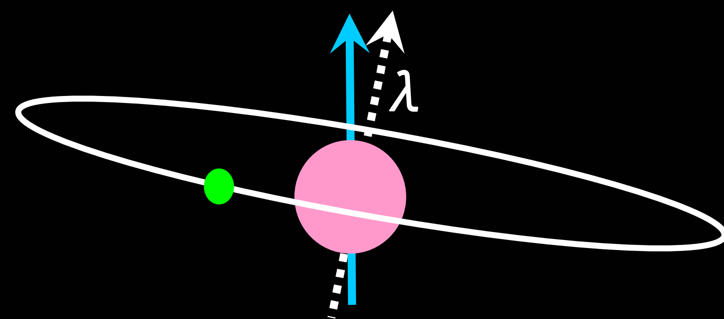
Transiting extra-solar planets: spin-orbit misalignment and rings



Yasushi Suto *Department of Physics, University of Tokyo*

Korea Astronomy and Space Science Institute

KASI colloquium
September 26, 2006

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

- **SDSS galaxy and quasar statistics**
  - genus statistics and phase correlation of SDSS galaxies (Hikage et al. 2003, 2004,2005; Hikage, Matsubara, and Suto 2004; Park et al. 2005)
  - 3pt correlation functions of SDSS galaxies (Kayo, Suto, Nichol et al. 2004; Nichol et al. 2006)
  - widest-separation lensed quasar from SDSS (Inada et al. 2003; Oguri et al. 2004; Ota et al. 2006)
  - 2pt correlation functions of SDSS quasars and cosmological constant (Yahata et al. 2005)
  - constraints on the deviation from Newton's law of gravity from SDSS galaxy power spectrum (Shirata, Shiromizu, Yoshida & Suto 2005)
  - SDSS galaxy number counts and SFD dust map (Yahata et al. astroph/0607098)

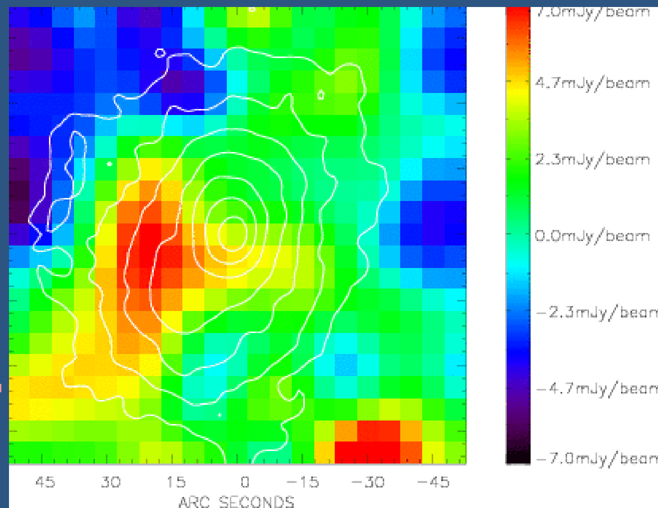
Recent Activities of Observational Cosmology Group, University of Tokyo (2)

- **Dark halo and galaxy cluster**
  - highest-angular resolution SZ maps in submm and mm (Komatsu et al. 1999, 2001; Kitayama et al. 2004)
  - triaxial modeling of dark matter halos (Jing & Suto 2002; Oguri, Lee & Suto 2003; Lee, Jing & Suto 2005)
- **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)
  - first detection of the spin-orbit misalignment in an extrasolar planetary system using the Rossiter effect (Ohta, Taruya & Suto 2005; Winn et al. 2005)

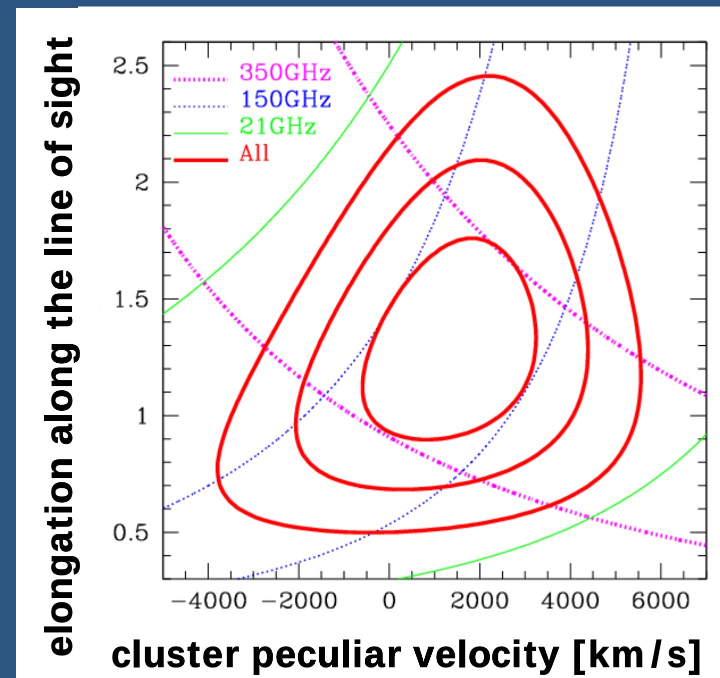
Observation of the Sunyaev-Zel'dovich effect

the most luminous X-ray cluster: RX J1347.5-1145

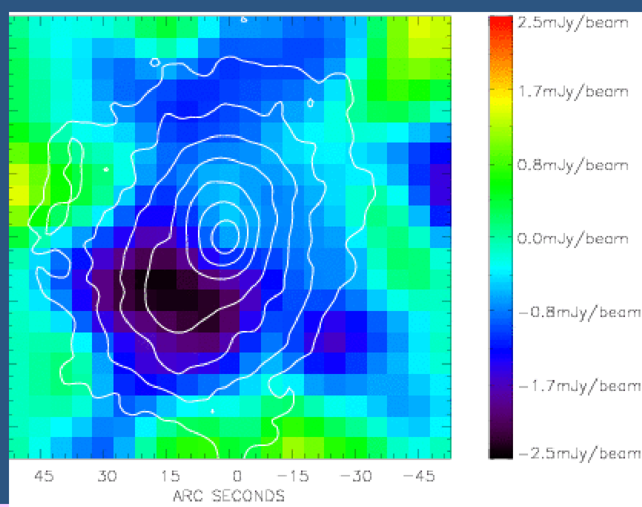
The ***first submm*** SZ map with **SCUBA, JCMT**



submm SZ map



The ***highest angular resolution*** (σ_{FWHM}=13'') mm SZ map with **NOBA, Nobeyama**



mm SZ map: discovery of substructure

Komatsu et al.
ApJ 516 (1998) L1
PASJ 53 (2001) 57
Kitayama et al.
PASJ 56 (2004) 17

Widest-separation lensed quasars

Inada, Oguri et al. (2003)

Subaru 8.2m telescope

Subaru image

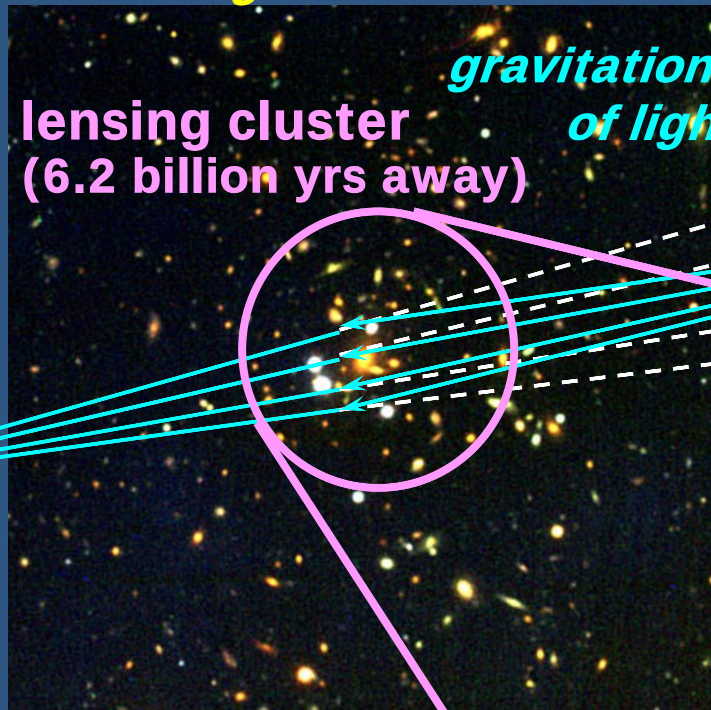


image 1

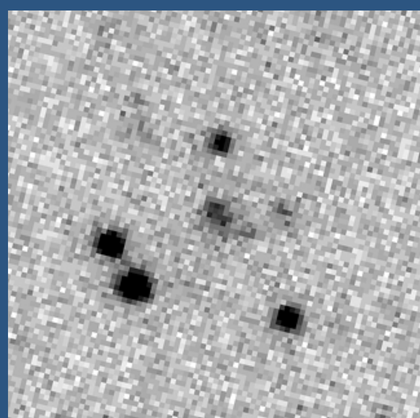
image 2

SDSS J1004 (9.8 billion yrs away)

image 3

image 4

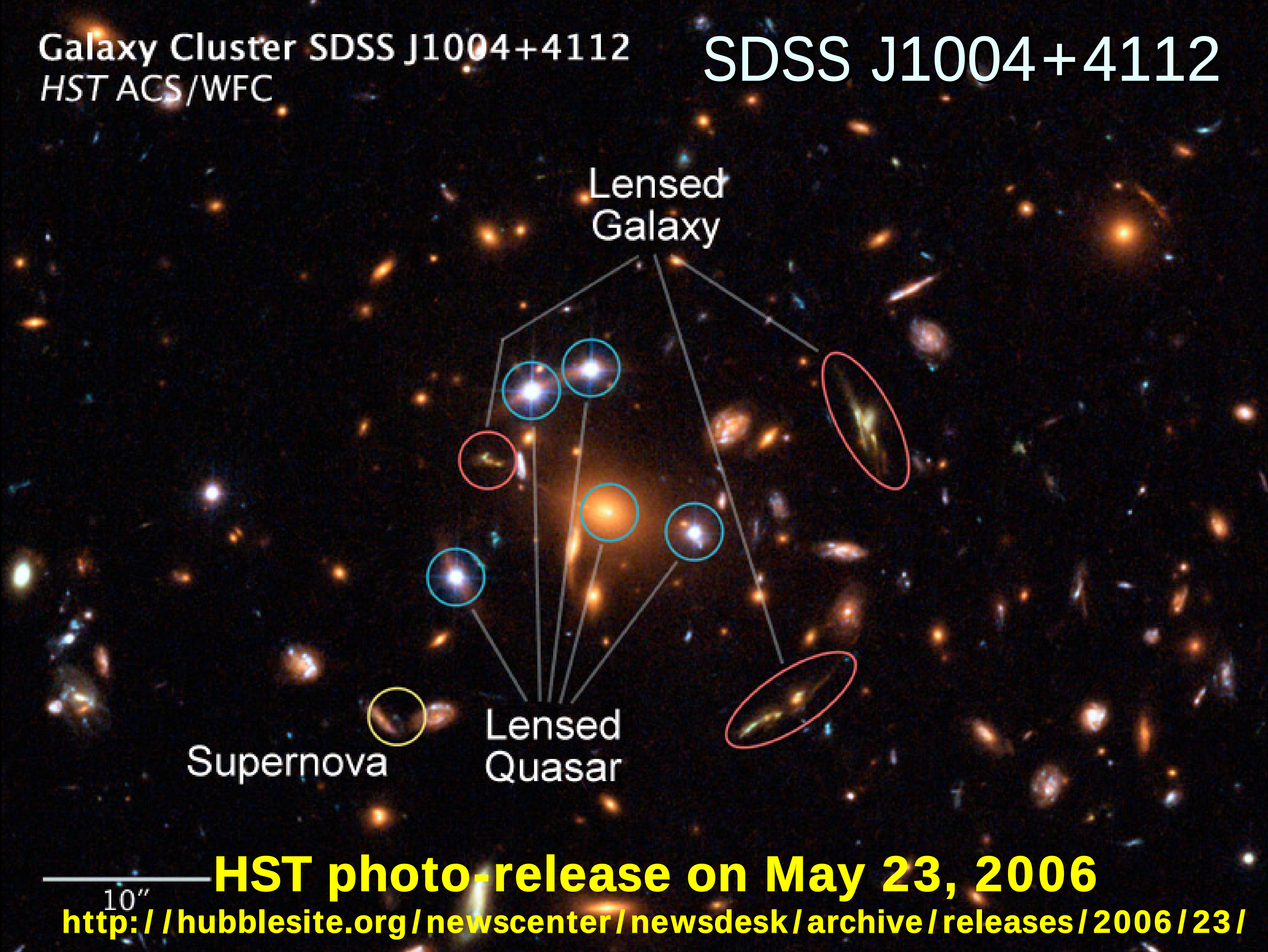
SDSS 2.5m telescope



SDSS image

Zoomed Subaru image

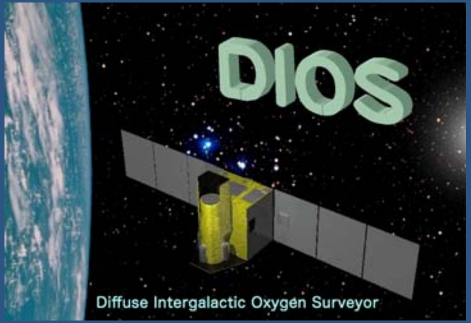
SDSS J1004+4112



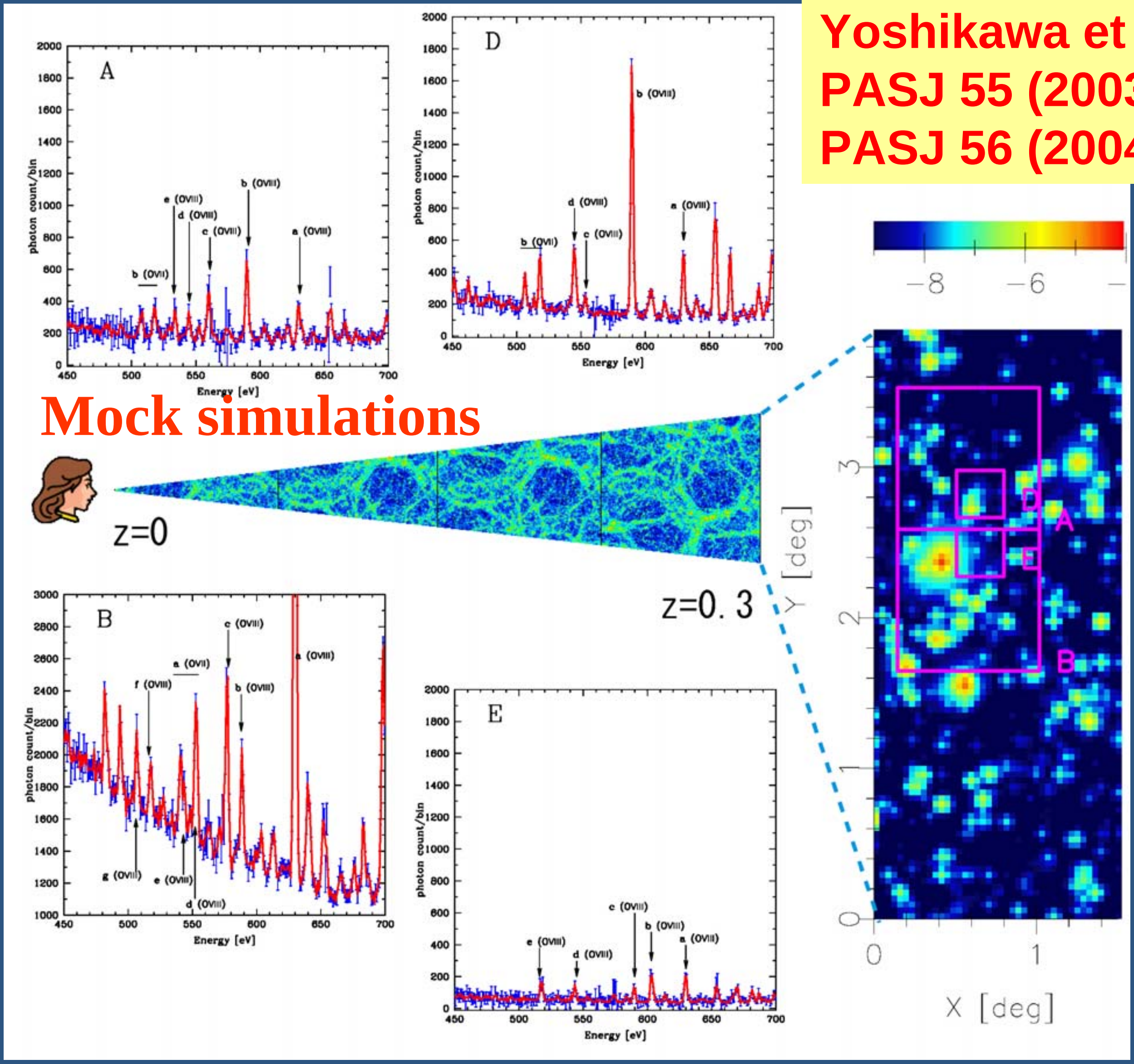
HST photo-release on May 23, 2006

http://hubblesite.org/newscenter/newsdesk/archive/releases/2006/23/

Searching for cosmic missing baryons with DIOS
(Diffuse Intergalactic Oxygen Surveyor)



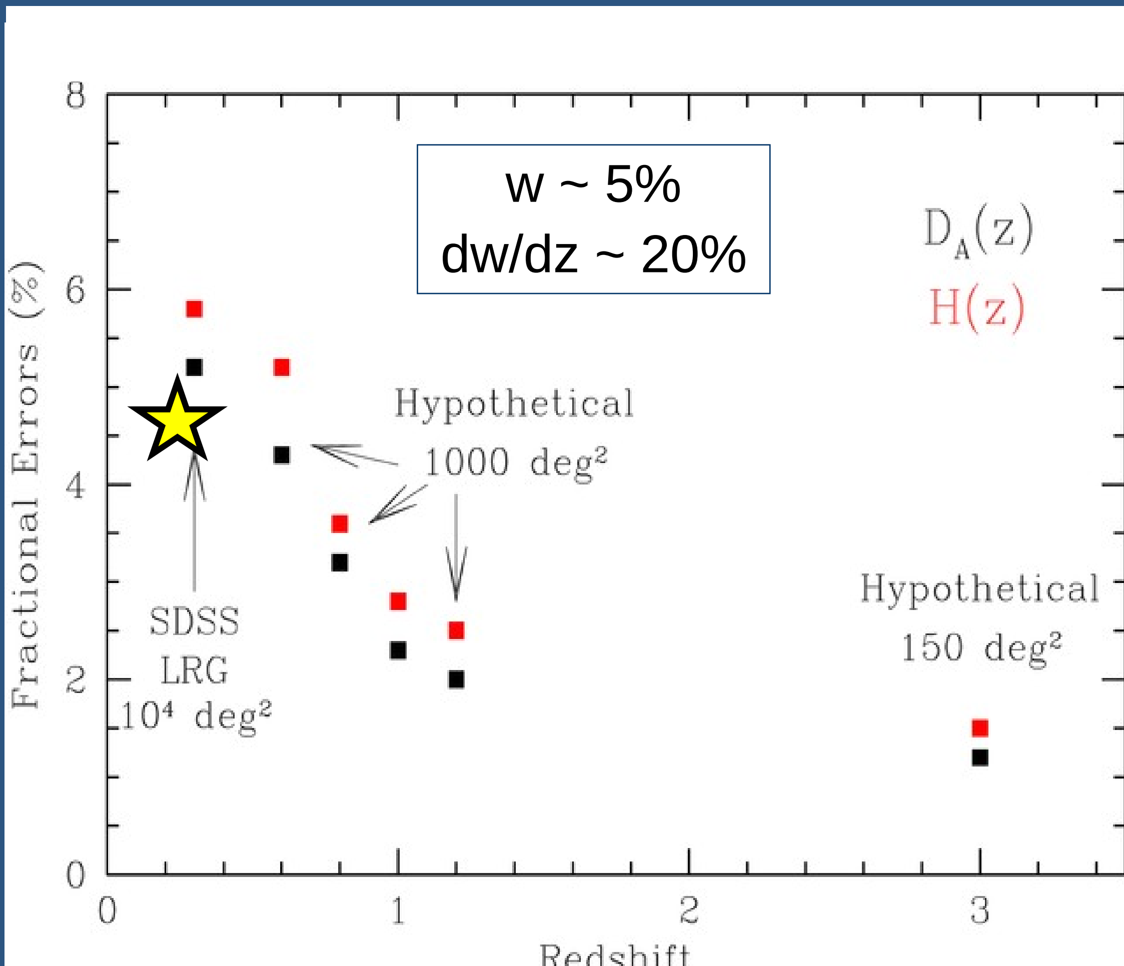
Yoshikawa et al.
PASJ 55 (2003) 879
PASJ 56 (2004) 939

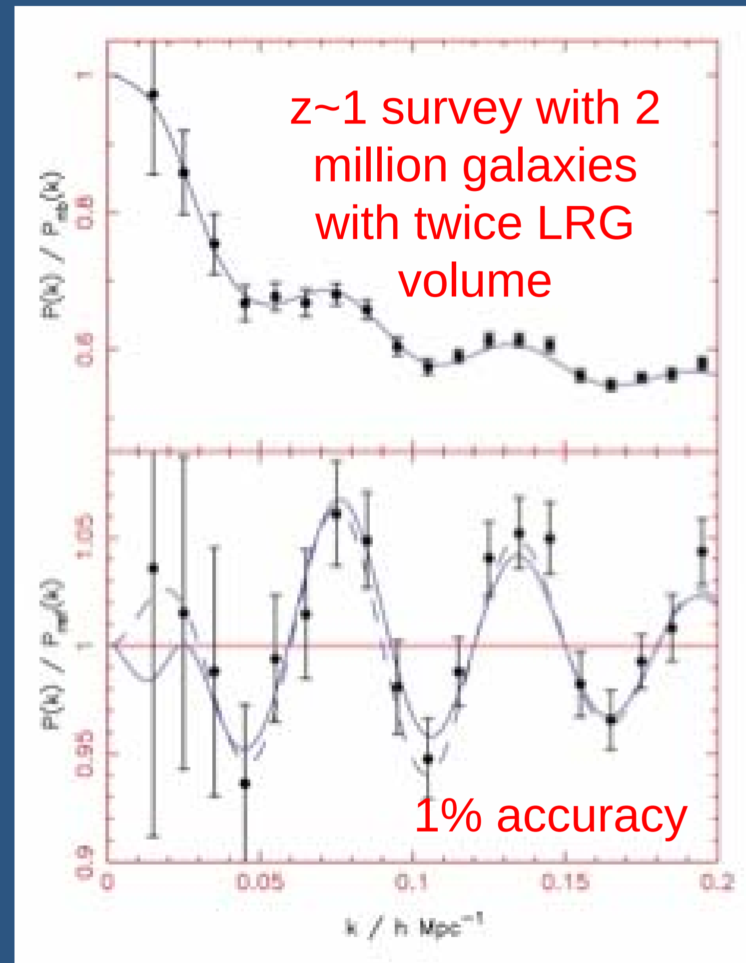


Tokyo Metropolitan Univ.:
T. Ohashi
JAXA/ISAS:
N. Yamasaki
K. Mitsuda
Nagoya Univ.:
Y. Tawara
Univ. of Tokyo:
K. Yoshikawa
Y.Suto

Hyper Suprime-Cam and WFMOS on Subaru

3000 thousands of fibers over a 1.5 degree field-of-view
on an 8-meter class telescope (Subaru/Gemini)





Taken from WFMOS Feasibility Study by NOAO, JHU, AAO, Oxford, Durham, Portsmouth, UA

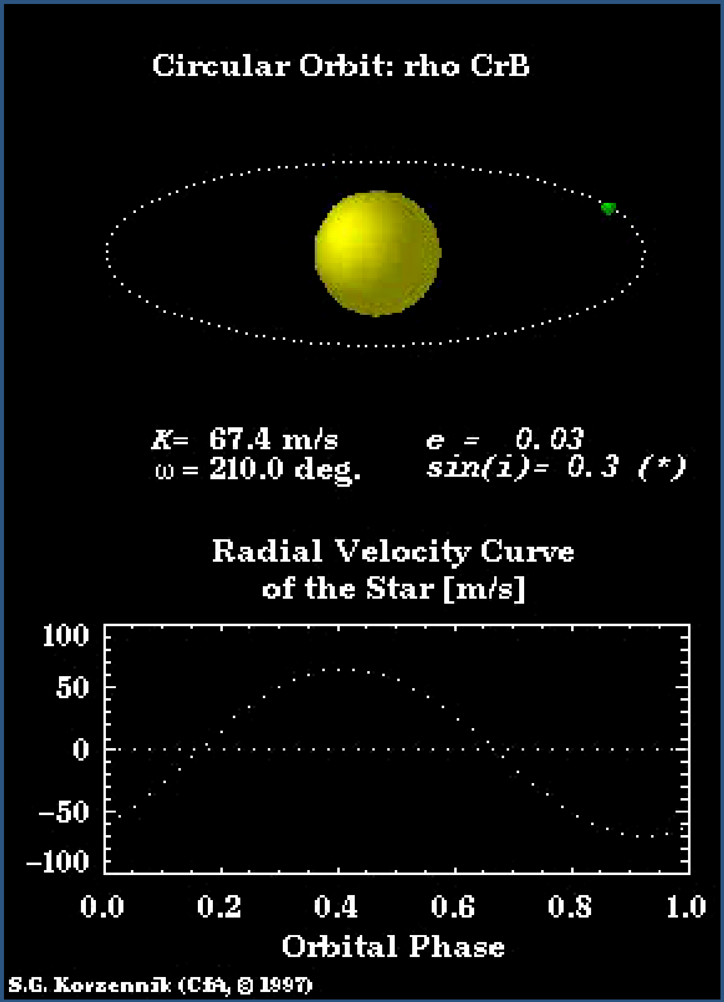
A brief history of the discovery of extrasolar planets

- **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
- *200 extrasolar planets* are reported (Sept. 2006)

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:

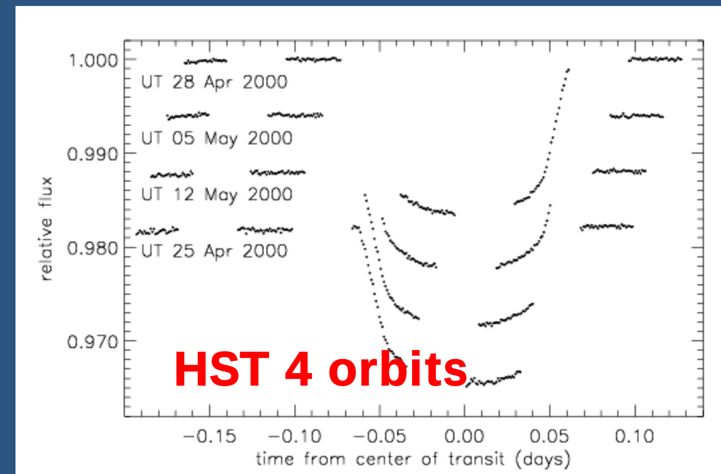
12.5 m / s（Jupiter）

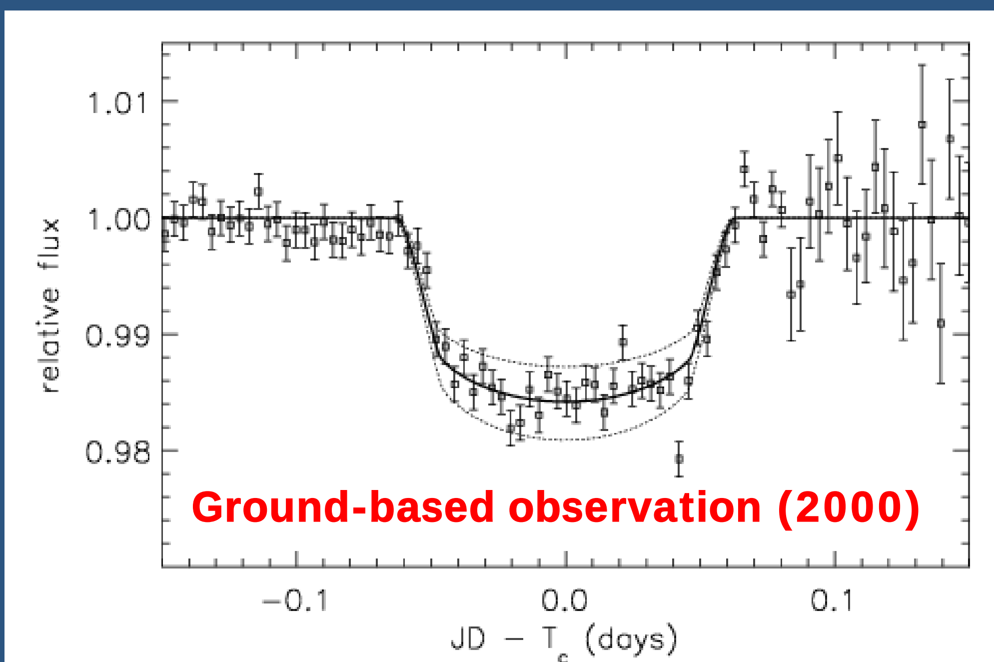
0.1 m / s（Earth）

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

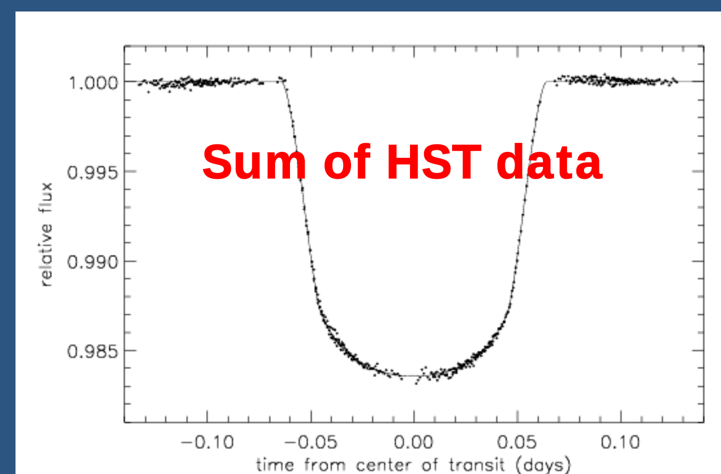
the first discovery of the transit of a planet: HD209458

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





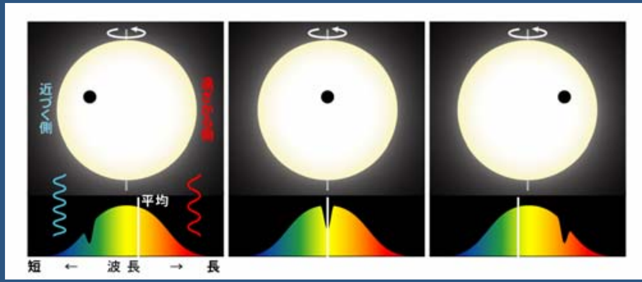
[redacted]



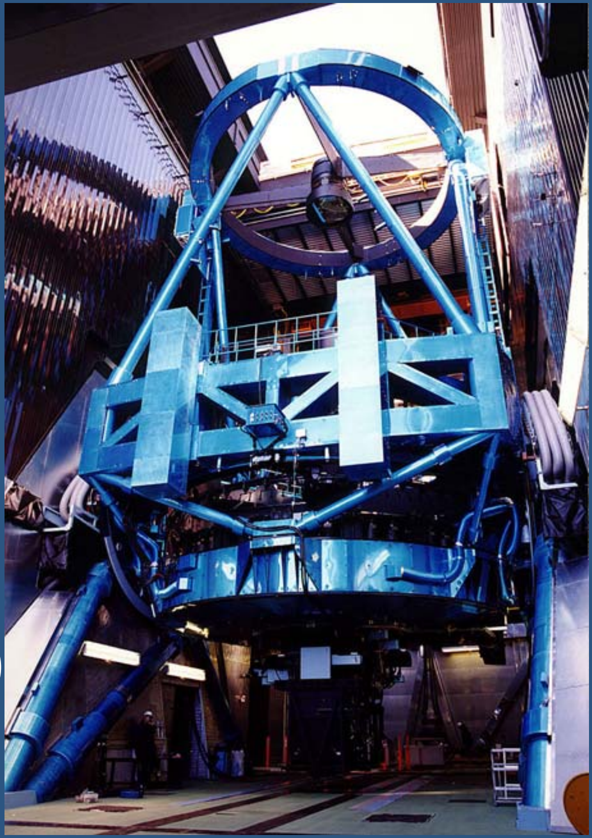
Brown et al. (2001)

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)

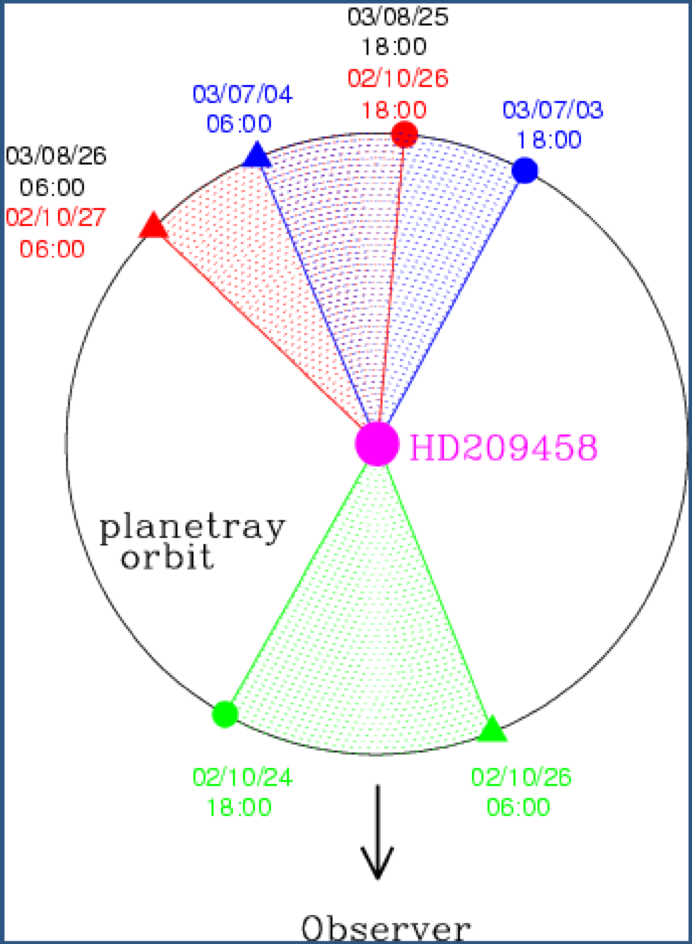
Toru Yamada, Wako Aoki (National Ast. Obs. Japan)

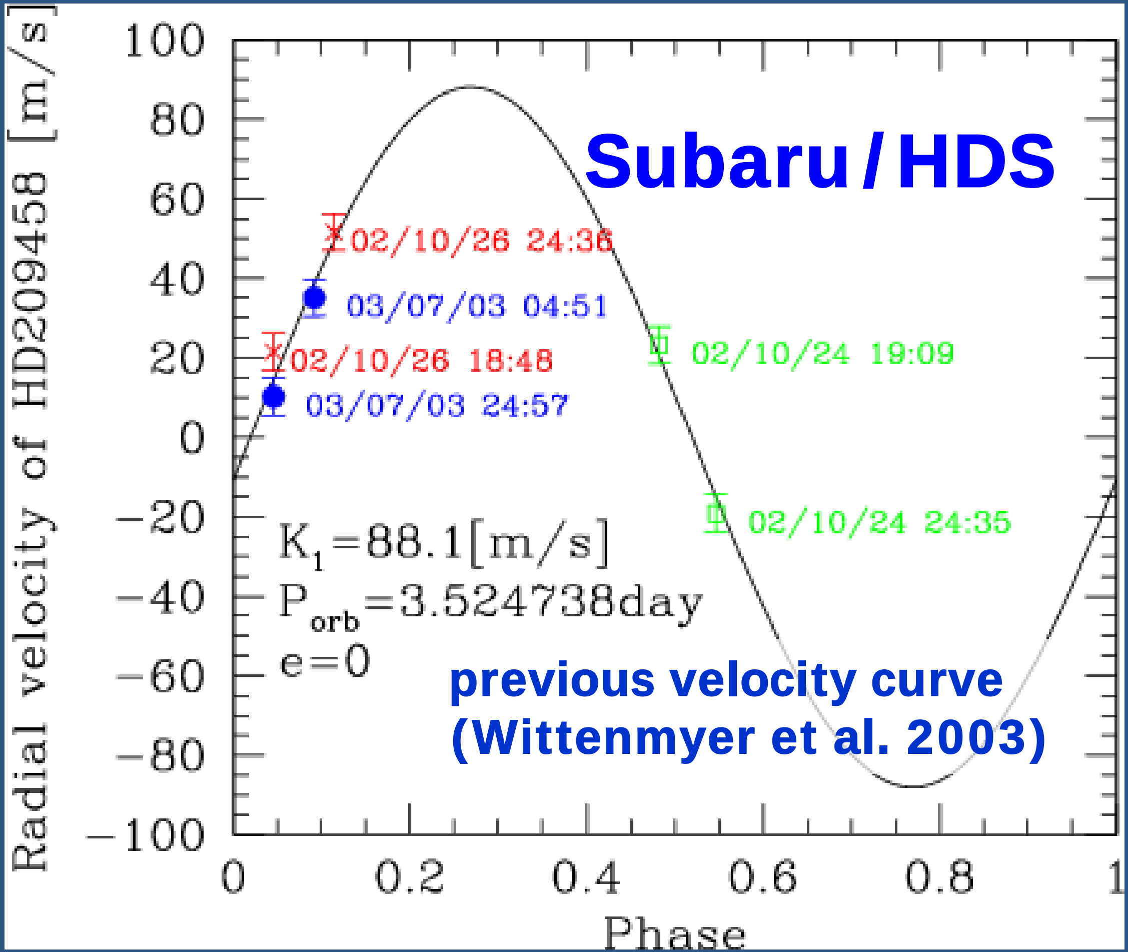
Bun-ei Sato (Kobe Univ.)

Edwin L. Turner (Princeton Univ.)

Josh Winn (Harvard Univ.)

Orbital phase and radial velocity of HD209458b at our observing runs

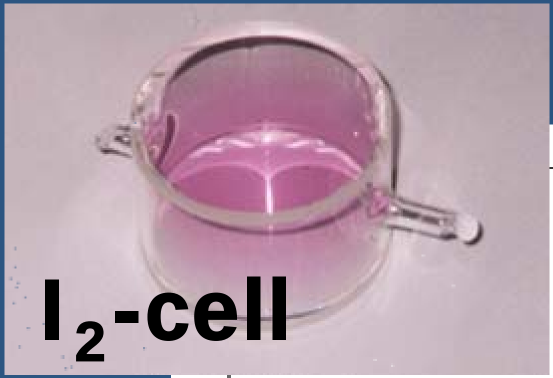


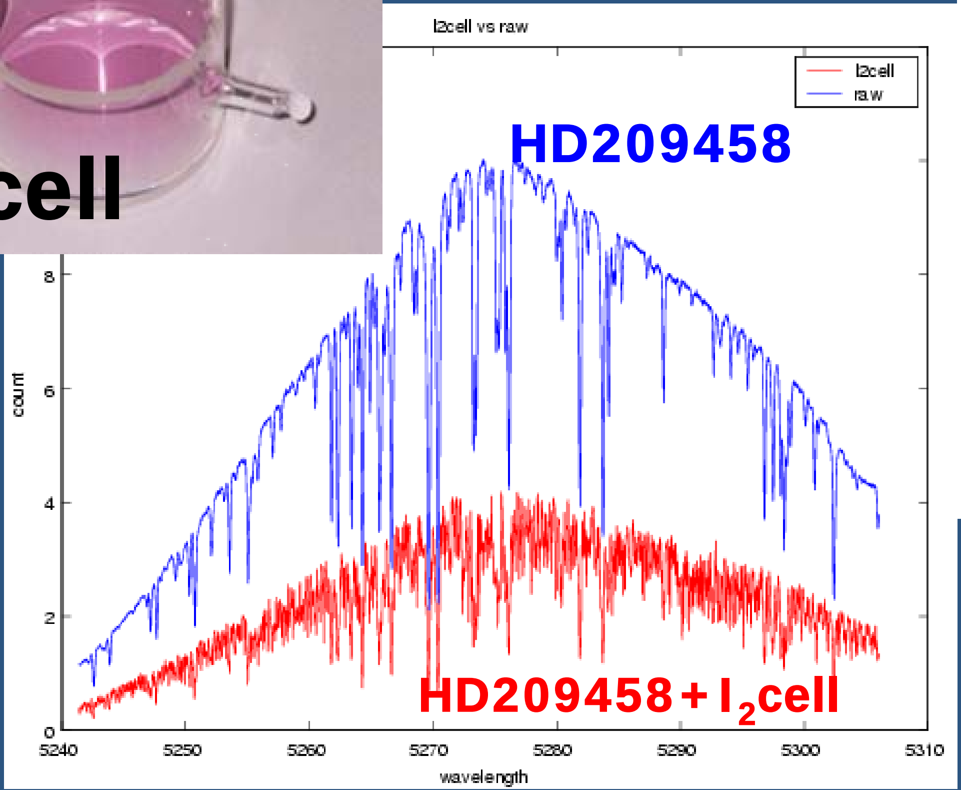


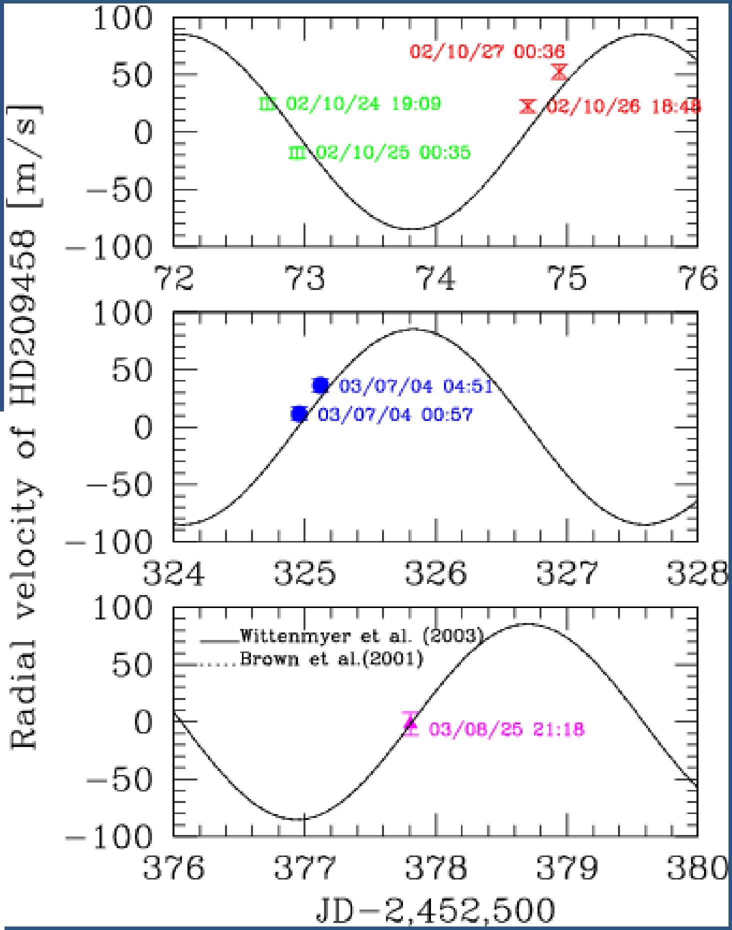
Winn et al. PASJ 56(2004) 655, astro-ph/0404469
Narita et al. PASJ 57(2005)471 , astro-ph/0504450

radial velocity measurement with I_2-cell

- Absorption lines of I_2 as accurate standard rulers
- Accuracy ～3m/s achieved



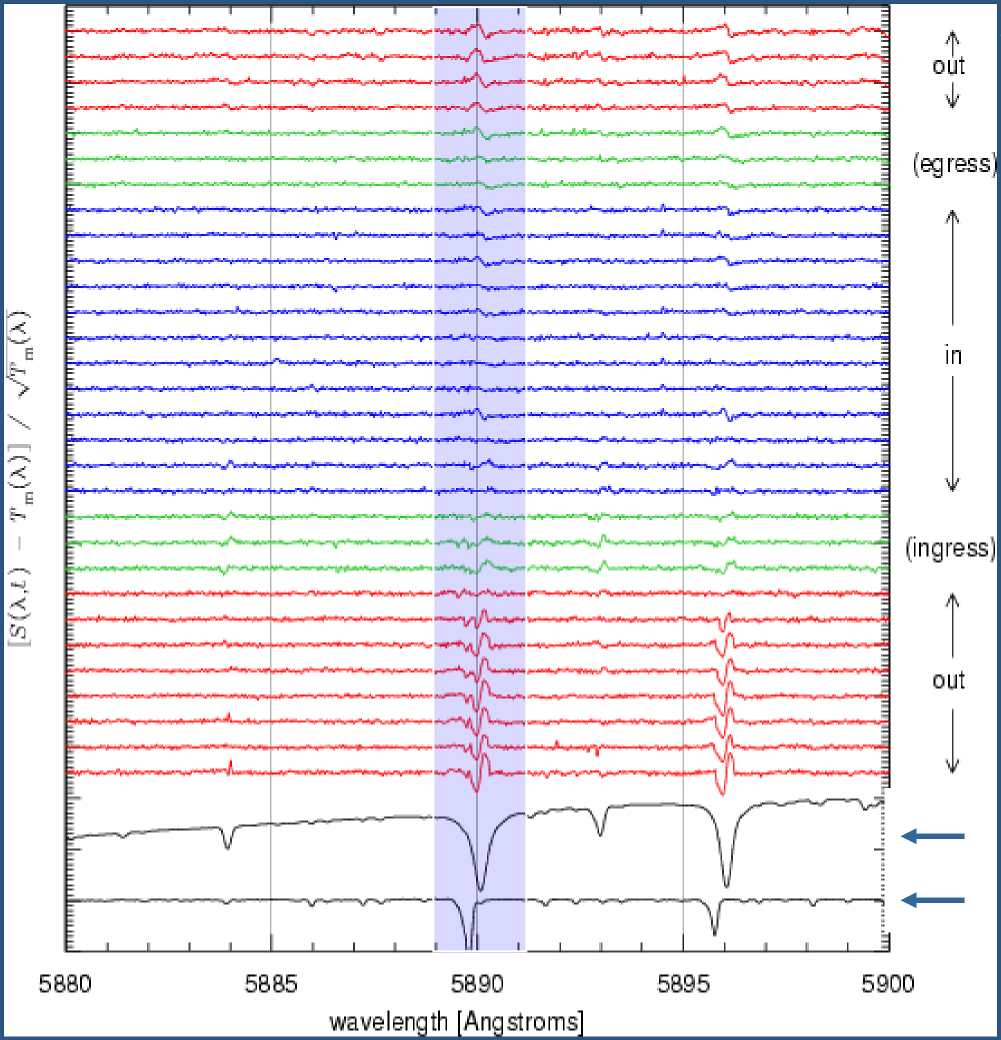


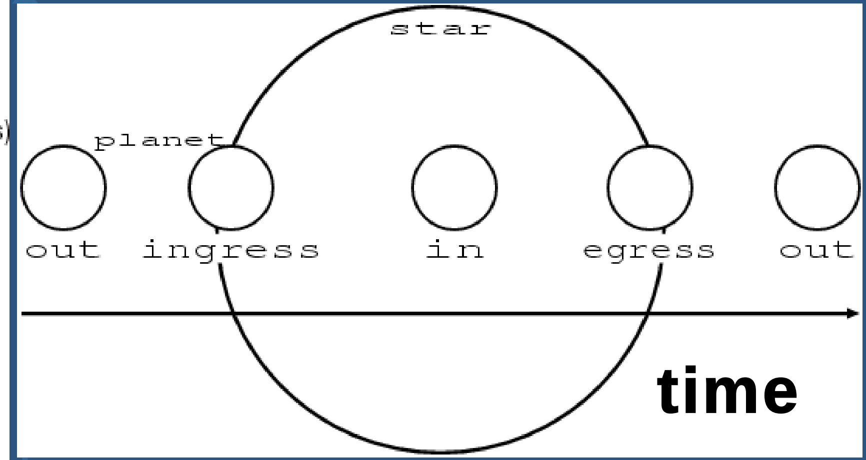


HDS on Subaru

Winn et al. (2004)

Transit transmission spectroscopy





planetary orbital phase

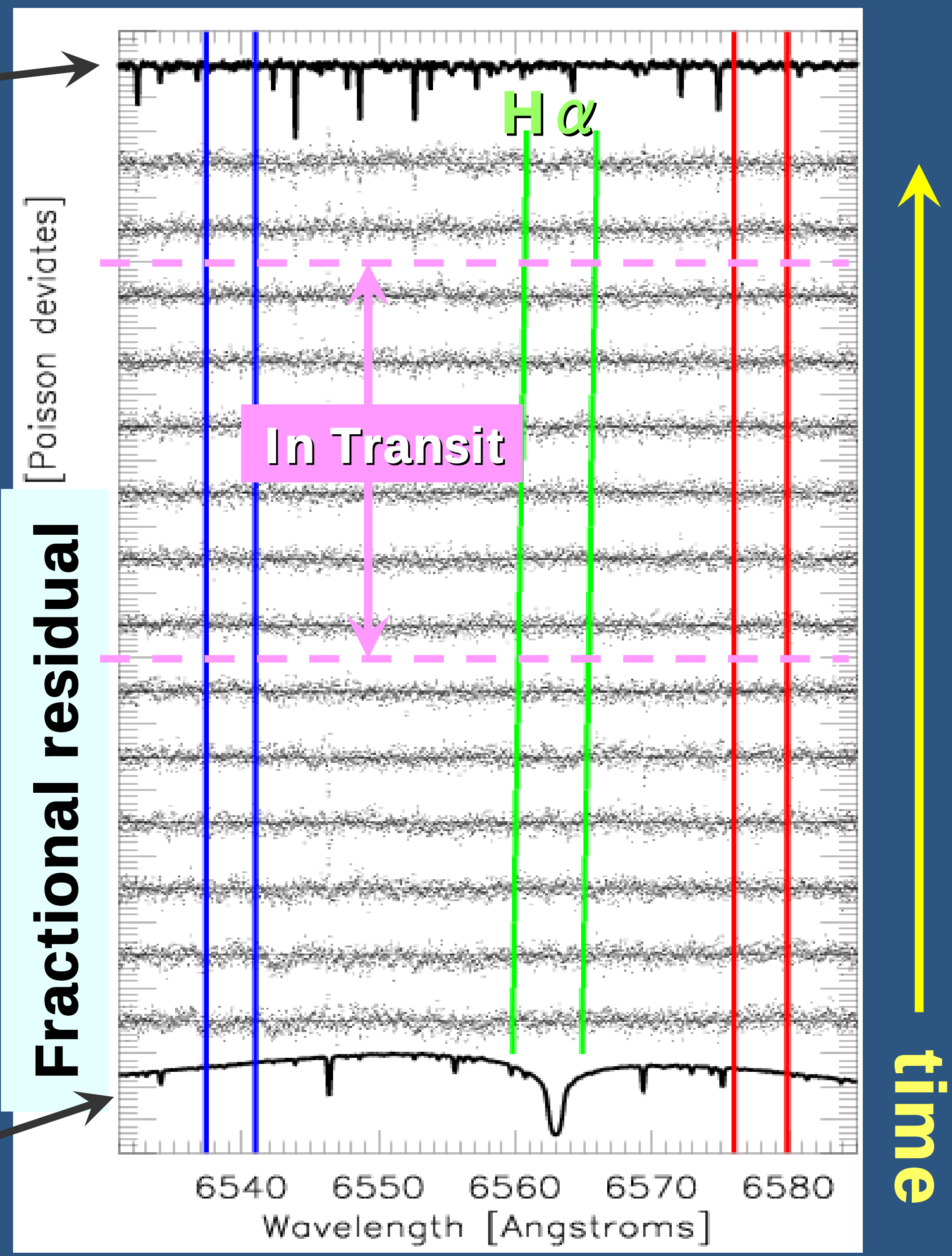
template

telluric

Narita et al. (2005)

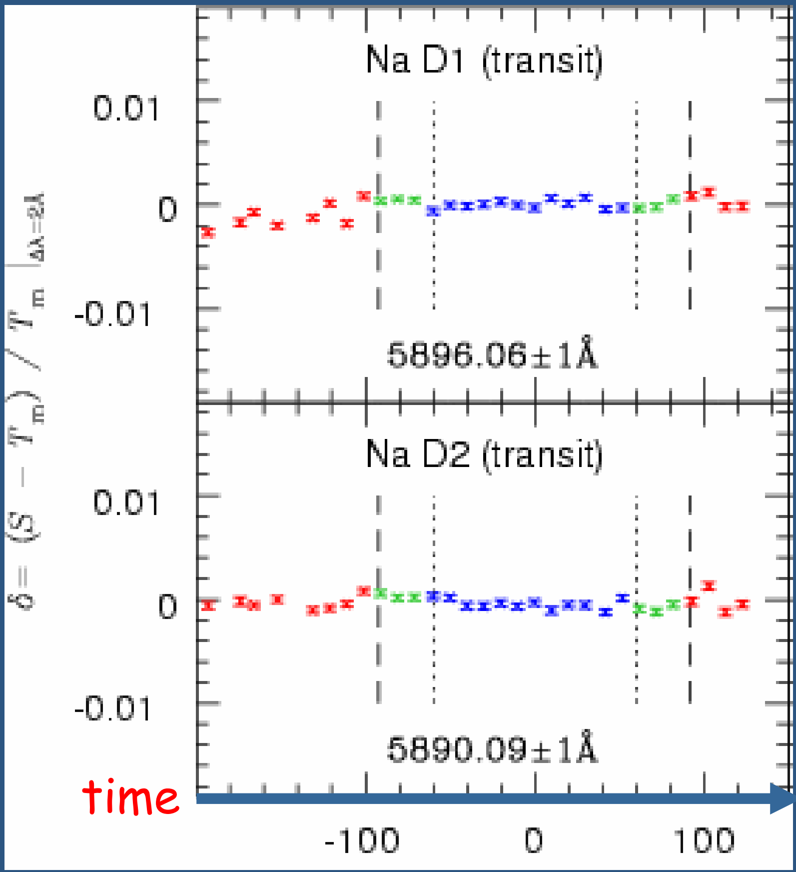
Search for H α absorption due to the atmosphere of HD209458b

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

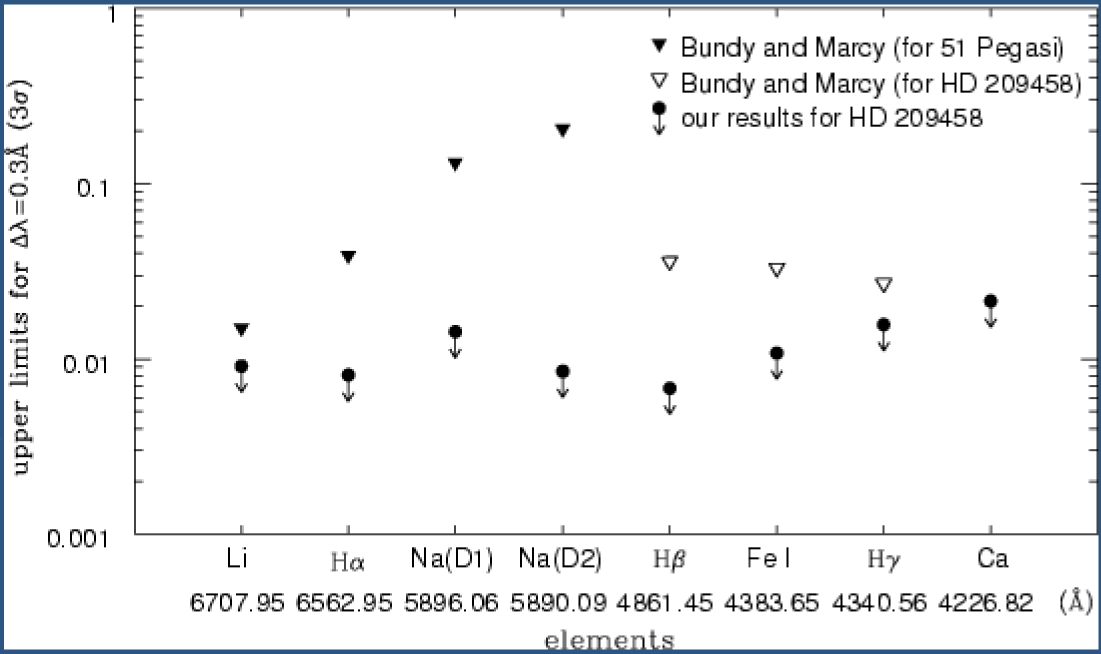


Winn et al. (2004)

most stringent upper limits from ground-based optical observations

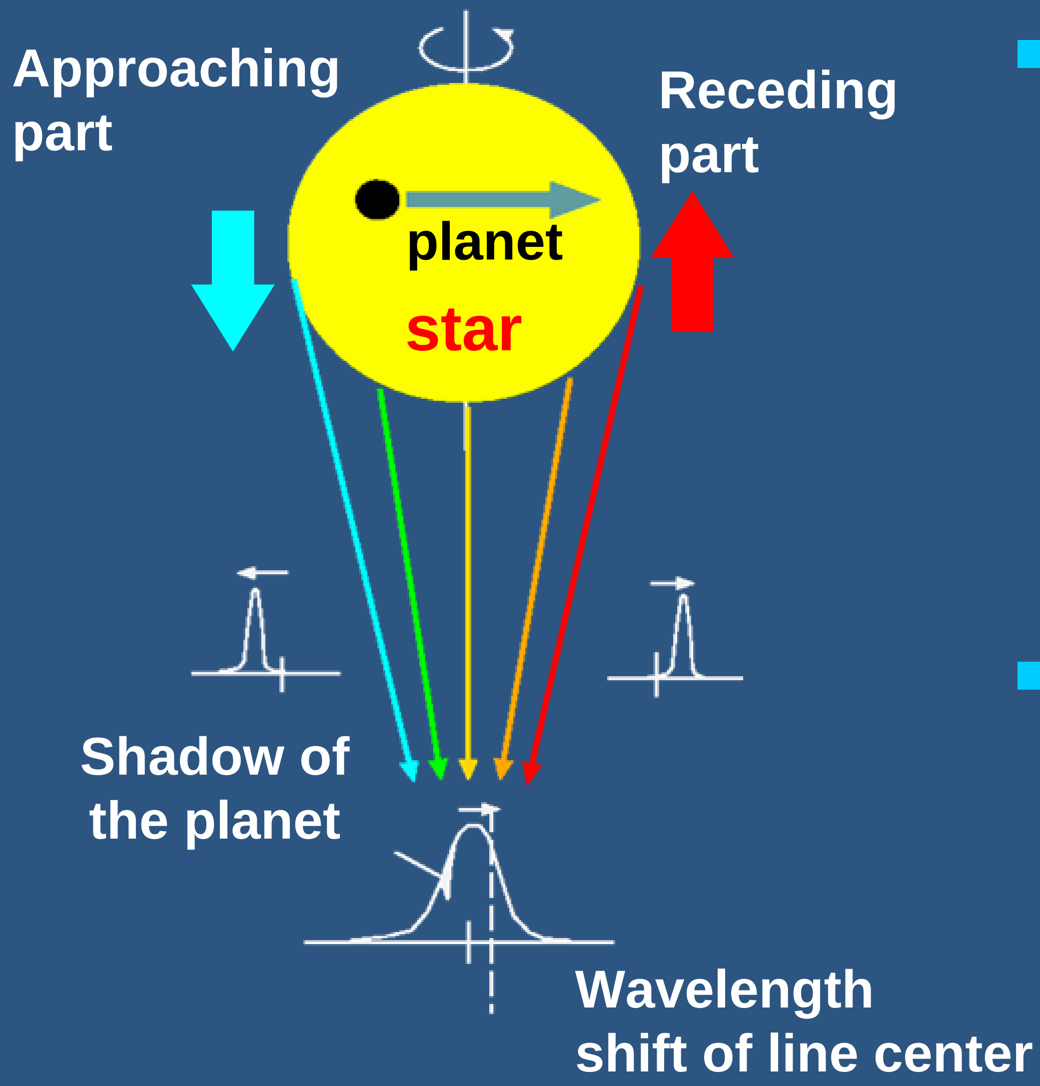


Comparison with previous results for 0.3 angstrom bandwidth (Bundy and Marcy 2000)



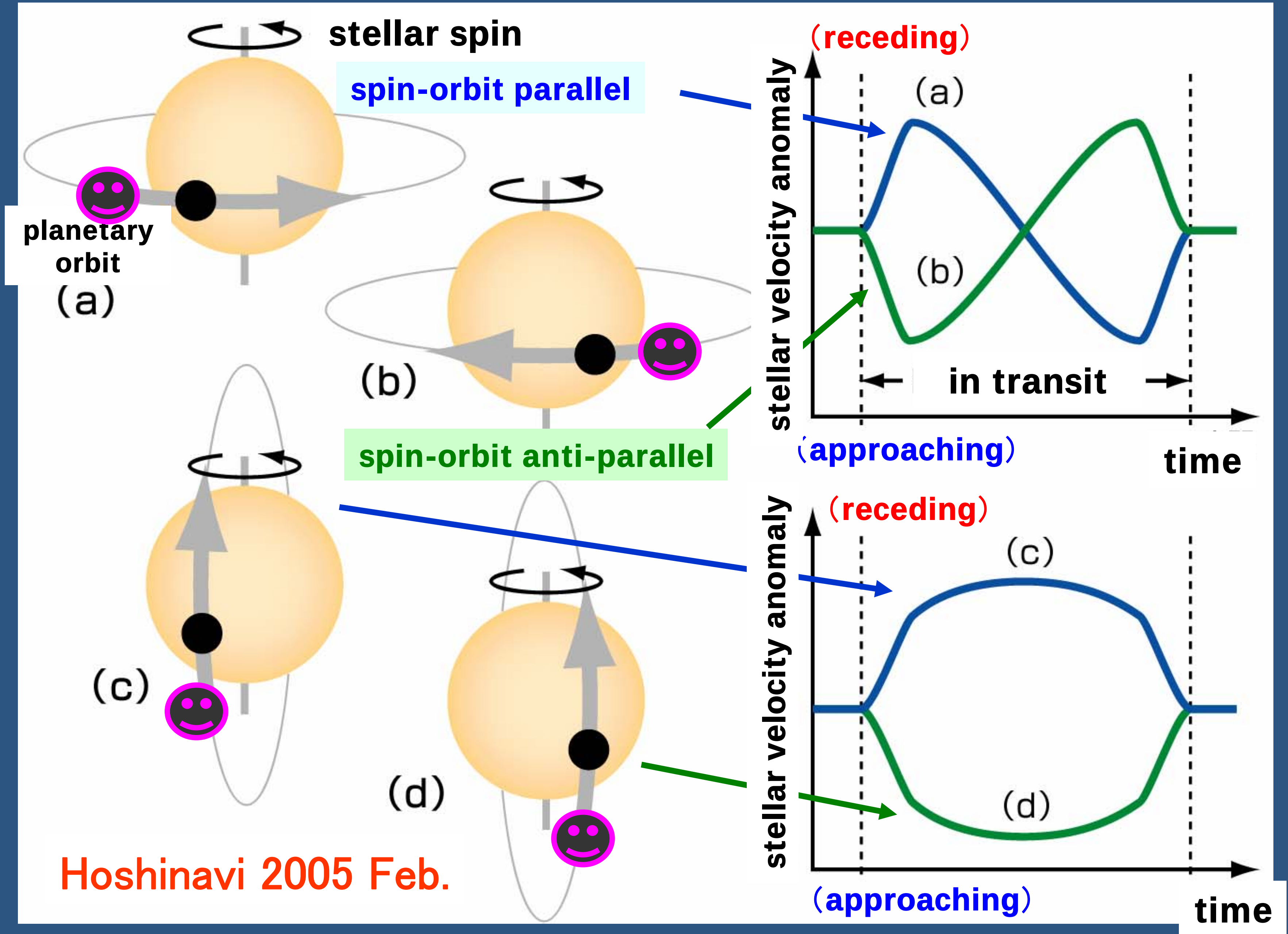
Narita et al. (2005)

Spectroscopic transit signature: the Rossiter-McLaughlin effect



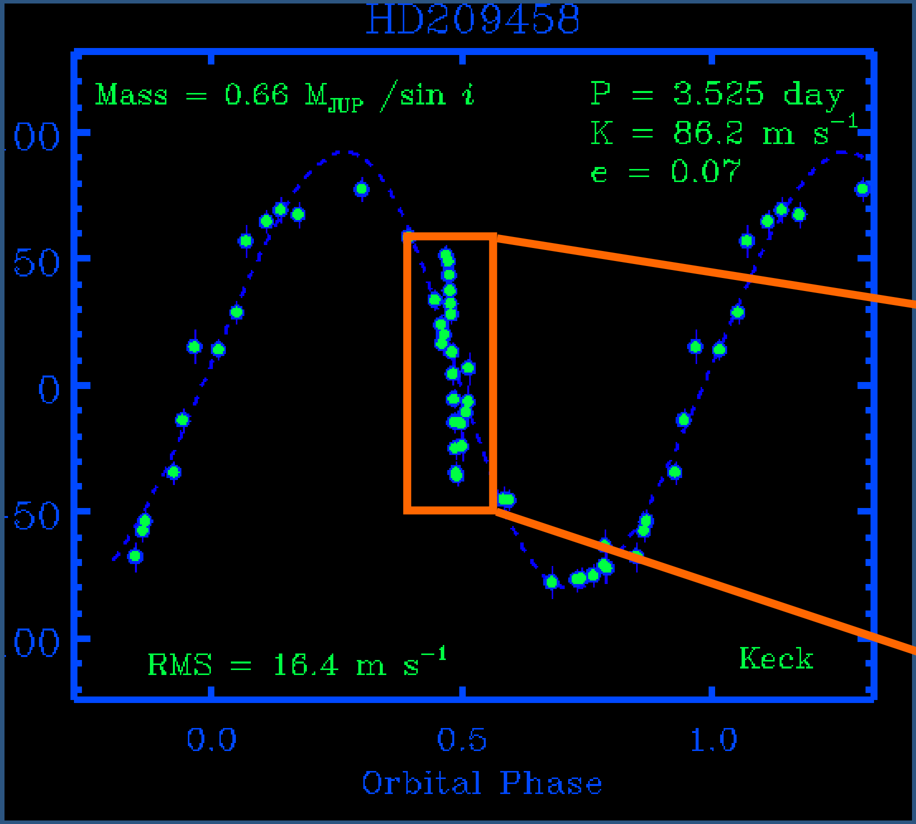
- Time-dependent asymmetry in the stellar Doppler broadened line profile
  - an apparent anomaly of the stellar radial velocity
- originally discussed in eclipsing binary systems
  - Rossiter (1924)
  - McLaughlin (1924)

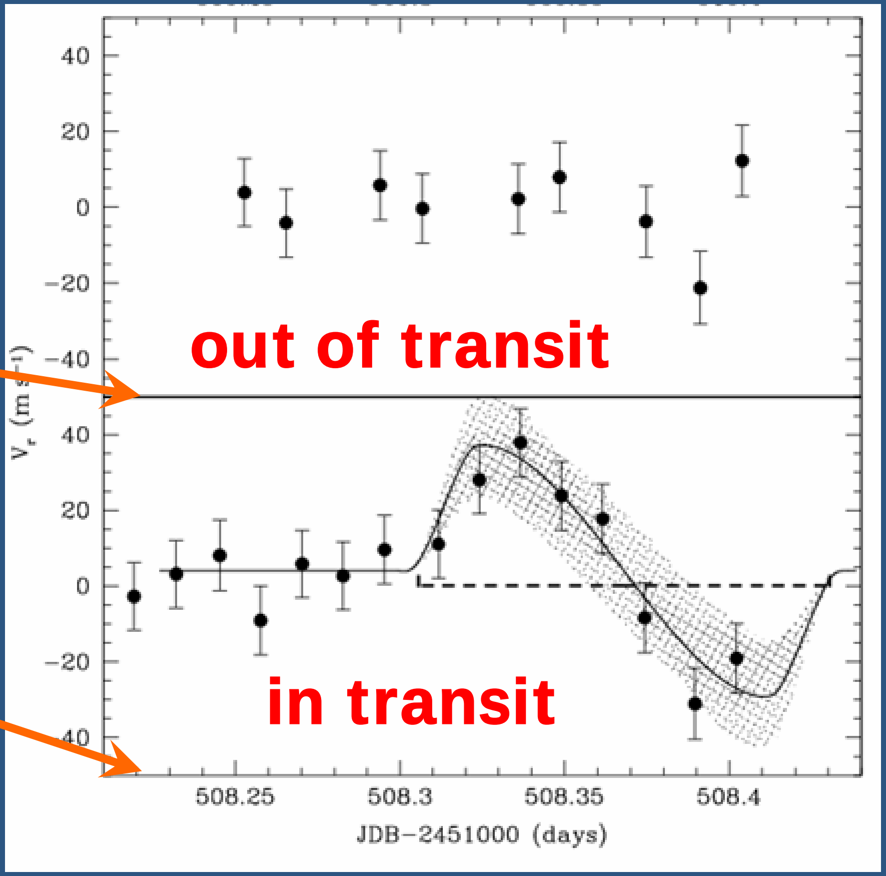
Velocity anomaly due to the Rossiter effect



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/

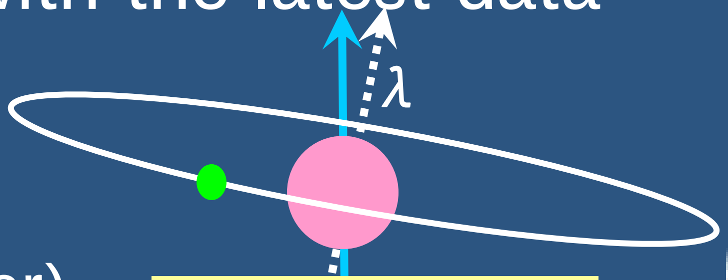
Stellar rotation and planetary orbit
Queloz et al. (2000) A&A 359, L13
ELODIE on 193cm telescope

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)

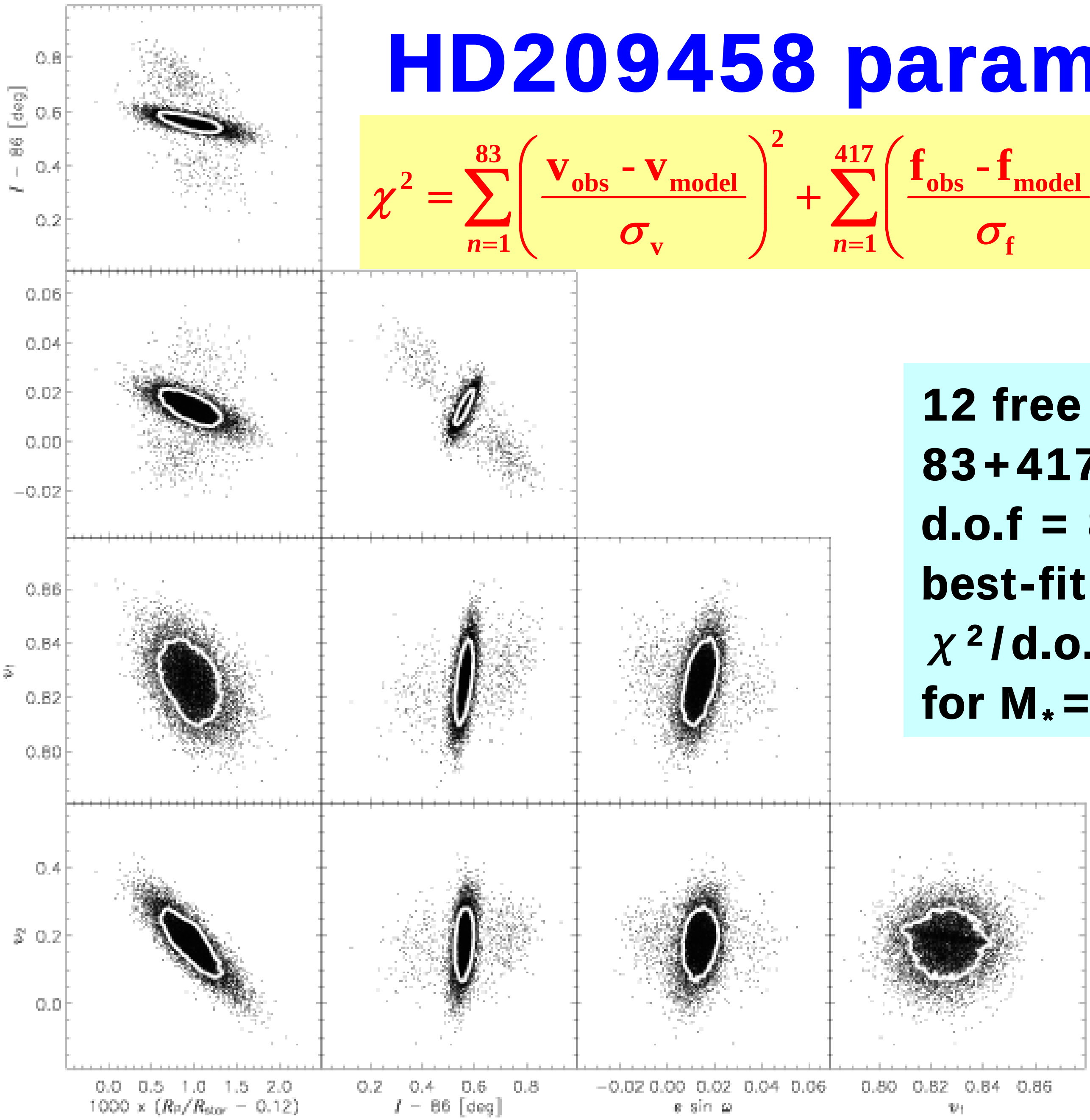


$$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$$

- **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

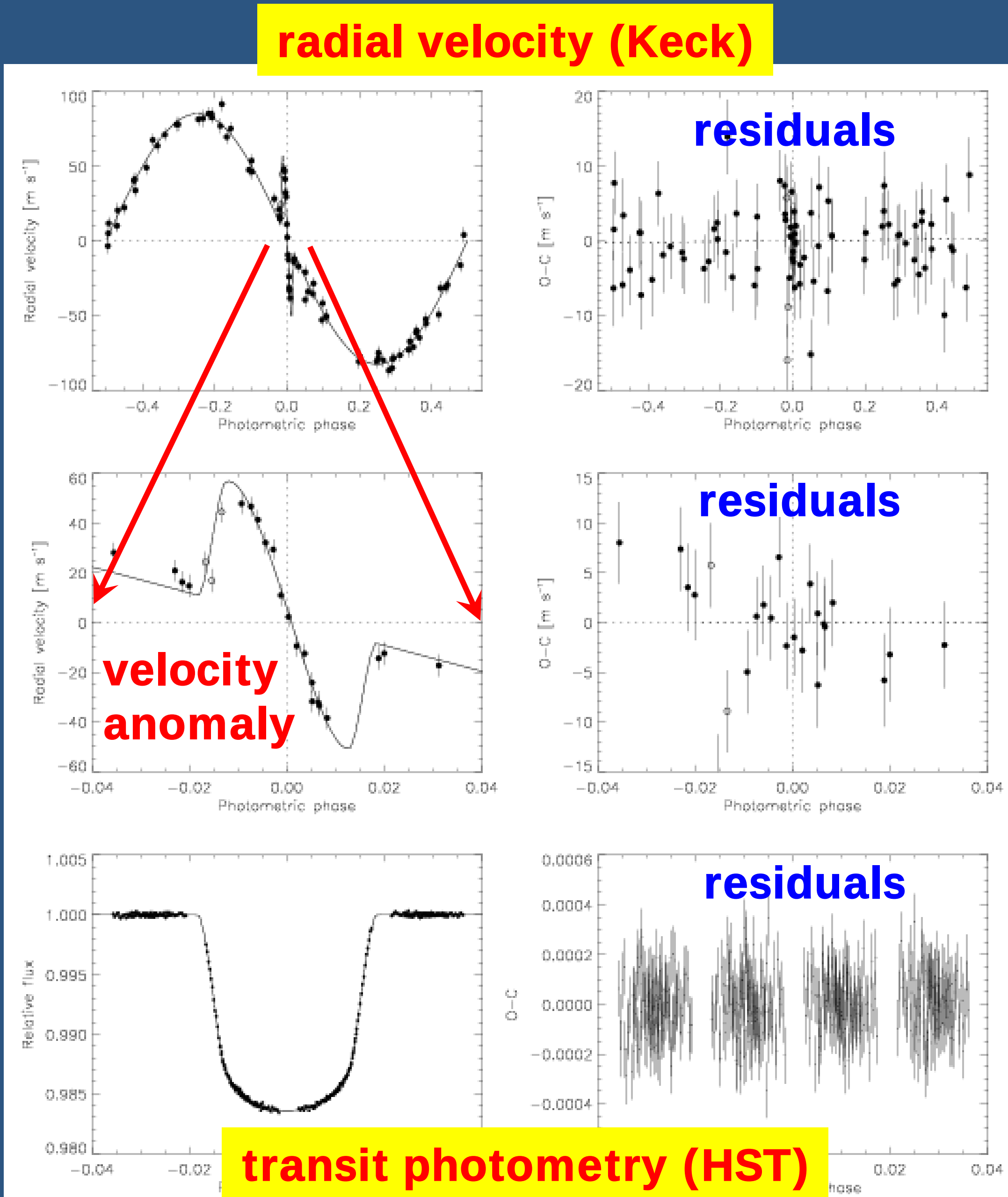
HD209458 parameter fit

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

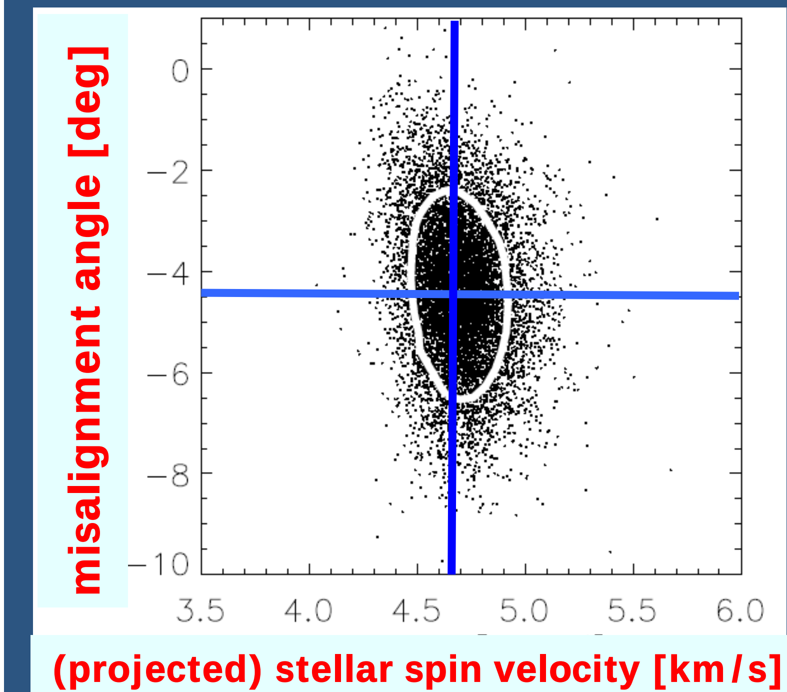


12 free parameters
83+417+1 data points
d.o.f = 83+417+1-12=489
best-fit :
χ^2/d.o.f=528/489=1.08
for $M_* = 1.06 M_{sun}$

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



first detection of non-zero λ !

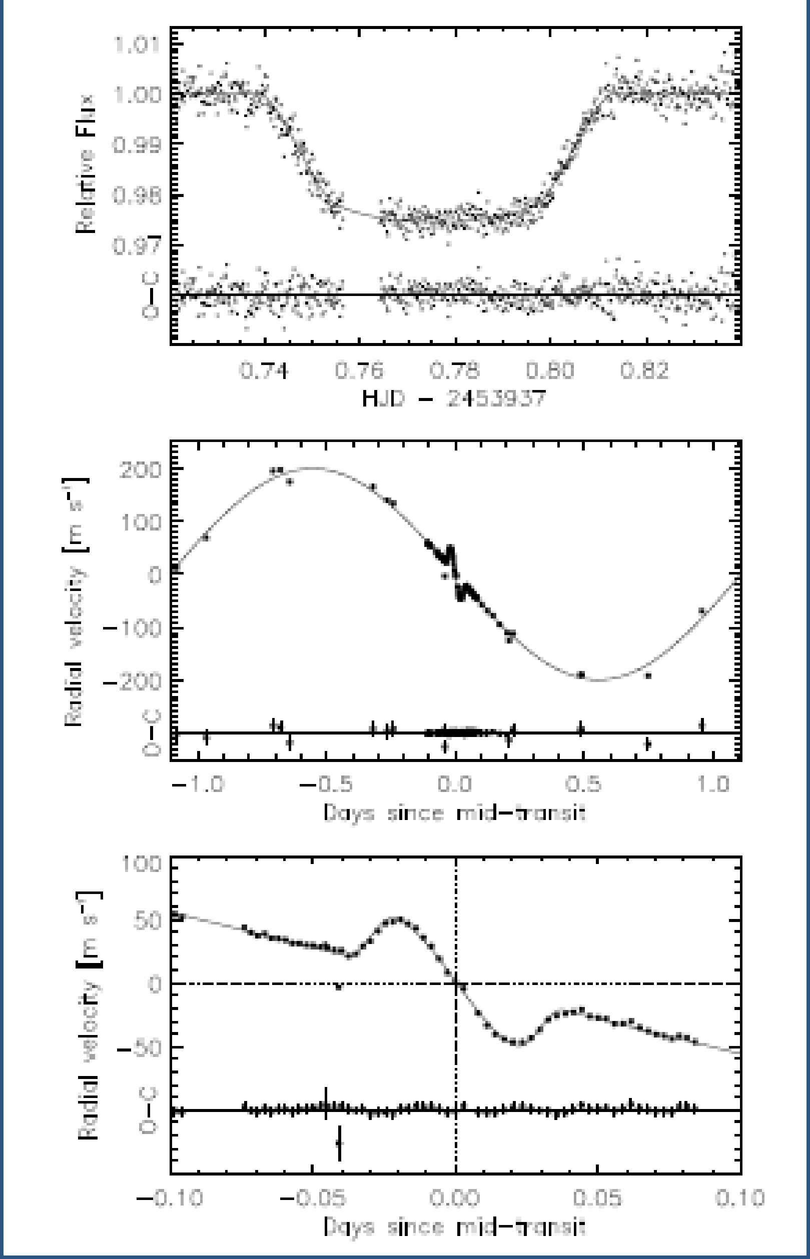


$$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$$

3 σ detection !

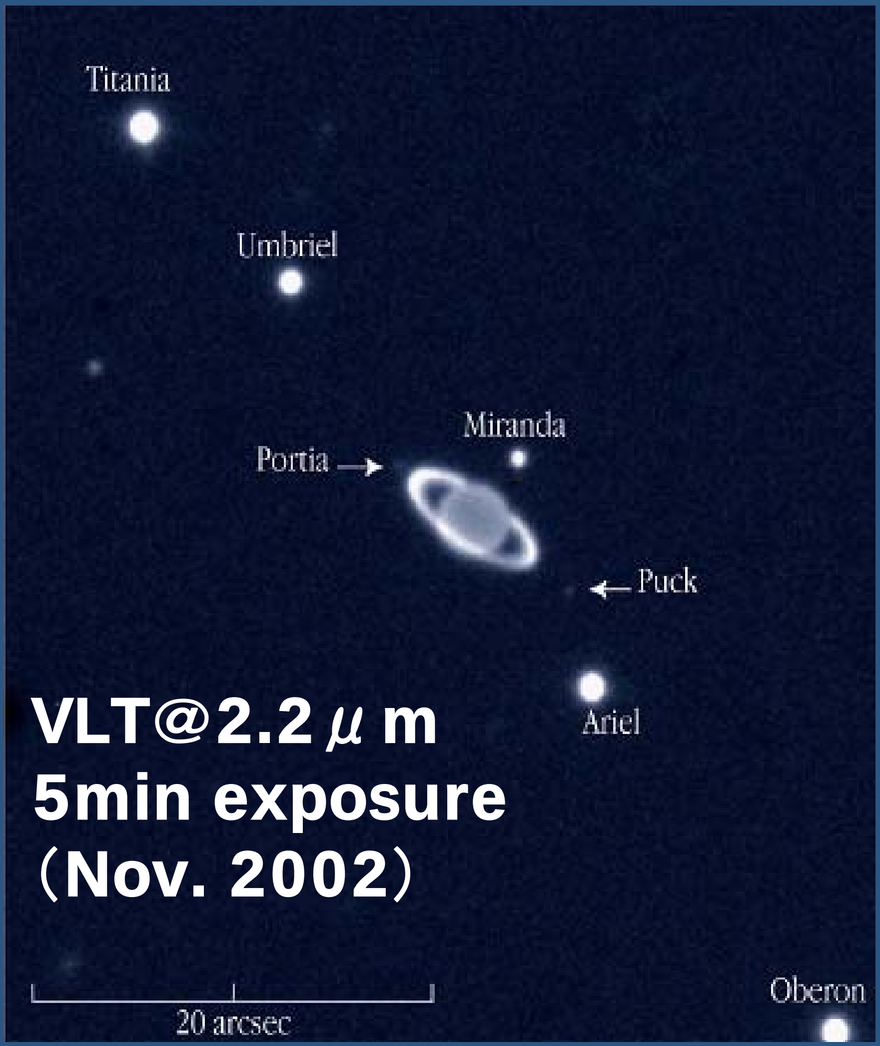
Winn et al. astro-ph/0504555 ApJ 631(2005)1215

another example: HD189733



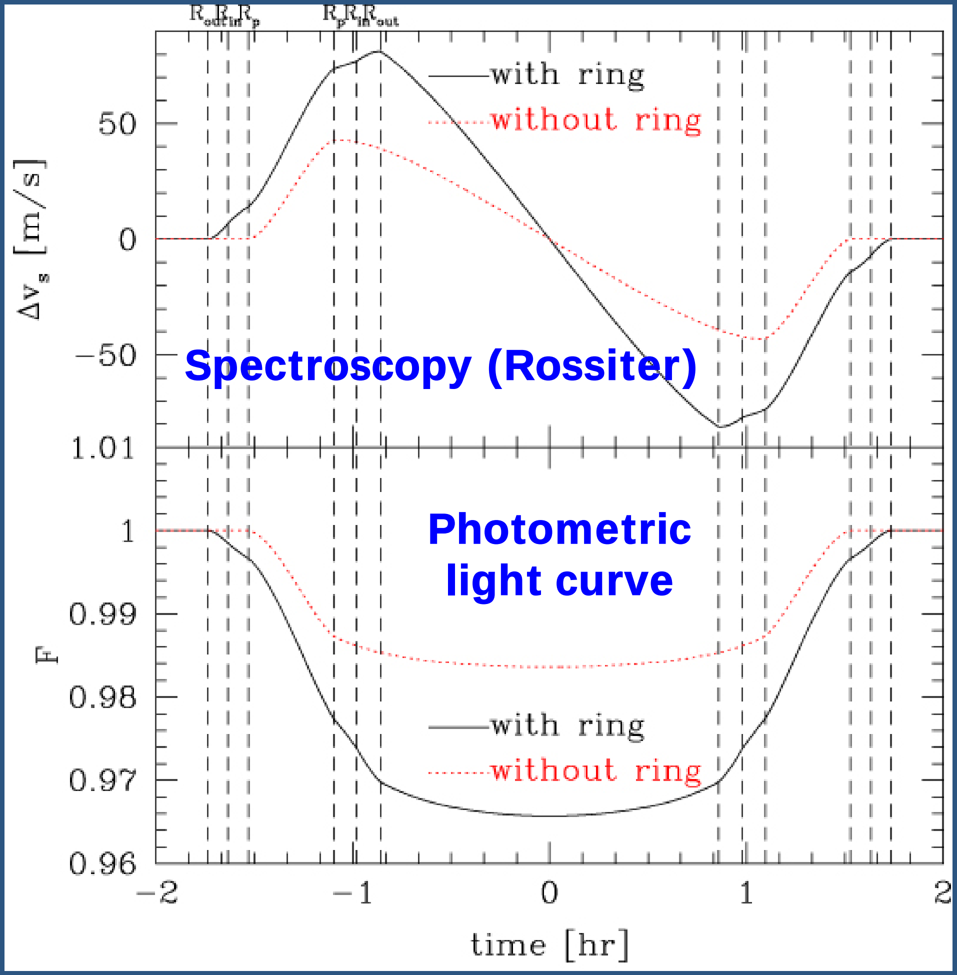
- **HD 189733**
  - Bouchy et al. (2005)
  - K-dwarf (V=7.7)+1.15$M_J$planet
  - 2.2 day orbital period
  - 2.5% photometric transit signal
- Winn et al. ApJL, submitted (astro-ph/0609506)
  - λ=-1.4° ±1.1°
  - consistent with zero

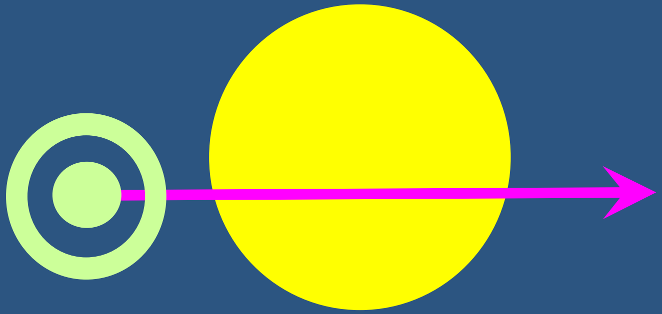
Discovery of the Uranus rings



- **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

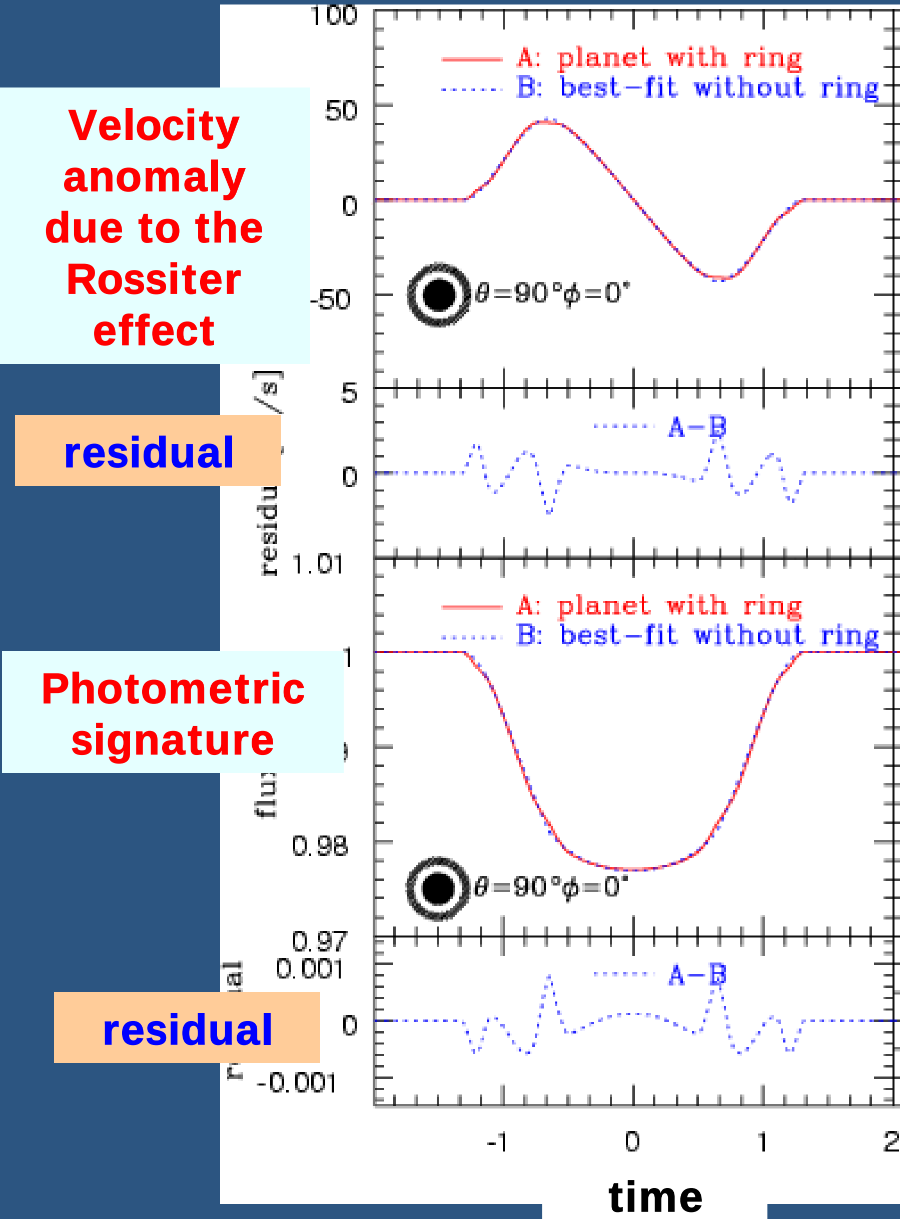




- Ring's inner and outer radii, gap, planet's radius imprints strong features in the photometric and spectroscopic data
- Statistical analysis of the residuals with respect to the best-fit ringless model

Ohta, Taruya & Suto, in preparation

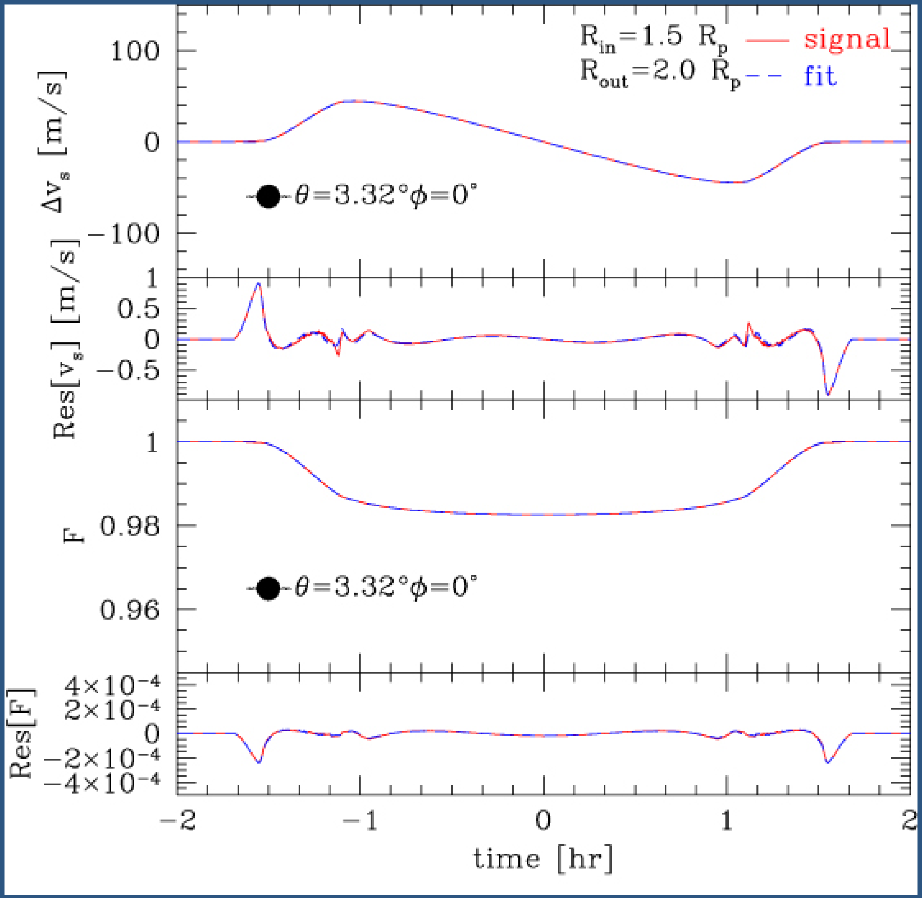
Detectability of a ring

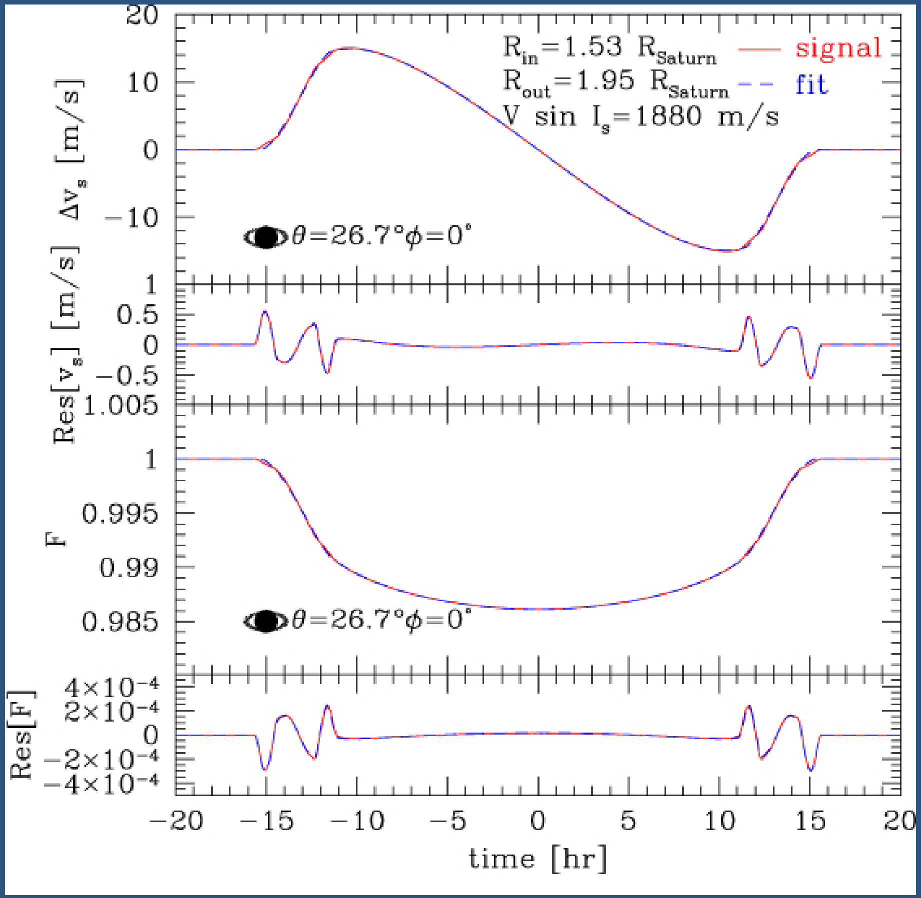


- a hypothetical ring around HD209458
  - $1.5R_{pl} < R_{ring} < 2R_{pl}$
  - deviation from a best-fit single planet
  - $\delta v \sim 1 m/s$
  - $\delta F/F \sim 0.1\%$
- marginally detectable level even with the current technology

Ohta, Taruya & Suto, in preparation

How about hot Jupiter and Saturn rings ?





Ohta, Taruya & Suto, in preparation

- **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 planet

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

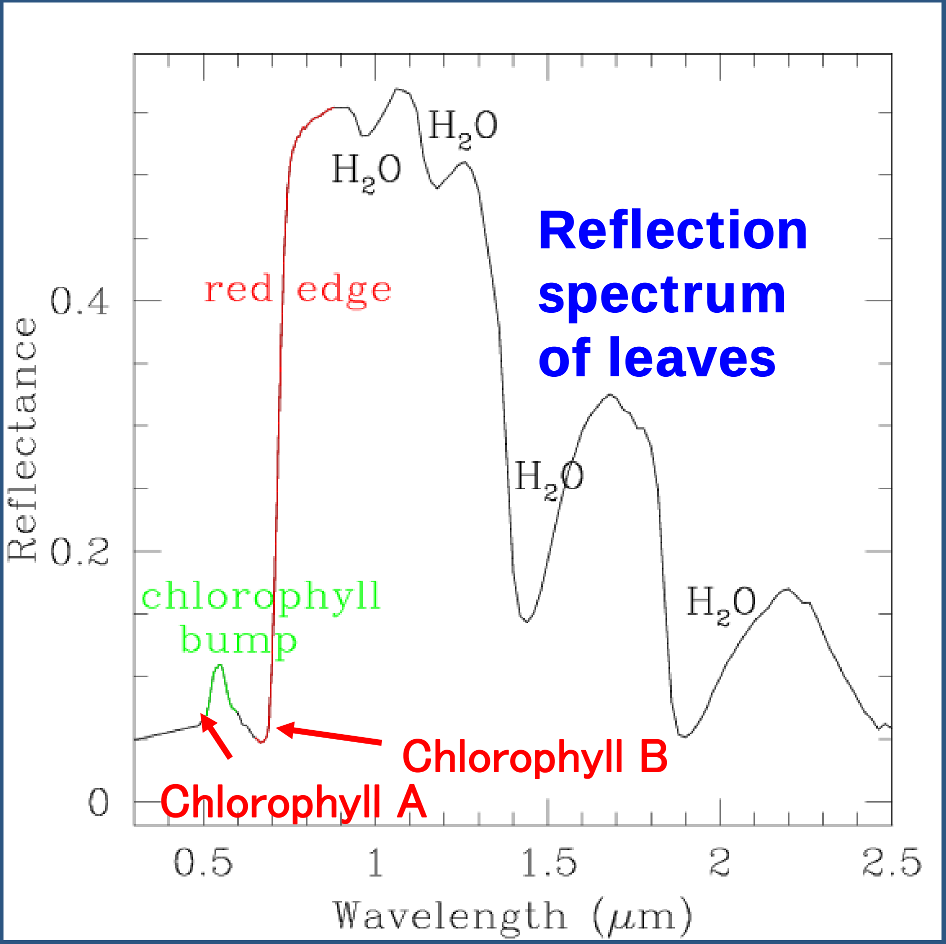
Astrobiology ?   Not yet

- 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

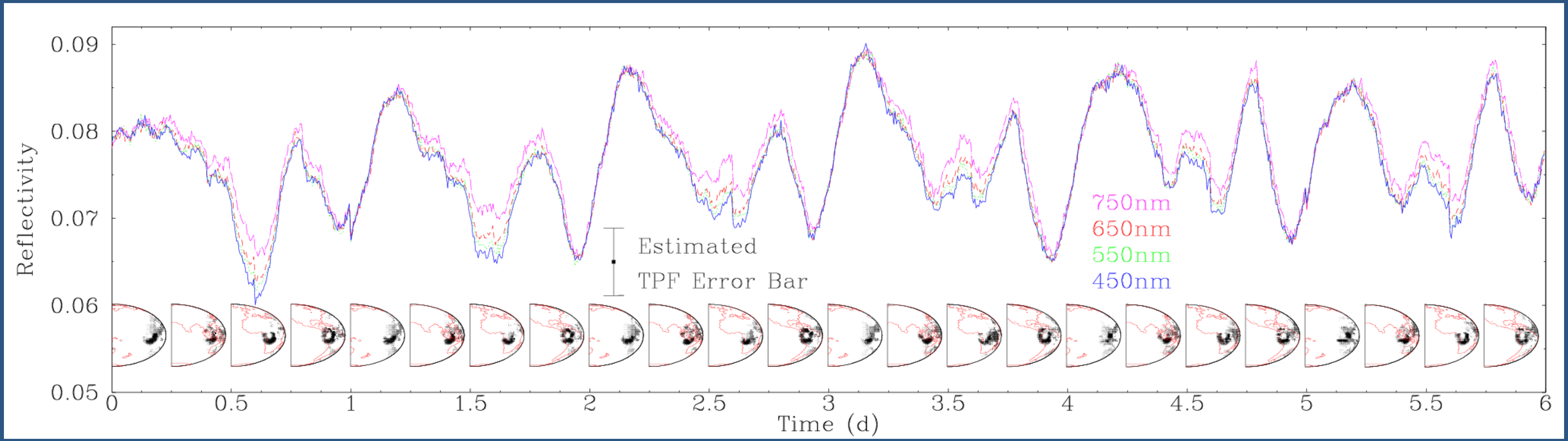
Red edge of (extrasolar) plants: a biomarker in extrasolar planets

- 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

Expected daily change of the reflected light from the earth

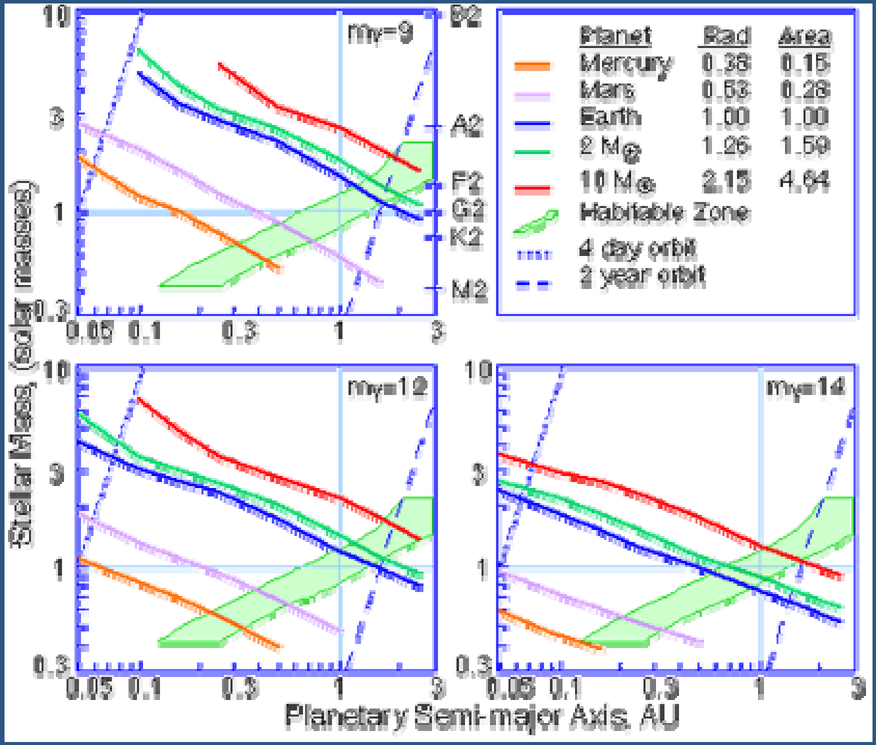


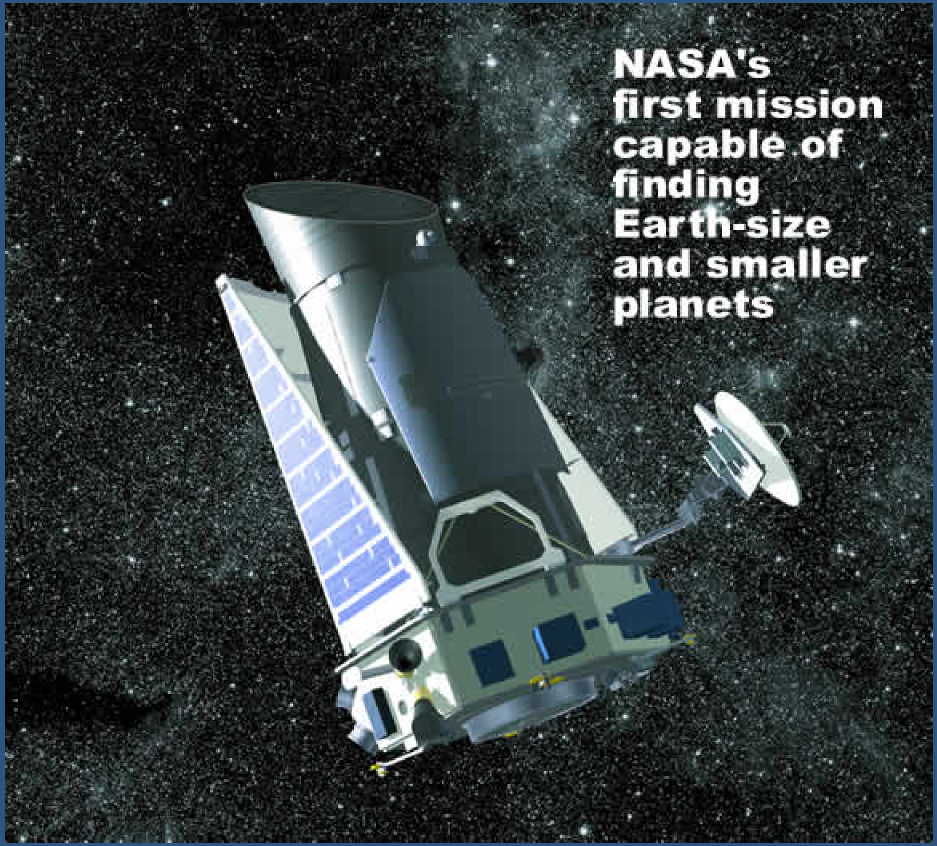
Ford, Seager & Turner: Nature 412 (2001) 885

- ***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 !***

Kepler mission (June 2008 launch?)

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





Kepler
A Search For Habitable Planets

http://kepler.nasa.gov/

Future of transiting planet research: follow Hantaro Nagaoka

写真 2：長岡半太郎（1865− 1950)

- Nagaoka's Saturn model of atom
  - Nagaoka: Phil. Mag. 7(1904) 445
  - ⇒ quantum atomic physics
- Transit planets
  - Orbital angular momentum（**L**）: radial velocity
  - Spin of star（**S**）: Rossiter effect
  - Spin of planet（**s**）: ring, satellite
- From planets to atomic physics
- From atomic physics to planets

Extra-solar planet can have a ring ?

- **Final sec. of the Nagaoka paper**
  - There are various problems which will possibly be capable of being attacked on the hypothesis of a Saturnian system
  - The rough calculation and rather unpolished exposition of various phenomena above sketched may serve is a hint to a more complete solution of atomic structure

写真 2：長岡半太郎（1865－1950）