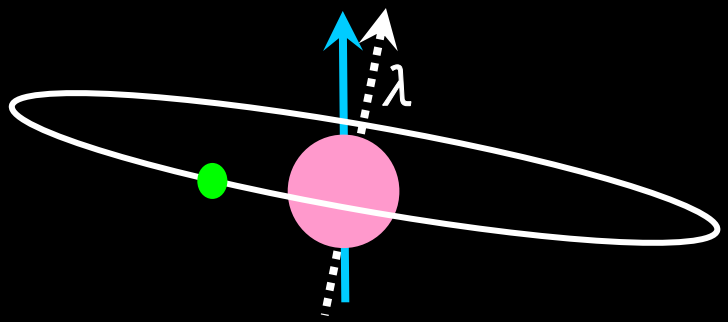
Unveiling orbits of transiting exoplanets with the Rossiter-McLaughlin effect

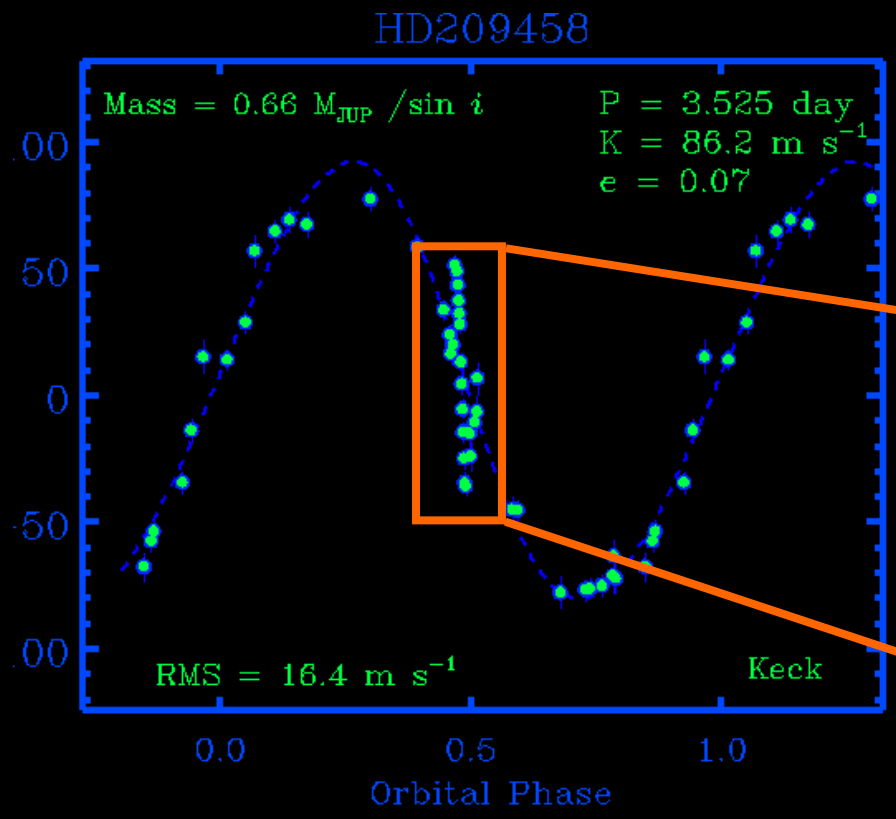


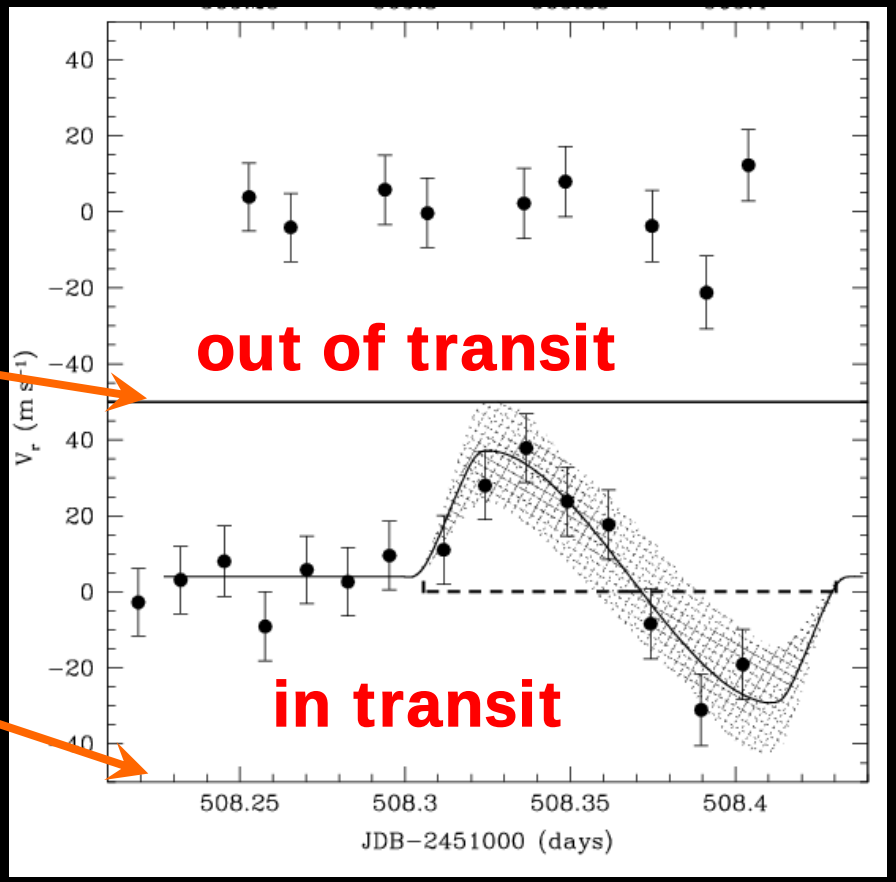
Yasushi Suto

Department of Physics, the University of Tokyo & Global Scholar, Department of Astrophysical Sciences, Princeton University

planet group talk @Peyton, November 30, 2009

the Rossiter-McLaughlin effect for an extrasolar transit planetary system HD209458

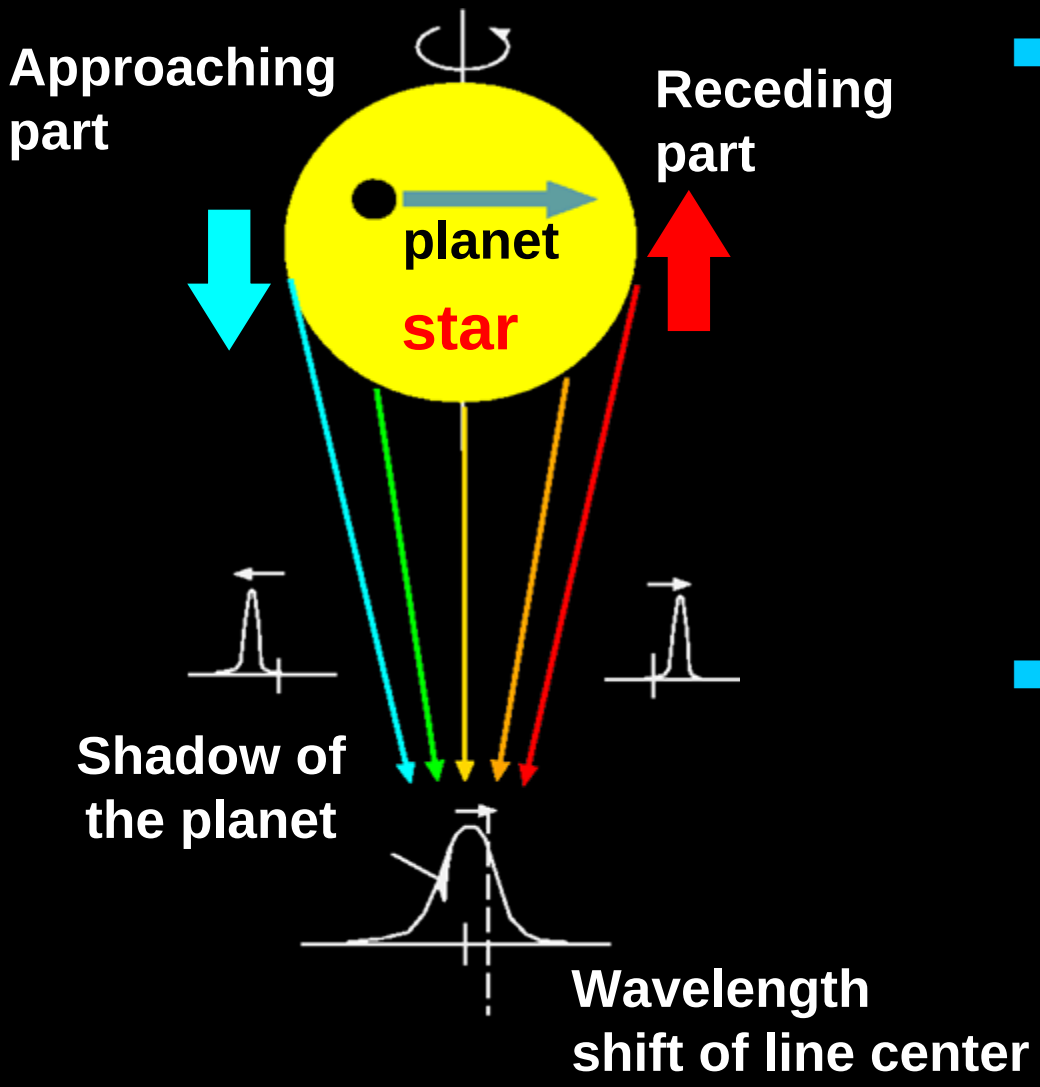




HD209458 radial velocity data
http://exoplanets.org/

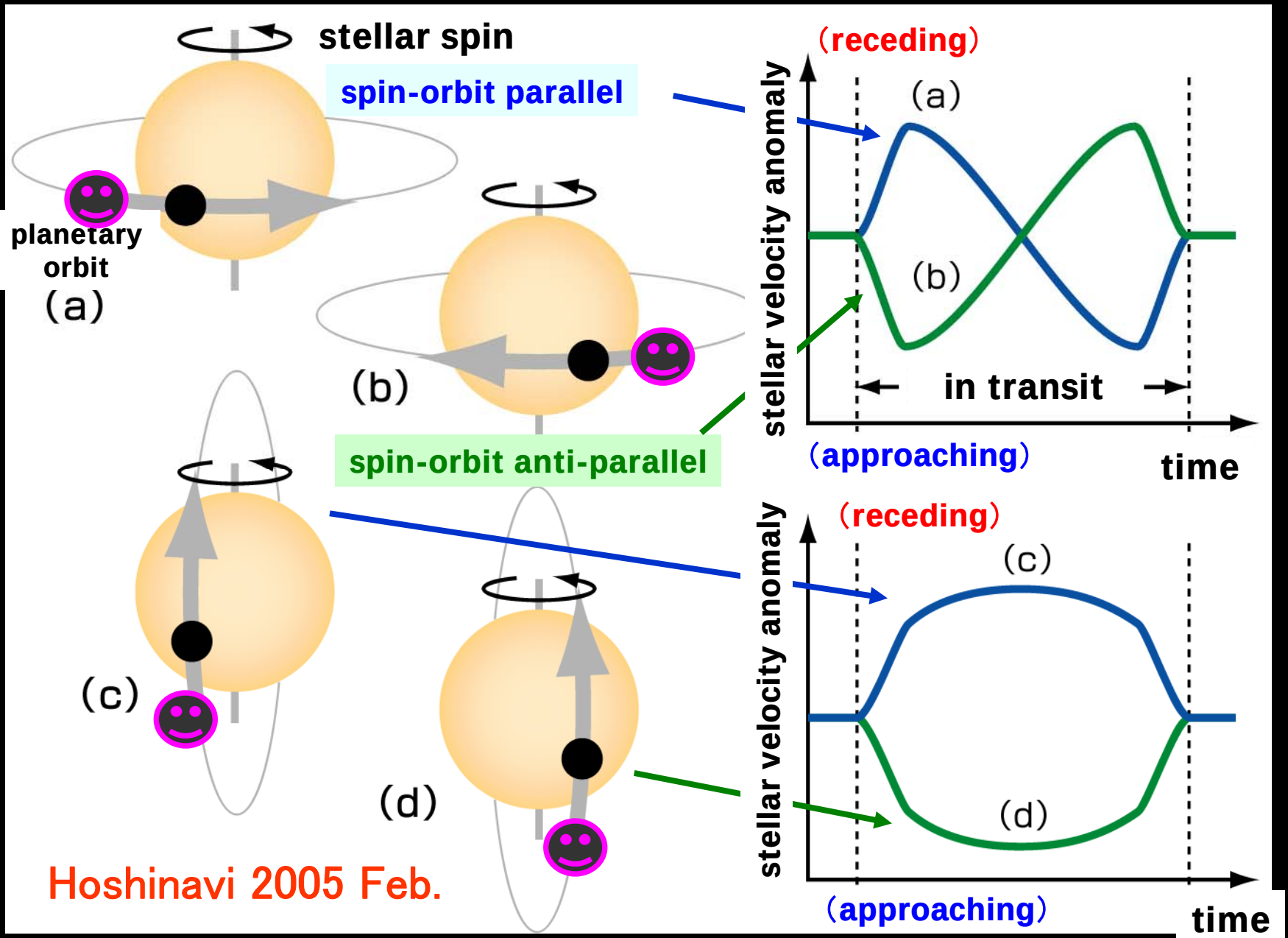
Stellar rotation and planetary orbit
Queloz et al. (2000) A&A 359, L13
ELODIE on 193cm telescope

Spectroscopic transit signature: the Rossiter-McLaughlin effect



- Time-dependent asymmetry in the stellar Doppler broadened line profile
  - an apparent anomaly of the stellar radial velocity
- originally discussed in eclipsing binary systems
  - Rossiter (1924)
  - McLaughlin (1924)

Velocity anomaly due to the Rossiter effect

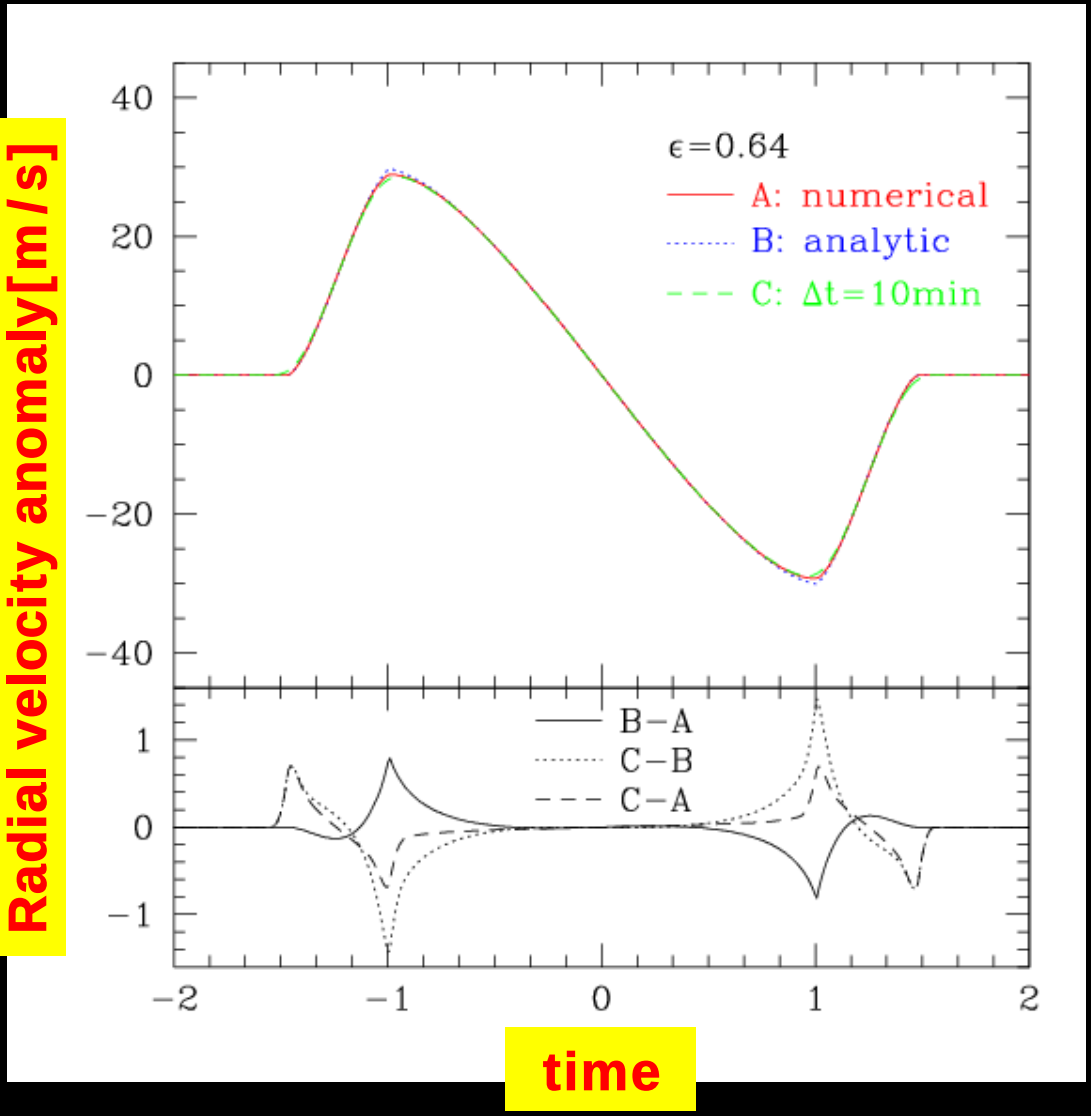


Analytic templates for the velocity anomaly due to the Rossiter -McLaughlin effect

Limb darkening:
$B = 1 - \varepsilon (1 - \cos\theta)$

- perturbation theory
- 1st moment of absorption line profiles (stellar + planet)

Ohta, Taruya & Suto:
ApJ 622(2005)1118



THE ASTROPHYSICAL JOURNAL, 622:1118–1135, 2005 April 1

Ohta, Taruya & Suto: ApJ 622(2005)1118

THE ROSSITER-McLAUGHLIN EFFECT AND ANALYTIC RADIAL VELOCITY CURVES FOR TRANSITING EXTRASOLAR PLANETARY SYSTEMS

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Received 2004 October 13; accepted 2004 December 10

Among the recently discovered transiting extrasolar planetary systems, i.e., TrES-1 by the Trans-Atlantic Exoplanet Survey (Alonso et al. 2004) and OGLE-TR 10, 56, 111, 113, 132 by the Optically Gravitational Lens Event survey (e.g., Udalski et al. 2002c, 2002b, 2002a, 2003; Konacki et al. 2003; Bouchy et al. 2004; Pont et al. 2004), TrES-1 has similar orbital period and mass to those of HD 209458b, but its radius is smaller. Thus, it is an interesting target to determine the spin parameters via the RM effect; if its planetary orbit and the stellar rotation share the same direction as discovered for the HD 209458 system, it would be an important confirmation of the current view of planet formation out of the protoplanetary disk surrounding the protostar. If not, the result would be more exciting and even challenge the standard view, depending on the value of the misalignment angle λ.

We also note that the future satellites *COROT* and *Kepler* will detect numerous transiting planetary systems, most of which will be important targets for the RM effect in 8–10 m class ground-based telescopes. We hope that our analytic formulae presented here will be a useful template in estimating parameters for those stellar and planetary systems.

In conclusion, we have demonstrated that the radial velocity anomaly due to the RM effect provides a reliable estimation of spin parameters. Combining data with the analytic formulae for radial velocity shift Δv_s, this methodology becomes a powerful tool in extracting information on the formation and the evolution of extrasolar planetary systems, especially the origin of their angular momentum. Although it is unlikely, we may even speculate that a future RM observation may discover an extrasolar planetary system in which the stellar spin and the planetary orbital axes are antiparallel or orthogonal. This would have a great impact on the planetary formation scenario, which would have to invoke an additional effect from possible other planets in the system during the migration or the capture of a free-floating planet. While it is premature to discuss such extreme possibilities at this point, the observational exploration of transiting systems using the RM effect is one of the most important probes for a better understanding of the origin of extrasolar planets.

Indeed my motivation was to find a retrograde planet !

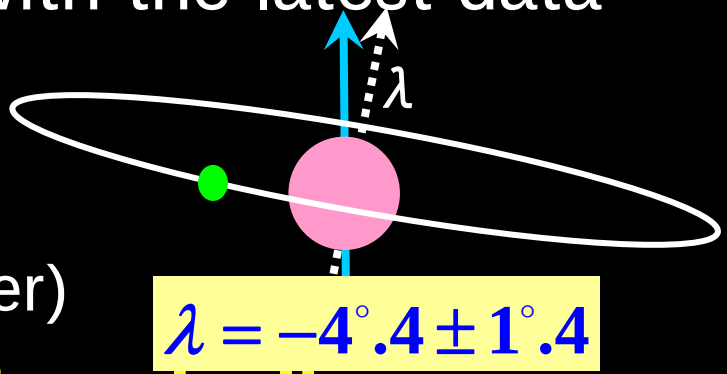
Measurement of Spin-Orbit alignment in an Extrasolar Planetary System

- **Joshua N. Winn (MIT)**, R.W. Noyes, M.J. Holman, D.B. Charbonneau, Y. Ohta, A. Taruya, Y. Suto, N. Narita, E.L. Turner, J.A. Johnson, G.W. Marcy, R.P. Butler, & S.S. Vogt

- ApJ 631(2005)1215 (astro-ph/0504555)

Precision analysis of the Rossiter-McLaughlin effect for HD209458

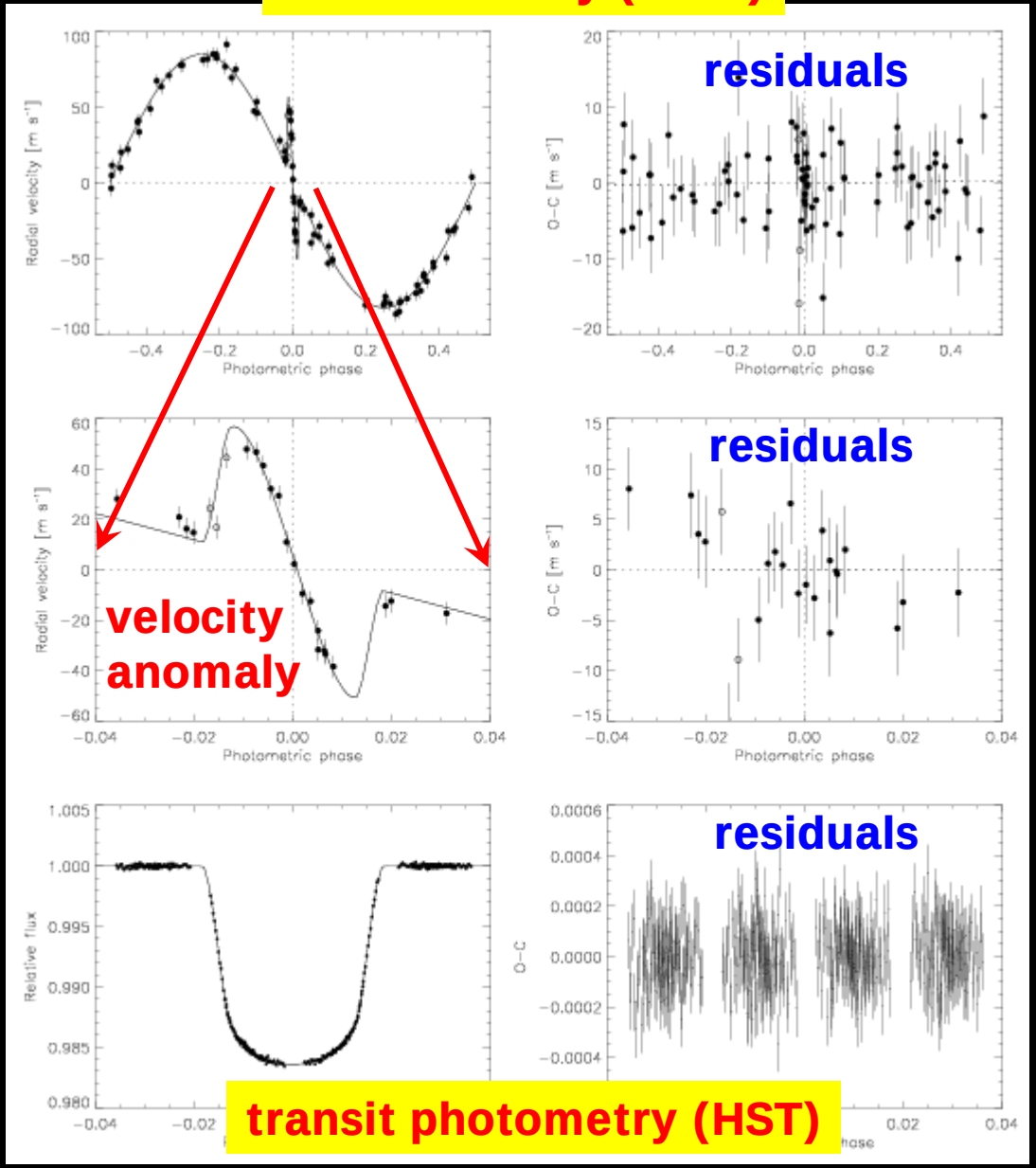
- Modified the formula of Ohta et al. (2005)
- HD209458 re-examined with the latest data
  - radial velocity data (Keck)
  - optical photometry (HST)
  - infrared photometry (Spitzer)



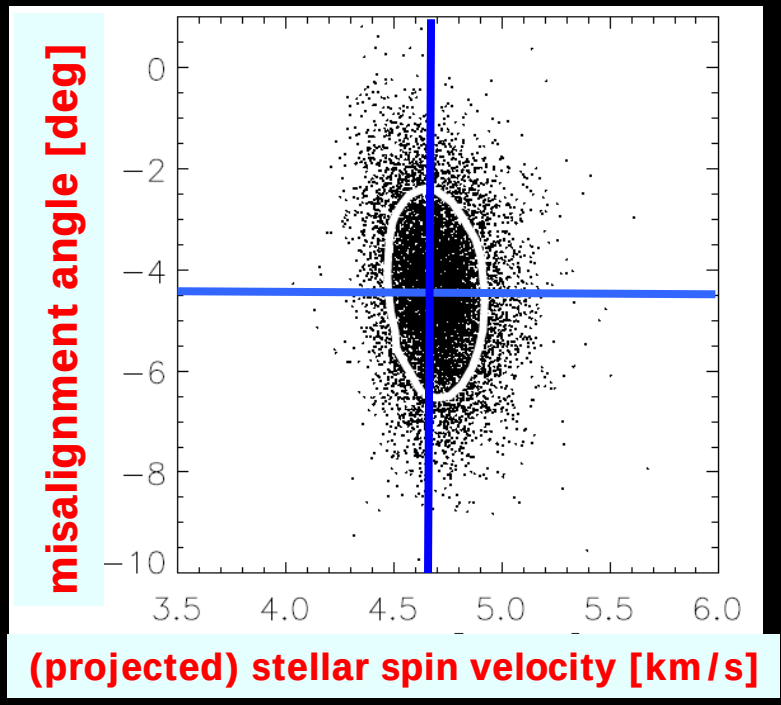
$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$

- **the first detection of the misalignment between the stellar spin and the planetary orbital axes by (−4.4±1.4)deg**
  - more than an order-of-magnitude improvement of the previous error-bar (maybe useless but impressive result !)
  - c.f., 6 degree misalignment for the Solar system

radial velocity (Keck)



first detection of non-zero λ !

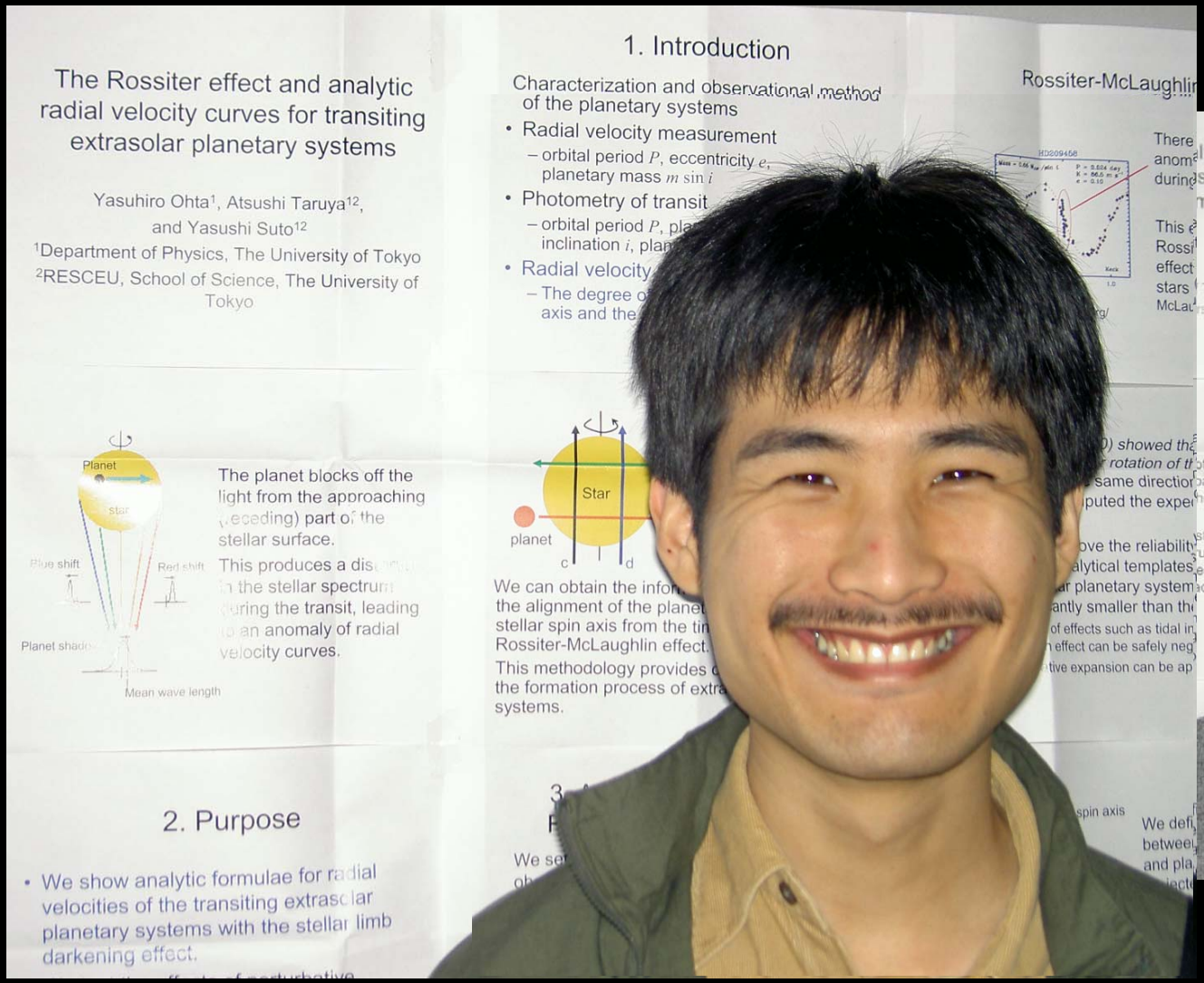


$$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$$

3 σ detection !

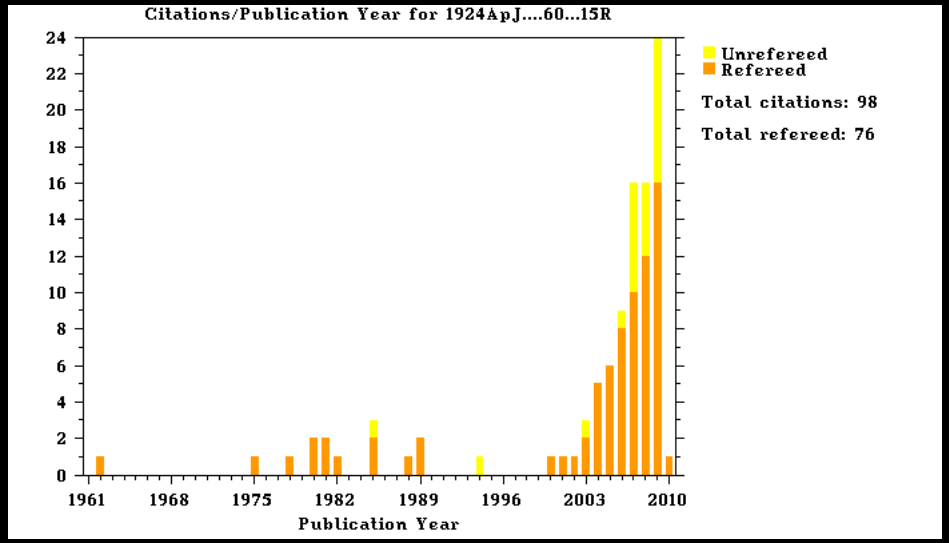
Winn et al. astro-ph/0504555 ApJ 631(2005)1215

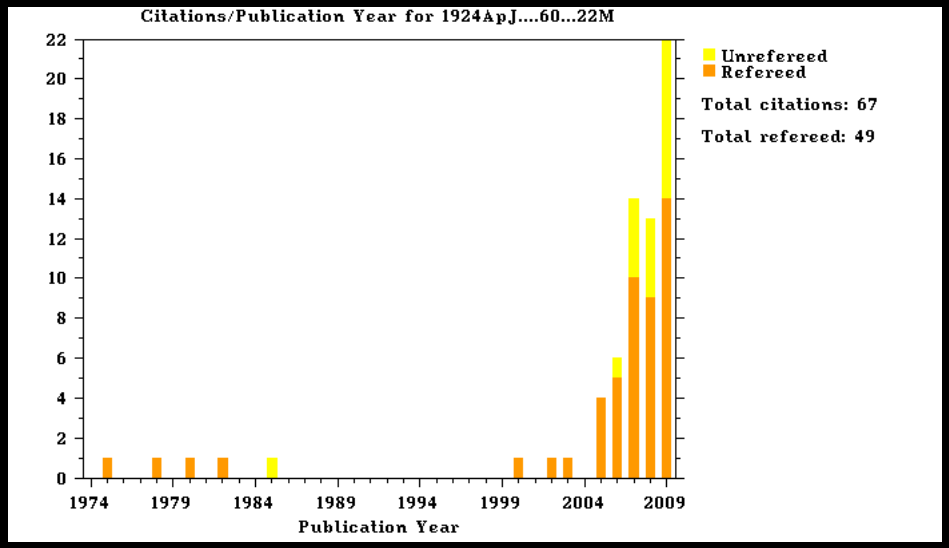
Collaborators: Y.Ohta + A.Taruya



Citation history of the RM papers

R.A. Rossiter
ApJ 60(1924)15





D.B. McLaughlin
ApJ 60(1924)22

Digression: EPR “paradox”

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

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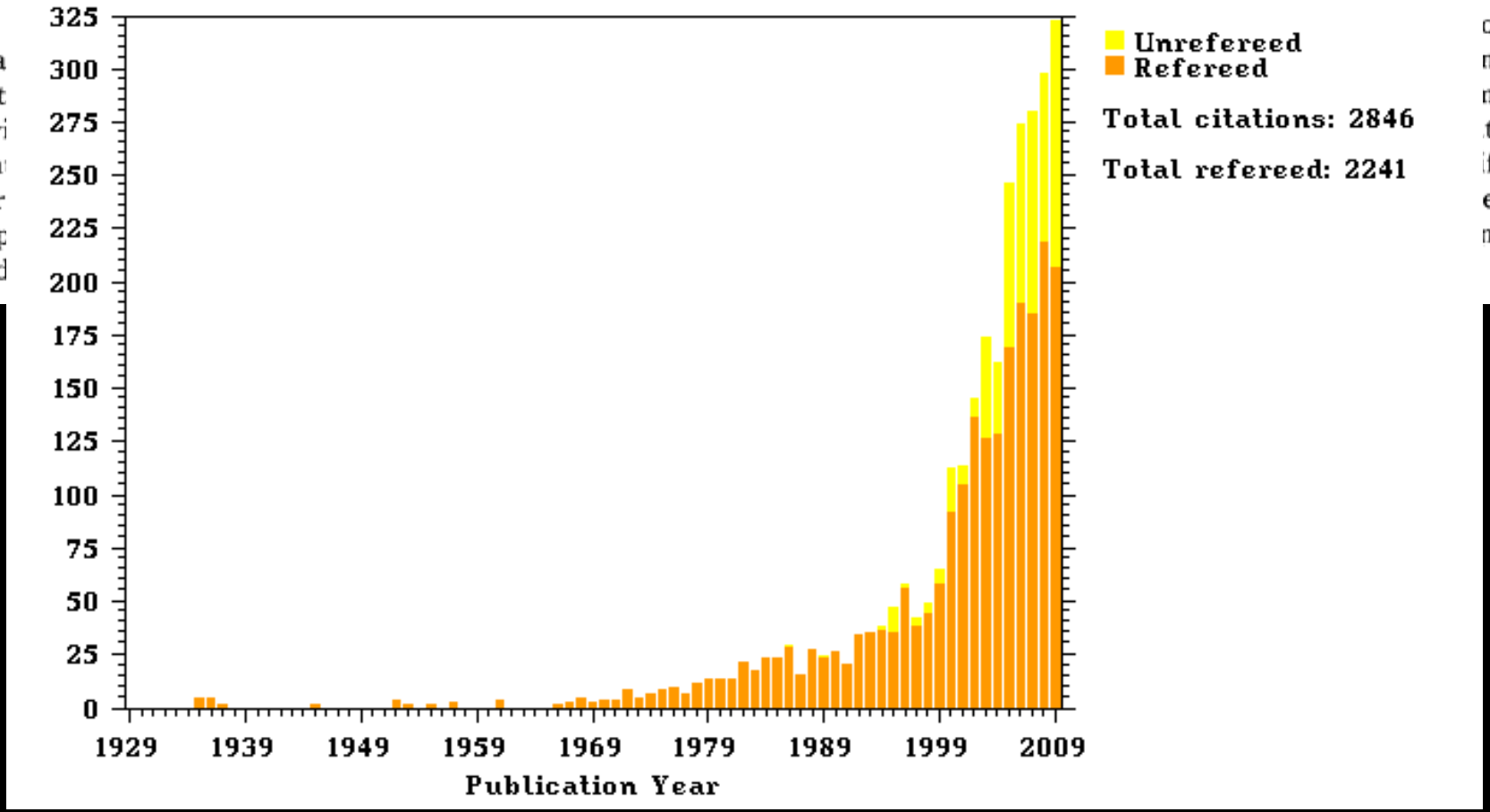
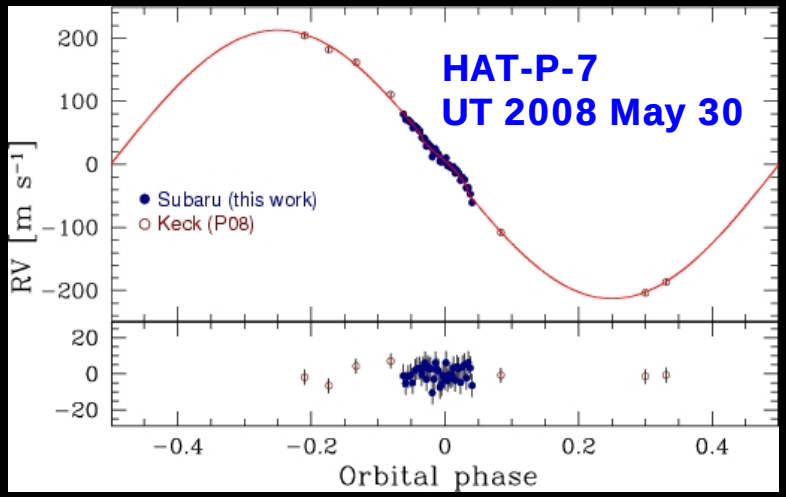
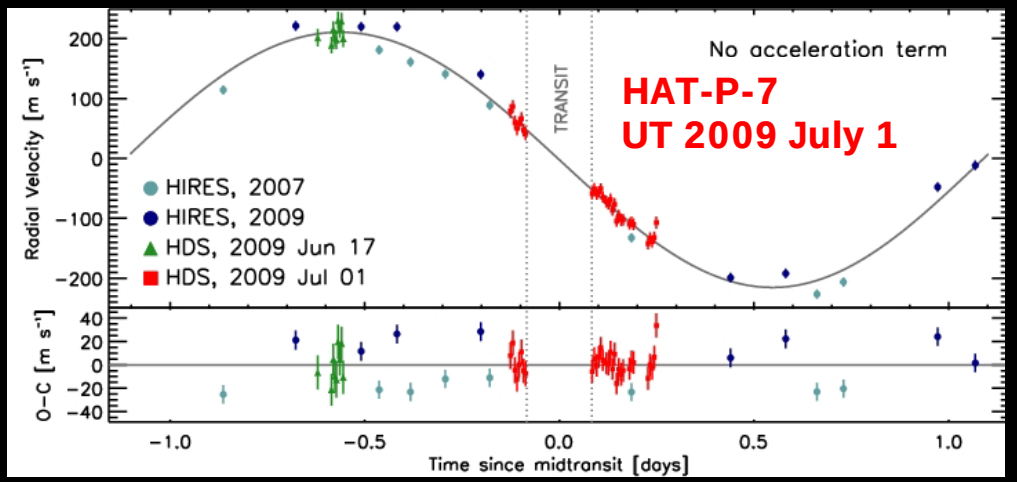
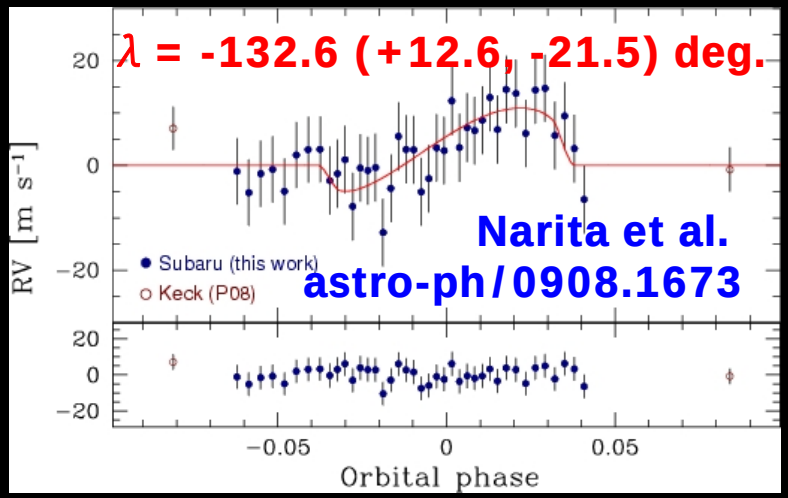
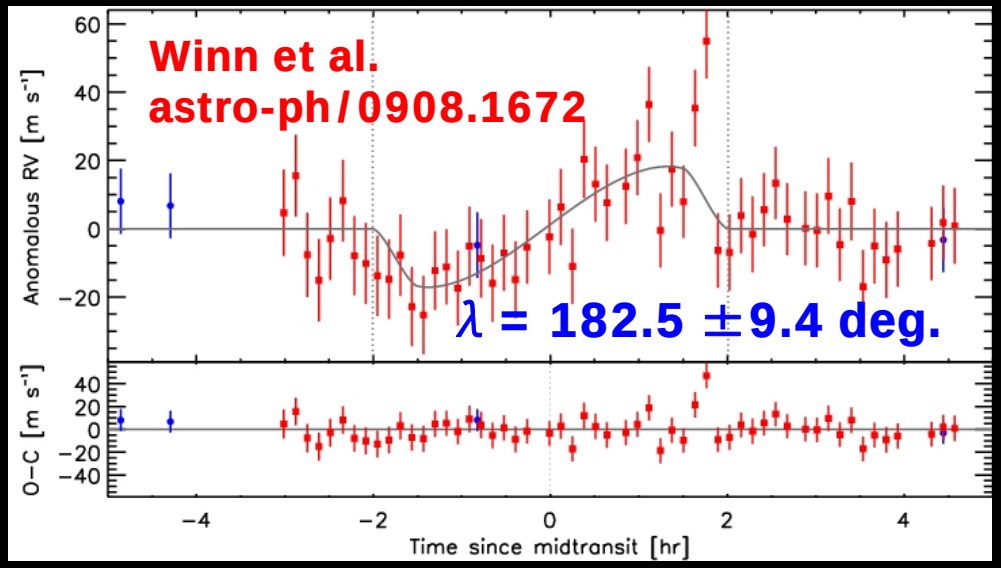


Discovery of a retrograde orbit of HAT-P-7 with Subaru via the RM effect









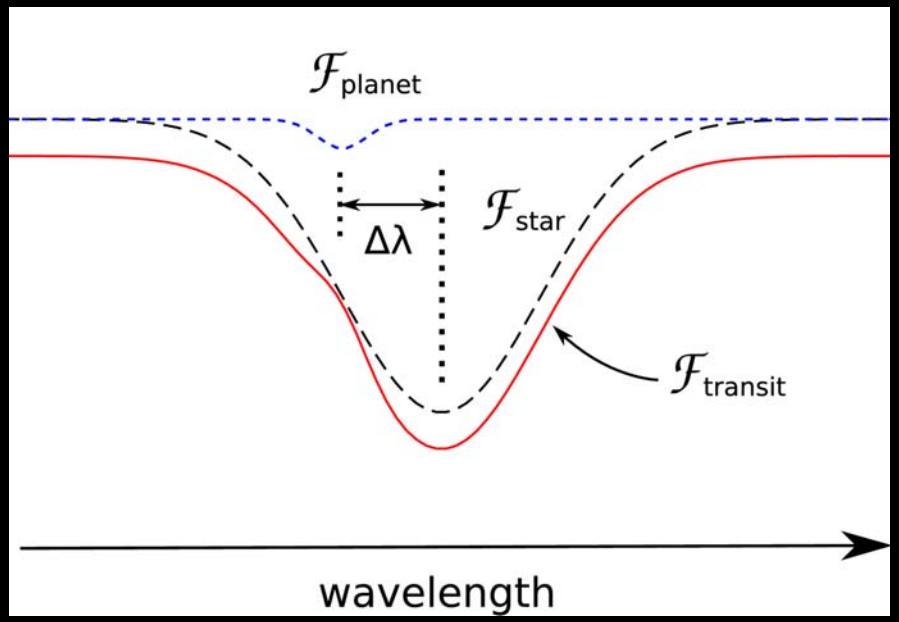
- Origin of the retrograde orbit is **unknown**

Toward a more accurate analytic template for the RM effect

- Bias in the amplitude of the velocity anomaly ?
  - Winn et al. (2005) found that the OTS formula systematically underpredicts the velocity anomaly by ∼20% compared with the output Keck analysis routine of mock data for HD209458.
  - Johnson et al. (2008) and Winn et al. (2008) did not find any systematic bias for HAT-P-1 and TrES-2.
- Real analysis routines do not use the simple moment method as OTS adopted.
  - The moment method does not depend on the stellar absorption line width.

New analytic template using the cross-correlation method

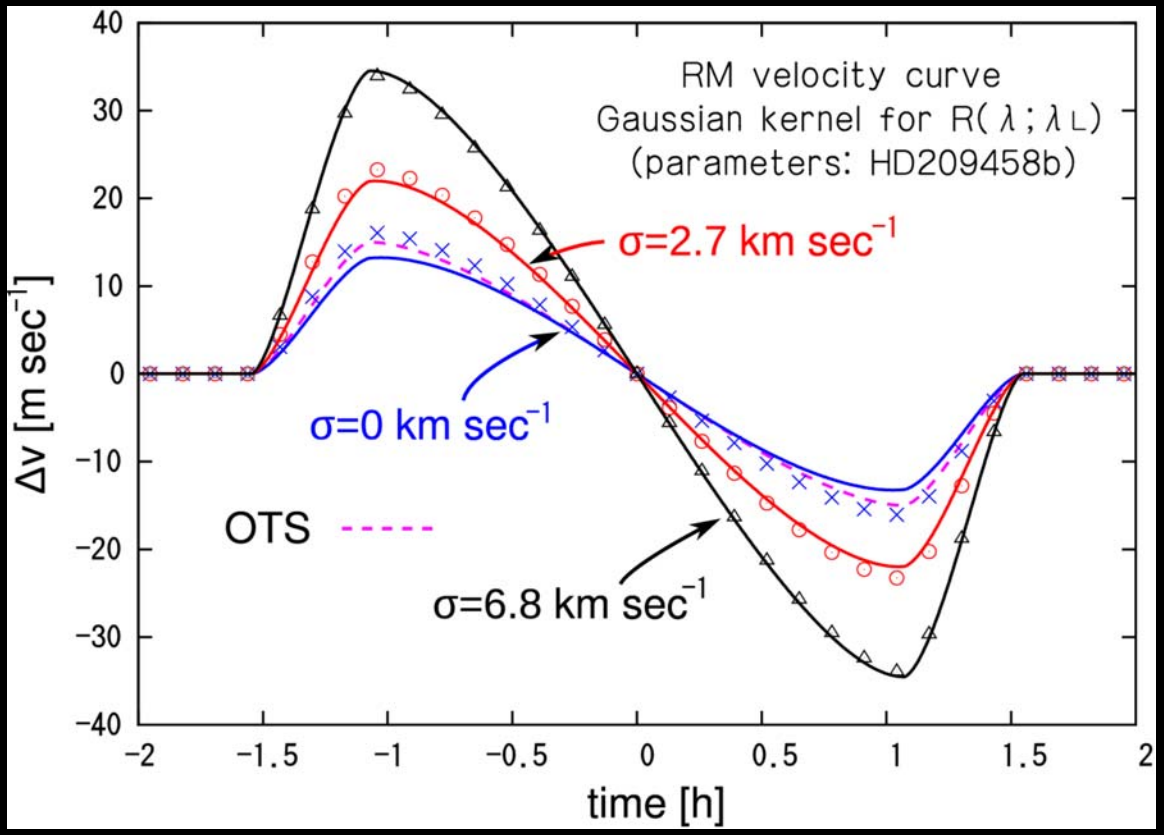
- Find the shift $\Delta\lambda$ which minimizes the cross-correlation function: dC/dx=0



$$C(x) = \int_{-\infty}^{\infty} F_{star}(\lambda - x) F_{transit}(\lambda) d\lambda$$

Hirano, Suto, Taruya, Narita, Sato, Johnson & Winn, ApJ (2010) in press, arXiv:0910.2365

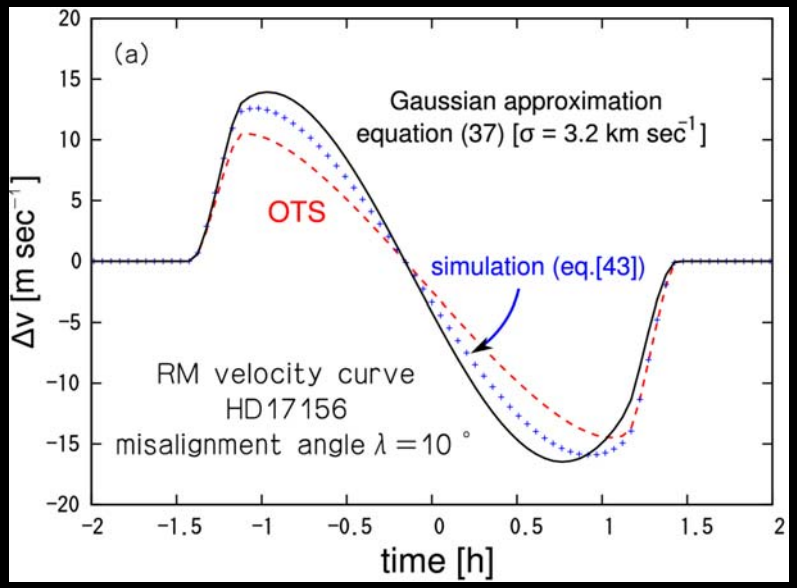
Dependence on the stellar line width (effect of rotation broadening)

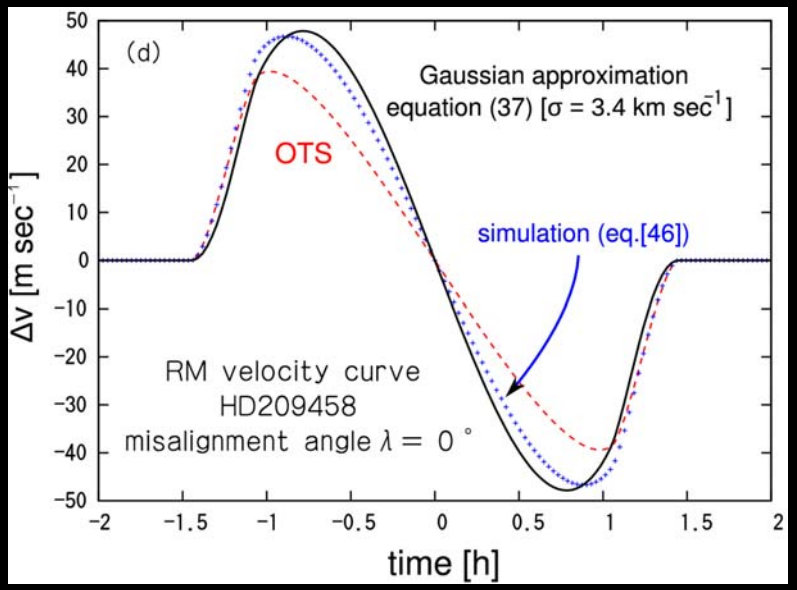


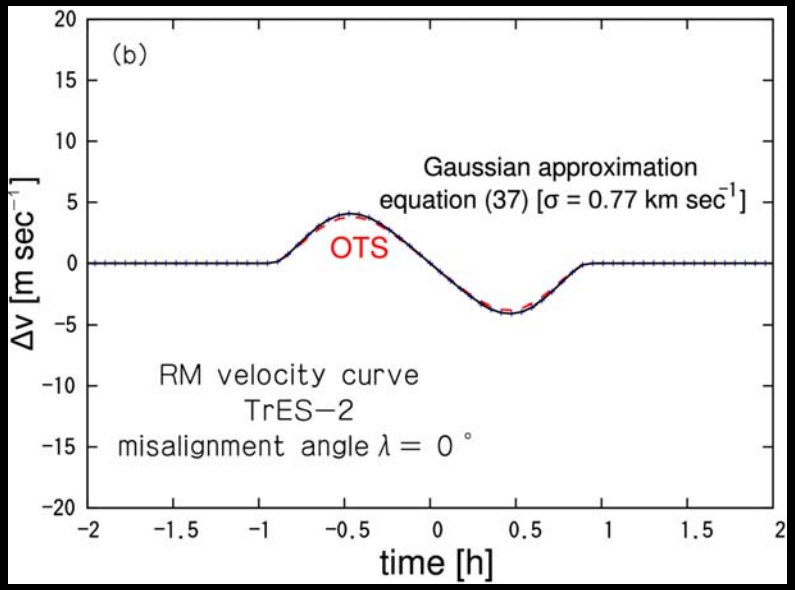
- Parameters for the HD209458 system
- Approximate the line by Gaussian
- Three different values assumed for the Gaussian width

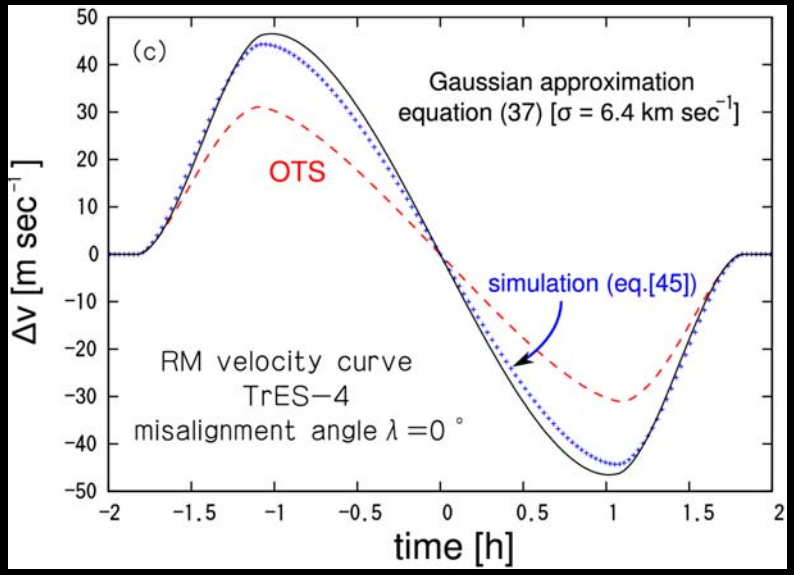
Hirano et al. ApJ (2010) in press, arXiv:0910.2365

Application to existing exoplanets







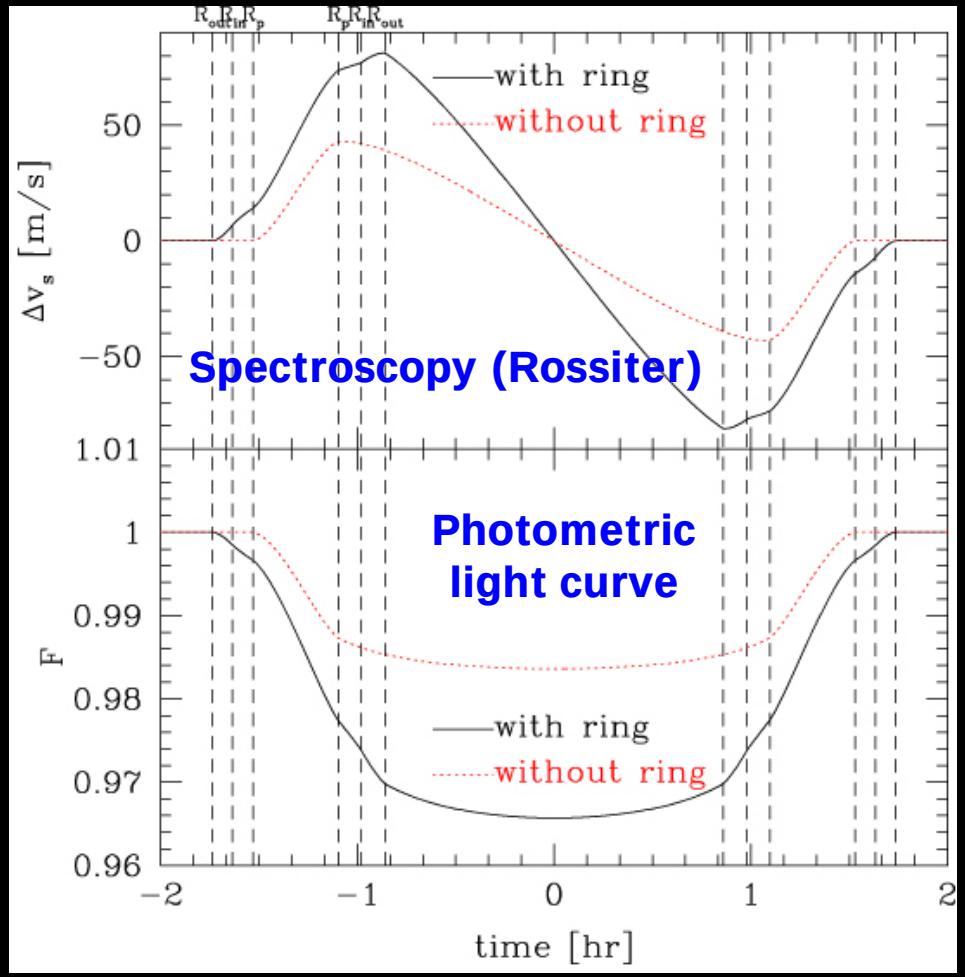


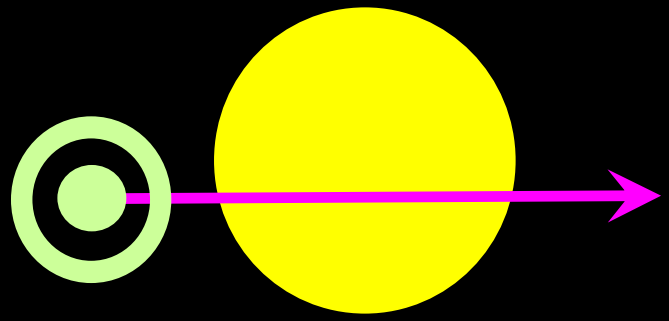
Hirano et al. ApJ (2010) in press, arXiv:0910.2365

Lessons that we learned

- Quantitative interpretation of the RM velocity anomaly has to be done carefully
  - Outputs from specific analysis routines (usually a black box for end users) have to be interpreted in terms of the same modeling
  - In particular, estimate of the RM velocity anomaly, and therefore of the stellar spin rotation velocity is sensitive to the model of line profile (Gaussian approximation is reasonably good, but not perfect in some cases)
  - Misalignment angle λ is fairly robust against the details of the modeling
- What is the physics behind the retrograde planet formation ?

Signatures of planetary rings ?

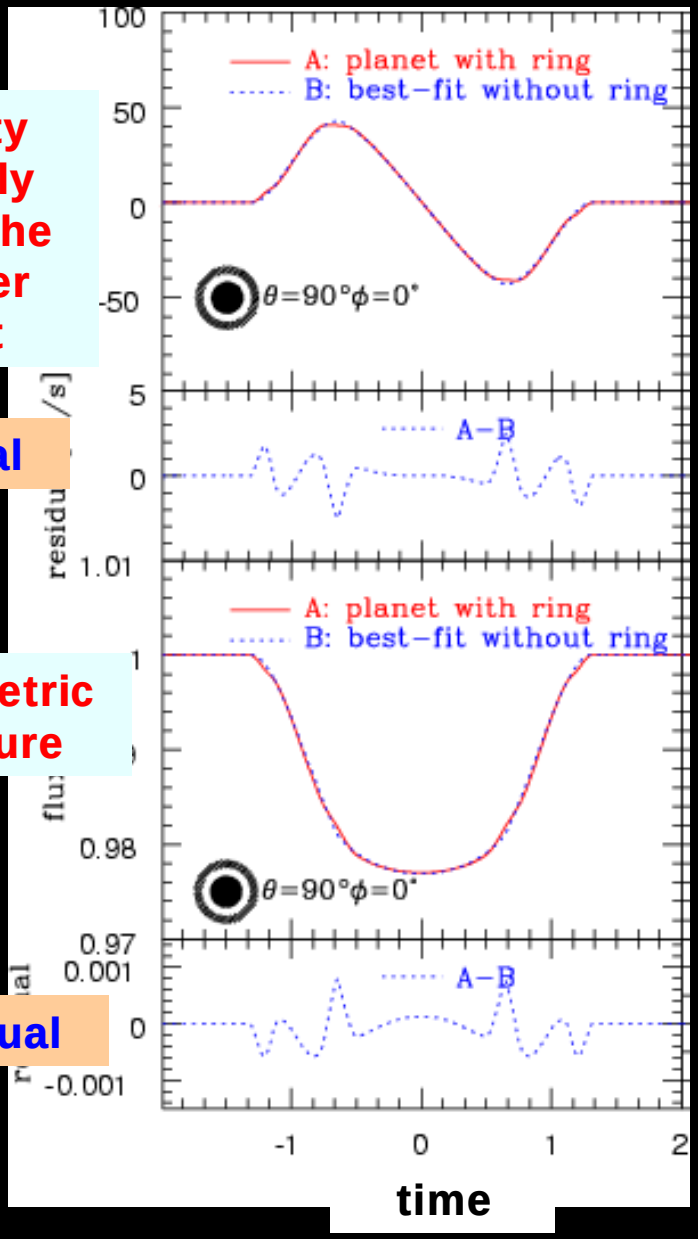




- Ring's inner and outer radii, gap, planet's radius imprints strong features in the photometric and spectroscopic data
- Statistical analysis of the residuals with respect to the best-fit ringless model

Ohta, Taruya & Suto: ApJ 690(2009)1

Detectability of a ring



Velocity anomaly due to the Rossiter effect

residual

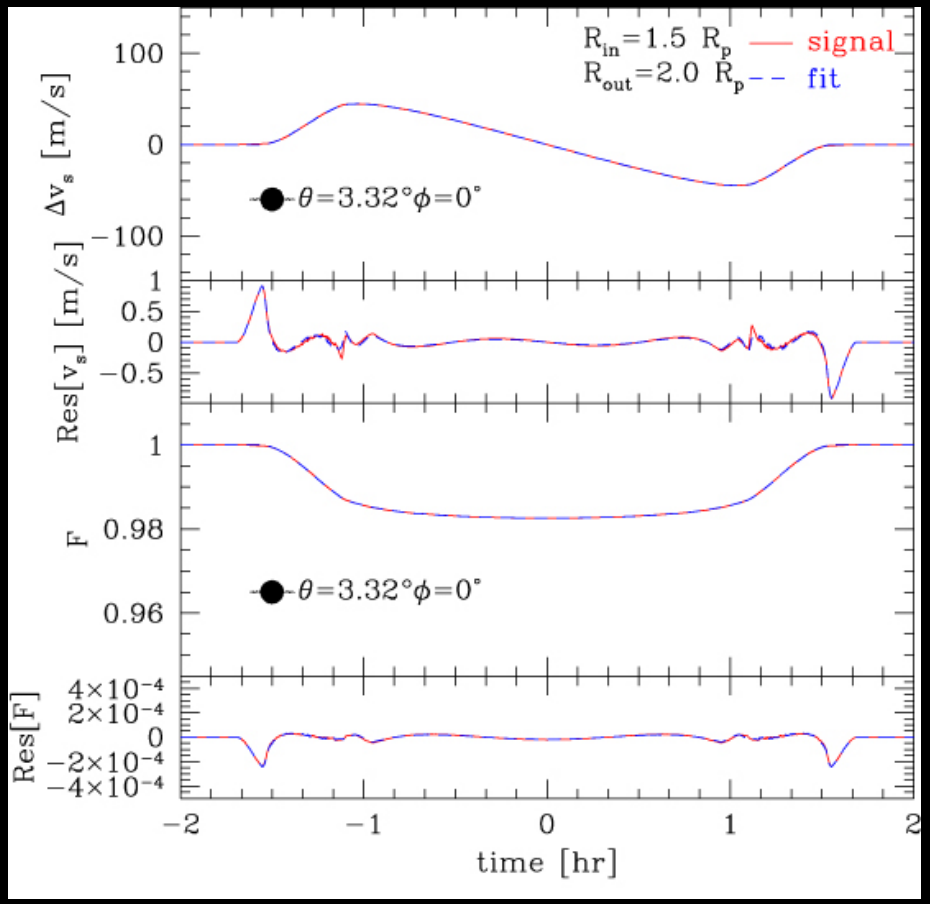
Photometric signature

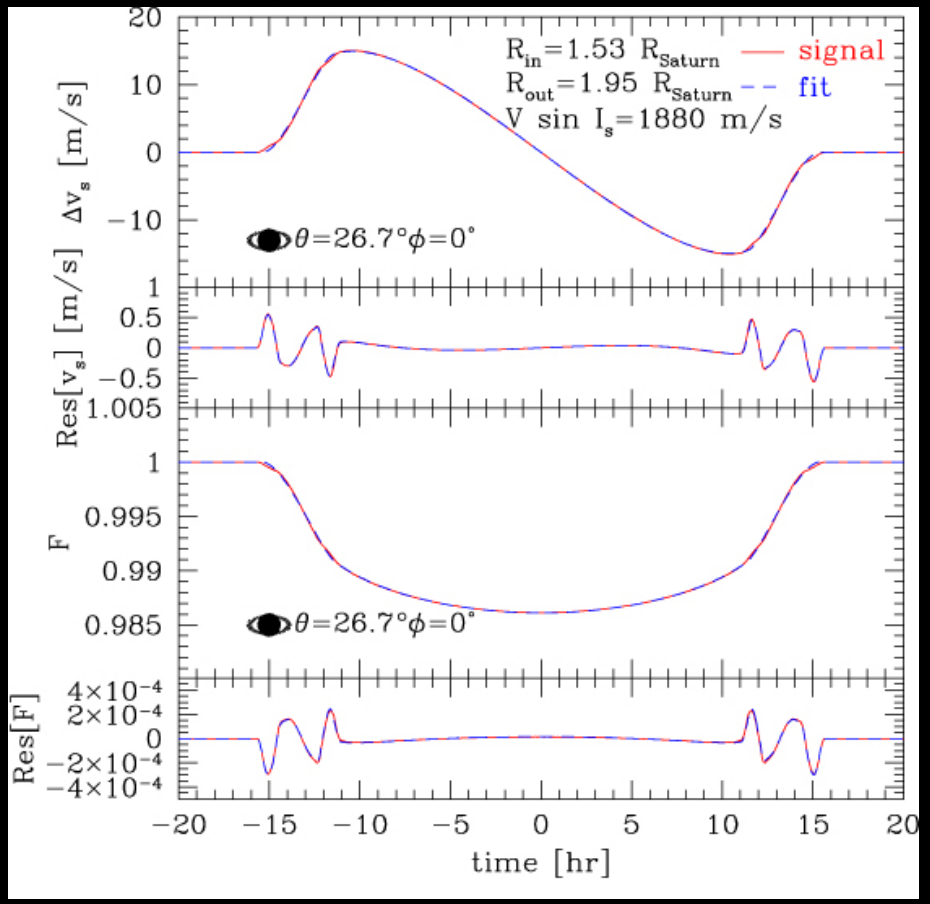
residual

- **a hypothetical ring around HD209458**
  - $1.5R_{pl} < R_{ring} < 2R_{pl}$
  - deviation from a best-fit single planet
  - $\delta v \sim 1 m/s$
  - $\delta F/F \sim 0.1\%$
- **marginally detectable level even with the current technology**

Ohta, Taruya & Suto: ApJ 690(2009)1

How about hot Jupiter and Saturn rings ?





Ohta, Taruya & Suto: ApJ 690(2009)1

- **Hot Jupiter: edge-on rotation due to the tidal locking**
- **Saturn: 30 deg. inclined, but spin of the Sun is small**
- **Worse in either case, but still detectable potentially (S/N=3)**