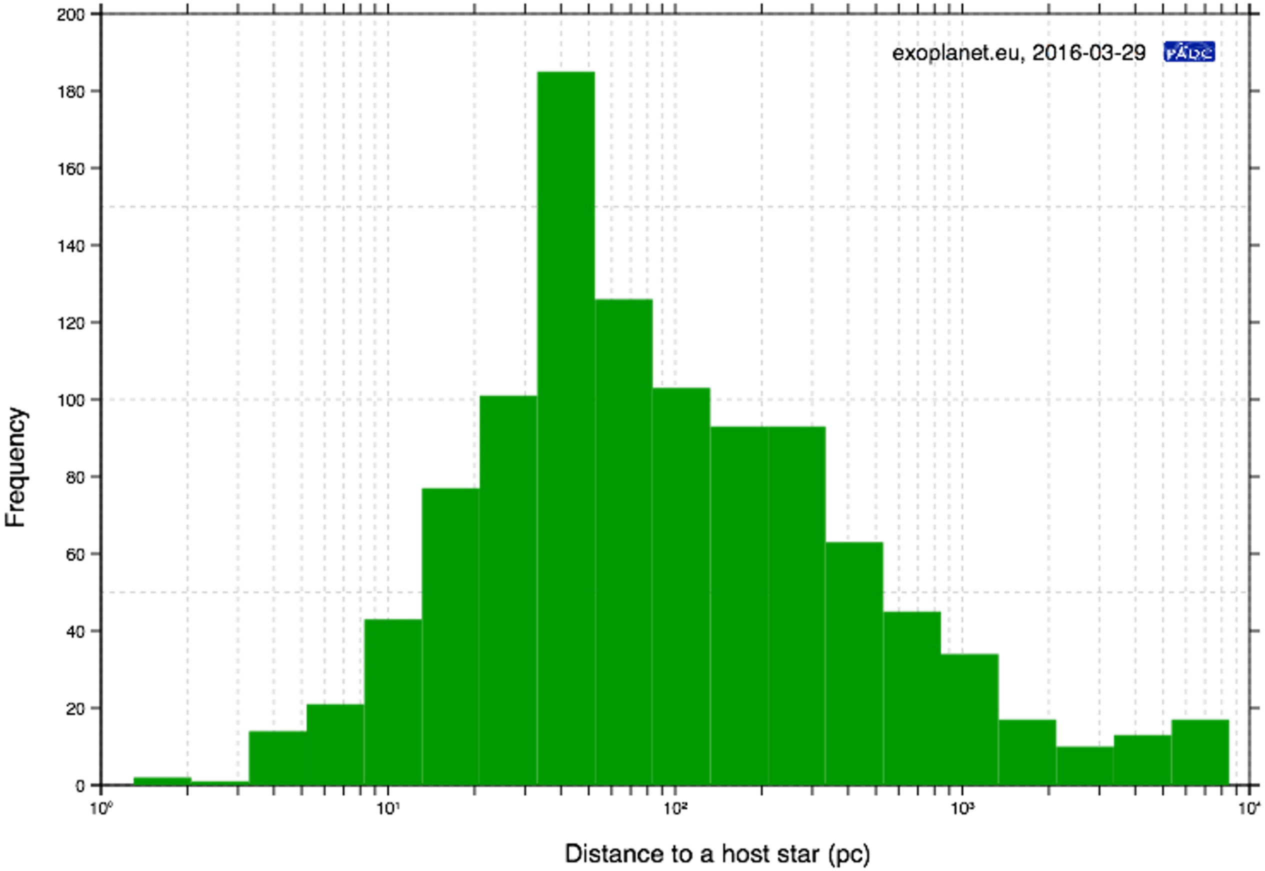
Distances of exoplanets

Most planets found between 10 and 1000 pc

Number of stars increases with sampled volume

Signal-to-noise ratio of stellar data decreases with increasing distance

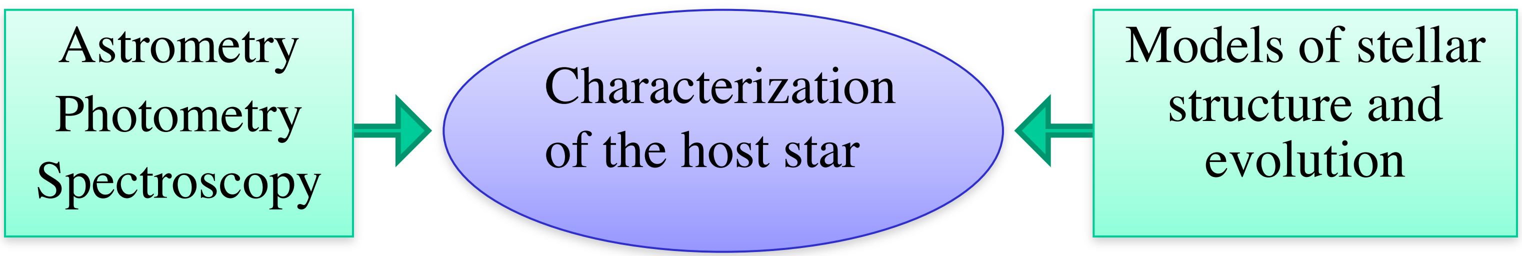


Characterization of the host stars

- 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



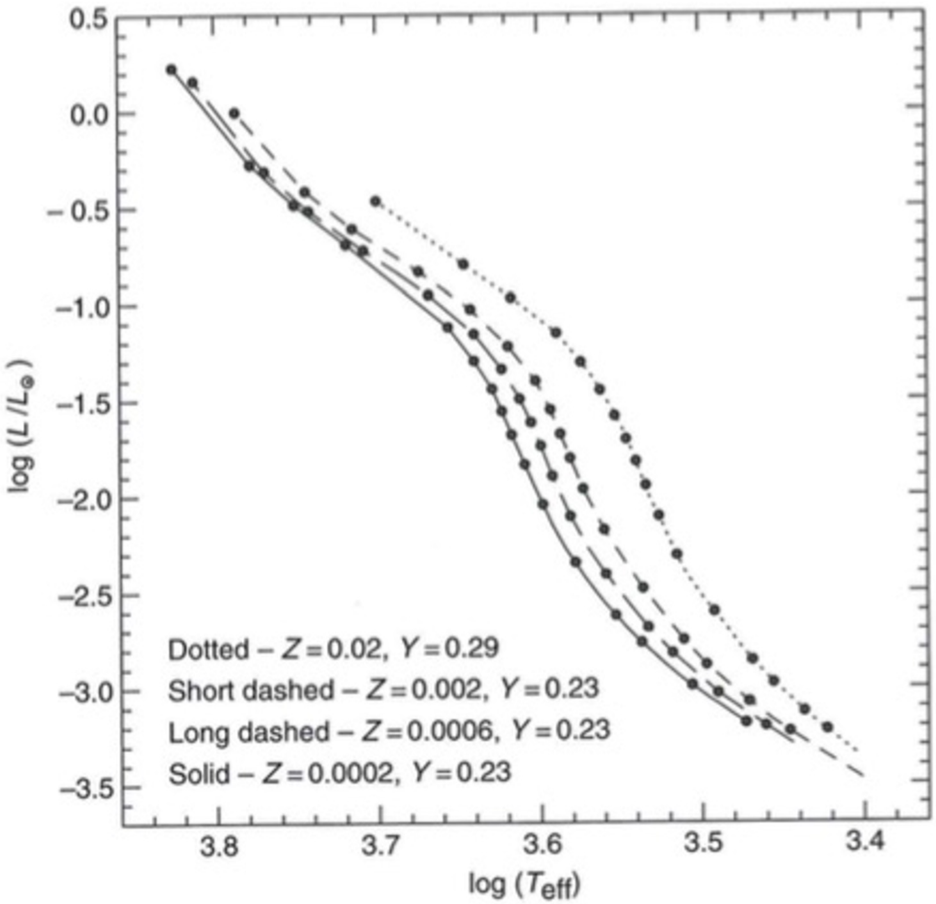
- Exoplanets have been found around stars with different masses, at different stages of evolution, and at different locations in the Galaxy

Hertzprung-Russel (HR) diagram

Theoretical diagram: L_* versus T_{eff}

Zero-age main sequences for low-mass stars versus

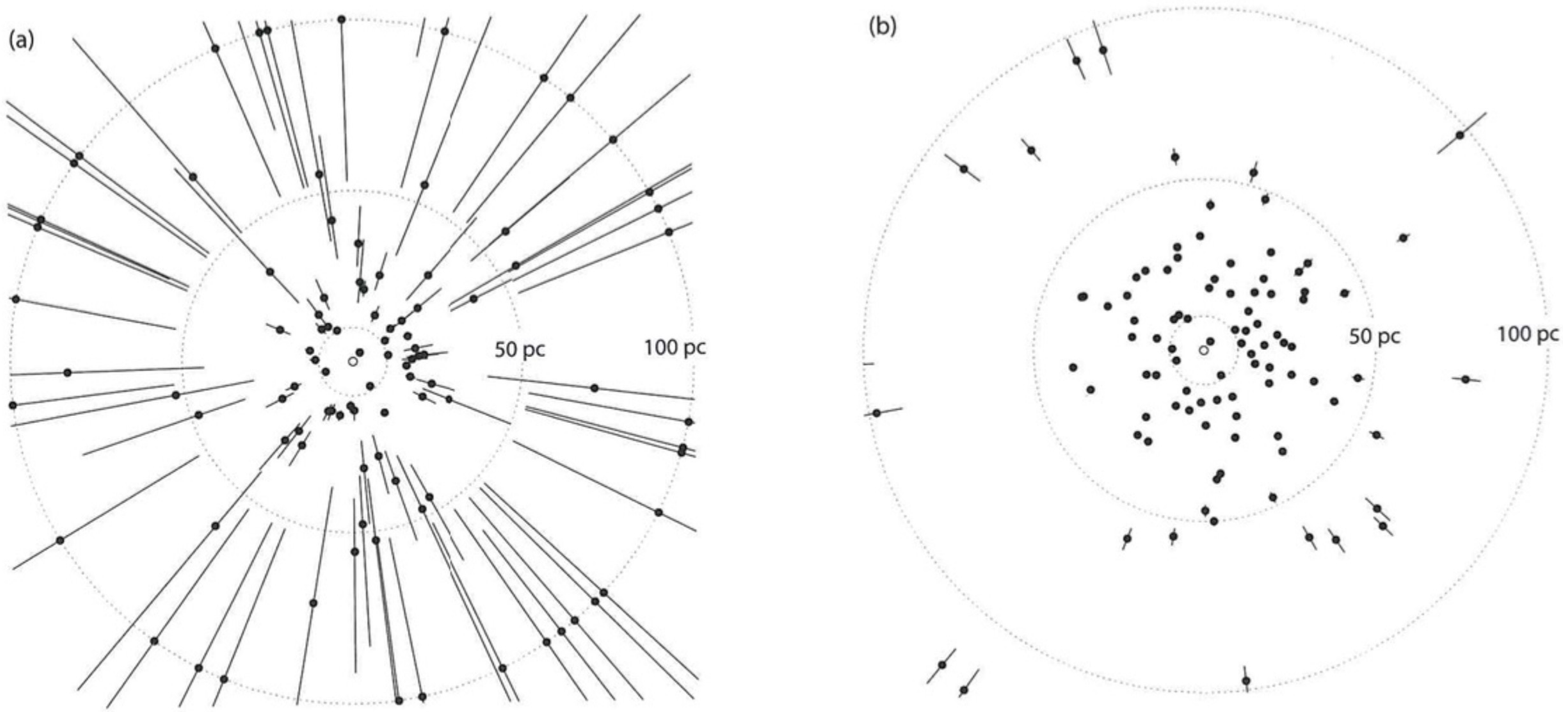
Helium and "metal"abundances (*Y* and *Z*, respectively)



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

Absolute luminosity ← stellar distances

- Astrometric measurements provide the database of the most accurate determinations of parallatic angles and stellar distances
- Early 1990's: Hipparcos satellite ➔ 1 mas accuracy for about 1.2x10^5 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

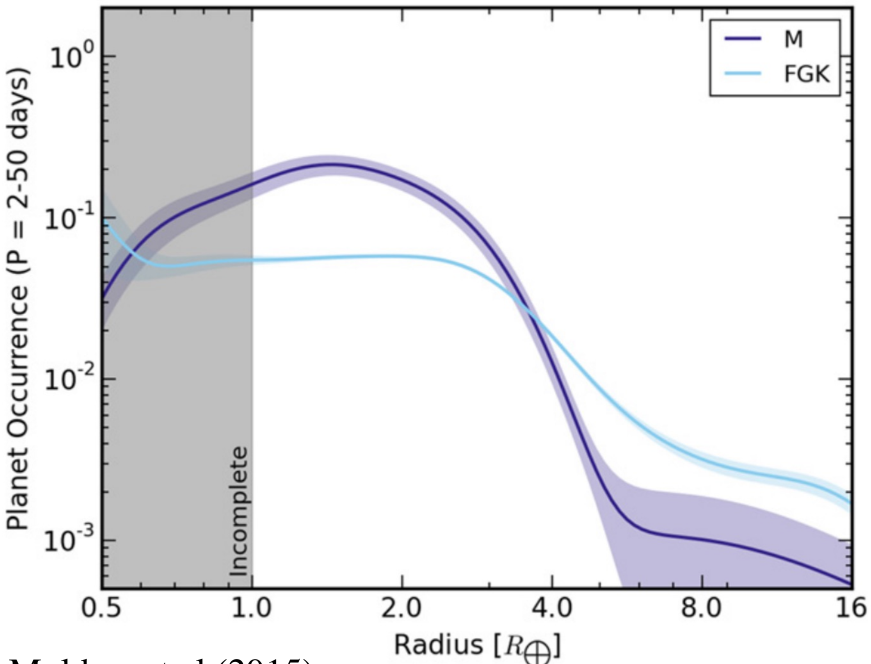
- The Gaia mission (ESA)
  - http://gaia.esa.int
  - Unbiased survey of $>10^9$ point-like Galactic sources (6-20 mag)
  - Astrometric precision, up to 10 μas for the brightest sources, in the range of a few tens μas for other sources
  - Intermediate resolution spectra for ~ 150 x 10^6 stars

  - 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

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

Planet fraction vs stellar mass

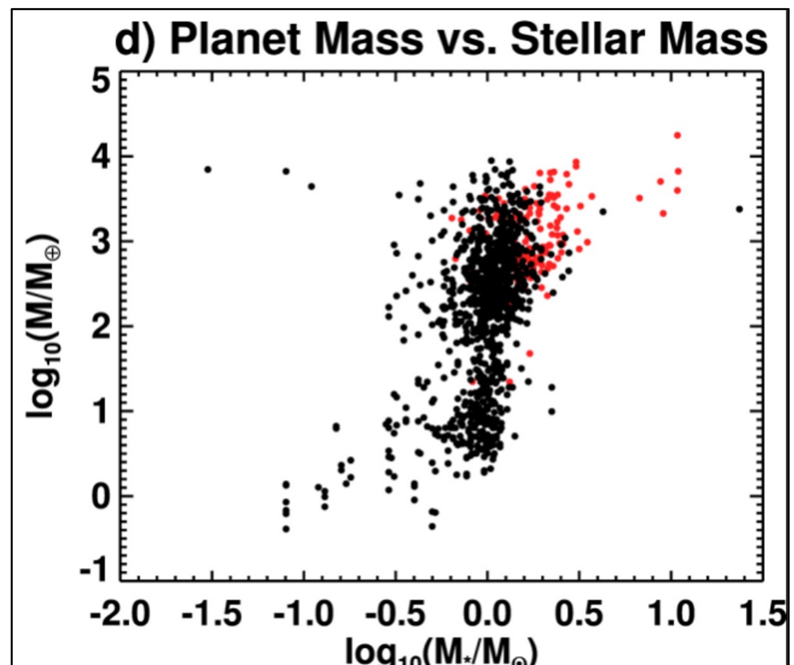


Mulders et al.(2015)

- significant different between the distribution of radii of planets orbiting M-type stars vs planets orbiting FGK-type stars

- differences within the FGK-type star group are much smaller

- stellar and planetary masses seems correlated, although not strongly



black: Main Sequence stars
red: Red Giant stars

Jiang & Zhu (2018)

Metallicity of the host star

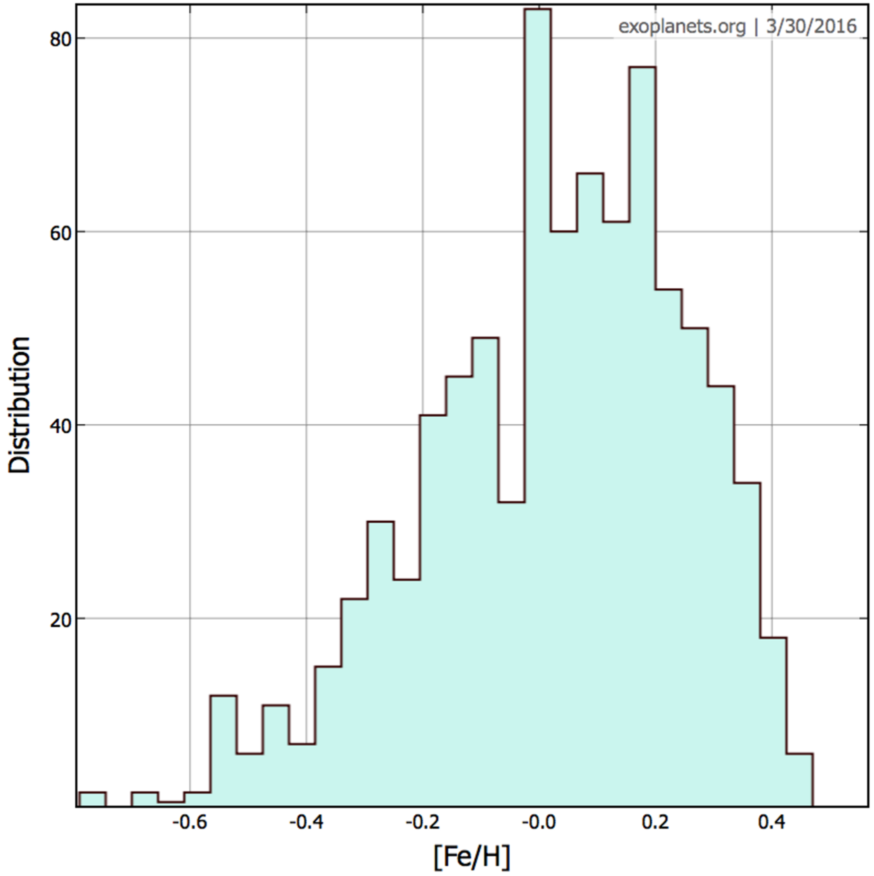
- Definition
  – The abundance by number of an element X relative to hydrogen (also called "absolute abundance") is usually expressed in logarithmic units, relative to a reference value of solar abundance:

$$[\mathrm{X/H}] = \log\,(N_\mathrm{X}/N_\mathrm{H}) - \log\,(N_\mathrm{X}/N_\mathrm{H})_\odot$$

  – 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

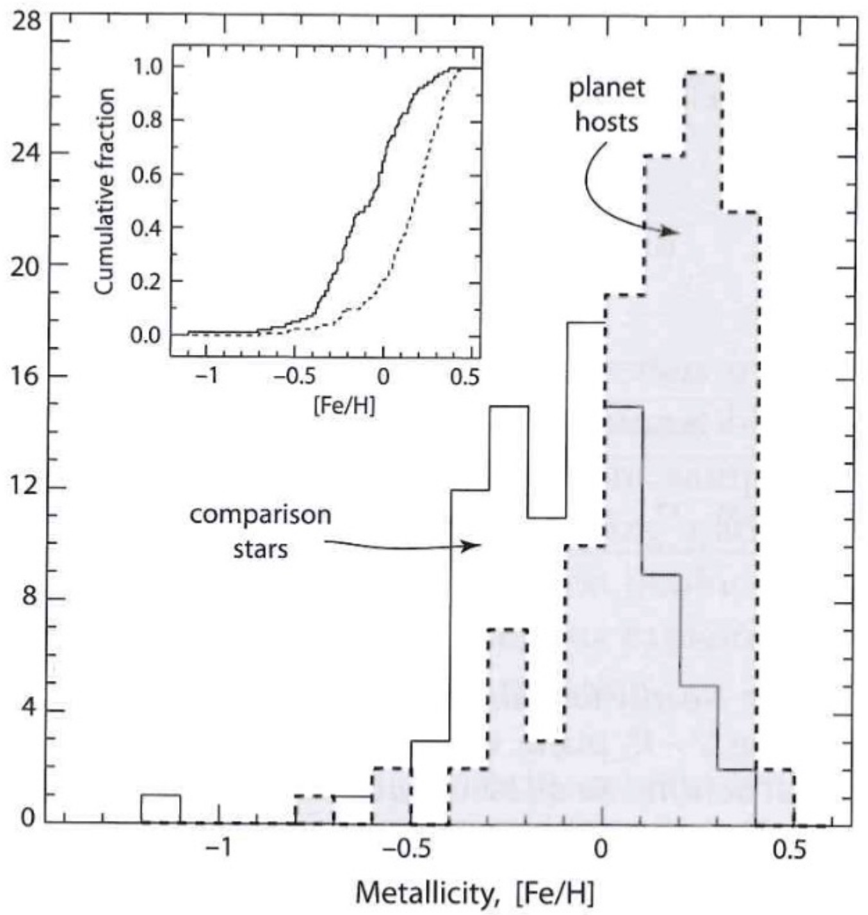


Metallicity distribution:
planet-hosting stars versus comparison stars

- 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

<u>Undetected low-mass planets could be present in the comparison sample</u>

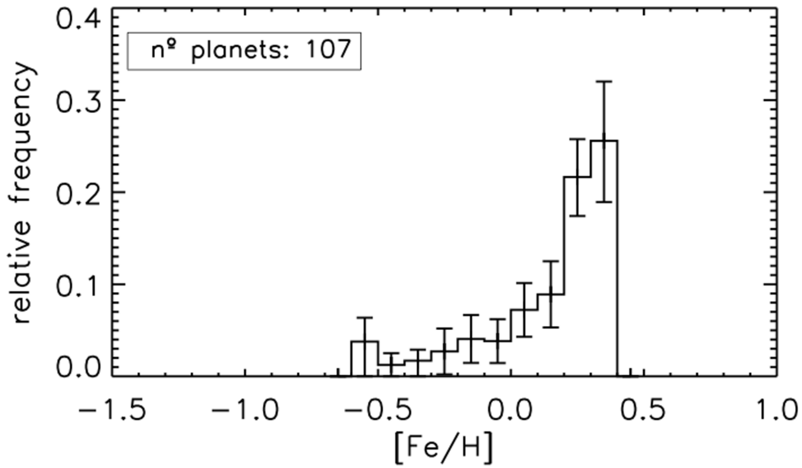


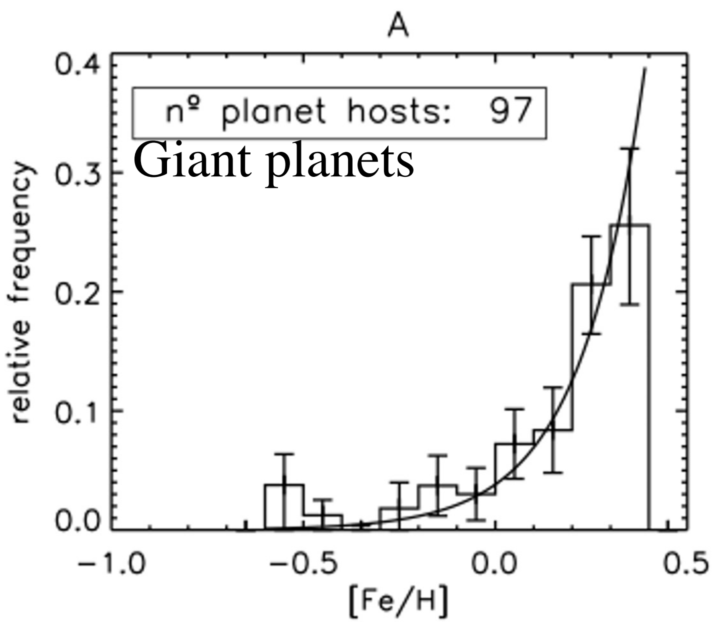
The trend with metallicity is observed for giant planets, but not for planets with lower mass

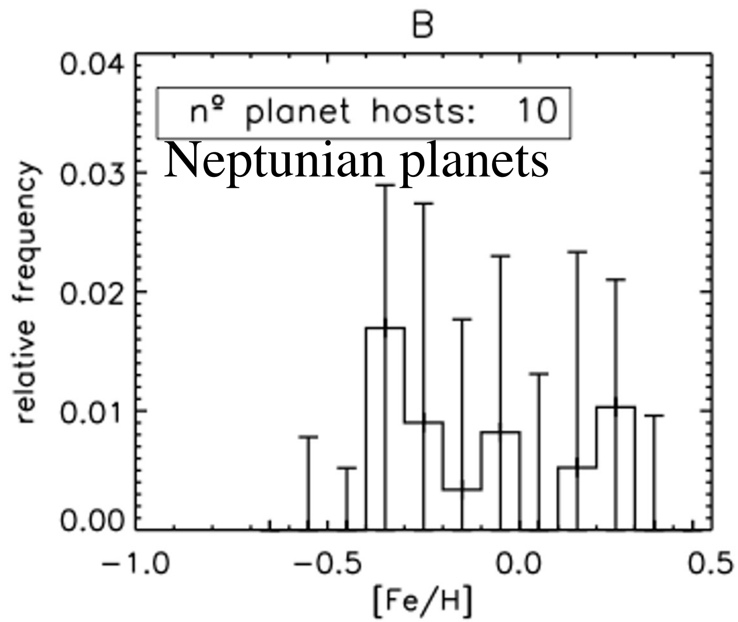
(Sousa et al. 2011)

Confirmed also by more recent works, e.g.:

- Adibekyan (2019)
- Jiang et al. (2020)



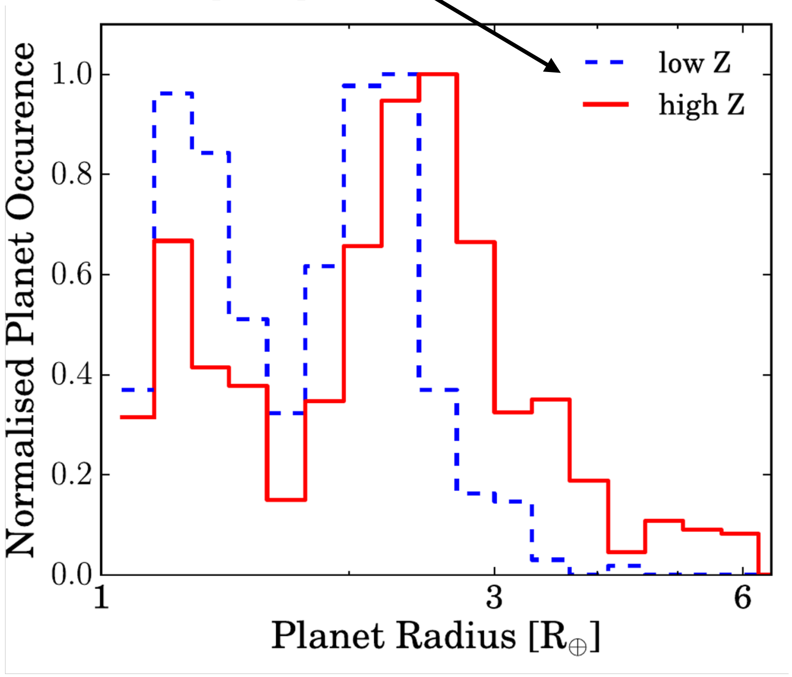




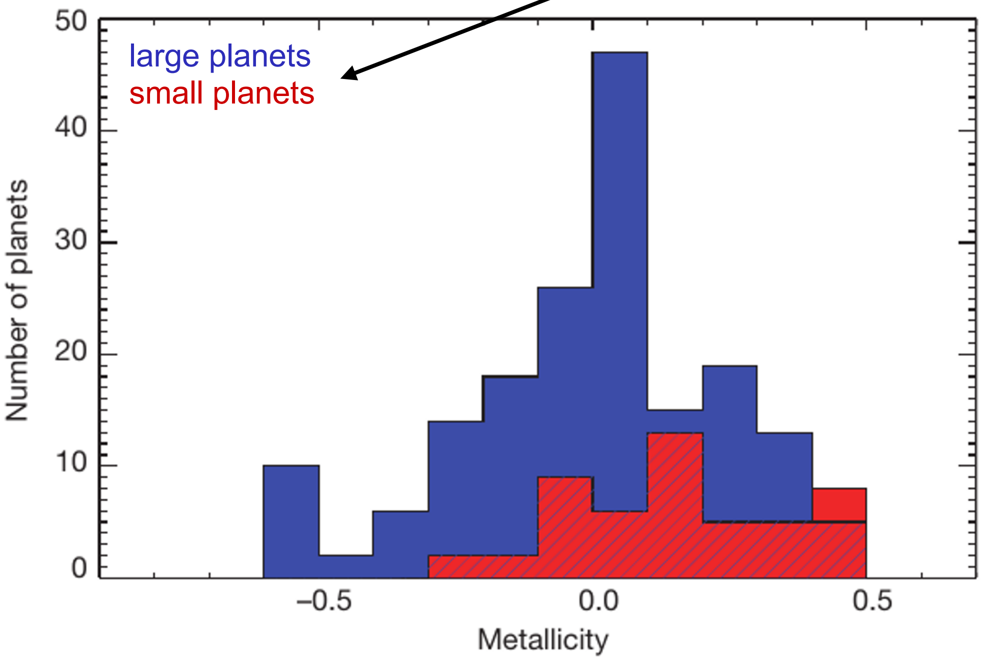
Trends with metallicity
for different planetary radii

threshold at [Fe/H]=0.05

threshold at 4 Earth radii



Owen and Murray-Clay (2018)



Buchhave et al. (2012)

More metallic stars host, on average, larger planets

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 selection bias is not important, three types of interpretation have been advanced
  - Primordial occurrence
  - Self-enrichment
  - Different Galactic origins (not discussed here)

- Understanding 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

Metallicity distribution of planet-hosting stars: interpretation

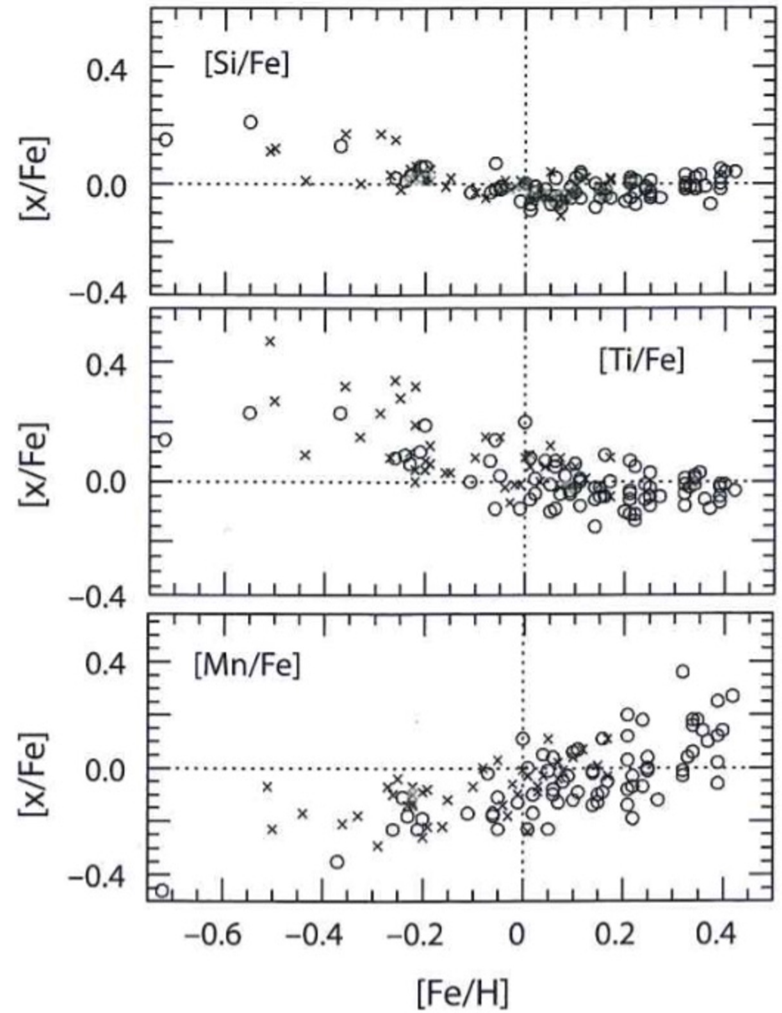
- Primordial occurrence
  - According to this hypothesis, the high metallicity observed in certain hosts is a bulk property of the star, and represents the original composition out of which the protostellar and protoplanetary disk formed
  - In this picture, <u>the higher the metallicity of the primordial cloud, the higher the dust-to-gas ratio in the protoplanetary disk</u>
  - <u>A high dust-to-gas ratio facilitates condensation of solids and accelerates protoplanetary accretion before the gas disk is lost</u>
  - 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
  - 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 a planet onto the star as a result of dynamical friction
  - Stars with protoplanetary disks would accrete more rocky material and hence their surface metallicity would rise
  - This hypothesis was advanced when the metallicity-occurrence trend was discovered, but is not supported by observational evidence

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
- With a few exceptions, most studies indicate that the relative abundances [X/Fe] are basically similar in stars with and without planets



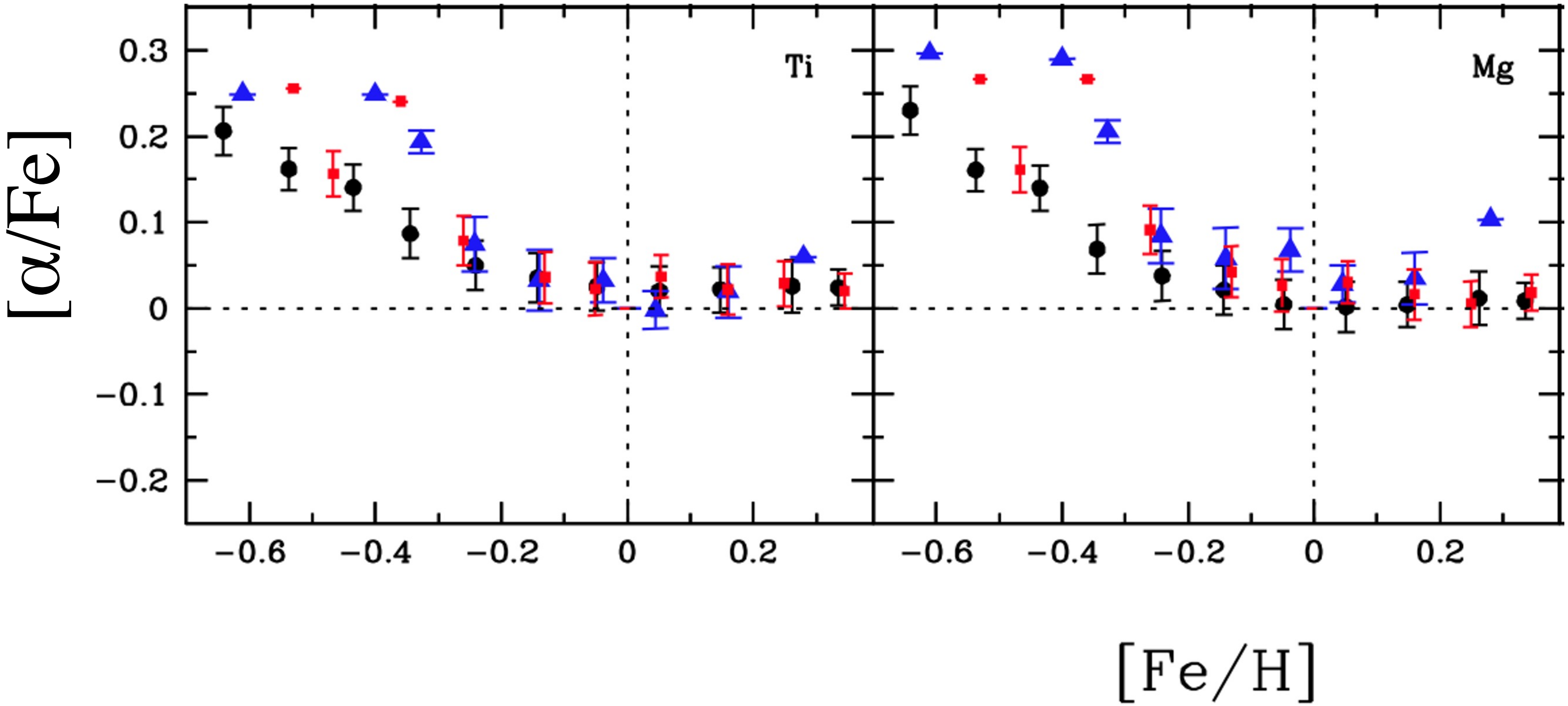
Open circles: planet host stars
Crosses: comparison stars
Dashed lines: solar abundances

Tentative evidence for enrichment of α 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

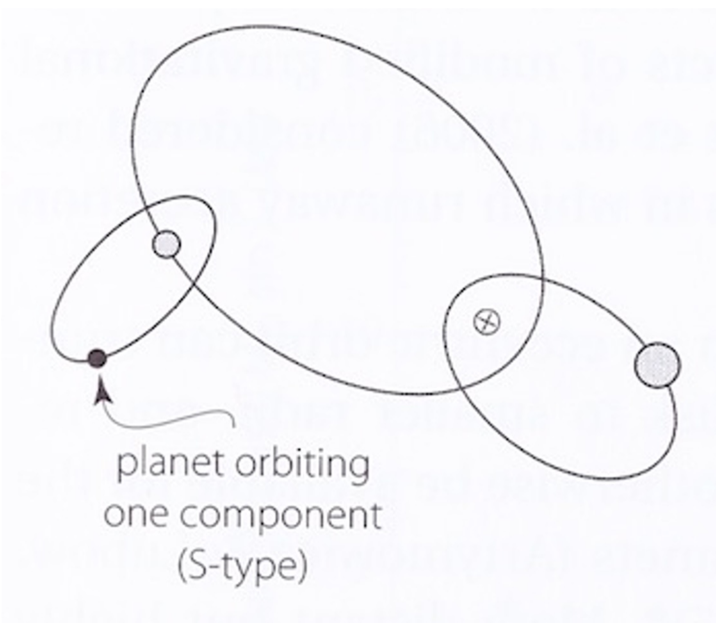


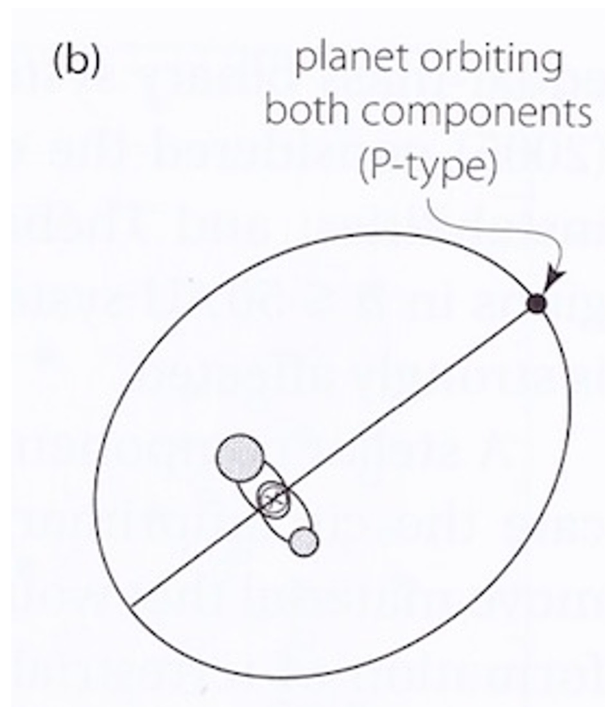
- The lack of a strong trend between planet occurrence and element-to-element abundance ratios suggests that:
  - the metal enrichment of planet hosting stars is primordial, rather than due to self-enrichment
  - it is not necessary to invoke exceptional events of chemical enrichment (such as the pollution 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

Planets in binary stellar systems

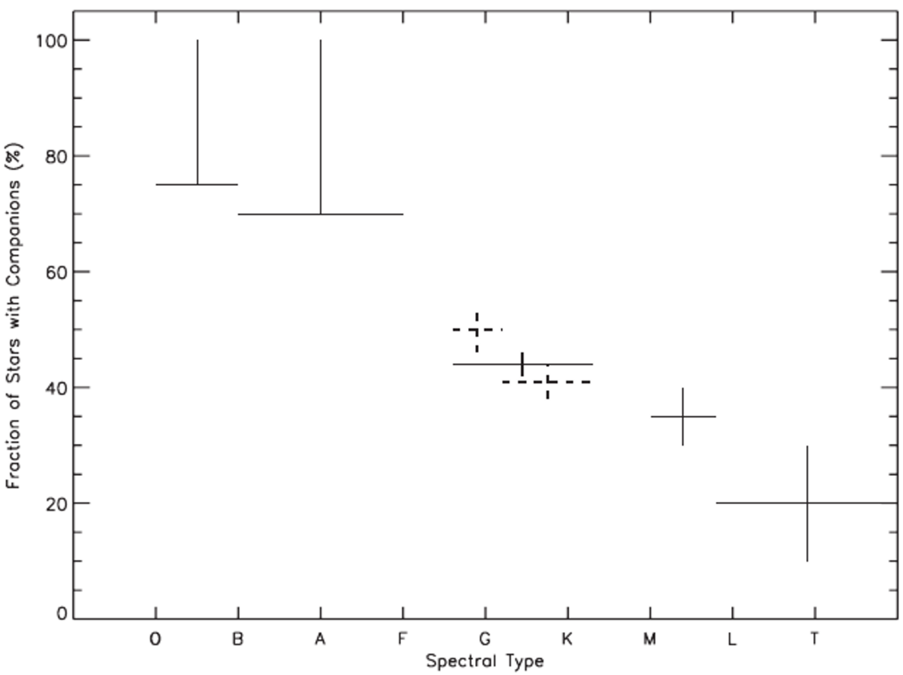
- Planets in binary/multiple stellar systems
  - A significant fraction (~50%) of stars in our Galaxy are binary (or higher multiplicity) stars
  - Exoplanets have been found around binary stars (~220 of which ~50 in high multiplicity star systems)

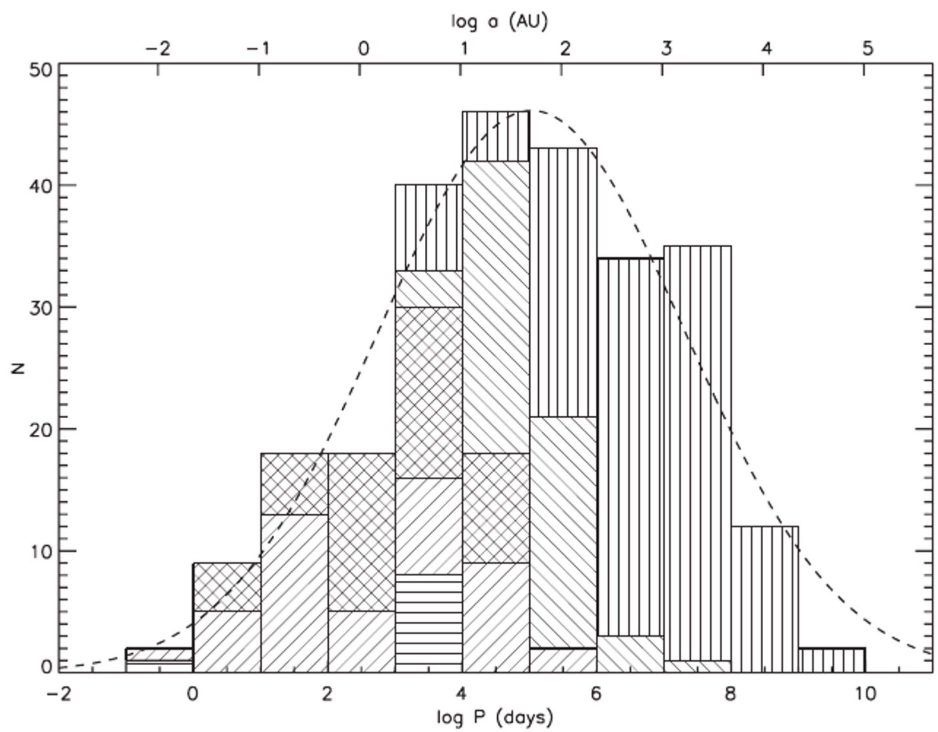




Planets in binary stellar systems

- High-mass stars (OBA) tend to have companions more often than low-mass stars (M)
- Huge variety of binary semi-major axis values: from 0.01 to 10^5 AU
  (for comparison: 1 pc = 2×10^5 AU)

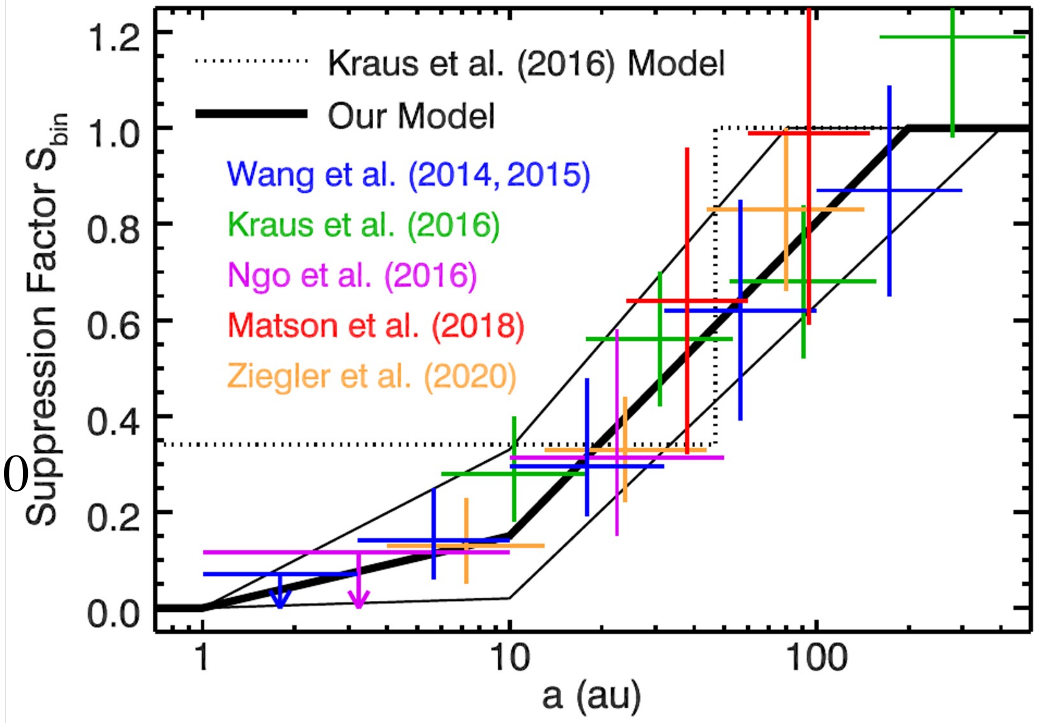




Raghavan et al. (2010)

Circumstellar planets

- Most of the known planet-hosting binary systems have planets in S-type orbits
- The presence of a binary companion seems to suppress the occurrence rate with respect to single stars
- This suppression acts logarithmically for binary semi-major axis $a_b < 200$ AU, reaching 0 for ~10 AU
- There are outliers: shortest period planet-hosting binary have a_b=1.1 AU

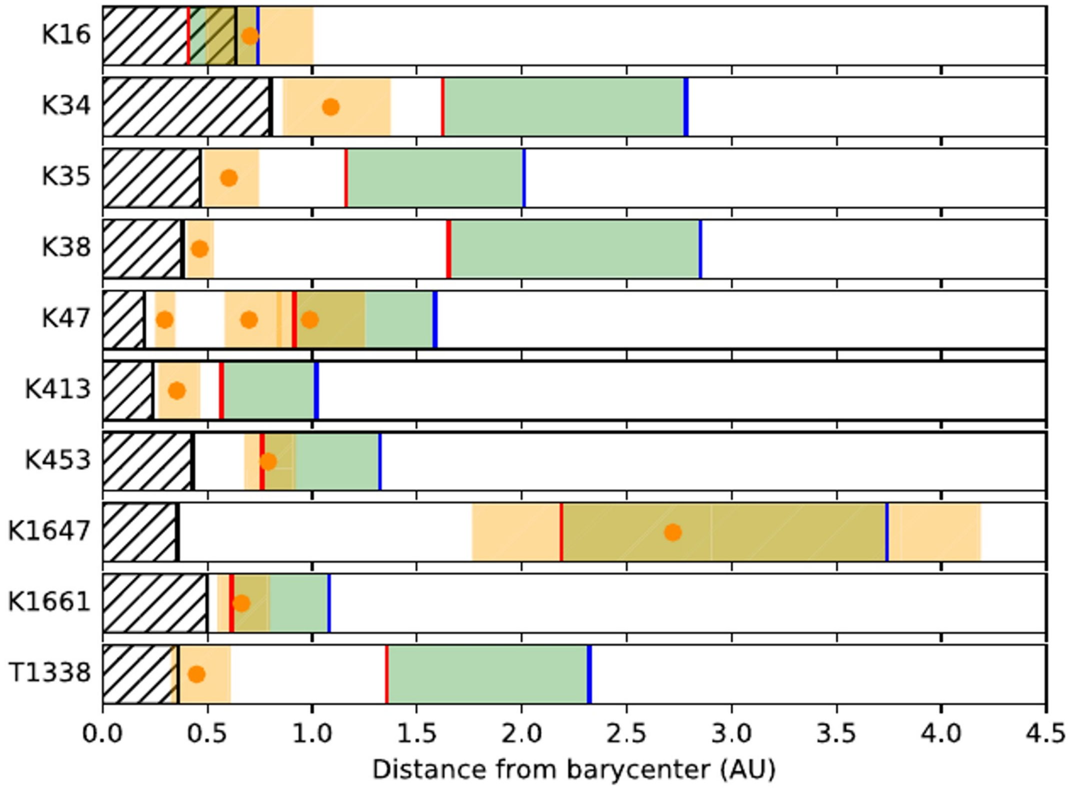


Moe & Kratter (2021)

Circumbinary planets

- The number of known circumbinary planets is considerably smaller than the number of known circumstellar ones
- Possibly difficult to form planets if $a_b > 0.3$ AU
- Protoplanetary disks observed also around stars up to ~20 AU of separation, but most of those with $a_b > 1$ AU are dynamically unstable

Known (in summer 2020) Main Sequence binary systems hosting circumbinary planets



Simonetti et al. (2020)