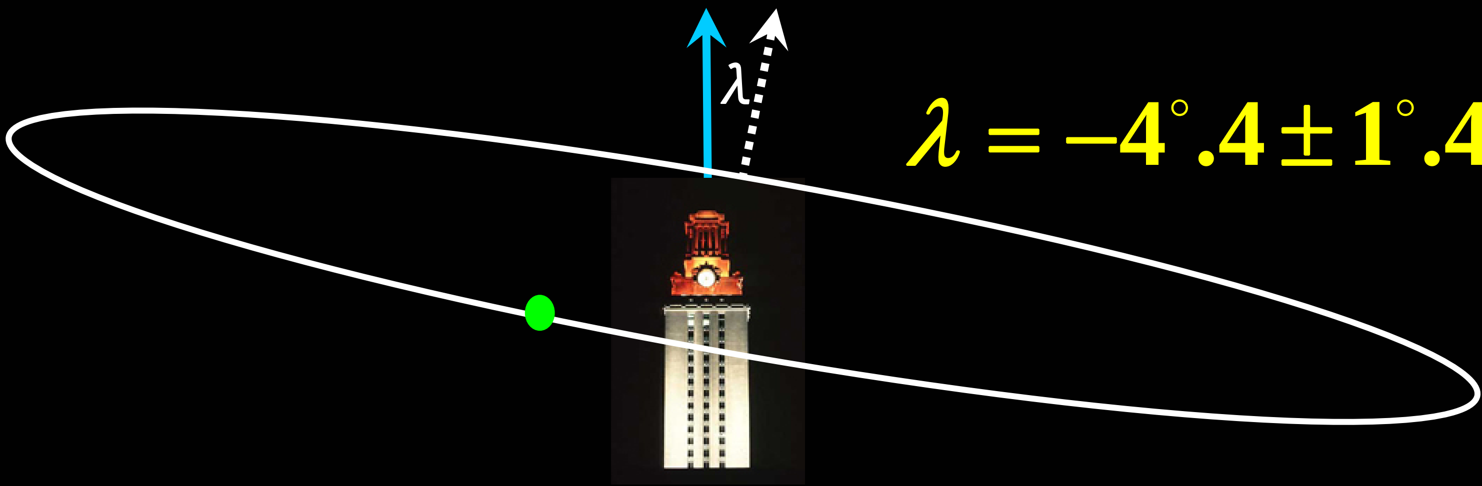
High-resolution spectroscopic observations of a transiting extrasolar planet HD209458b

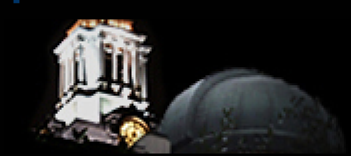


$$\lambda = -4^\circ.4 \pm 1^\circ.4$$

Yasushi Suto *Department of Physics, University of Tokyo*

東京大学
THE UNIVERSITY OF TOKYO

planets and life seminar (3:30pm-, October 19, 2005)



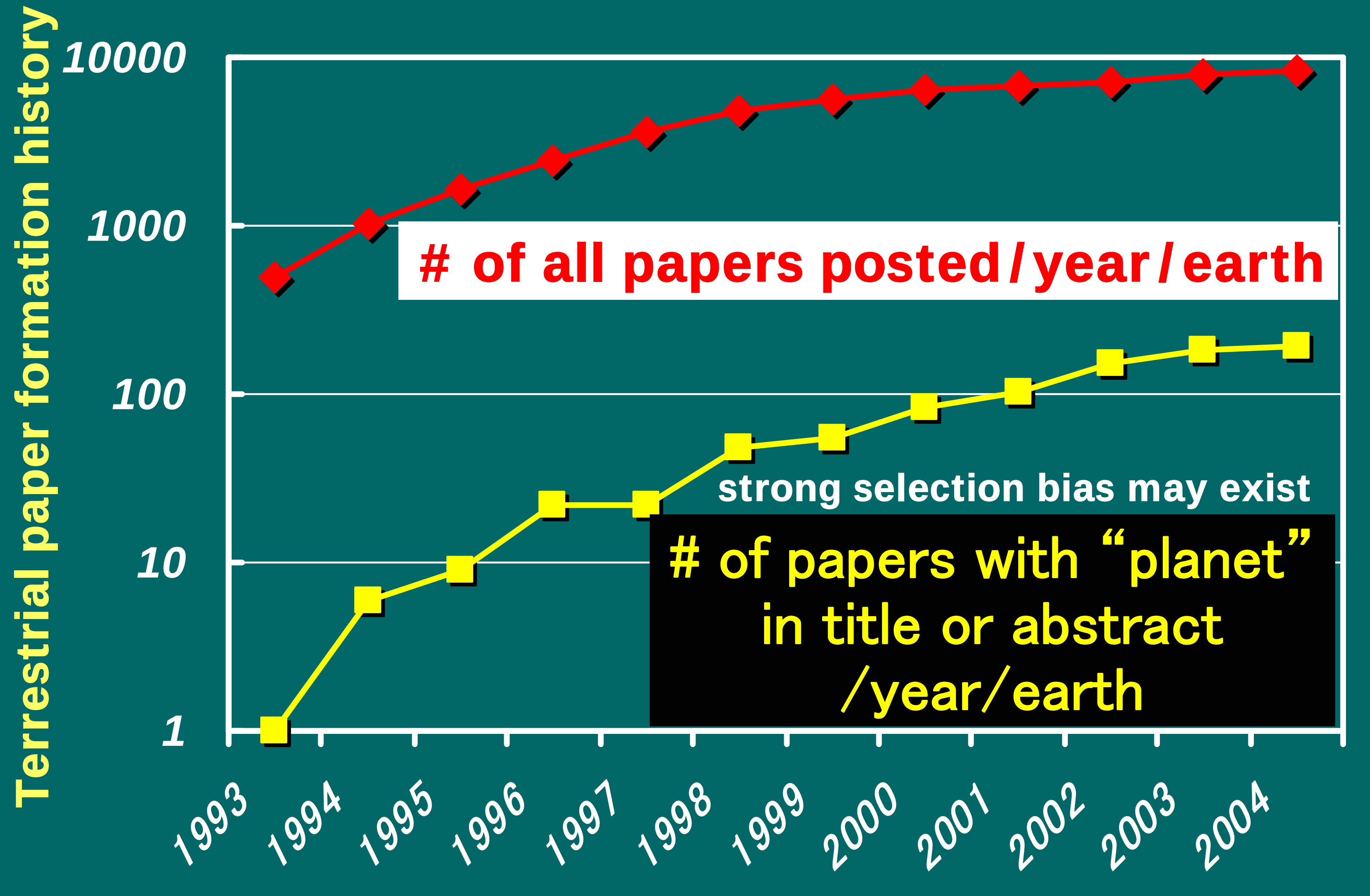
DEPARTMENT OF ASTRONOMY
THE UNIVERSITY OF TEXAS AT AUSTIN

A brief history of the discovery 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:** spin-orbit misalignment via the Rossiter effect
- *169 extrasolar planets* are reported (October, 2005)

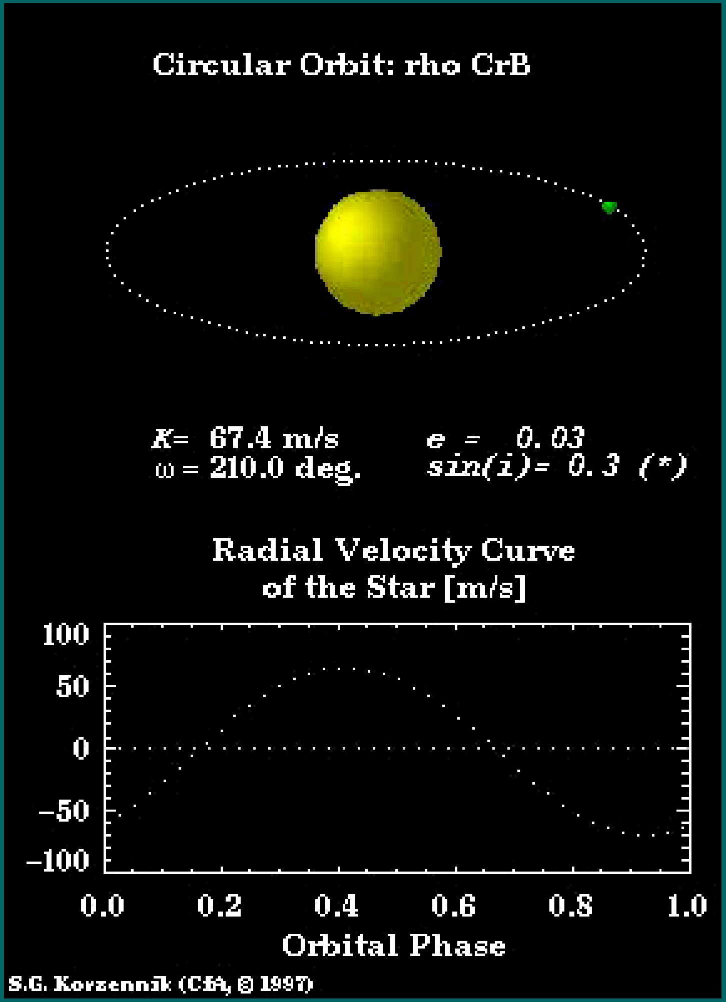
http://exoplanets.org/

“Evolution” of extra-solar planet research



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:

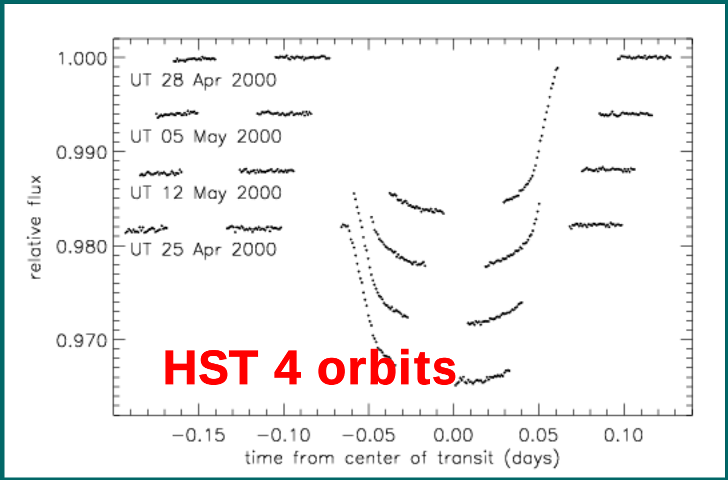
12.5 m / s（Jupiter）

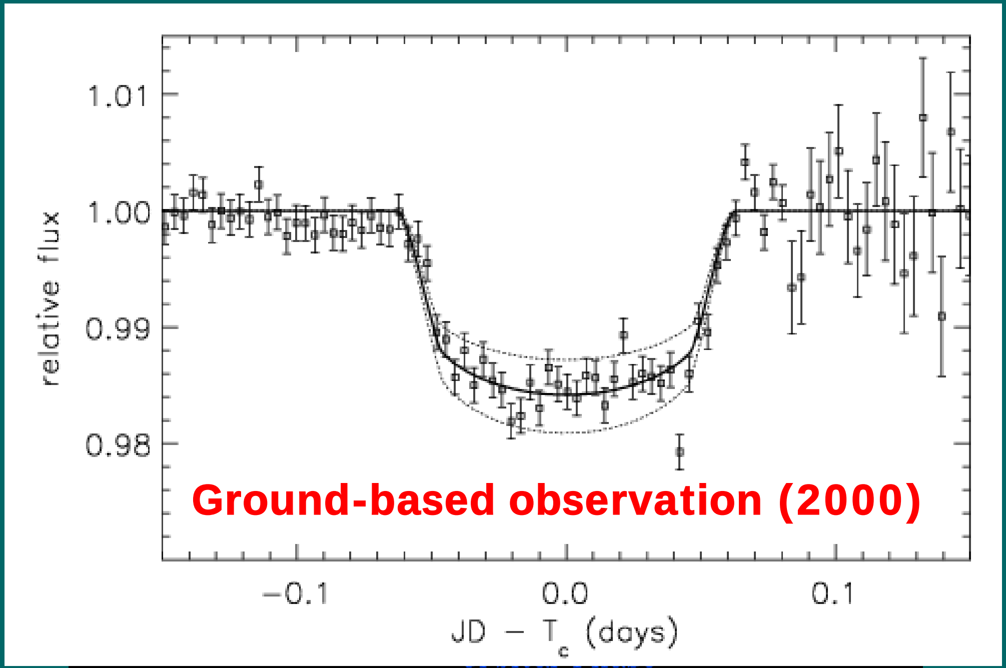
0.1 m / s（Earth）

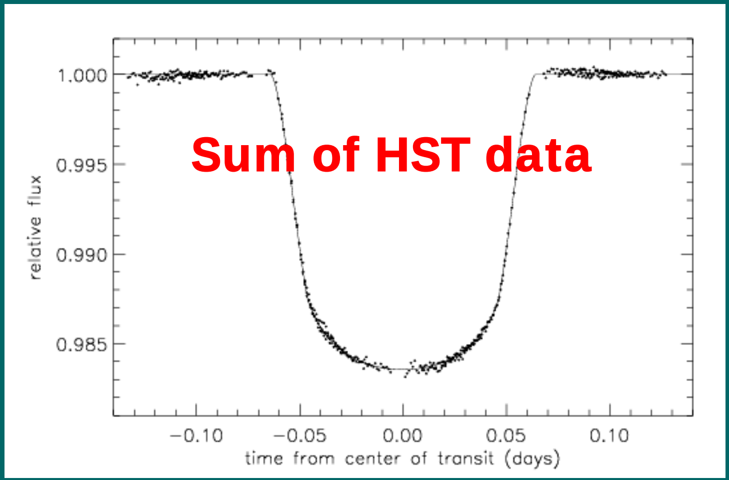
an accuracy of 1m/s achieved from the ground observation
⇒ the current major method in search for Jupiter-sized planets

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)

Estimated parameters of HD209458b

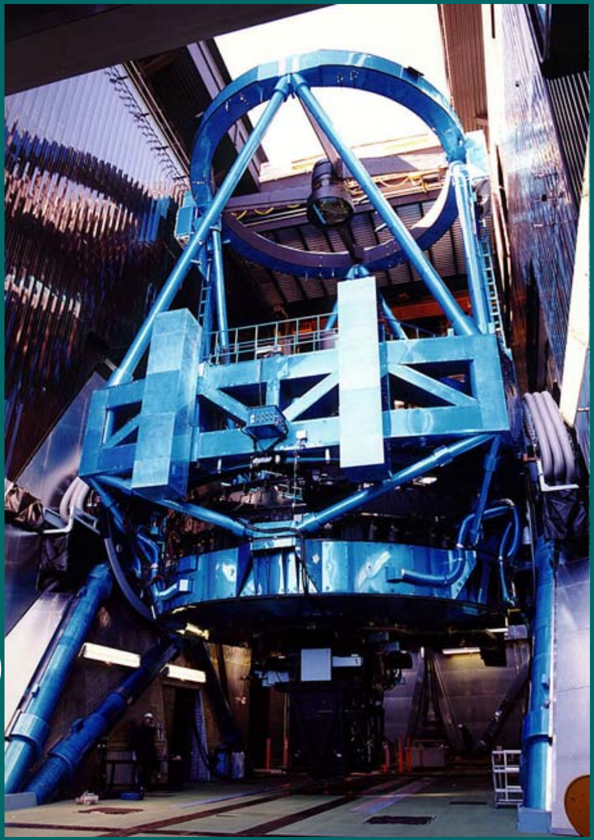
HD209458	**G0V V=7.58 (d=47pc)**	
HD209458b	**Orbital Period**	**3.52474 ± 0.00004 days**
	viewing angle	**86.68±0.14 deg**
	Mass	**0.63 $M_{Jupiter}$**
	Size	**1.347±0.060 $R_{Jupiter}$**

- First ever convincing evidence for the case of an extrasolar planet !
- M_p=0.63 M_J, R_p=1.3 R_J
- ρ =0.4 g/cm^3 < Saturn's density
- Gas planet ! (not black hole, rock …)
- g=970 cm/s^2

Extrasolar 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.)

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)

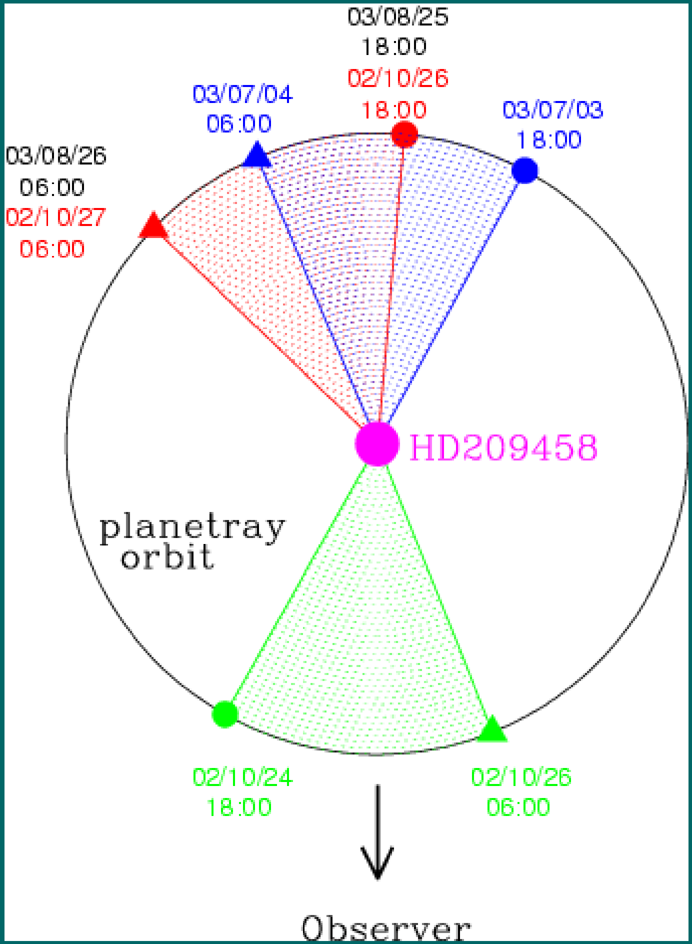
Toru Yamada, Wako Aoki (National Ast. Obs. Japan)

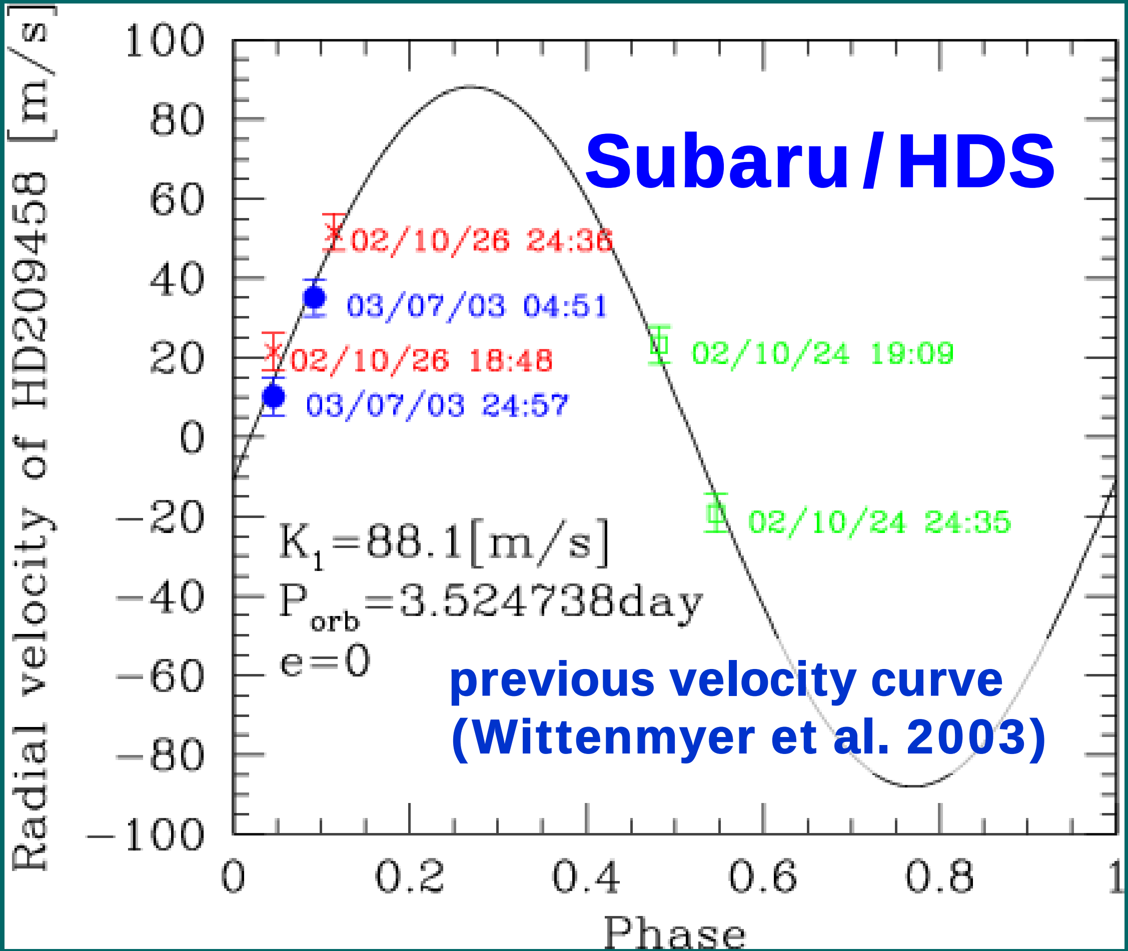
Bun-ei Sato (Kobe Univ.)

Edwin L. Turner (Princeton Univ.)

Josh Winn (Harvard Univ.)

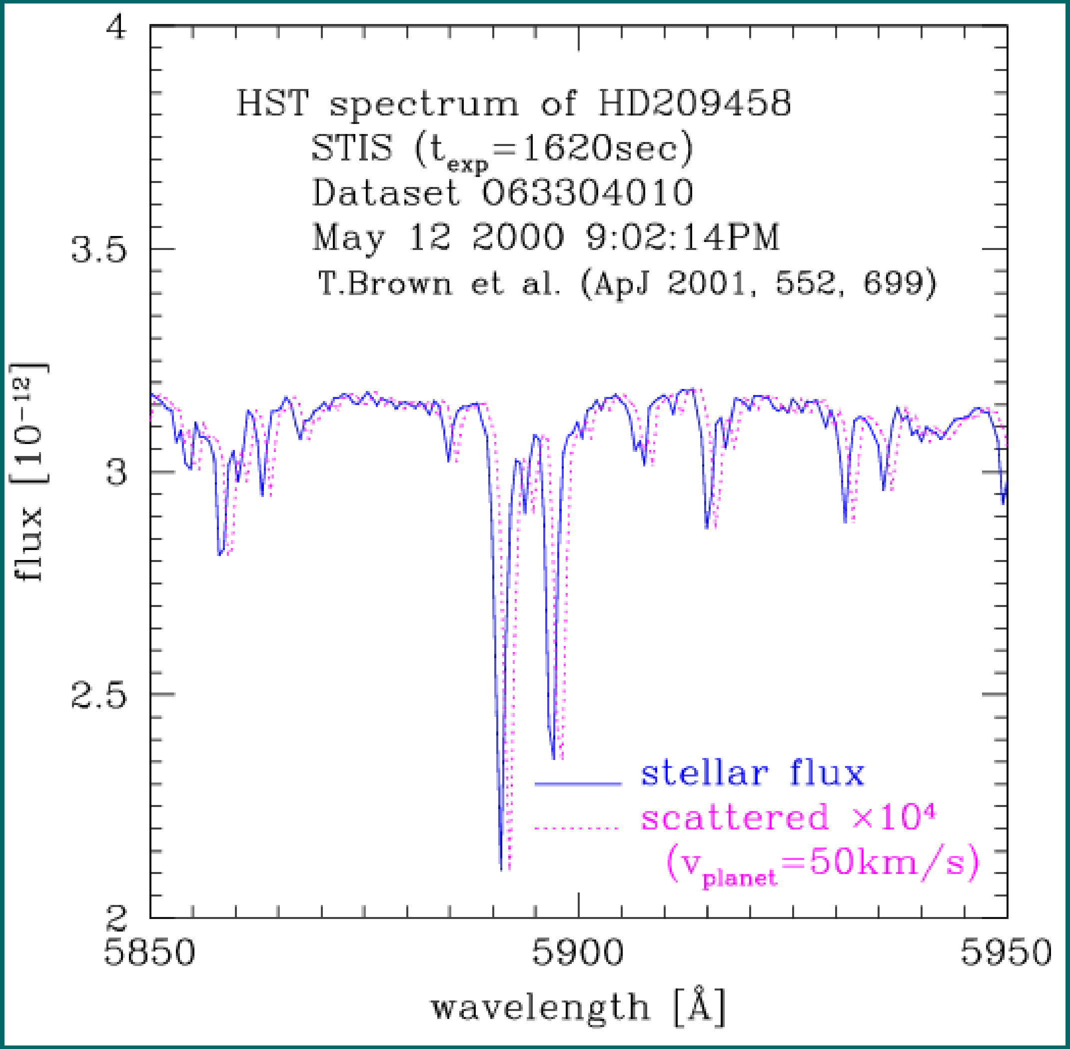
Orbital phase and radial velocity of HD209458b at our observing runs





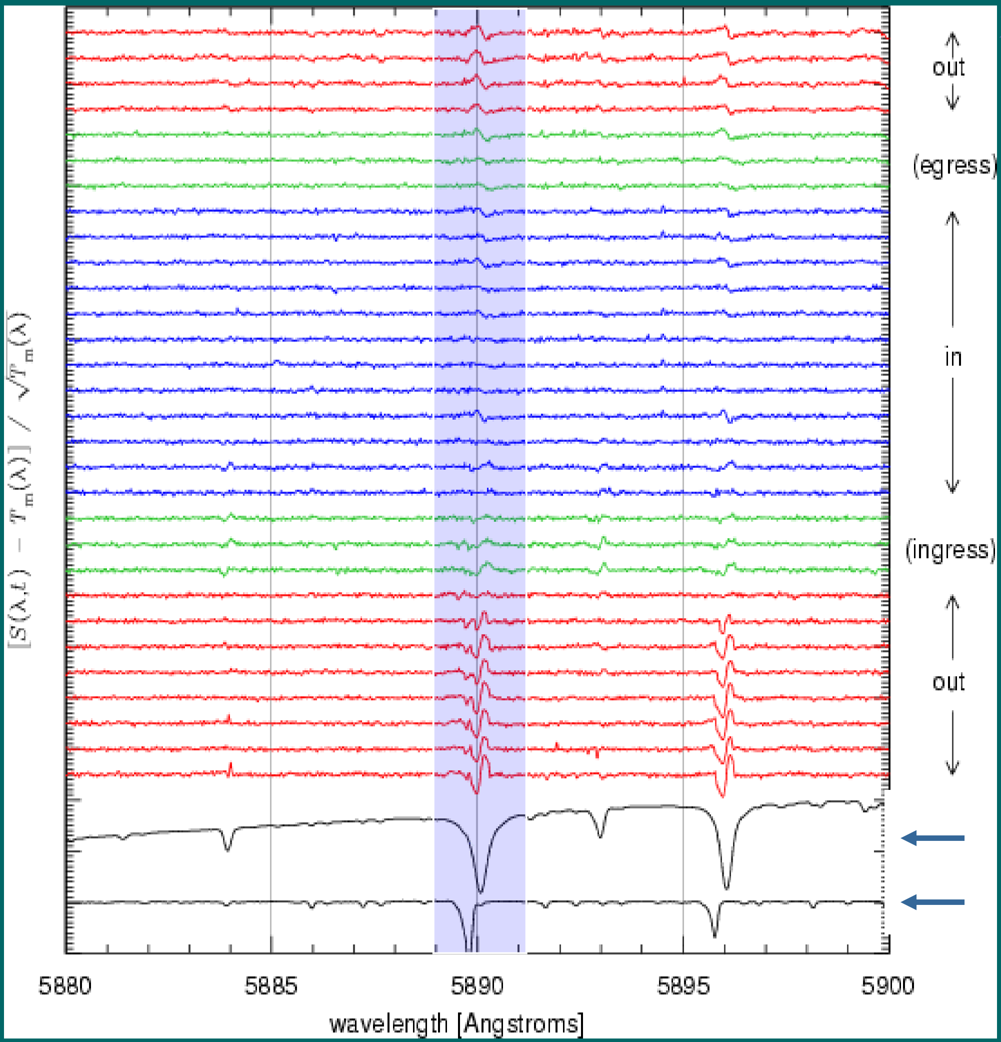
Winn et al. PASJ 56(2004) 655, astro-ph/0404469
Narita et al. PASJ 57(2005)471 , astro-ph/0504450

Search for scattered light from HD209458b



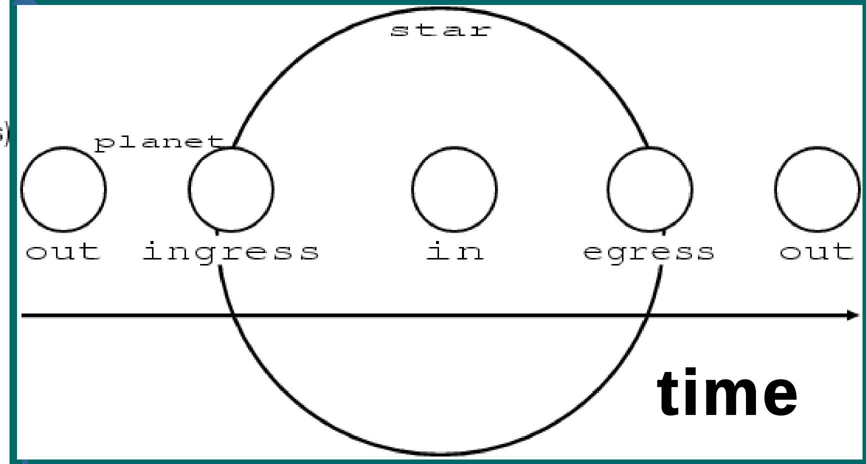
- Statistical search for the scattered components Doppler-shifted at $v_p(t)$ from the stellar absorption lines.
- The spectral resolution of HDS ($\lambda/\Delta\lambda$=50000) is 10 times better than that of STIS, HST ($\lambda/\Delta\lambda$=5540).

Transit transmission spectroscopy



template

telluric

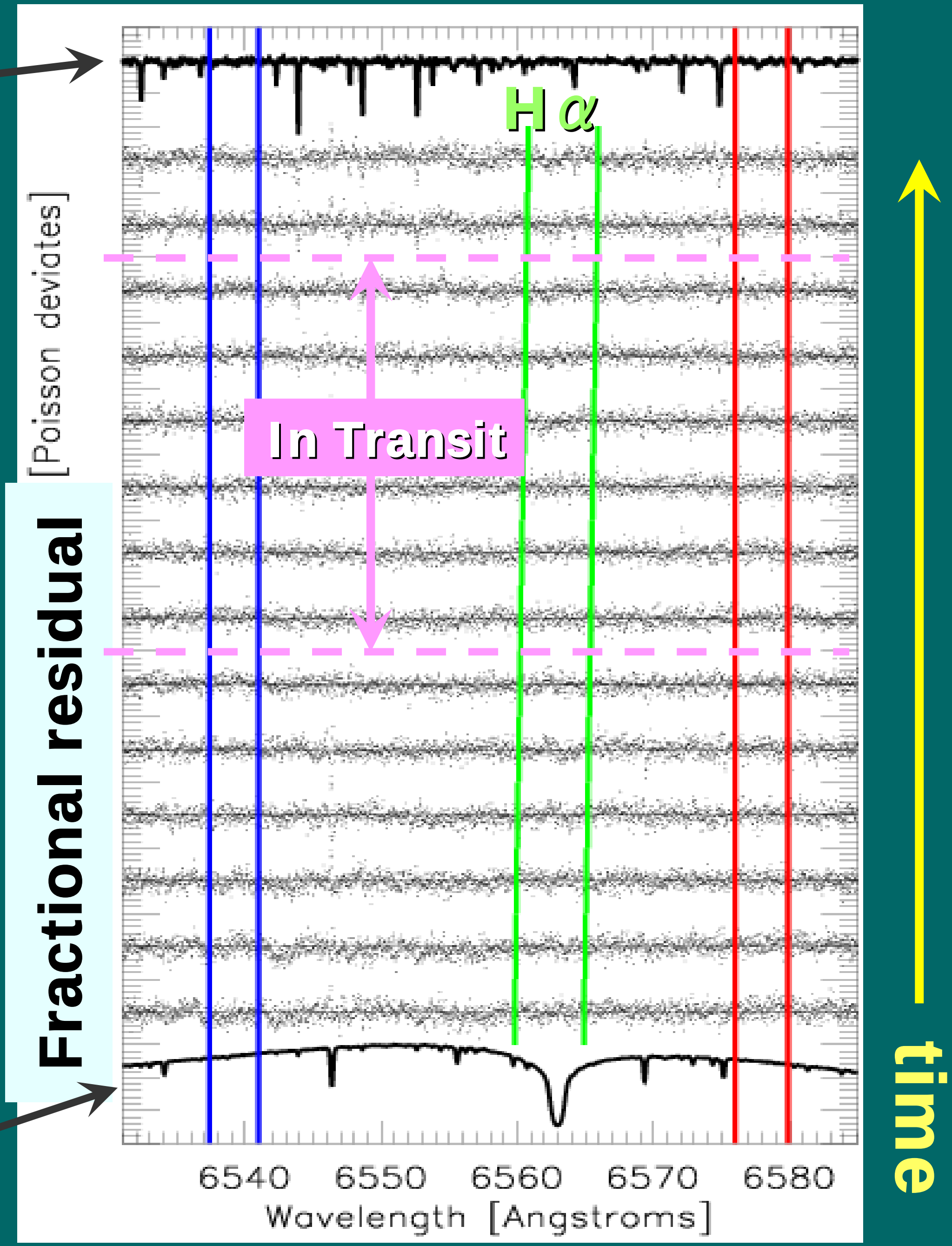


planetary orbital phase

Narita et al. (2005)

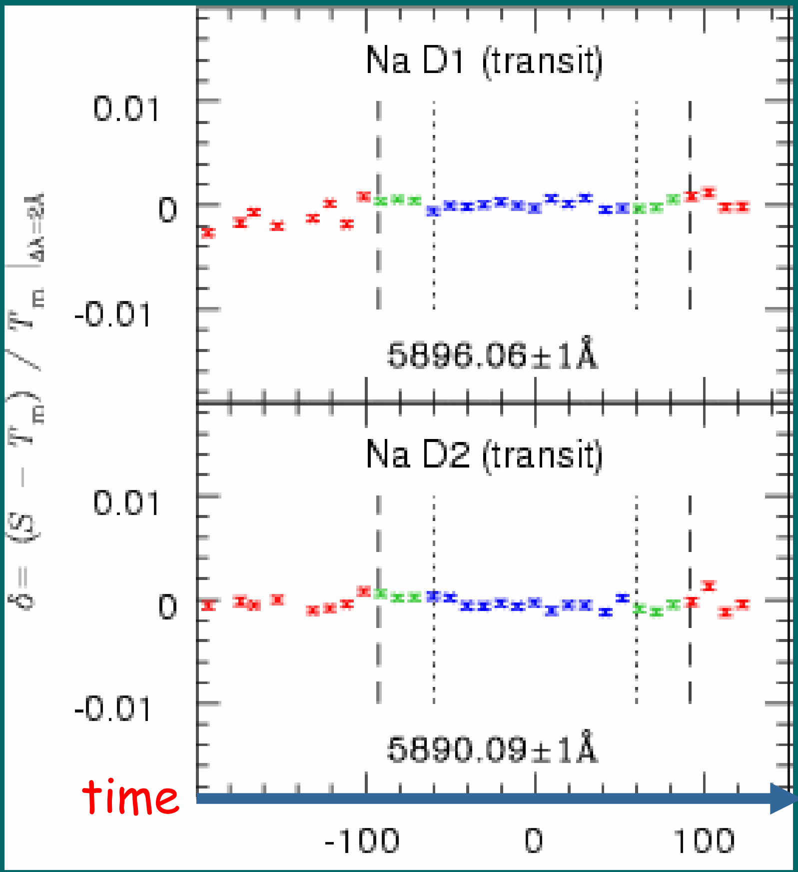
Search for Hα absorption due to the atmosphere of HD209458b

Na I (D2)	5889.97 Å
Na I (D1)	5895.94 Å
Hα	6562.81 Å
Hβ	4861.34 Å
Hγ	4340.48 Å



Winn et al. (2004)

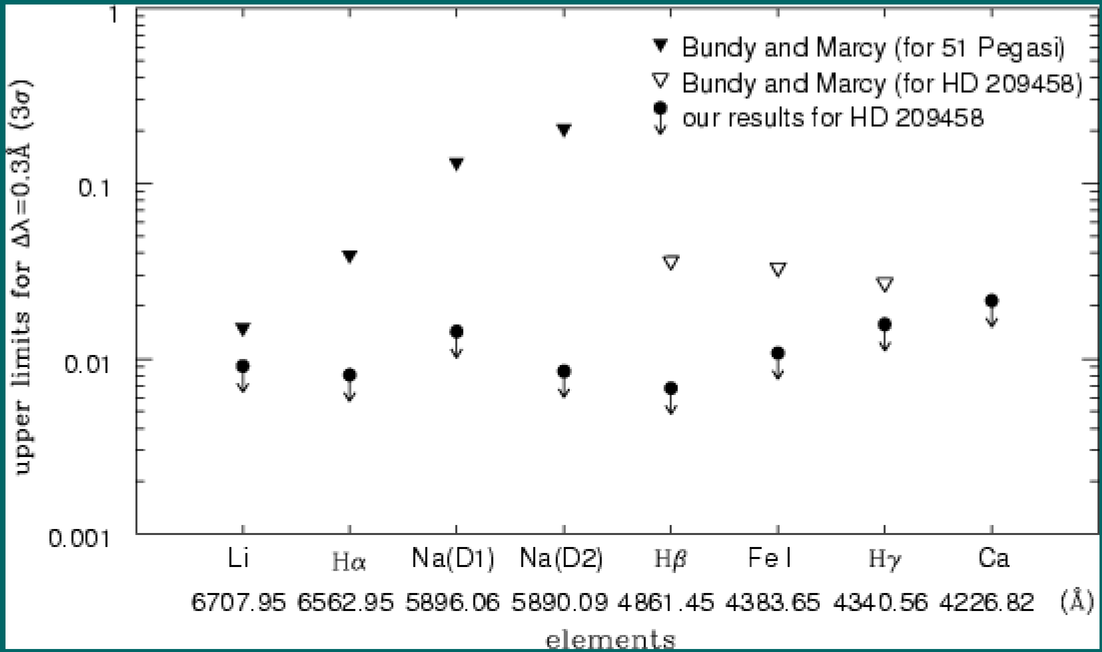
most stringent upper limits from ground-based optical observations



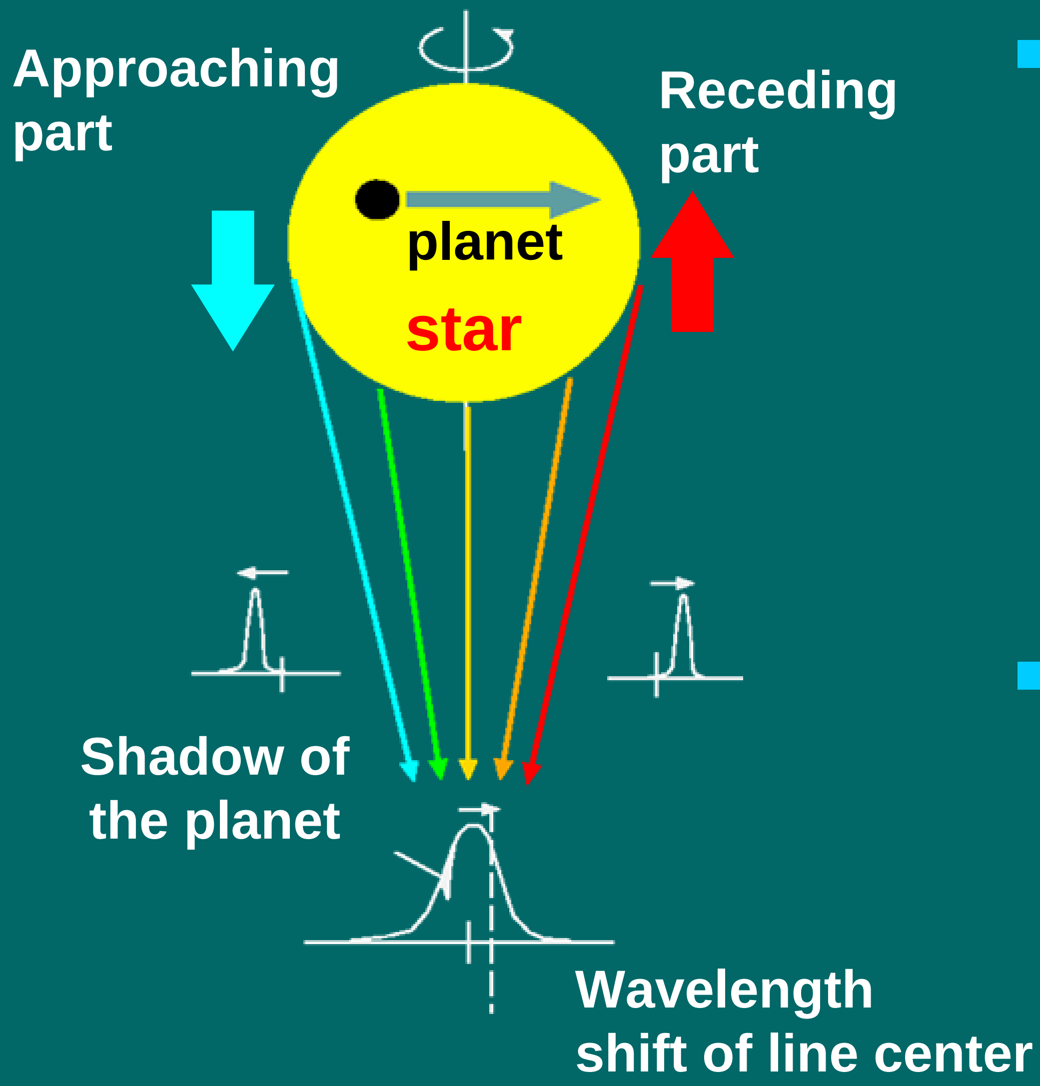
Narita et al. (2005)

Comparison with previous results for 0.3 angstrom bandwidth

(Bundy and Marcy 2000)

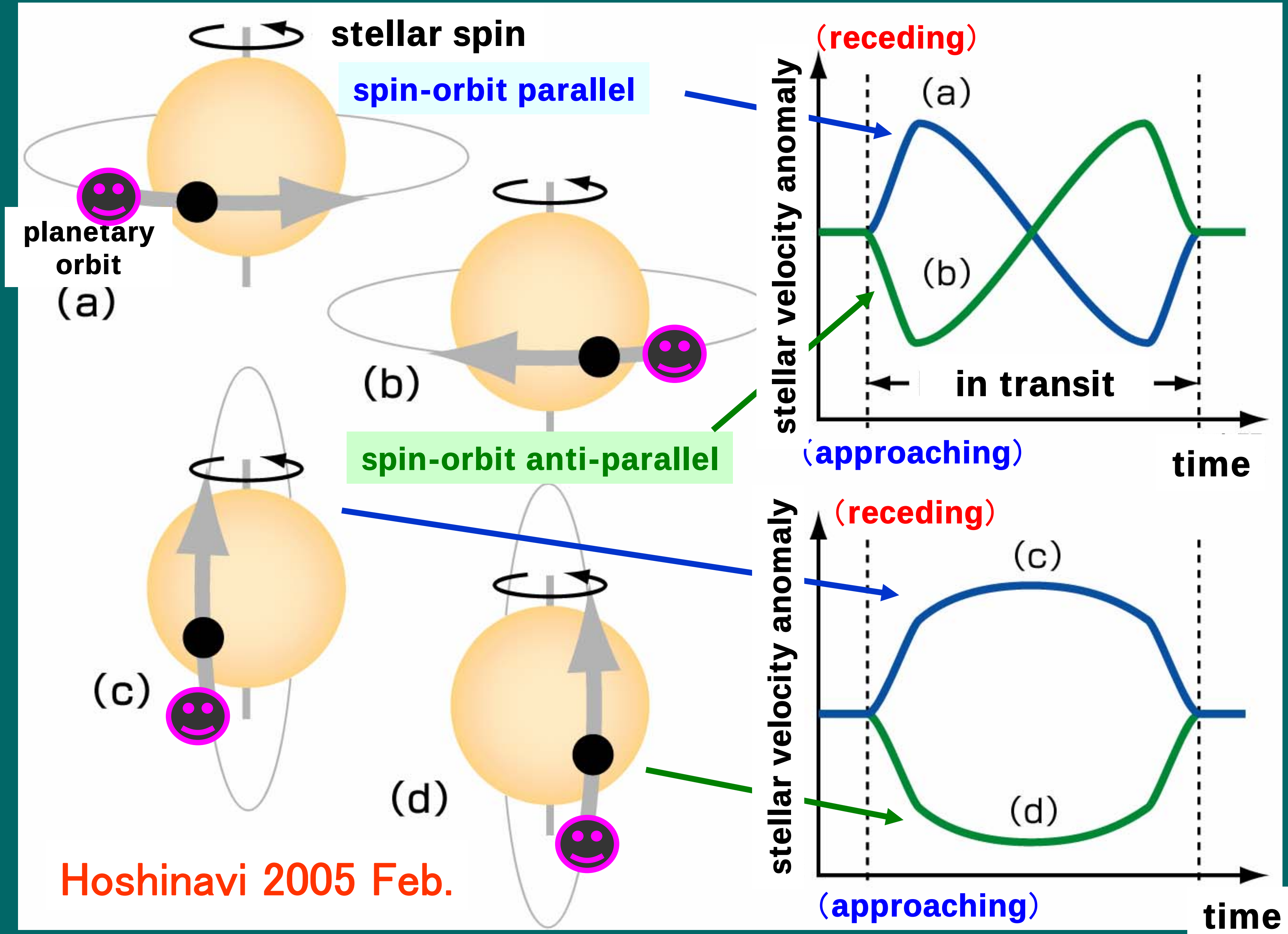


Spectroscopic transit signature: the Rossiter-McLaughlin effect



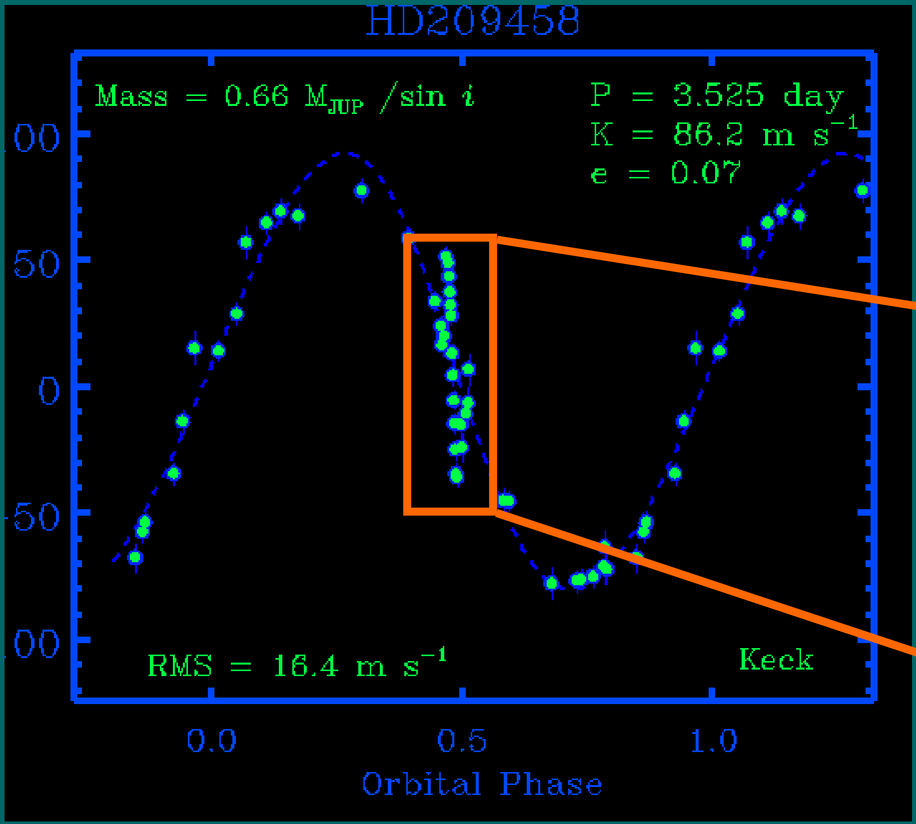
- Time-dependent asymmetry in the stellar Doppler broadened line profile
  - an apparent anomaly of the stellar radial velocity
- originally discussed in eclipsing binary systems
  - Rossiter (1924)
  - McLaughlin (1924)

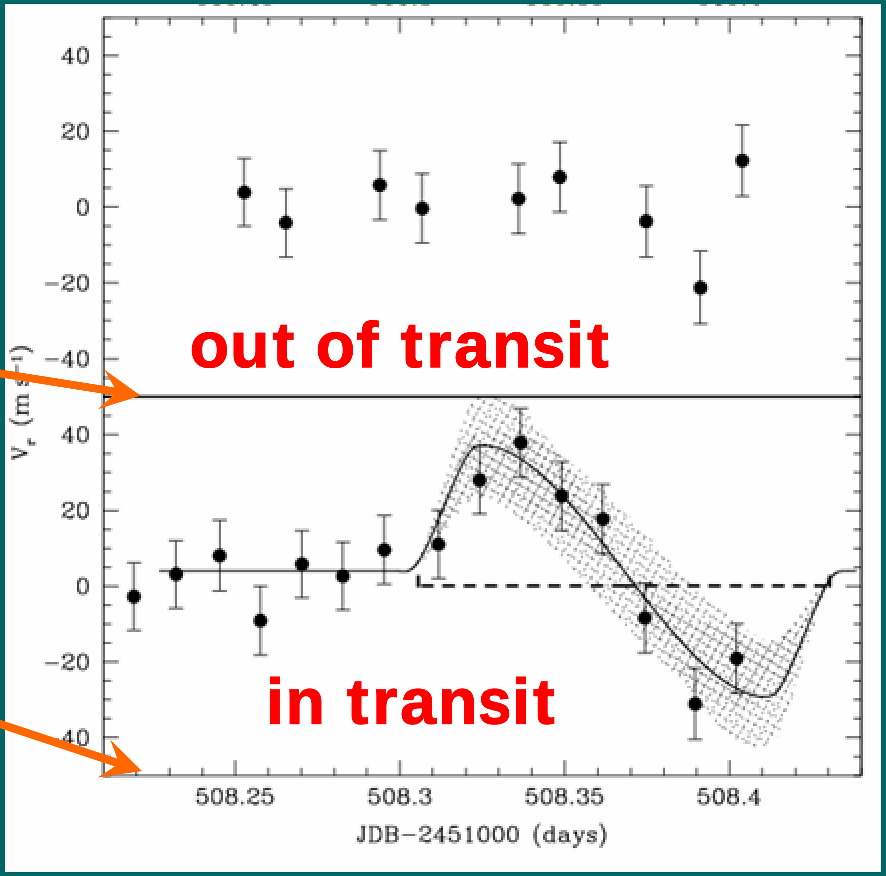
Velocity anomaly due to the Rossiter effect



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/

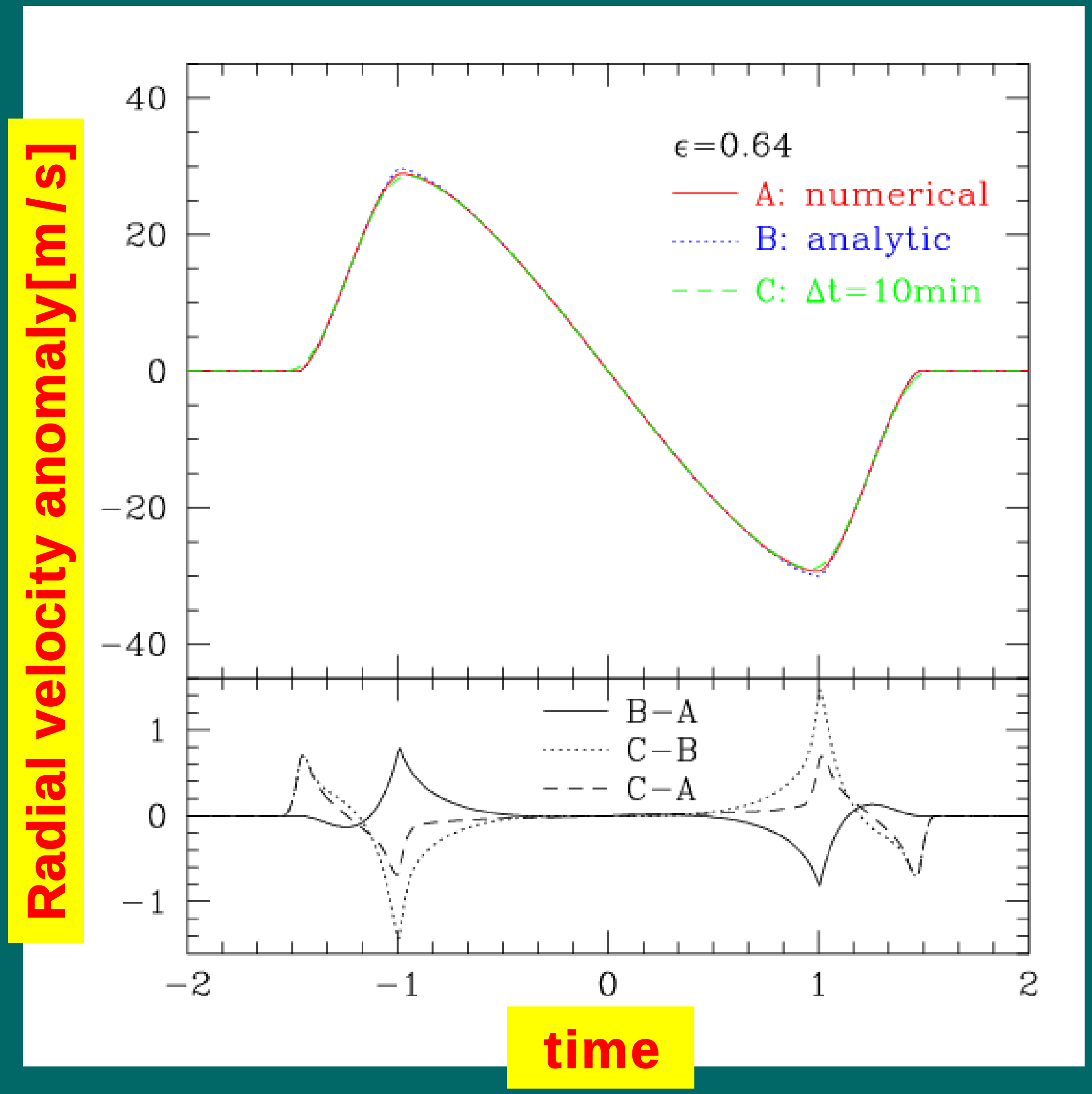
Stellar rotation and planetary orbit
Queloz et al. (2000) A&A 359, L13
ELODIE on 193cm telescope

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

Limb darkening:
B= 1- ε (1-cos θ)

First analytic formula using perturbation theory

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



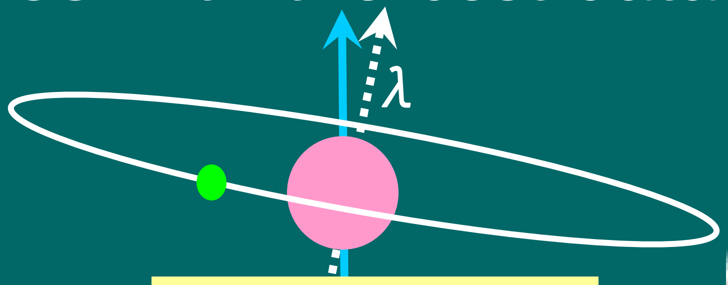
Measurement of Spin-Orbit alignment in an Extrasolar Planetary System

- 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)

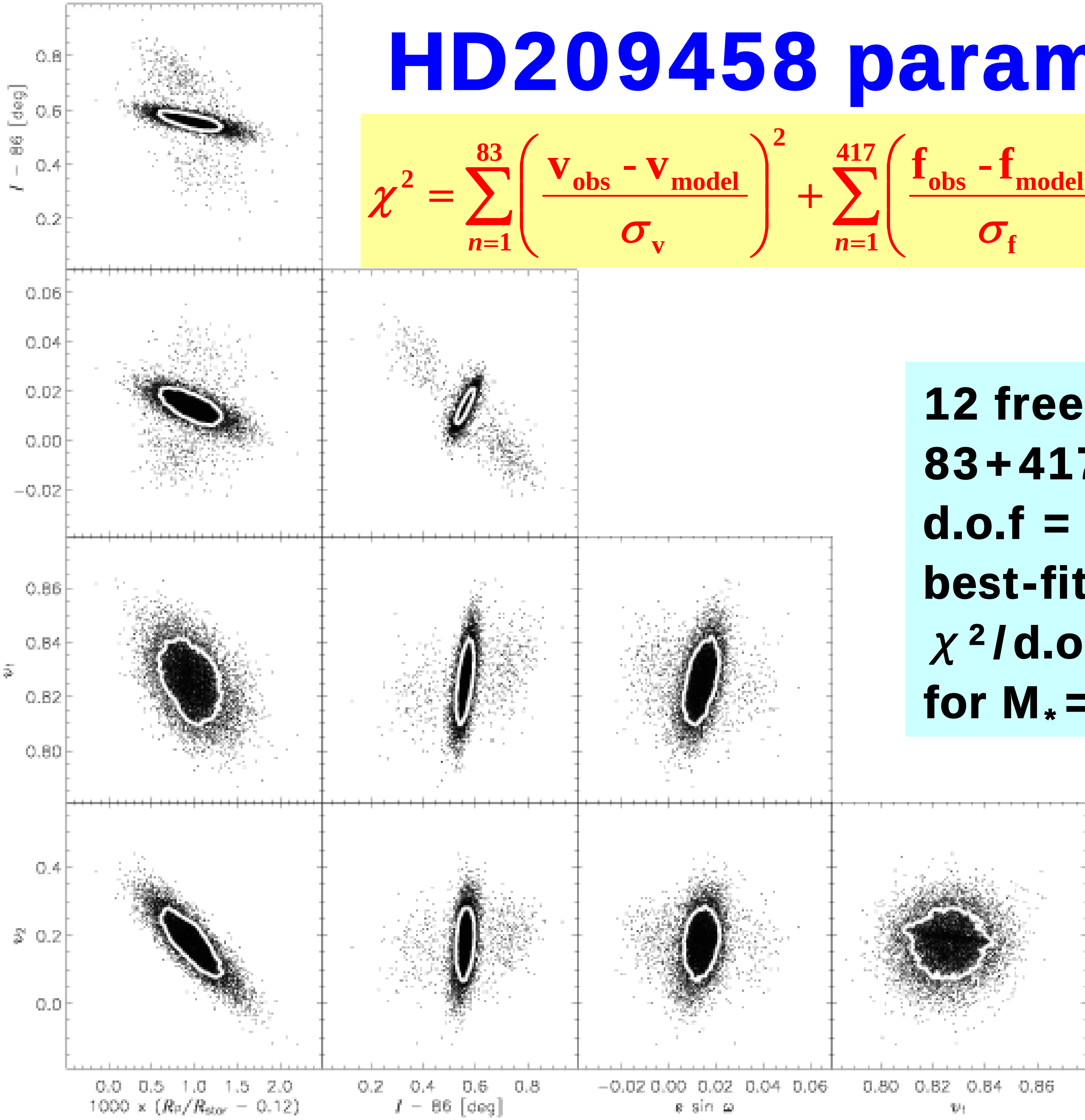


$$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$$

- **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 (maybe useless but impressive result !)
  - c.f., 6 degree misalignment for the Solar system
- **$\lambda \neq 0$ problem other than in cosmology !**

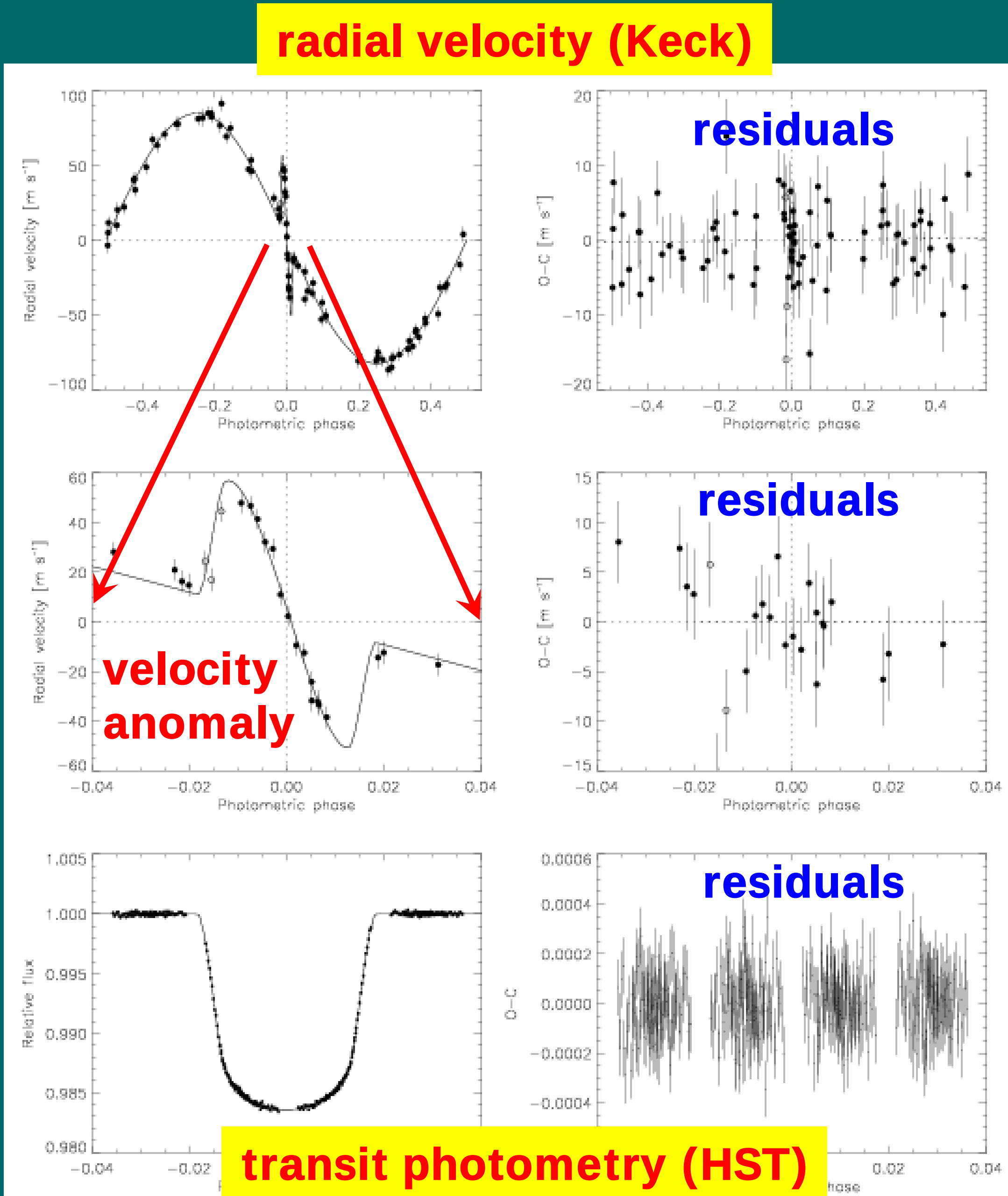
HD209458 parameter fit

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

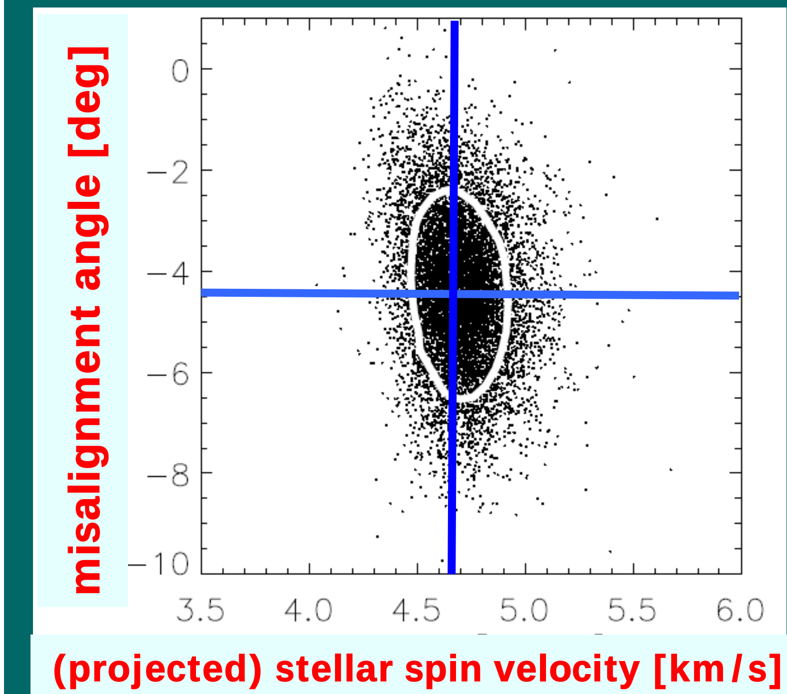


12 free parameters
83+417+1 data points
d.o.f = 83+417+1-12=489
best-fit :
χ^2/d.o.f=528/489=1.08
for $M_* = 1.06 M_{sun}$

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



first detection of non-zero λ !



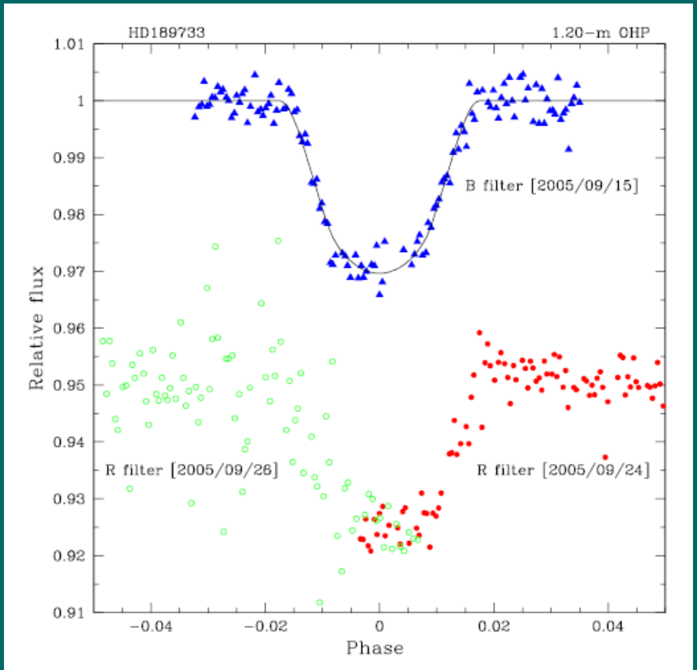
$$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$$

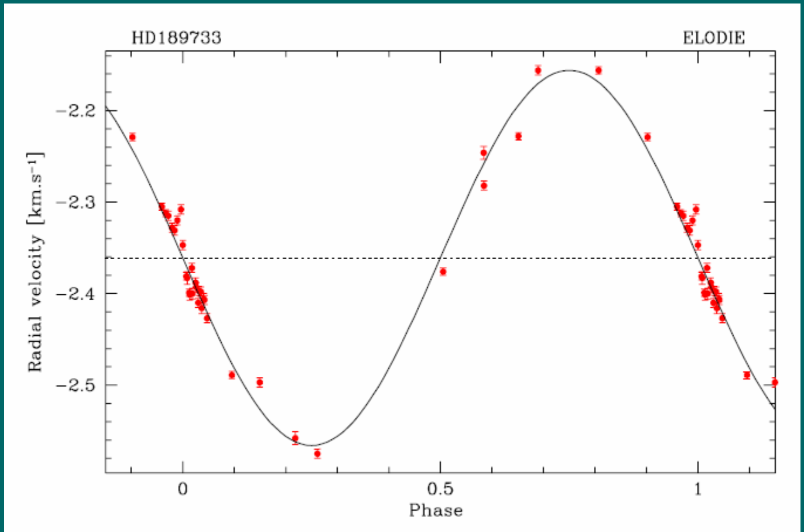
3 σ detection !

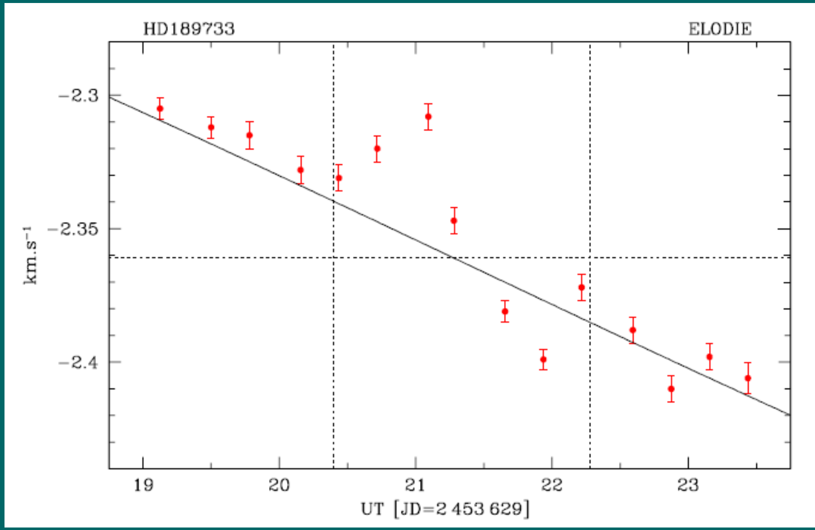
Winn et al. astro-ph/0504555 ApJ 631(2005)1215

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

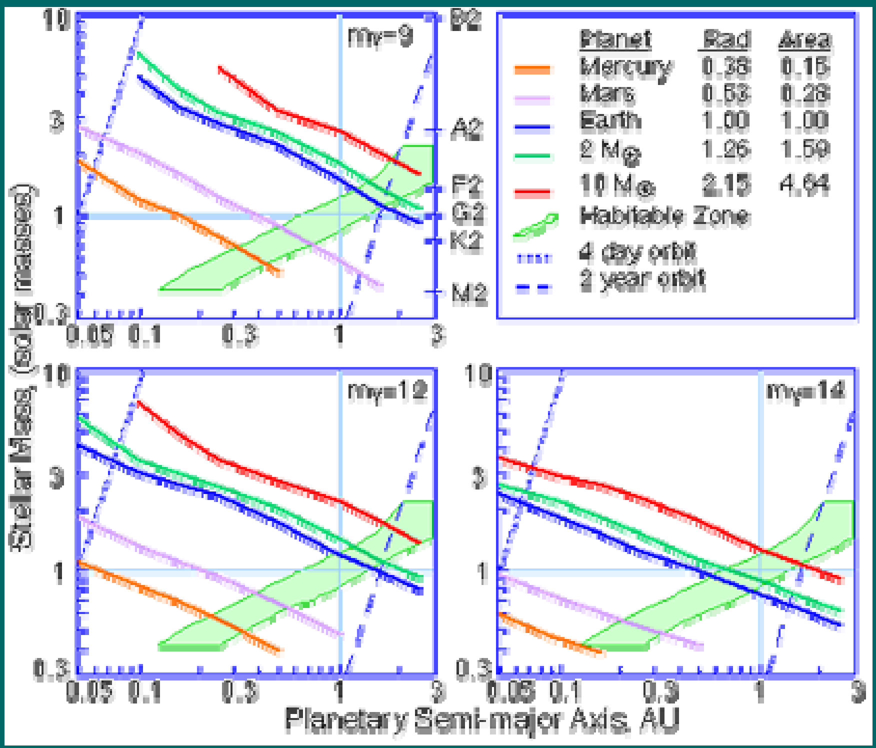


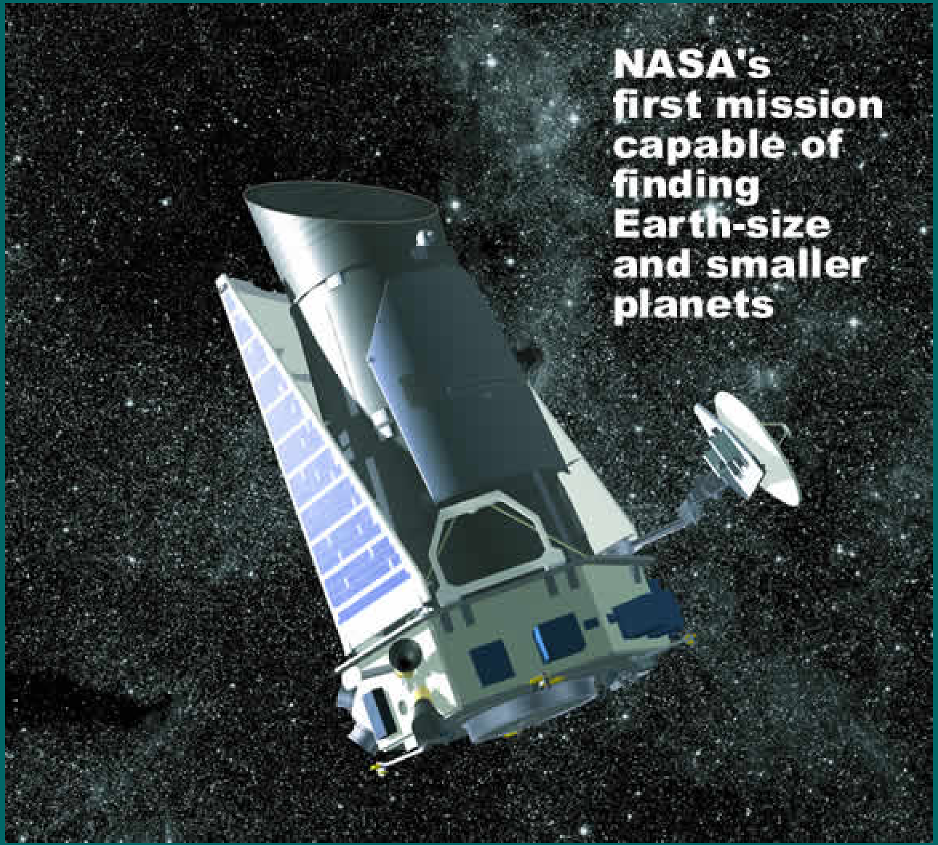




Kepler mission (June 2008 launch?)

differential photometry survey of transit planets
expect to discover > 50 terrestrial planets in 4 years ?

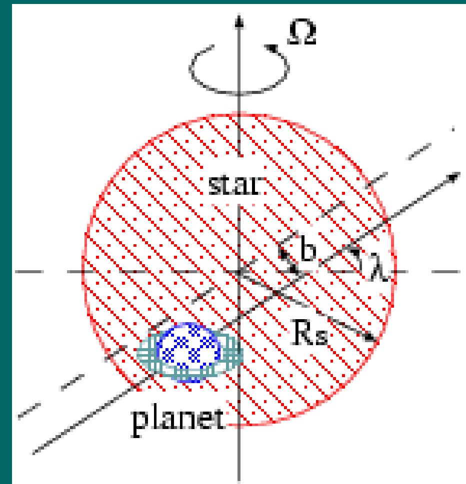


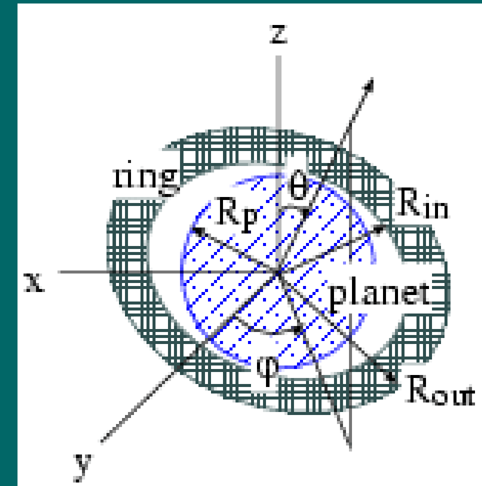


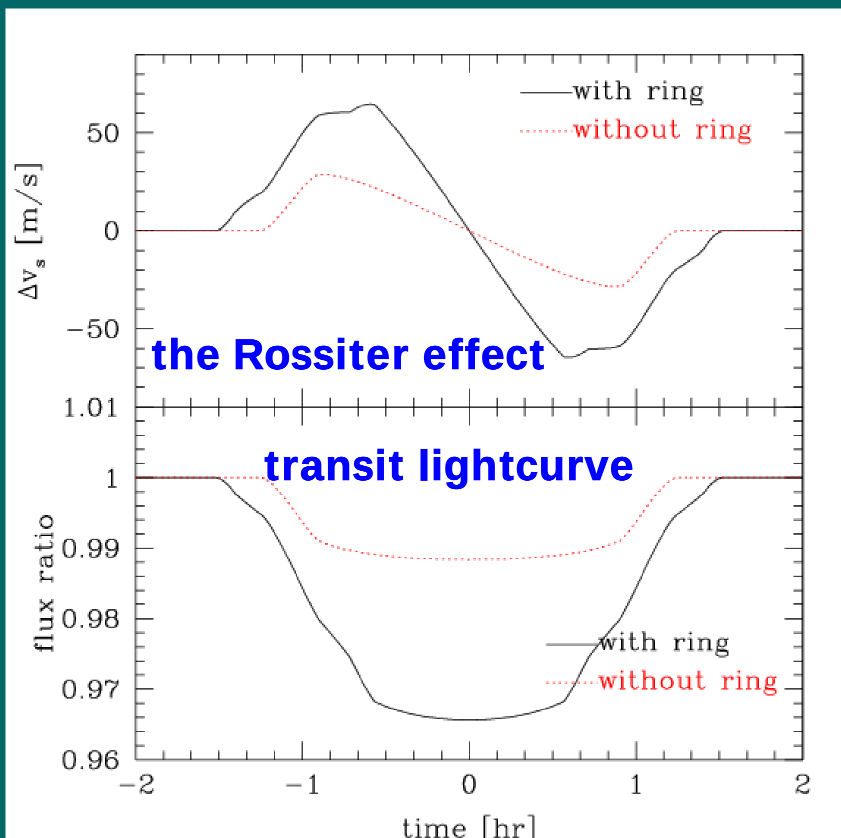
http://kepler.nasa.gov/

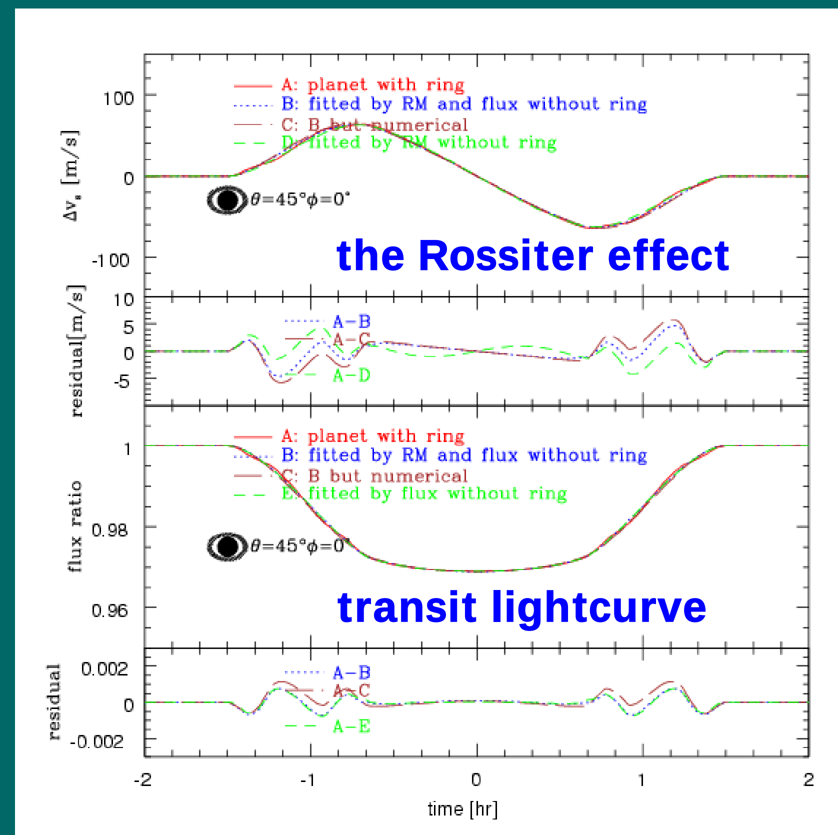
signatures of a ring

Ohta, Taruya & Suto in preparation.

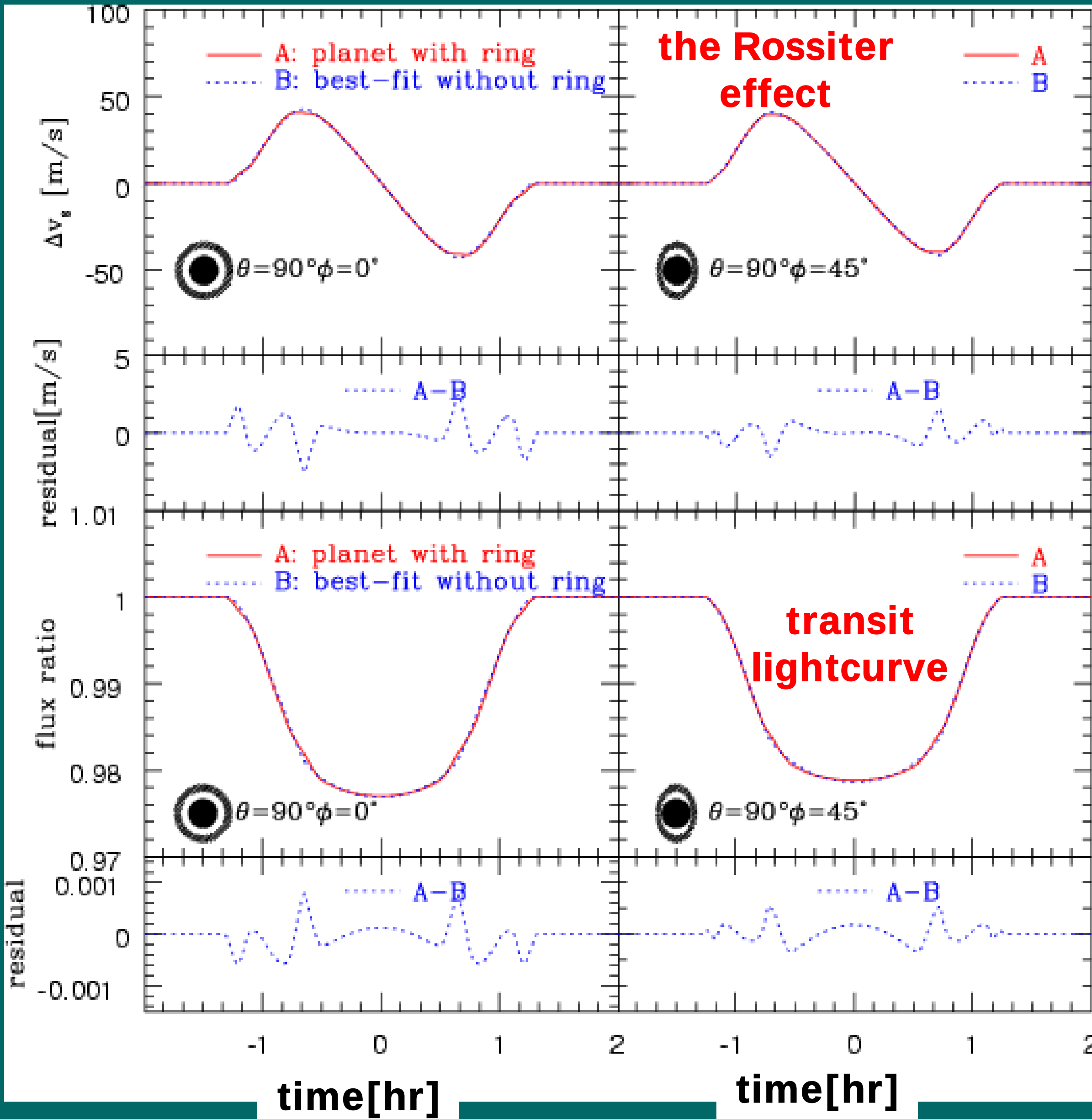








Detectability of a ring of extrasolar planets



- 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 technology (if they exist at all around hot Jupiters !)

A possible roadmap of sciences of extrasolar planet

- Discovery phase of gas giant planets
- Discovery phase of planetary atmosphere

- Detailed spectroscopic study of planets

- - -

- Discovery of terrestrial planets
- ***Identifying Biomarker***
  - Red-edge of extrasolar plant ?
- ***Discovery of Habitable planet***
- ***Discovery of Extraterrestrial life***

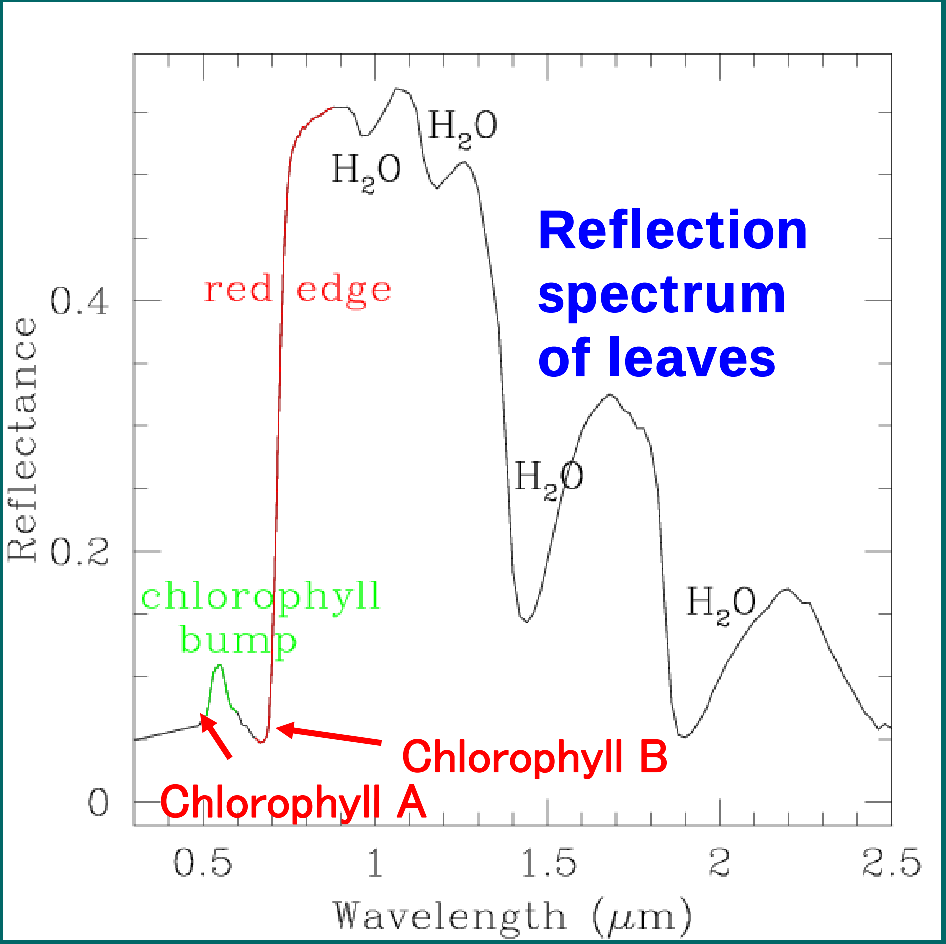
Astrobiology ? Not yet

- Discovery of extrasolar planets is a wonderful breakthrough in astronomy (and philosophy, maybe)
- But mere discovery has no biological information
- **How can we identify the signature of life ?**
  - **Biomarker**
- Suppose our earth is  located at 10pc away. Can we identify any signature of life from photometric and spectroscopic data alone ?
  - **Earth-shine**

http://modarch.gsfc.nasa.gov/
http://www.nasa.gov/home/index.html

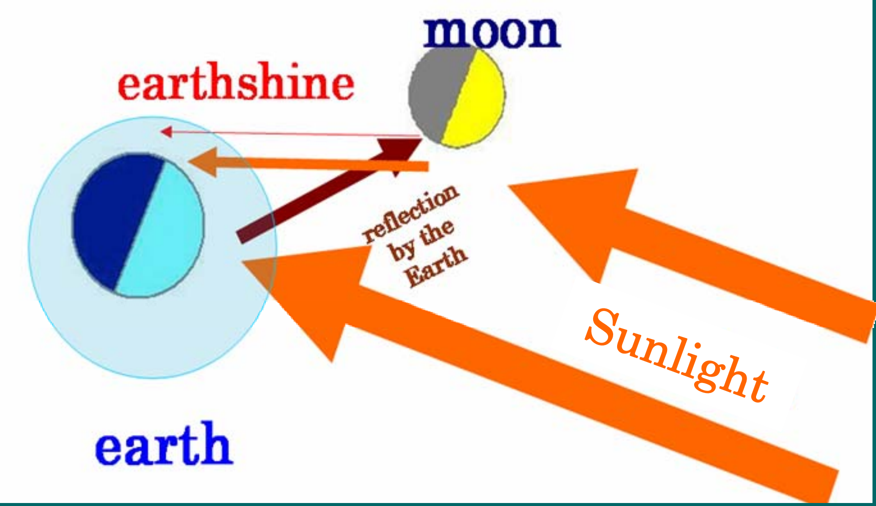
Red edge of *(extrasolar) plants:* a biomarker in *extrasolar planets*

- Significant reflectivity of leaves of terrestrial planets for $\lambda > 7000$ Å
- An interesting (maybe unique) candidate for a biomarker ?
- ***extrasolar plants*** as a biomarker in *extrasolar planets*



Seager, Ford & Turner astro-ph/0210277

earthshine spectroscopy: *red-edge in a pale blue dot ?*



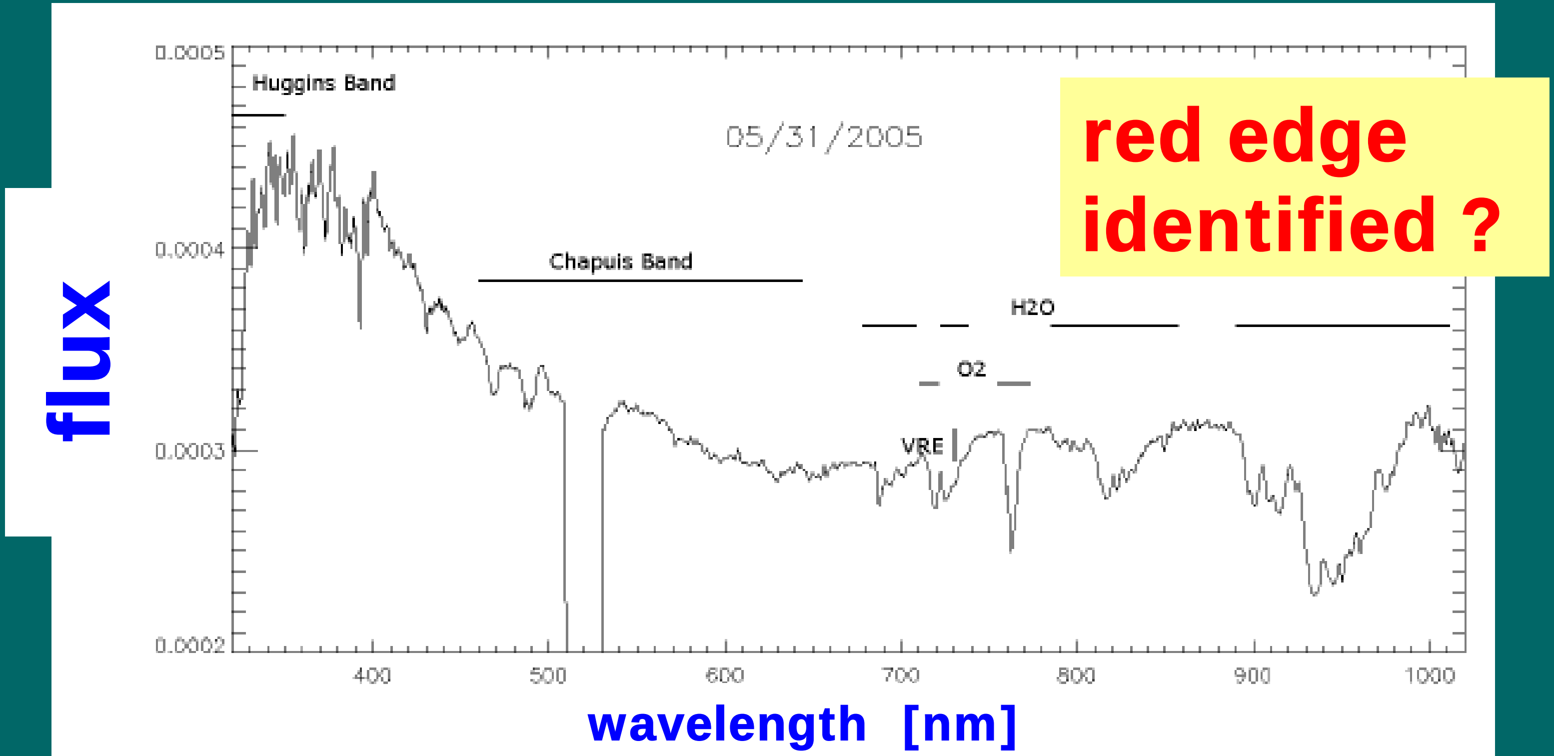
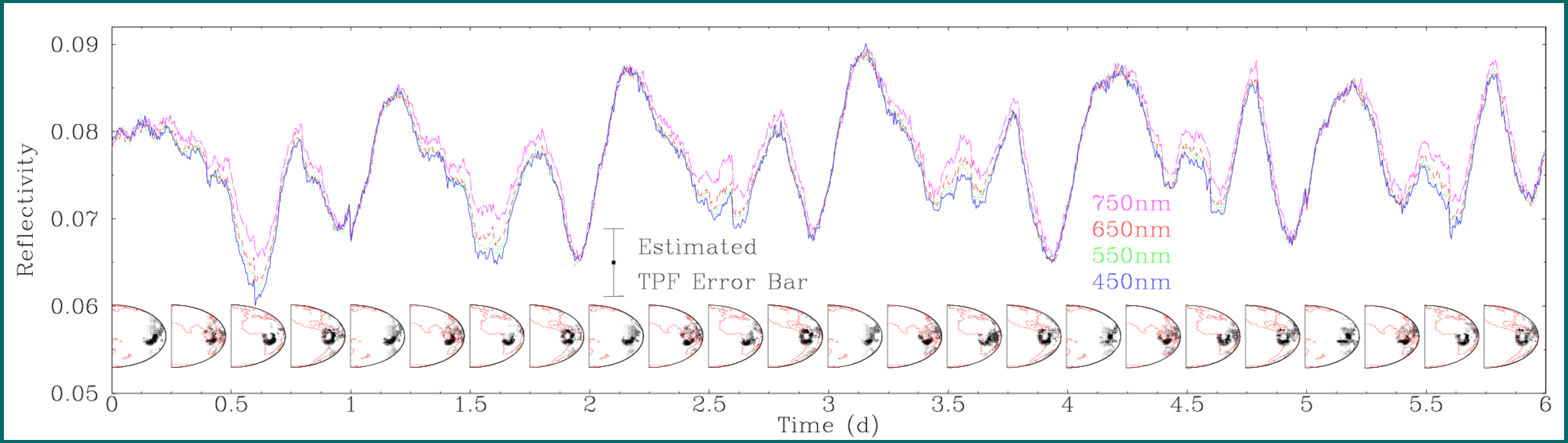


Fig. 1. Earth relfectance spectra for the West Africa and part of the Atlantic Ocean.

Hamdani et al. astro-ph/0510384

Expected daily change of the reflected light from the earth



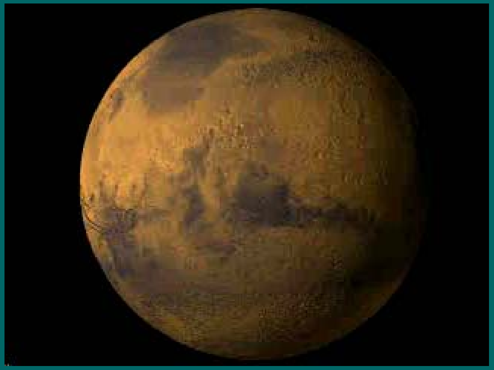
Ford, Seager & Turner: Nature 412 (2001) 885

- ***Assume*** that the earth's reflected light is completely separated from the Sun's flux !
  - TPF (Terrestrial Planet Finder) in (10～20) years from now ?
- ***Periodic change of 10% level*** due to different reflectivity of land, ocean, forest, and so on
- Cloud is the most uncertain factor: ***weather forecast !***

Vesto Melvin Slipher (1875–1969)

Red-edge as a biomarker (at least) in 1924 !

- Discovered redshifts of “spiral nebulae” now known as galaxies
- Essential contribution for Hubble’s discovery of expanding universe



“Observations of Mars in 1924 made at the Lowell Observatory: II spectrum observations of Mars”

PASP 36(1924)261

reflection spectrum. The Martian spectra of the dark regions so far do not give any certain evidence of the typical reflection spectrum of chlorophyl. The amount and types of vegetation required to make the effect noticeable is being investigated by suitable terrestrial exposures.

Astrobiology indeed in 1924 !

From astronomy to astrobiology ?

- We are in the most exciting epoch for 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 !


Thanks !
This presentation file is located at
http://www-utap.phys.s.u-tokyo.ac.jp
/~suto/mypresentation_2005e.html