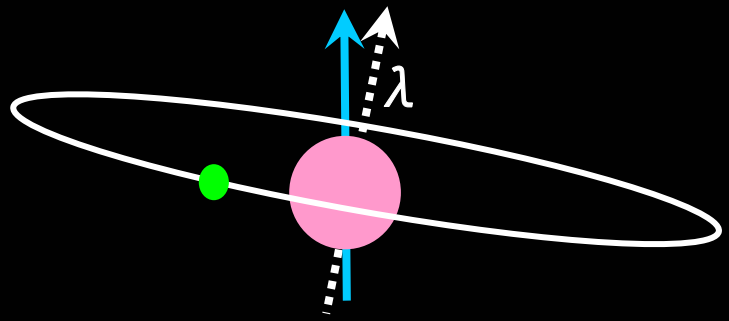
Unveiling the nature of transiting extrasolar planets with the Rossiter effect



Yasushi Suto *Department of Physics, the University of Tokyo*

東京大学 大学院
理学系研究科・理学部
SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

MPA cosmology seminar
July 3, 2007

Recent Activities of Observational Cosmology Group, University of Tokyo (1)

- **Large-scale structure of the universe**
  - constraints on the deviation from Newton's law of gravity from SDSS galaxy power spectrum (Shirata et al. 2005, 2007)
  - Prospects to constrain modified gravity models from future surveys (Yamamoto et al. 2006, 2007)
  - Galactic dust map against SDSS galaxy number counts and FIR emission (Yahata et al. 2007)
  - Bispectrum and nonlinear biasing of galaxies (Nishimichi et al. 2007)
  - Perturbation theory approach to baryon acoustic oscillations (Nishimichi et al. 2007)

Recent Activities of Observational Cosmology Group, University of Tokyo (2)

- **Dark halos and galaxy clusters**
  - triaxial modeling of dark matter halos (Jing & Suto 2002; Oguri, Lee & Suto 2003; Lee, Jing & Suto 2005)
  - Systematic bias of cluster temperature and H_0 from the SZ effect (Kawahara et al. 2006, 2007)
- **Warm/hot intergalactic medium (WHIM)**
  - a proposal of oxygen emission line search with DIOS (Yoshikawa et al. 2003, 2004)
  - feasibility of an absorption line search with XEUS along bright quasars and GRB afterglow (Kawahara et al. 2006)
- **Spectroscopy of transiting extrasolar planets**
  - constraints on planetary atmosphere (Winn et al. 2004; Narita et al. 2005)
  - detection of the spin-orbit misalignment using the Rossiter effect (Ohta, Taruya & Suto 2005, 2007; Winn et al. 2005, 2006, 2007; Narita et al. 2007)

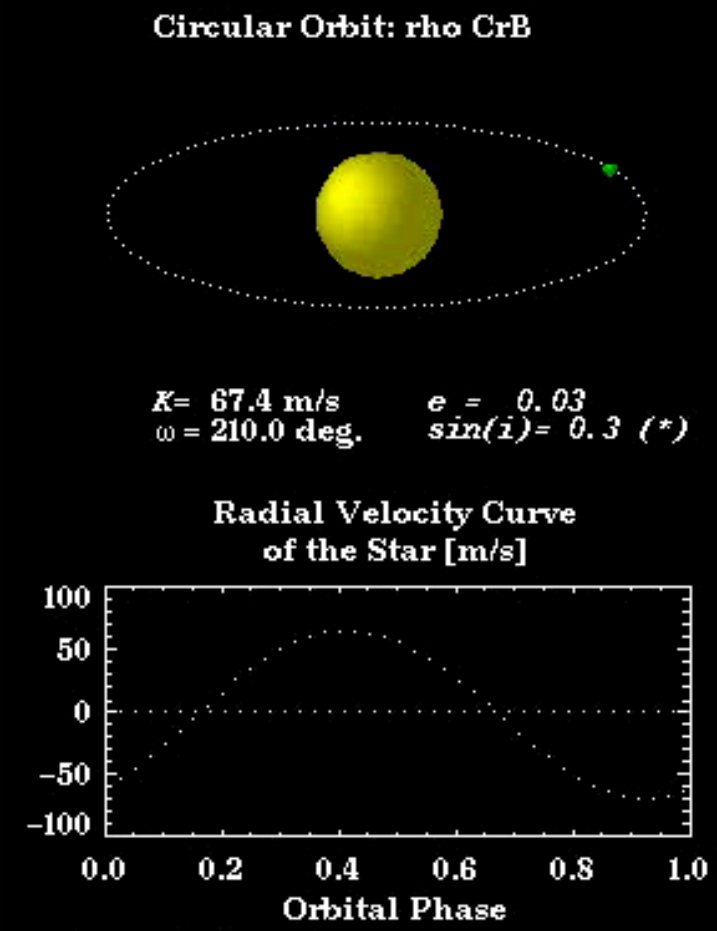
A brief history of extrasolar planets

- **1995 :** the first extrasolar planet around the main sequence star 51 Pegasi (Mayor & Queloz)
- **1999 :** transit of a known planet around HD209458 (Charbonneau et al., Henry et al.)
- **2001 :** Na in the atmosphere of HD209458b
- **2003**: first discovery of a planet by transit method *alone* (1.2 day orbital period: OGLE)
- **2005:** first detection of the spin-orbit misalignment via the Rossiter effect (Winn et al.)
- *More than 250 extrasolar planets* are reported (July 2007)

http://exoplanets.org/

Radial velocity of a star perturbed by a planet

- Even if planets are not directly observable, their presence can be inferred dynamically

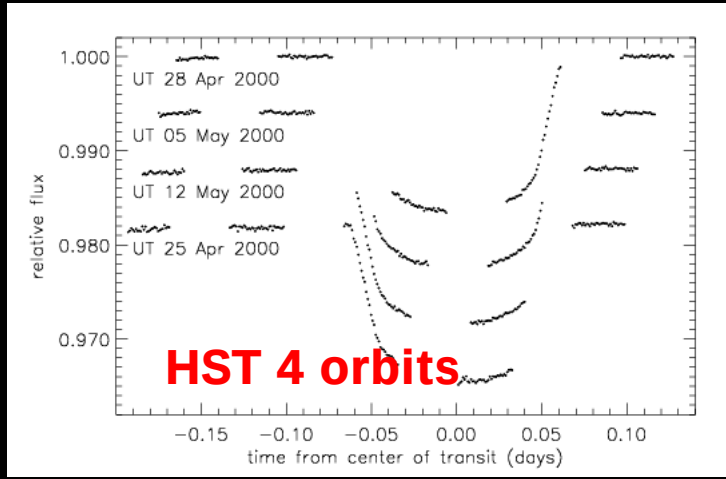


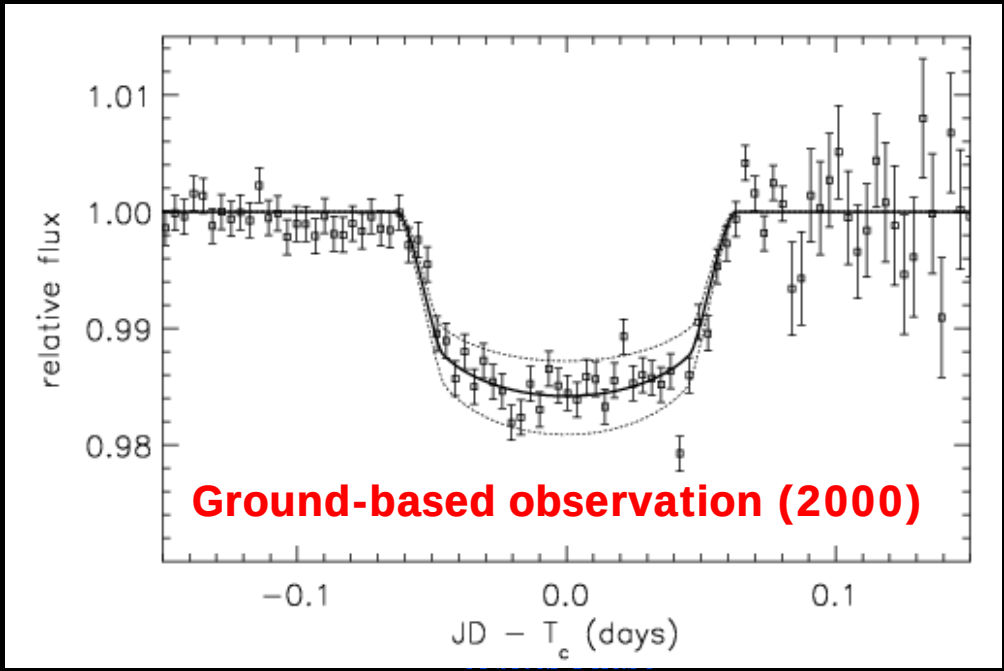
- velocity modulation of the Sun:
  - 12.5 m/s（Jupiter）
  - 0.1 m/s（Earth）
- an accuracy of 1m/s achieved from the ground observation

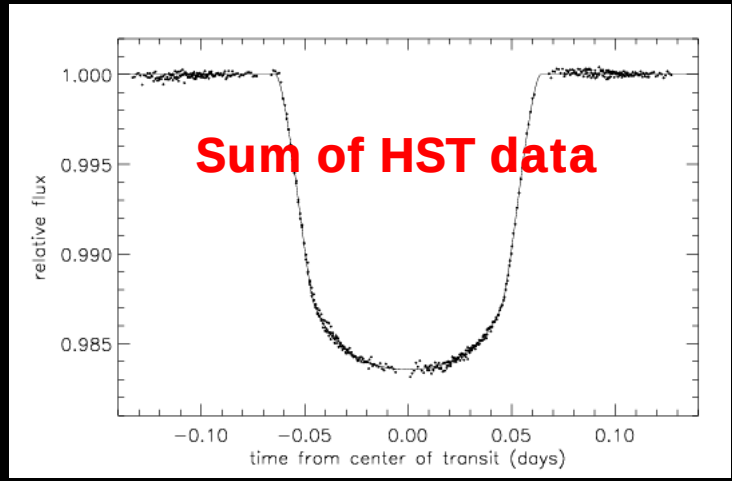
⇒ the major method of (Jovian) planet search

the first discovery of a transiting planet: HD209458

- detected the light curve change at the phase consistent with the radial velocity (Charbonneau et al. 2000, Henry et al. 2000)



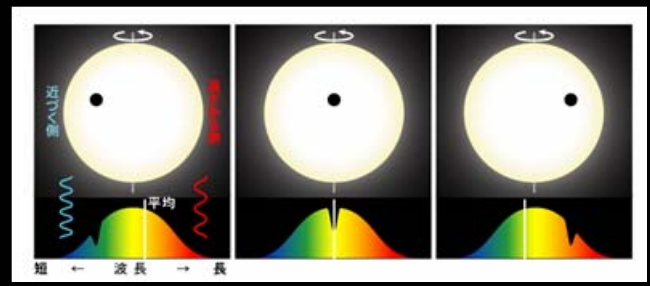




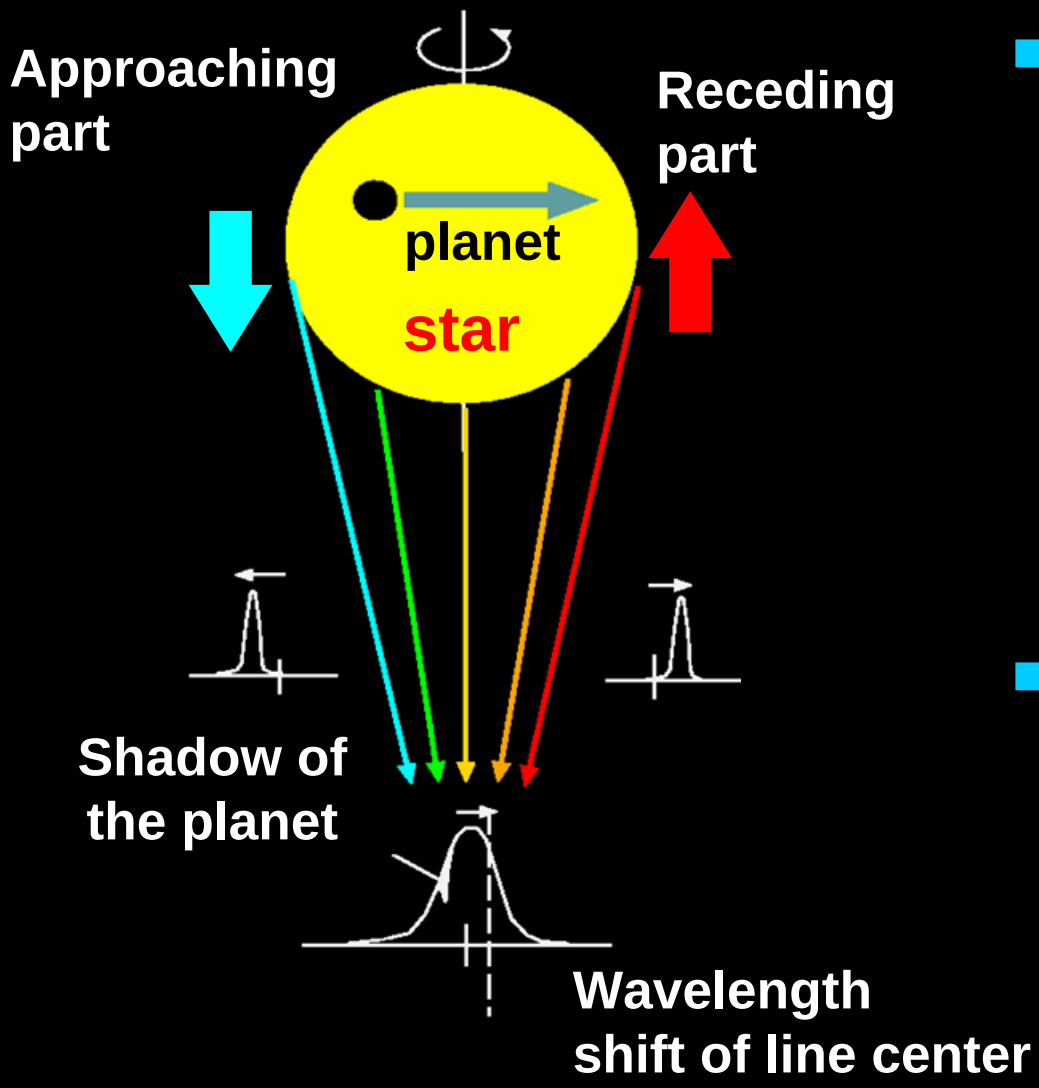
Brown et al. (2001)

Transiting planet projects at Univ. of Tokyo

- **Search for the planetary atmosphere with Subaru**
  - the most stringent upper limits from ground-based obs.
  - Winn et al. PASJ 56(2004) 655 (astro-ph/0404469)
  - Narita et al. PASJ 57(2005) 471 (astro-ph/0504450)
- **Constraining the stellar spin and the planetary orbital axes from the Rossiter-McLaughlin effect**
  - New analytic formulae (Ohta, Taruya & Suto 2005, ApJ, 622, 1118)
  - First detection (Winn et al. 2005 ApJ, 631, 1215)
- **Search for reflected light from planets**
  - collaboration with Andrew Cameron (St. Andrews Univ.) & Chris Leigh (Liverpool John Moores Univ.)

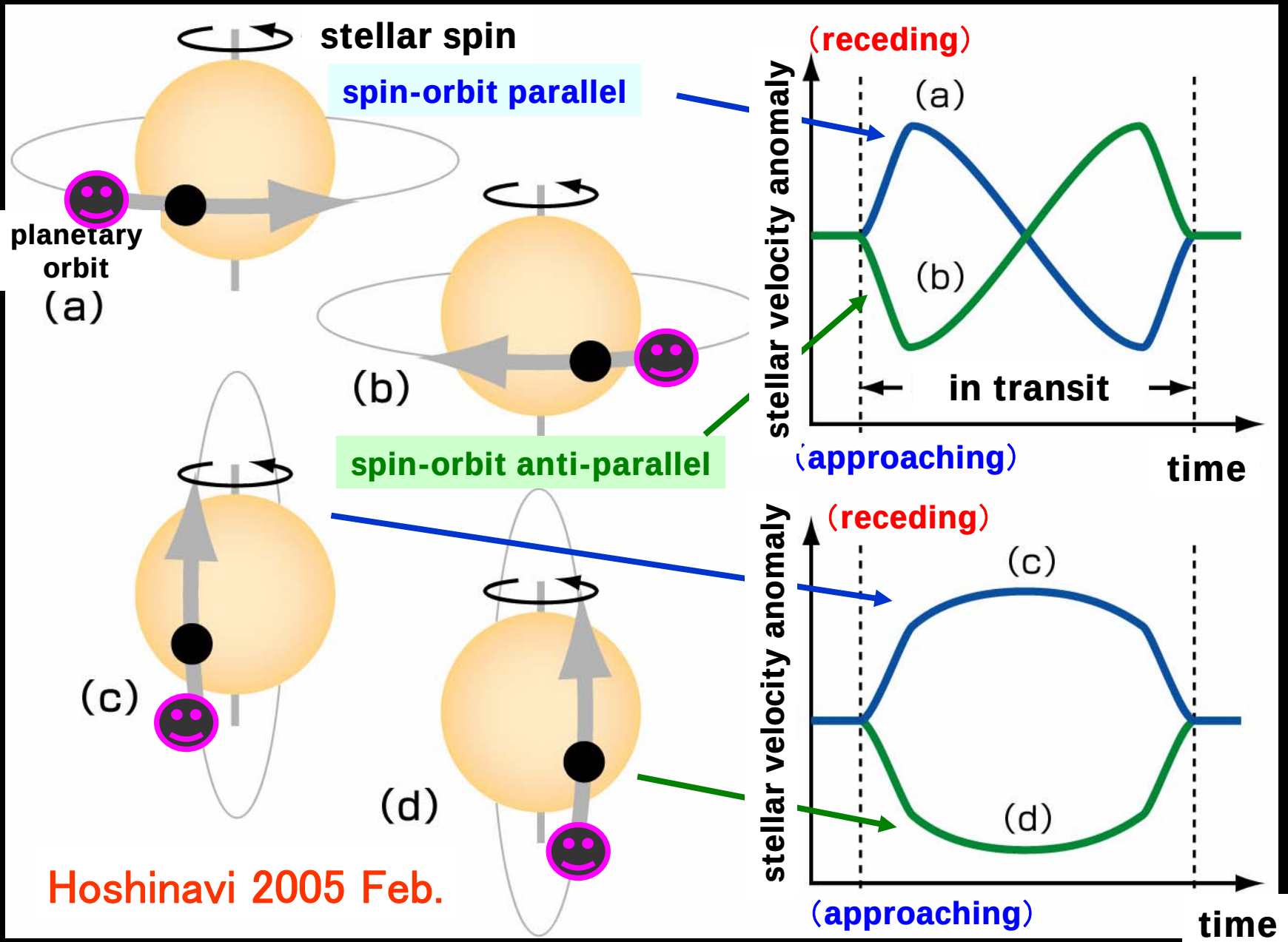


Spectroscopic transit signature: the Rossiter-McLaughlin effect



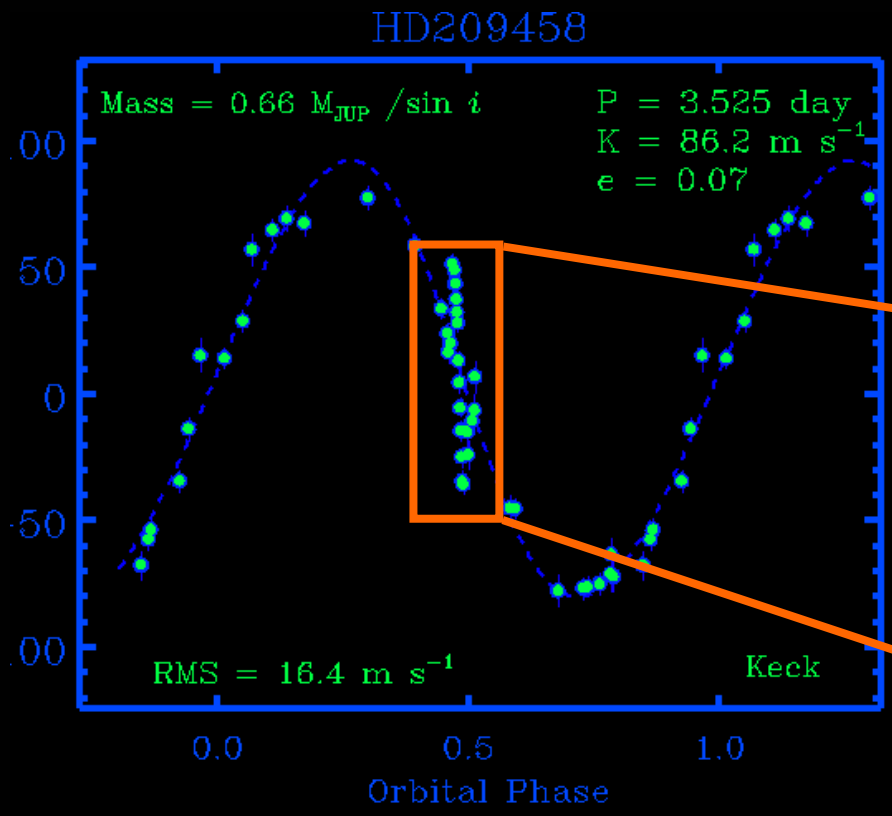
- Time-dependent asymmetry in the stellar Doppler broadened line profile
  - an apparent anomaly of the stellar radial velocity
- originally discussed in eclipsing binary systems
  - Rossiter (1924)
  - McLaughlin (1924)

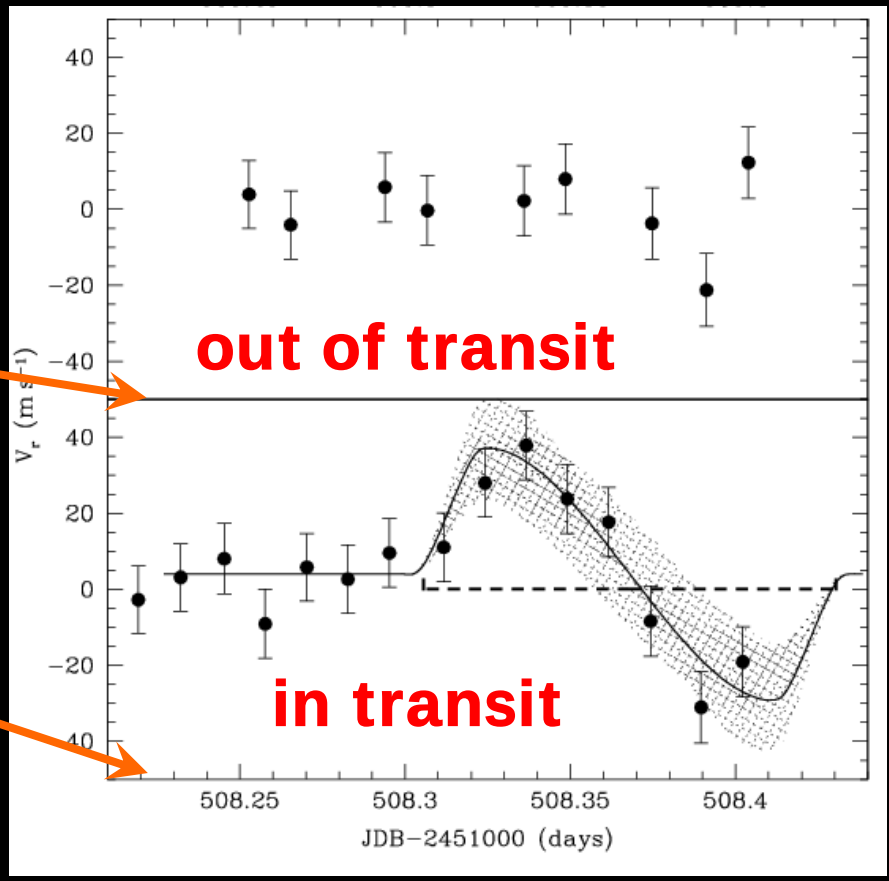
Velocity anomaly due to the Rossiter effect



Previous result of the Rossiter-McLaughlin effect for HD209458

Origin of angular momentum





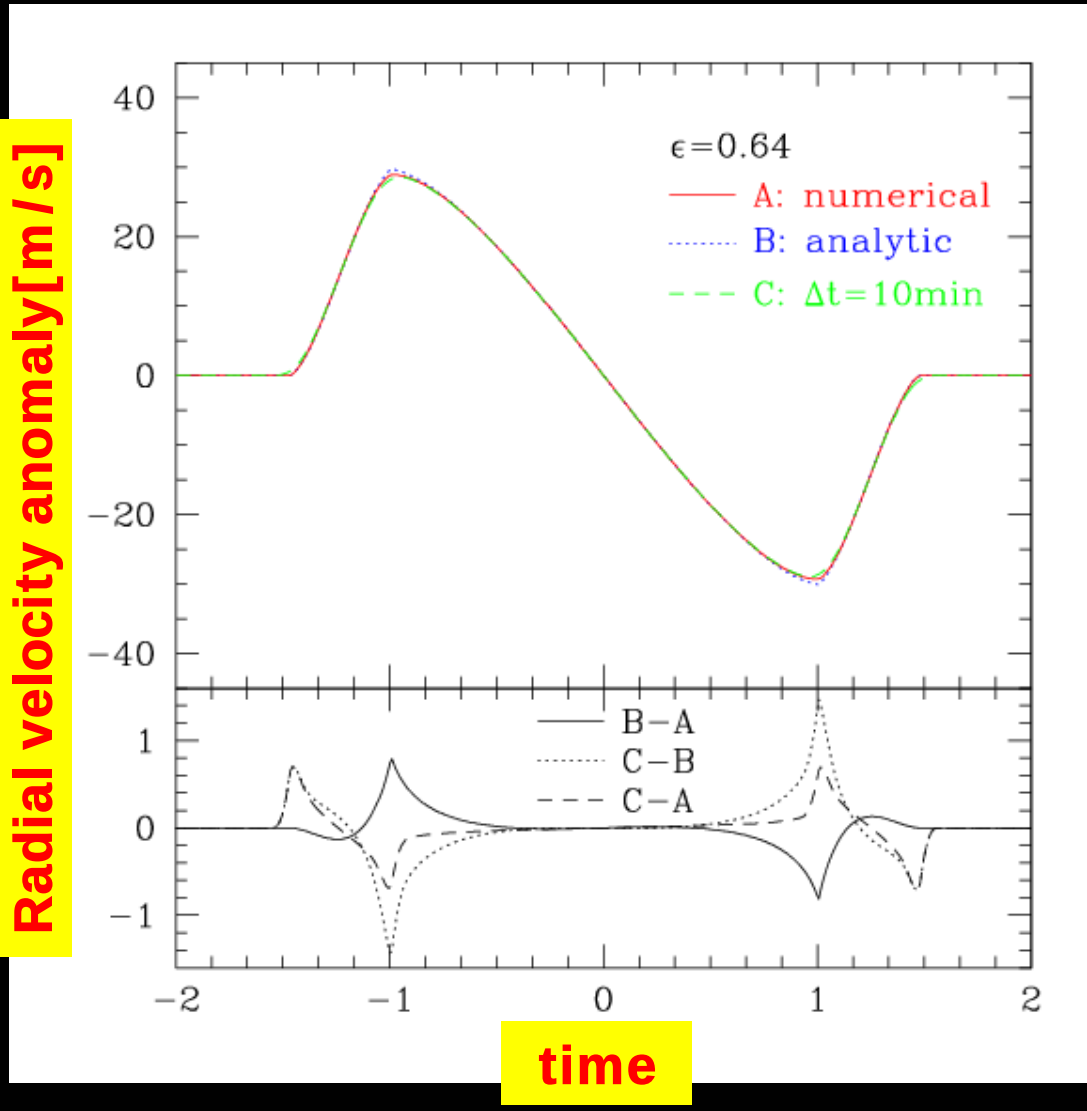
HD209458 radial velocity data
http://exoplanets.org/

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

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

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

First analytic formula using perturbation theory



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

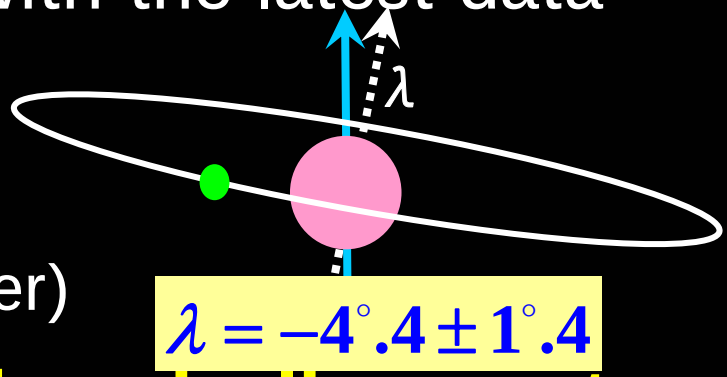
Measurement of Spin-Orbit alignment in an Extrasolar Planetary System

- **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

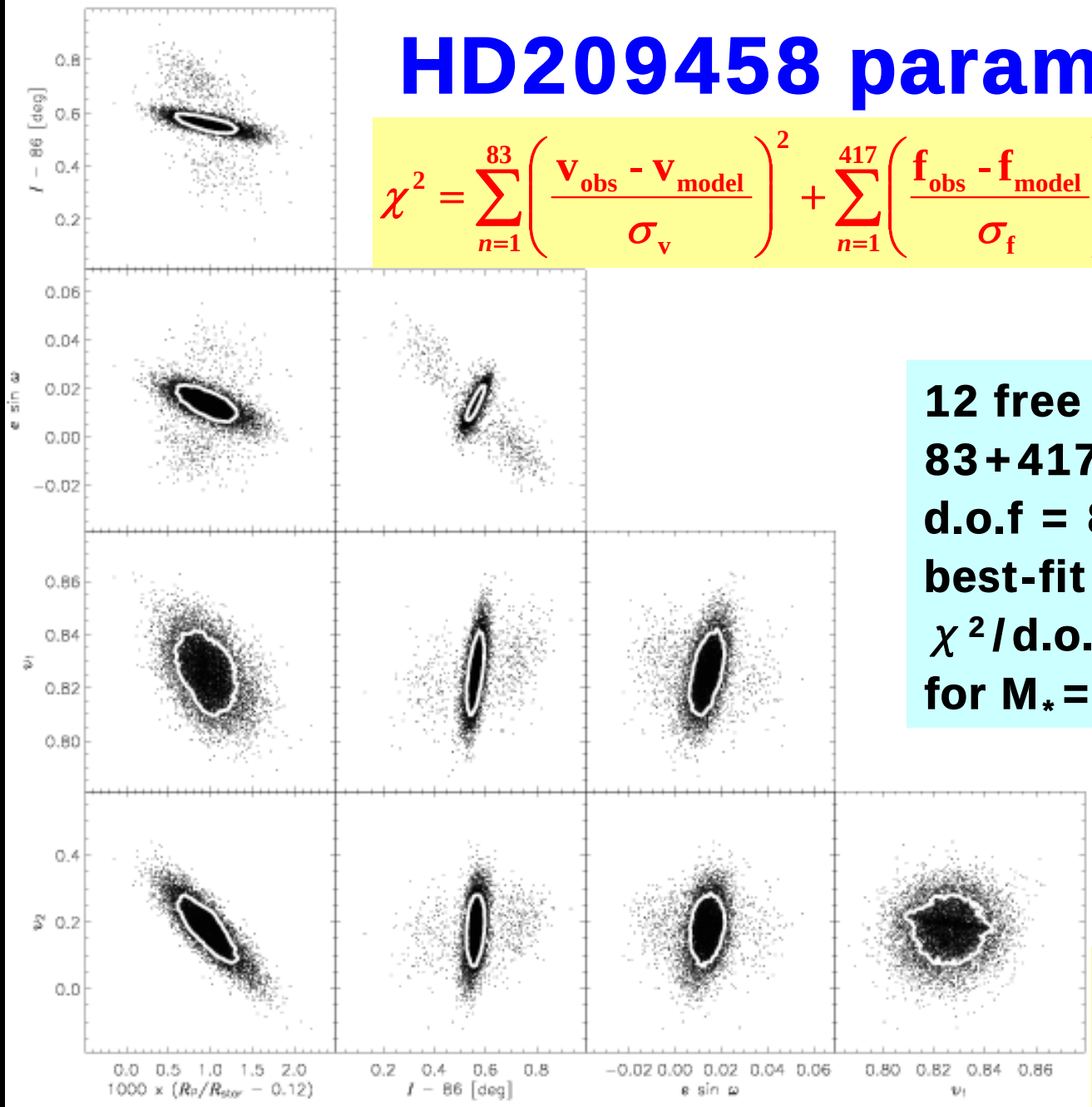
- perturbation formula by Ohta et al. (2005)
- HD209458 re-examined with the latest data
  - radial velocity data (Keck)
  - optical photometry (HST)
  - infrared photometry (Spitzer)



- **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

HD209458 parameter fit

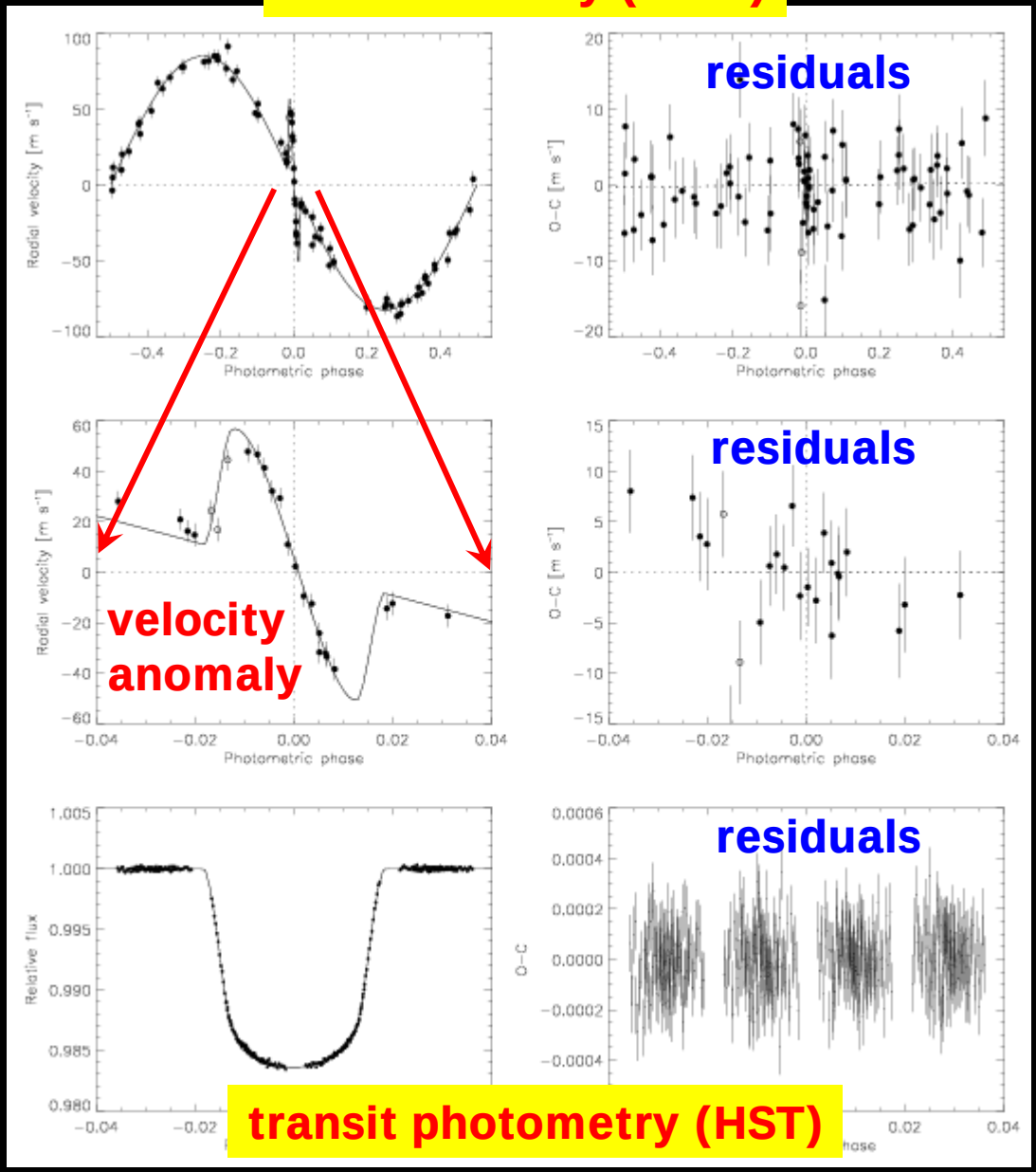
$$\chi^2 = \sum_{n=1}^{83}\left(\frac{v_{obs} - v_{model}}{\sigma_v}\right)^2 + \sum_{n=1}^{417}\left(\frac{f_{obs} - f_{model}}{\sigma_f}\right)^2 + \left(\frac{t_{2nd,obs} - t_{2nd,model}}{\sigma_t}\right)^2$$



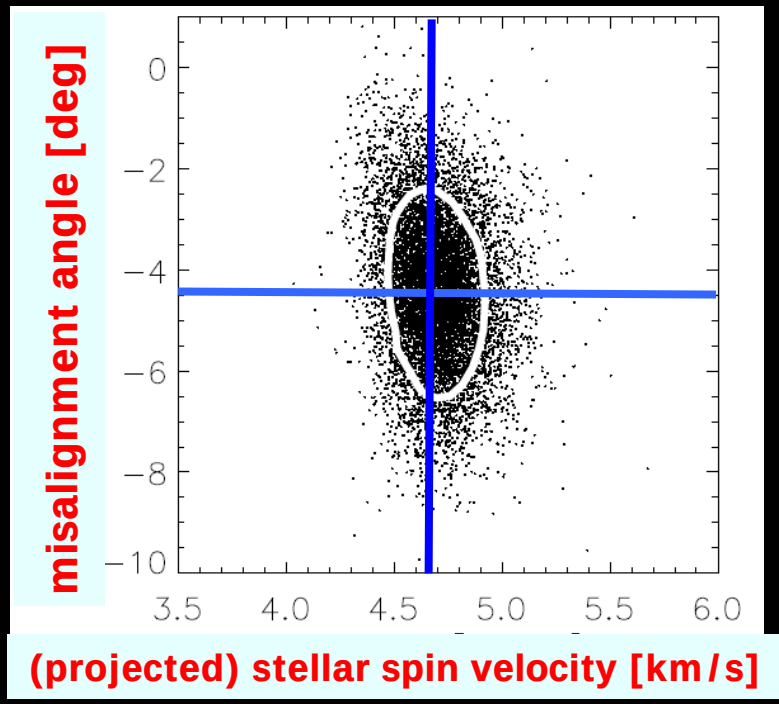
12 free parameters
83+417+1 data points
d.o.f = 83+417+1-12=489
best-fit :
χ^2/d.o.f=528/489=1.08
for $M_* = 1.06 M_{sun}$

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

radial velocity (Keck)



first detection of non-zero λ !



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

3σ detection !

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

Our group detected the Rossiter effect for 4 transiting planets so far

- HD209458b (Winn et al. 2005) λ = -4.4±1.4deg
- HD189733b (Winn et al. 2006) λ = -1.4±1.1deg
- TrES-1b (Narita et al. 2006) λ = 30±21deg
- HAT-P-2b (Winn et al. 2007) λ = 0.3±9.8deg

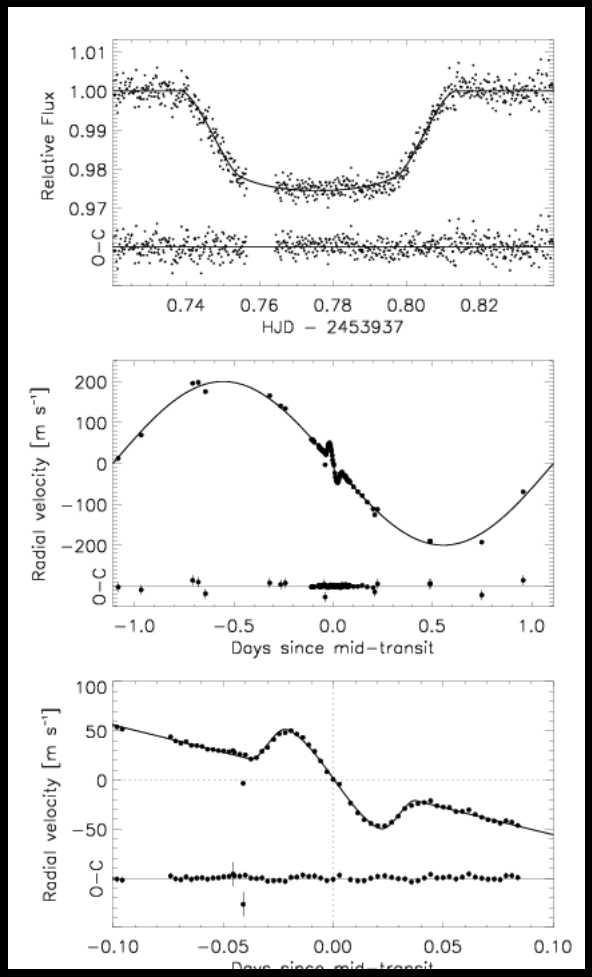
More to come !

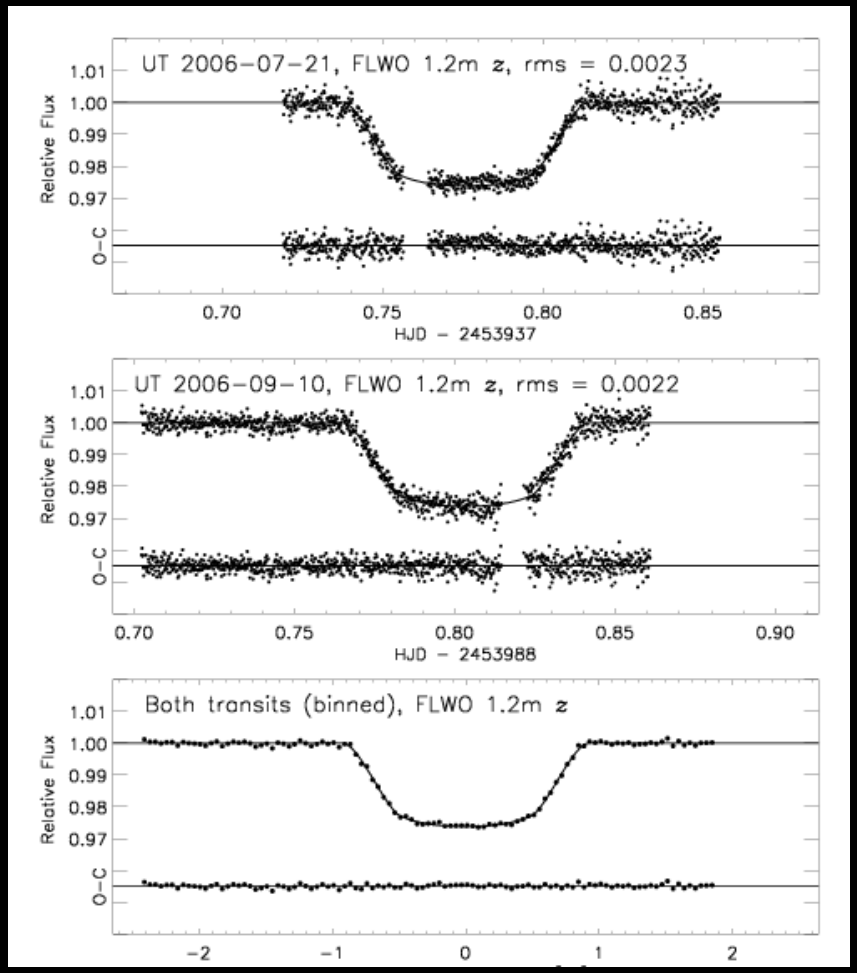
Subaru (radial velocity) & MAGNUM (photometry) simultaneous observation campaign

P.I. N.Narita

Measurement of the Spin-Orbit Alignment in the Exoplanetary System HD 189733

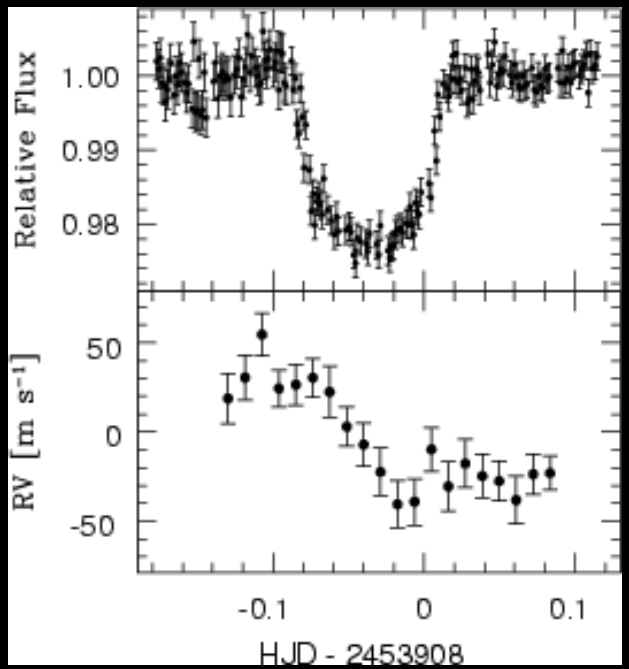
- Winn et al. ApJ 653(2006)L69, AJ 133(2007)1828

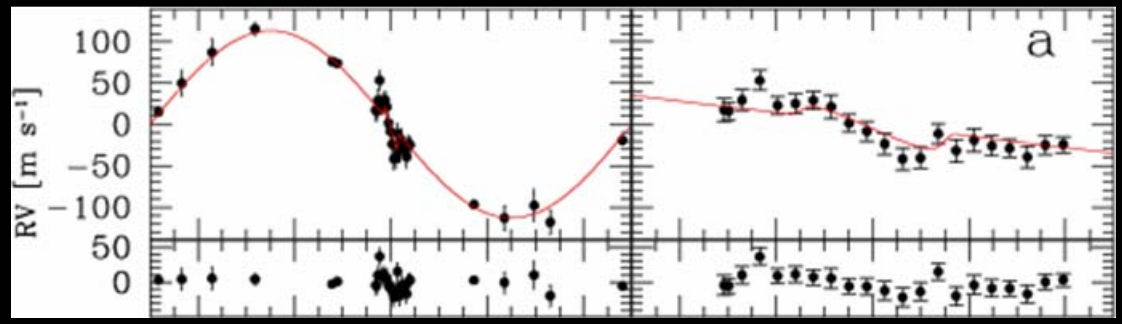


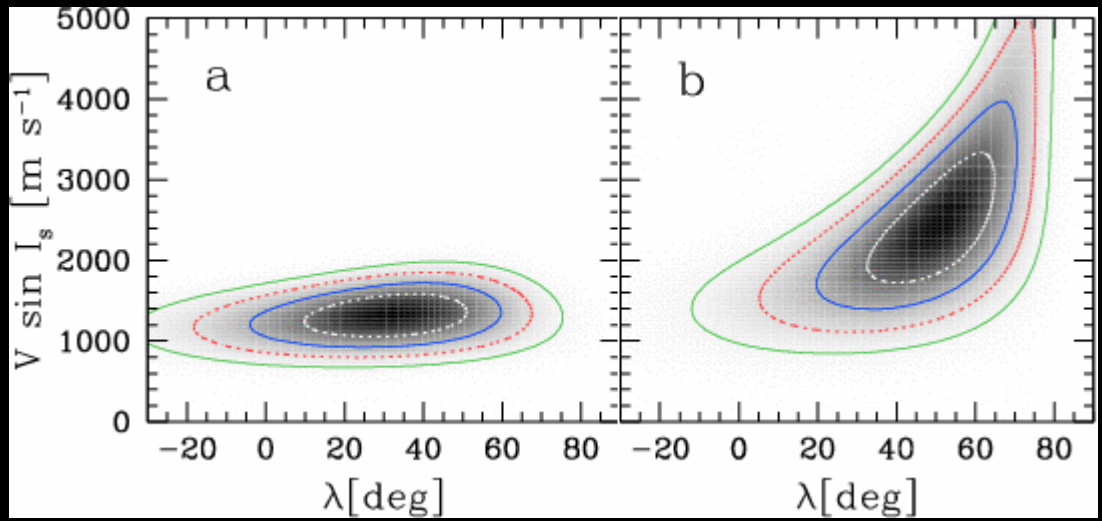


Measurement of the Rossiter-McLaughlin Effect in the Transiting Exoplanetary System TrES-1

- Narita et al. PASJ (2007) in press, astro-ph/0702707

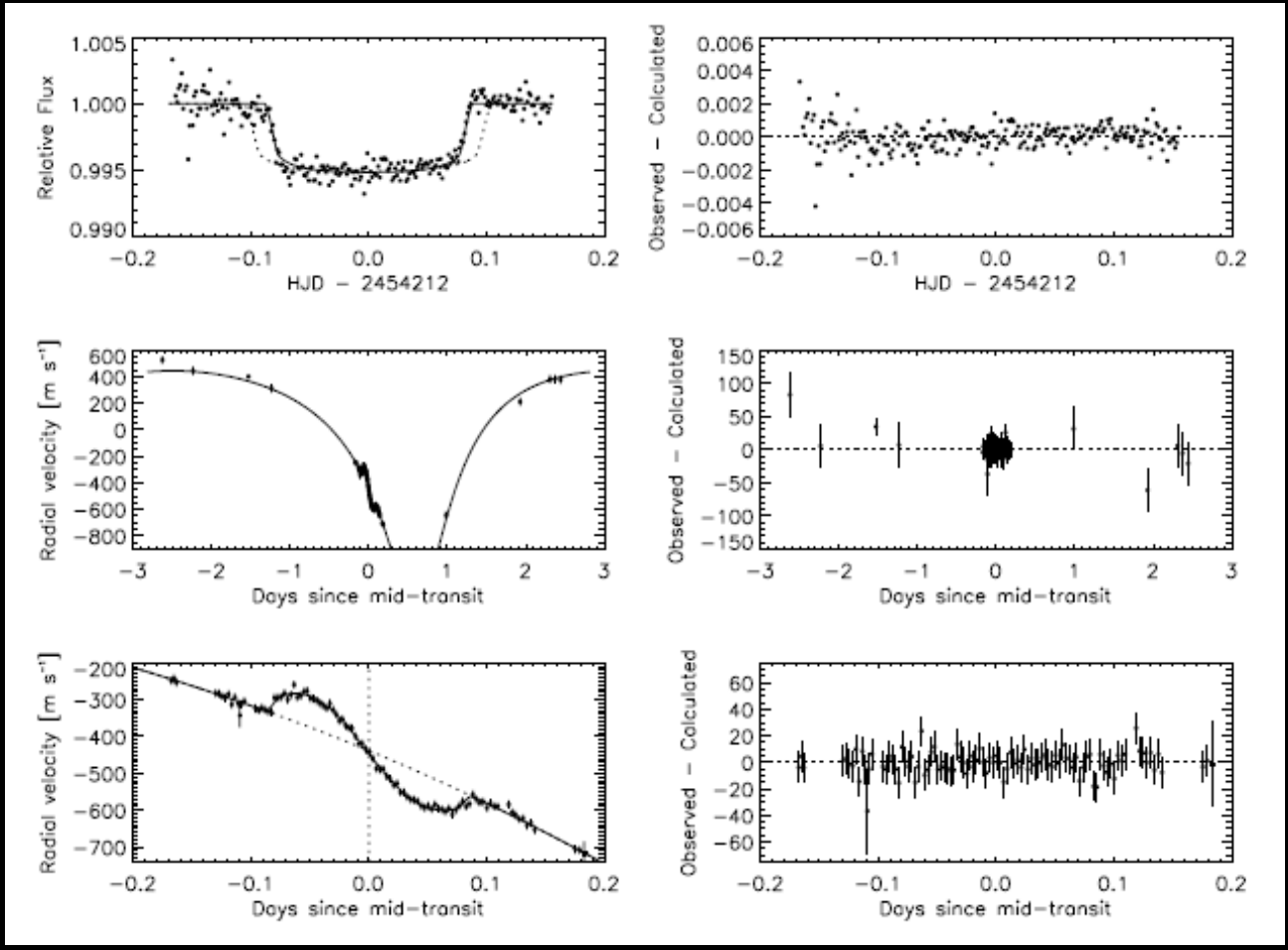






Spin-Orbit Alignment in the Exoplanetary System HAT-P-2

- Winn et al. ApJL(2007) submitted



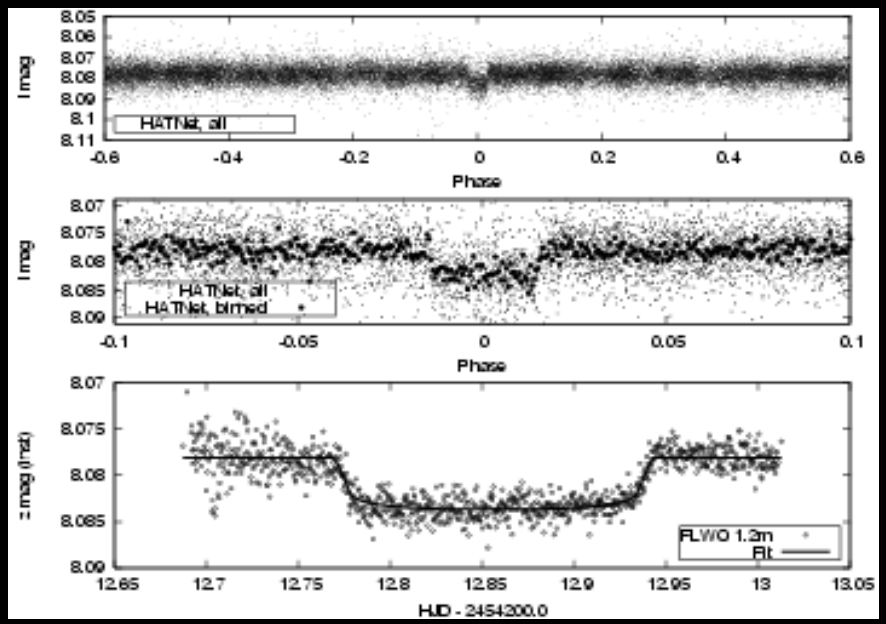
HATnet: *Hungarian-made Automated Telescope*

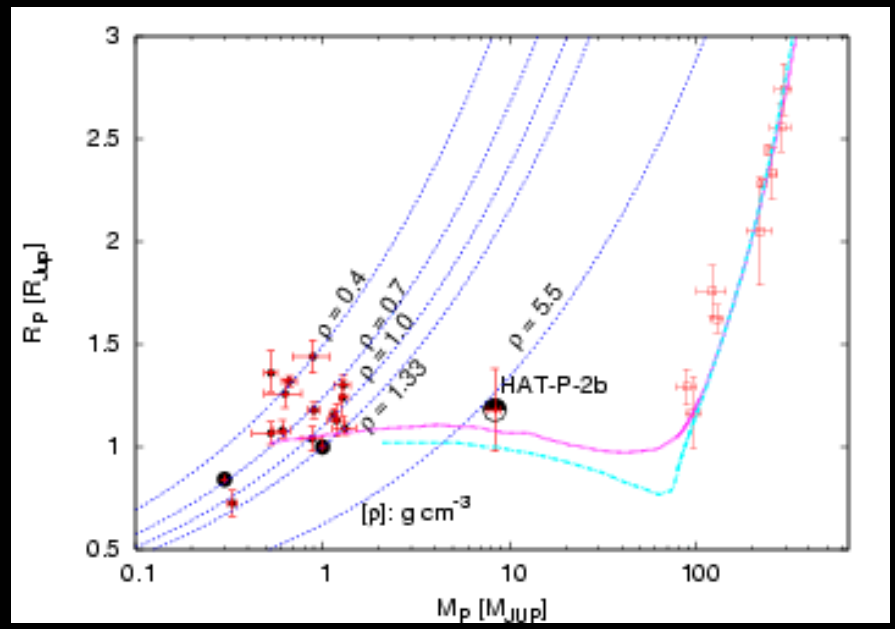
- HATNet is a network of six small (11cm diameter), wide-field (8x8deg), fully-automated "HAT" telescopes
- a multi-site and multi-instrument network searching for the tiny (1%) transit signature of extrasolar planets

Mauna Kea, Hawaii
Fred Lawrence Whipple Obs., Arizona
Wise, Israel

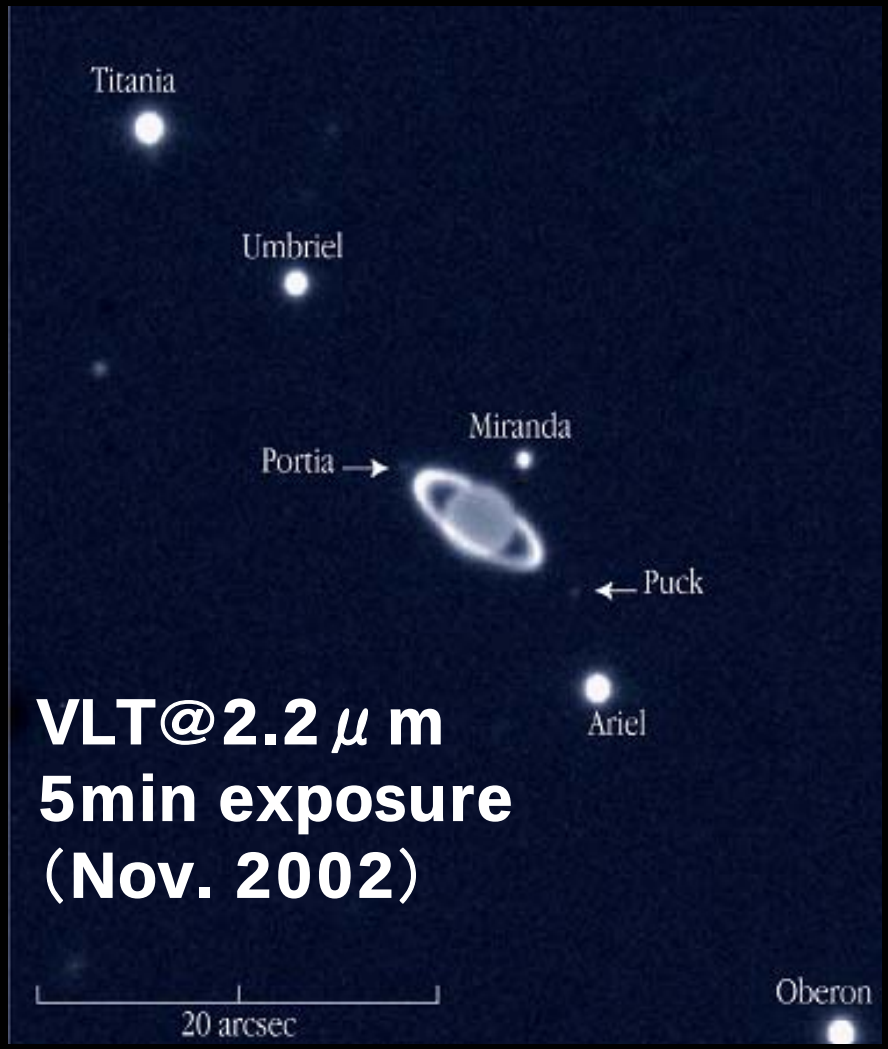
HAT-P-2b: A Super-Massive Planet in an Eccentric Orbit Transiting a Bright Star

- Central star: HD147506
  - V=8.7, F8V, d=135pc, 4.3L_{sun}, 1.35M_{sun}, 1.8R_{sun}
- Planet: HD147506b=HAT-P-2b
  - P=5.63day, e=0.5, 8.2M_J, 1.2R_J, ρ =6.6g/cc





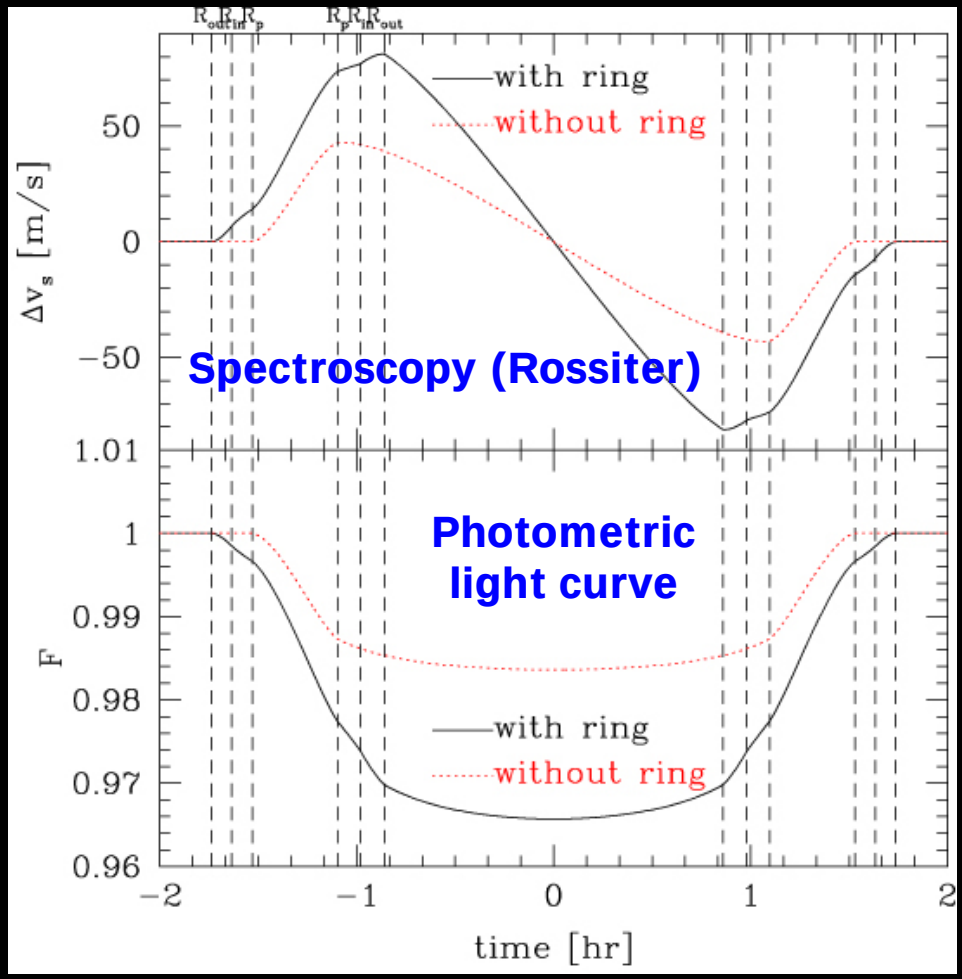
Discovery of the Uranus rings

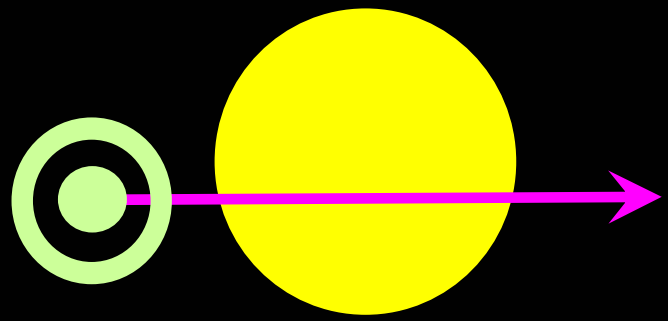


VLT@2.2 μ m
5min exposure
（Nov. 2002）

- **Serendipitous discovery**
  - Uranus's transit against a background star (Elliot et al. 1977)
  - Neptune's ring was discovered also by transit technique in 1986
- **Transit proved to be useful in detecting rings of the Solar planets !**

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 & YS: astro-ph/0611466

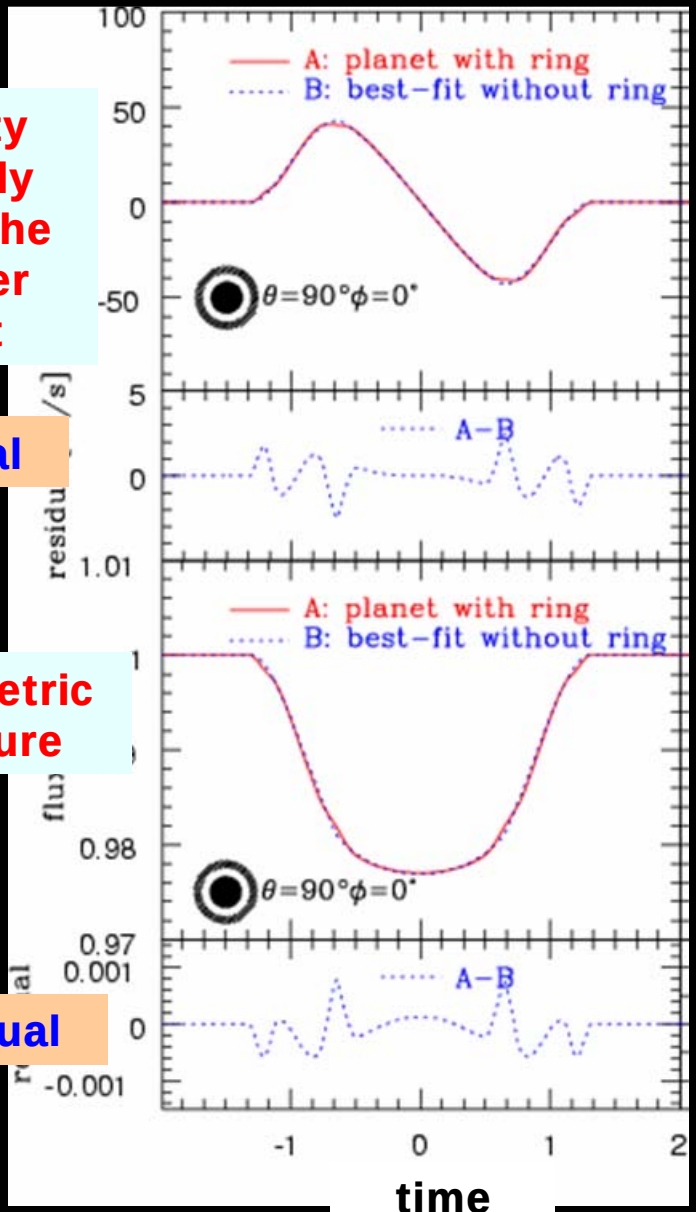
Detectability of a ring

Velocity anomaly due to the Rossiter effect

residual

Photometric signature

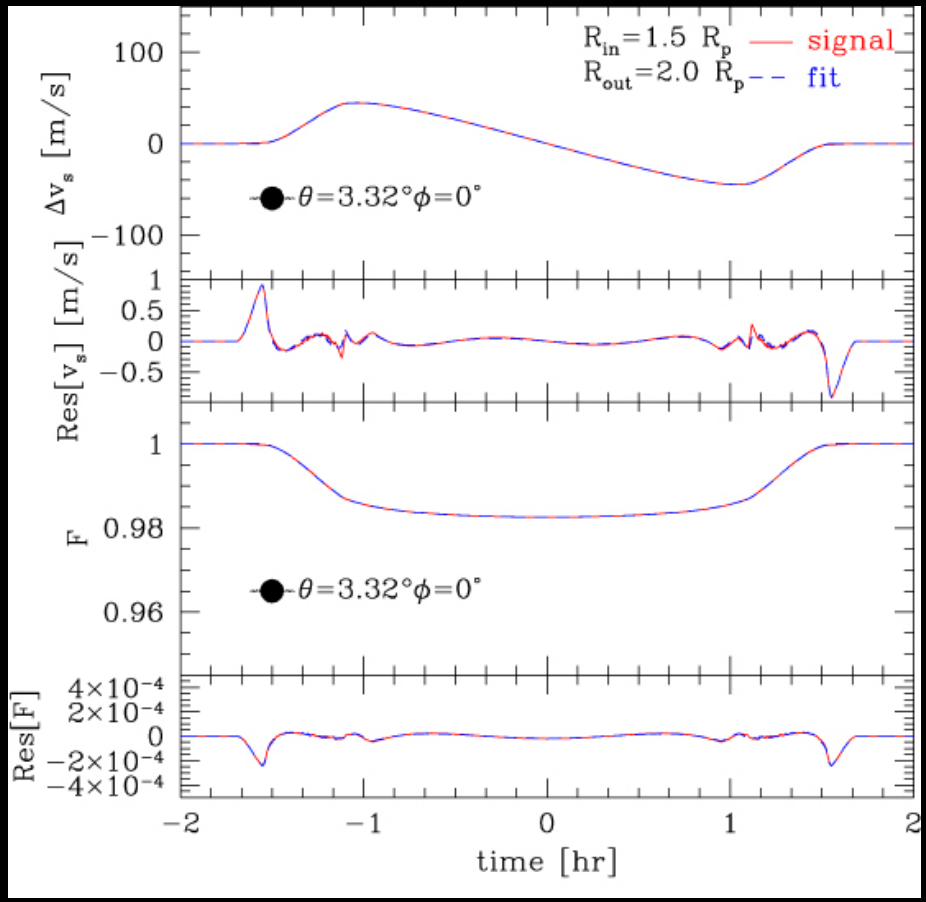
residual

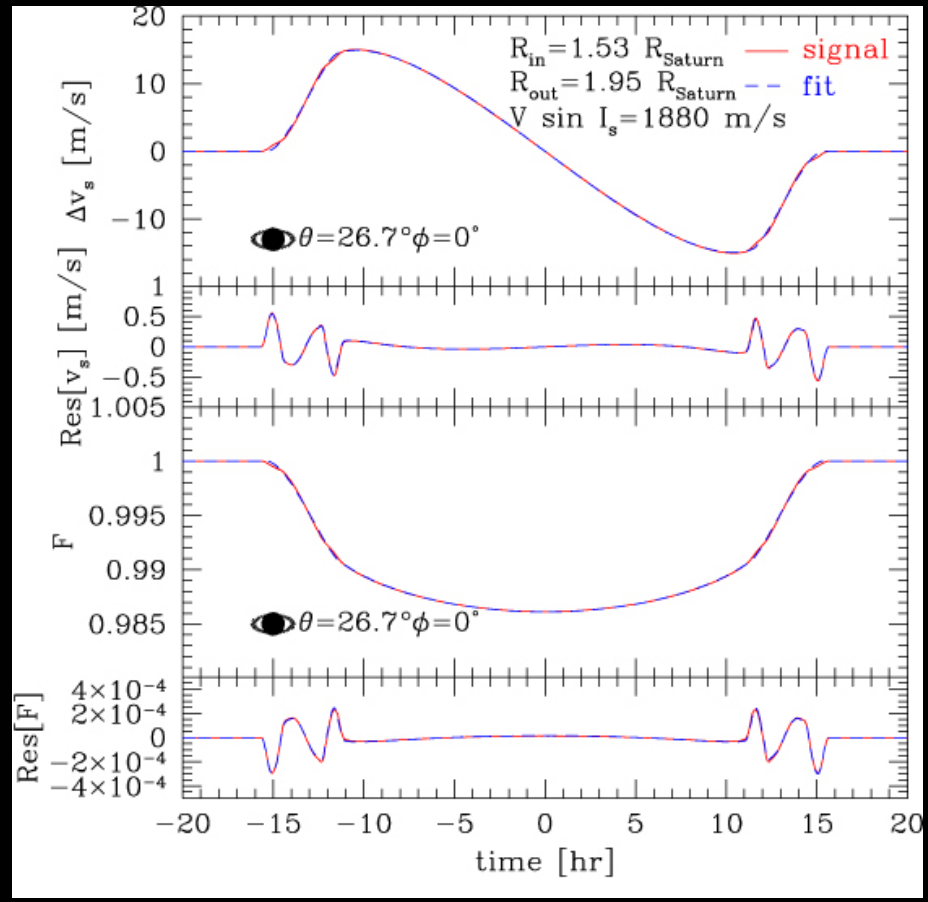


- a hypothetical ring around HD209458
  - $1.5R_{pl} < R_{ring} < 2R_{pl}$
  - deviation from a best-fit single planet
  - $\delta v \sim 1 m/s$
  - $\delta F/F \sim 0.1\%$
- marginally detectable level even with the current technology

Ohta, Taruya & YS: astro-ph/0611466

How about hot Jupiter and Saturn rings ?





Ohta, Taruya & YS: astro-ph/0611466

- **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=1)**

A possible roadmap of sciences of extrasolar planets

- Discovery phase of gas giant planets (1995-)
- Discovery of planetary atmosphere (2002)
- Detailed spectroscopic study of planets
- Discovery of IR emission of planets (2005)

- Discovery of visible reflection light
- Discovery of planetary ring
- Discovery of extrasolar planetary satellite
- Discovery of terrestrial planets

- ***Discovery of habitable terrestrial planet***
- ***Identifying biomarker***
  - Red-edge of extrasolar plant ?
- ***Discovery of extraterrestrial life***