THE UNIVERSITY OF TOKYO
UTAP
THEORETICAL ASTROPHYSICS
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@ NAOJ

Measurements of Stellar Obliquities for Transiting Exoplanets with Subaru/HDS

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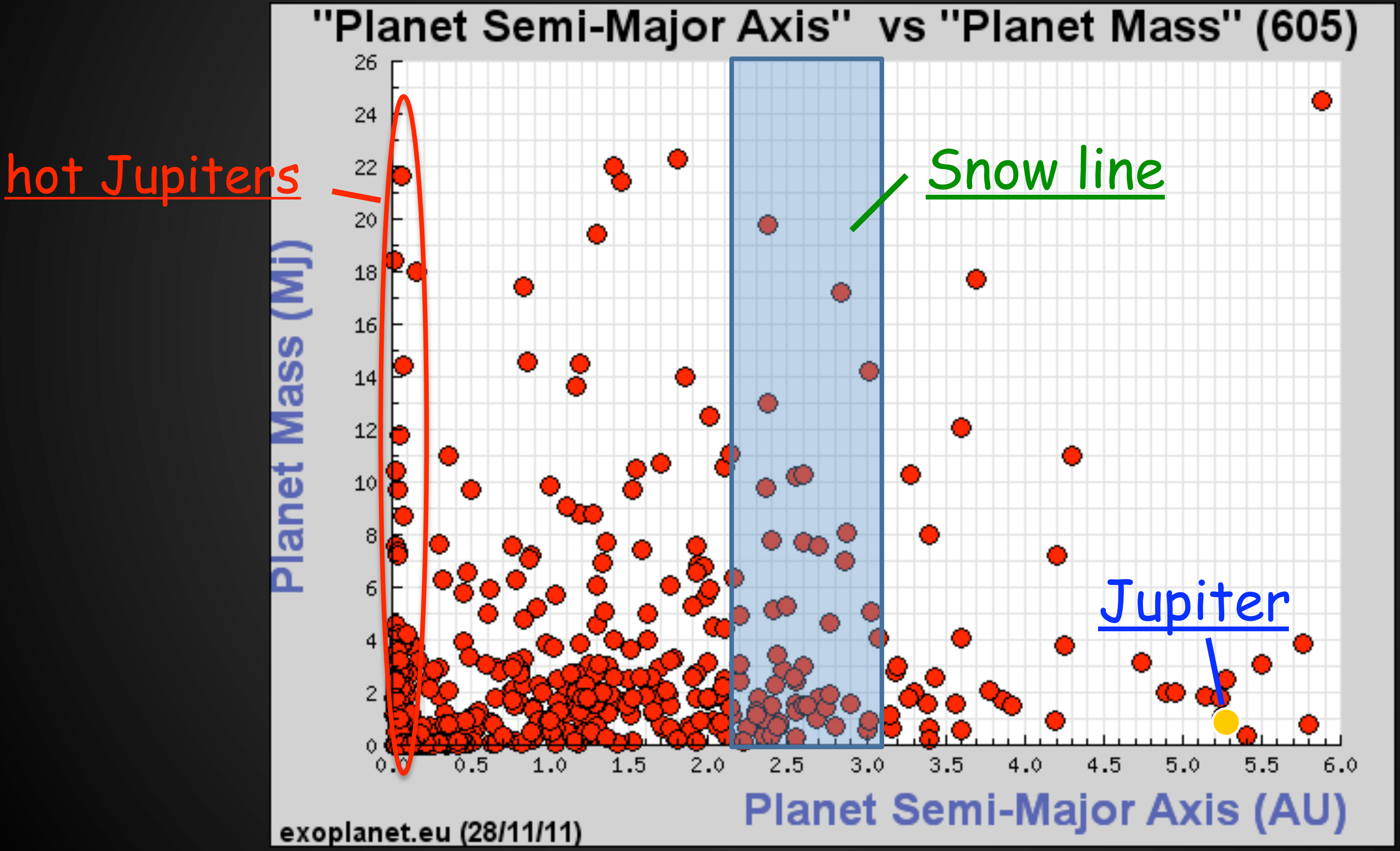
Collaboration with NAOJ, MIT, TIT

Outline

1. Diverse distribution of exoplanetary systems
2. Observational status of the Rossiter-McLaughlin effect
3. Measurements of spin-orbit alignment along the line-of-sight
4. Summary

Diverse distribution of exoplanets



http://exoplanet.eu/

Formation of Hot-Jupiters

The Standard Scenario

→ Hot Jupiters have originally formed at a few AU away from their host stars, then migrated inward by some migration processes.

⬇

- What process can make planets migrate?
- Is there any possibility to observationally distinguish between migration scenarios ?

Migration Processes

1. Interactions between proto-planets and proto-plantary disk

→ Planets had gradually migrated inward due to gravitational interactions with proto-planetary disk (e.g. Lin et al. 1996, Lubow & Ida 2010)

↕

2. Planet-planet scattering (or Kozai cycles) + tidal interactions

→ When multiple planets form or there exists a companion star, they interact with each other and sometimes cause orbital crossing, which can pump up eccentricities. Subsequent tidal interactions with host stars may cause orbital circularization.

(e.g. Chatterjee et al. 2008, Wu et al. 2007, Fabrycky & Tremaine 2007)

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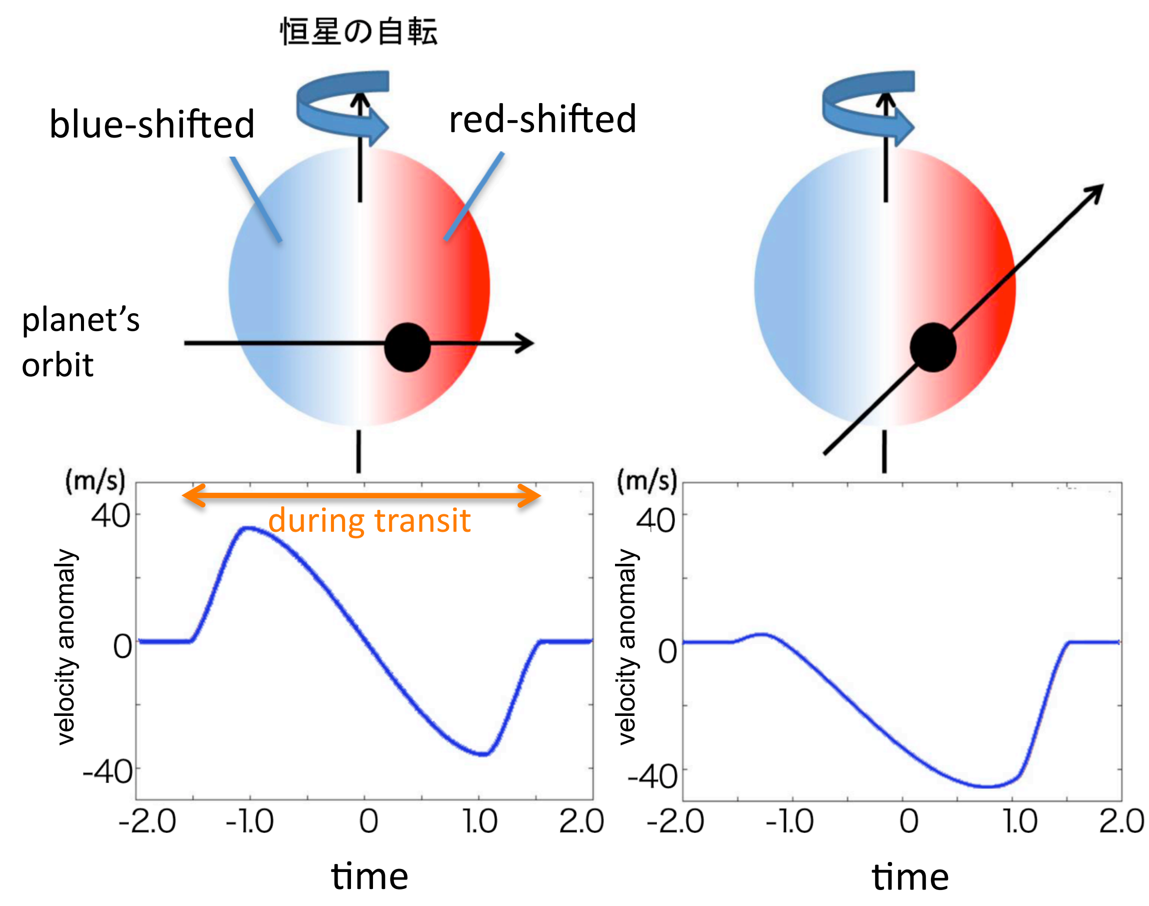
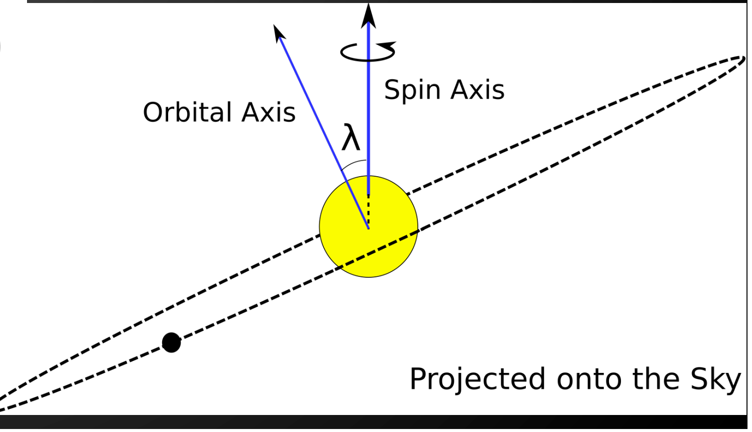
3. Observational Status of the Rossiter-McLaughlin effect

The Rossiter-McLaughlin Effect for Planets

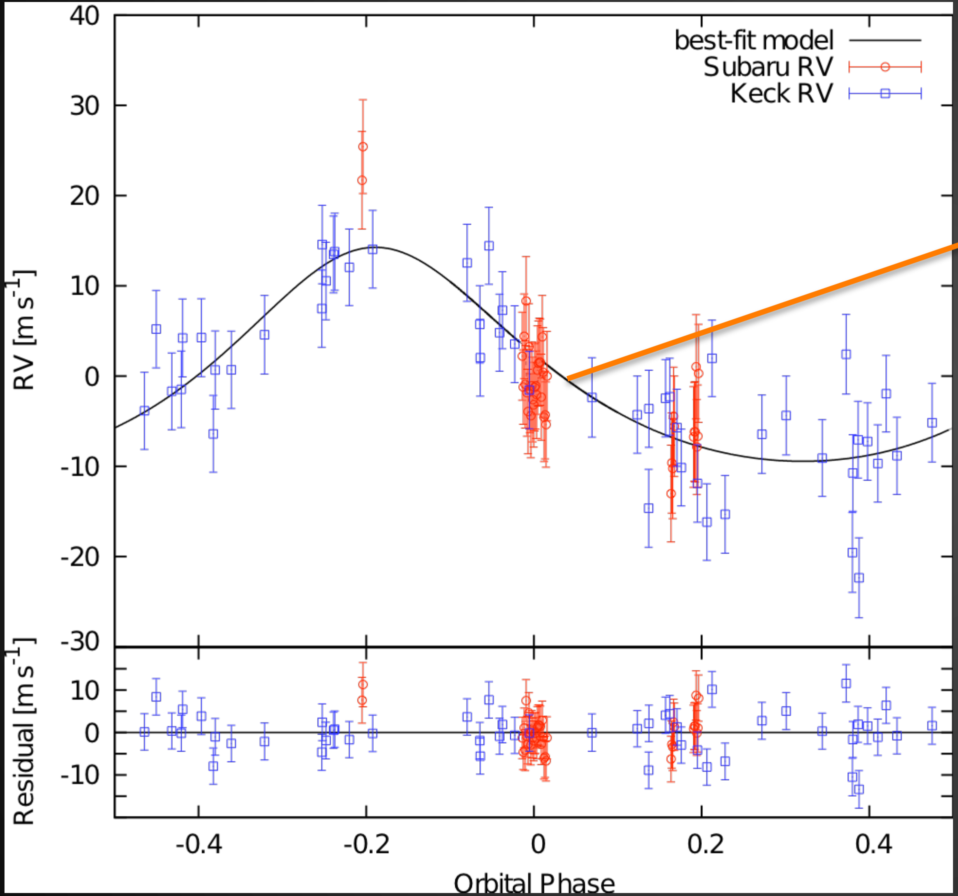


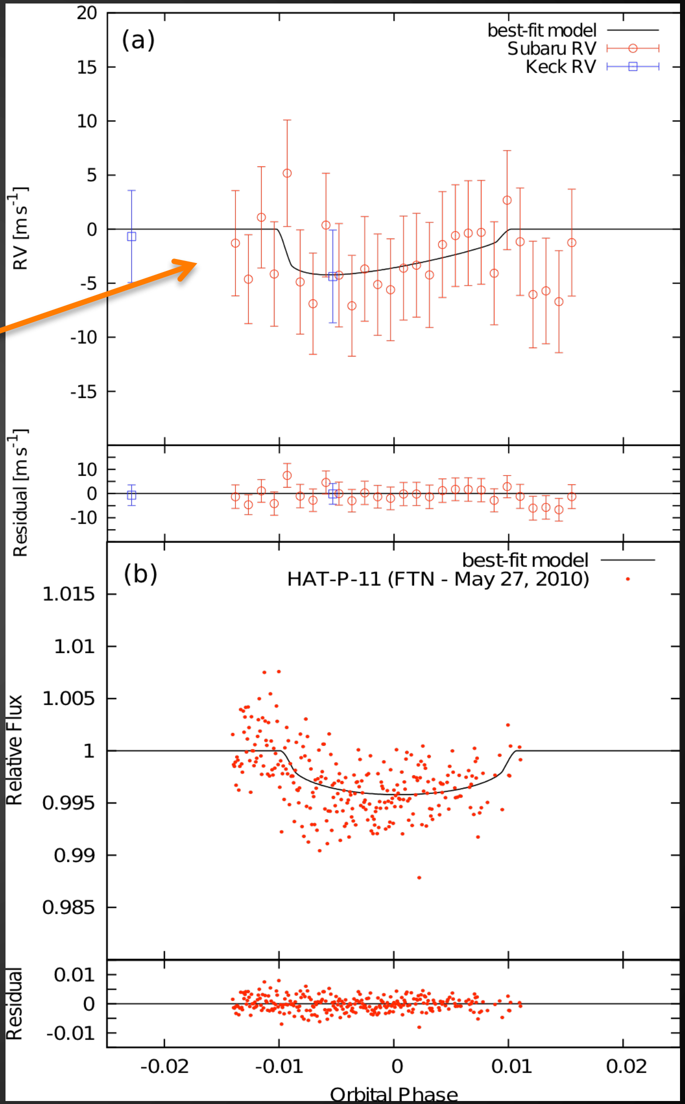
←vertical axis: radial veliocity anomaly during a transit

Through the RM effect, we can estimate the angle between the stellar spin axis and the planetary orbital axis, which is closely related to the planetary migration.



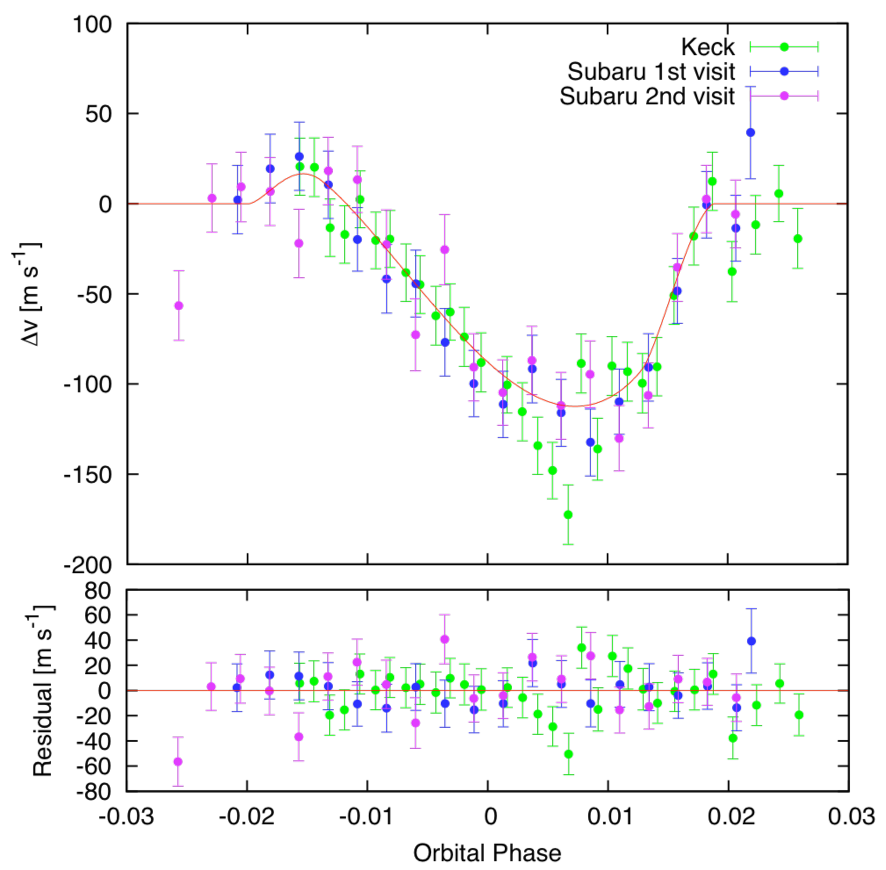
The RM Effect for a Super-Neptune





The detection of the RM effect for a Neptune-sized exoplanet HAT-P-11b → λ = 103° +20° -20° (Hirano + 2011)

Latest Results



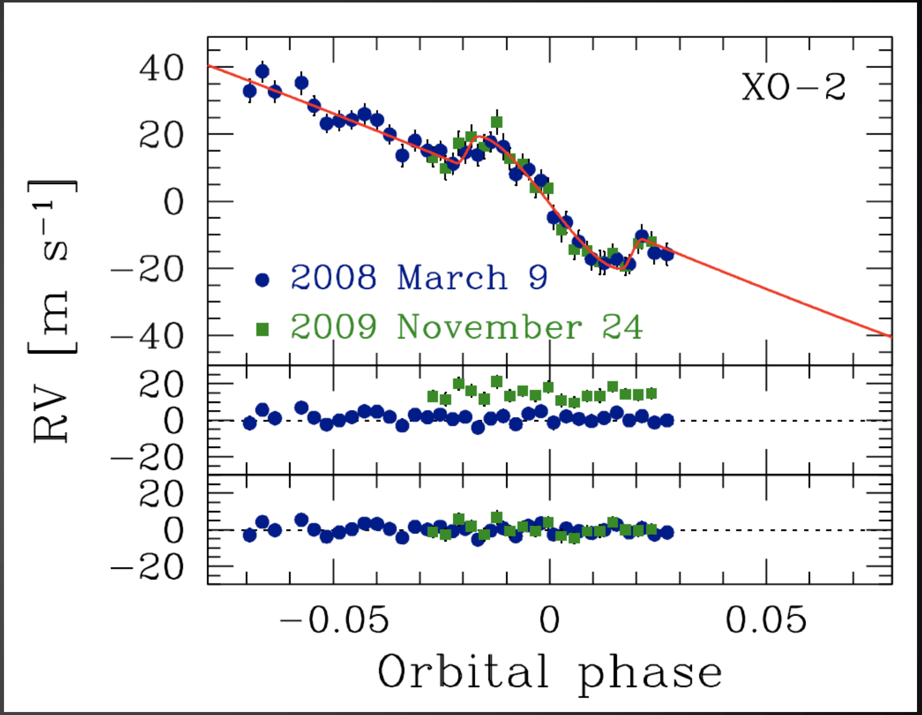
↑ XO-3:

T$_{\text{eff}}$ = 6429 ± 100 K

λ = 37.4° ± 2.2°

*v*sin*i* = 18.4 ± 0.8 km/s

T.H.+ 2011, PASJ



↑ XO-2:

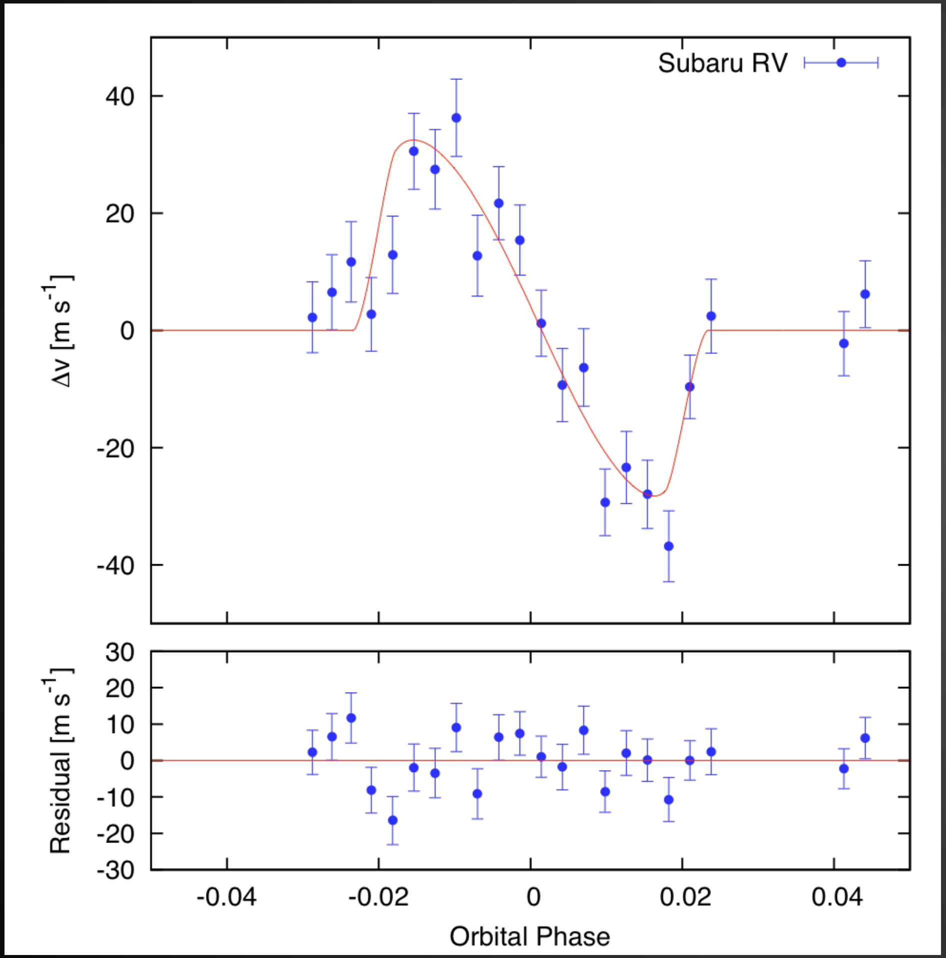
T$_{\text{eff}}$ = 5340 ± 32 K

λ = 10° ± 72°

*v*sin*i* = 1.5 + 2.7 - 0.1 km/s

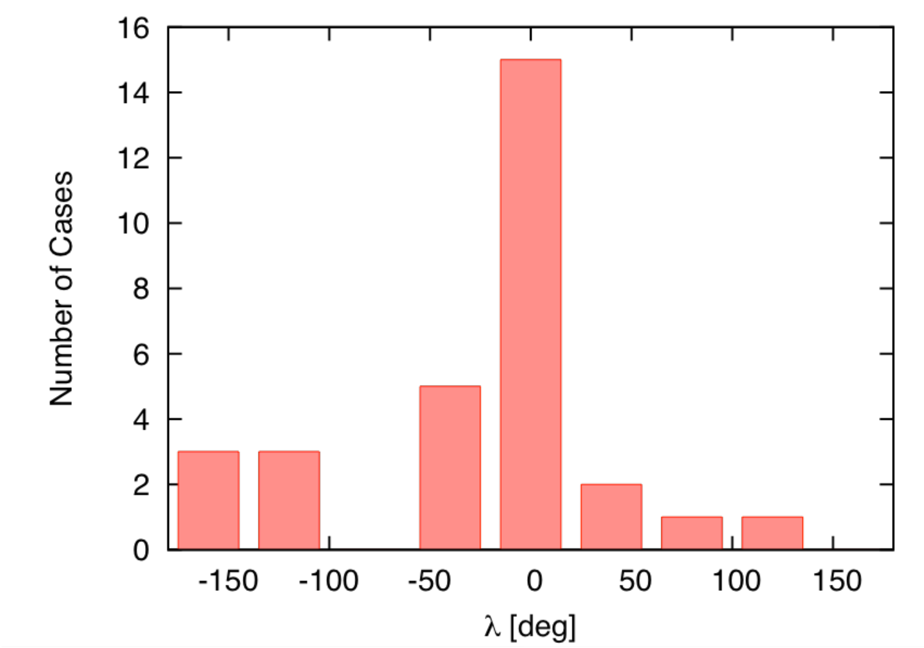
Narita + 2011, PASJ

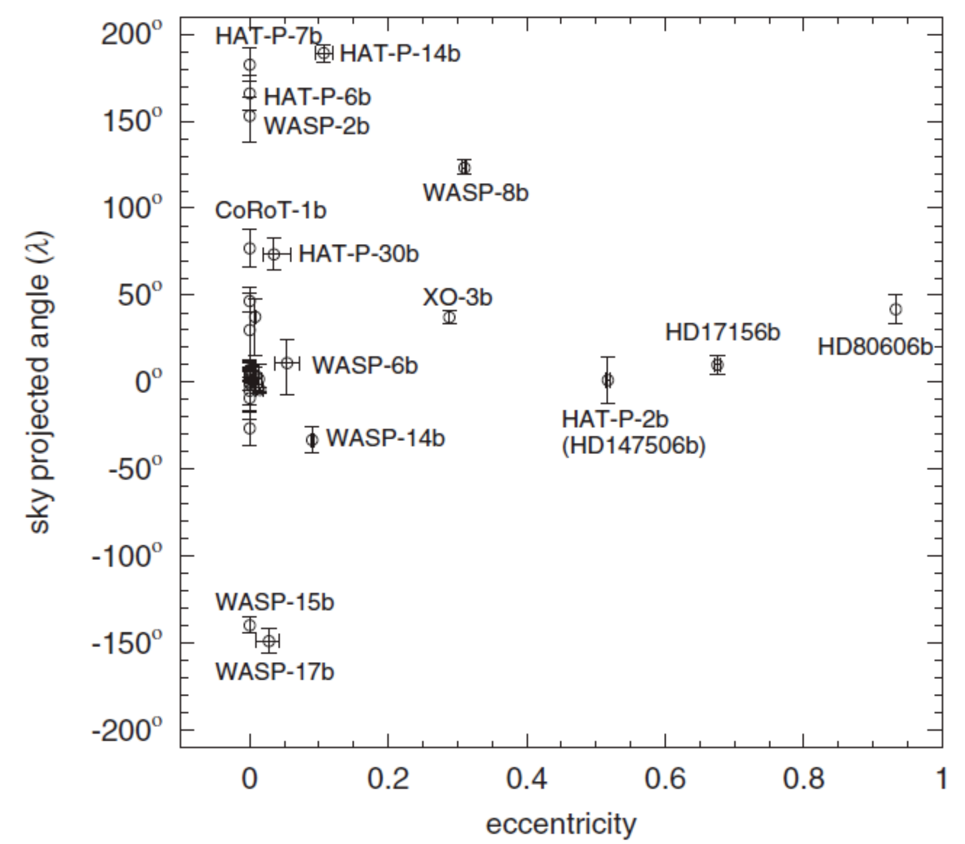
More Latest Results



HAT-P-16:
Teff = 6158 ± 80 K
λ = -8.4° ± 7.0°
*V*sin*I* = *3.9* ± *0.3* km/s
Hirano et al. in prep.

Summary of RM Measurements



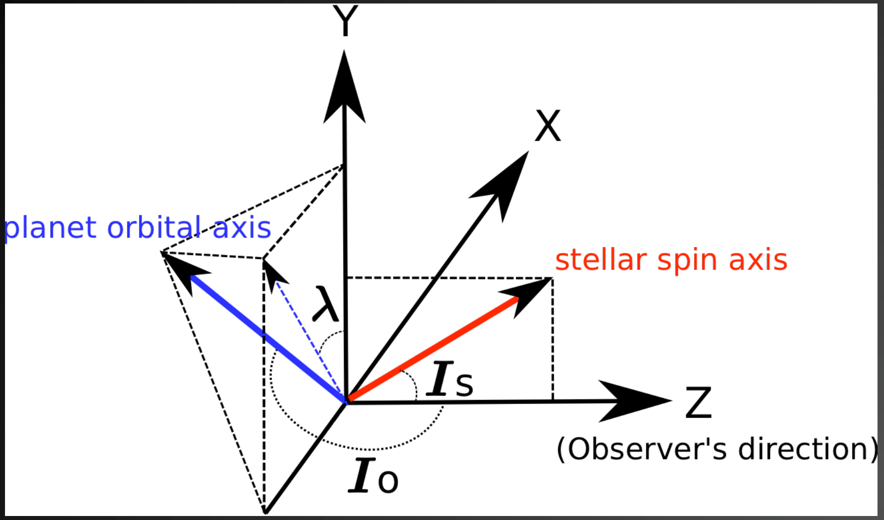


Nagasawa & Ida 2011

1) More than half of the systems show a spin-orbit alignment.
2) Stars with eccentric planets are likely to have significant misalignments.

4. Measurements of Stellar Obliquities along the Line-of-sight

Limitation of the RM Measurements



$$\cos\psi = \sin I_s \cos\lambda \sin I_o + \cos I_s \cos I_o .$$

→ In order to estimate the 3D angle *ψ*, we need to measure the stellar inclination I_s.

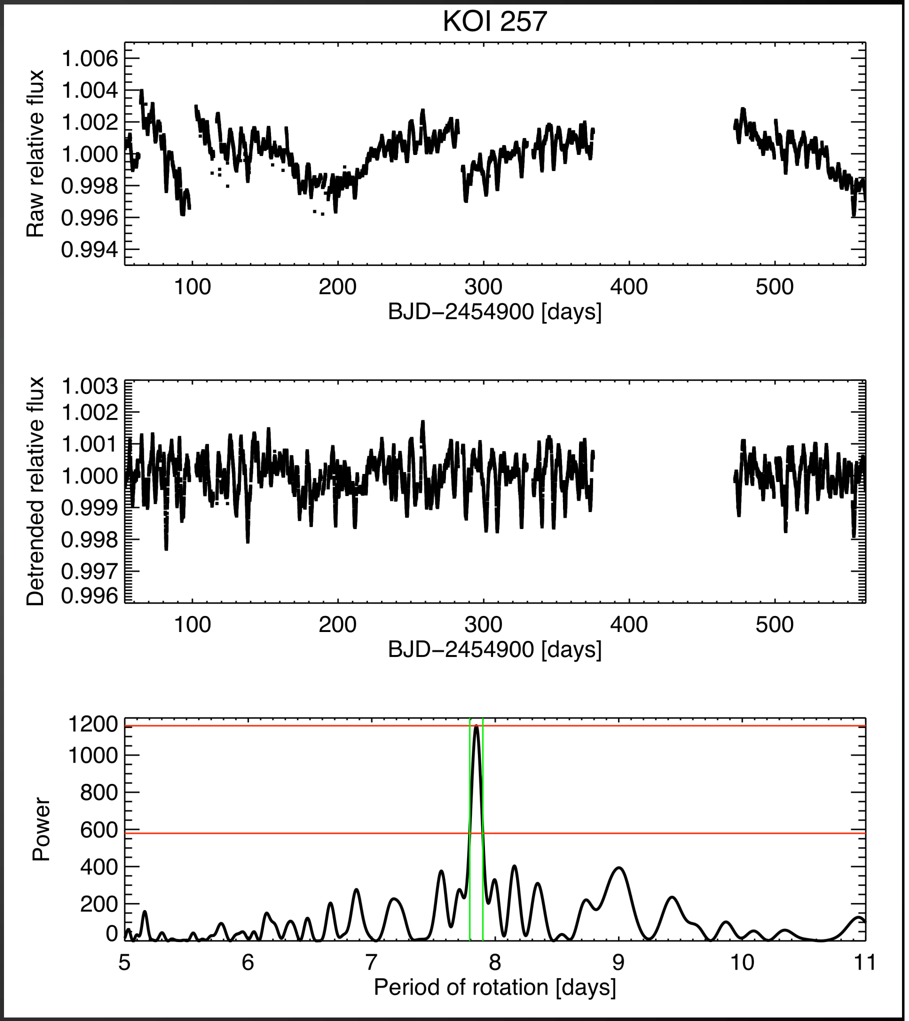
a. The RM measurements have been conducted for systems with hot Jupiters (Neptunes).

b. When the size of the transiting planet becomes small (~ Earth-sized planet), the detection of the RM effect becomes very challenging.

c. In order to confirm or refute possible hypothesis on the planetary migration (and relevant tidal interaction), we need to expand the parameter space for which the RM effect is investigated.

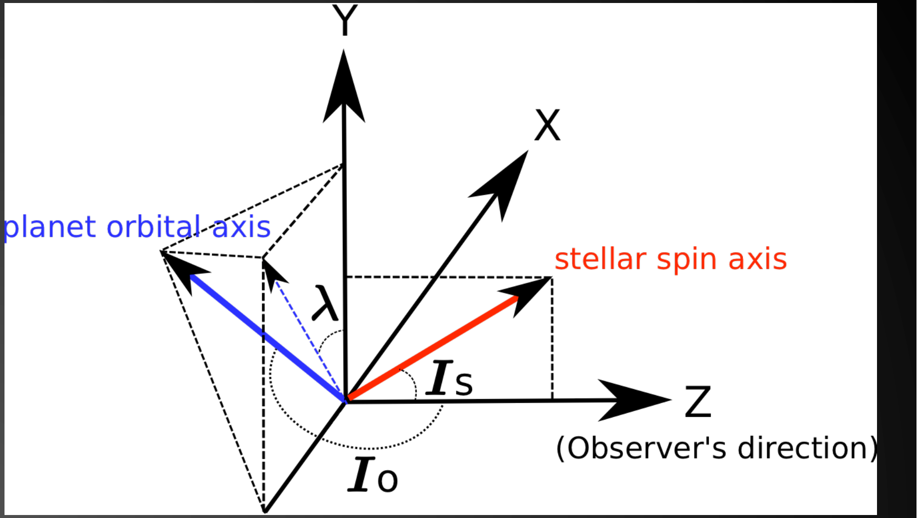
Kepler Ultra-precise Photometry

- ✓ *Kepler* is an ambitious project designed to "determine the frequency of Earth-size planets in and near the habitable zone of solar-type stars".
- ✓ As of today, more than two thousand planetary candidates were announced by the *Kepler* team (Borucki et al. 2010, 2011, Batalha et al. 2012).
- ✓ Some of the light-curves taken by *Kepler* show periodic flux variations due to rotation of stellar spots.



Estimation of Stellar Inclinations by Starspots

$$I_s = \arcsin\left\{\frac{P_s(V\sin I_s)_{\rm spec}}{2\pi R_s}\right\}$$



✓ The rotational period P_s of the host star is estimated by *Kepler* photometry.

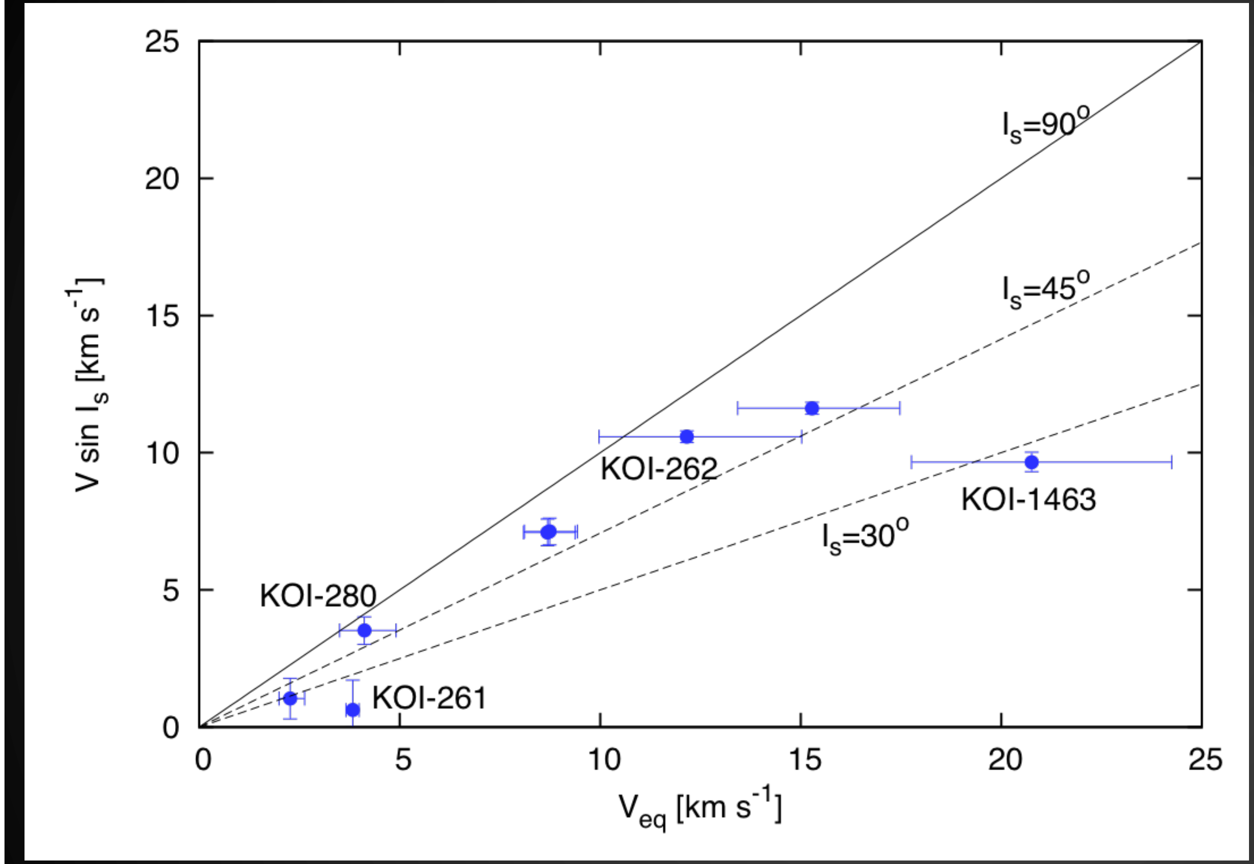
✓ The projected rotational velocity ($V\sin I_s$) and stellar radius are estimated by spectroscopy.

We can estimate stellar inclination I_s.

a. Since the orbital inclination of a transiting exoplanet is close to 90°, a small value of I_s implies a spin-orbit misalignment.

b. This method can be applied regardless of the size of the planet, enabling us to discuss spin-orbit alignment/misalignment for smaller exoplanets.

Preliminary Result



x axis -> rotational velocities estimated by Kepler photometry

y axis -> projected rotational velocities estimated by spectroscopy

Solid line indicates $V_{eq} = V \sin I_s$.

KOI-261 and KOI-1463 may have possible spin-orbit misalignments along the line-of-sight.

Conclusion and Summary

- ✓ Observations of the RM effect have yielded unexpected relation between stellar spin axis and planetary orbital axis. The dependence of the stellar obliquities on host stars' properties (e.g. $T_{\rm eff}$ or age) are also intriguing.

- ✓ Combination of *Kepler* ultra-precise photometry and spectroscopic observations enables us to estimate the spin-orbit relation along the line-of-sight.

- ✓ Further measurements of the stellar obliquities with a wide range of stellar and planetary parameters are required in order to confirm or refute the possible migration scenarios and relevant tidal interaction between the planet and its host star.

Thank you for your attention!