# Statistical properties of exoplanets

Planets and Astrobiology (2020-2021)
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# Main results of exoplanets studies

## Statistical properties

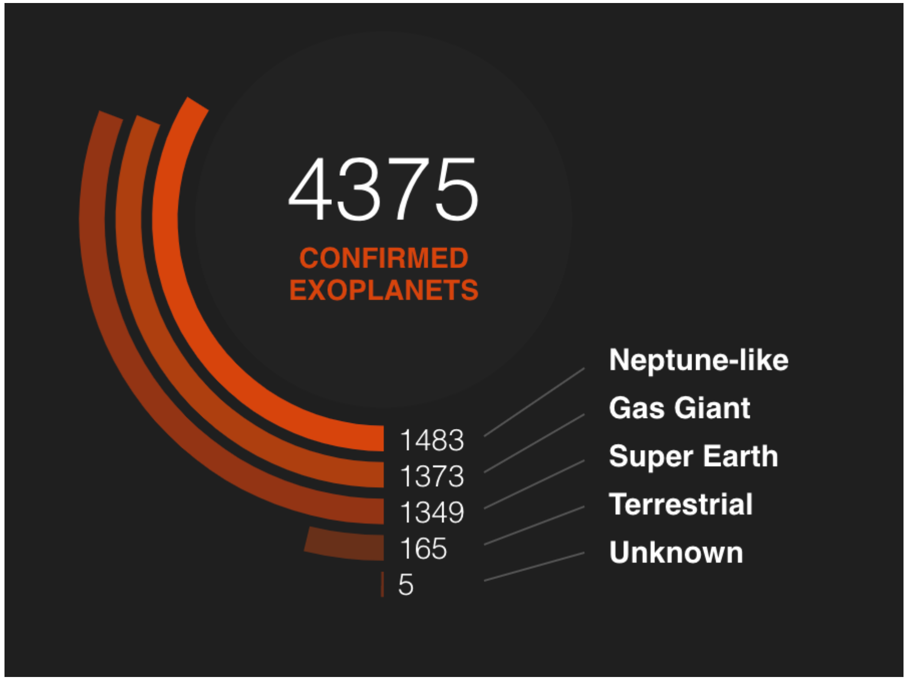
Most statistics based on the results obtained with the Doppler and Transit methods

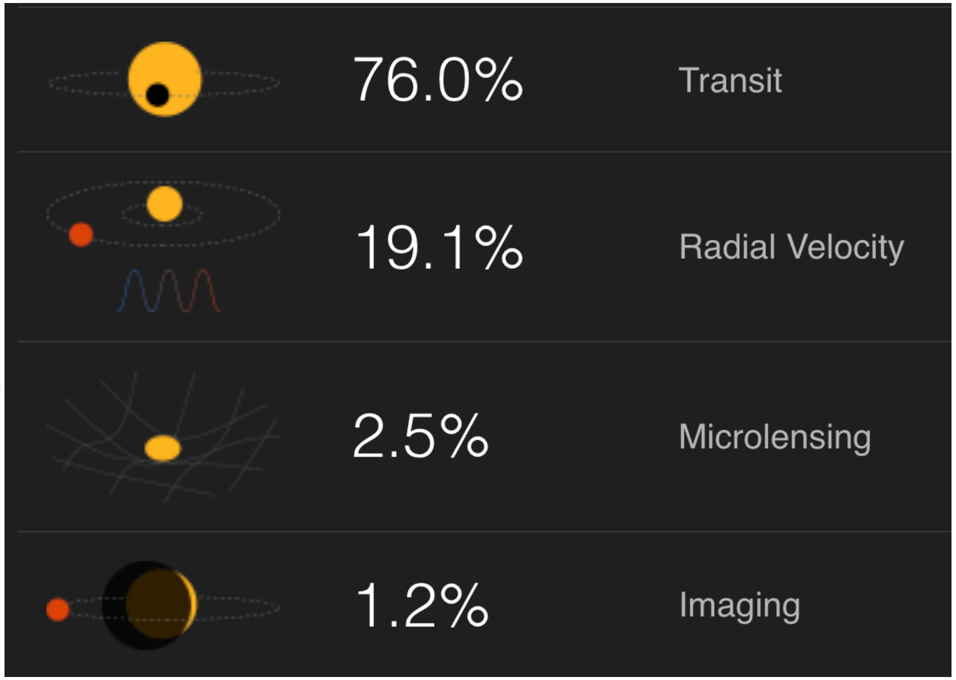
Updated results can be found at:

exoplanets.org          exoplanets.nasa.gov          exoplanet.eu

Understanding observational biases is fundamental to interpret the observed statistical properties

# Exoplanet statistics




- Main results
  - Great variety of orbital parameters and planetary masses/radii
  - Such a variety is not found in the Solar System

# Exoplanet statistical properties

- General properties investigated with statistical methods
  - Orbital properties

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

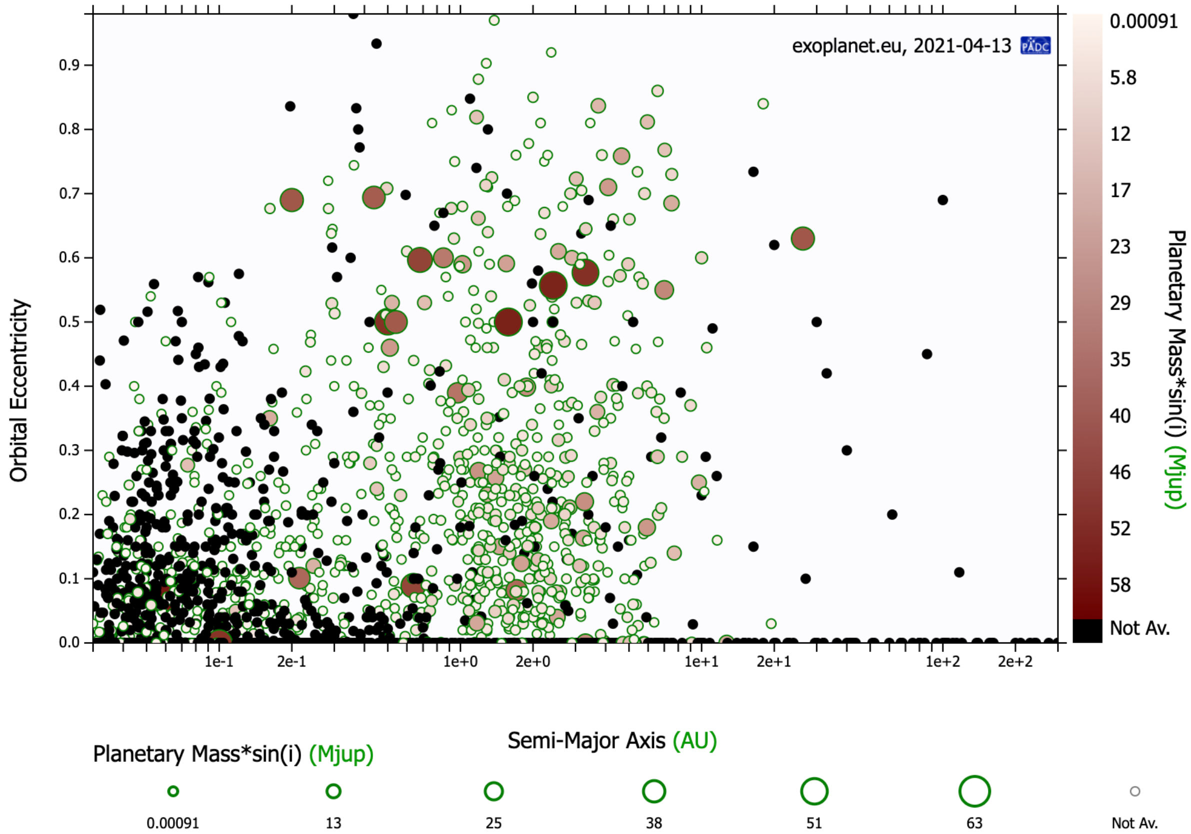
    Masses and radii

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

    Metallicities, chemical abundance patterns

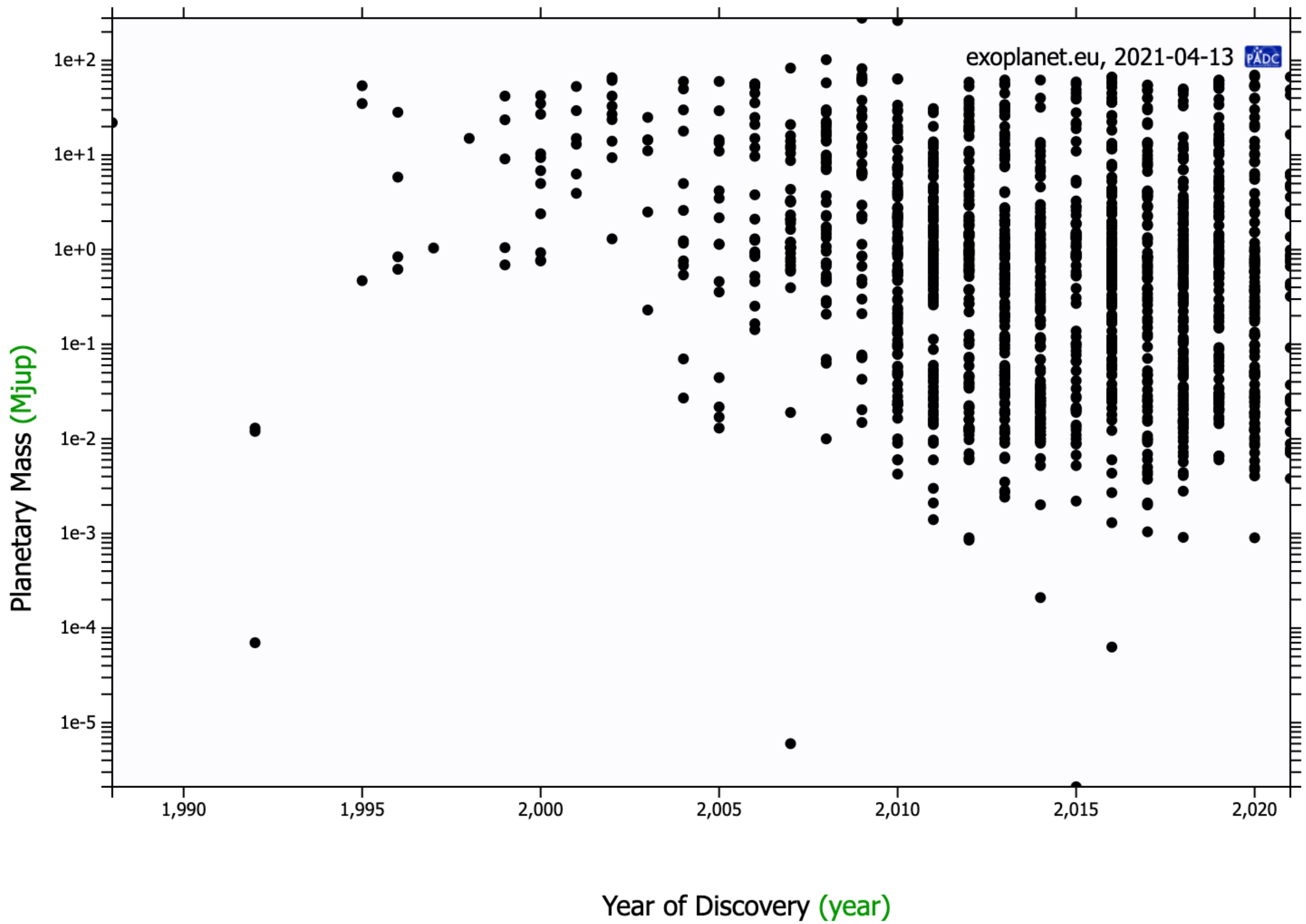
# The variety of orbital properties

- Eccentricity *e* versus semimajor axis *a*; the symbol sizes are proportional to the minimum mass (*M* sin *i*)
- The plot shows the great dispersion of the orbital parameters (*a*, *e*) and planetary masses
- In the Solar System, the eccentricities are usually small and other regions of the parameter space are not covered



# Exoplanetary masses

## The detection limit of the Doppler method improves over the years



# The variety of exoplanetary masses

"Jupiters"

$M \sim 1\ M_J$

"Saturns"

$M \sim 0.3\ M_J$

"Neptuns"

$M \sim 0.05\ M_J$

"Super-Earths"

$M \sim 0.015\ M_J$

$M_p \sim 10\ M_{Earth}$

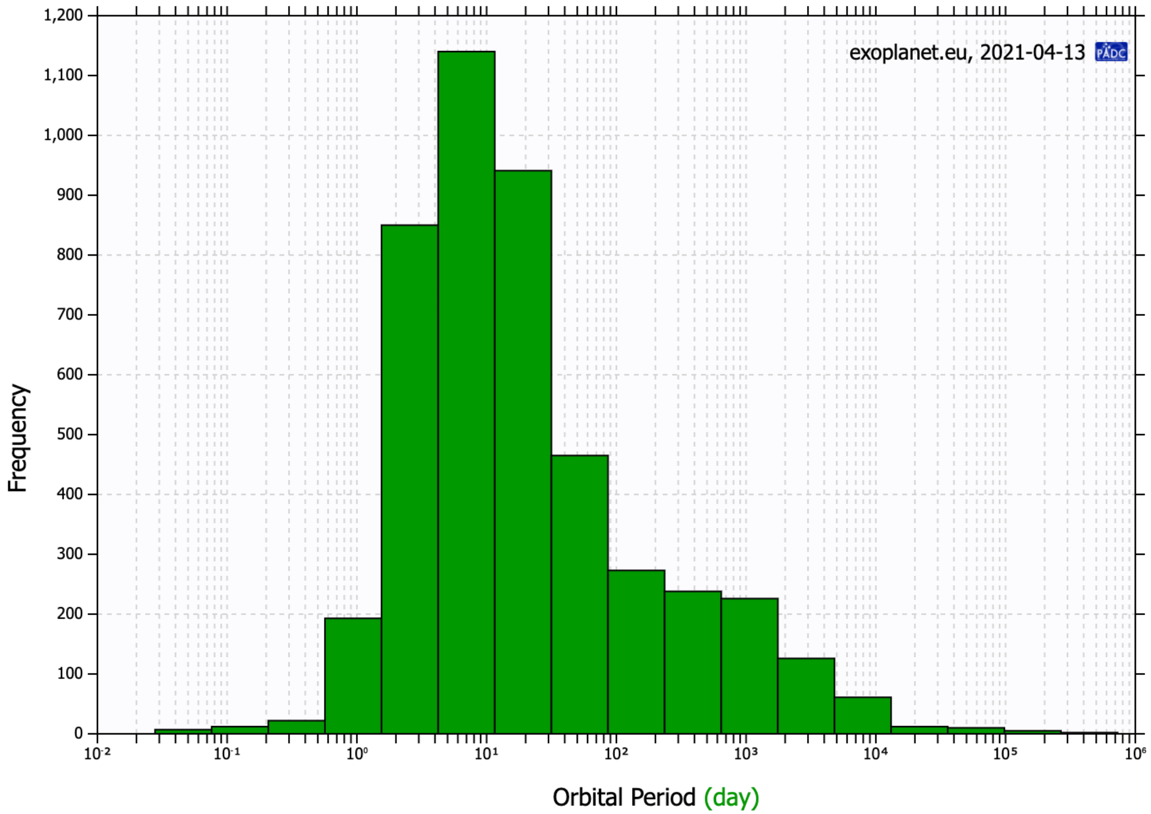
Super-Earths do not exist in the Solar System

Terrestrial

$M \sim 0.003\ M_J$

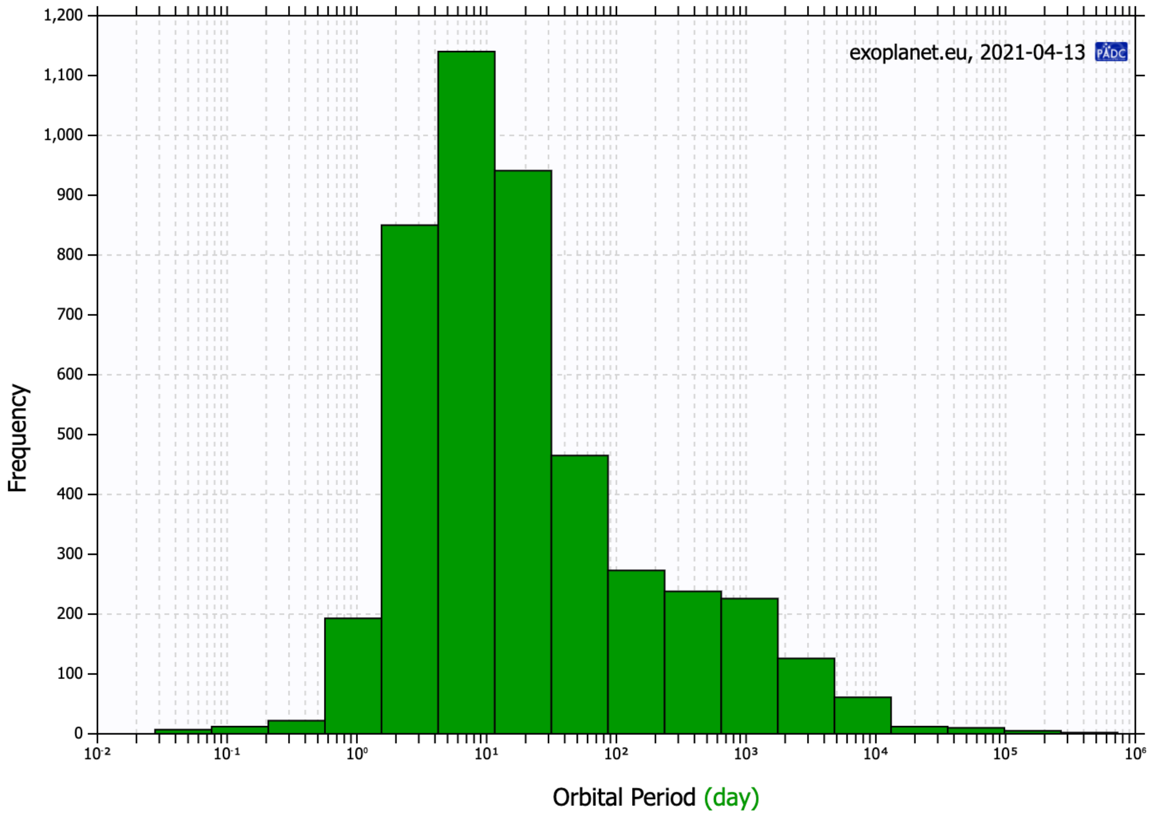
# Distribution of orbital periods

- Peaks at short orbital periods
  - In part because of selection effects:
    - The limited temporal baseline of the observations favours short periods
    - Planets with short period generate a strong reflex motion of the host star
    - Planets close to the star have a high geometric probability for transits



# Distribution of orbital periods

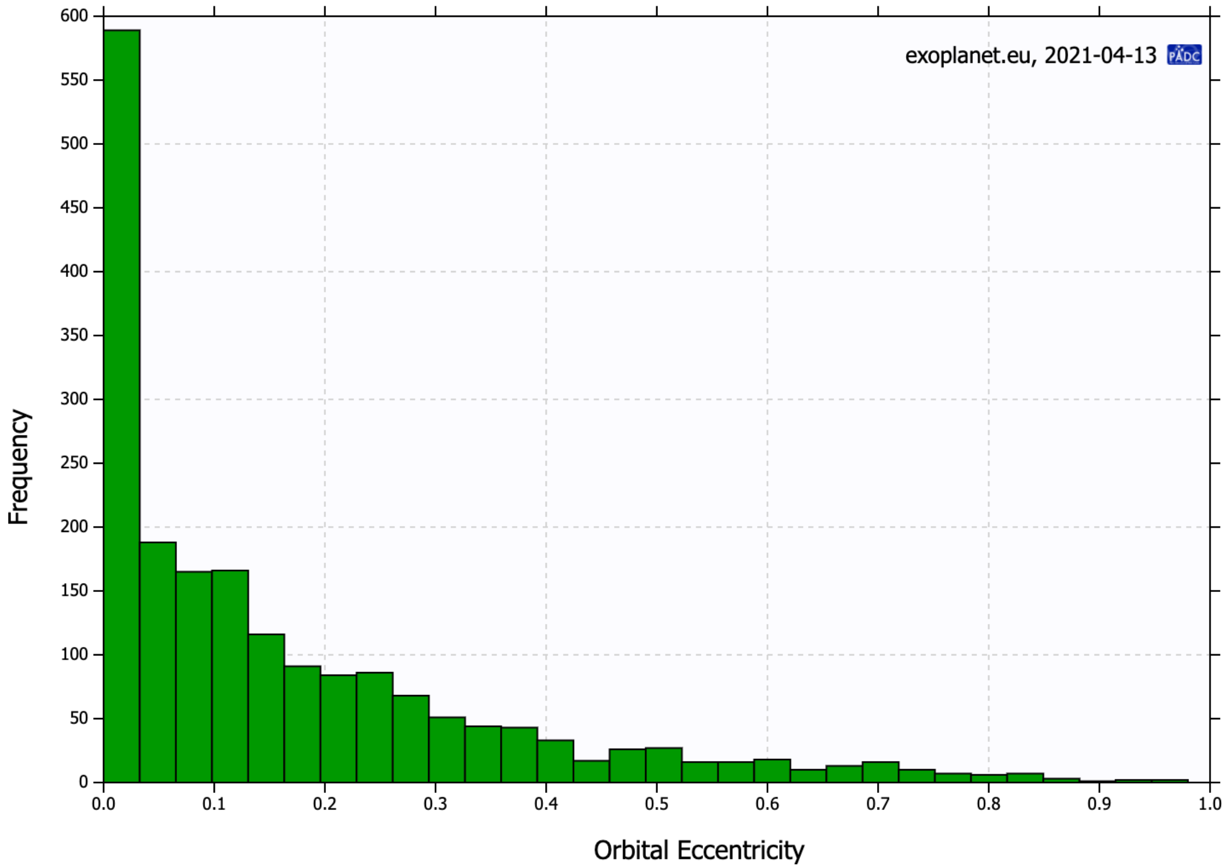
- Peak at $P \cong 3$ days
  - Is real: the decrease of frequency at shorter periods cannot be attributed to selection effects
  - Its existence constrains models of planetary formation and evolution
  - Suggests the existence of a mechanism that breaks the migration of planets towards the central star



# Distribution of eccentricities

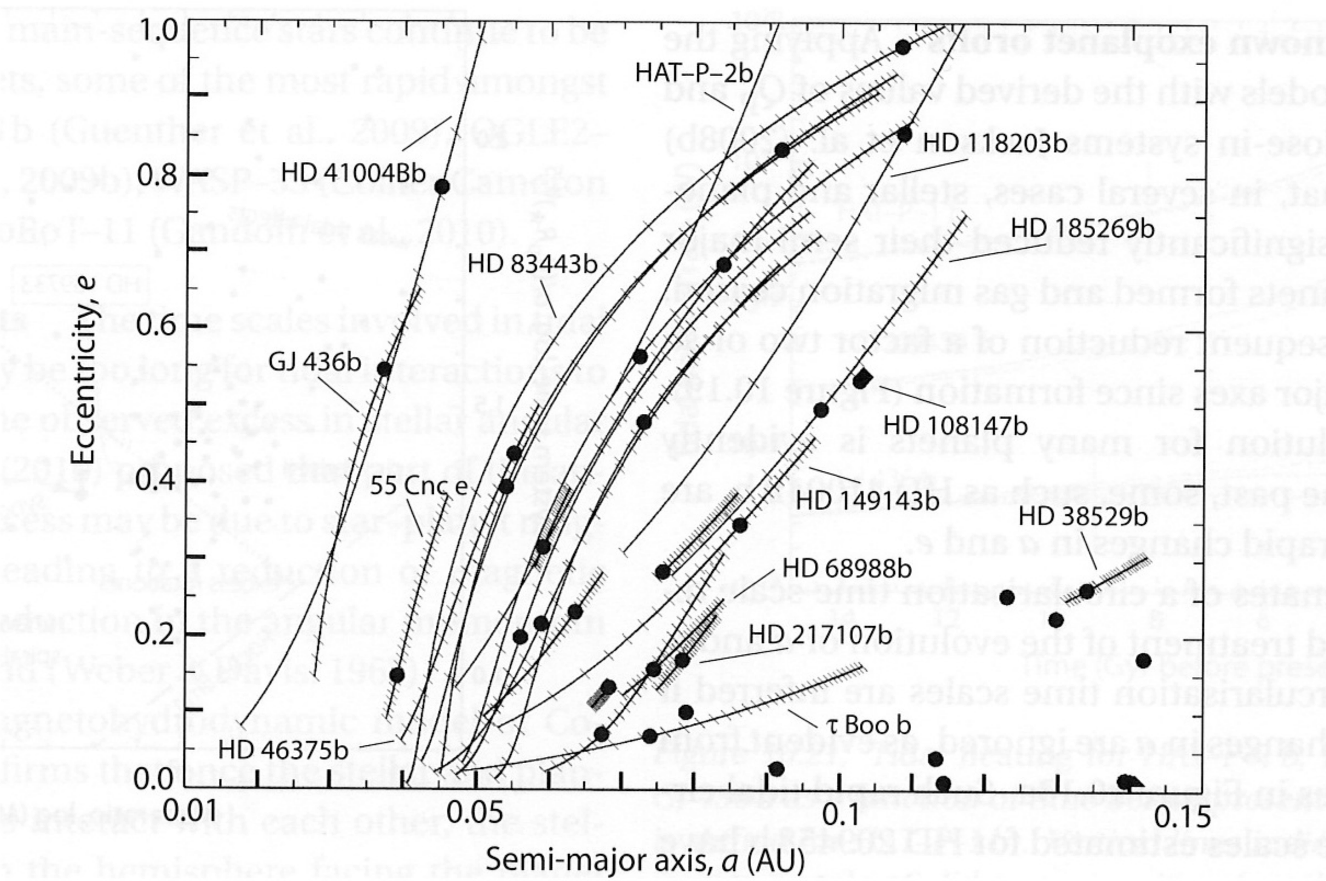
- The distribution shows the existence of planets in highly eccentric orbits
  - virtually the whole possible interval of eccentricities is found
  - the vast majority of eccentricities is higher than in Solar System planets
- Low eccentricity orbits are more frequent

The shape of the observed distribution is affected by selection effects and can vary according to the observational method used to collect the sample



- The large fraction of planets in low-eccentricity orbits is interpreted as the result of orbital evolution in presence of tidal interactions with the host star
  - Dynamical models indicate that the eccentricity tends to decrease in the course of planetary system evolution

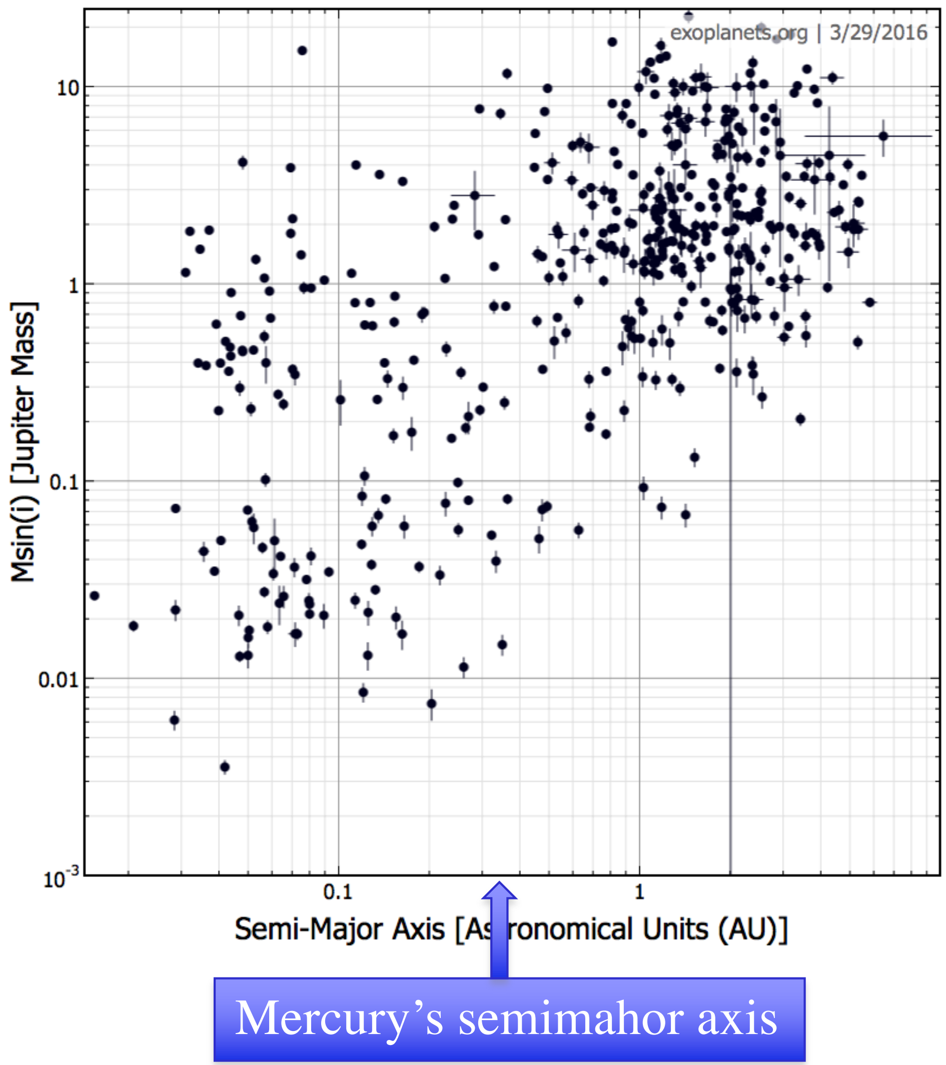
Jackson et al. (2008)



# Planetary mass versus semimajor axis

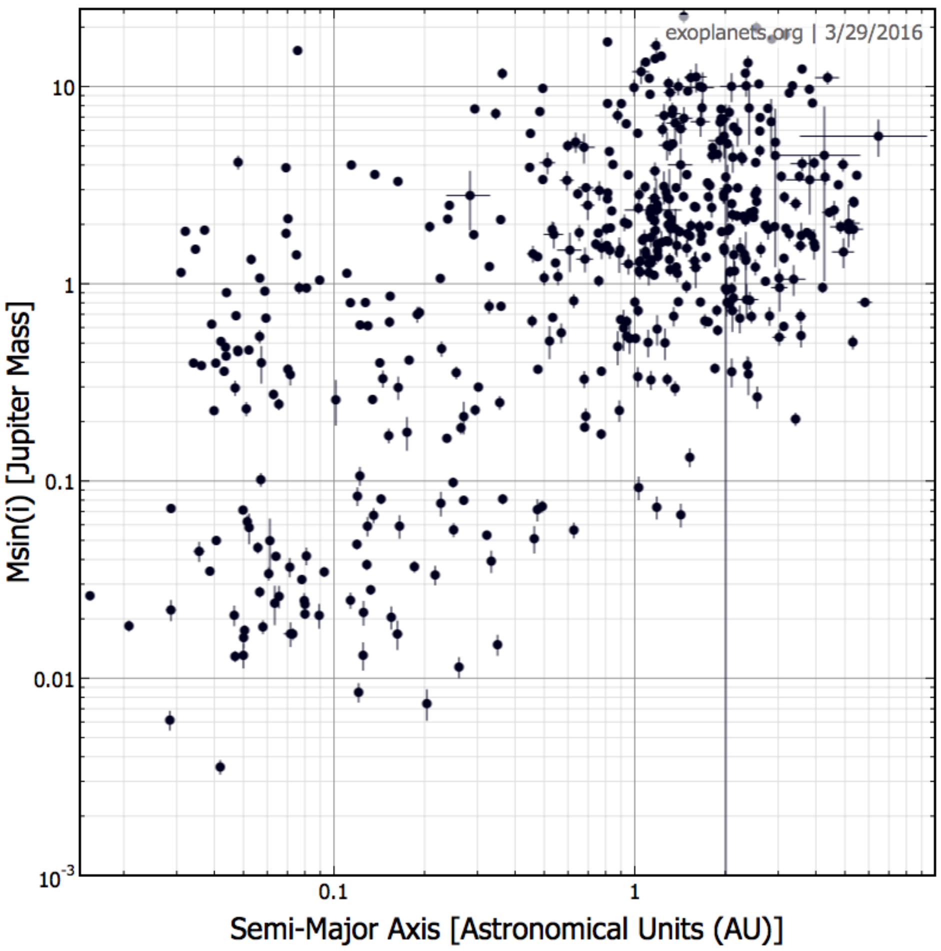
- Results from the Doppler method
  - Most detected planets lie within a few AU from the central star

- Discovered "hot-Jupiters", i.e. giant planets within ≤ 1 AU from the stars
  - Unexpected result from our previous understanding of the Solar System architecture

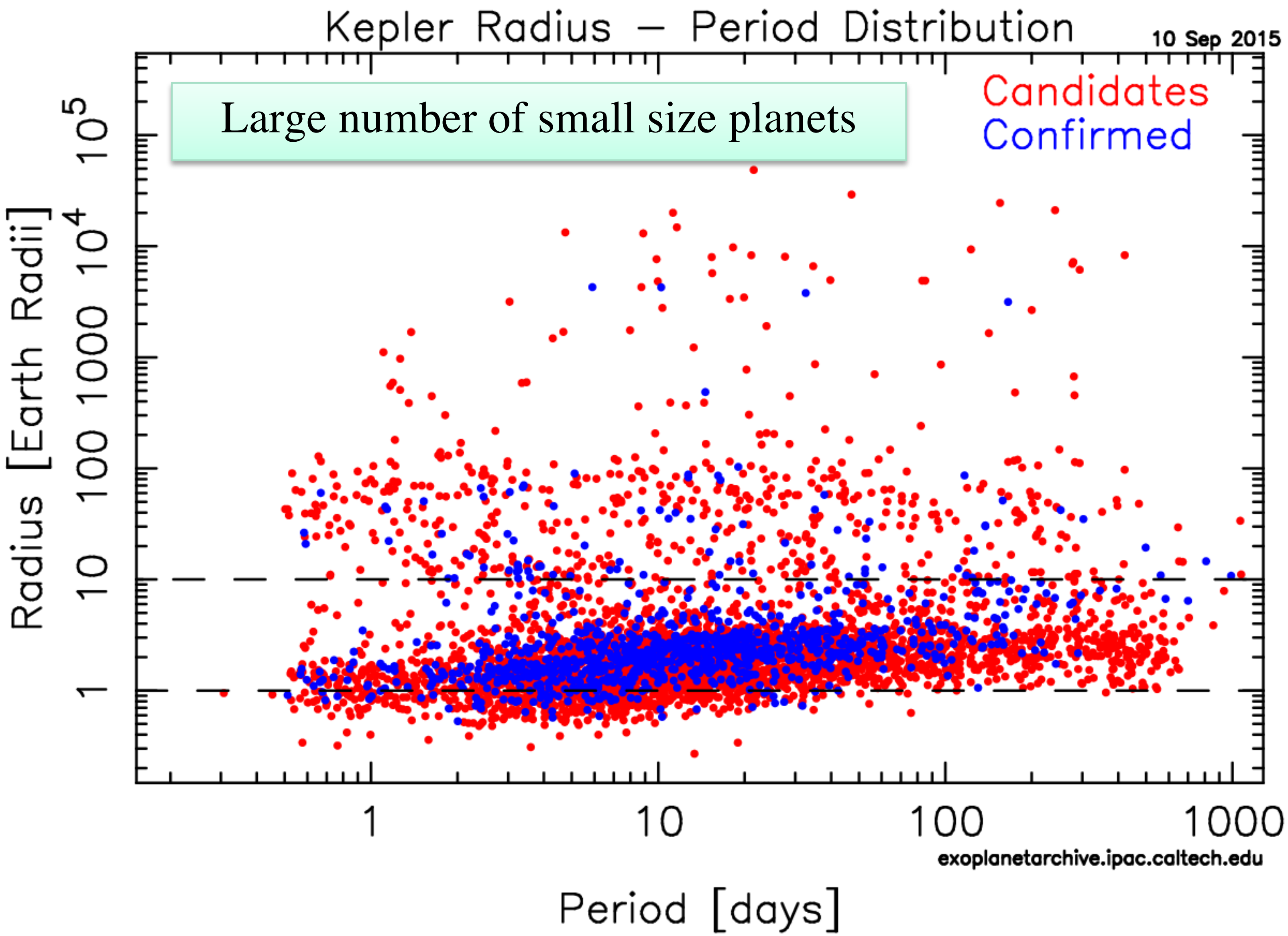


# Planetary mass versus semimajor axis

- 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

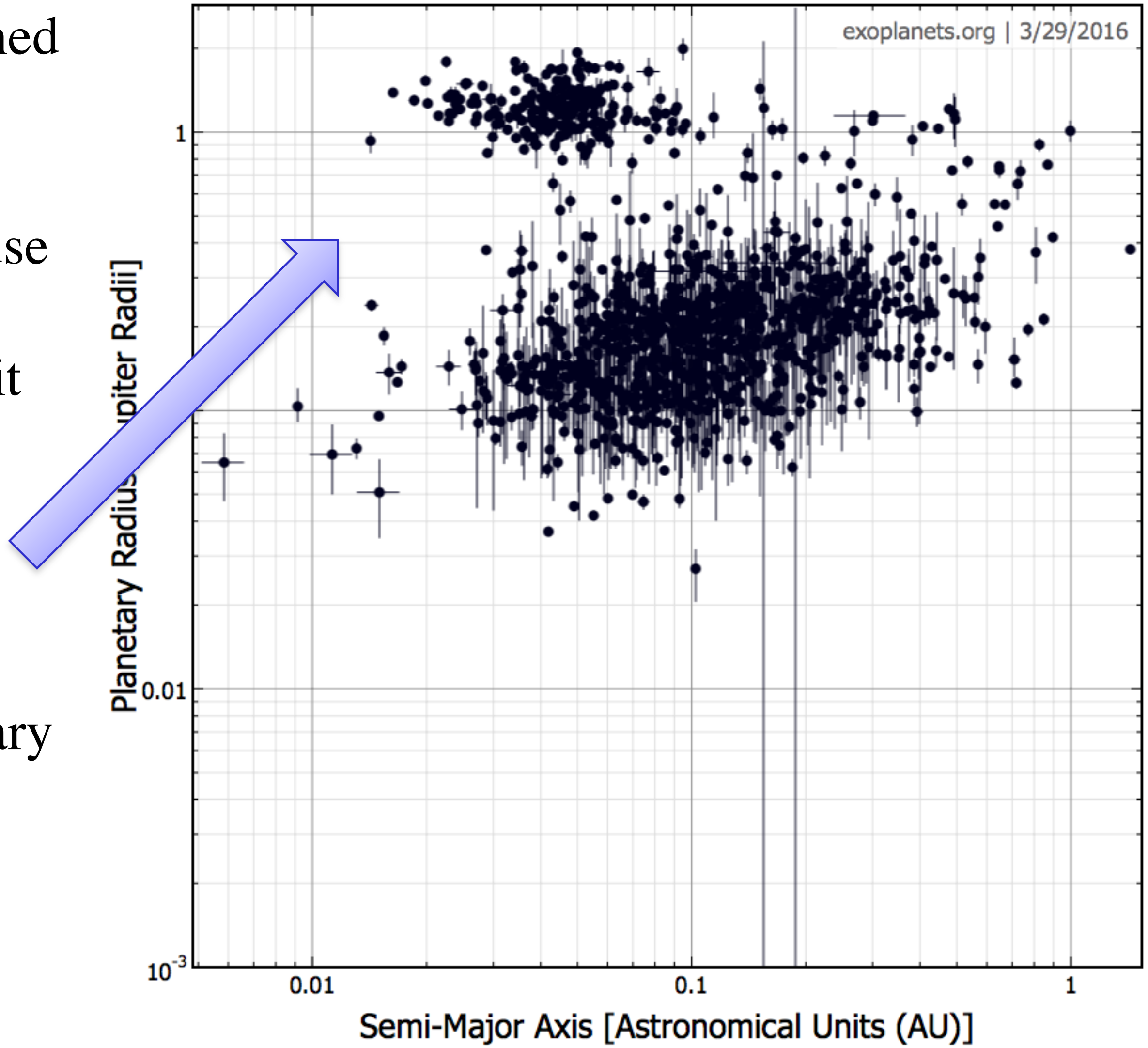


# Radii versus period: Kepler data



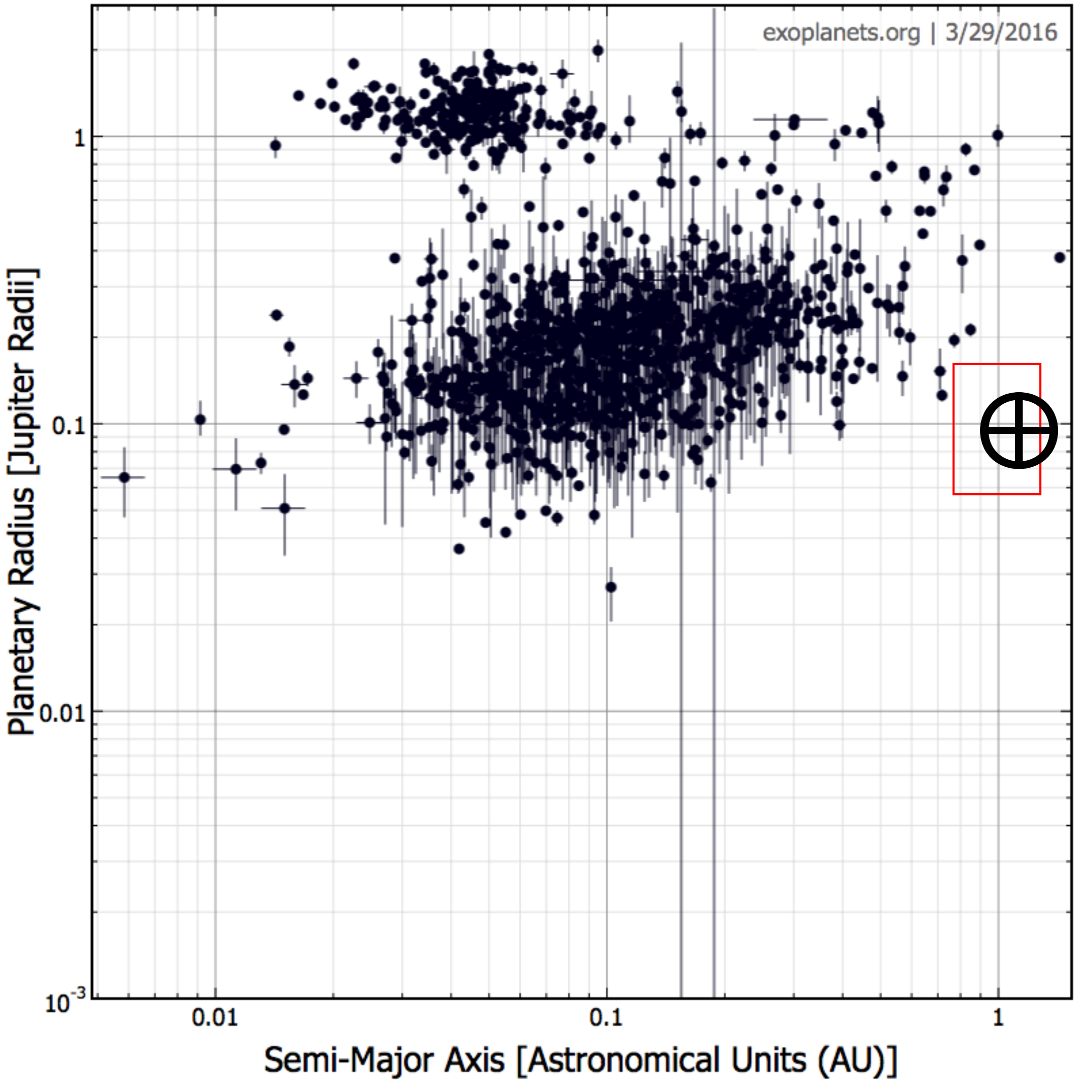
# Exoplanets radii versus semimajor axis

- Sample of exoplanets obtained with the transit method, not corrected for selection bias
- The results are biased because the geometric probability scales as $R_*/a$ and the transit depth scales as $(R_p/R_*)^2$
- However, the "sub-jovian" desert seems to be real
- Its interpretation is complex an requires invoking planetary migration and disruption (Matsakos & Koenig 2016)



# Exoplanets radii versus semimajor axis

- A large number of terrestrial-size planets are found, despite the difficulty of detecting small planets
- Terrestrial-size planets are still difficult to detect at large values of semimajor axis



# 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 are extremely unlikely and would yield a very small fraction of planetary systems

# Occurrence rates around FGK stars

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

**Table 1 Planet occurrence rates around FGK stars**

| Study | Technique | Period range | Size range | Occurrence [%] |
|---|---|---|---|---|
| Wright et al. (2012) | Doppler | <10 days | $>30\,M_\oplus$ | $1.20 \pm 0.38$ |
| Mayor et al. (2011) | Doppler | <11 days | $>50\,M_\oplus$ | $0.89 \pm 0.36$ |
| Cumming et al. (2008) | Doppler | <5.2 years | $>100\,M_\oplus$ | $8.5 \pm 1.3$ |
| | | <100 days | $>100\,M_\oplus$ | $2.4 \pm 0.7$ |
| Howard et al. (2010) | Doppler | <50 days | $3–10\,M_\oplus$ | $11.8^{+4.3}_{-3.5}$ |
| | | <50 days | $10–30\,M_\oplus$ | $6.5^{+3.0}_{-2.3}$ |
| Mayor et al. (2011) | Doppler | <50 days | $3–10\,M_\oplus$ | $16.6 \pm 4.4$ |
| | | <50 days | $10–30\,M_\oplus$ | $11.1 \pm 2.4$ |
| | | <10 years | $>50\,M_\oplus$ | $13.9 \pm 1.7$ |
| Fressin et al. (2013) | Transit | <10 days | $6–22\,R_\oplus$ | $0.43 \pm 0.05$ |
| | | <85 days | $0.8–1.25\,R_\oplus$ | $16.6 \pm 3.6$ |
| | | <85 days | $1.25–2\,R_\oplus$ | $20.3 \pm 2.0$ |
| | | <85 days | $2–4\,R_\oplus$ | $19.9 \pm 1.2$ |
| | | <85 days | $1.25–22\,R_\oplus$ | $52.3 \pm 4.2$ |
| Petigura et al. (2013) | Transit | 5–100 days | $1–2\,R_\oplus$ | $26 \pm 3$ |
| | | 5–100 days | $8–16\,R_\oplus$ | $1.6 \pm 0.4$ |

$$\frac{dN}{d\ln P \; d\ln R_p}$$

# 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

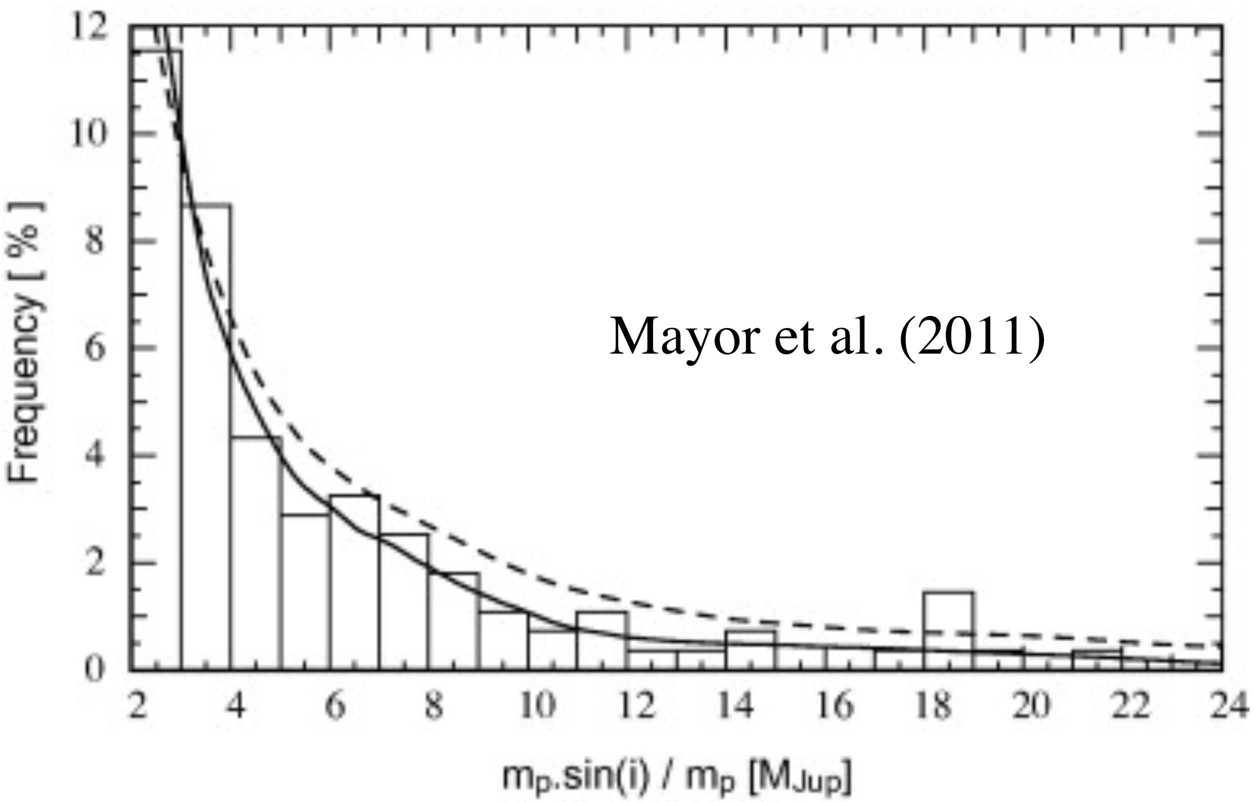
$$\frac{dN}{d\ln P\ d\ln M_p} \propto M_p^{\alpha}\, P^{\beta}$$

  - 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

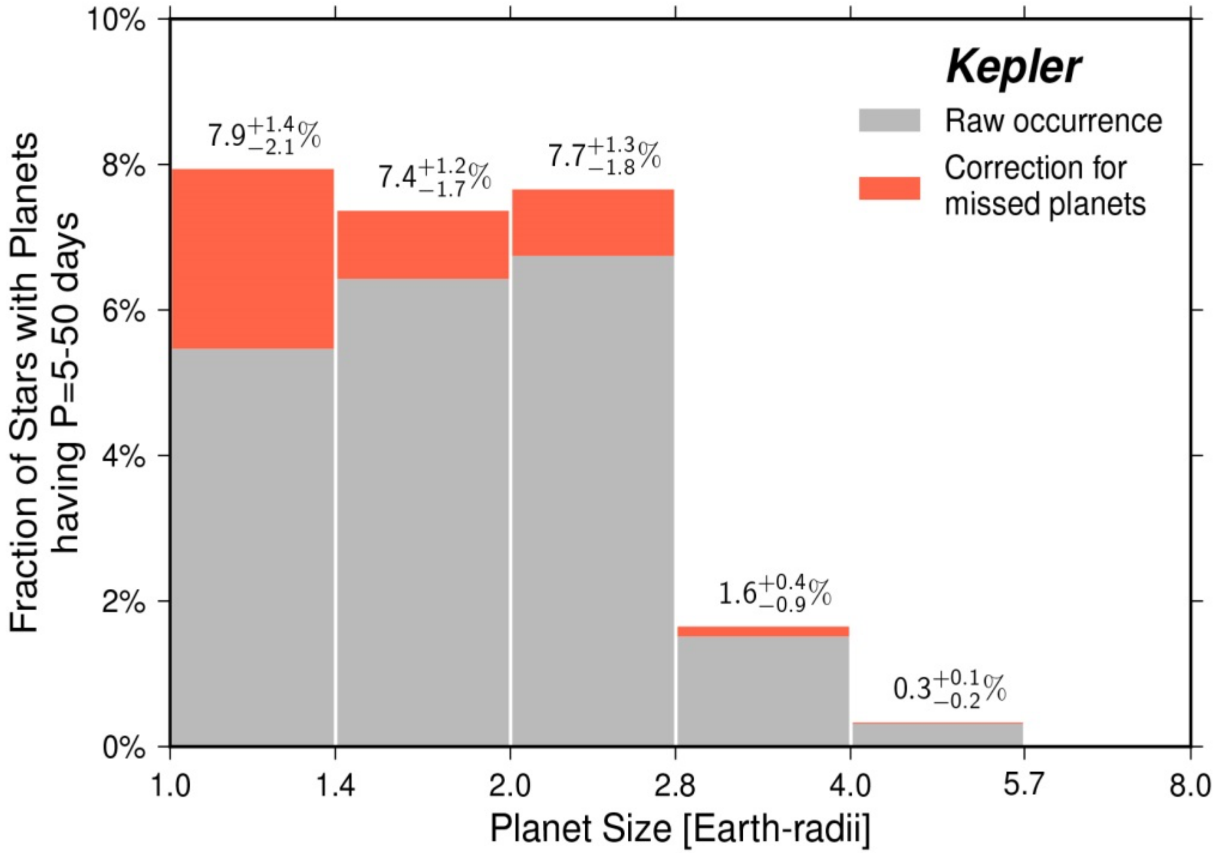
– *M* sin *i* distribution obtained with the Doppler method

- 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 indicates that small-size planets are more frequent than large planets



# Occurrence rates of Earth-like planets

- The occurrence rate of Earth-like planets is usually calculated taking into account the planet mass (or size) <u>and</u> 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 | $34 \pm 14$ | 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 | $11 \pm 4$ | 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.