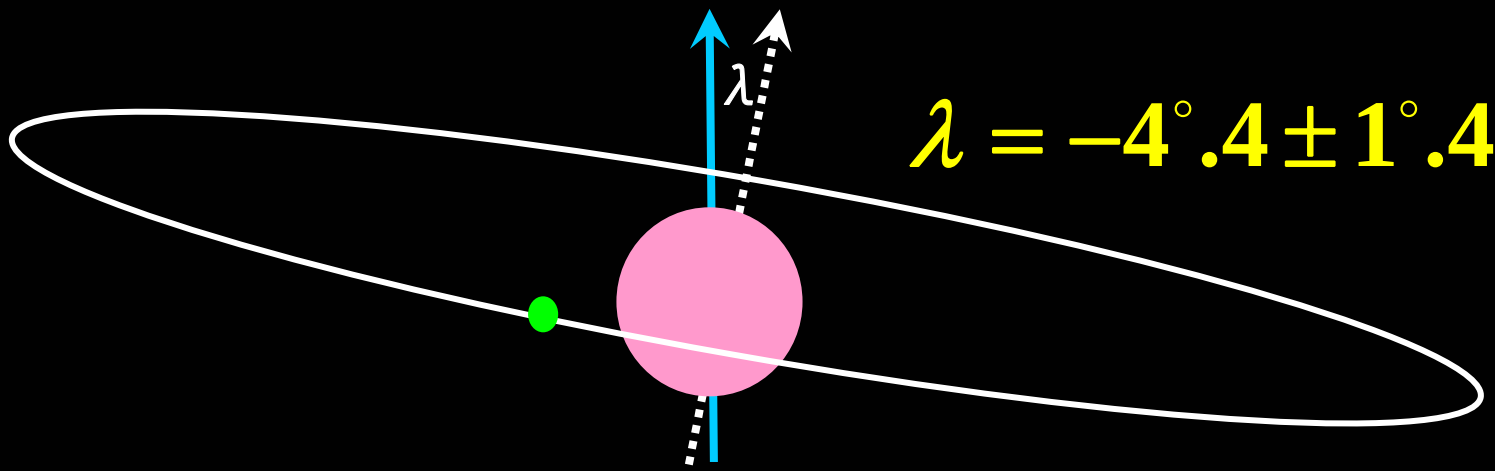
The Rossiter effect of transiting extra-solar planets

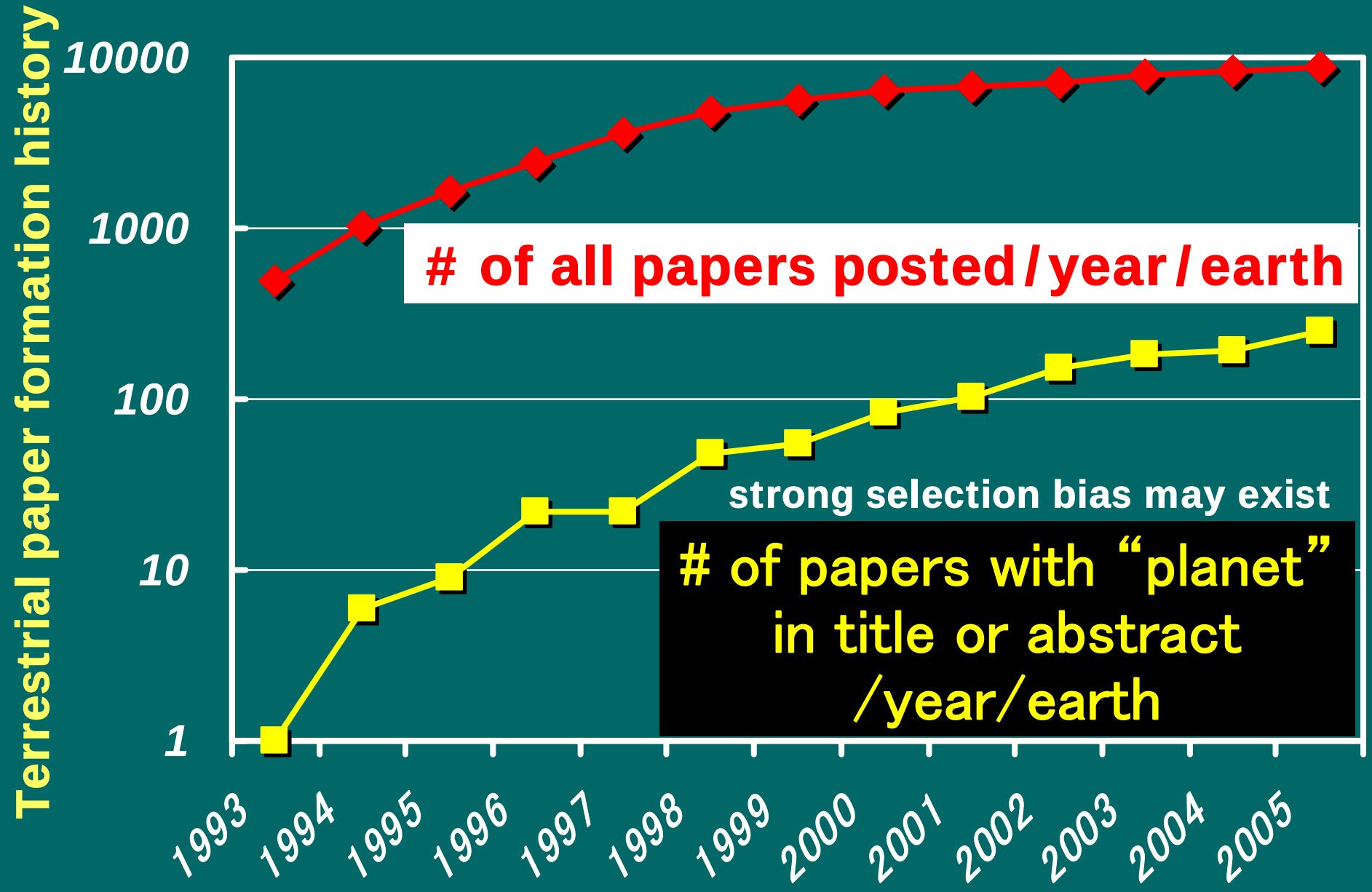


$$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$$

Yasushi Suto *Department of Physics, University of Tokyo*

International Workshop on the 10th Gravitational Microlensing and Related Topics
- extrasolar planets and cold dark matters -
Nagoya Univ. January 16-19, 2006

“Evolution” of extra-solar planet research

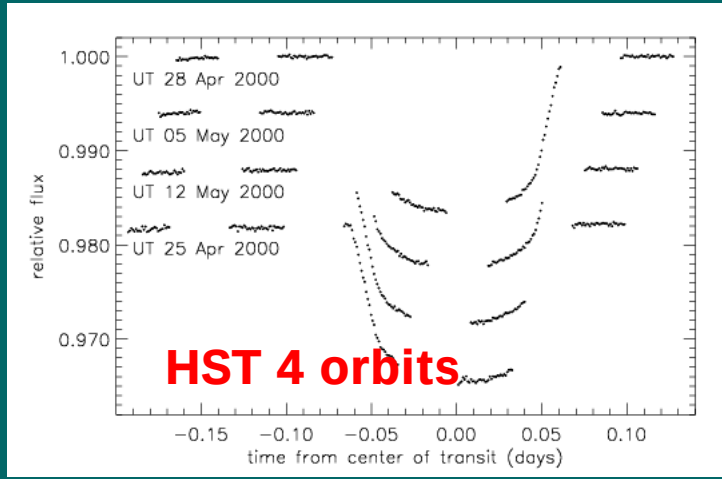


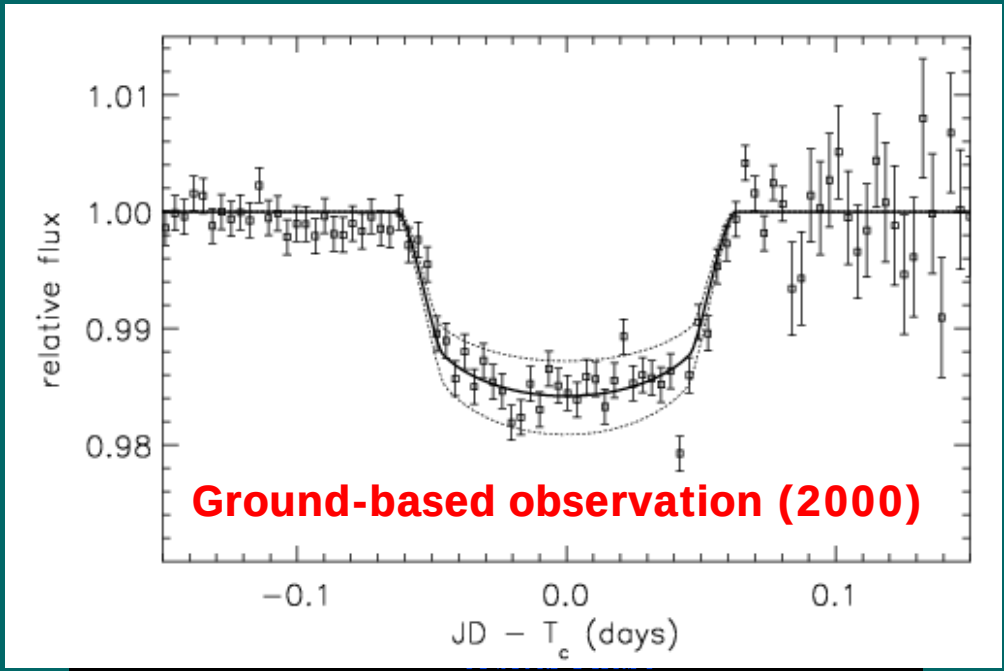
The ***first*** astro-ph paper with a word "planet" in its abstract

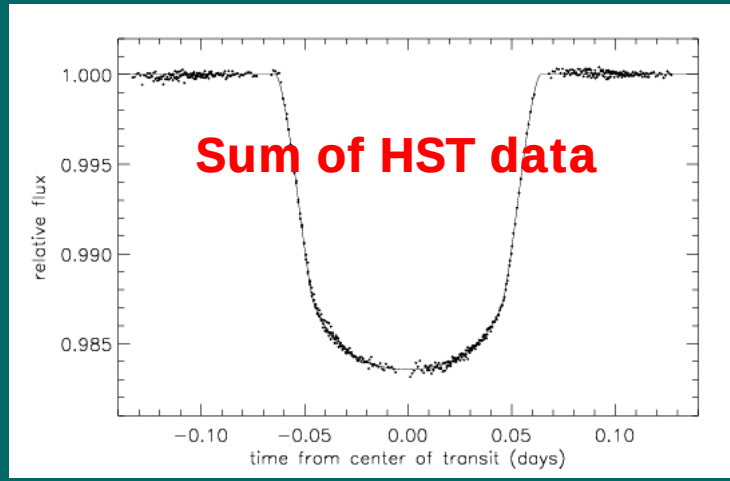
- Astro-ph/9309052
- MACHO discovery paper by C.Alcock et al.
- **Possible Gravitational Microlensing of a Star in the Large Magellanic Cloud**
  - … A less exotic alternative is normal matter in the form of bodies with masses ranging from that of a large planet to a few M_{sun}…
- ***Quite relevant for this workshop***
  - but this is a false-positive from a viewpoint of searching for extrasolar planet paper candidates

the first discovery of the transit of a planet: HD209458

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



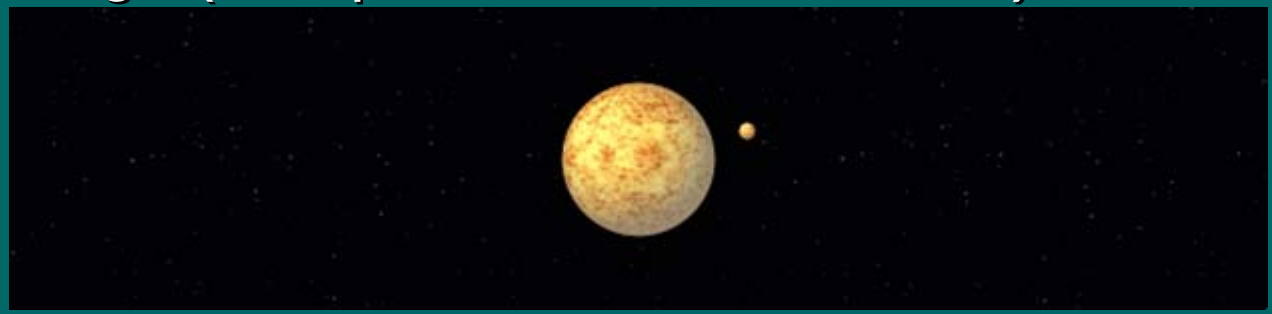




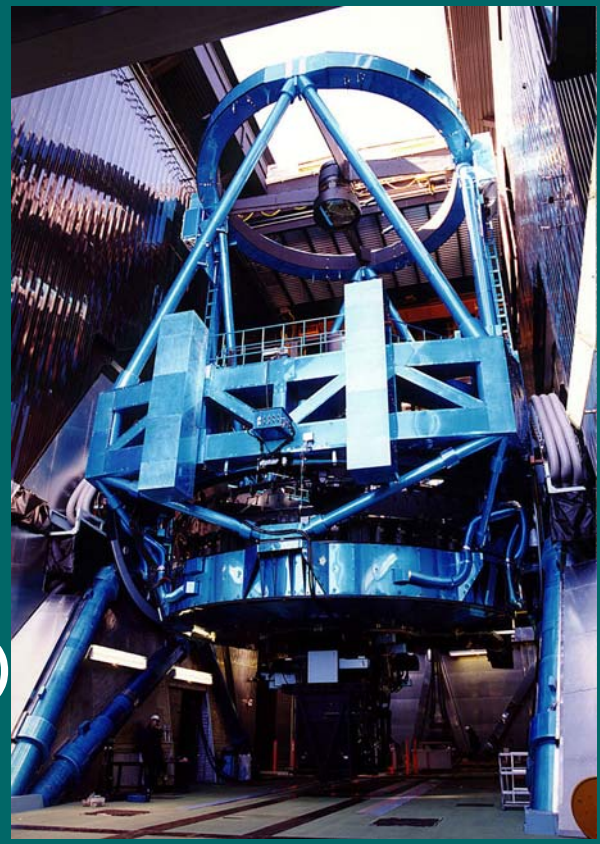
Brown et al. (2001)

Extrasolar planet projects of our group

- **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 spin-orbit alignment 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.)



Subaru observation with HDS



“Spectro-photometric search for scattered light from HD209458b”

S02B-16 on October 24 and 26, 2002

Yasushi Suto, Norio Narita (Univ. of Tokyo)

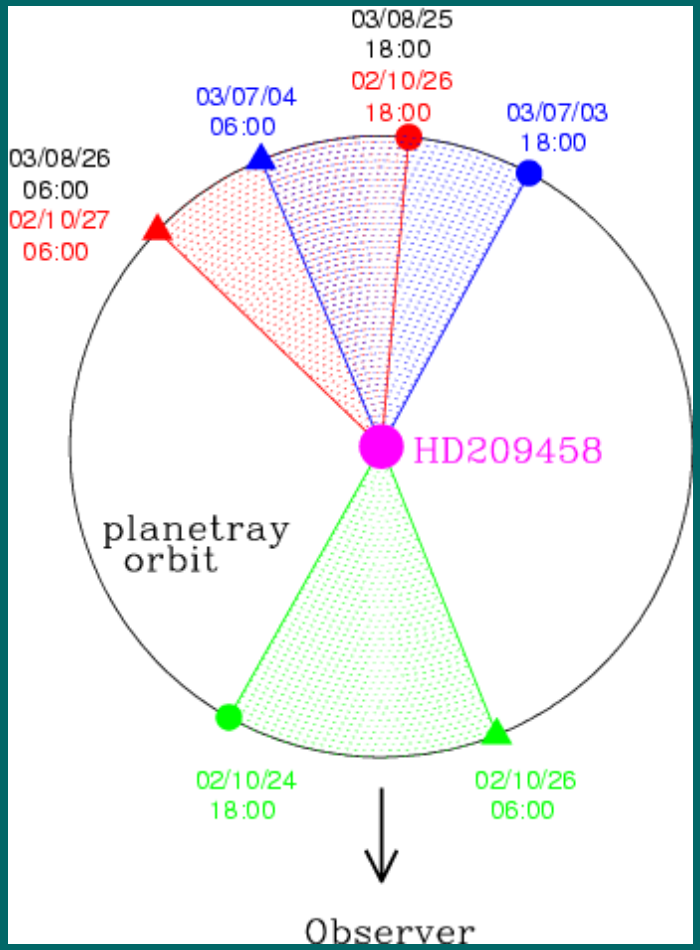
Toru Yamada, Wako Aoki (National Ast. Obs. Japan)

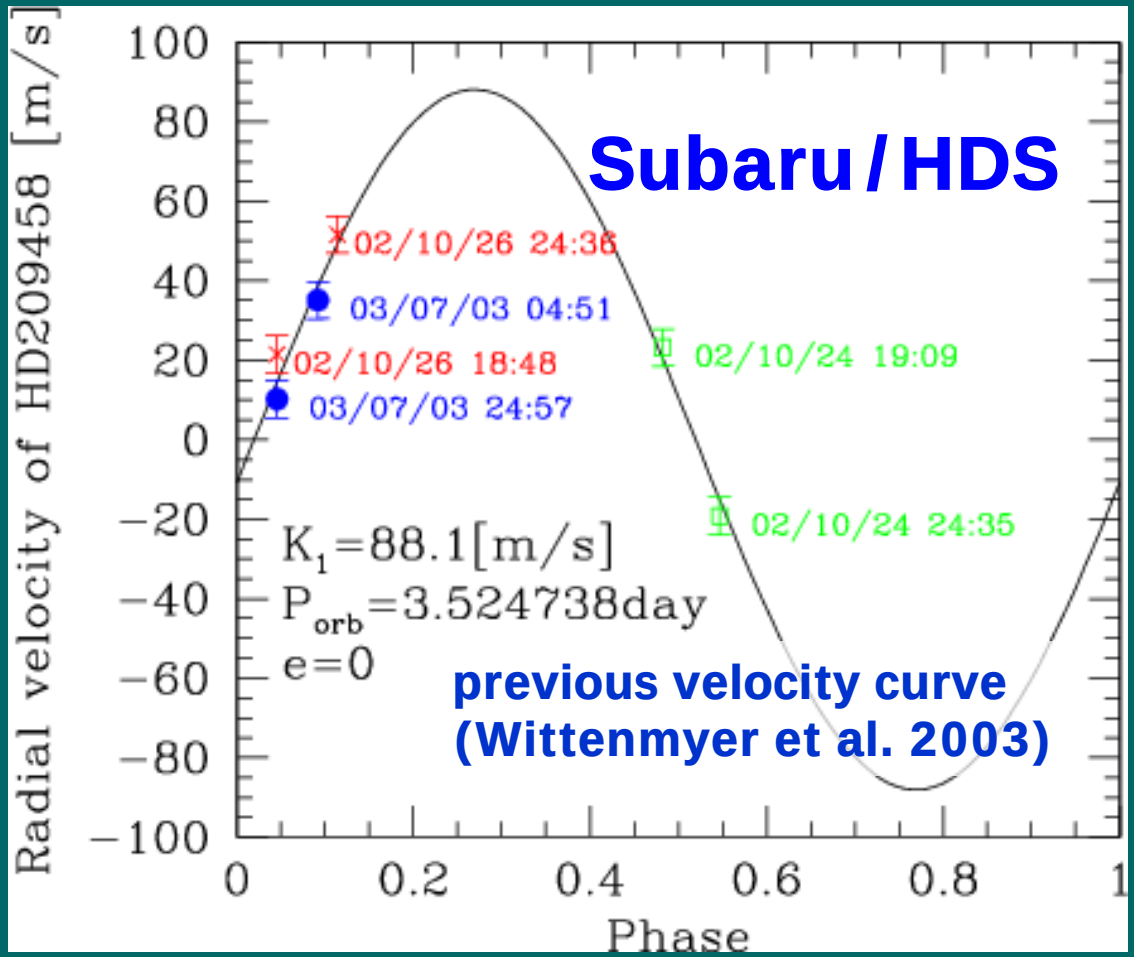
Bun-ei Sato (Kobe Univ.)

Edwin L. Turner (Princeton Univ.)

Josh Winn (Harvard Univ.)

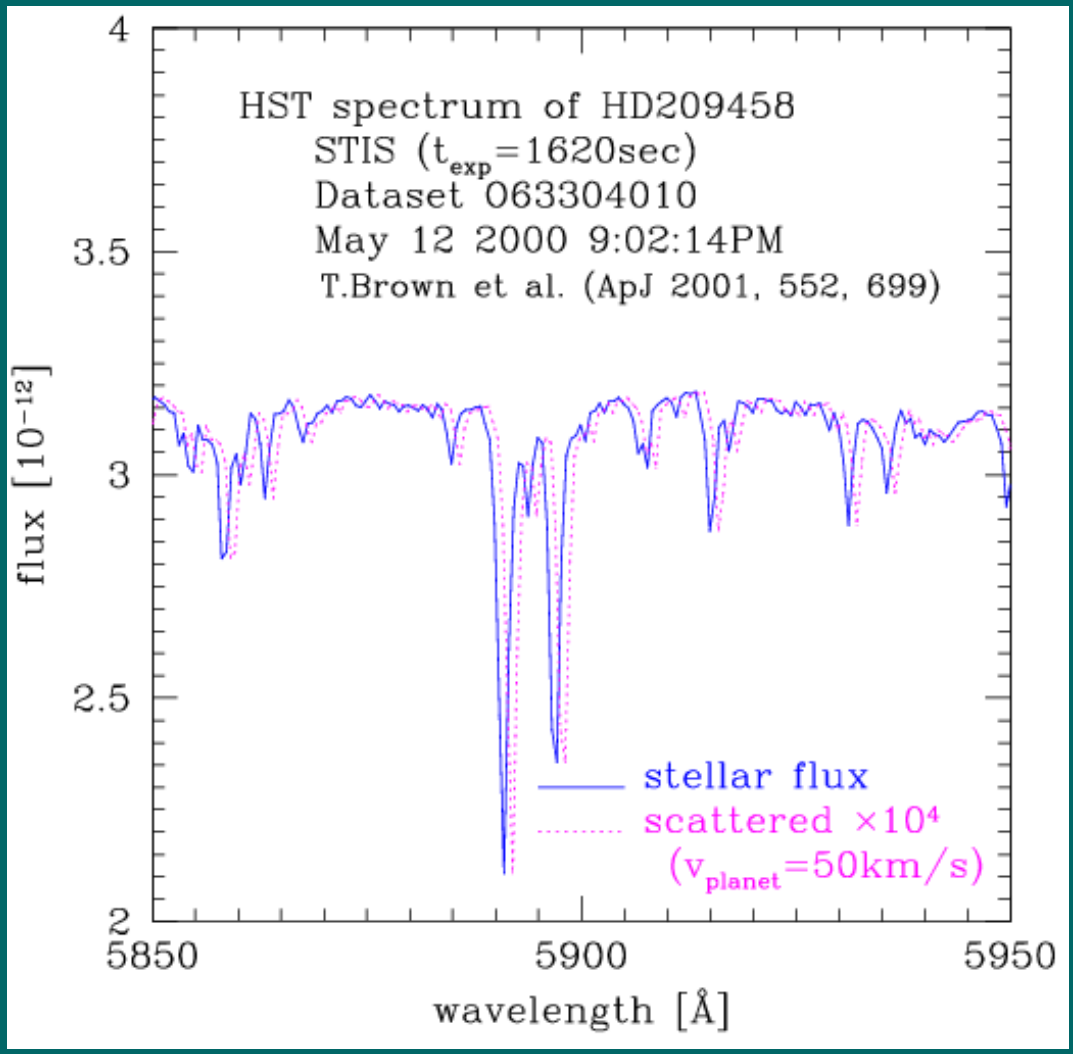
Orbital phase and radial velocity of HD209458b at our observing runs





Winn et al. PASJ 56(2004) 655, astro-ph/0404469
Narita et al. PASJ 57(2005)471 , astro-ph/0504450

Search for scattered light from HD209458b



- Statistical search for the scattered components Doppler-shifted at $v_p(t)$ from the stellar absorption lines.
- The spectral resolution of HDS ($\lambda/\Delta\lambda$=50000) is 10 times better than that of STIS, HST ($\lambda/\Delta\lambda$=5540).

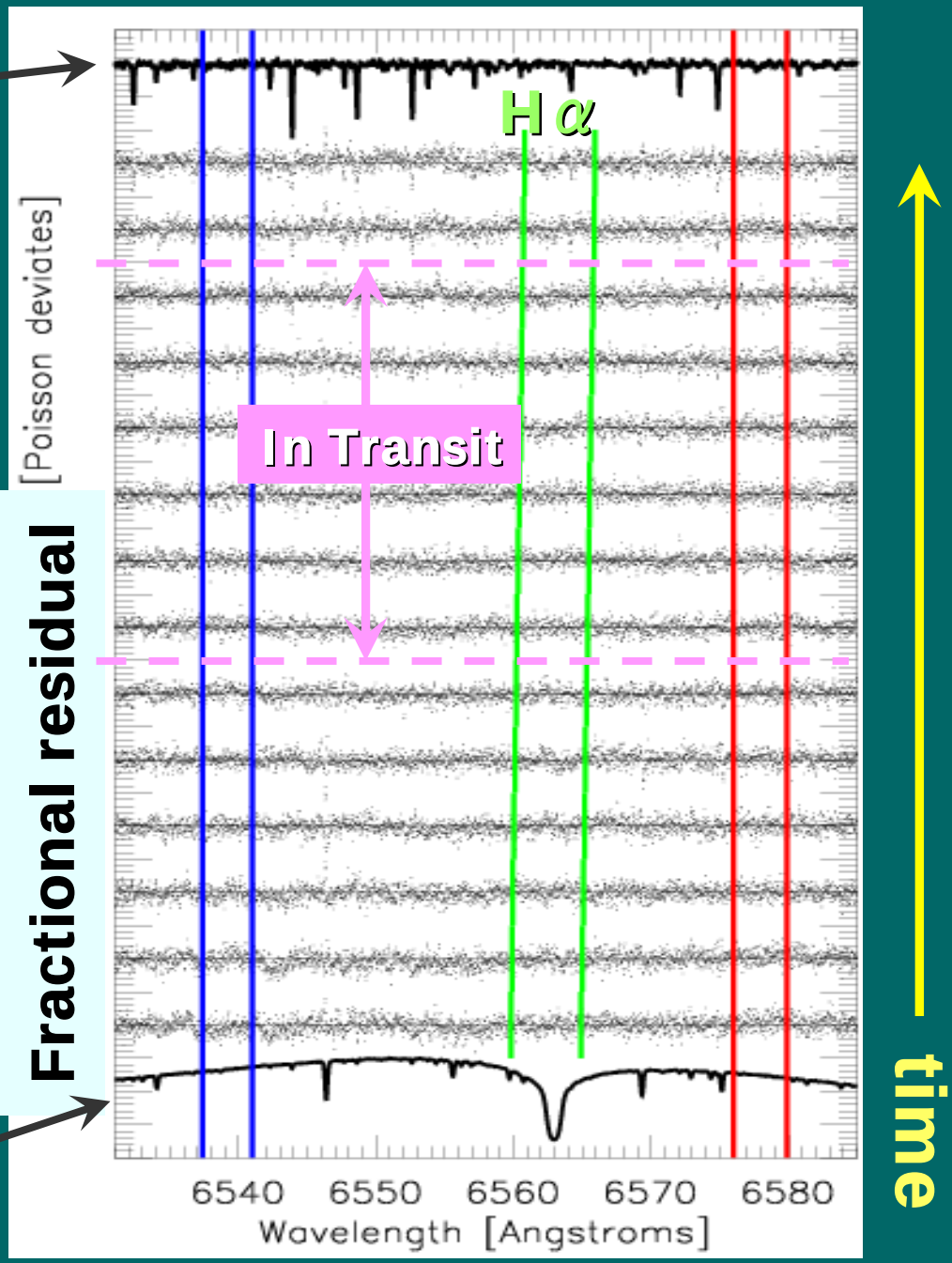
Telluric spectrum

Search for H α absorption due to the atmosphere of HD209458b

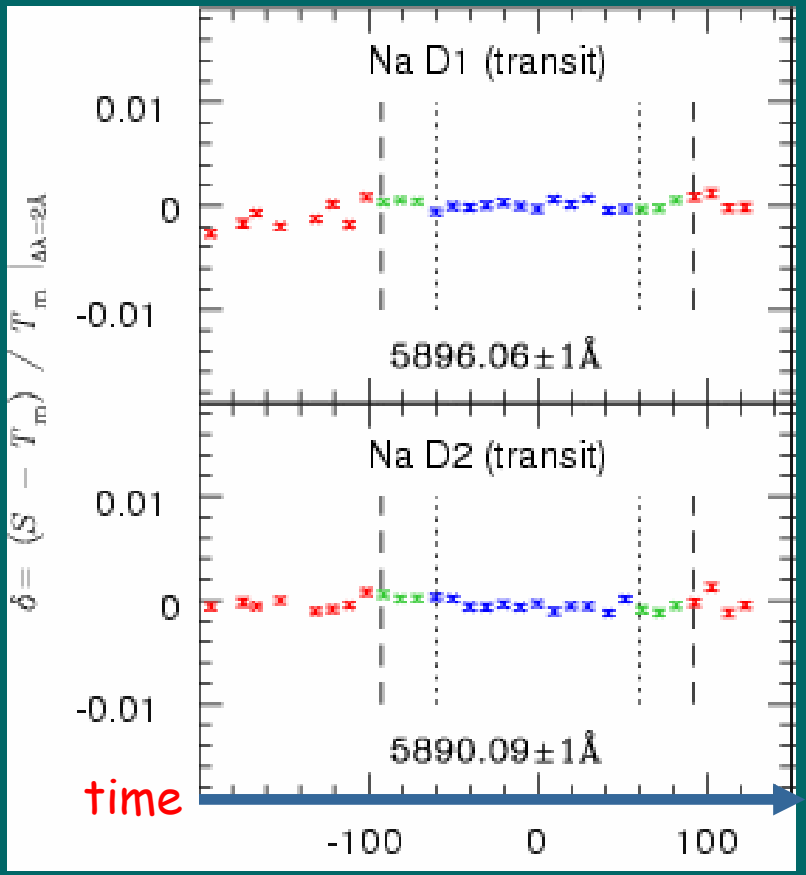
Na I (D2)	5889.97 Å
Na I (D1)	5895.94 Å
H α	6562.81 Å
H β	4861.34 Å
H γ	4340.48 Å

Template steller spectrum

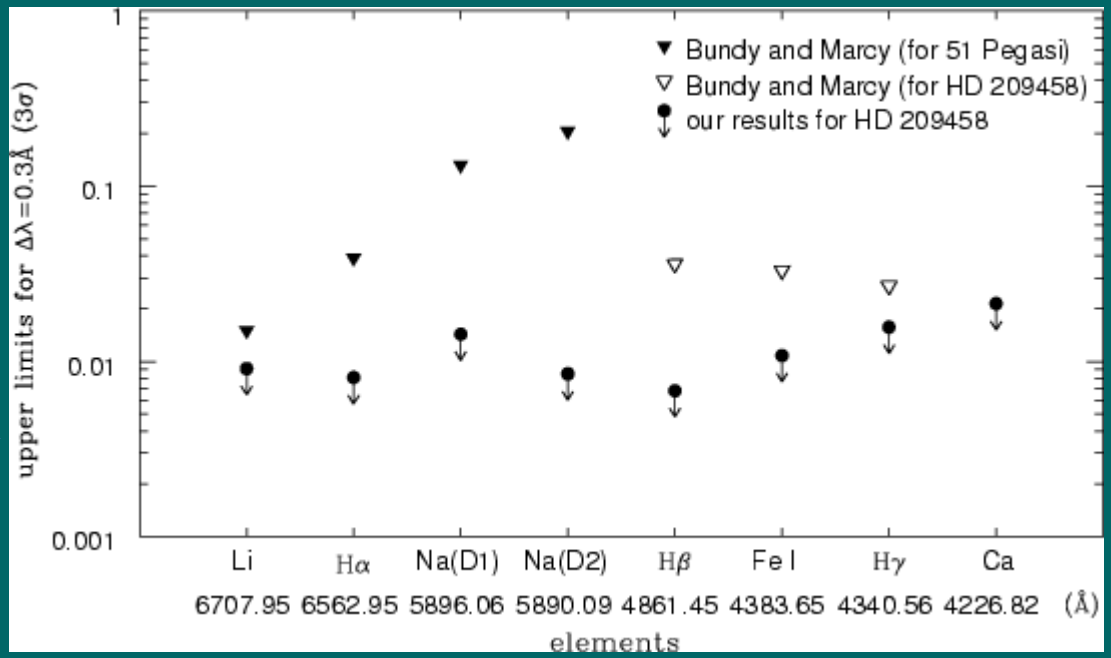
Winn et al. (2004)



most stringent upper limits from ground-based optical observations

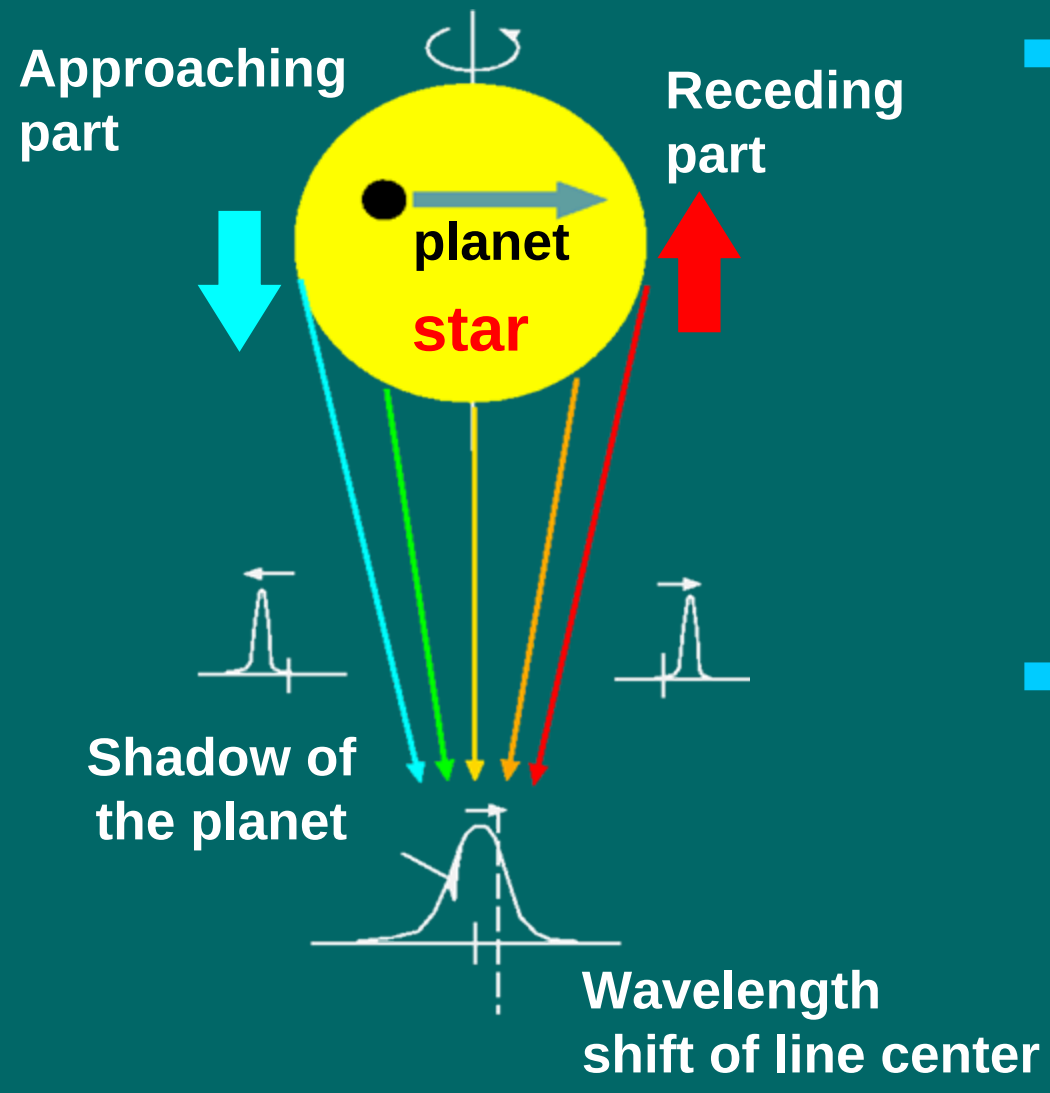


Comparison with previous results for 0.3 Å smoothing (Bundy and Marcy 2000)



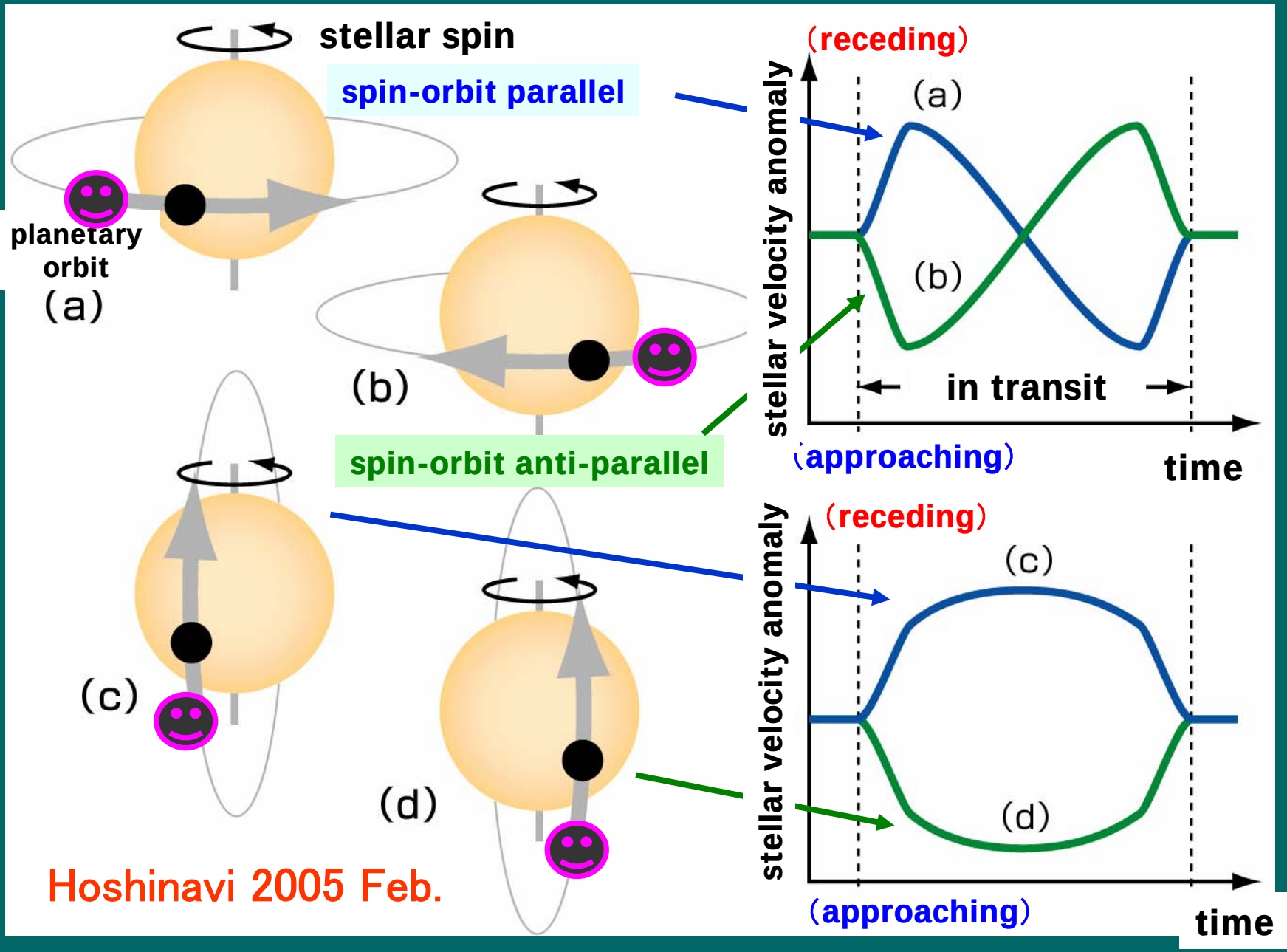
Narita et al. (2005)

Spectroscopic transit signature: the Rossiter-McLaughlin effect



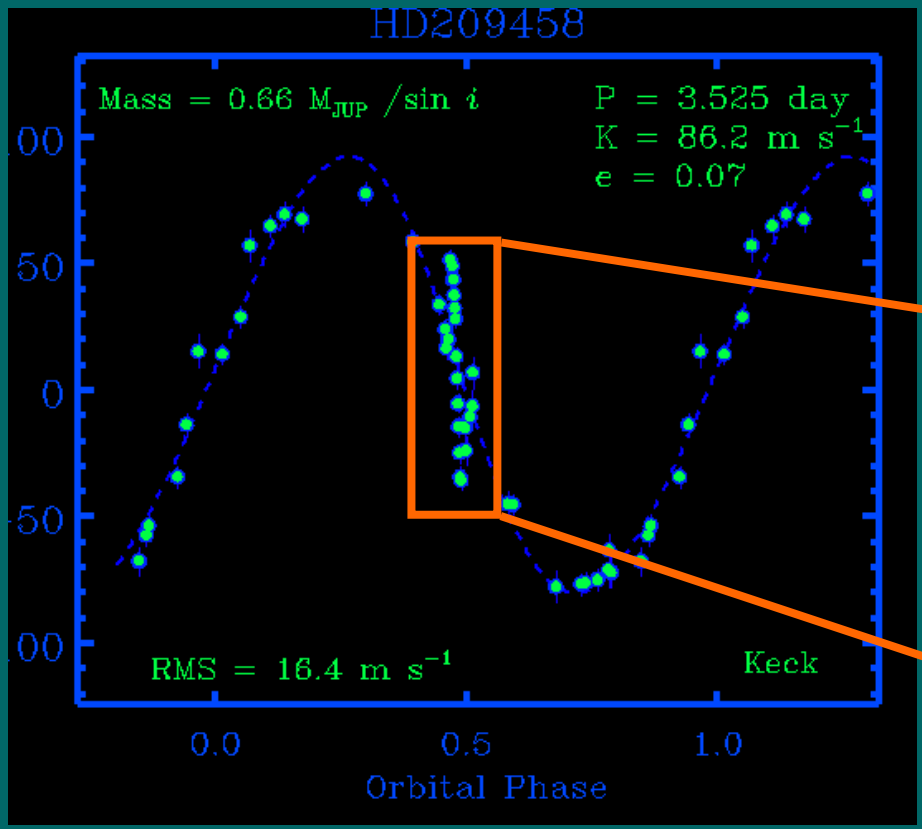
- Time-dependent asymmetry in the stellar Doppler broadened line profile
  - an apparent anomaly of the stellar radial velocity
- originally discussed in eclipsing binary systems
  - Rossiter (1924)
  - McLaughlin (1924)

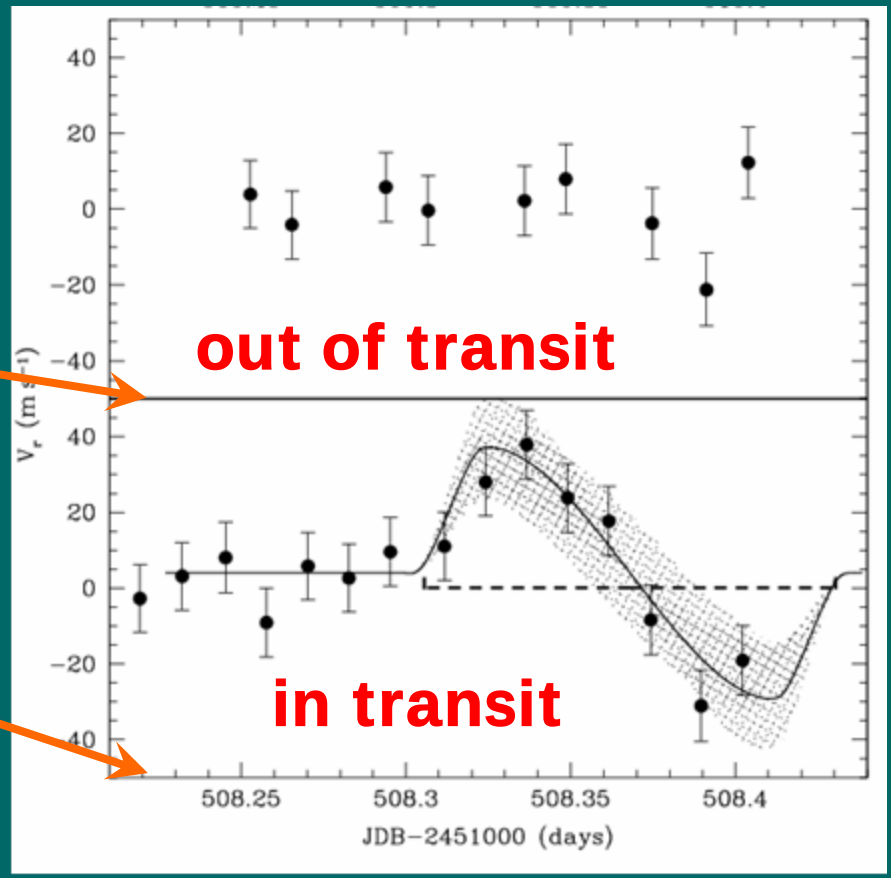
Velocity anomaly due to the Rossiter effect



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

Origin of angular momentum





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

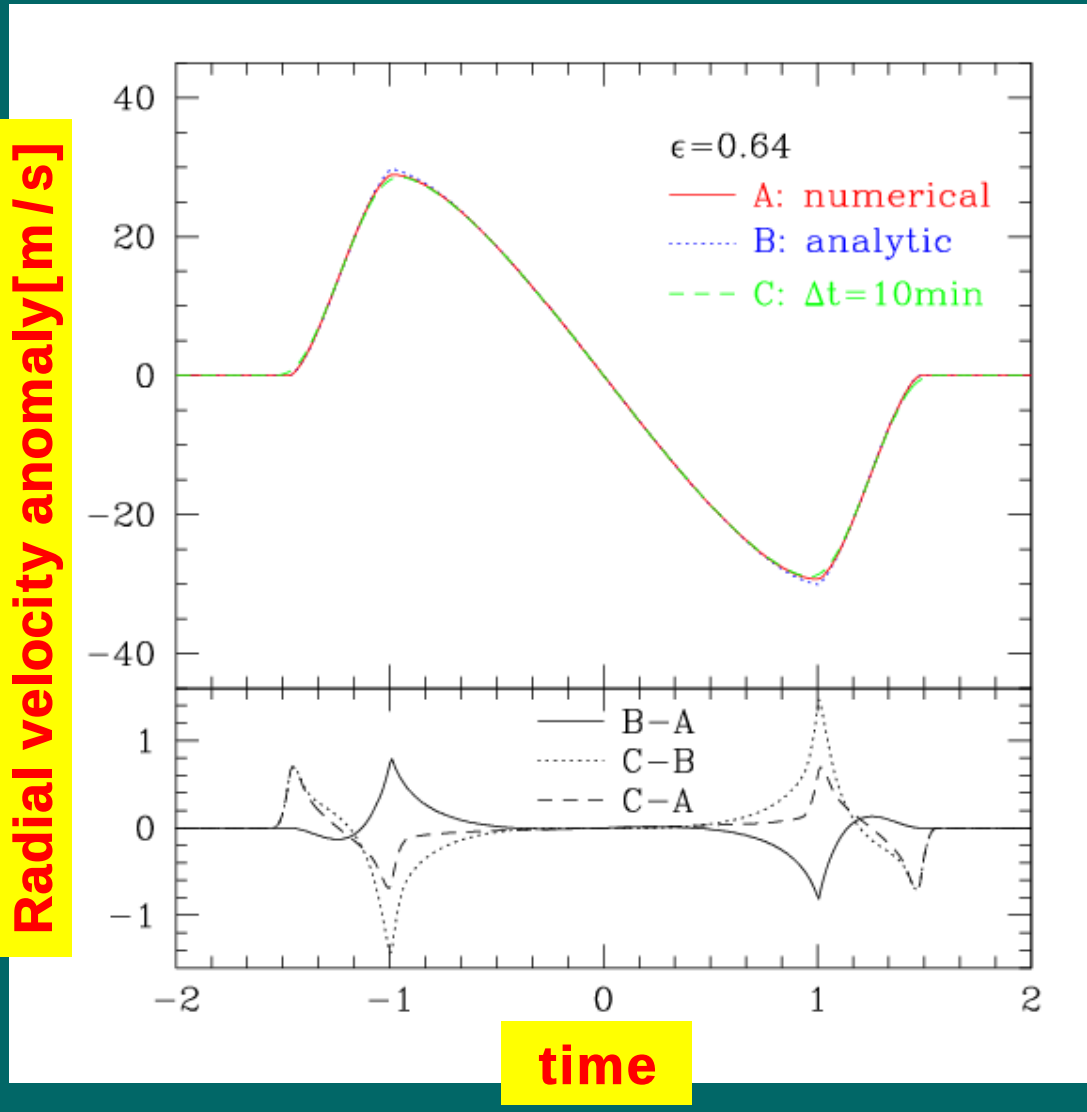
Stellar rotation and planetary orbit
Queloz et al. (2000) A&A 359, L13
ELODIE on 193cm telescope

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 2005, 622, 1118)



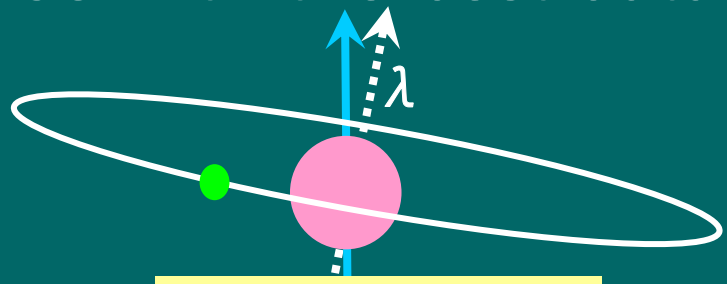
Measurement of Spin-Orbit alignment in an Extrasolar Planetary System

- Joshua N. Winn (CfA→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

- Ohta et al. (2005) stimulated Josh Winn
- Josh re-examined HD209458 with the best data available
  - radial velocity data (Keck)
  - optical photometry (HST)
  - infrared photometry (Spitzer)

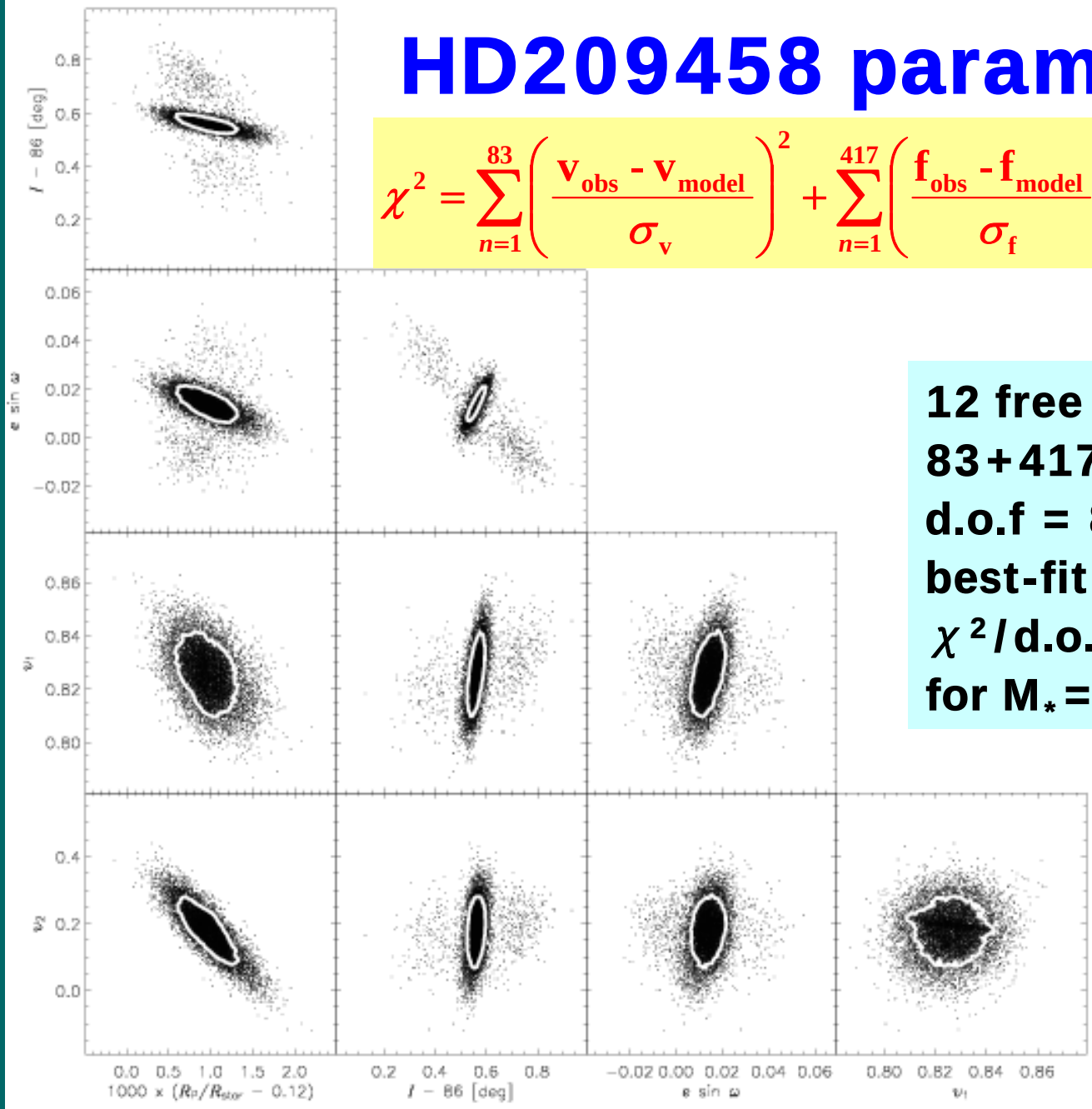


$\lambda = -4^\circ.4 \pm 1^\circ.4$

- **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 !
  - c.f., 6 degree misalignment for the Solar system
- **$\lambda \neq 0$ problem other than in cosmology !**

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

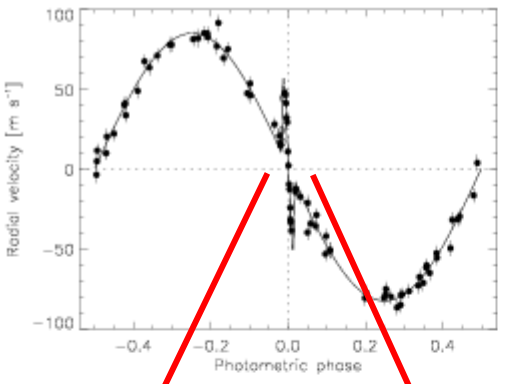
for $M_* = 1.06 M_{sun}$

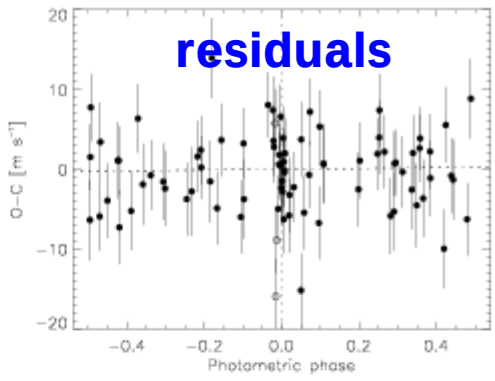
Winn et al.

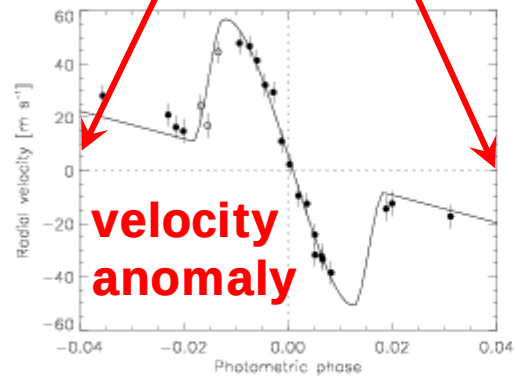
astro-ph/0504555

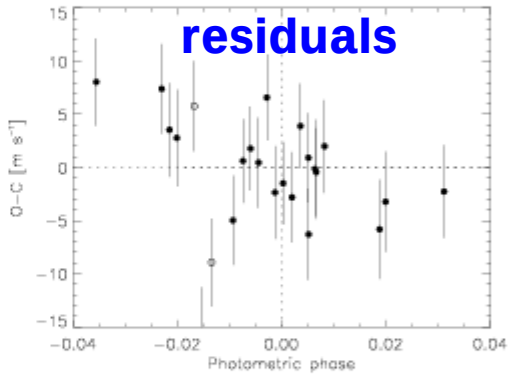
ApJ 631(2005)1215

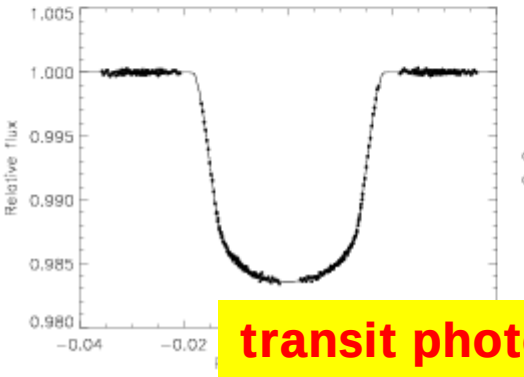
radial velocity (Keck)

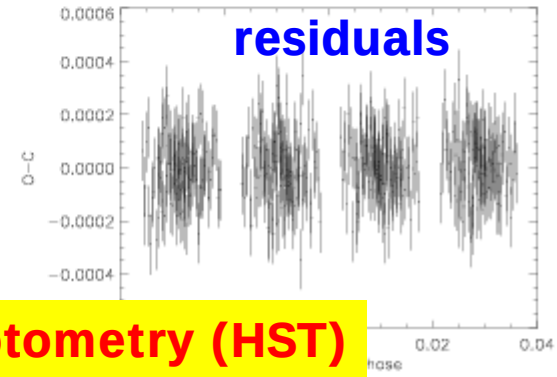






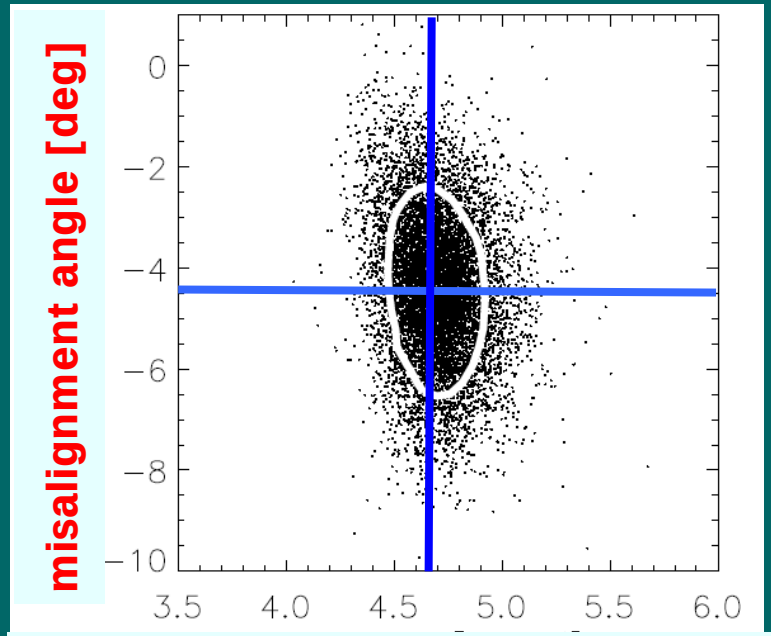






transit photometry (HST)

first detection of non-zero λ !

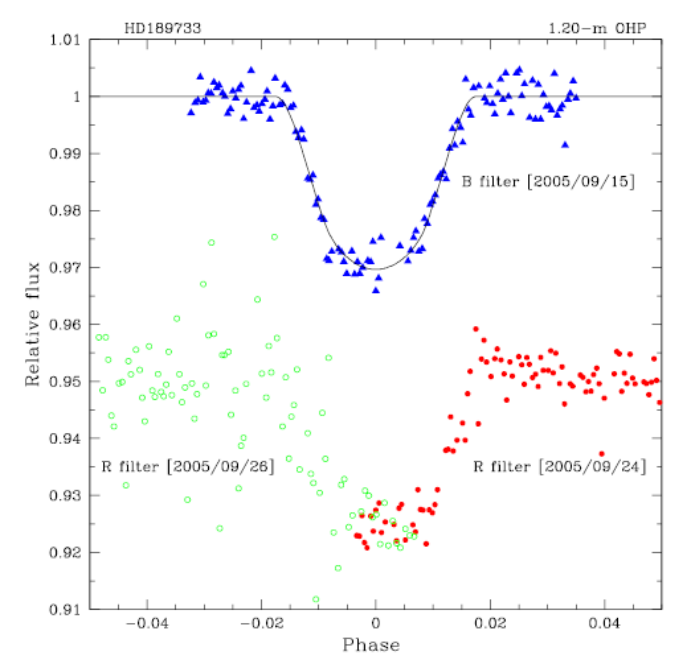


$$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$$

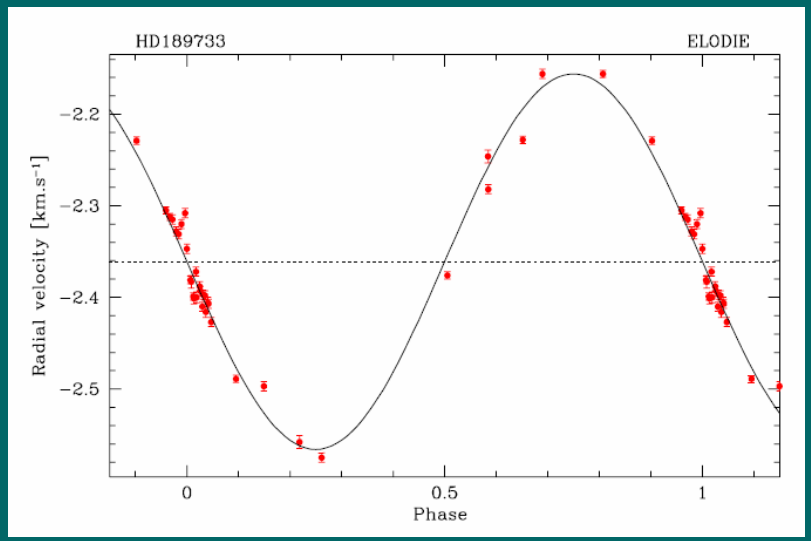
3σ detection !

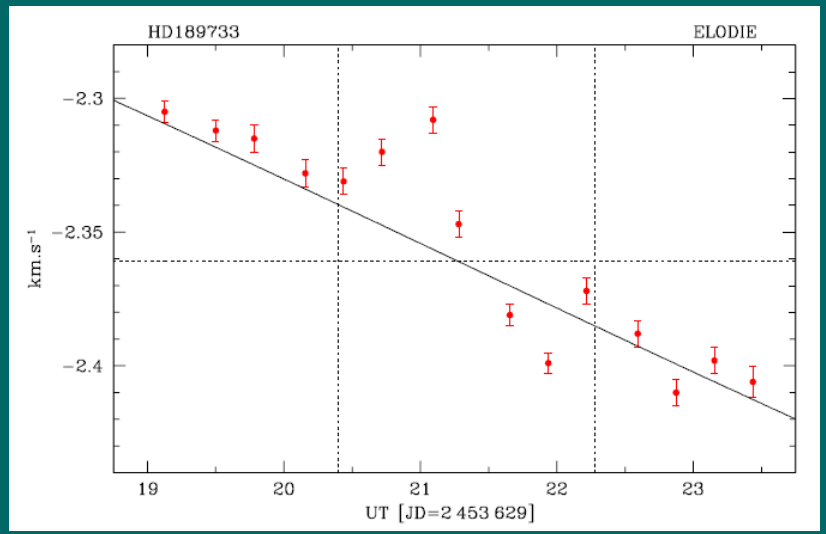
Winn et al. astro-ph/0504555 ApJ 631(2005)1215

More to come !



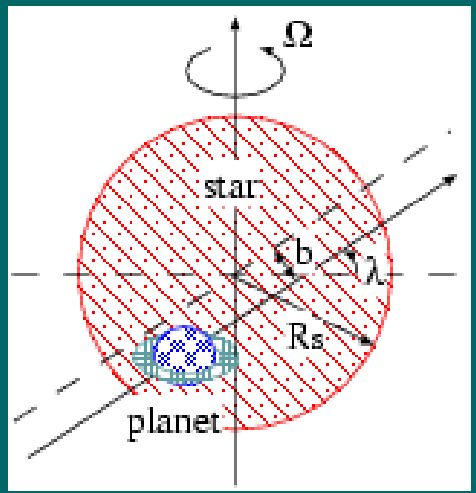
- **Rossiter effect is observed for 3 out of 9 known transit planetary systems**
- **HD189733 V=7.67 K1-K2**
  - P=2.2day, M=1.15M_J, R=1.26R_J
  - Bouchy et al. astro-ph/0510119
- **HD149026, V=8.15 G0IV**
  - P=2.9day,M=0.36M_J, R=0,73R_J
  - Sato et al. astro-ph/0507009
- **Our Subaru+MAGNUM obs. of TrES1 scheduled in June 2006**

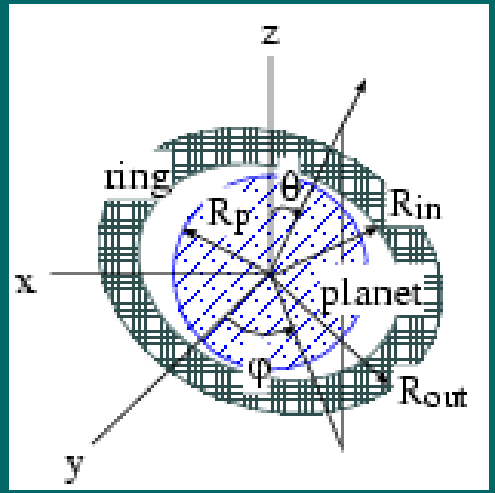


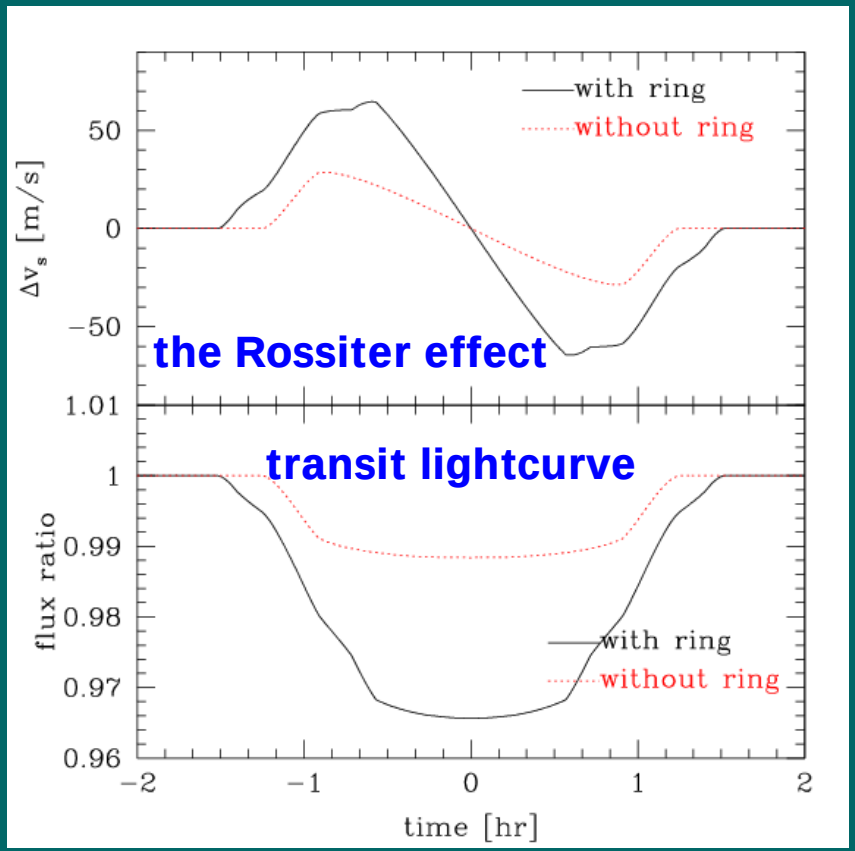


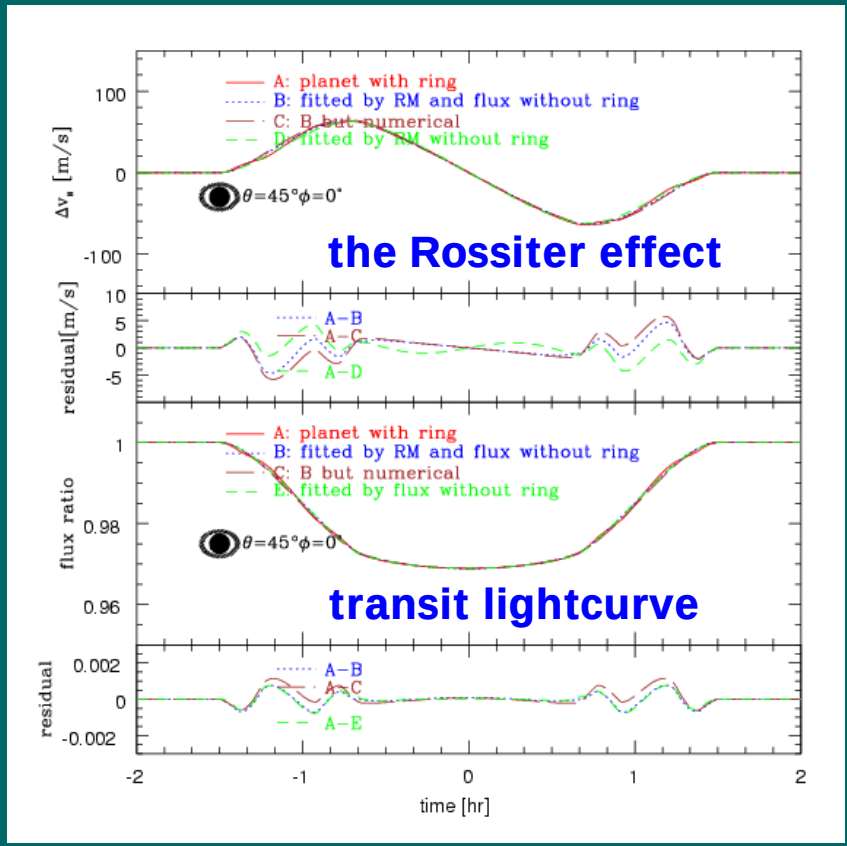
Signatures of a ring

Ohta, Taruya & Suto in preparation.

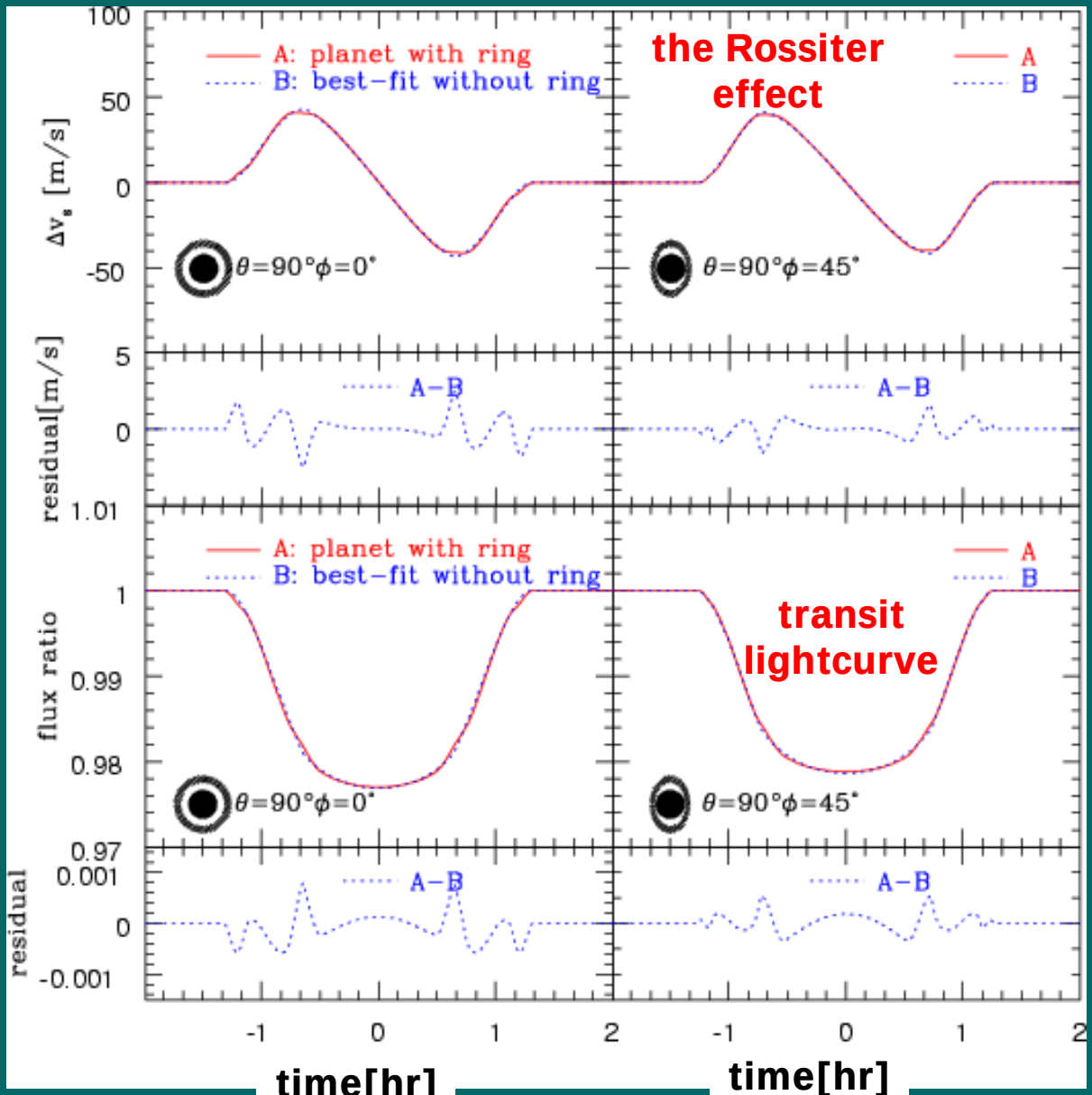








Detectability of a ring of extrasolar planets



- a hypothetical ring around HD209458
  - $1.5R_J < R_{ring} < 2R_J$
  - deviation from a best-fit single planet
  - $\delta v \sim 1 m/s$
  - $\delta F/F \sim 0.1\%$
- marginally detectable even with the current precision (if they exist at all around hot Jupiters !)

Future prospects

- exciting era of extrasolar planet research
  - Just like cosmology in 1965 (Penzias and Wilson) or in 1992 (COBE)
  - Simply 10-40 years behind ? i.e., bright future !
- What if we discover more than 1000 terrestrial planets in the next decade ?
  - Just like cosmology in 2003 (WMAP+others) ?
- ***How to convince ourselves of the presence of extra-terrestrial life simply from remote observations ?***
  - Precision extrasolar planet research ?
  - Go (back) to SETI after all ?
  - Ultra-precise spectroscopy is the key !