Architecture of planetary systems

Planets and Astrobiology (2022-2023)

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Multiple planetary systems

- The study of multiple systems of exoplanets around a given star allows us to investigate the architecture of planetary systems, i.e. the relative locations of planets of different types inside a given planetary system

- Open questions:
  - How planets of different sizes and masses are located with respect to the host star?

    Are giant planets typically closer or distant from the star?

    Which is the relative location and orbital periodicity of terrestrial planets in the systems ?

    Is there evidence for mean motion resonance?
  - Is the Solar System architecture representative of a large fraction of planetary systems or is it anomalous?

- Multiple planetary systems provide tests of planetary formation
  - Models of planetary formation are extremely complex and do not provide unique solutions: the output of model simulations are very sensitive to even little variations of initial conditions
  - Given this situation, it is impossible to predict the general configuration of a planetary systems from the observed properties of the Solar System
  - From a statistical sample of planetary systems we can estimate the probability of occurrence of a particular planetary configuration
  - In this way, the models of planetary formation are constrained to reproduce, from the statistical point of view, the observed distribution of planetary architectures

Observations of multiple planetary systems

- All the methods of exoplanet observations are able, in principle, to detect multiple planetary systems

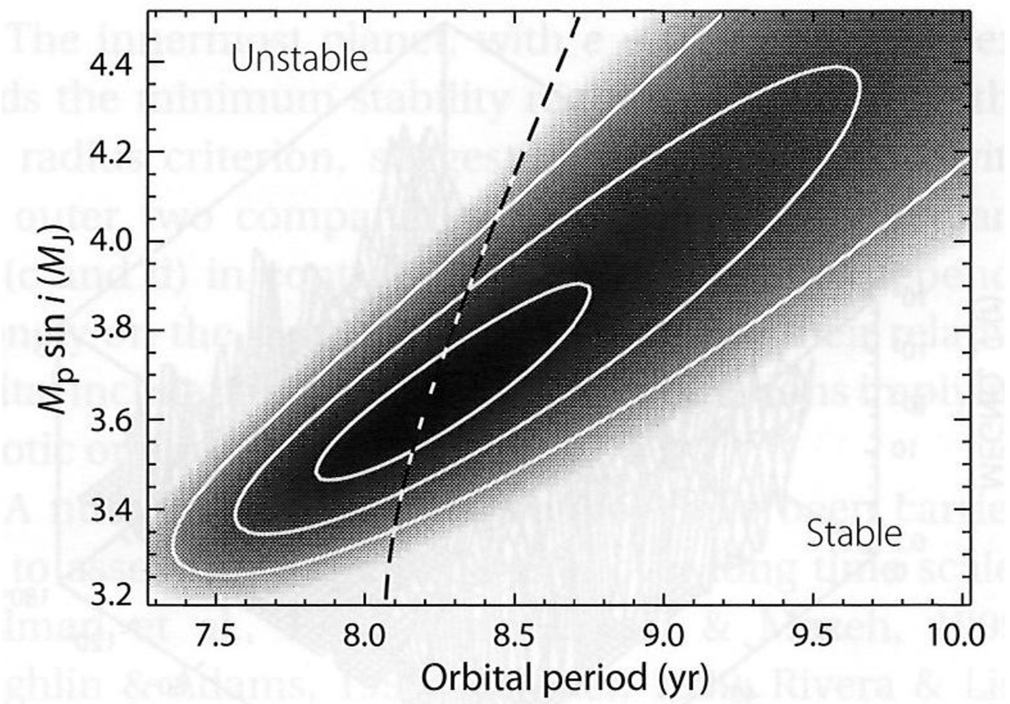
  - The first confirmed exoplanets, detected in 1992 with the pulsar timing technique, were actually part of a multiple planetary system (Wolszczan & Frail, 1992)

- Given the large efficiency of the Doppler and transit methods, statistical properties of multiple planetary systems are based on data collected with such observational methods

- Simulations of dynamical stability are performed to test the reliability of the detections of multiple planets and to constrain the error bars of dynamical quantities inferred from the observations

Analysis of dynamical stability of multiple planetary systems

- This type of analysis requires integration of the orbits by means of numerical methods
  - the goal is to test whether the orbital parameters inferred from the observations correspond to a long-term stable physical configurations
  - this test can also be used to constrain the parameter space of the results, especially when the experimental error bars are large
- Among different types of numerical integrators, "symplectic integrators" are preferred



HD 183263 b,c (Wright et al. 2009)

Symplectic integrators

- In describing the motion of dynamical systems, a sequence of deterministic algebraic steps are executed from an initial to some final state
  - Such algebraic mappings include the classical fourth-order Runge-Kutta iteration for the approximate solution of ordinary differential equations (e.g. Press et al. 2007)
- Conventional integrators carry the penalty of "numerical dissipation", which results in a secular change of energy even in a conservative system
  - Positional errors grow quadratically with time
- Symplectic integrators do not suffer from these disadvantages, since they are built in such a way to preserve the total energy and angular momentum of the N-body system
  - The positional errors grow linearly with time

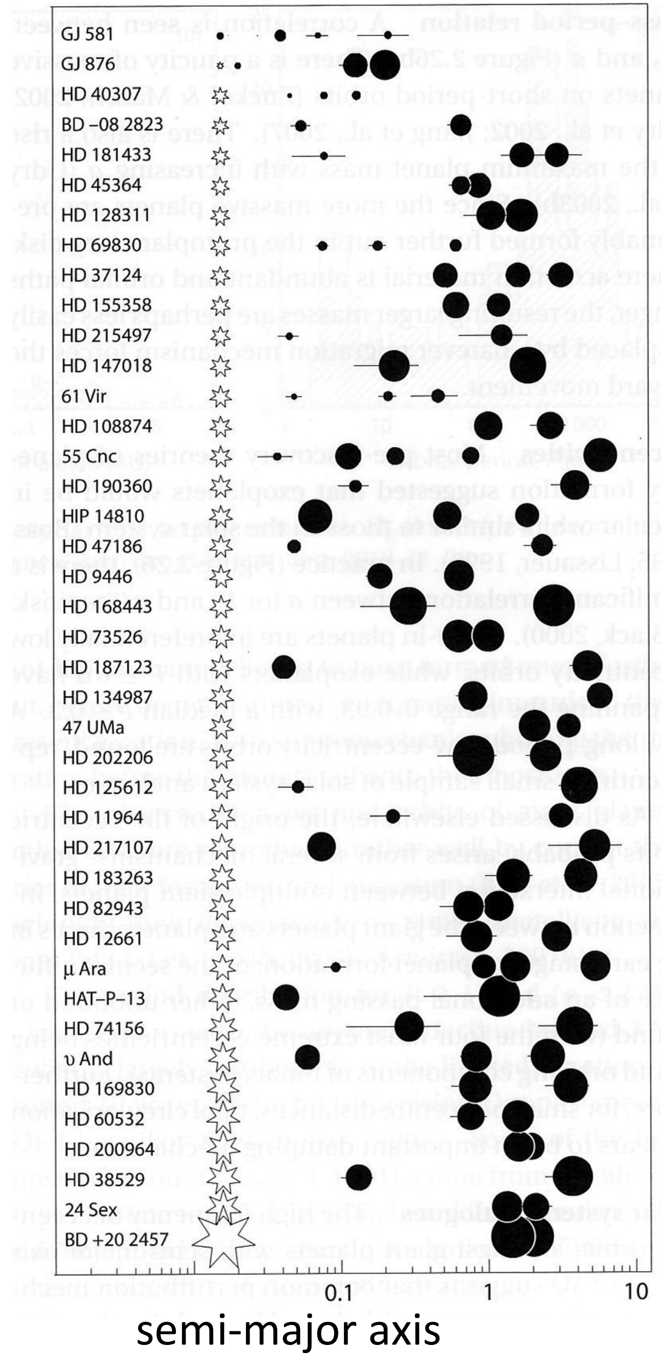
Statistics of planetary systems discovered with the Doppler and transit methods

Multiple planetary systems discovered with the Doppler method (Marcy et al. 2008)

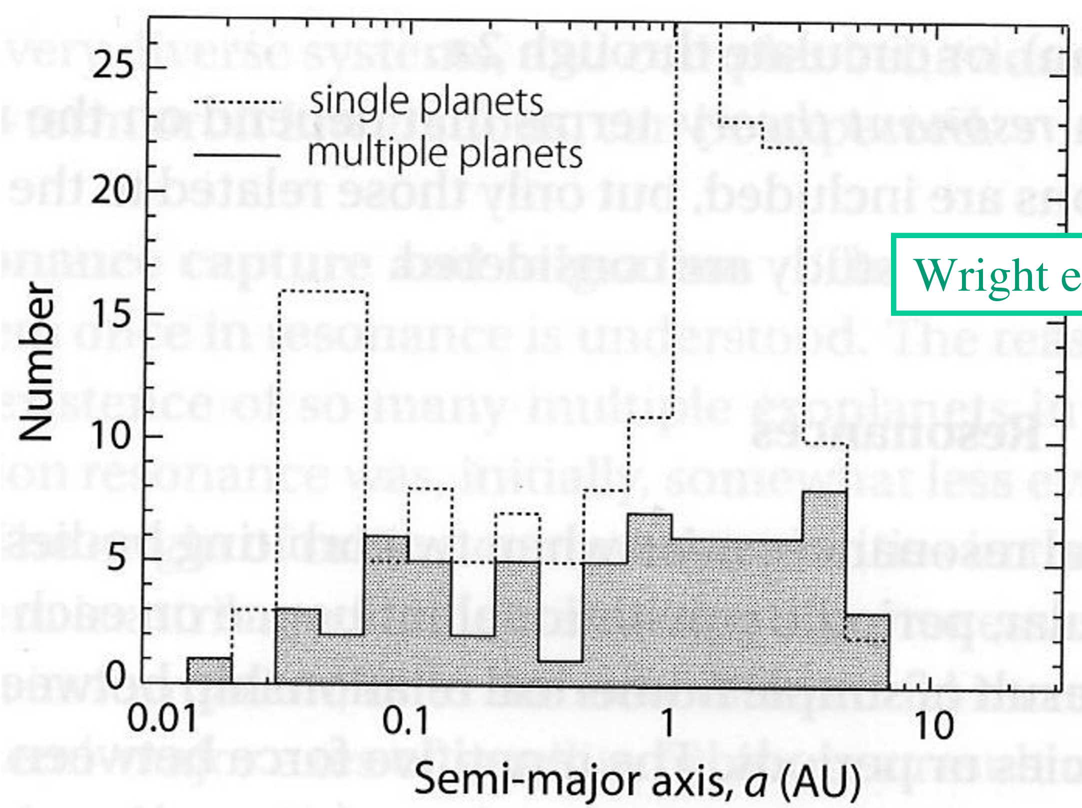
- Frequency
  - About 10-15% of all the exoplanet systems detected with the Doppler method happen to be multiple systems
  - The fraction of multiple systems discovered tends to increase with increasing accuracy of the observations and increasing temporal baseline of the observations
  - The true fraction of multiple systems is expected to be higher, probably most planets being in multiple systems

Multiple planetary systems discovered with the Doppler method (Marcy et al. 2008)

- Architecture
  - Planetary systems show a large variety in their architecture
  - Giant planets can be either close or distant from the central star
  - The frequency of "hot jupiters" is apparently small, despite selection bias that favours their detection

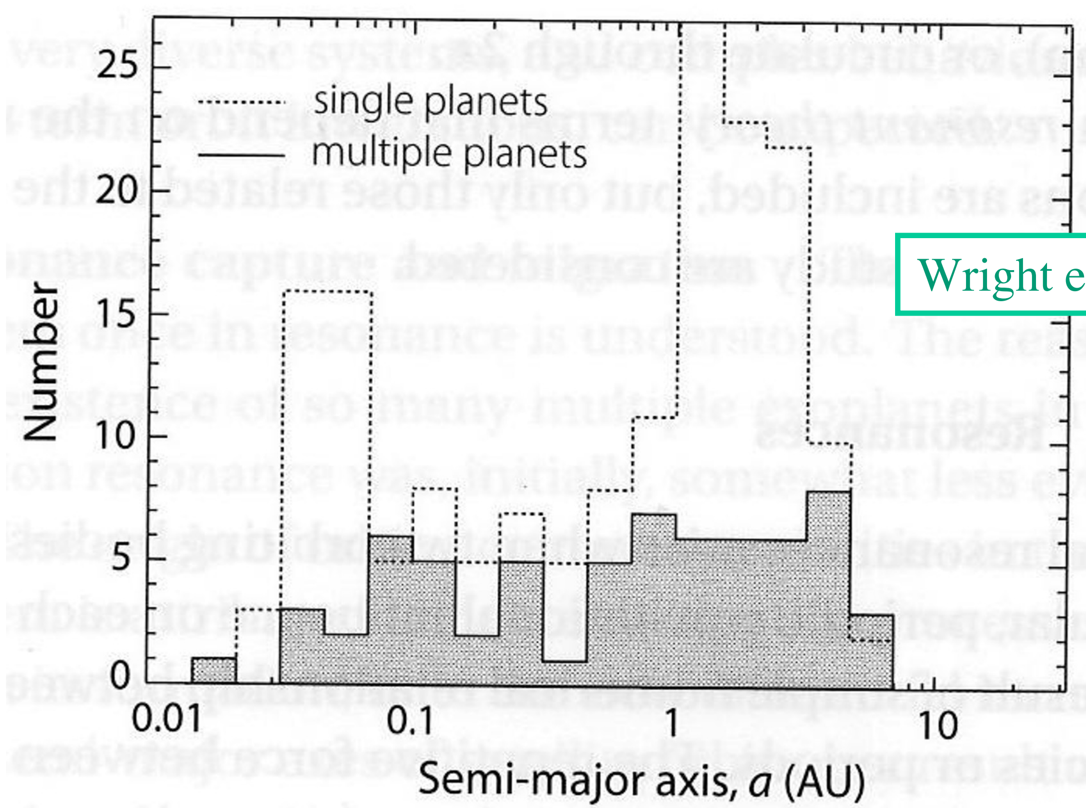


- Planet distribution versus semi-major axis
  - even if the statistics is still relatively small, some systematic differences appear to be present between single planets and multiple systems
  - for example, the planet distribution as a function of semimajor axis seems to be flatter for multiple systems than for single planets
  - A peak of “hot jupiters” around $a \sim 0.03$-0.07 AU and of giant planets beyond $a \sim 1$ AU are not seen in the statistics of multiple systems



Wright et al. (2009)

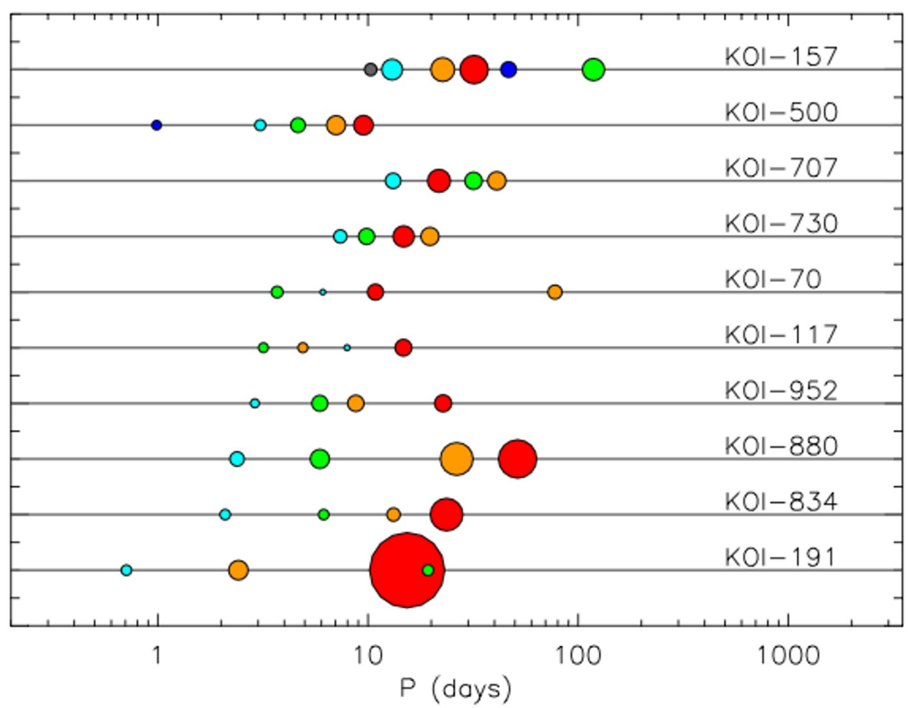
- Interpretation of the spatial distribution of the planets
  - Apparently, the mechanisms that yield an accumulation of giant planets at small and large semimajor axis are not working in multiple systems
  - The differences suggest the existence of different mechanisms of planet migration, still hard to understand given the low statistics and the presence of selection effects
  - <u>Migration of giants from outer to inner regions might destroy multiplicity</u>



Wright et al. (2009)

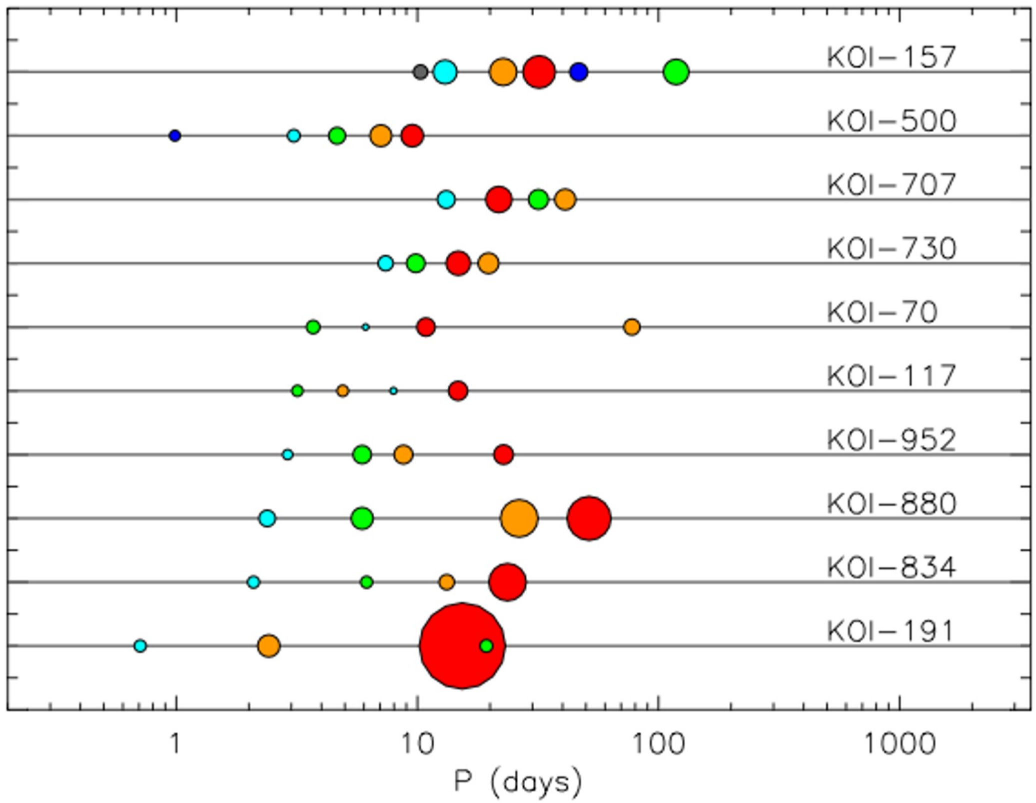
Multiple planetary systems: Kepler results

- Planetary systems with more than 4 planets discovered with Kepler (Lissauer et al. 2011)
  - Large variety of planetary architectures
  - In this sample, smaller planets tend to lie closer to the star than giant planets



Multiple planetary systems: Kepler results

- Interpretation
  - Selection effects cannot explain the distribution of small planets close to the star (the transit method favours the detection of large planets close to the star)
  - The migration of giant planets towards the central star could alter the orbital inclinations of smaller planets; as a result, the probability for them to be discovered with the transit method would become smaller

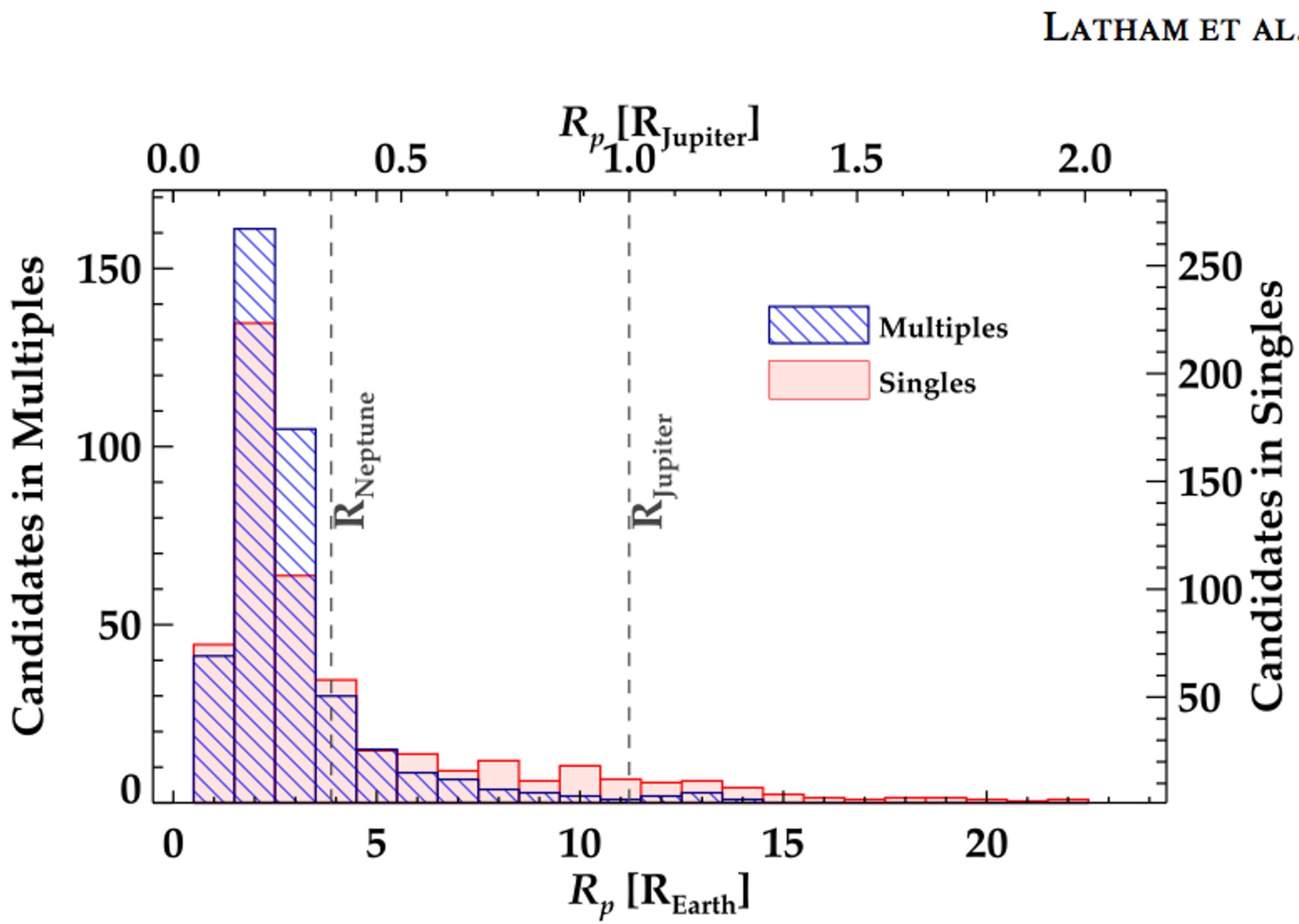


Multiple planetary systems: Kepler results

In multiple planetary systems the fraction of small (neptunian) planets is higher (86%) than in single systems (69%)

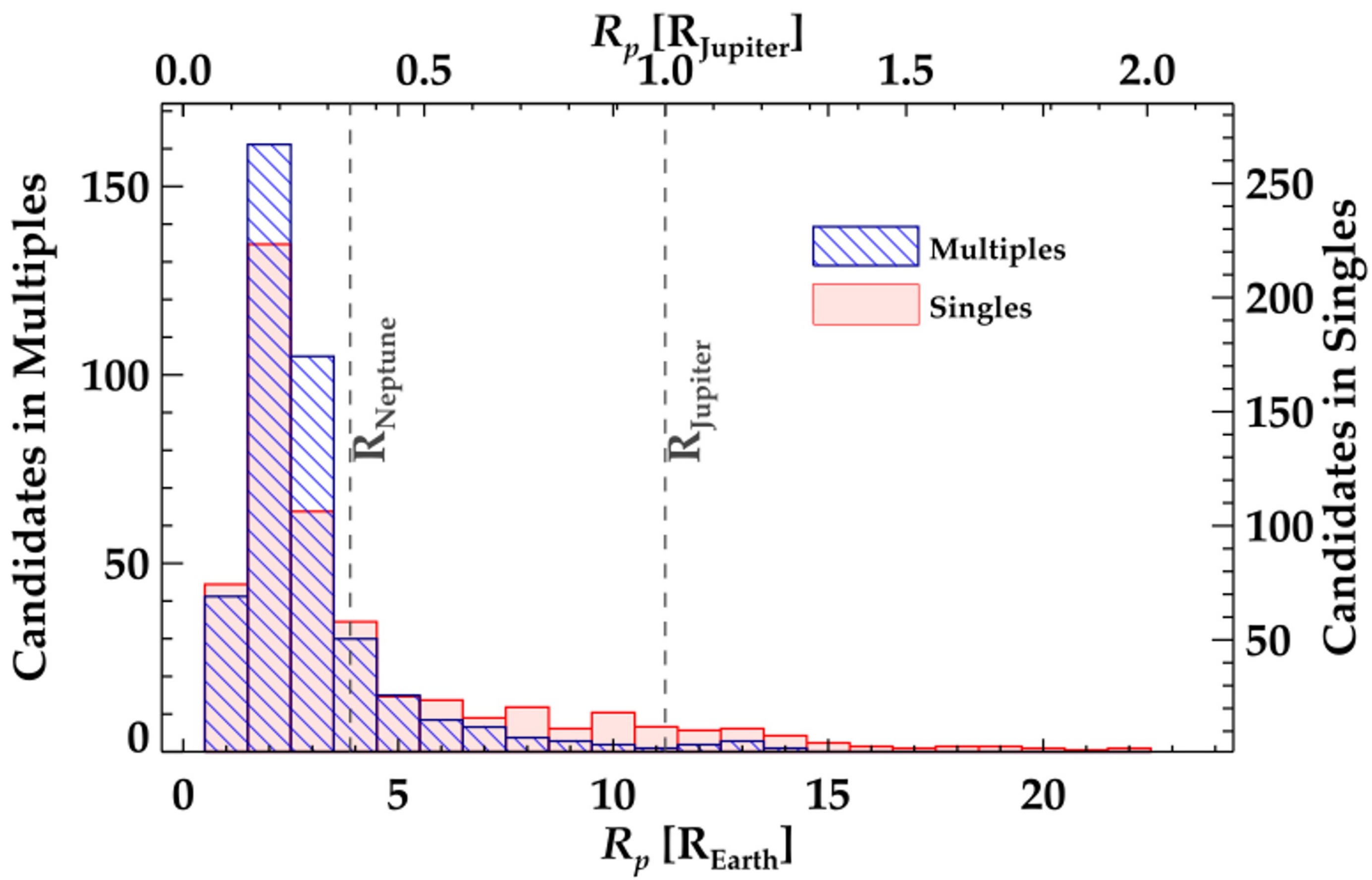
Latham et al. (2011)

Small planets are more predominant in multiple systems than in single systems



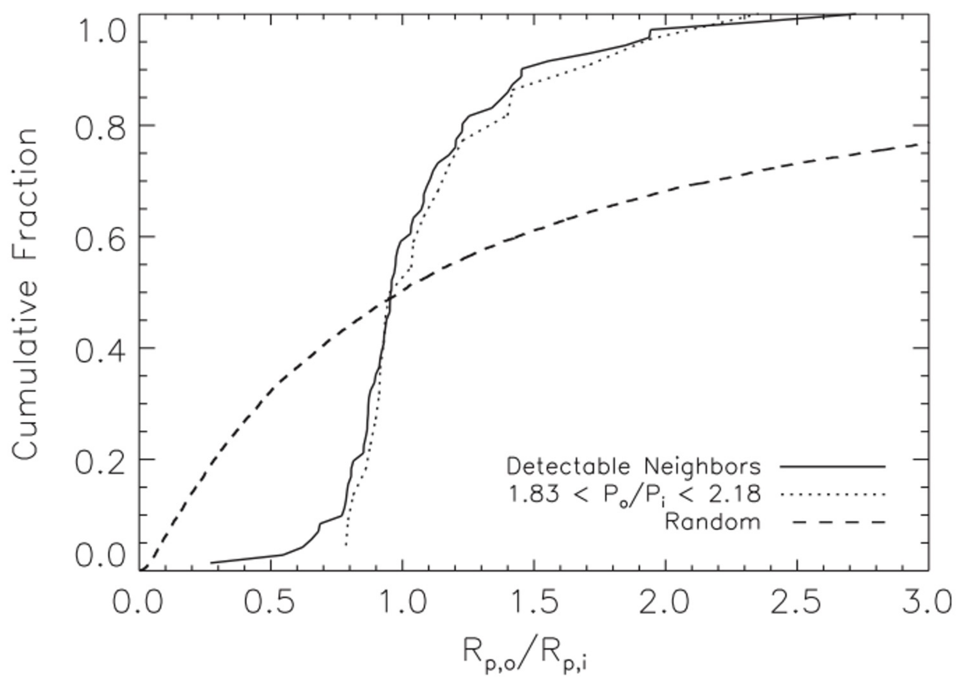
- Possible interpretation of the size distribution
  - The mass of protoplanetary disk that is not used to build up giant planets is available to be incorporated in small planets

LATHAM ET AL.



Multiple planetary systems: Kepler results

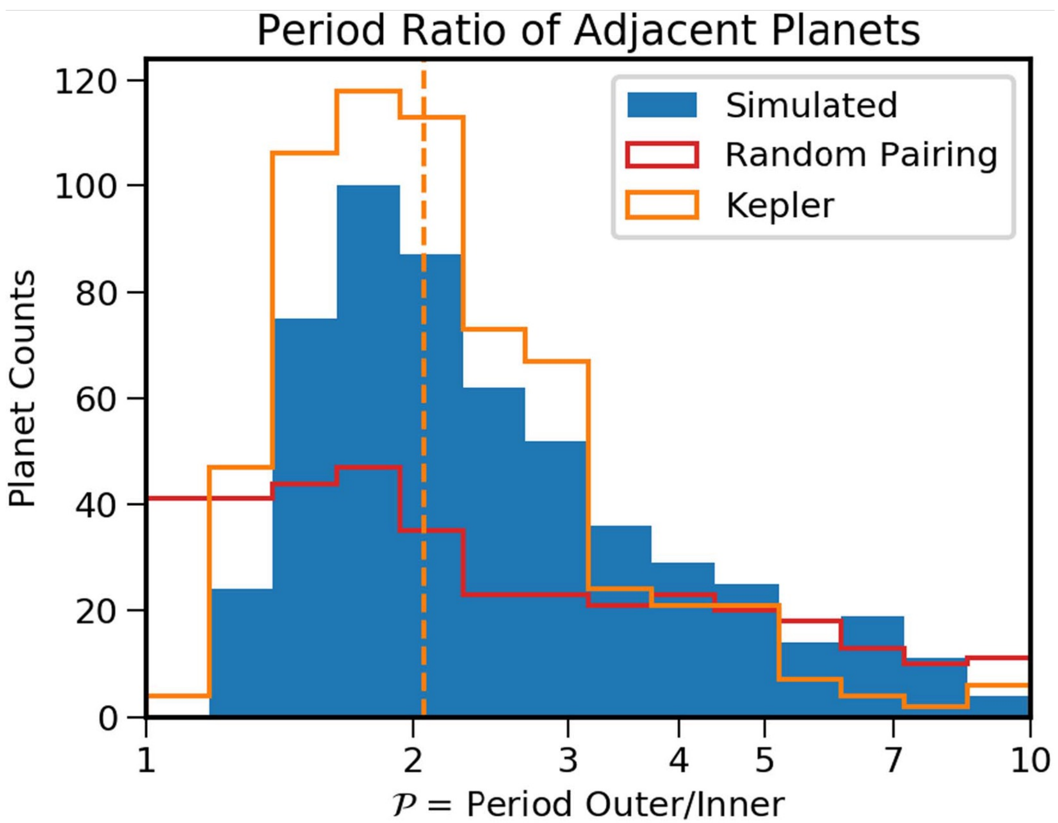
- Nearby planets in a given system tend to have similar radii
  - Results inferred from the cumulative distribution of the ratio of the radii of neighbouring planets
  - In absence of migration mechanisms, this result suggests that the final size of the planets at the epoch of their formation depends on the properties of the protoplanetery disk at a given distance from the star
  - The result is considered to be unaffected by selection bias



Multiple planetary systems: Kepler results

Ratio between the orbital periods of adjacent planets:

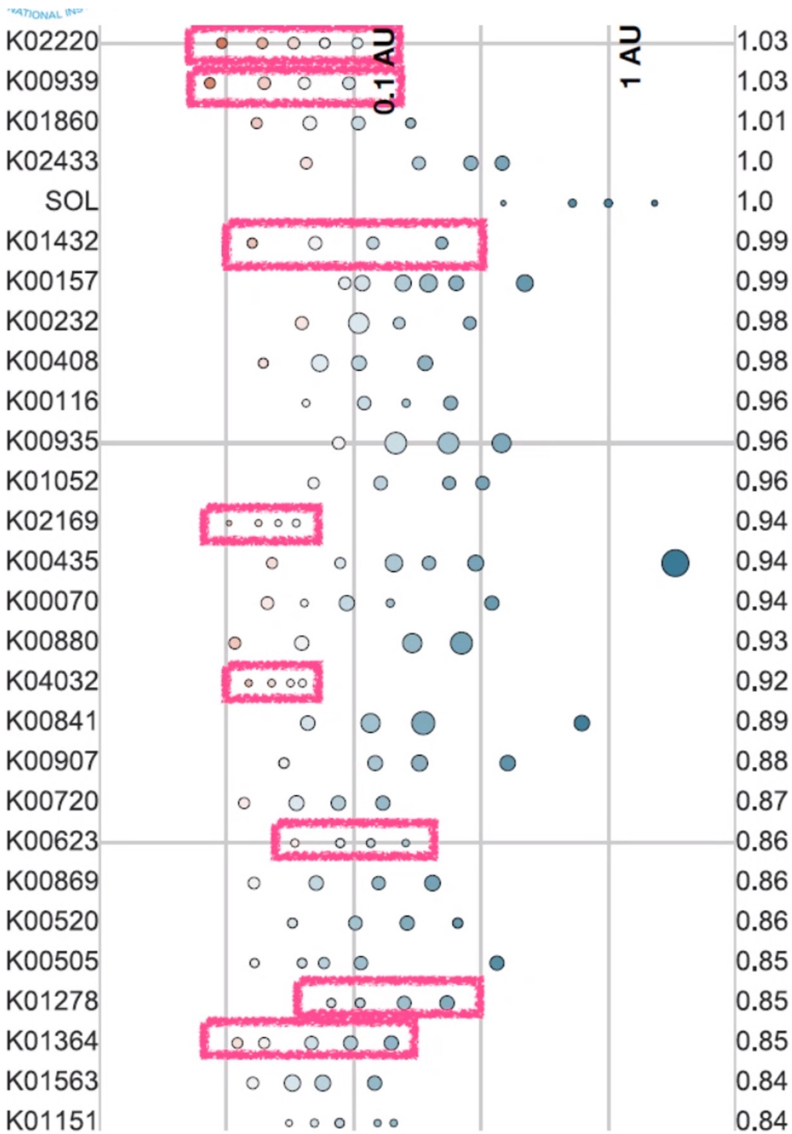
- orange histogram obtained from known systems
- red histogram obtained from randomly picking planets from the radius-period distribution of known objects
- blue histogram obtained from a synthetic population generated using a Rayleigh distribution of period ratios



- biased to short ratio values by observational methods, still uncertain if this is an artifact
- if not an artifact, it might be a universal feature related to both formation (Izidoro et al. 2022) and evolution mechanisms (e.g. Lammers et al. 2023)

Mulders et al. 2018

“Peas in a pod” ?



Kepler multiple systems have:
Similar sizes
Similar spacings

Rossiter-McLaughlin effect

Distortion of the stellar absorption-line profiles induced by the transit of a planet in front of the stellar disk

Its detection requires both the transit and Doppler techniques

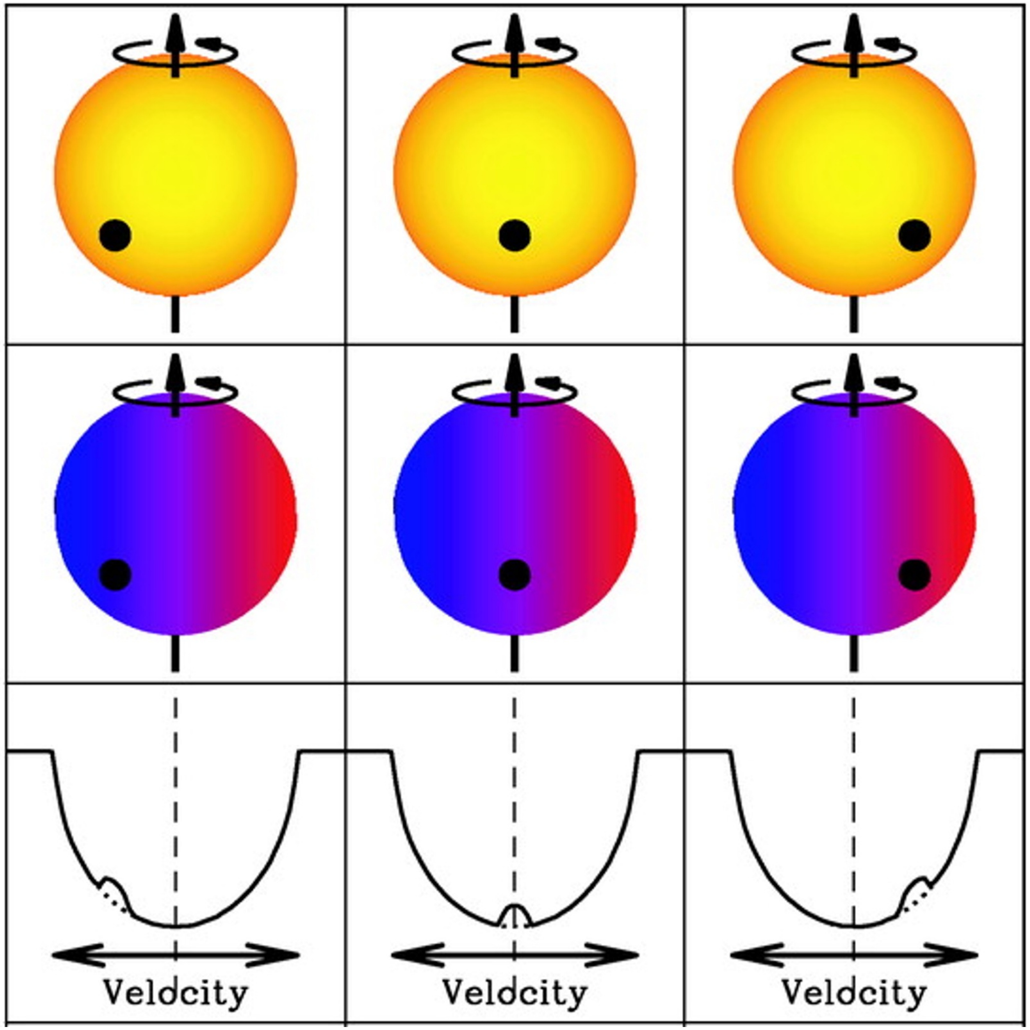
The same effect was discovered in stellar binaries by Rossiter and McLaughlin almost one century ago

The Rossiter–McLaughlin (RM) effect

Effect on the stellar magnitude

Effect on the radial velocity

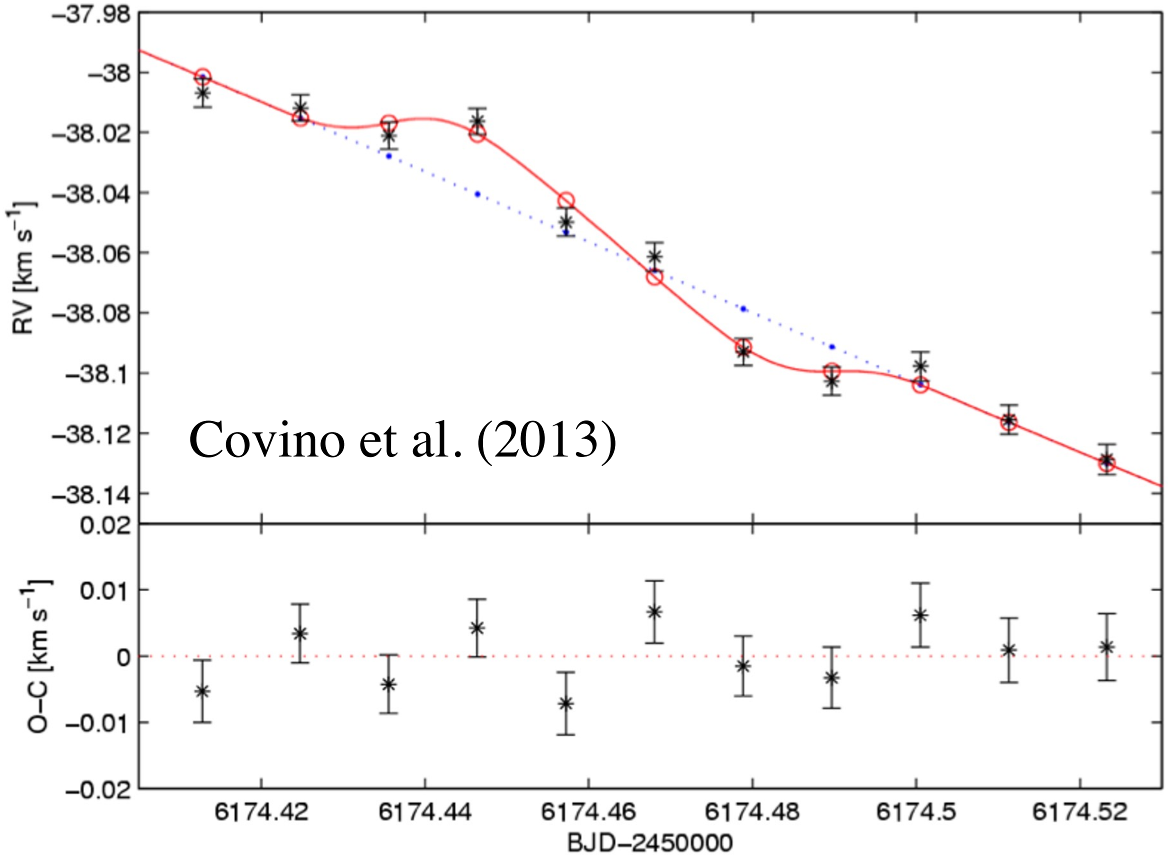
Line profile of the stellar photospheric absorption



Gaudi & Winn (2007)

The Rossiter–McLaughlin (RM) effect

Produces an anomalous signal in the Keplerian radial velocity curve during the transit



days

The Rossiter–McLaughlin (RM) effect

The radial velocity profile of the Rossiter-McLaughlin signal depends on the angle λ between the planetary orbit and the stellar equatorial plane of rotation

By modelling the radial velocity profile we can estimate λ

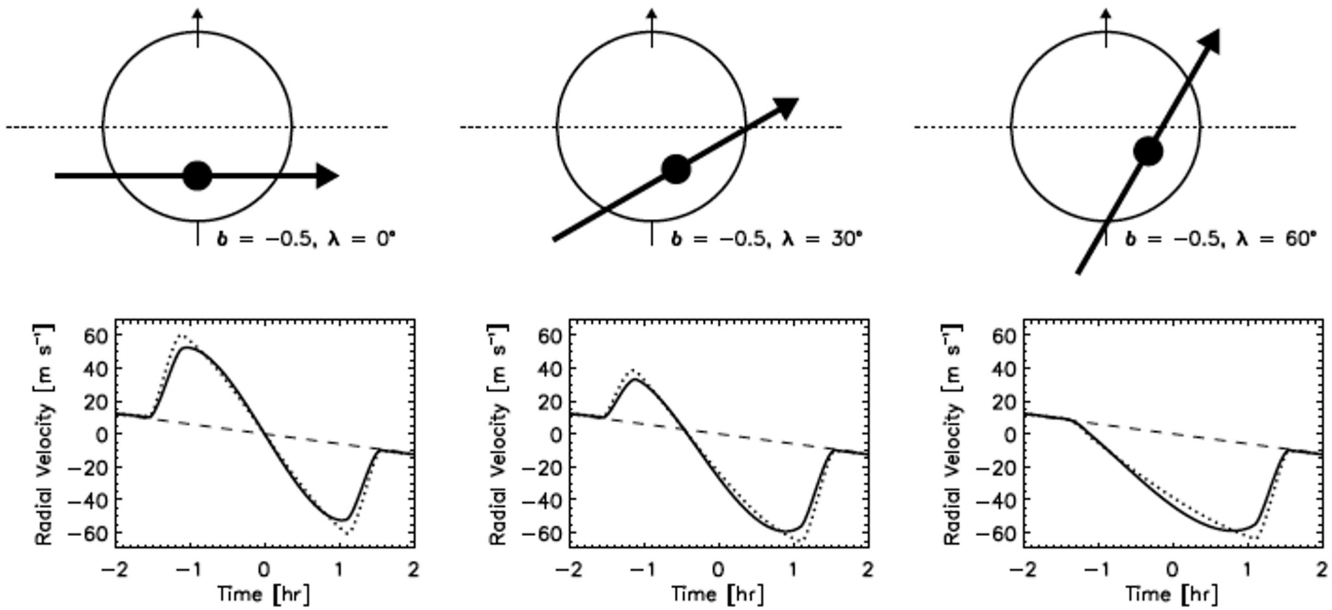


Figure 2.: The dependence of the RM waveform on λ, from Gaudi & Winn (2007). Three different trajectories of a transiting planet are shown along with the corresponding RM waveform. Solid lines include the effect of limb darkening; dotted lines neglect limb darkening.

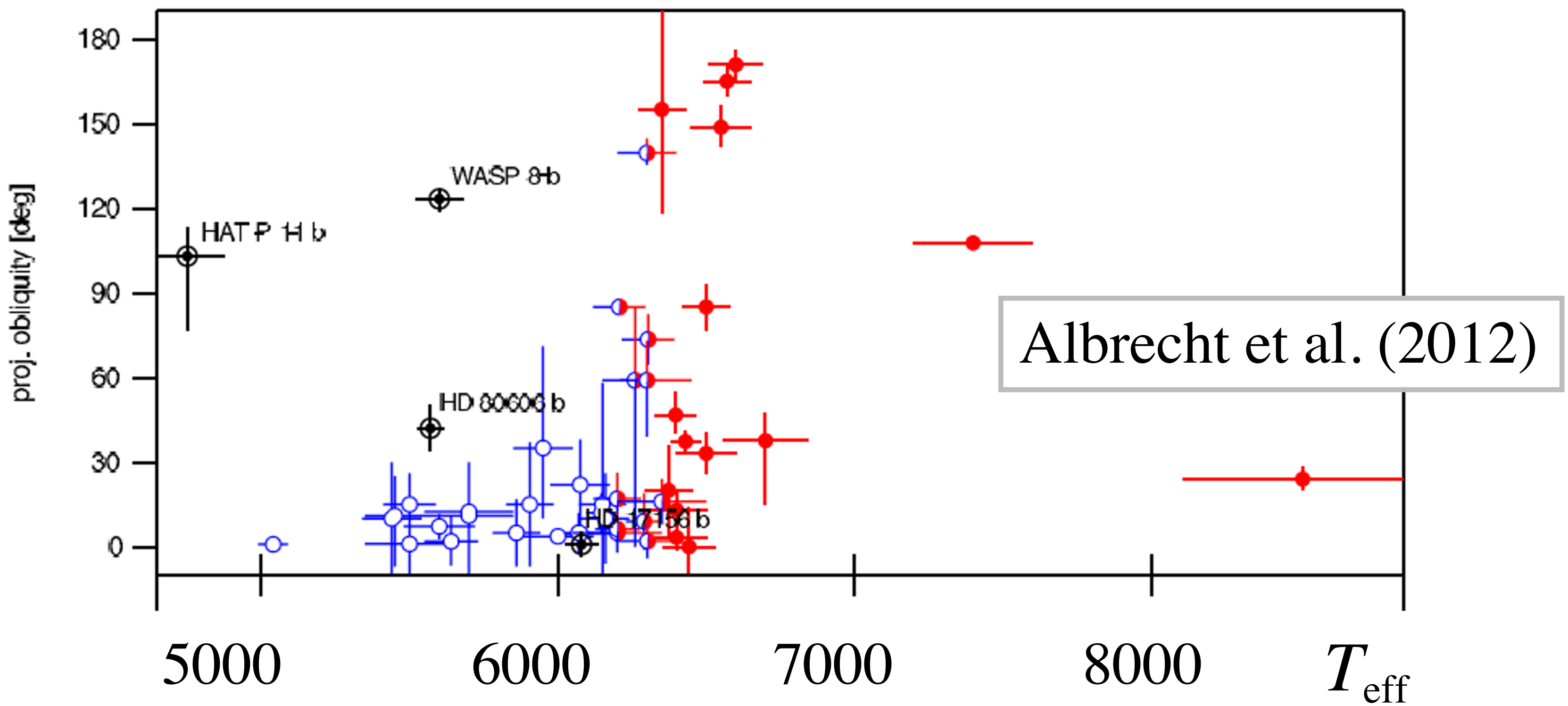
The Rossiter–McLaughlin (RM) effect

- Measuring λ provides information on the dynamical processes that have taken place during planetary formation and evolution
  - The direction of the star rotation spin indicates the original angular momentum of the protoplanetary accretion disk
  - The planetary orbital spin may have changed as a result of dynamical interactions among planetary system bodies

Statistical studies of λ in different systems cast light on the different possible evolutions of planetary architectures

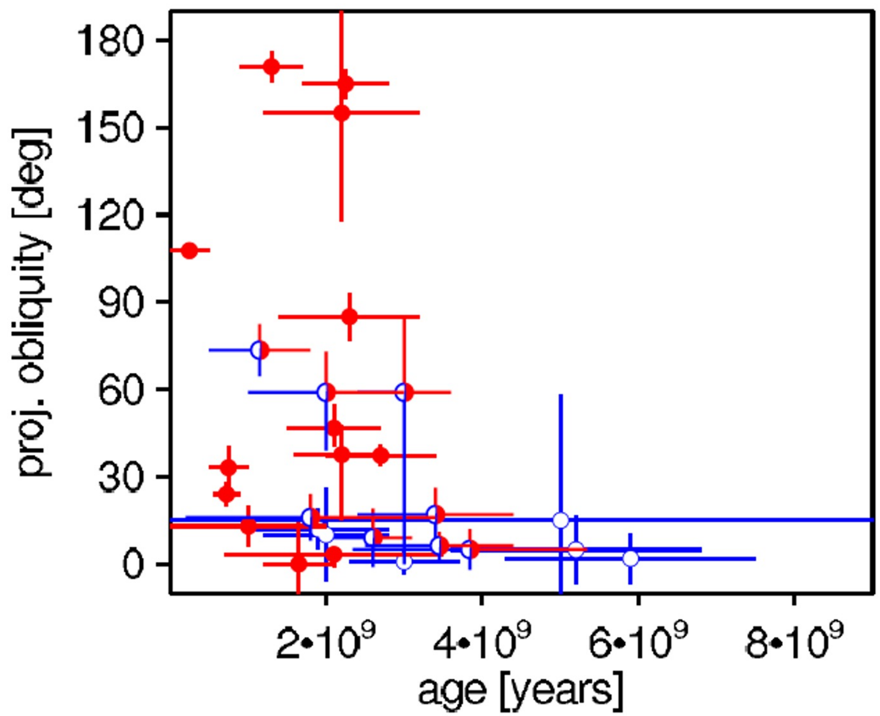
The Rossiter–McLaughlin (RM) effect:
analysis of sample of “hot jupiters”

- The obliquity tends to decrease at low effective temperature of the star, T_{eff}
- Interpretation:
  - the outer layers of stars with low T_{eff} are characterized by convection
  - tidal interactions with the convective layers align the rotation and orbital spins



The Rossiter–McLaughlin (RM) effect:
analysis of sample of "hot jupiters"

- The obliquity of the spins, λ, tends to decrease with time
  - In the first stages after planetary formation, a significant fraction of "hot jupiters" show a high obliquity
- Possible interpretation
  - The migration of Hot Jupiters has been driven by dynamical instabilities, rather than a gradual movement along the plane of the protoplanetary disk
  - With time, the orbital and rotation spins become aligned



Albrecht et al. (2012)

The Rossiter–McLaughlin (RM) effect

- Application to confirm candidate transit planets
  - Confirmation by means of the Doppler method of planet candidates discovered with the transit method is extremely time consuming (requires several orbital periods)
  - This observational effort can be dramatically reduced by observing the radial velocity signal <u>only during the transit epoch</u>
  - The detection of an anomalous radial-velocity signal with Rossiter-McLaughlin characteristics provides an immediate confirmation of the planetary origin of the minimum of the light-curve