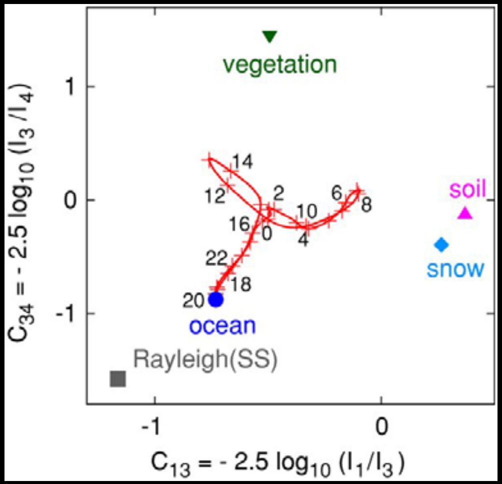
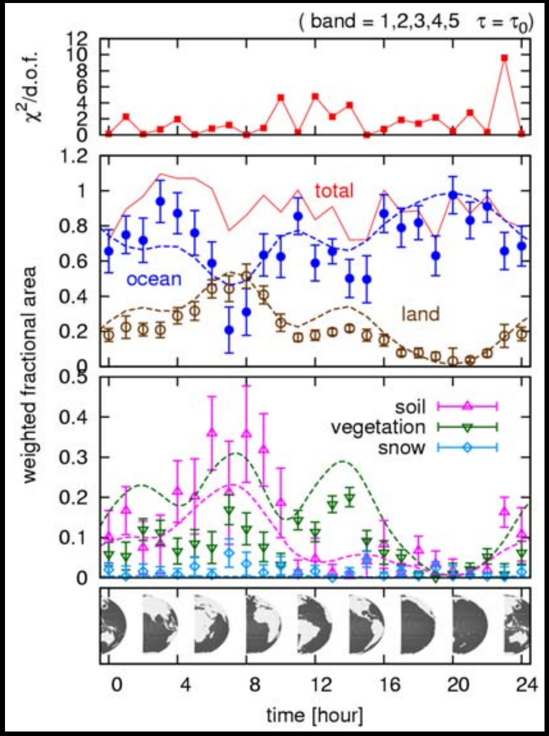
Colors of a second Earth: towards exoplanetary remote-sensing





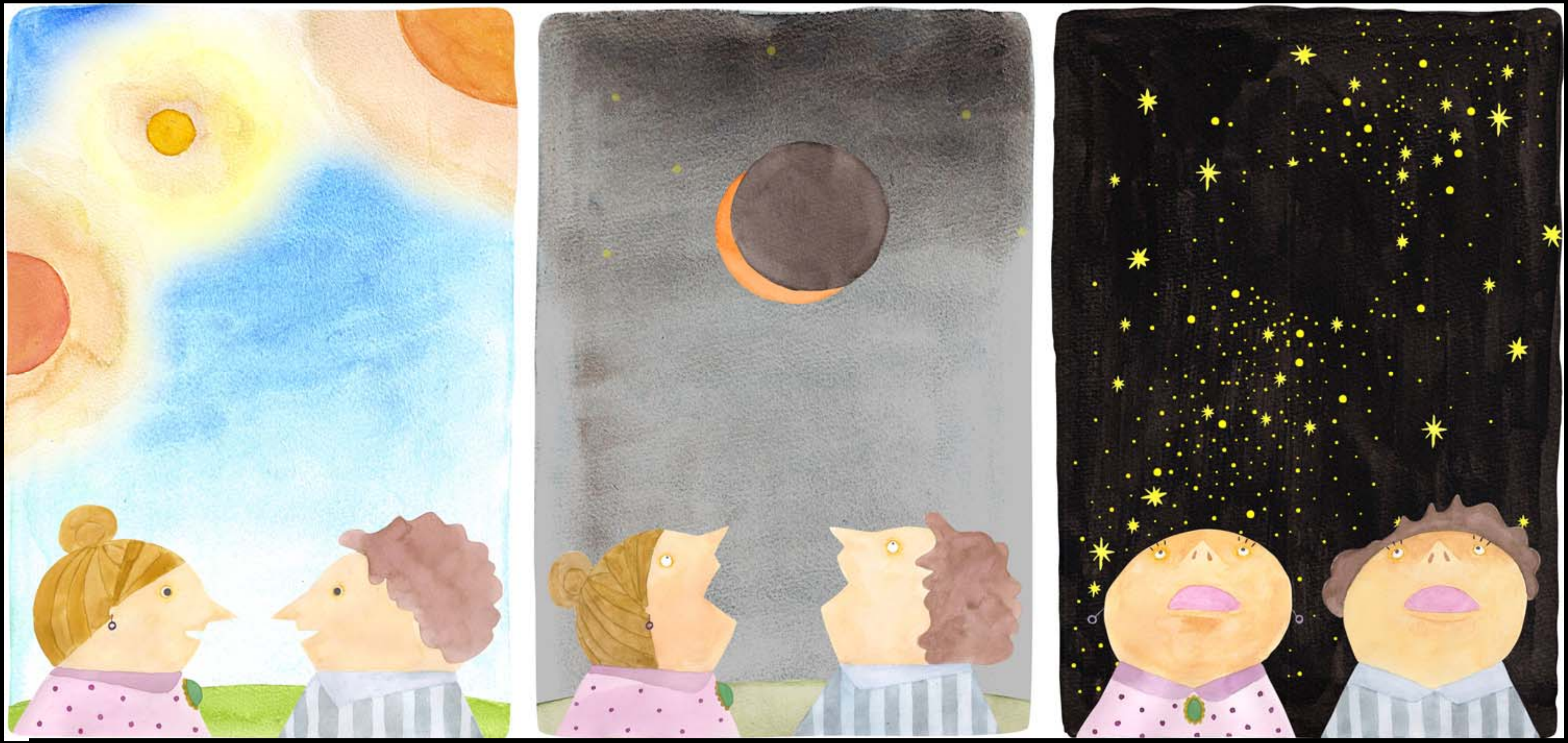
Yasushi Suto

東京大学 THE UNIVERSITY OF TOKYO

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

JPL colloquium, 16:00-, June 24, 2010

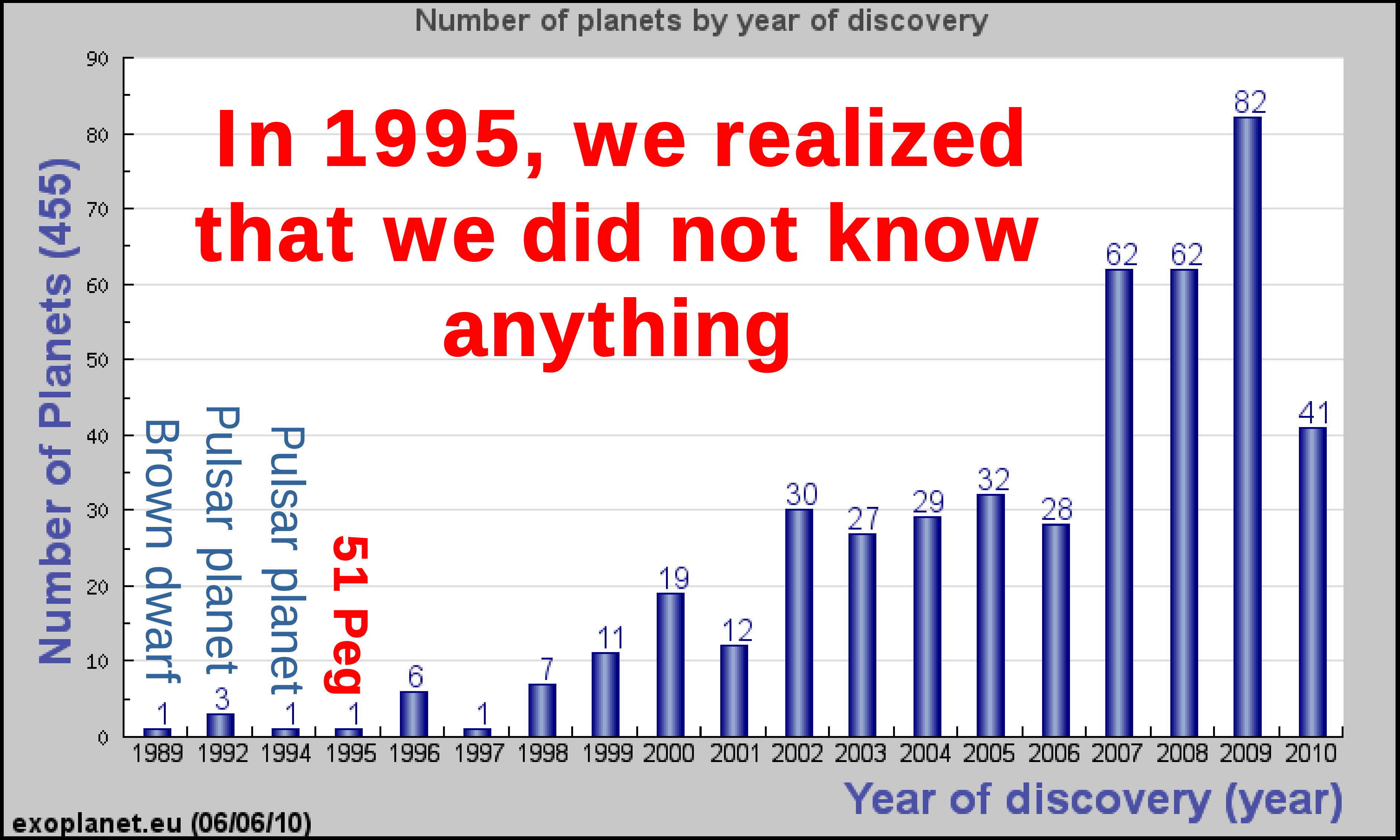
Nightfall: We didn't know anything



(Alisa Haba)

- no "night" except the total eclipse due to another planet every 2049 years on a planet "Lagash"
- People realized the true world for the first time through the darkness full of "stars" *(Issac Asimov: Nightfall)*

History of exoplanet discovery



Search for extrasolar planets

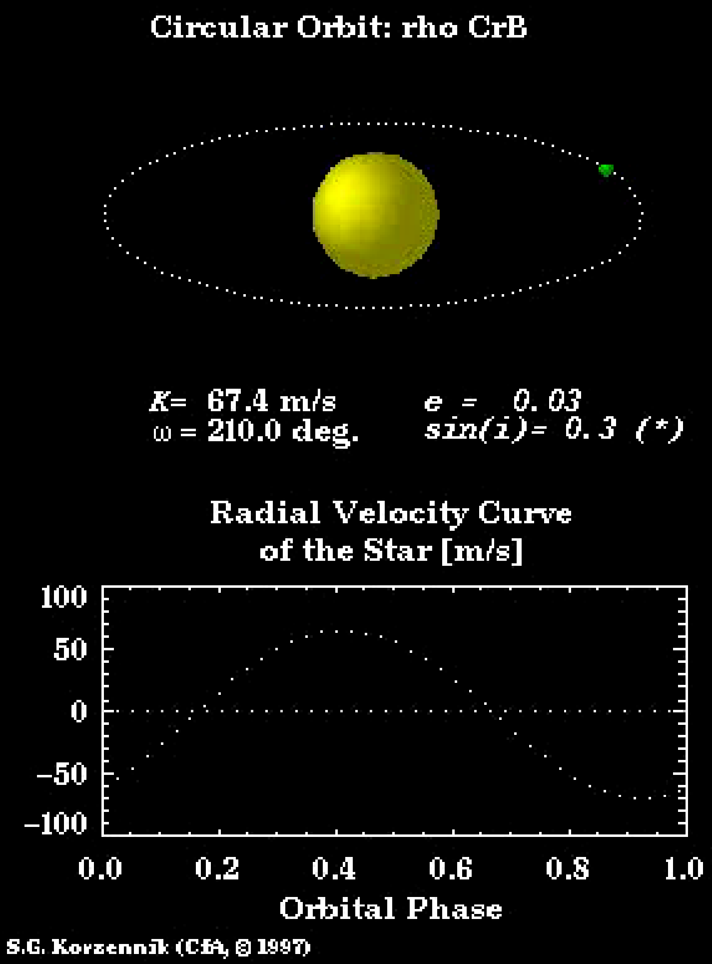
- the ***final*** goal: ***Are we alone ?***
  - origin of the earth
  - origin of the Solar System
  - ***habitable*** planets ⇒ origin of life
  - signature of extra-terrestrial life ?

    ⇒ extra-terrestrial intelligence ?

"Where are they ?" E.Fermi (1950)

Radial velocity of a star perturbed by a planet

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

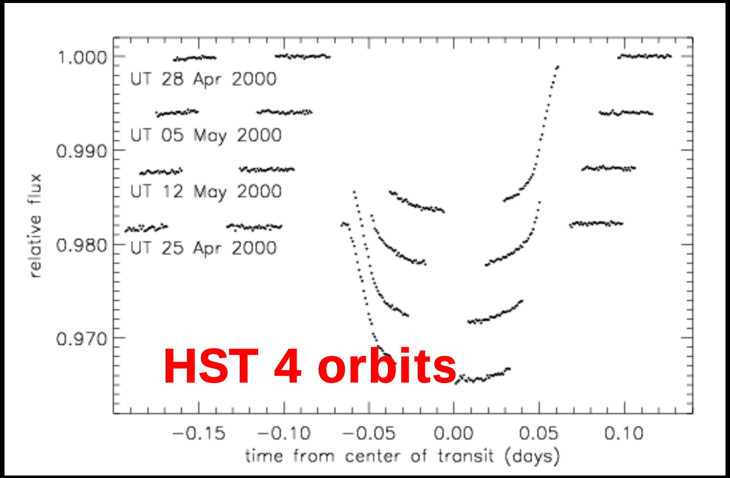


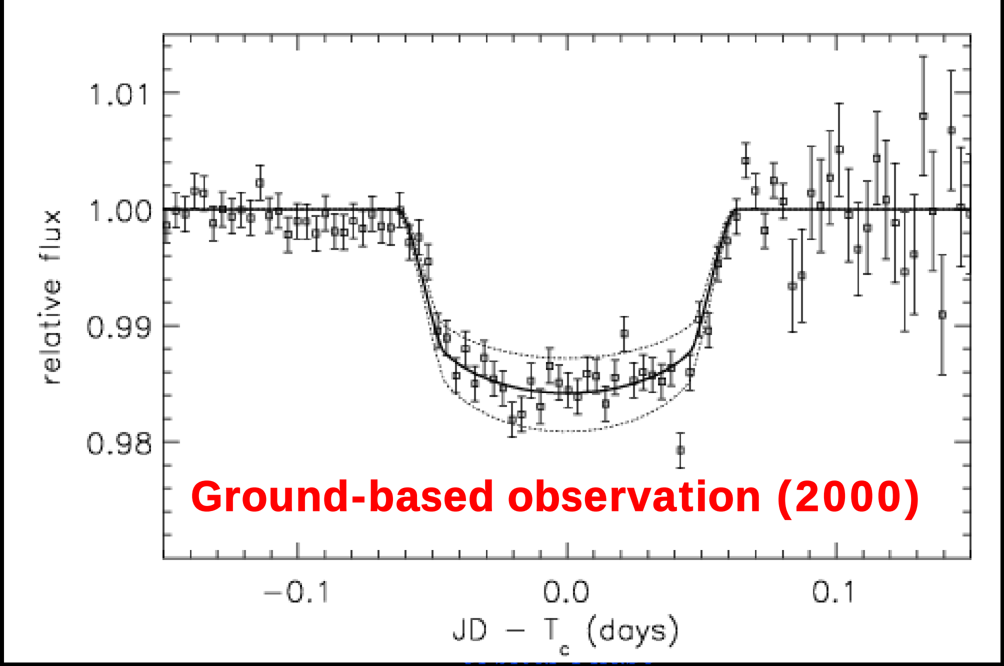
- velocity modulation of the Sun:
  - 12.5 m/s (Jupiter)
  - 0.1 m/s (Earth)
- an accuracy of 0.3m/s now achieved from the ground observation

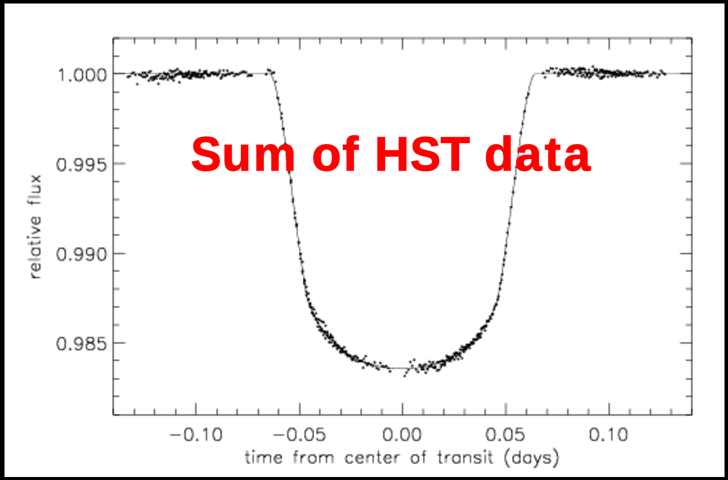
⇒ the major method of (Jovian) planet search

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)





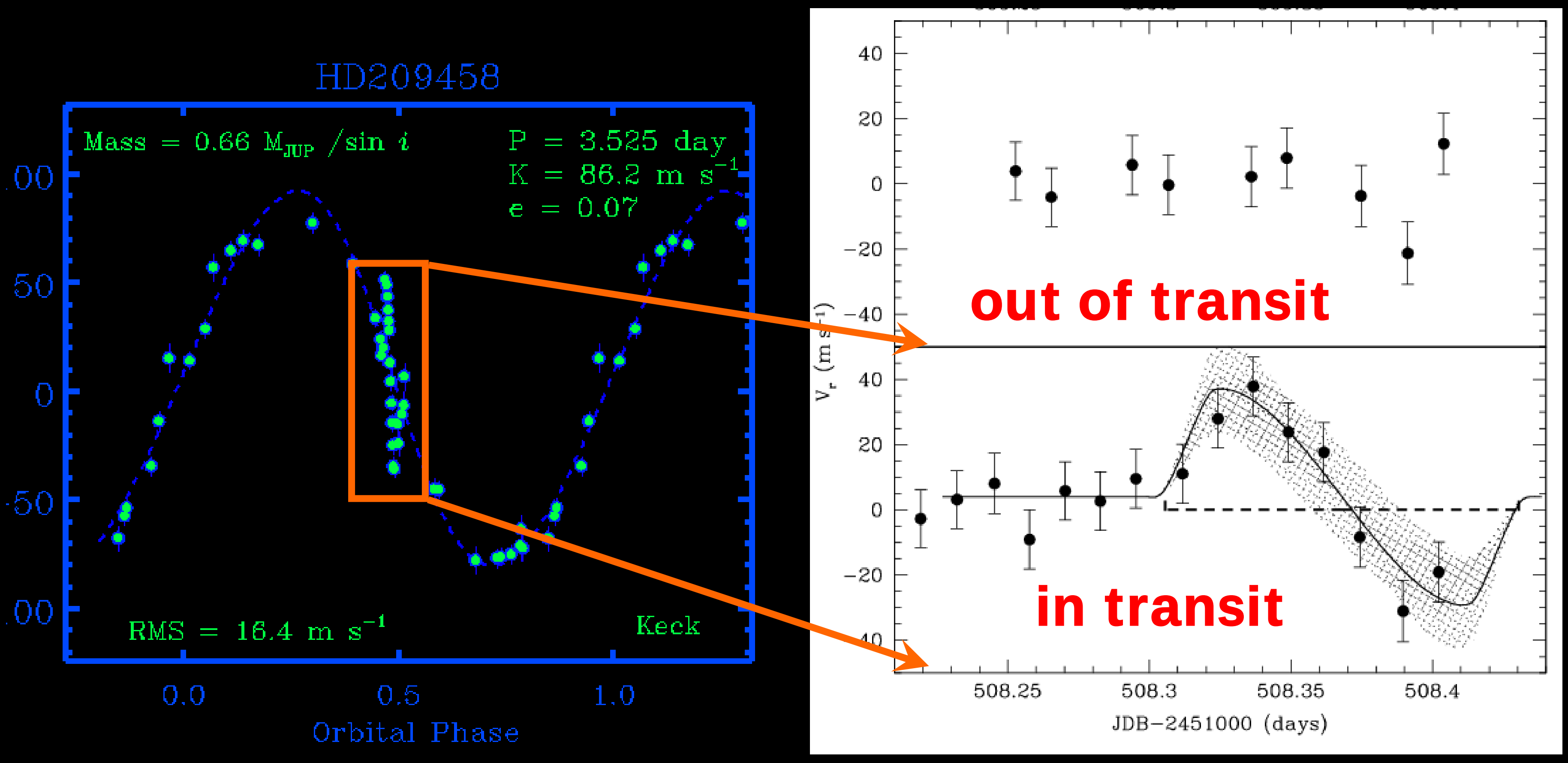


Brown et al. (2001)

exoplanet projects in my group at Univ. of Tokyo

- **Search for the planetary atmosphere with Subaru**
  - 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**
  - analytic perturbation formulae (Ohta et al. 2005, ApJ, 622, 1118; Hirano et al. 2010, ApJ, 709, 458)
  - First accurate detection (Winn et al. 2005 ApJ, 631, 1215)
  - application to ring detection (Ohta et al. 2009, ApJ, 690, 1)
- **Colors of a second earth**
  - Estimating the fractional areas of surface components from simulated photometry data (Fujii et al. 2010 ApJ, 715, 866)

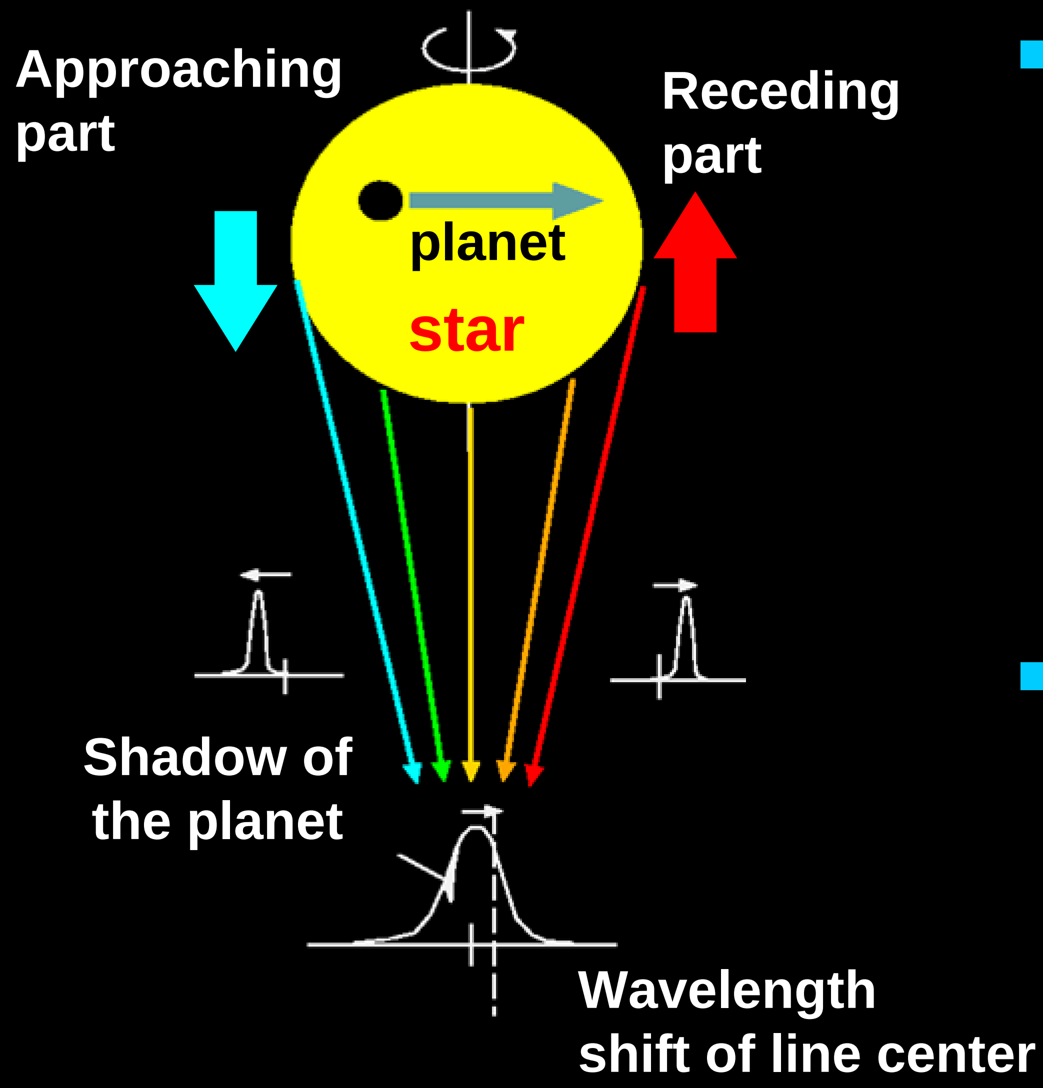
the Rossiter-McLaughlin effect for an extrasolar transit planetary system HD209458



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

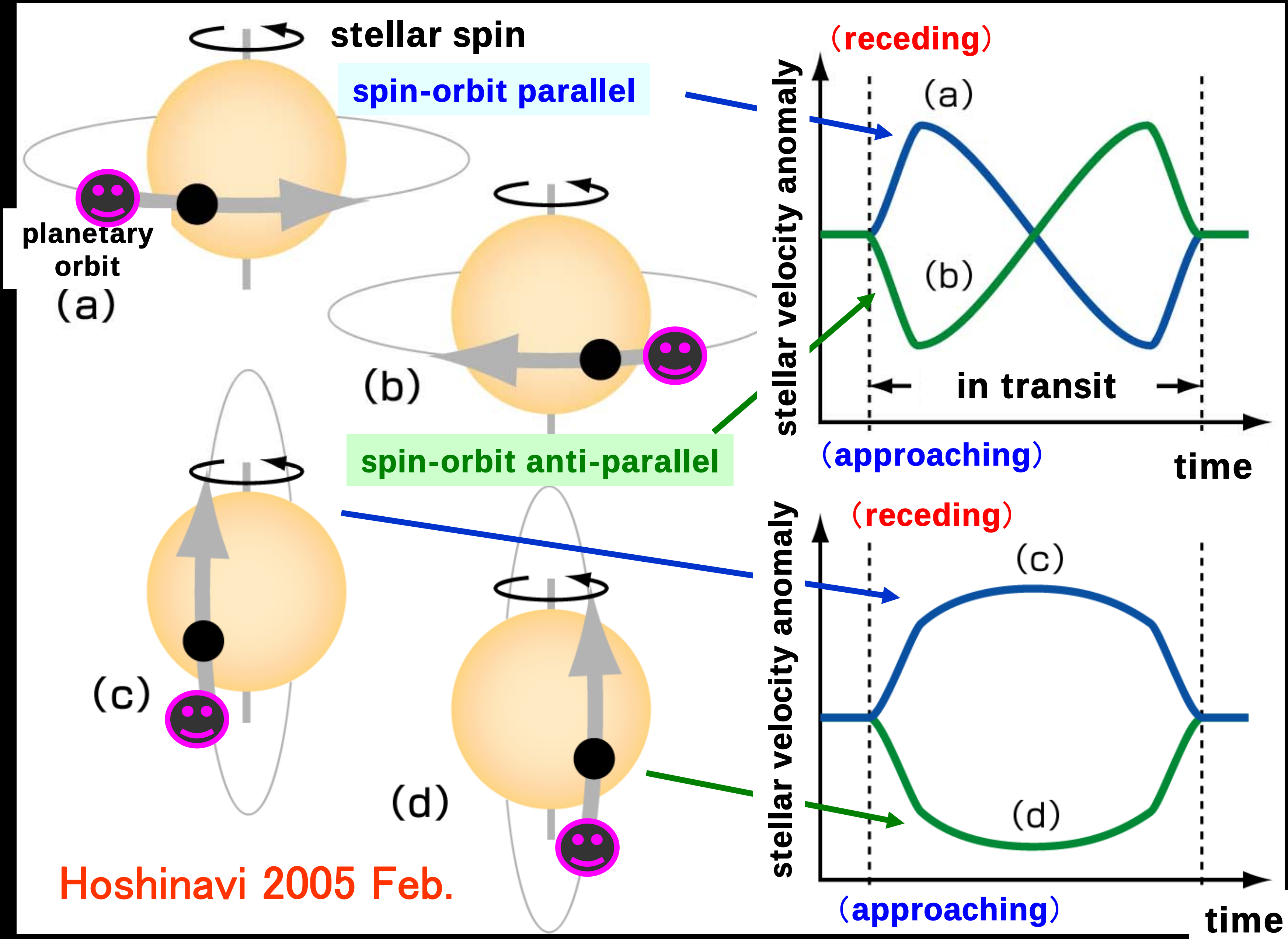
Stellar rotation and planetary orbit
Queloz et al. (2000) A&A 359, L13
ELODIE on 193cm telescope

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

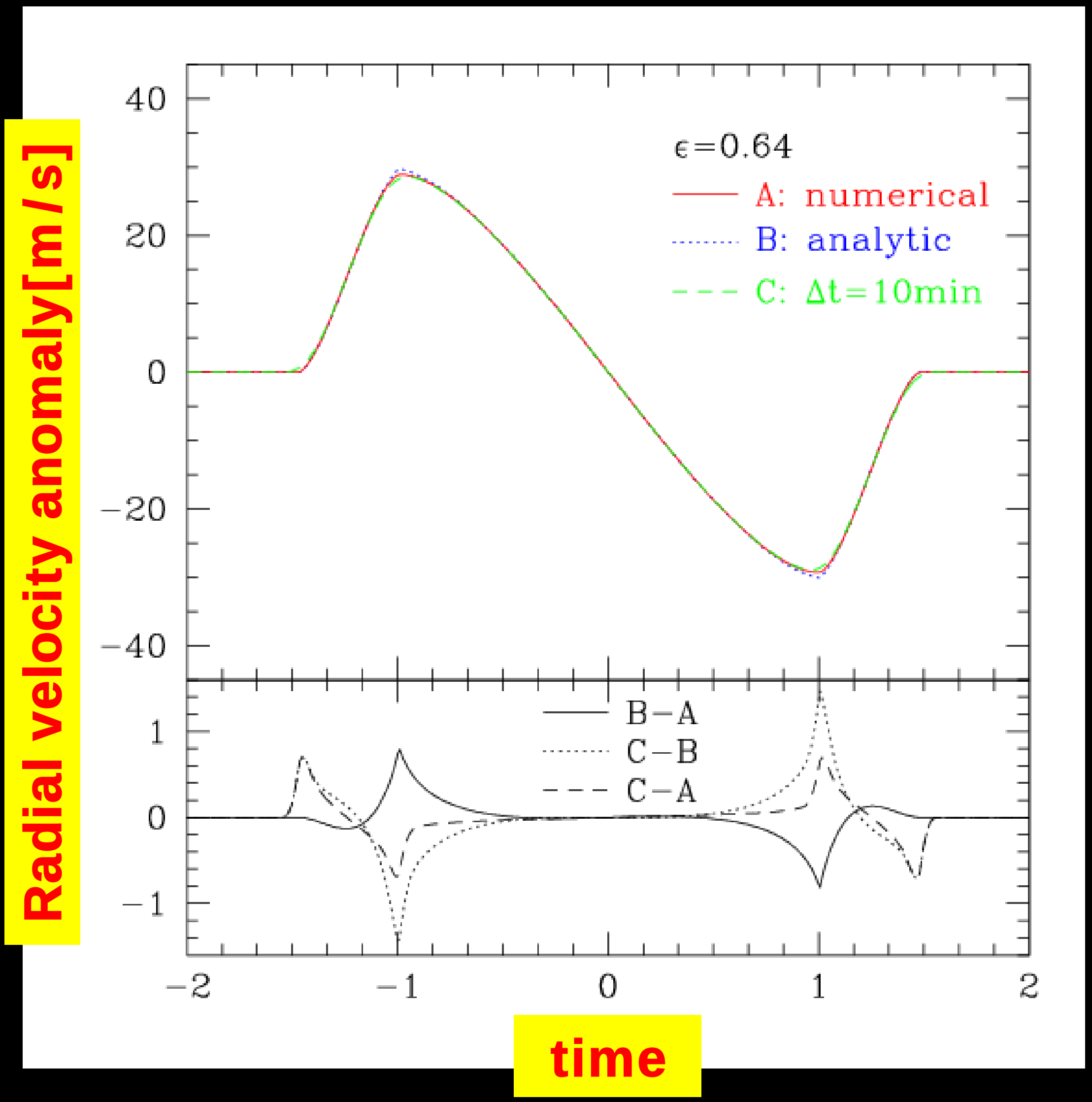


Analytic templates for the velocity anomaly due to the Rossiter -McLaughlin effect

Limb darkening:
B= 1- ε (1-cos θ)

- 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

Yasuhiro Ohta, Atsushi Taruya,[1] and Yasushi Suto[1]
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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.

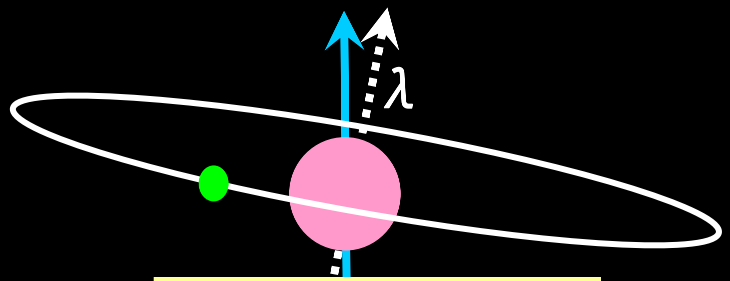
We also note that the future satellites *COROT* and *Kepler* will detect numerous transiting planetary systems, most of which will be important targets for the RM effect in 8–10 m class ground-based telescopes. We hope that our analytic formulae presented here will be a useful template in estimating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

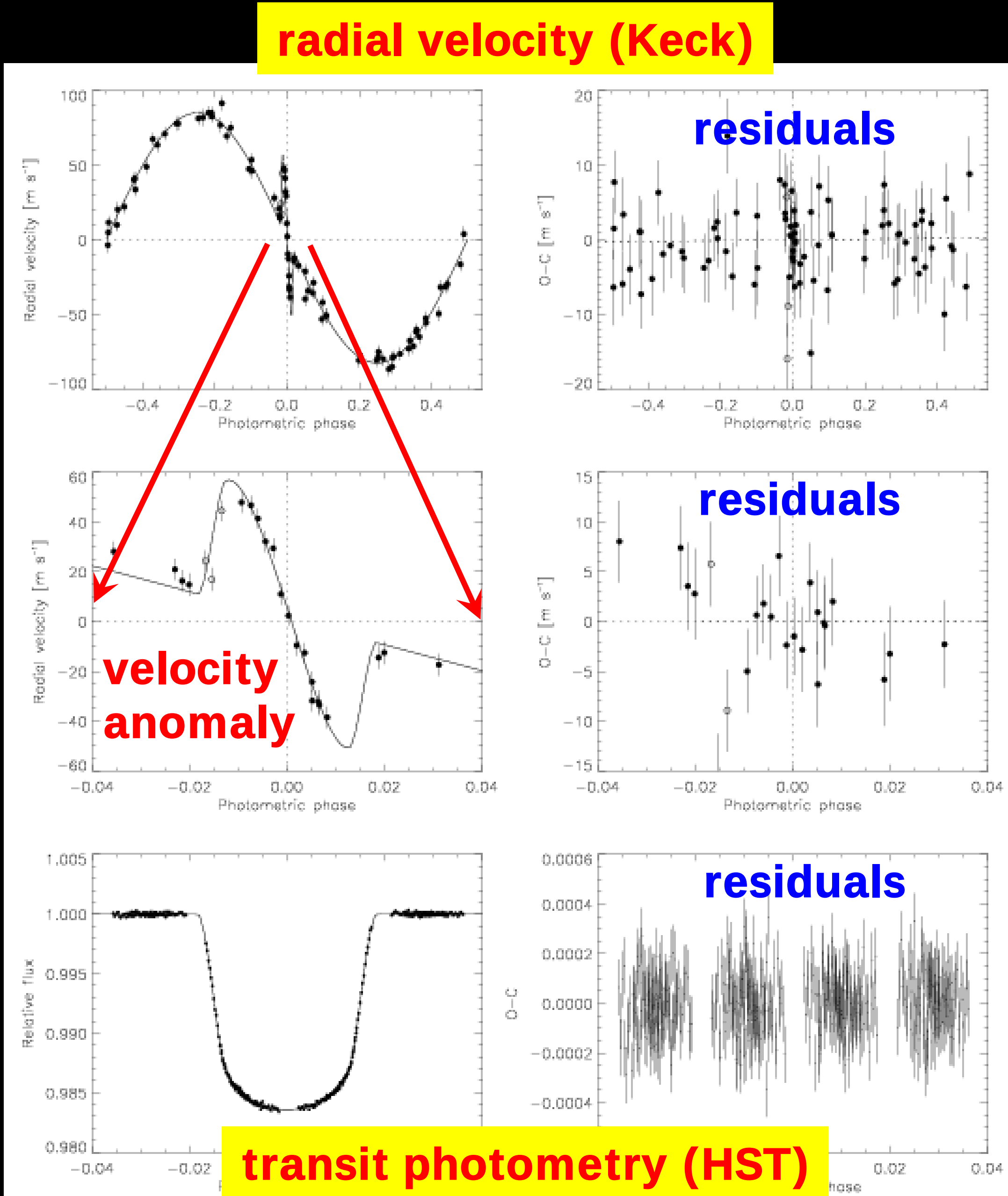
Indeed my motivation was to find a retrograde planet !

Measurement of Spin-Orbit alignment in an Extrasolar Planetary System

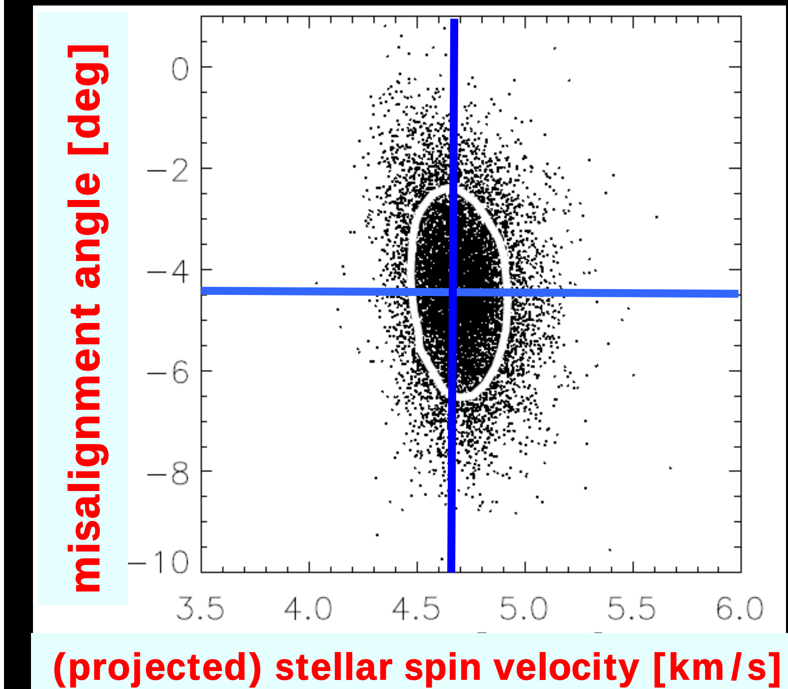
- **Joshua N. Winn (MIT)**, R.W. Noyes, M.J. Holman, D.B. Charbonneau, Y. Ohta, A. Taruya, Y. Suto, N. Narita, E.L. Turner, J.A. Johnson, G.W. Marcy, R.P. Butler, & S.S. Vogt
  - ApJ 631(2005)1215 (astro-ph/0504555)



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



first detection of non-zero λ !

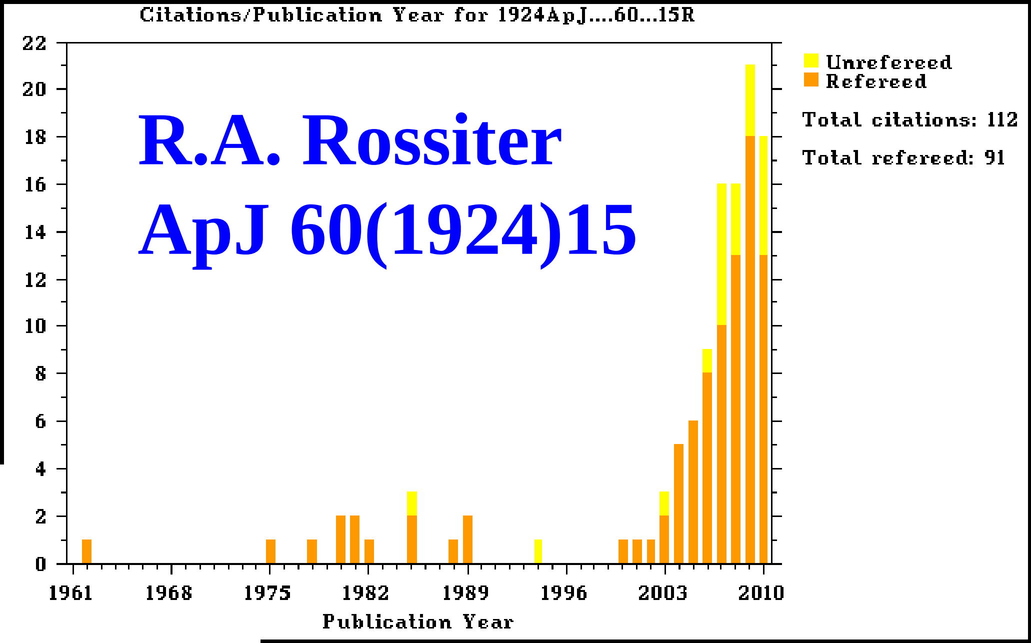


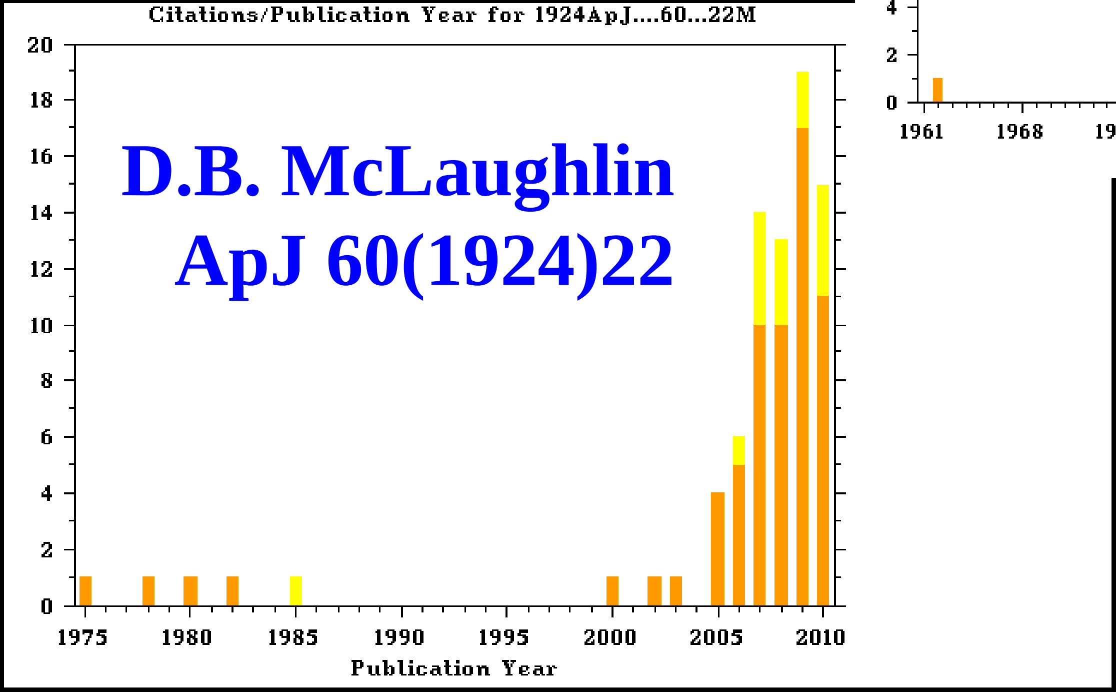
$$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$$

3σ detection !

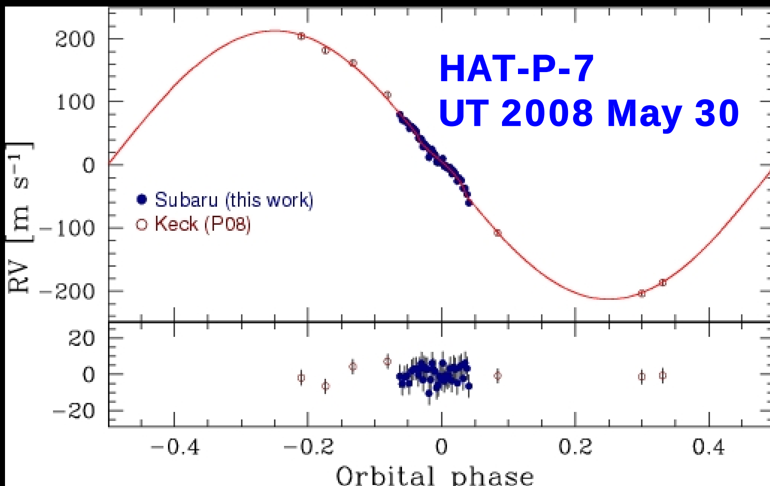
Winn et al. astro-ph/0504555 ApJ 631(2005)1215

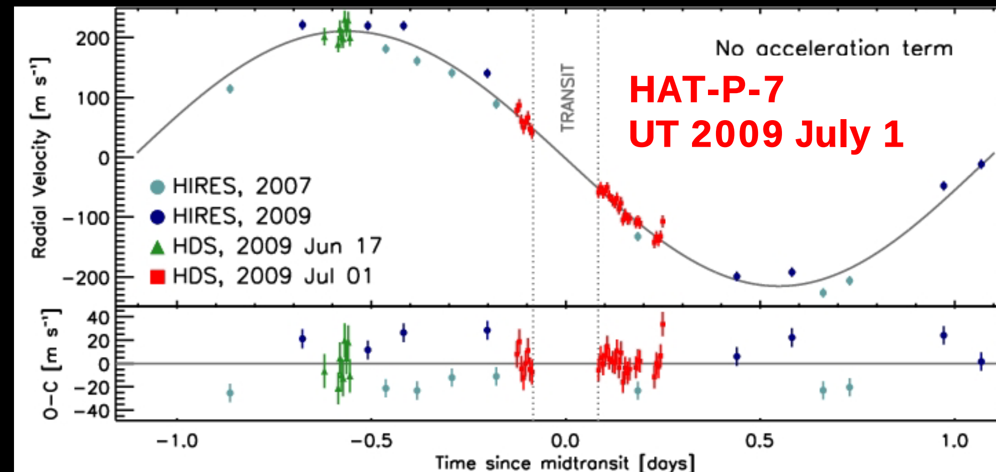
Citation history of the RM papers

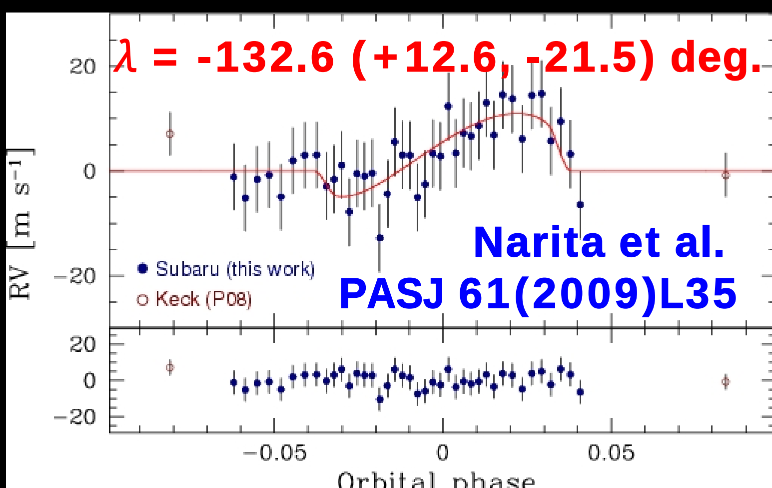


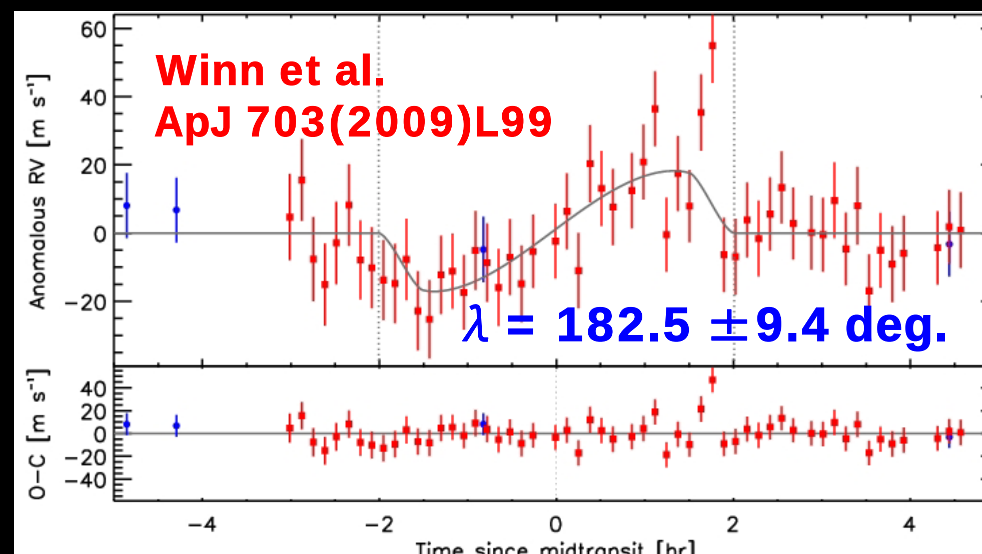


Discovery of a retrograde / polar orbit of HAT-P-7 with Subaru via the RM effect









- Origin of the retrograde/polar orbit is unknown

What we have learned so far...

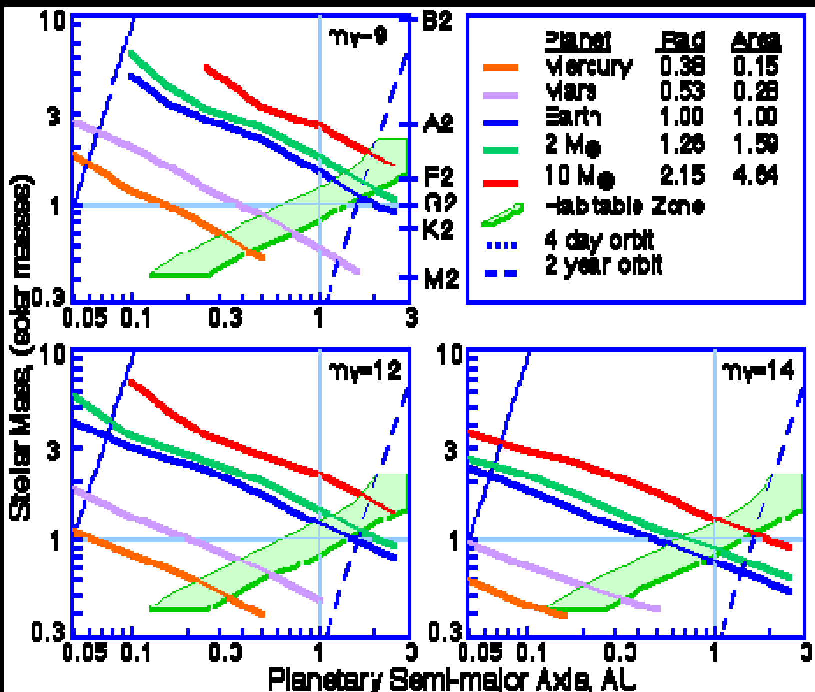
- Planets are not rare, but fairly common
  - >10 percent of sun-like stars have planets
- Diversity of planetary systems
  - Hot Jupiter, super earth,,,
  - Prograde/retrograde/polar-orbit planet
- Various observational approaches
  - High-dispersion spectroscopy (radial velocity), precise photometry (transit, micro-lens), direct imaging
  - Planetary atmosphere
  - Reflected light from planet

What's next ?

Kepler mission (March 6, 2009 launch)

Photometric survey of transiting planets

Searching for terrestrial (and habitable) planets



Kepler
A Search For Habitable Planets

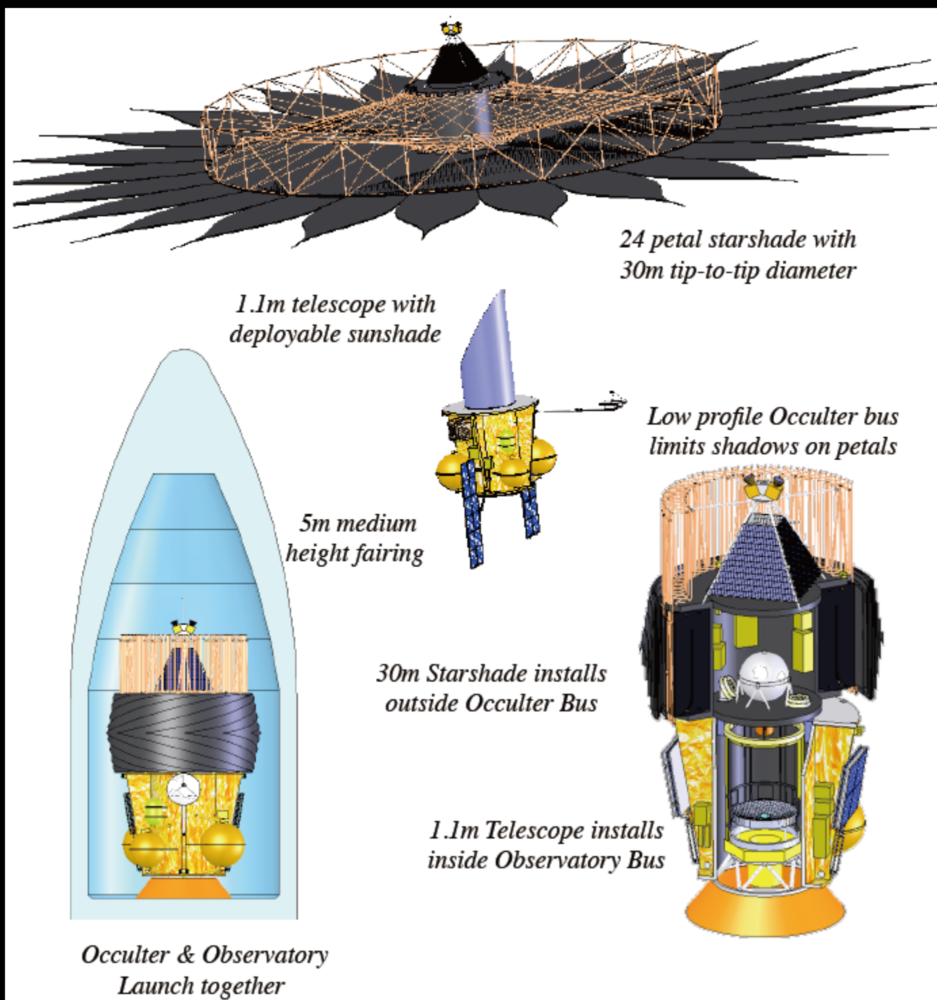
1st public data release
706 transiting planet candidates
(Borucki et al. arXiv:1006.2799)

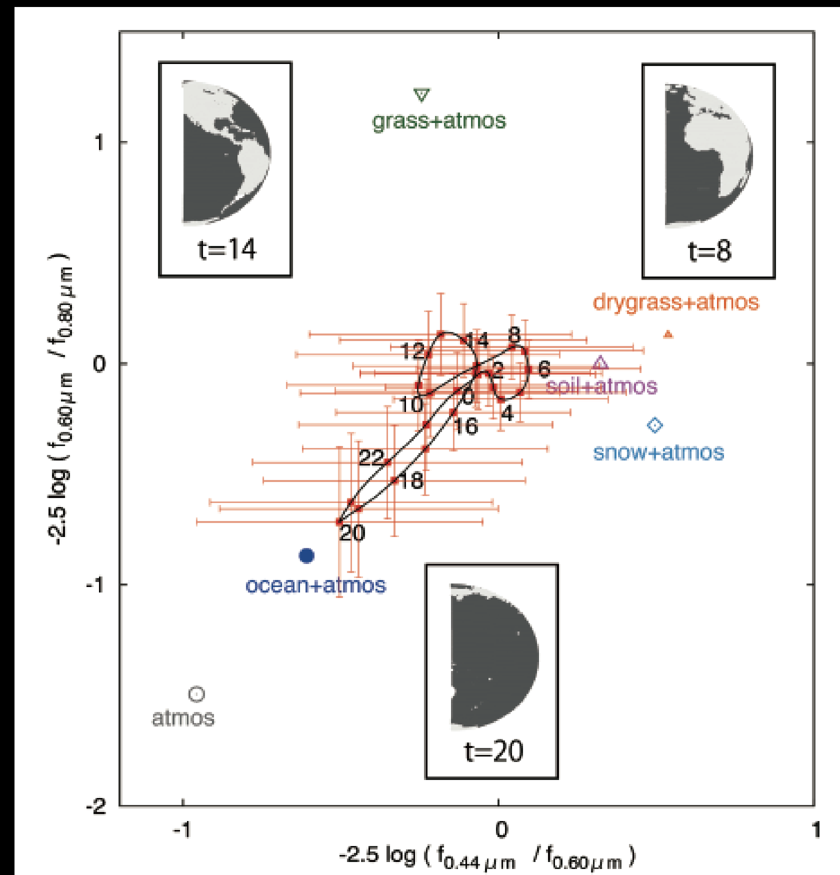
http://kepler.nasa.gov/

O_3: The Occulting Ozone Observatory

O_3: The Occulting Ozone Observatory

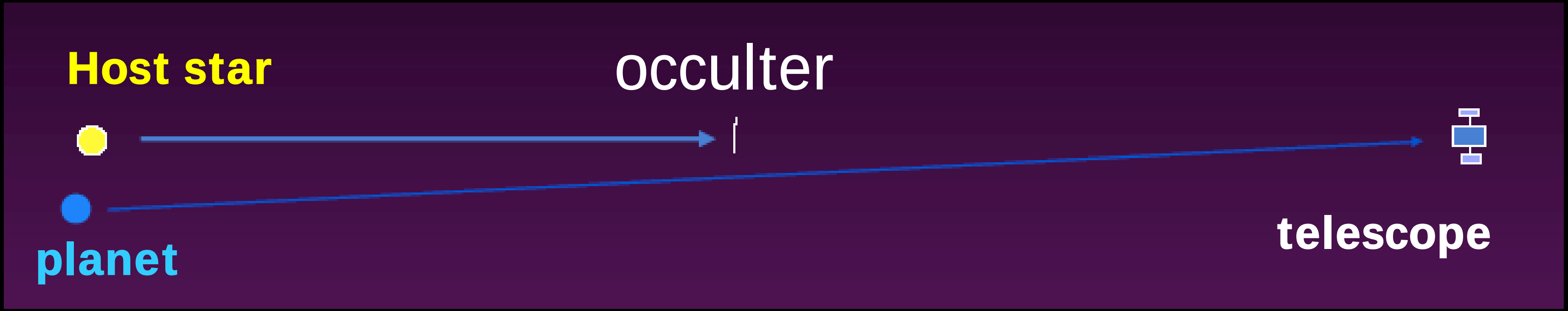
N. Jeremy Kasdin[1], David N. Spergel[1], P. Doug Lisman[2], Stuart B. Shaklan[2], Dmitry Savransky[1], Eric Cady[1], Edwin L. Turner[1], Robert Vanderbei[1], Mark W. Thomson[2], Stefan R. Martin[2], K. Balasubramamian[2], Steven H. Pravdo[2], Yuka Fujii[3], Yasushi Suto[3]
[1]Princeton University, [2]Jet Propulsion Laboratory, [3]University of Tokyo





- Princeton+JPL+…

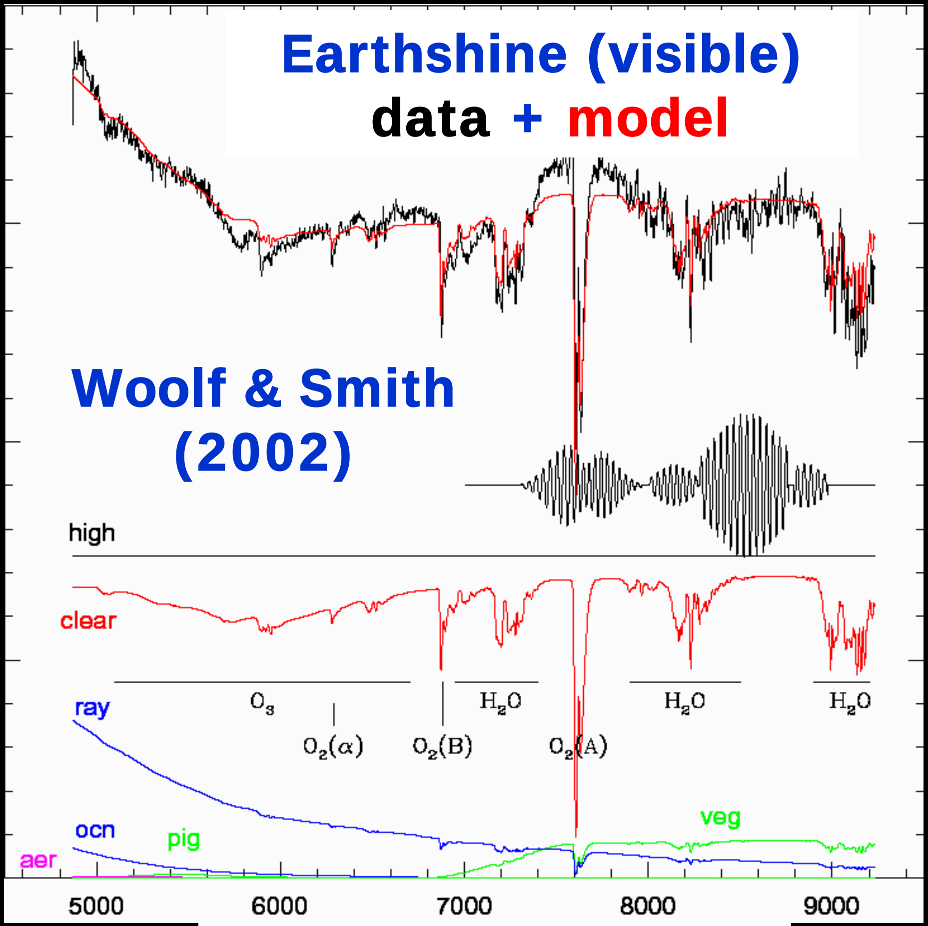
The New Worlds Mission: search for terrestrial planets



http://newworlds.colorado.edu/

- Visible-band mission with 2-4m apertuer@L2
  - Occulter mission @7x10^{4}km away
  - Photometric and spectroscopic monitor of planets
  - Search for biomarker
  - US+UK project; Univ. of Colorado

Conventional biomarkers (signature of life)



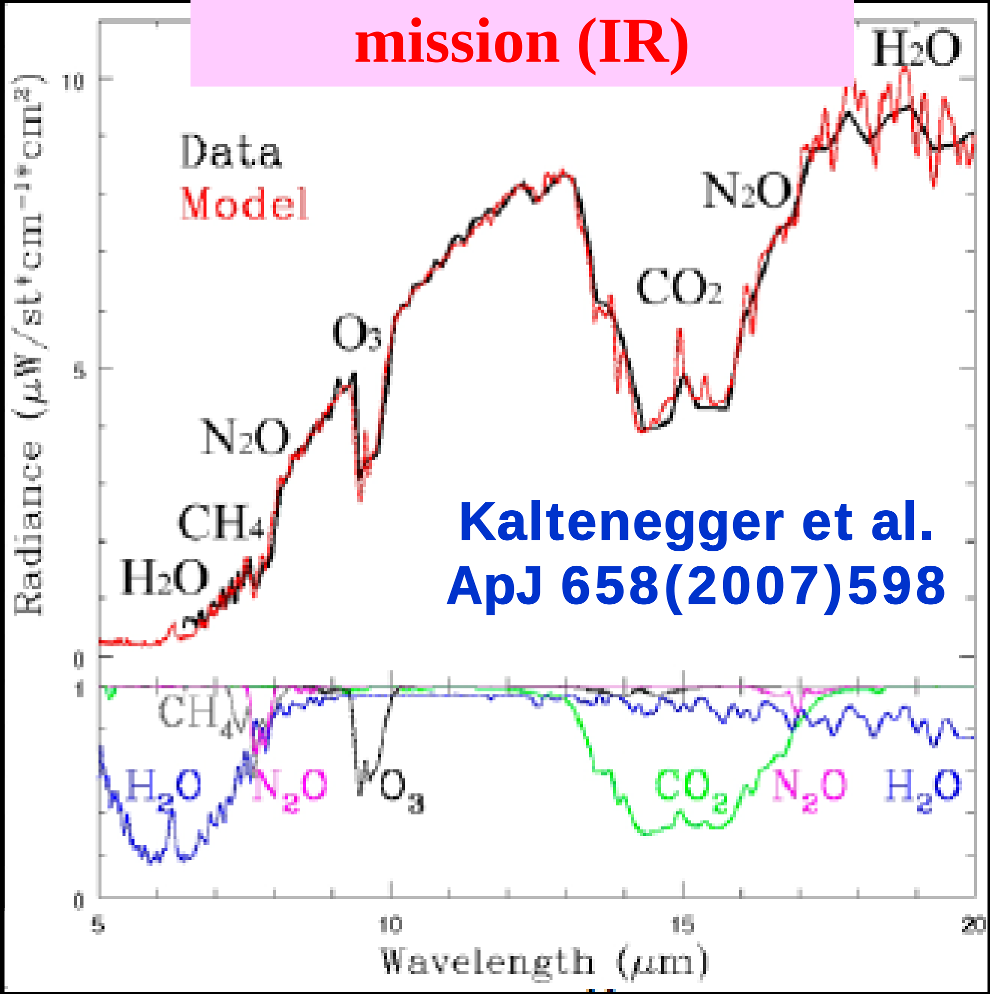
wavelength [Å]

- O_2
  - A-band@0.76 μm
  - B-band@0.69 μm
- H_2O
  - 0.72, 0.82, 0.94 μm
- O_3
  - Chappuis band @(0.5-0.7) μm
  - Hartley band @(0.2-0.3) μm

Kasting et al. arXiv:0911.2936
"Exoplanet characterization and the search for life"

Earth's IR spectrum and biomarkers

Earth observing mission (IR)



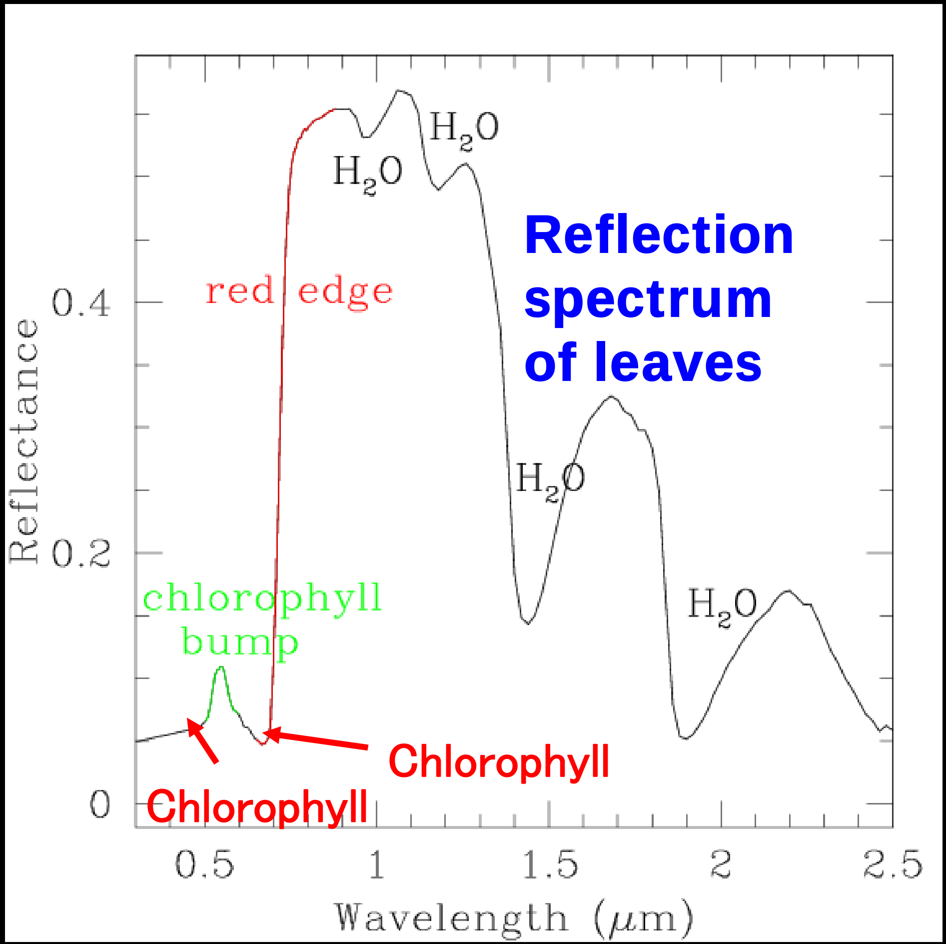
Kaltenegger et al. ApJ 658(2007)598

- O_3@9.6μm
  - Good tracer of O_2
- H_2O @<8μm,>17μm
- CH_4@7.7μm
  - Biotic origin?

Kasting et al. arXiv:0911.2936
"Exoplanet characterization and the search for life"

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

- **Red-edge**
  - Significant increase of reflectivity of leaves on Earth (terrestrial planets) for $\lambda > 7000$ Å
- An interesting and unique biomarker ?
- Widely used in the remote-sensing of our Earth



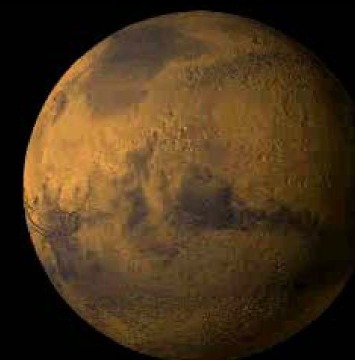
Seager, Ford & Turner astro-ph/0210277

Vesto Melvin Slipher (1875–1969)

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

- Discovered redshifts of "spiral nebulae" now known as galaxies

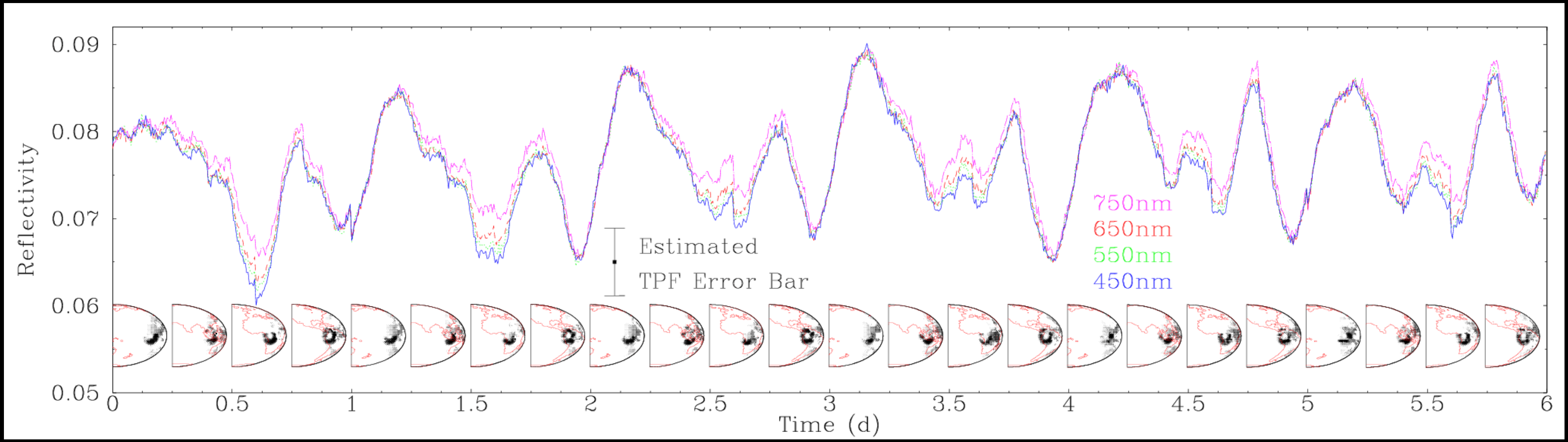
"Observations of Mars in 1924 made at the Lowell Observatory: II spectrum observations of Mars" **PASP 36(1924)261**



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 !

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 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 !***

Colors of a Second Earth: estimating the fractional areas of ocean, land and vegetation of Earth-like exoplanets

- Yuka Fujii, H.Kawahara, A.Taruya, Y.Suto (Dept. of Phys., Univ. of Tokyo), S.Fukuda, T.Nakajima (Univ. of Tokyo, Center of climate system research), Edwin Turner (Princeton Univ.)
  - ApJ 715(2010)866; arXiv:0911.5621

http://www.space.com/scienceastronomy/color-changing-planets-alien-life-100513.html

Color-Changing Planets Could Hold Clues to Alien Life: posted 13 May 2010 (Adam Hadhazy, SPACE.com staff writer)

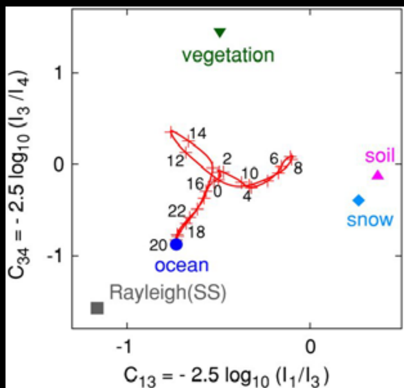
- A new way of comparing the color and intensity changes of light reflected off of Earth's surface to the flickers from exoplanets may help reveal the presence of oceans, continents and – possibly – life on alien worlds.
- By comparing the changes in observed hues of an alien planet as it rotates to this distinct Earthly color palette, "we can infer the surface composition of the [exo]planet," said Yuka Fujii, a doctoral student at the University of Tokyo and lead author of a paper published in the May 4 issue of the Astrophysical Journal.

http://www.space.com/scienceastronomy/color-changing-planets-alien-life-100513.html

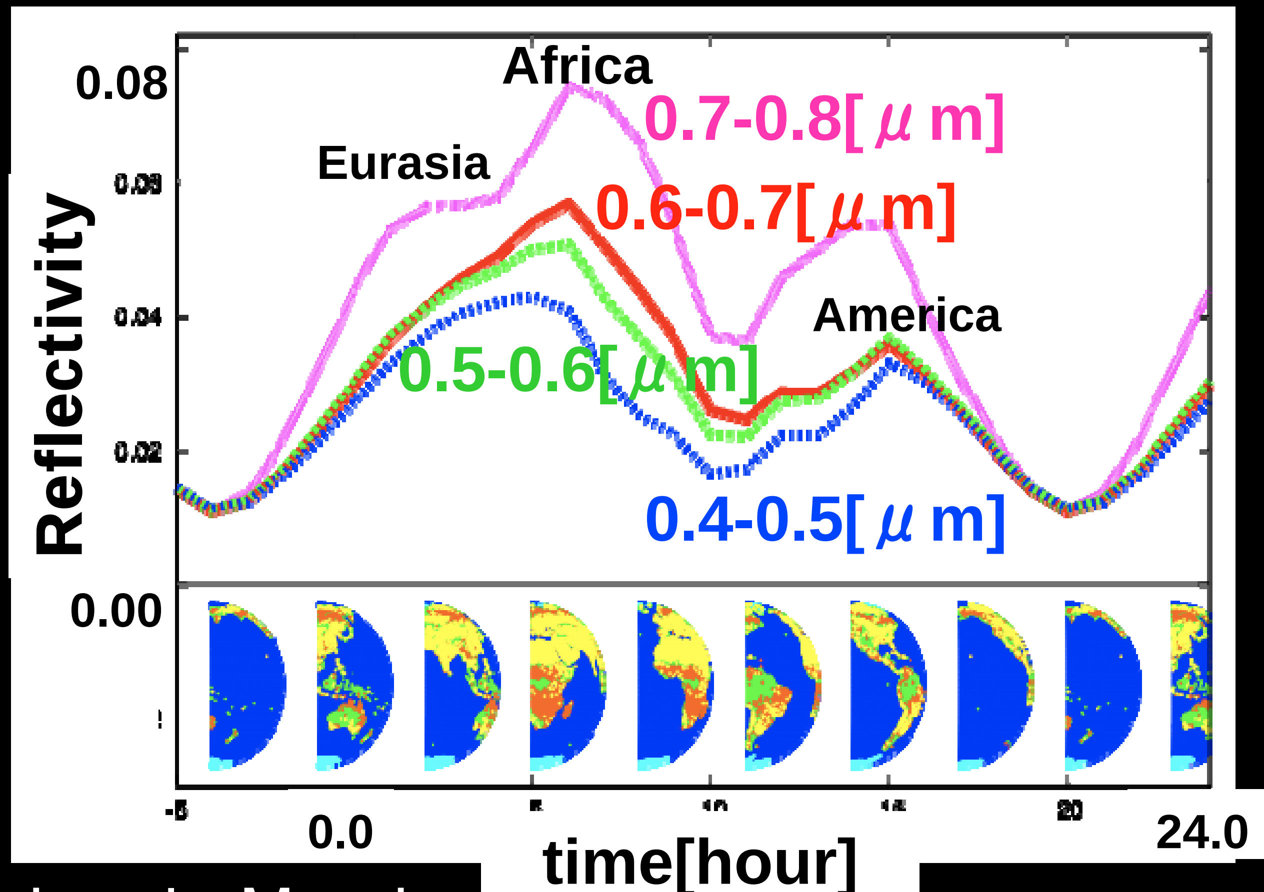
Method to generate simulated photometric data of Earth

- Simulated light-curves in 7 photometric bands using the actual data of MODIS detector on board Terra (Earth observing satellite)
  - Land: BRDF (Bidirectional Reflectance Distribution Function) coefficients for $2.5° \times 2.5°$ pixels on the earth
  - Ocean: BRDF model of Nakajima & Tanaka (1983)
  - Atmosphere: 1^{st}-order approximation of Rayleigh scattering
  - Cloudless !
  - Rotation with 24 hours period

A pale blue dot ? Not really



Simulated photometric light-curves of Earth



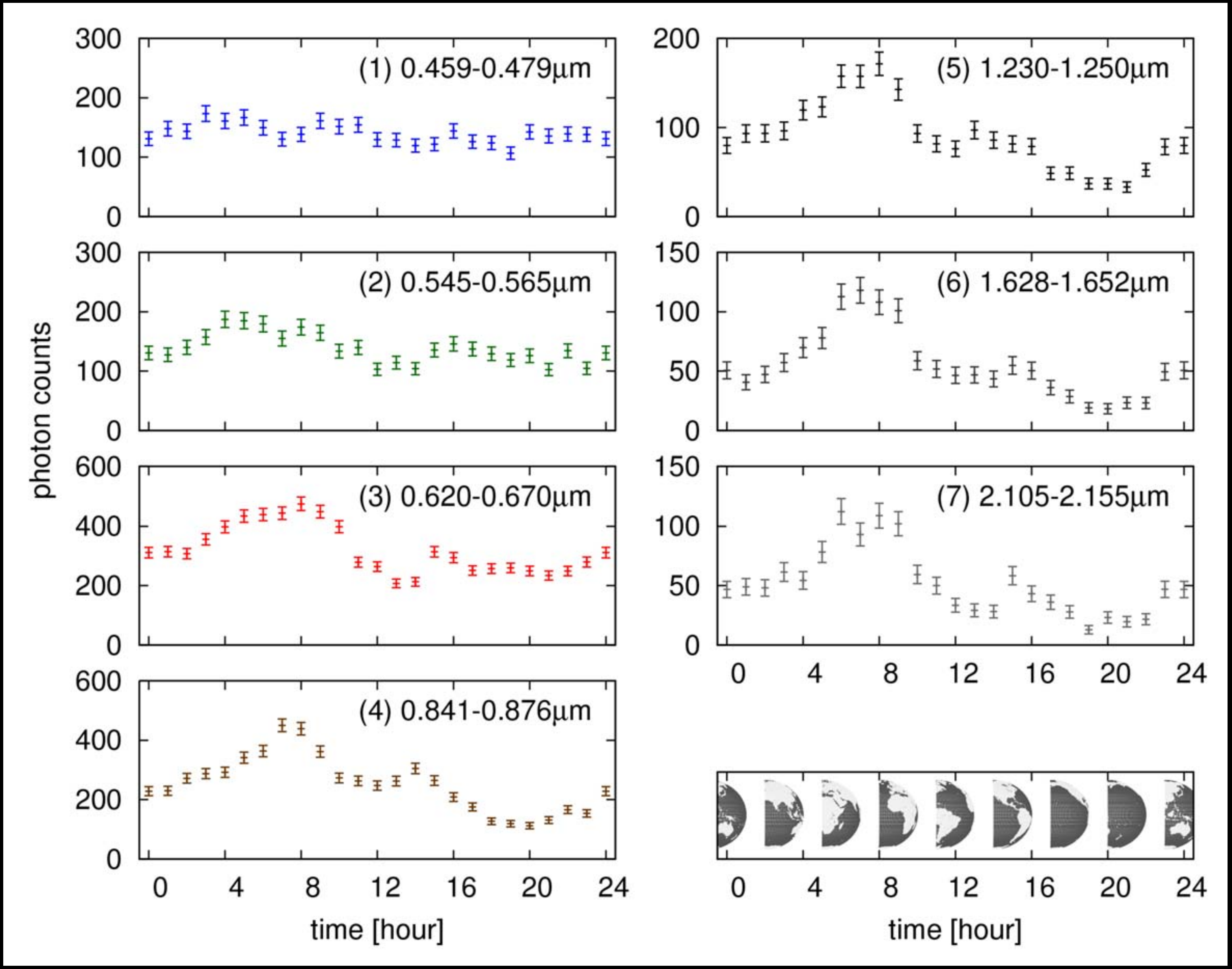
- Adopted Earth data in March
- Spin inclination = 0 (vernal equinox)
- cloudless

Fujii et al. (2010)

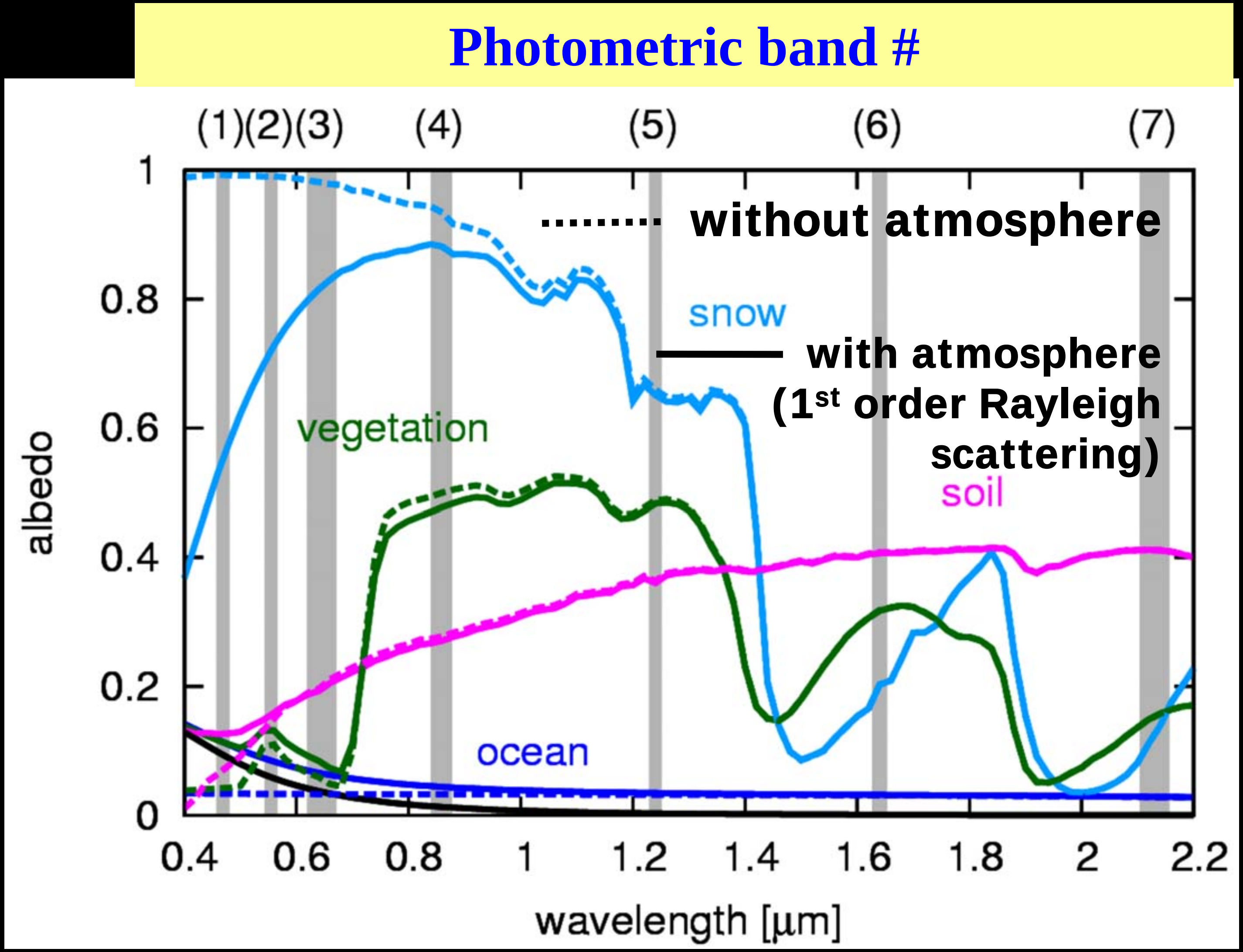
Estimation of fractional areas

- Fractional areas of 4 components (ocean, soil, vegetation and snow) estimated from the simulated light-curves (5 bands) + their template albedos assuming isotropic scattering
  - **Very idealized (theoretically best case)**
  - A cloudless earth at 10pc away
  - 2 week observation with space mission (2m aperture) + occulter (1hour x 14=14 hours exposure at each phase)
  - Neglect light from the central star
  - Consider the photon shot-noise alone

Simulated light-curves in 7 bands

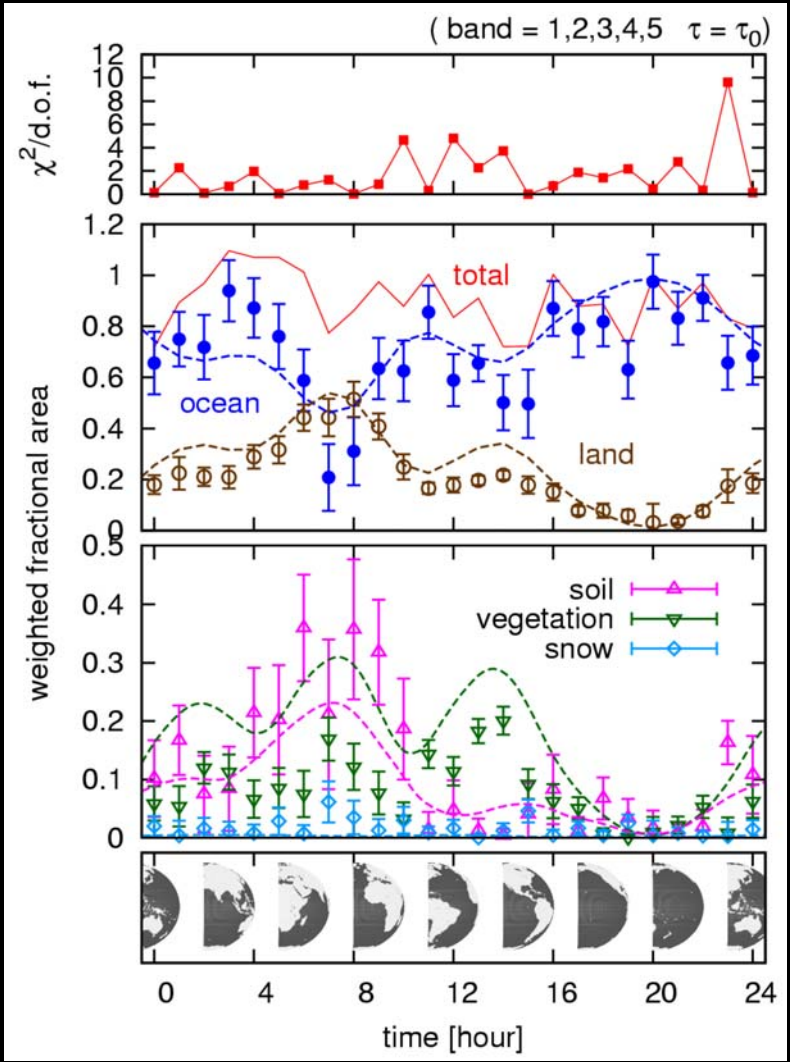


Adopted albedos (with atmosphere)



- Rayleigh scattering is important in identifying ocean

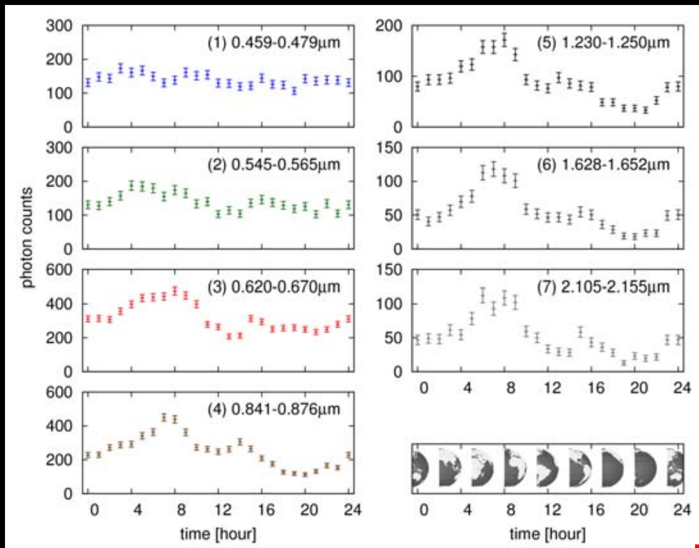
Inversion problem: fractional areas of the four components from colors of a second earth



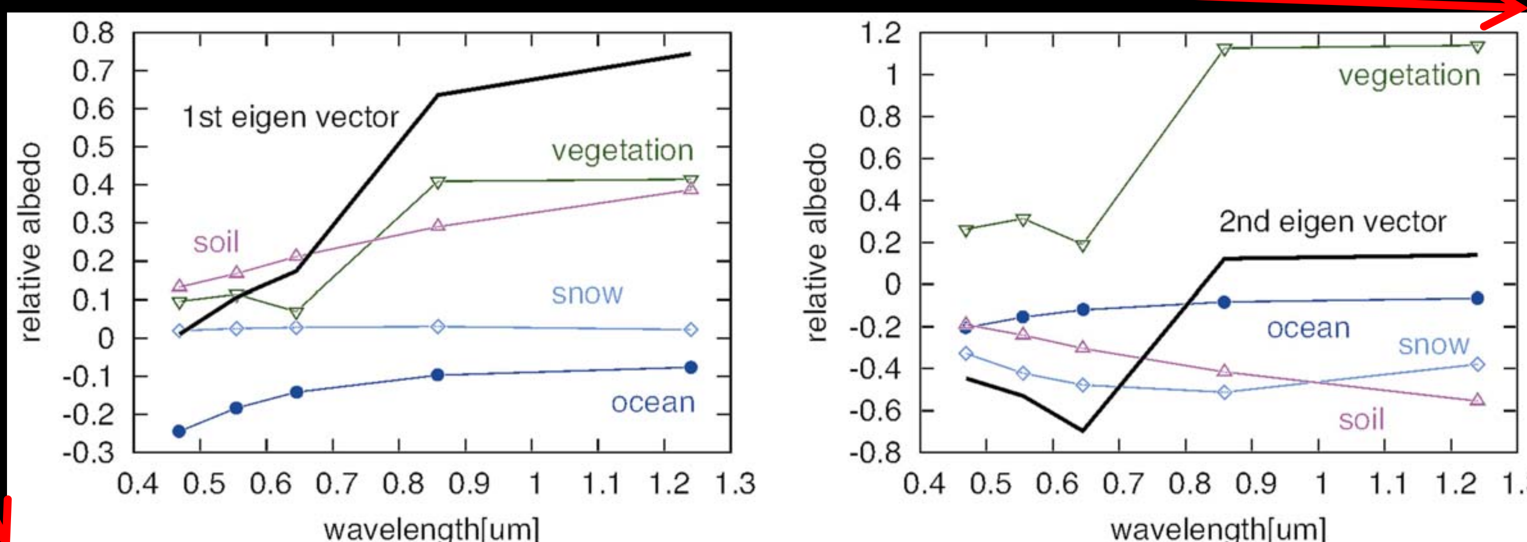
Fujii et al.（2010）

- Input data
  - 5 light-curves using anisotropic scattering (BRDF) model
  - 2 week observation of a cloudless Earth at 10 pc away
- Inversion assumptions
  - Ocean, soil, vegetation and snow only (with atmosphere)
  - Isotropic scattering assumed
- Results
  - Estimated areas (symbols) vs Surface classification data (dashed line)
  - Reasonably well reproduced.
  - Can identify vegetation !

PCA (principal component analysis)



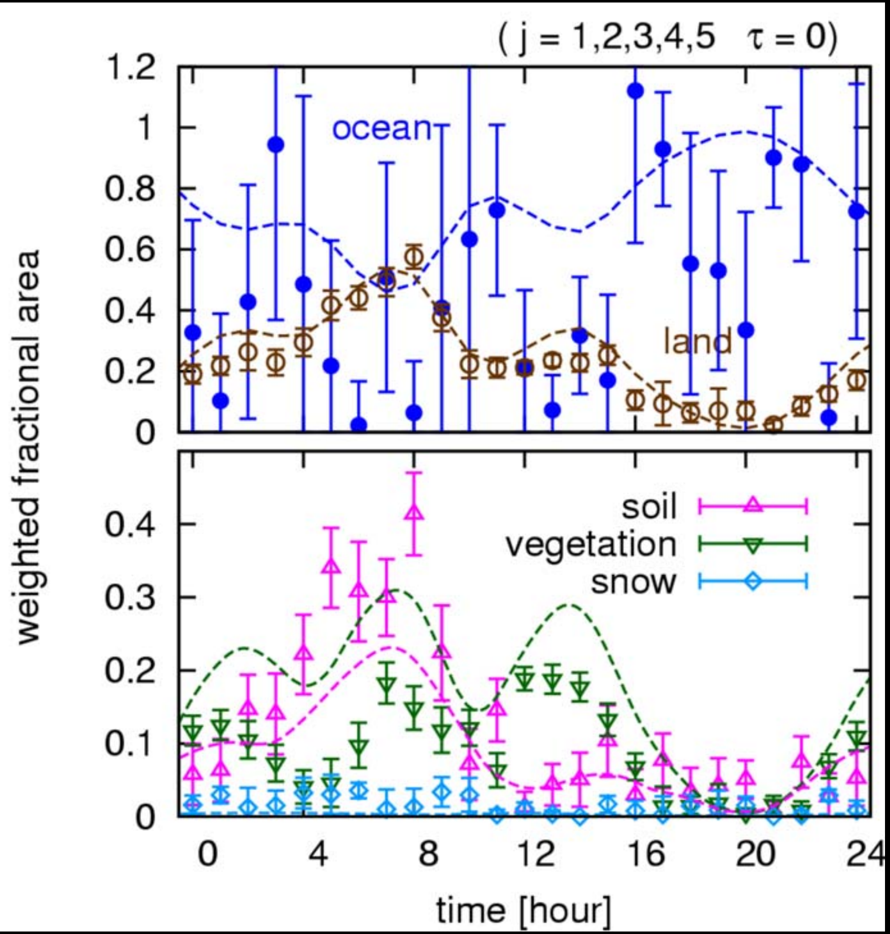
- 1st eigen vector
  - ≒ soil + vegetation – ocean
- 2nd eigen vector
  - ≒ vegetation – soil – ocean – snow



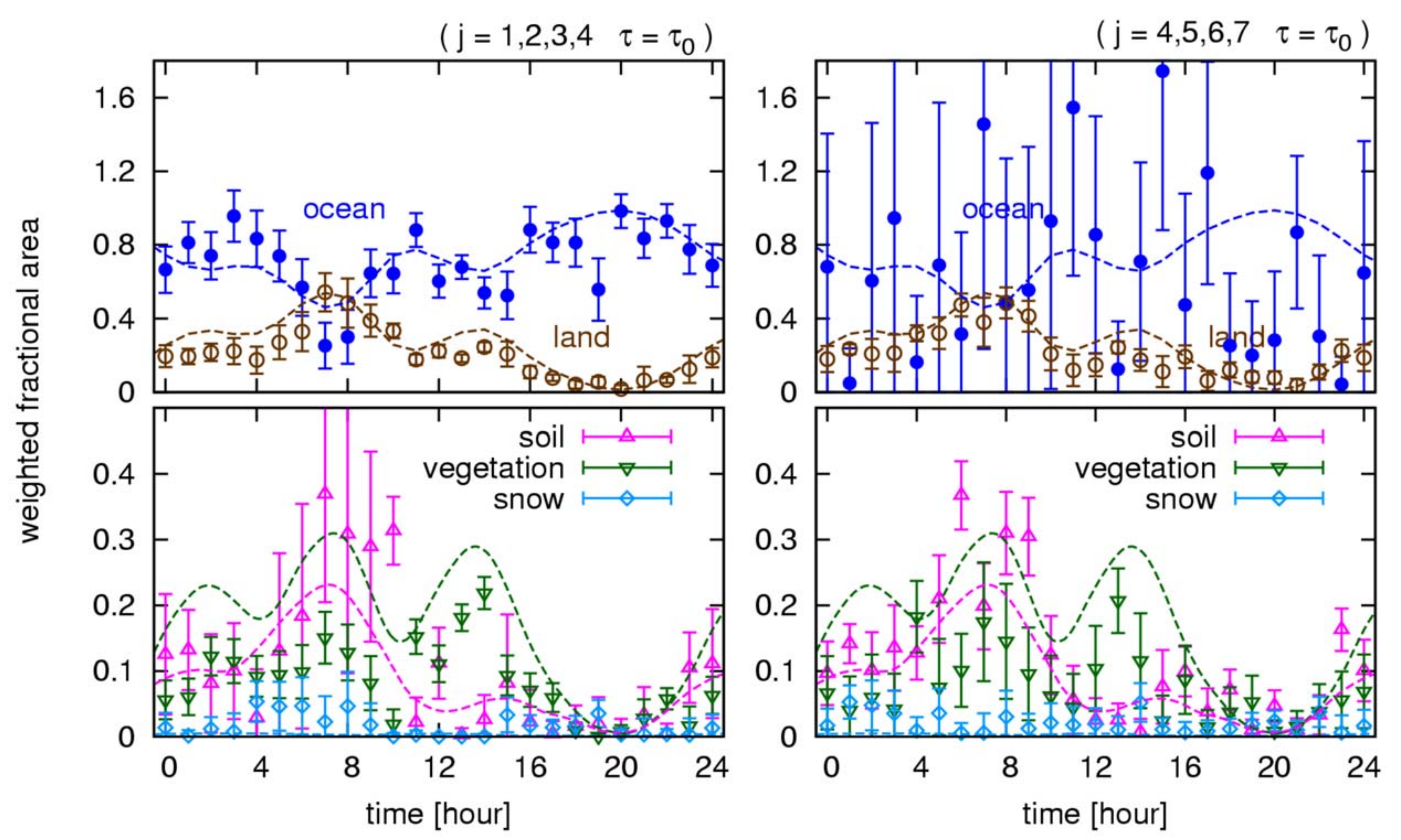
Effect of atmosphere (Rayleigh scattering)

$$\tau_R(\lambda) = \tau_0 \left(\frac{P}{1013[\text{hPa}]} \right) \left(\frac{\lambda}{1[\mu\text{m}]} \right)^{-4}$$

- Inversion of simulated light-curves without atmosphere (τ =0) does not properly identify ocean

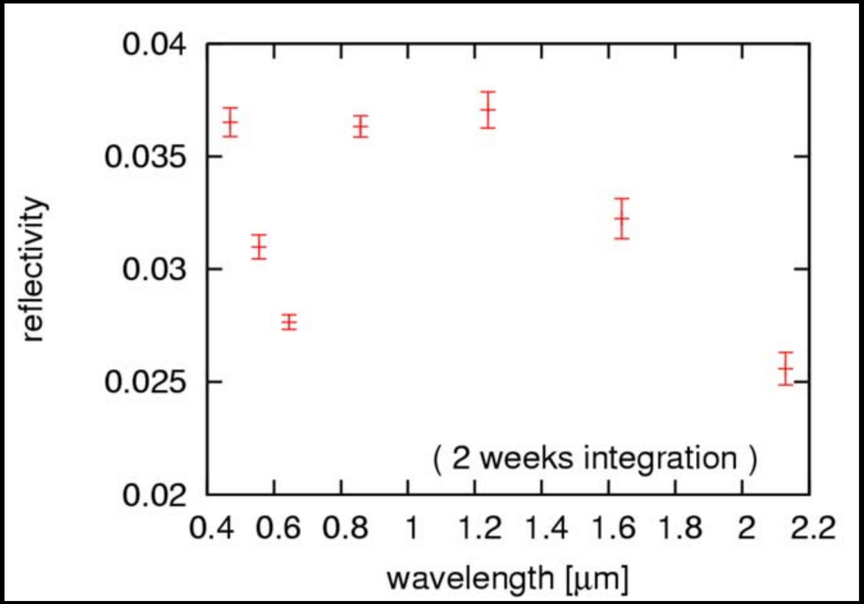


Different choice of photometric bands

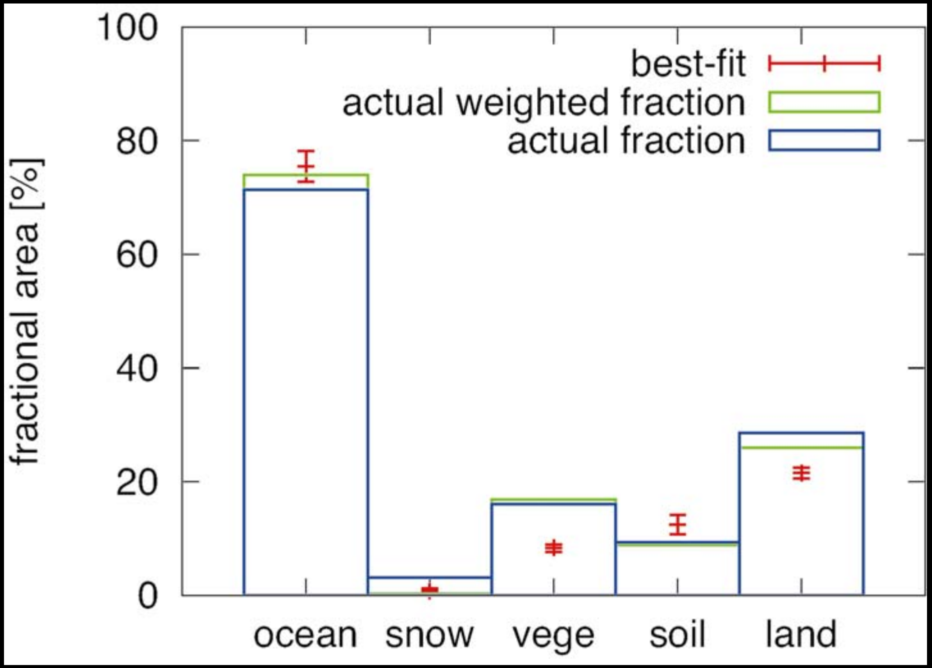


- Bluer bands: good for ocean
- Redder bands: good for soil

Average over the entire sphere



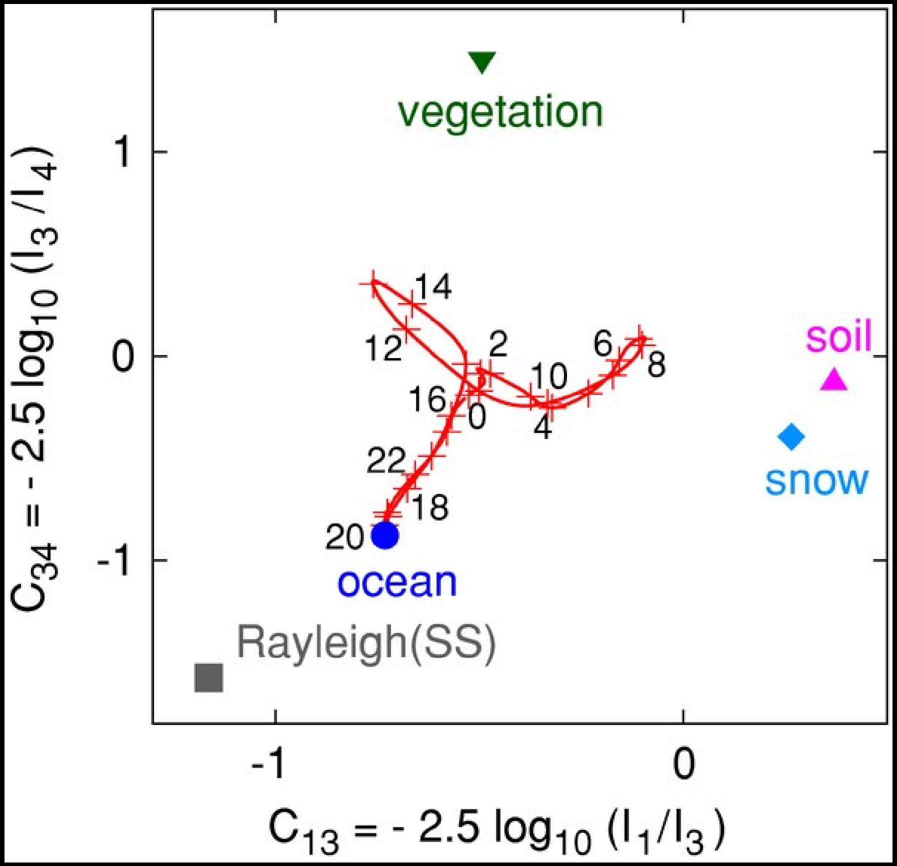
- Even without time-dependent analysis, fractional areas for each component are well estimated



So far so good, but still so many things to do next

- **Better modeling**
  - Effects of clouds
  - Radiation transfer
    - Rayleigh scattering beyond its 1st order approxmation
    - Absorption lines
    - Wider wavelength coverage (IR)
- **Diversity of a second earth**
  - Seasonal variation
  - Inclination angle of the earth
  - Simulating the earth at different eras
  - Signature of snowball earth, ocean planet, or land planet
  - Diversity of red-edge as a function of the spectral type of the host star and of a distance to the host star

Colors of a second earth



When can we conclude that

"We did not know anything" ?