Statistical properties of exoplanets

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Main results of exoplanets studies

Statistical properties

Most statistics based on the results obtained with the Doppler and Transit methods

Updated results can be found at:
exoplanets.org and exoplanet.eu

Understanding observational biases is fundamental to interpret the observed statistical properties

Exoplanet statistical properties

- General properties investigated with statistical methods
  - Orbital properties

    Orbital periods, semimajor axis, eccentricity, orbital inclinations
  - Planetary properties

    Masses and radii

    with the Doppler and transit methods, respectively
  - Occurrence rates
  - Distances
  - Properties of the host stars

    Metallicities, chemical abundance patterns

- Main result
  - Variety of orbital and planetary parameters larger than that of the Solar System

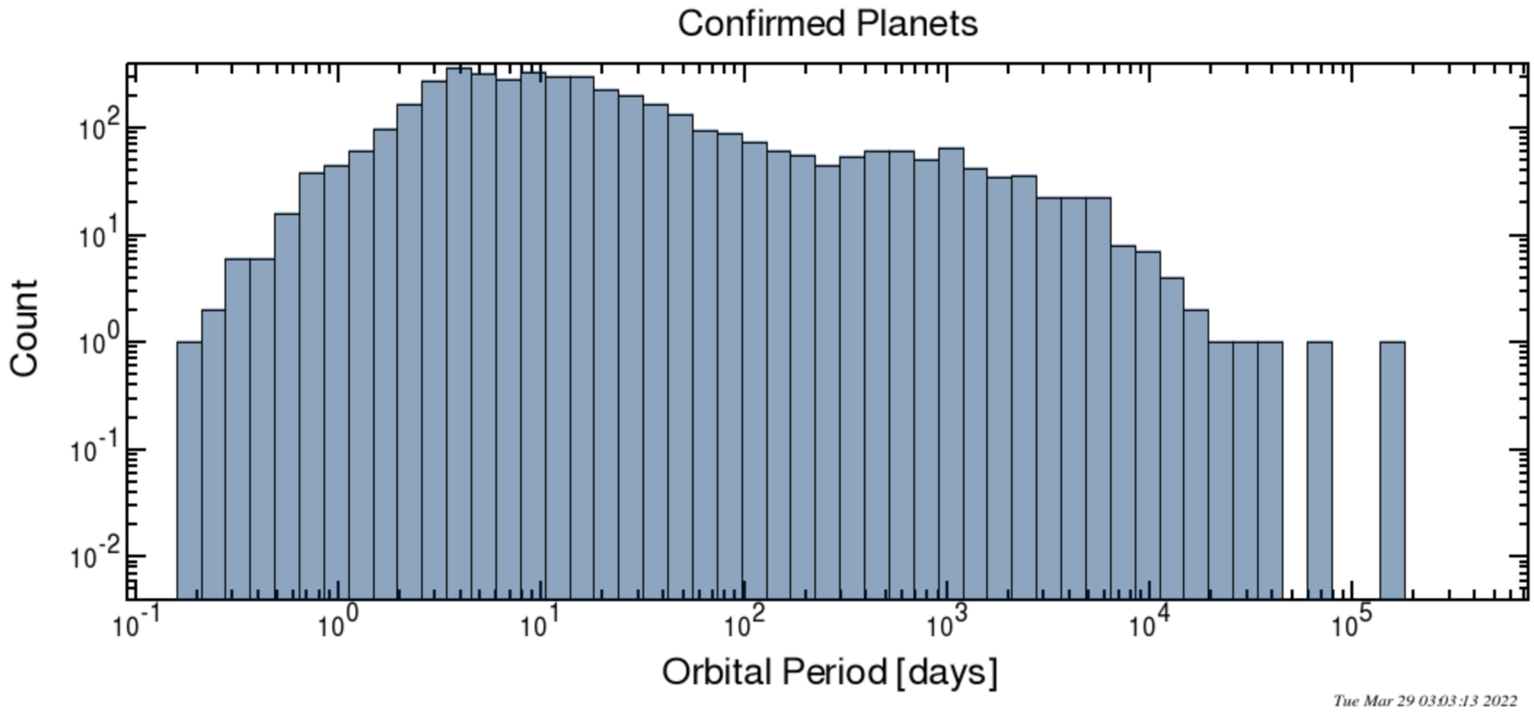
Distribution of orbital periods

- The distribution peaks at short orbital periods
  - Selection effects

    The limited temporal baseline of the observations tends to favour short orbital periods

    For a given planetary mass, a planet closer to the star (i.e. with shorter period) generates a stronger reflex motion of the host star

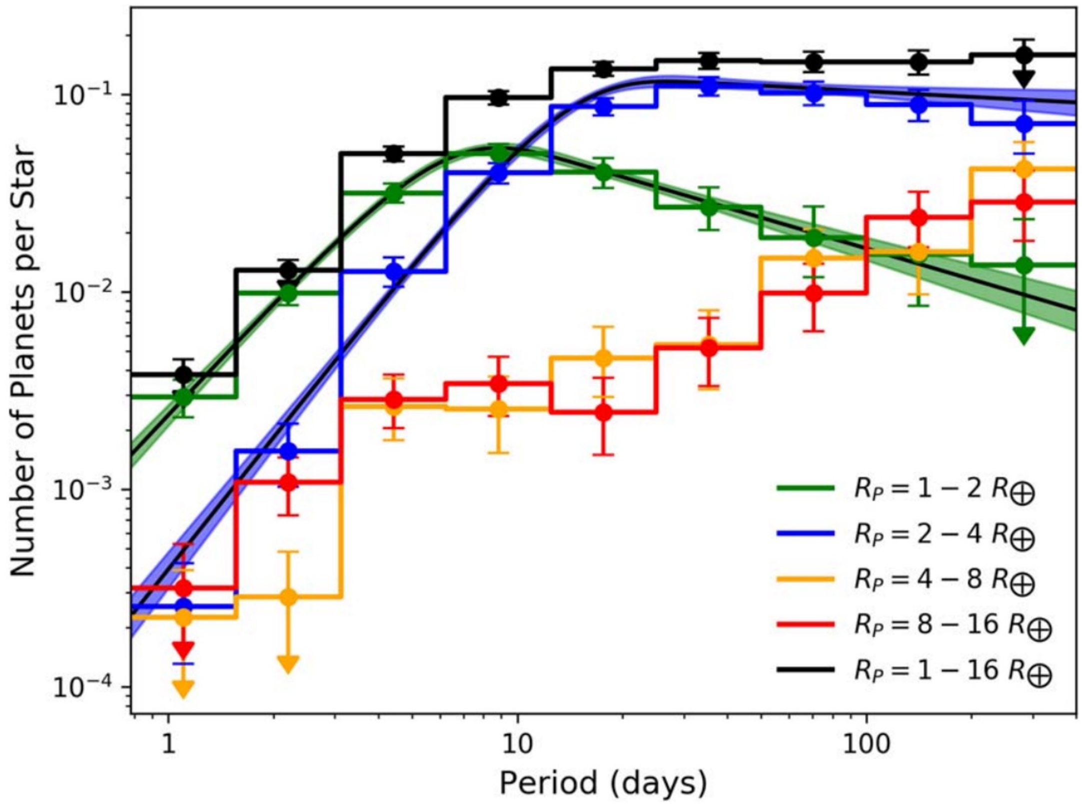
    A planet closer to the star has a higher geometric probability of detection with the transit method



Distribution of orbital periods

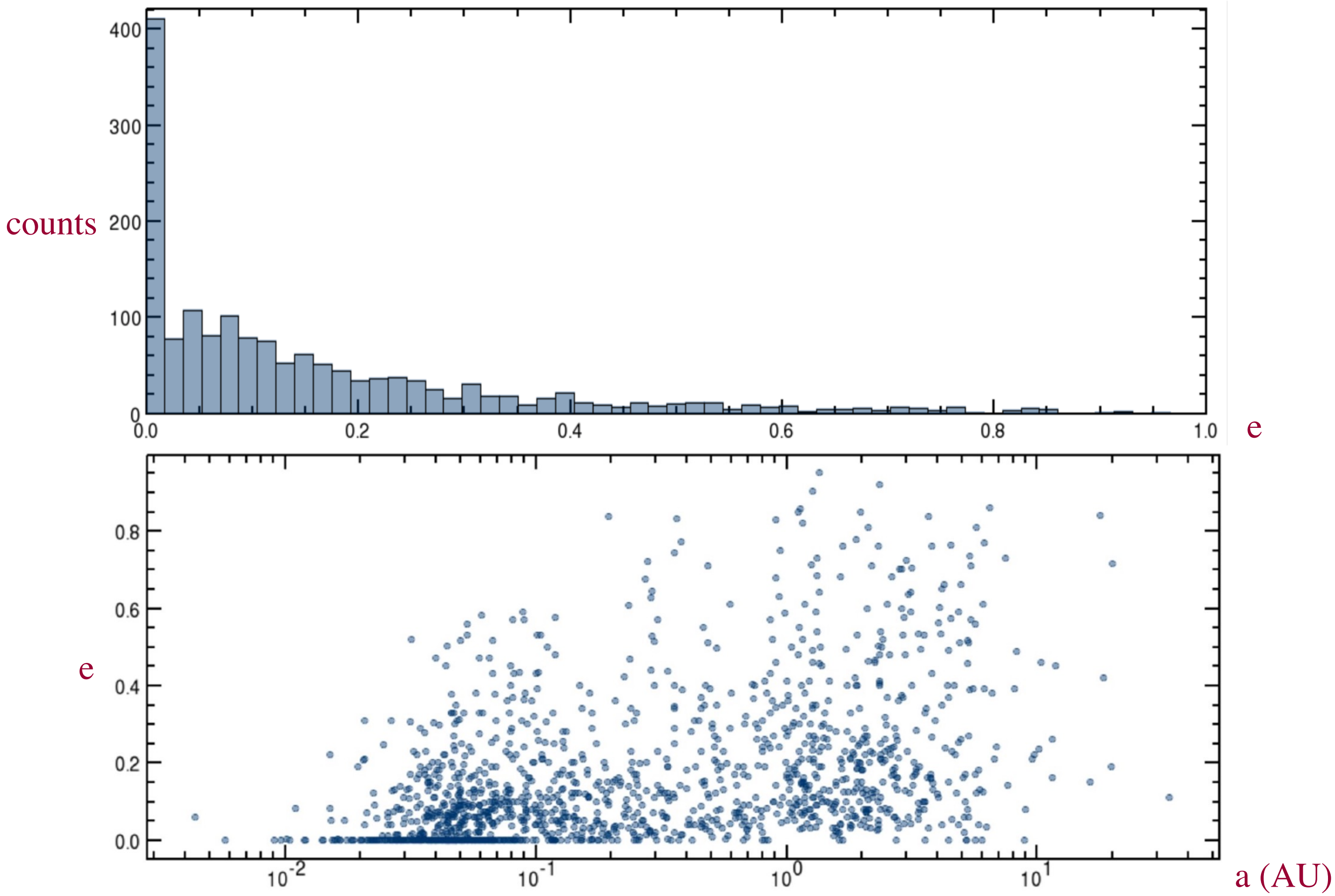
- Earths and super-Earths (green) have shorter orbits than Jupiters (yellow and red)
  - similar to our Solar System
  - possibly a selection effect due to the difficulties of detecting small planets in large orbits
  - if it is real, then physical mechanism: a large orbit means more material to collect

Kunimoto & Matthews (2020)



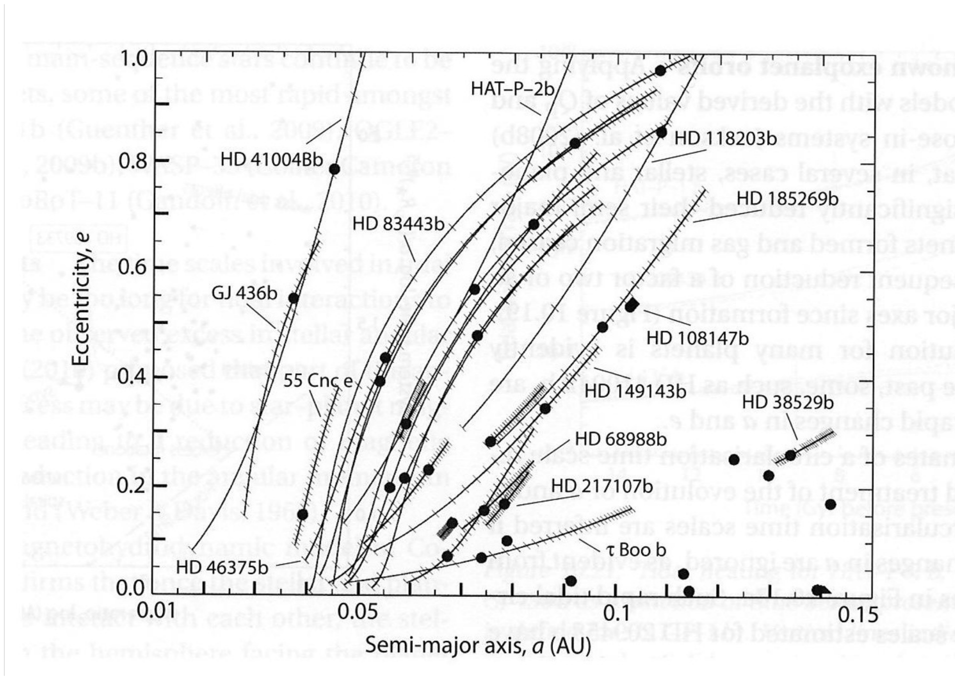
Distribution of eccentricities

- The distribution shows the existence of planets in highly eccentric orbits
  - all eccentricities possible, up to ~0.99
  - the vast majority of eccentricities is higher than in Solar System planets
  - average eccentricity for planets with $P > 6$ d: 0.29

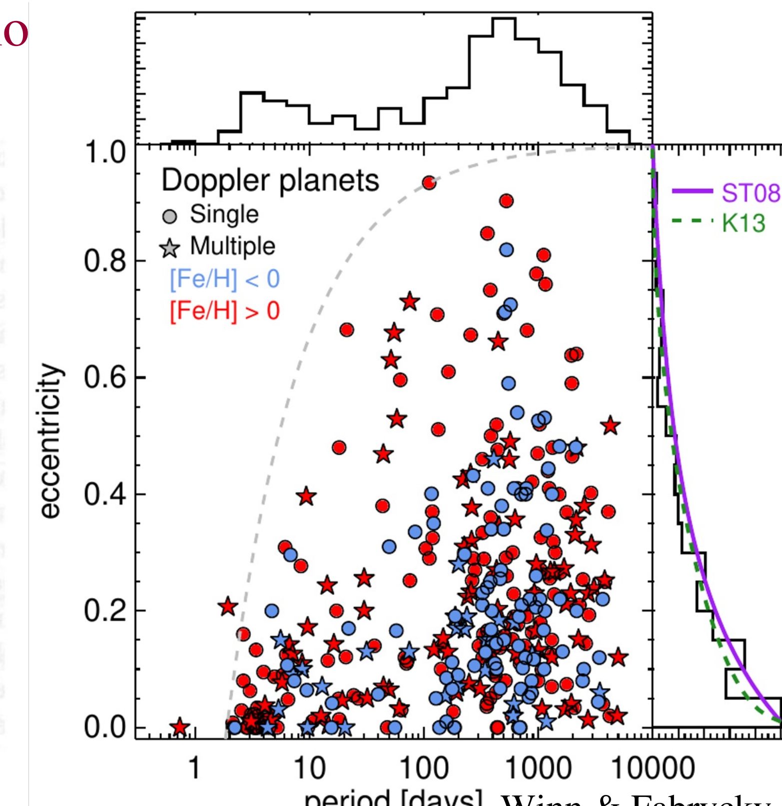


Distribution of eccentricities

- Correlated with metallicity: more metallic stars tend to host more eccentric planets
  - more protoplanets formed in metal-rich stars that can then interact, exciting eccentricities? (Dawson & Murray-Clay, 2013)
- Correlated with multiplicity: multiple-planet systems are less eccentric
  - multi-planet systems with low eccentricities are more dynamically stable
- Eccentricity limited by tidal circularization at very low orbital periods (corresponding to a minimum separatio



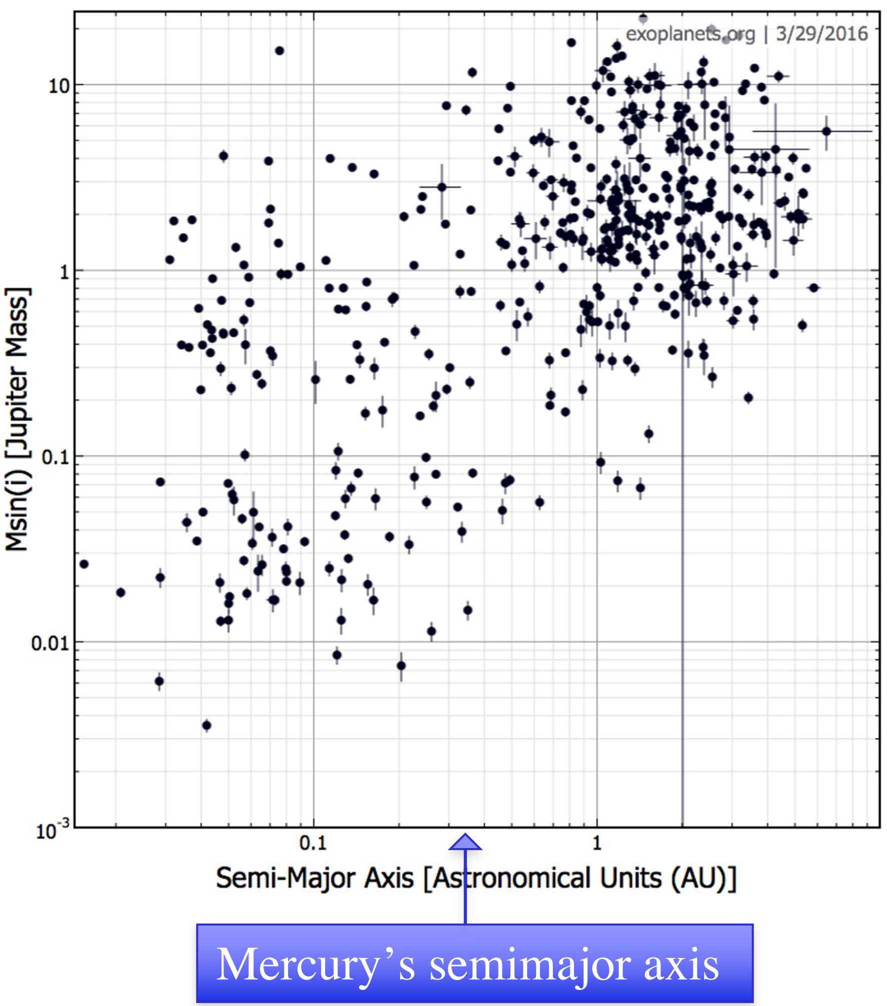
Jackson et al. (2008)



Winn & Fabrycky (2015)

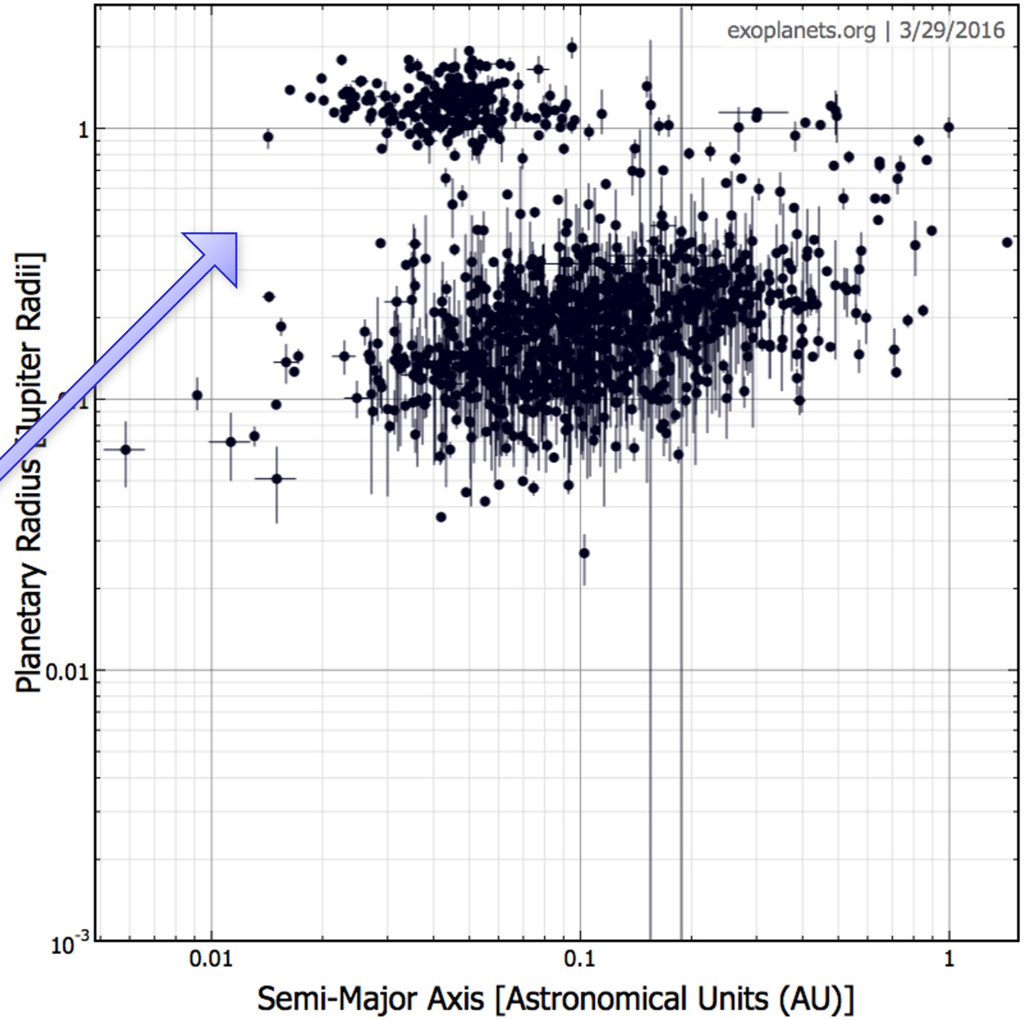
Planetary mass versus semimajor axis

- At large distances from the star, the detected planets are quite massive
  - Selection effect: at large semimajor axis, only massive planets have the capability to generate a significant reflex motion of the star
  - Physical effect: most massive planets form at larger distances from the central star, where the longer orbits provide more material for the planet to form by accretion



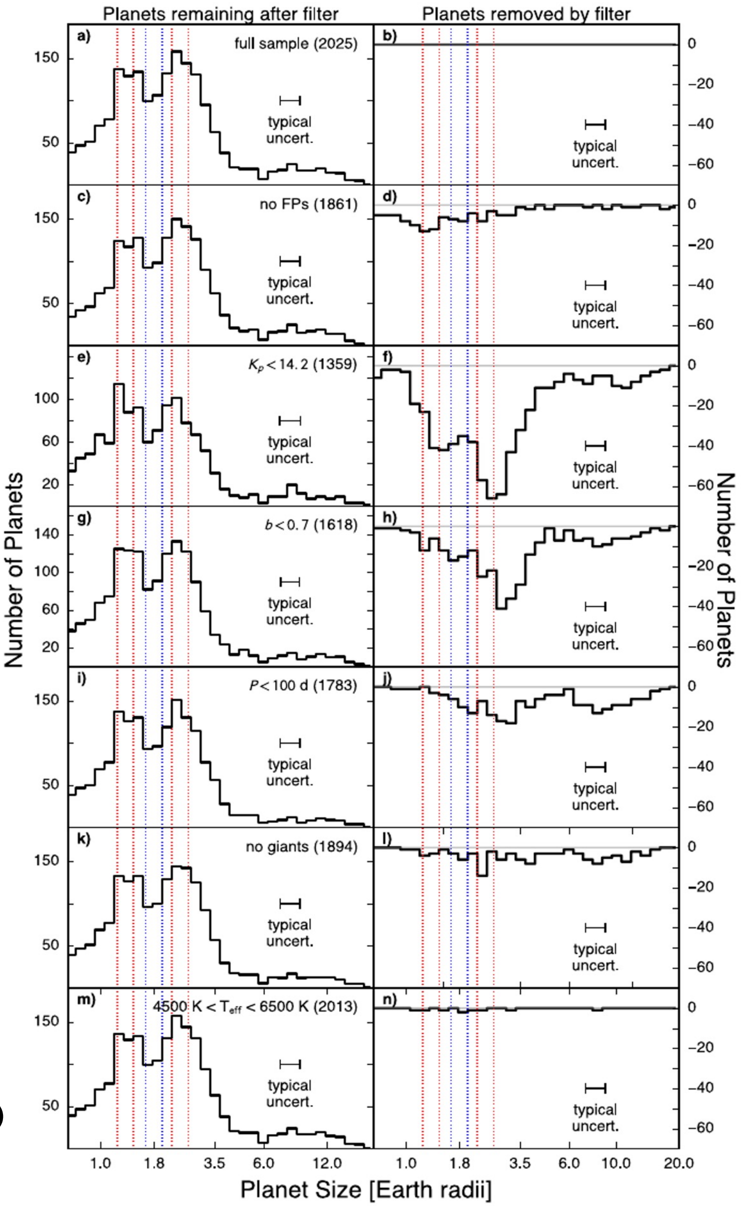
Exoplanets radii versus semimajor axis

- Sample of exoplanets obtained with the transit method, not corrected for selection bias
- However, the “Sub-Jovian” Desert is (most probably) real
- Lower border: photoevaporation (Kurokawa & Nakamoto, 2018)
- Upper border: tidal disruption (Owen & Lai, 2018)
- Other explanations involves different formation mechanisms coupled with observational biases



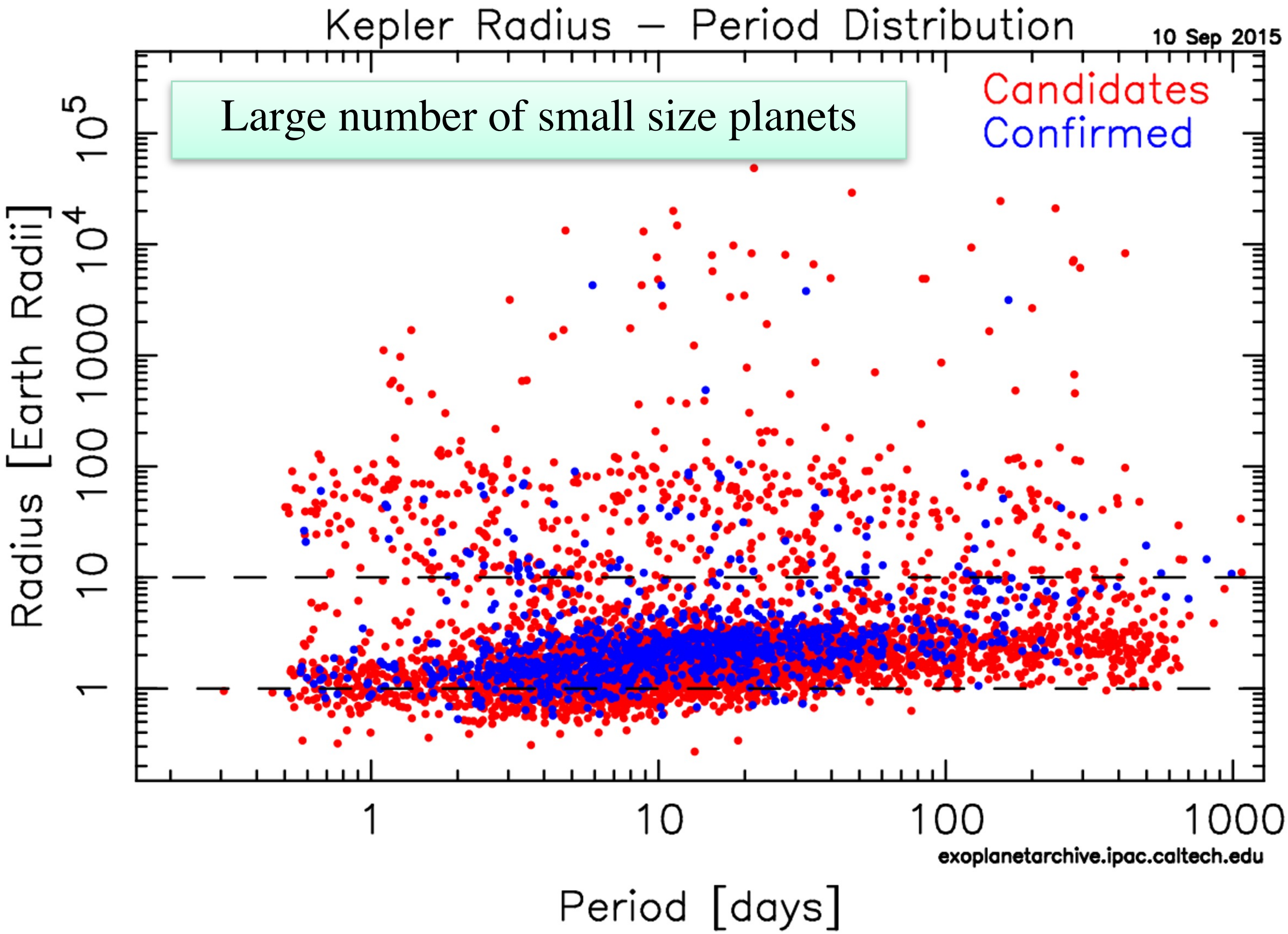
Exoplanets radii versus semimajor axis

- Sample of exoplanets obtained with the transit method, corrected by different filters
- The “no faint stars” and “no grazing transit” filters (red arrows) removes 20-35% of the the planets, but do not cancel the gap
- Robust determination of a <u>Sub-Neptune Desert</u>
- Explanations: rocky cores stripped by stellar radiations (Van Eylen et al. 2018) or by their own formation heat (Ginzburg 2018)



Fulton et al. (2017)

Radii versus period: Kepler data



Occurrence rates

- The occurrence rate is the mean number of planets per star having properties within a specified range
  - In practice, the planet properties are chosen among those measurable with a given observational technique
  - For instance, for a survey performed with the Doppler method, one can define the occurrence rate as the mean number of planets per star having masses and orbital periods within a specified range

$$\frac{dN}{d\ln P \, d\ln M}$$

  - To minimize selection effects, one limits the range of planetary quantities according to the observational limits
  - As an example, $M_p > 10\ M_\oplus$ and $P < 1$ yr

Occurrence rates

- The study of occurrence rates corrected for observational selection effects provides powerful constraints to models of planetary formation
- A general result provided by exoplanet surveys is that planetary systems are quite common around stars
- The high occurrence rate favours scenarios in which the process of planetary formation is closely related to the process of stellar formation
- A low occurrence rate would have left room for alternative scenarios, with planets arising from events that are distinct from star formation
  - An example was the tidal theory, where planets condense from material stripped from a star during an encounter with another star
    - Stellar encounters extremely unlikely and would yield a very small fraction of planetary systems

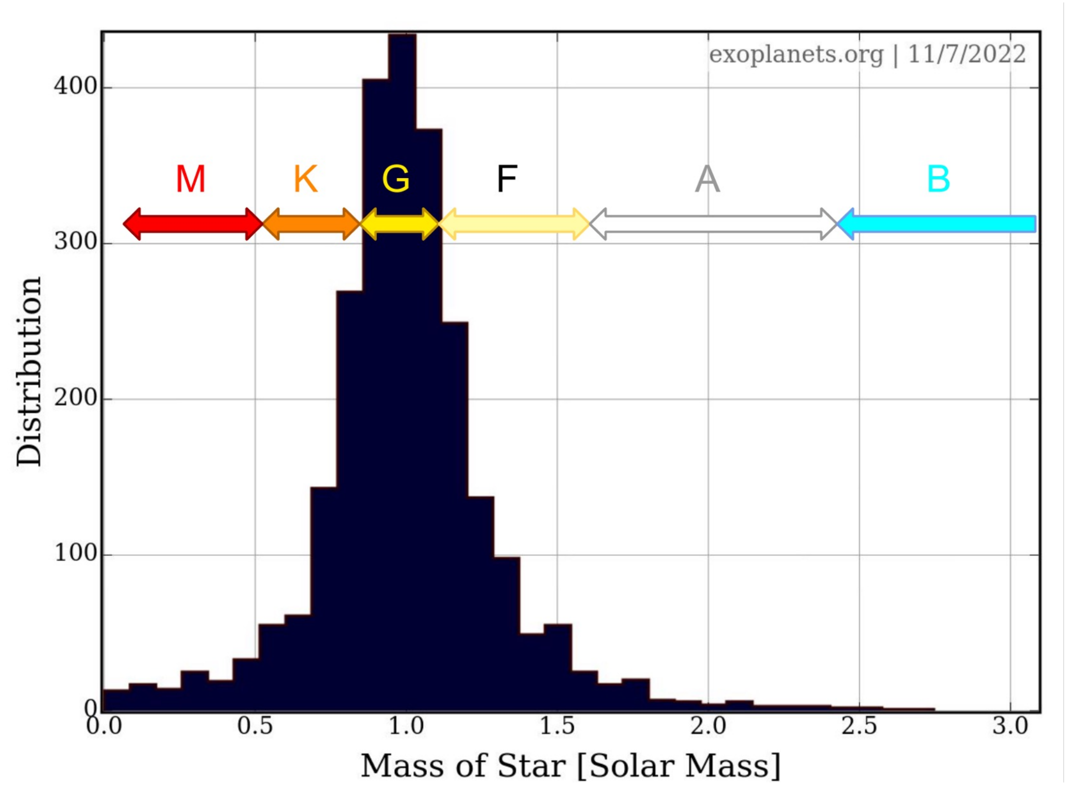
Occurrence rates

Occurrence rates around single AFGKM-type stars: ~30% (Zhu & Dong, 2021)

Average planetary multiplicity: 3

~⅓ of the known exoplanets orbit around G-type stars, but this is probably a selection effect: the Kepler mission focused on G-type star and contributed ~50% of the total discoveries

At very high stellar masses (>15 $M_\odot$), the total time in the Main Sequence is of the same order of magnitude as the planetary formation mechanisms (a few million years)



Trends of occurrence rates

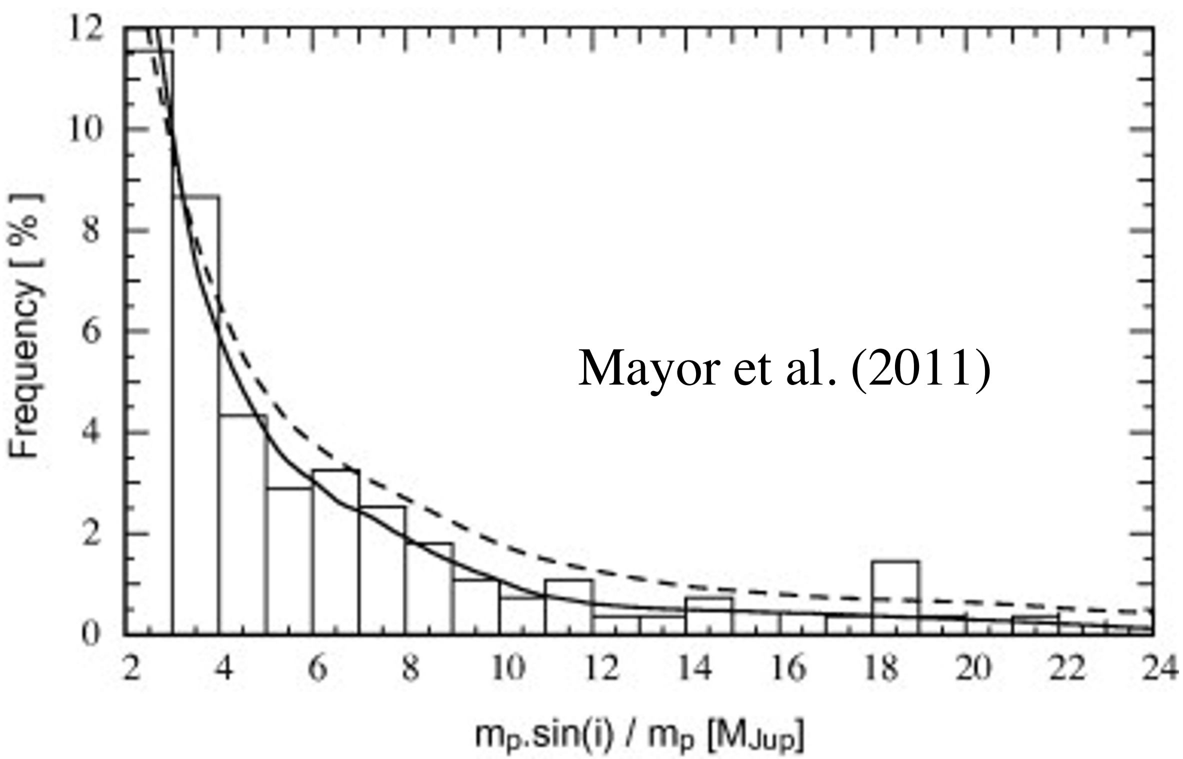
- Within the specified observational limits, occurrence rates can be modelled with analytical functions
  - For instance, the occurrence rate derived from Doppler surveys of FGK stars , $M_p > 100\ M_\oplus$ and $P < 5.5$ yr can be modelled as

$$\frac{dN}{d\ln P\ d\ln M_p} \propto M_p^\alpha\, P^\beta$$

  - with $\alpha=-0.31\pm0.20$ and $\beta=0.26\pm0.10$ (Cumming et al. 2008)
  - This result suggests that the planet frequency increases with decreasing planetary mass and increasing orbital period
  - The results cannot be extrapolated outside the observational limits

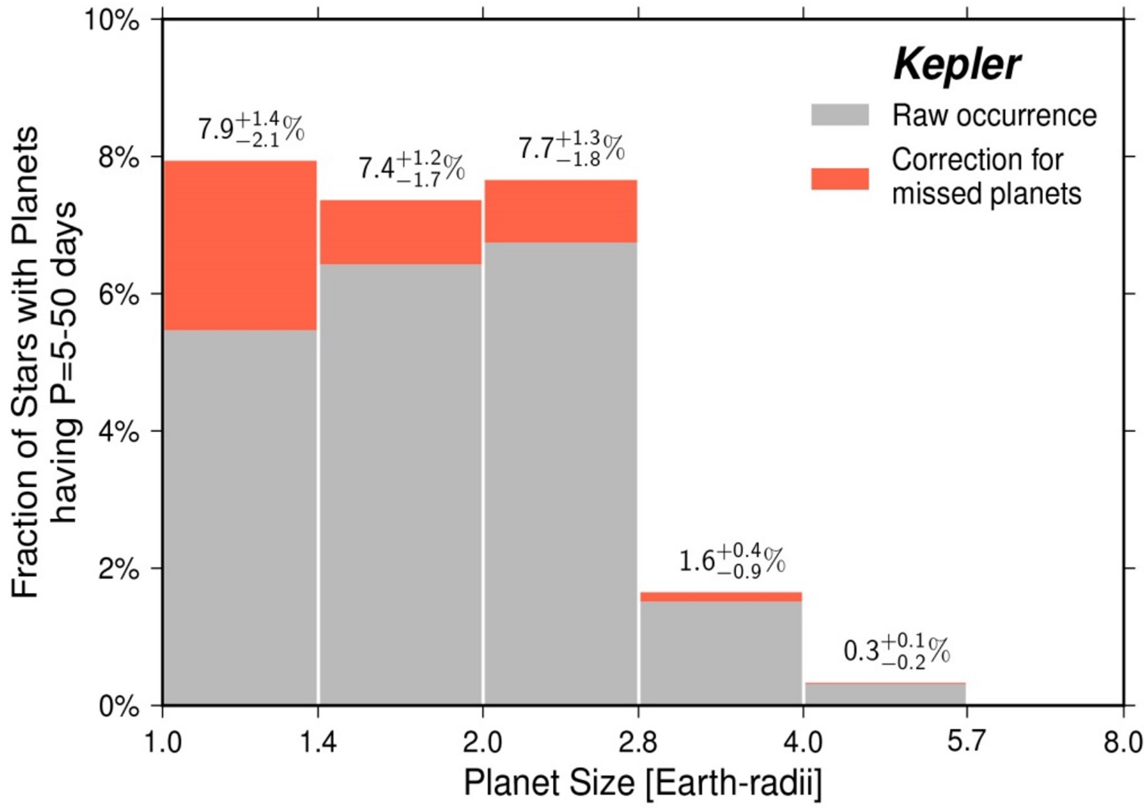
Distribution of planetary masses

- *M* sin *i* distribution obtained with the Doppler method
- The distribution increases towards values of low mass
  - Despite the selection effect that favours the detection of high mass planets
  - Whether this trend extends to the terrestrial mass regime needs to be confirmed with a larger sample of Earth-mass planets



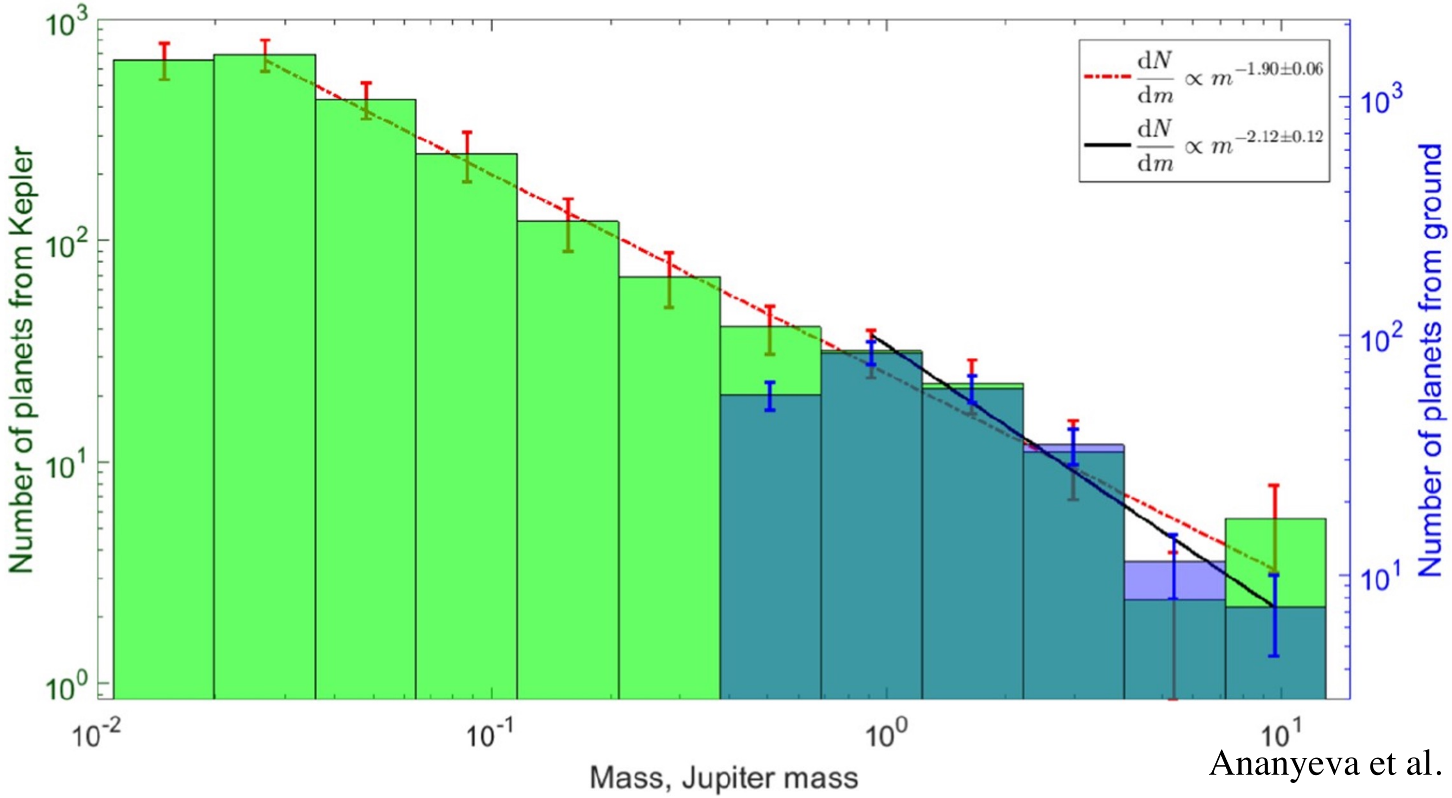
Distribution of planetary radii

– Once corrected for selection effects, also the distribution of radii (transit method) indicates that small-size planets are more frequent than large planets



Planetary Initial Mass Function

- Created combining Radial Velocity and Transit Methods
  - probably a single (power-law) mass distribution from Earths to the Brown Dwarf limit, pointing towards a common formation mechanism
  - if true, the Sub-Jovian and the Small Neptunes Deserts would be caused by evolutionary processes
  - uncertainties at the low-mass end of the spectrum due to observational biases



Ananyeva et al. (2020)

Occurrence rates of Earth-like planets

- The occurrence rate of Earth-like planets is usually calculated taking into account the planet mass (or size) and the insolation (rather than the orbital period or semimajor axis)
  - The insolation is a key parameter that governs the planet surface temperature and habitability

$$S = \frac{L_\star}{4\pi a^2}$$

  - The motivation for calculating the occurrence rate of Earth-size planets according to their level of insolation is astrobiological
  - The choice of the interval of insolations is related to the definition of circumstellar habitable zone (discussed in a subsequent lesson)

Occurrence rates of Earth-like planets

Table 2 Occurrence rates of Earth-like planets

Type of star	Type of planet	Approximate HZ boundaries[a] $[S/S_\oplus]$[b]	Occurrence rate [%]	Reference
M	1–10 $M_\oplus$	0.75–2.0	41^{+54}_{-13}	Bonfils et al. (2013)
FGK	0.8–2.0 $R_\oplus$	0.3–1.8	$2.8^{+1.9}_{-0.9}$	Catanzarite & Shao (2011)
FGK	0.5–2.0 $R_\oplus$	0.8–1.8	34 ± 14	Traub (2012)
M	0.5–1.4 $R_\oplus$	0.46–1.0	15^{+13}_{-6}	Dressing & Charbonneau (2013)
M	0.5–1.4 $R_\oplus$	0.22–0.80	48^{+12}_{-24}	Kopparapu (2013)
GK	1–2 $R_\oplus$	0.25–4.0	11 ± 4	Petigura et al. (2013)
FGK	1–2 $R_\oplus$	0.25–4.0[c]	~0.01[c]	Schlaufman (2014)
FGK	1–4 $R_\oplus$	0.35–1.0	$6.4^{+3.4}_{-1.1}$	Silburt et al. (2015)
G	0.6–1.7 $R_\oplus$	0.51–1.95	$1.7^{+1.8}_{-0.9}$	Foreman-Mackey et al. (2014)

[a] In many cases the actual habitable zone (HZ) definitions used by the authors were more complex; please refer to the original papers for details.

[b] S refers to the incident flux of starlight on the planet, and $S_\oplus$ to the Earth's insolation. All these works are based on *Kepler* data except Bonfils et al. (2013), which is based on the HARPS Doppler survey, and Schlaufman (2014), which is based on both *Kepler* and the Keck Doppler survey.

[c] The result is much lower than the others because the author also required the Earth-sized planet to have a long-period giant-planet companion.