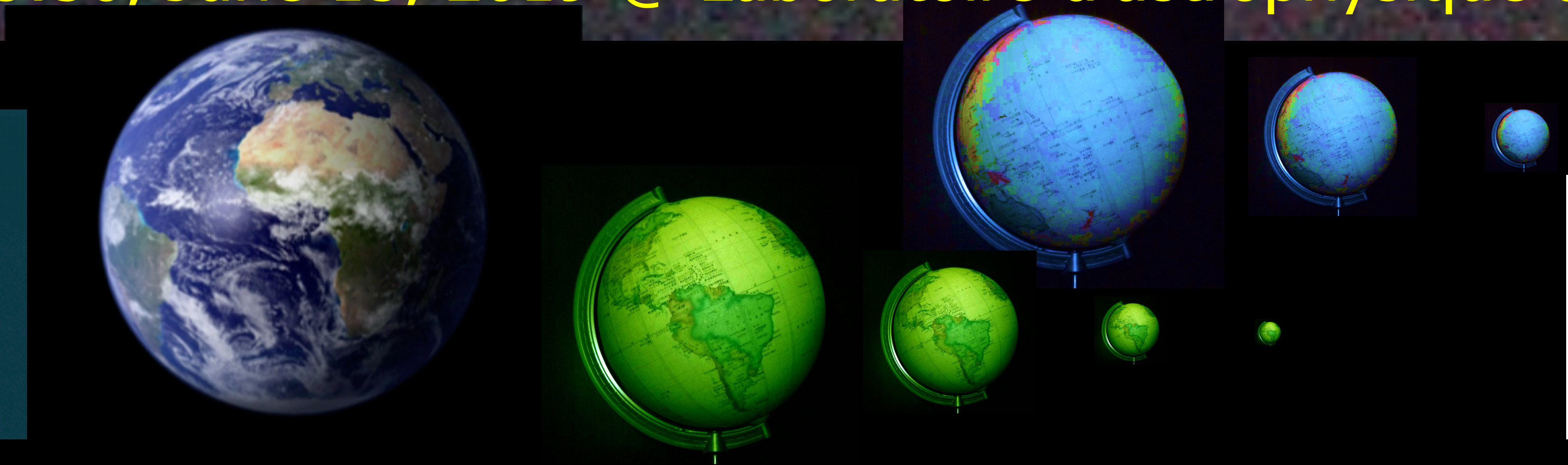
# Unveiling a pale blue dot: lands, oceans, clouds, vegetation, and spin-obliquity from photometric variation of a directly-imaged second earth


*Yasushi Suto*

*Department of Physics and Research Center for the Early Universe*

*the University of Tokyo*


14:30-15:30, June 13, 2019 @ Laboratoire d’astrophysique de Bordeaux



# Are we alone ?

# a Pale Blue Dot or pale blue dots ?

# Sciences with exoplanets

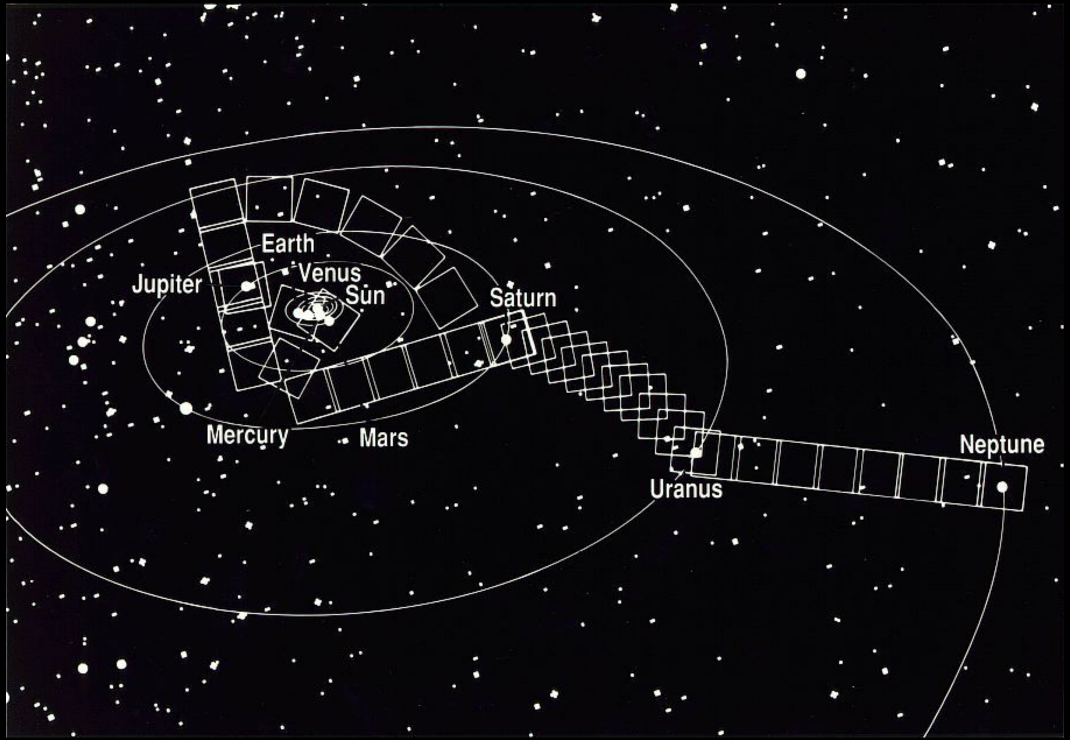
- the ***final*** question: ***Are we alone ?***
  - origin of the earth
  - origin of the Solar System
  - ***habitable*** planets ⇒ origin of life
  - signature of extra-terrestrial life ?

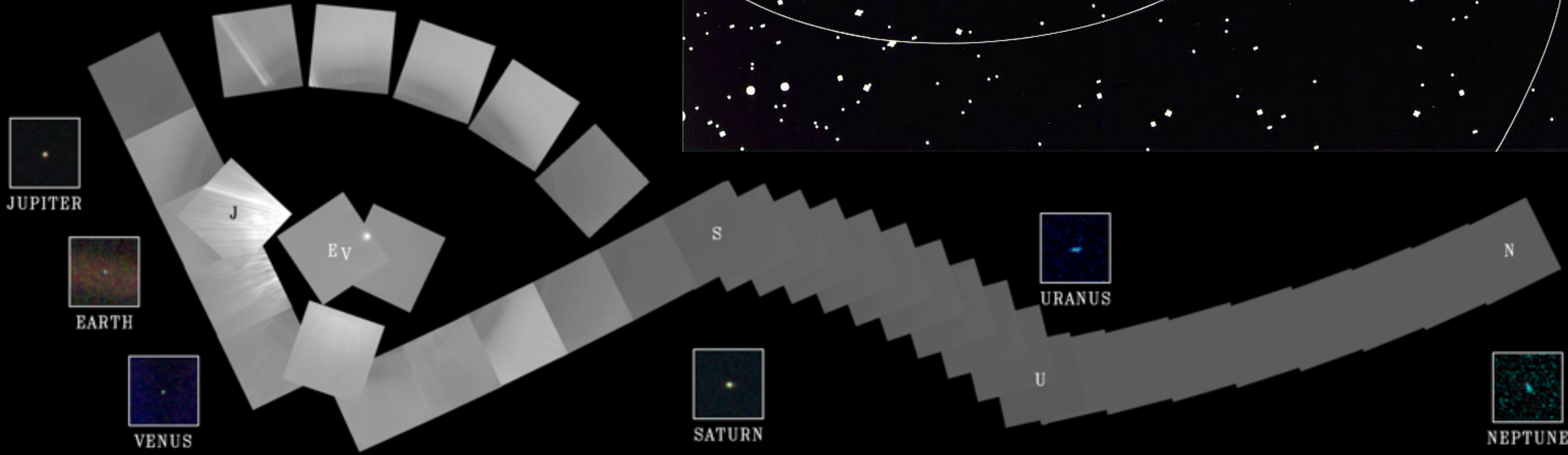
    ⇒ extra-terrestrial intelligence ?

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

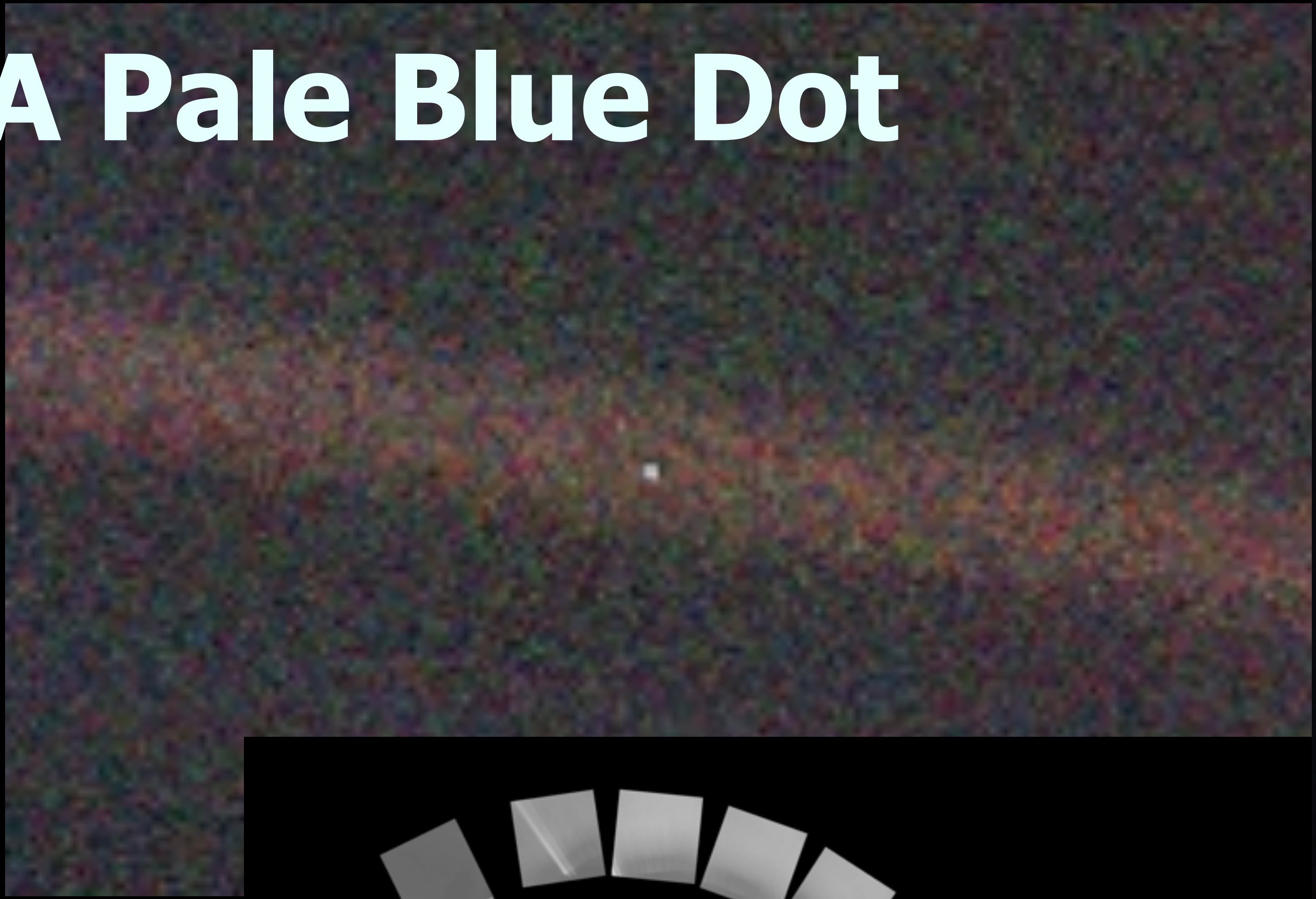
# Solar planets imaged by Voyager 1 (February 4, 1990)

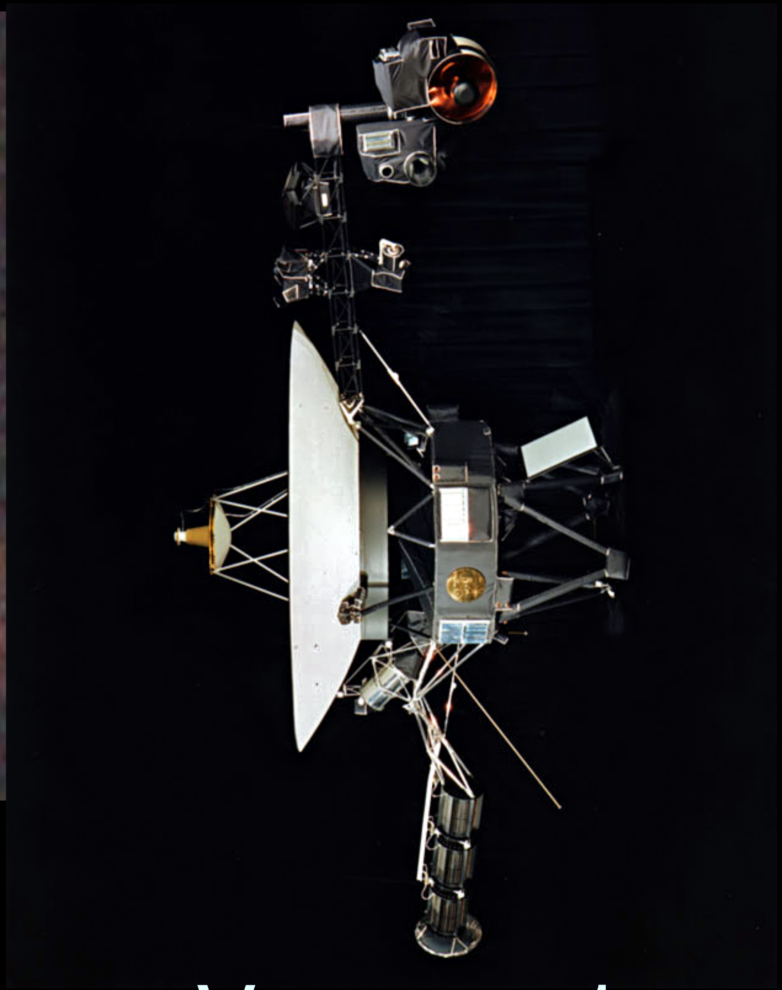
- Earth imaged at distance of 40 au away
- A Pale Blue Dot
  (Carl Segan)



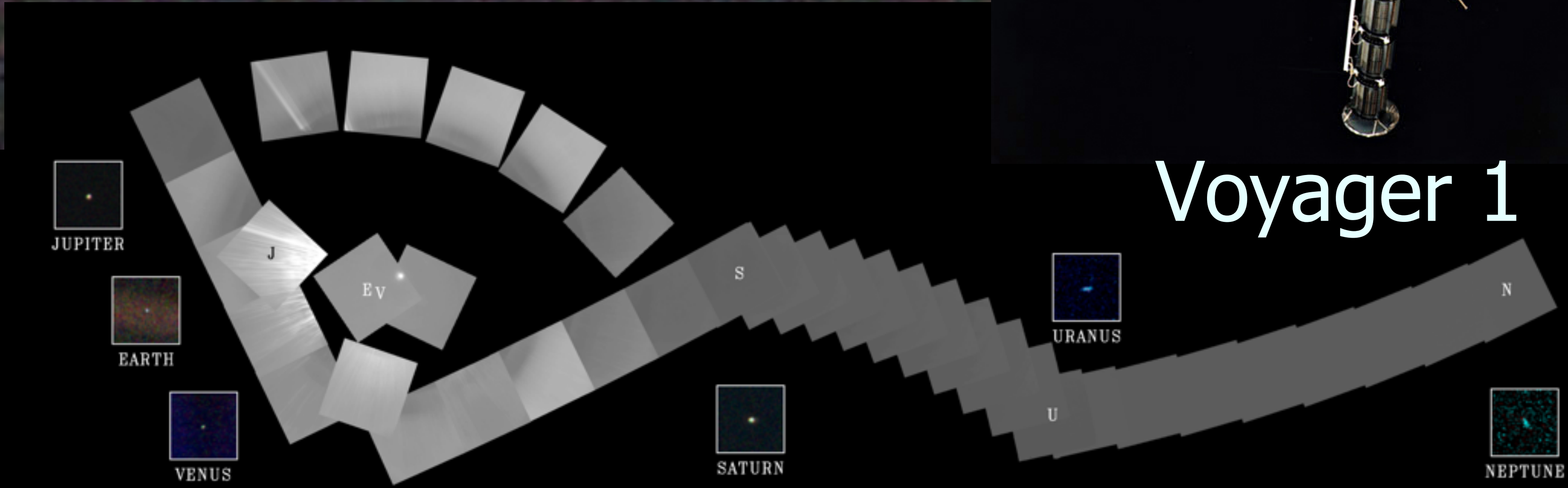



# A Pale Blue Dot

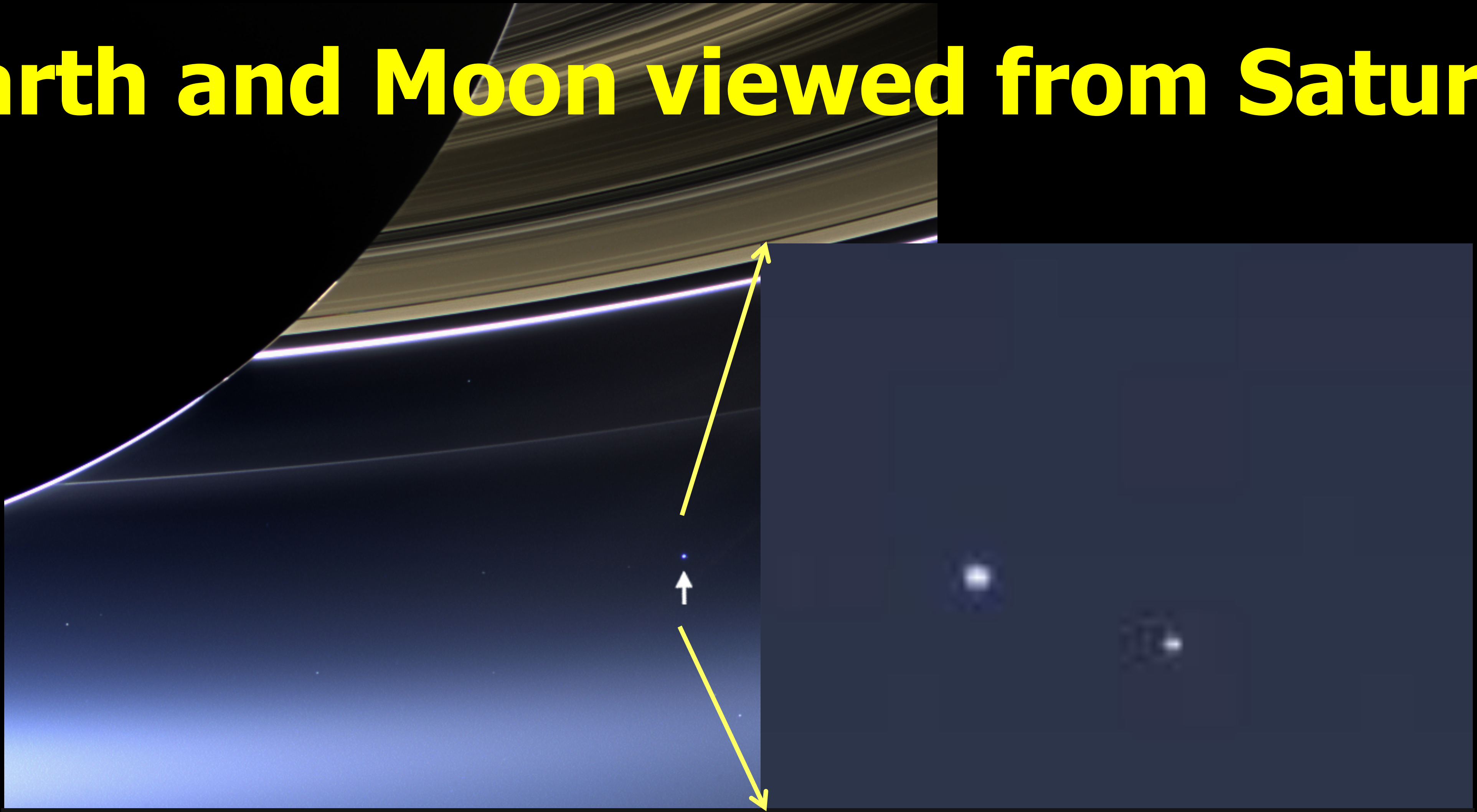




Voyager 1



# Earth and Moon viewed from Saturn

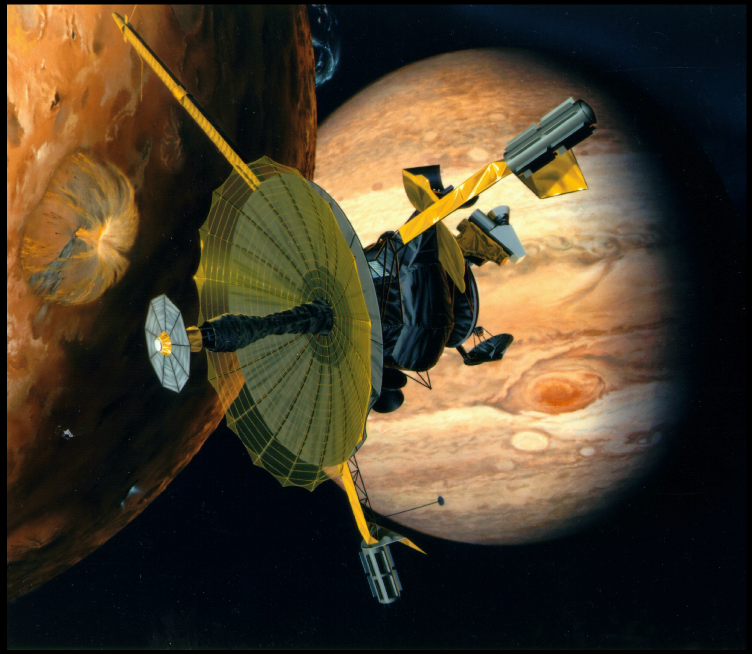


- Viewed from *Cassini* on July 20, 2013
  - about 20,000 happy Americans are waving their hands towards Cassini, but *how can we know that ?*

# Can we detect signatures of life on our Earth ?

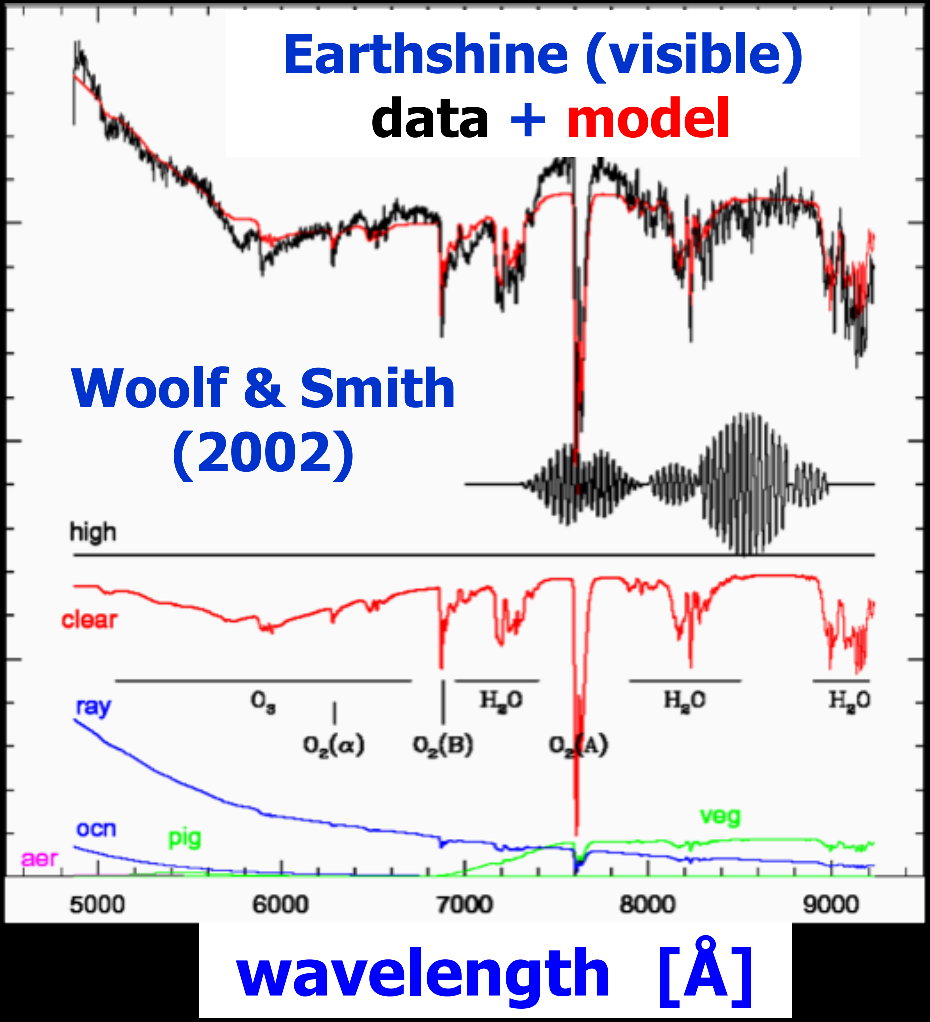
# Search for signatures of life on “Earth” with Galileo mission! (1990)

- Launched in May, 1986
- Earth observed on December 8, 1990
- ***Conclusion: it is likely that life exists on Earth !***
  - Abundant $O_2$
  - Red-edge of vegetation
  - $CH_4$ abundance out of thermal equilibrium
  - Artificial pulsed radio signal



Sagan, Thompson, Carlson, Gurnett & Hord: Nature 365(1993)715

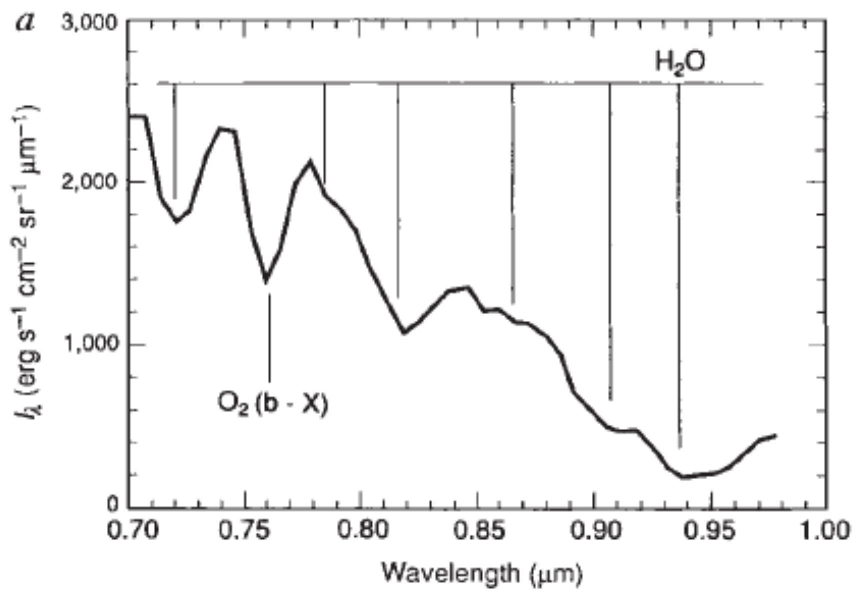
# Conventional bio-signatures

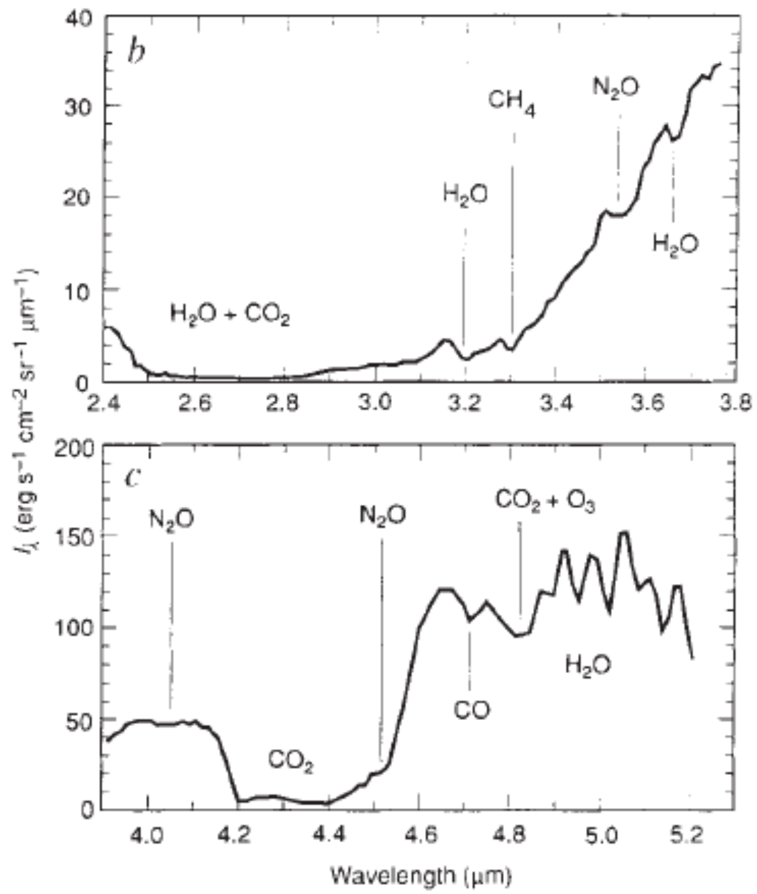



- $O_2$
  - A-band@0.76μm
  - B-band@0.69μm
- $H_2O$
  - 0.72, 0.82, 0.94μm
- $O_3$
  - Chappuis band@(0.5-0.7)μm
  - Hartley band@(0.2-0.3)μm

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

# Sagan et al. (1993): spectrum of atmosphere



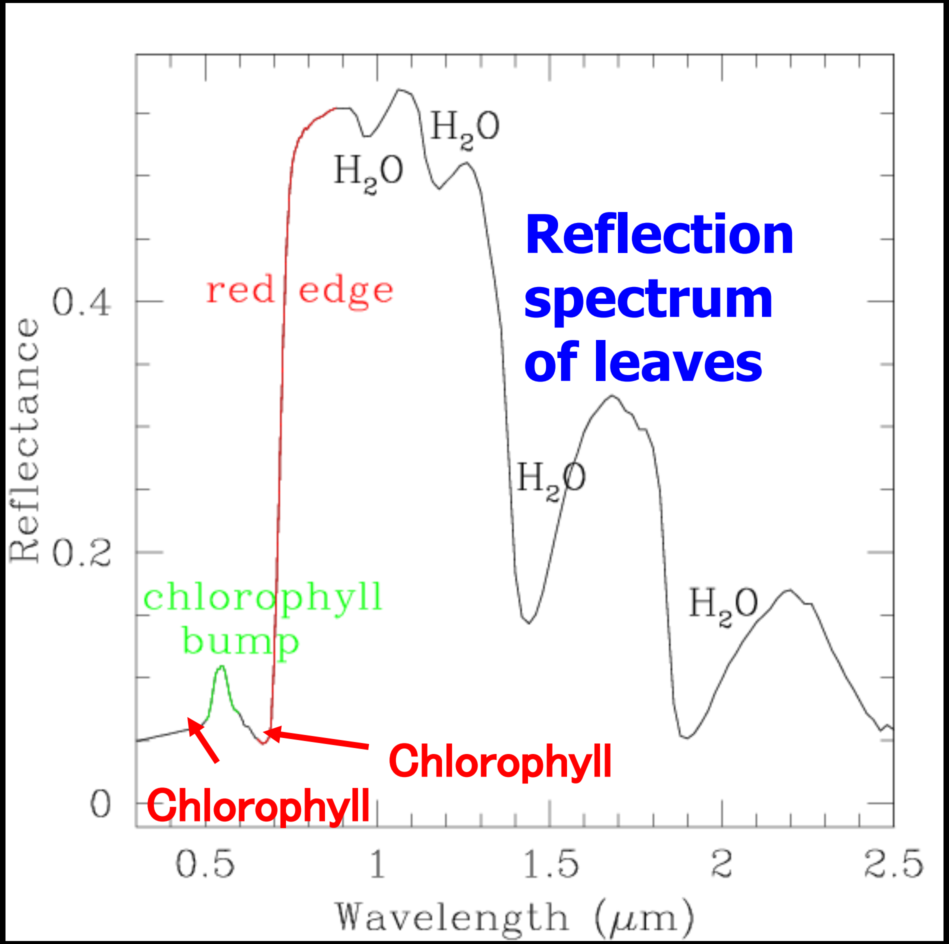




**Strong $O_2$ absorption @A-band(0.76μm)**

F the Earth over a relatively cloud-free region of the Pacific Ocean, north of Borneo. The incidence and emission angles are 77° and 57° respectively. The $(b'\Sigma_g^+ - X^3\Sigma_g^-)$ 0–0 band of $O_2$ at 0.76 μm is evident, along with a number of $H_2O$ features. Using several cloud-free regions of varying airmass, we estimate an $O_2$ vertical column density of 1.5 km-amagat ± 25%. *b* and *c*, Infrared spectra of the Earth in the 2.4–5.2 μm region. The strong $\upsilon_3$ $CO_2$ band is seen at the 4.3 μm, and water vapour bands are found, but not indicated, in the 3.0 μm region. The $\upsilon_3$ band of nitrous oxide, $N_2O$, is apparent at the edge of the $CO_2$ band near 4.5 μm, and $N_2O$ combination bands are also seen near 4.0 μm. The methane (0010) vibrational transition is evident at 3.31 μm. A crude estimate[10] of the $CH_4$ and $N_2O$ column abundances is, for both species, of the order of 1 cm-amagate (≡1 cm path at STP).

# Red edge of (exo)plants: a possible bio-signature in exoplanets

- Red-edge
  - Significant increase of reflectivity of leaves on Earth (terrestrial planets) for λ>7000Å
- Widely used in the remote-sensing of our Earth




Seager, Ford & Turner astro-ph/0210277

# Vesto Melvin Slipher (1875-1969)

- Discovered redshifts of galaxies and thus cosmic expansion via the Doppler method

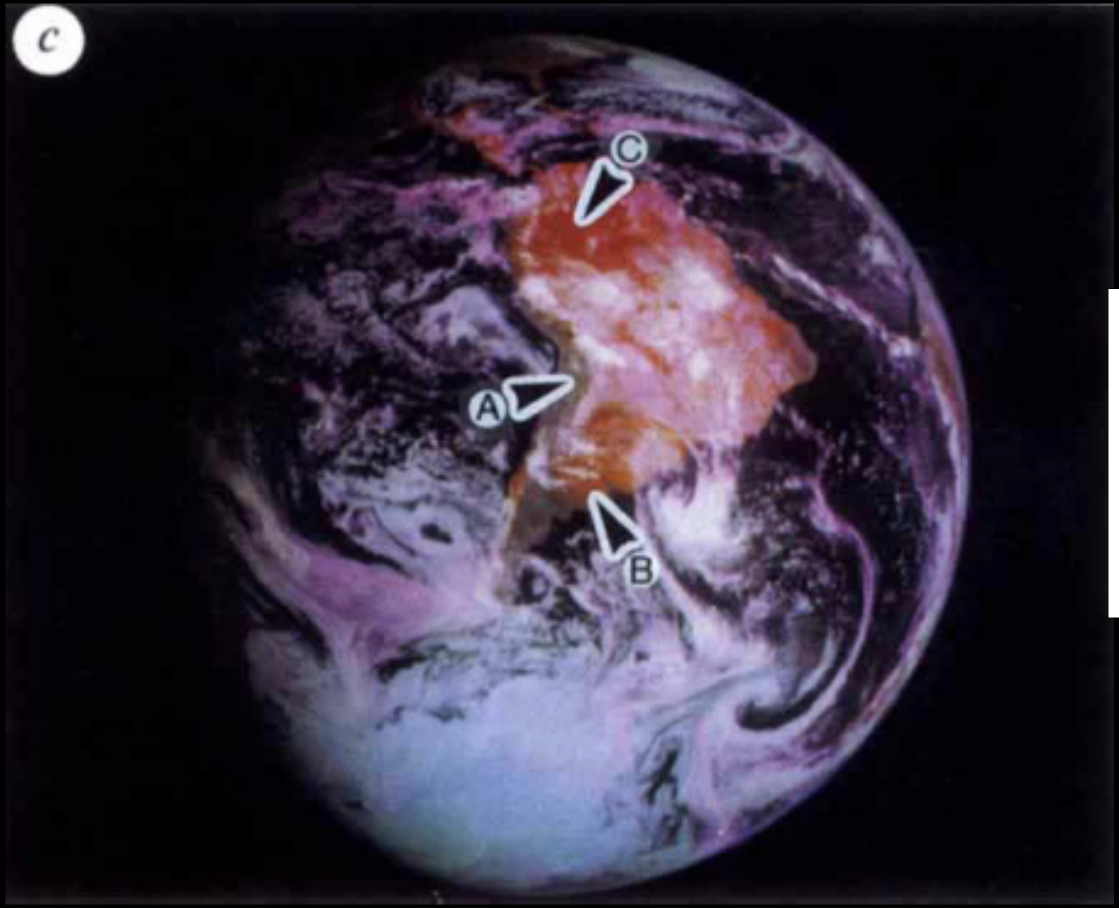
**"Observations of Mars in 1924 made at the Lowell Observatory: II spectrum observations of Mars''** **PASP 36(1924)261**

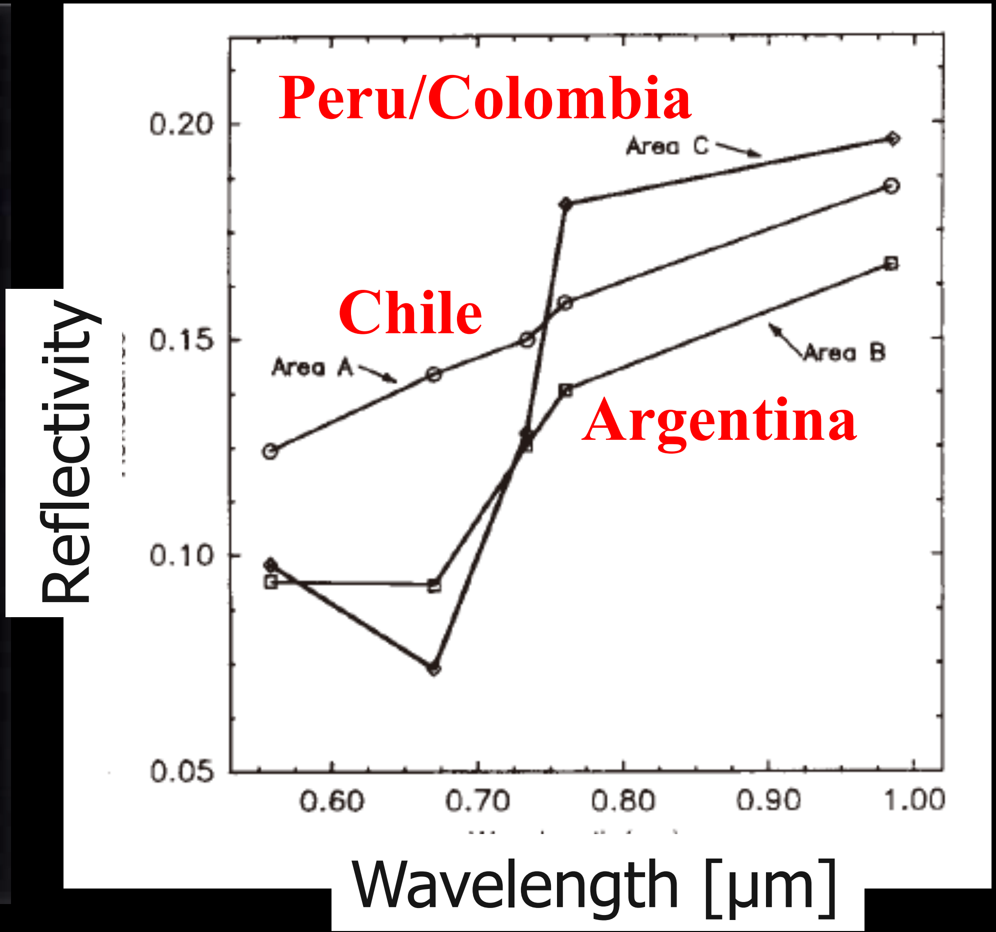
reflection spectrum. The Martian spectra of the dark regions so far do not give any certain evidence of the typical reflection spectrum of chlorophyl. The amount and types of vegetation required to make the effect noticeable is being investigated by suitable terrestrial exposures.

***Astrobiology indeed in 1924 !***

# Sagan et al. (1993): colors of the earth

**Red-edge of the vegetation on the earth detected by the Galileo mission**



# Sagan et al. (1993): radio observation

**Detection of pulsed radio signals unlikely of natural/astronomical origin**

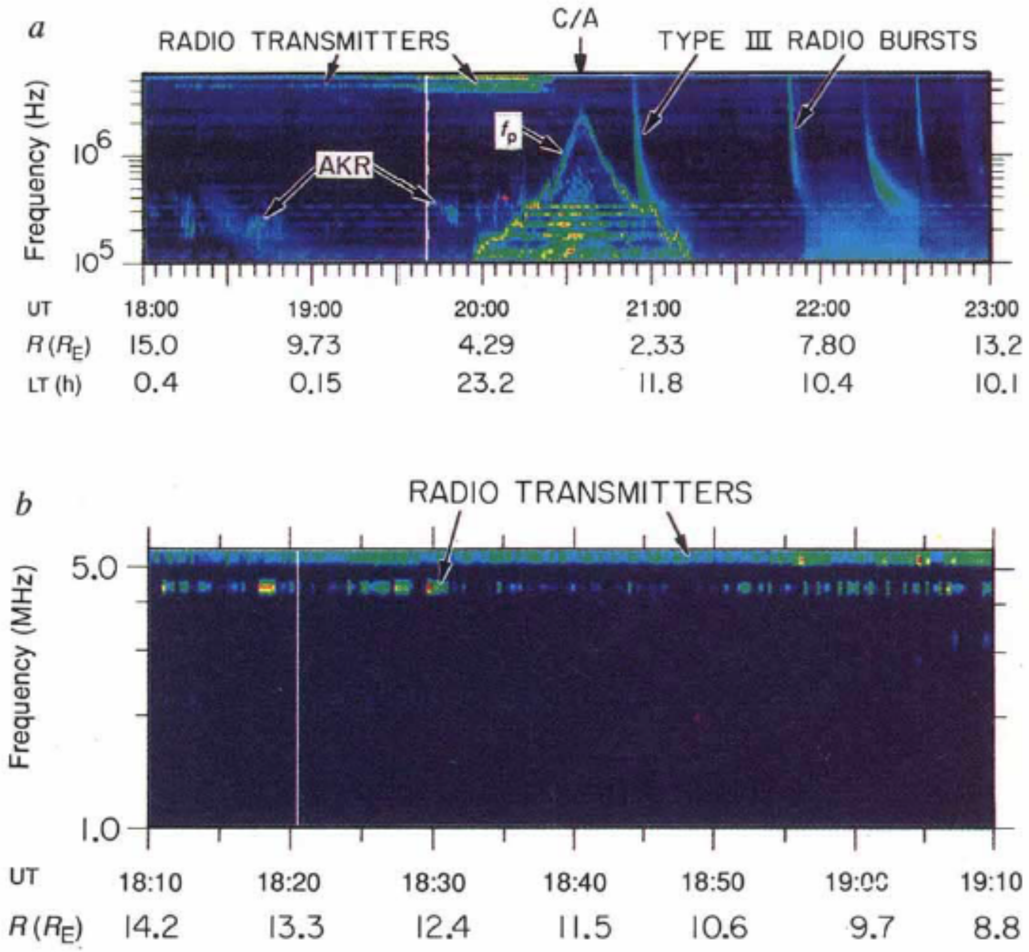
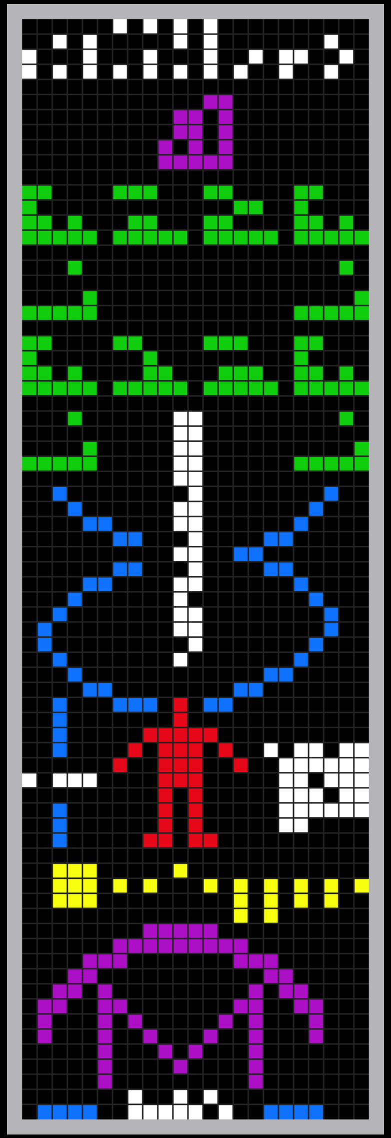



FIG. 4 A frequency–time spectrogram of the radio signals detected by the Galileo plasma wave instrument. The intensities are coded in the sequence blue–green–yellow–red, with blue lowest and red highest. Several natural sources of radio emission are shown in *a*, including auroral kilometric radiation (AKR). Modulated emission at $f > 4$ MHz is shown with an expanded time scale in *b*. Modulated patterns of this type are characteristic of the transmission of information, and would be highly unusual for a naturally occurring radio source. (UT, universal time; $R$ is distance of Galileo from Earth in units of Earth's radius, $R_E$; LT, local time.)

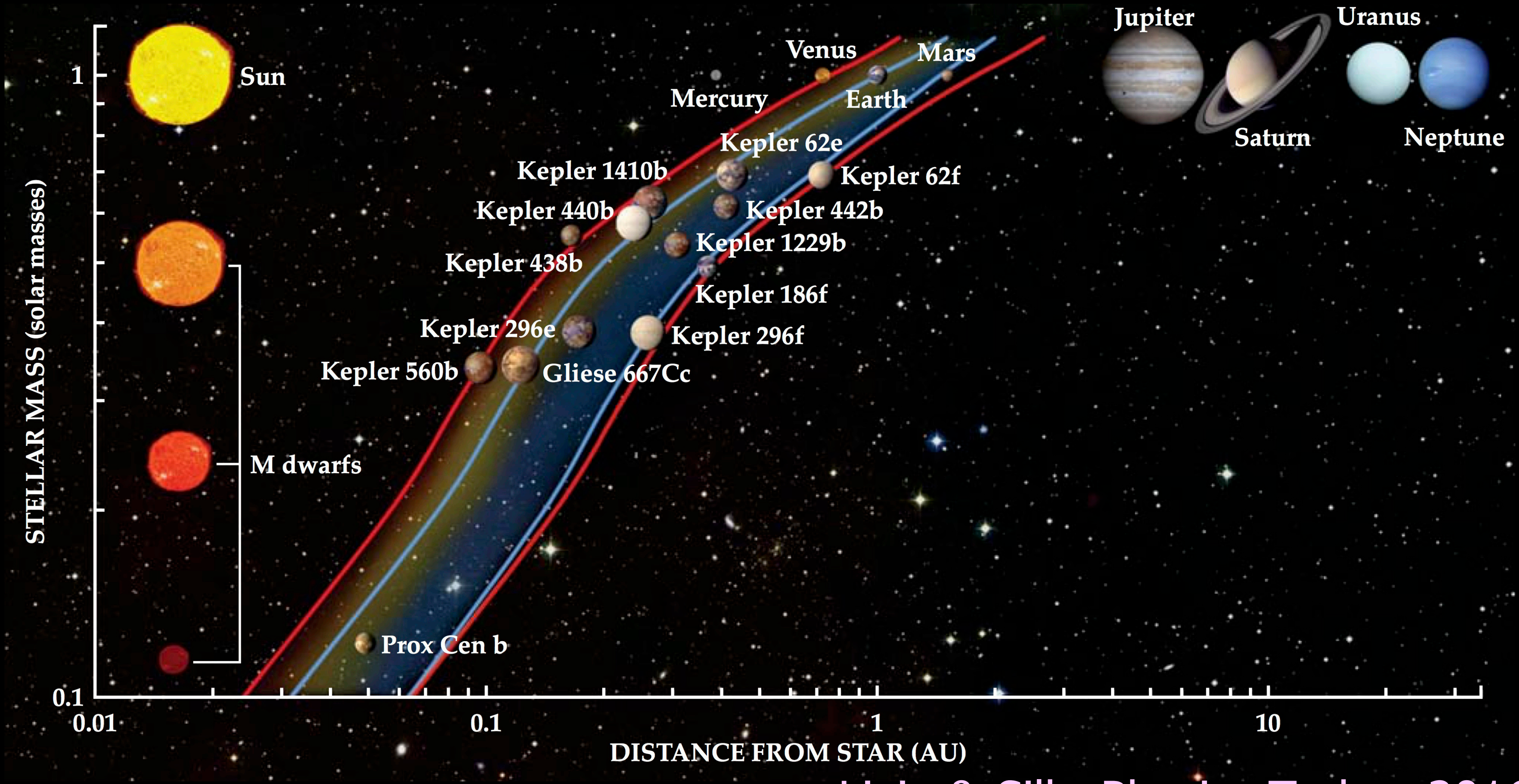
# Arecibo message (1974)

- Frank Drake sent a radio message from Arecibo radio observatory on November 16, 1974 towards globular cluster M13 (25,000 light-year away)
- The message, if decoded properly, should look like this.



# Simulated Earth observed at 10pc away

# Habitable zone around host stars




Livio & Silk: Physics Today, 2016 March

# Occurrence of earth-size habitable planets around Sun-like stars

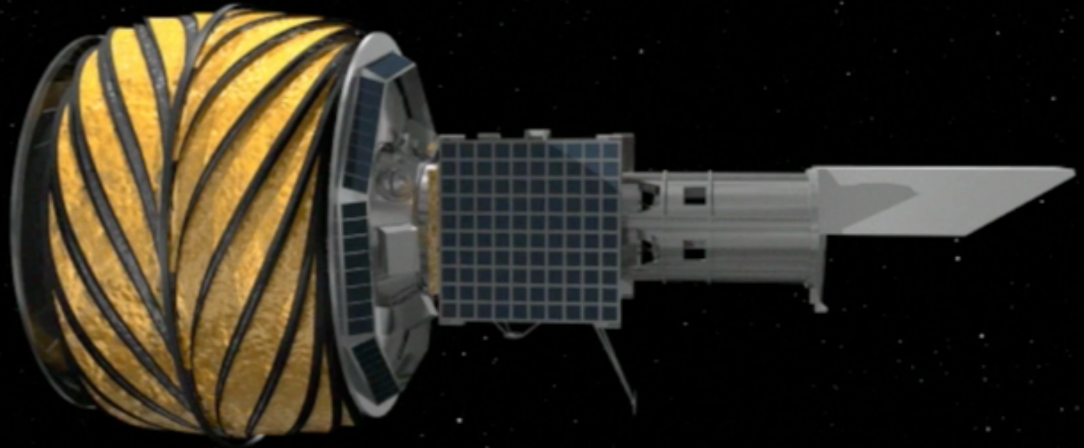
- Planets with (1-2) Earth radius around GKstars
  - Kepler Transit planets corrected for selection effect
  - 11±4 % (1-4 times the Solar flux on the earth)
  - 5.7+2.2-1.7 % (orbital period of 200-400days)

**Table 1. Occurrence of small planets in the habitable zone**

| HZ definition | $a_{inner}$ | $a_{outer}$ | $F_{P,inner}$ | $F_{P,outer}$ | $f_{HZ}$ (%) |
|---|---|---|---|---|---|
| Simple | 0.5 | 2 | 4 | 0.25 | 22 |
| Kasting (1993) | 0.95 | 1.37 | 1.11 | 0.53 | 5.8 |
| Kopparapu et al. (2013) | 0.99 | 1.70 | 1.02 | 0.35 | 8.6 |
| Zsom et al. (2013) | 0.38 | | 6.92 | | 26* |
| Pierrehumbert and Gaidos (2011) | | 10 | | 0.01 | ~50† |

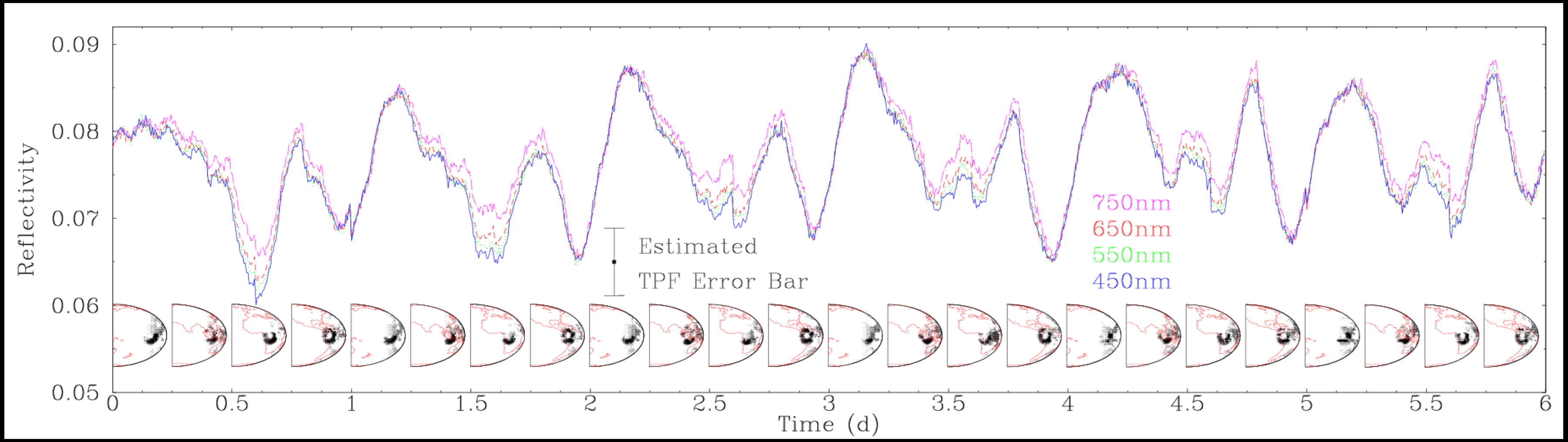
Petigura, Howard & Marcy: arXiv:1311.6806

# Starshade project:
# direct imaging of a second earth



Space telescope + occulting satellite at 50,000km away!
(Princeton Univ. + JPL/Caltech)

# Expected daily change of the reflected light of the earth




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

- *Assume* that the earth's reflected light is completely separated from the Sun's flux !
- *Periodic change of 10% level* due to different reflectivity of land, ocean, forest
- 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

**ApJ. 715(2010)866, arXiv:0911.5621**

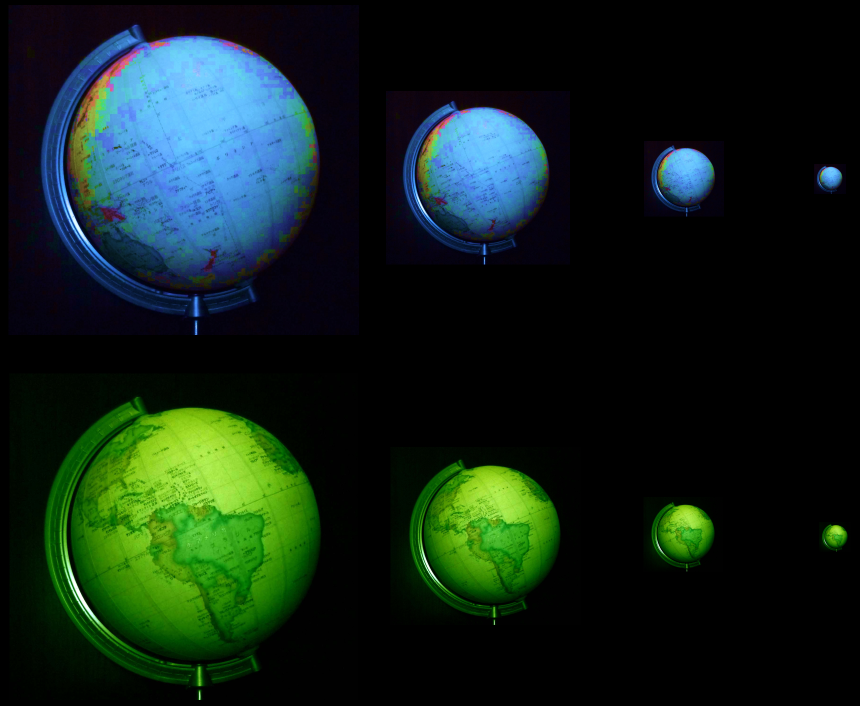
## Colors of a Second Earth. II: Effects of Clouds on Photometric Characterization of Earth-like Exoplanets

**ApJ. 738(2011)184, arXiv:1102.3625**

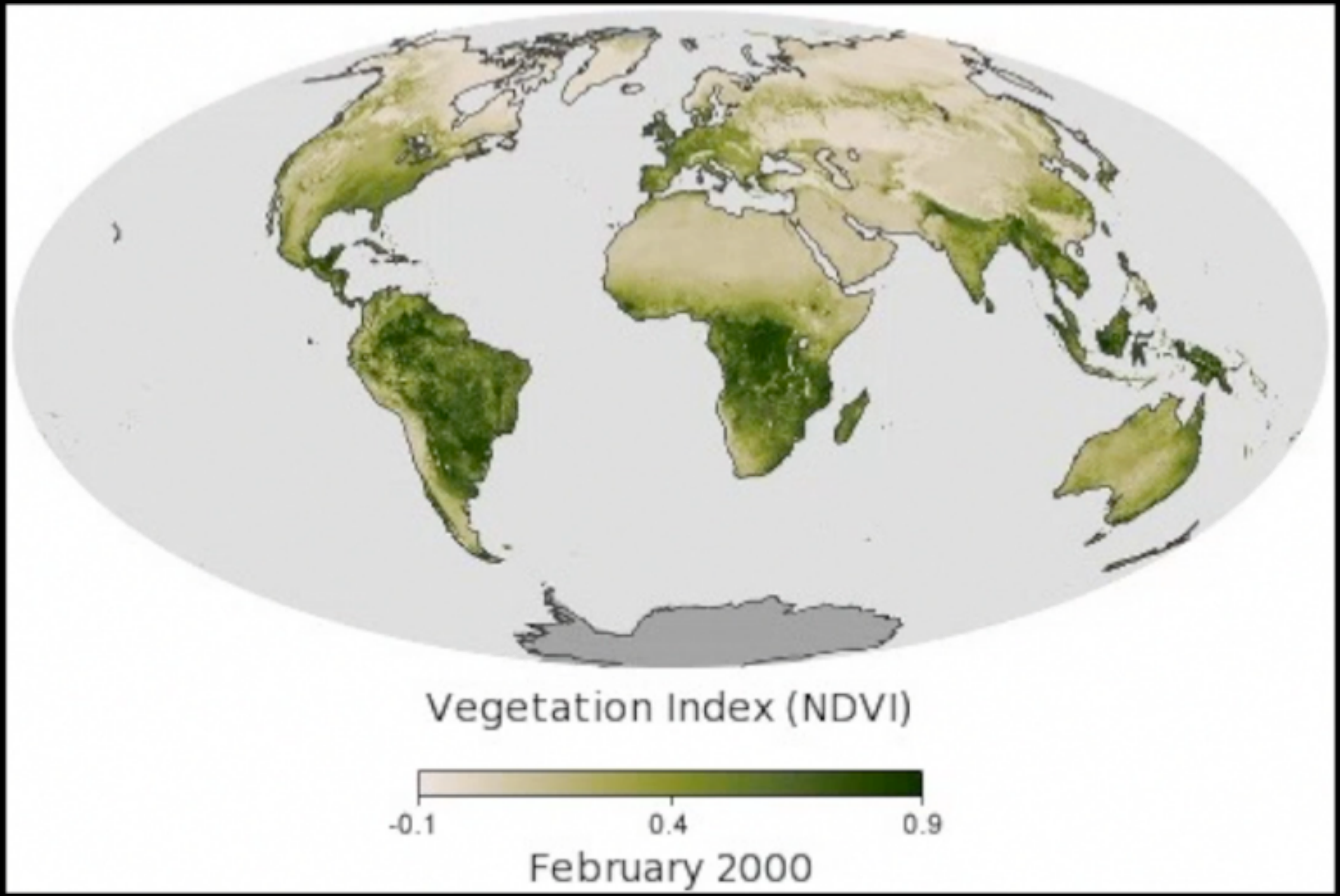

- Yuka Fujii, H.Kawahara, A.Taruya, Y.Suto (Dept. of Phys., Univ. of Tokyo), S.Fukuda, T.Nakajima (Center of climate system research, Univ. of Tokyo), Edwin Turner (Princeton Univ.)

# Colors of a second earth

- Beyond a pale blue dot
  - Impossible to spatially resolve the surface of a second earth
  - Color should change due to the rotation
  - A second earth = a color-changing dot

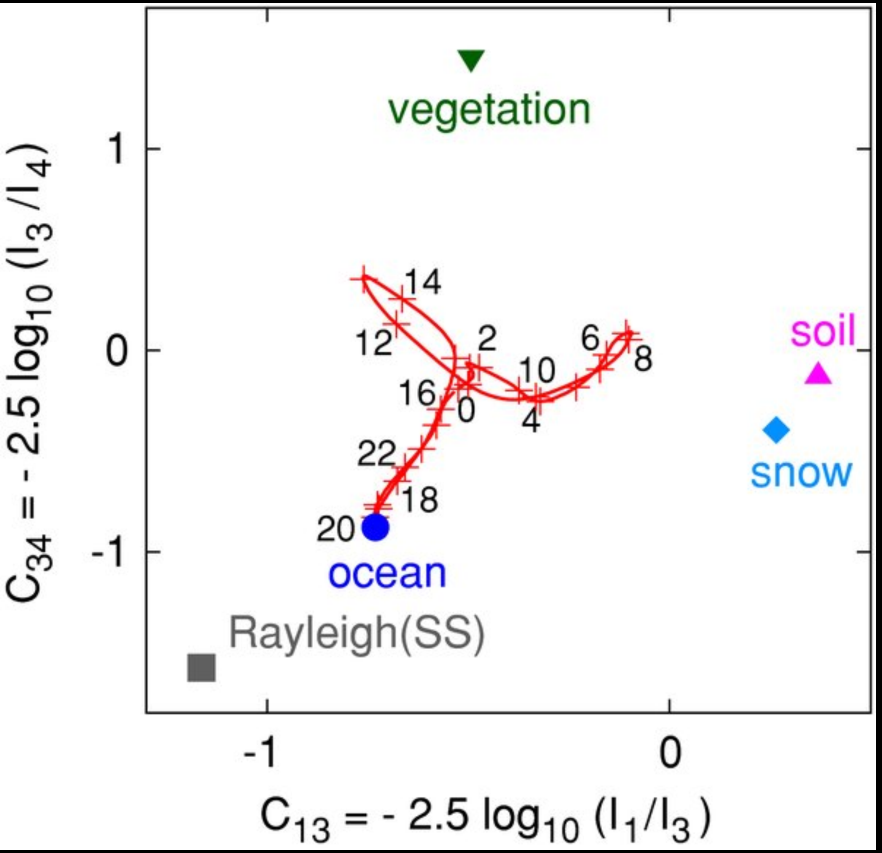


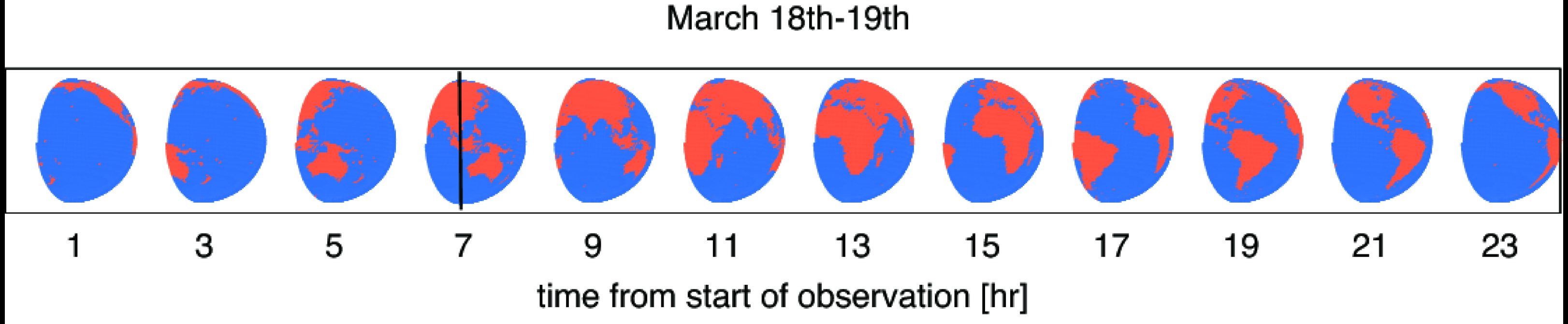
# annual vegetation global map by the earth observing satellite Terra



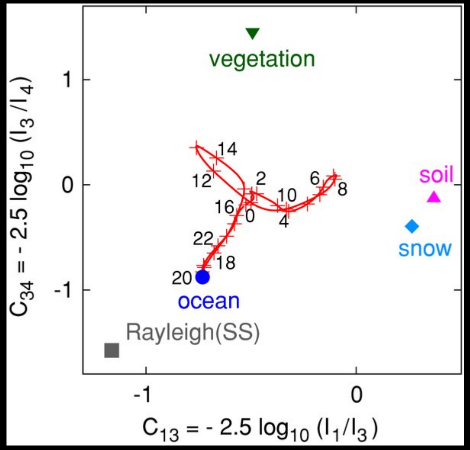

http://earthobservatory.nasa.gov/GlobalMaps/

# Colors of our earth

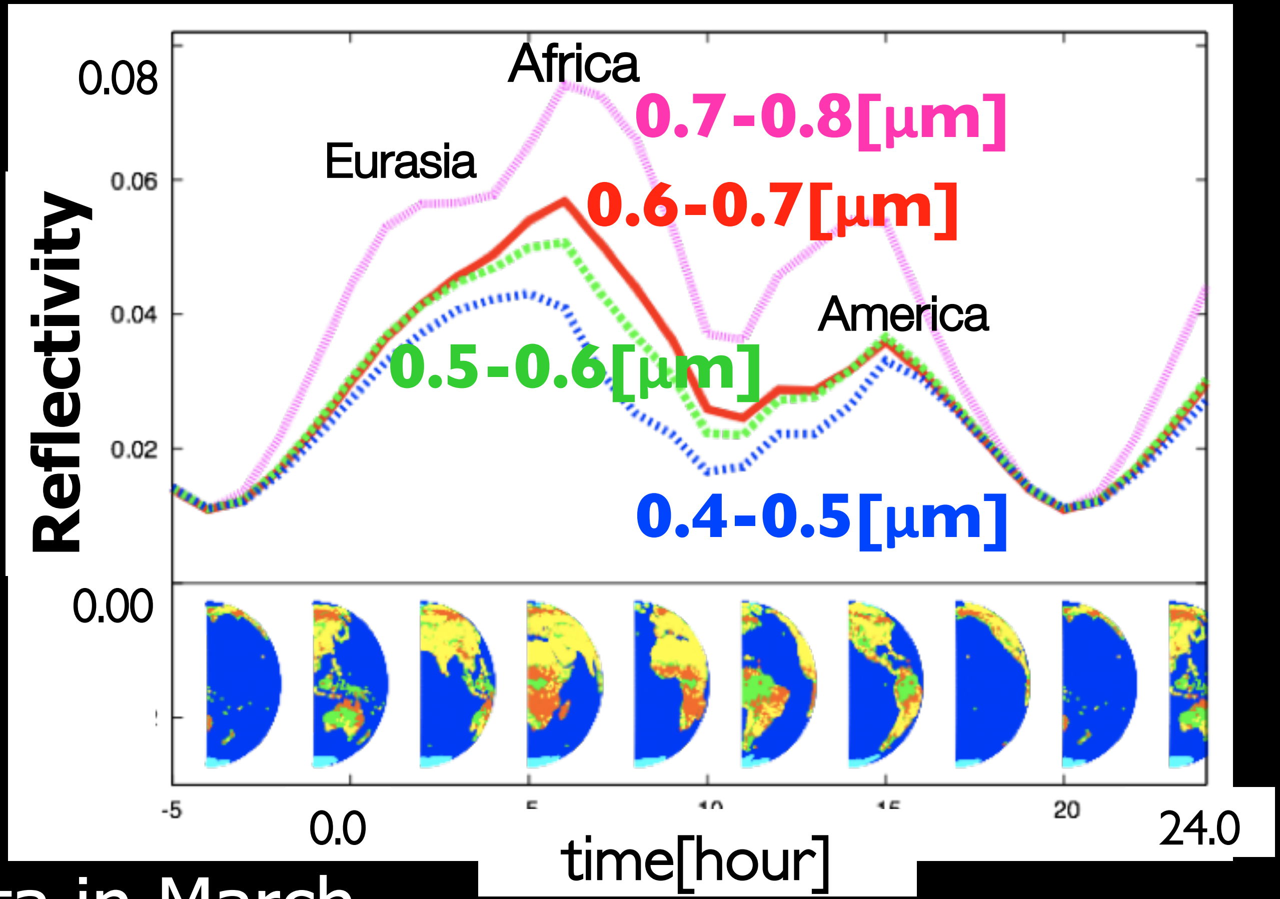


# A pale blue dot ? Not really



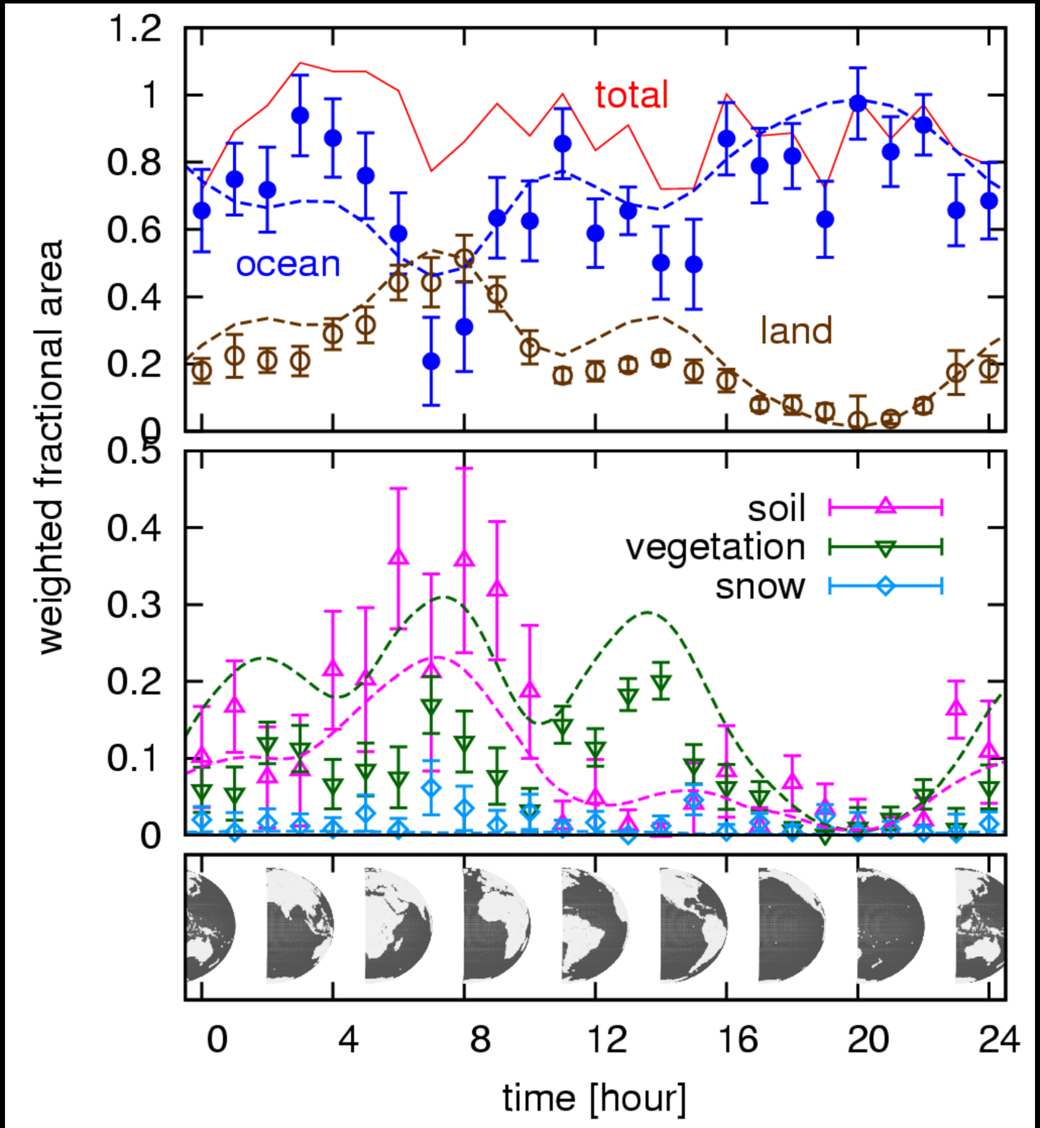

Simulated photometric light-curves of Earth




- Adopted Earth data in March
- Spin inclination = 0 (edge-one view at vernal equinox)
- cloudless

Fujii et al. (2010)

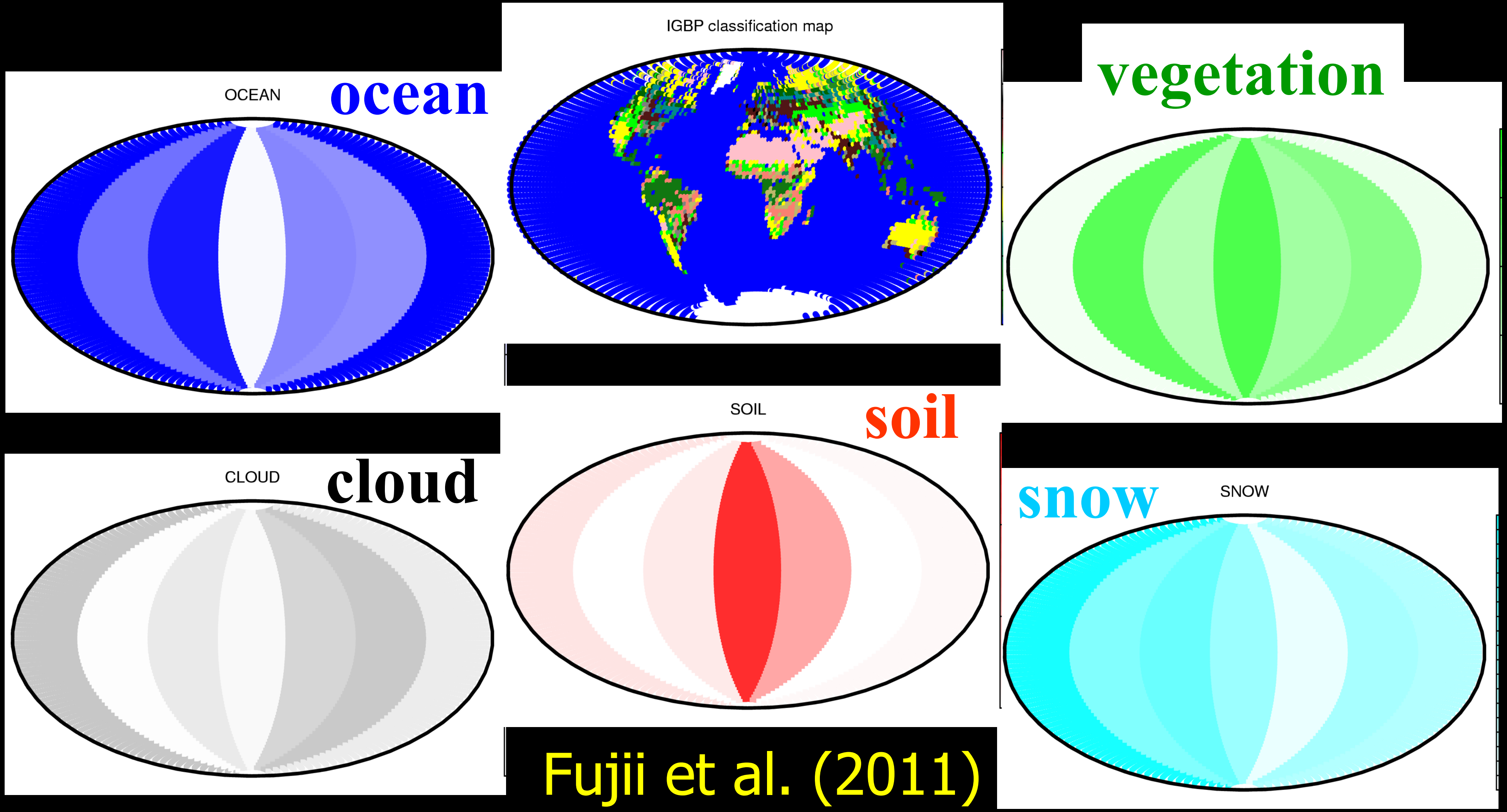
# Estimating fractional areas of surface components from colors of a second earth




- 2 week mock observation of a *cloudless* Earth at 10 pc away with 6m space telescope
- Reasonably well reproduced
- possible to identify vegetation !

Fujii et al.（2010）

# Surface latitude map estimated from real satellite data *with cloud model*



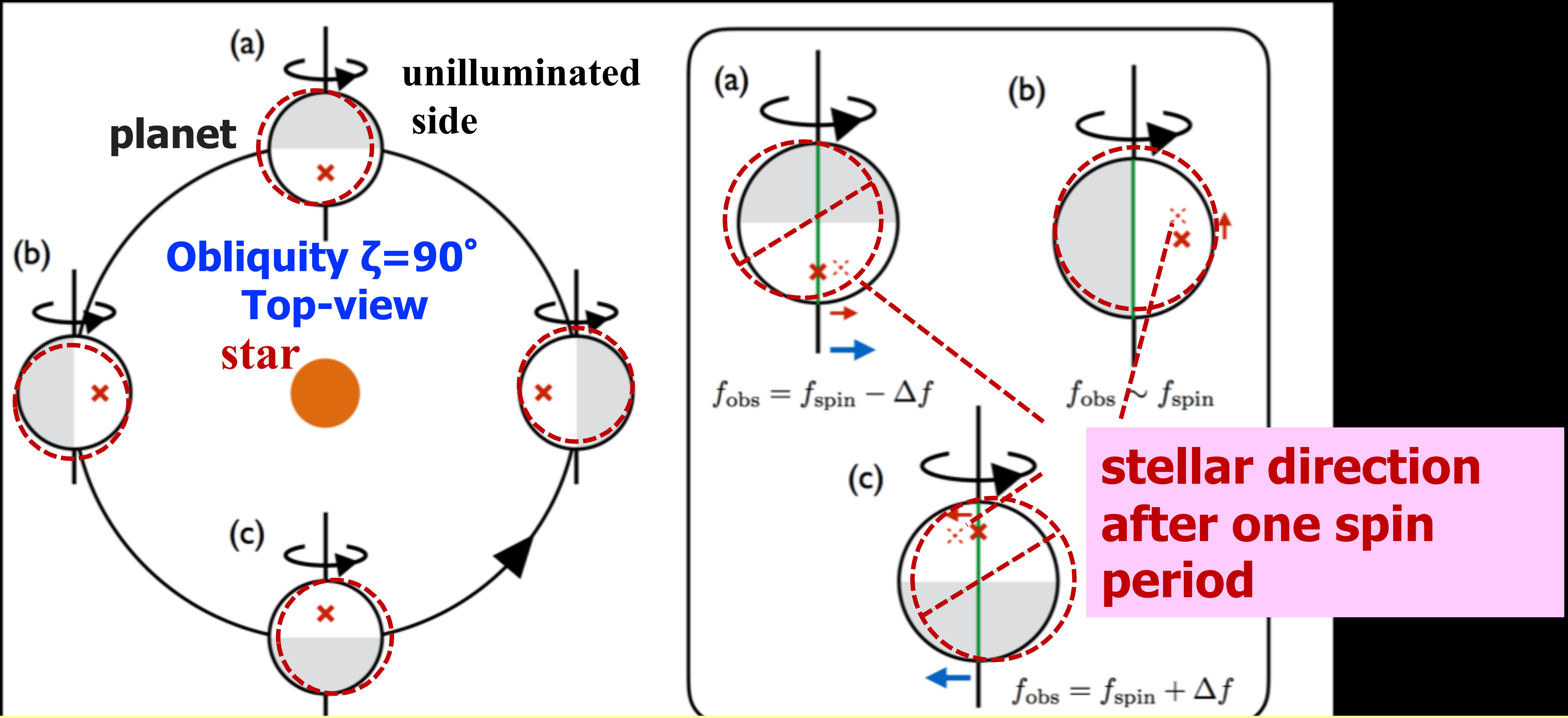

Fujii et al. (2011)

# Obliquity of an Earth-like planet from frequency modulation of its direct imaged light curve: analysis of the general circulation model simulation data for the Earth

**Yuta Nakagawa,** Master thesis (2018)

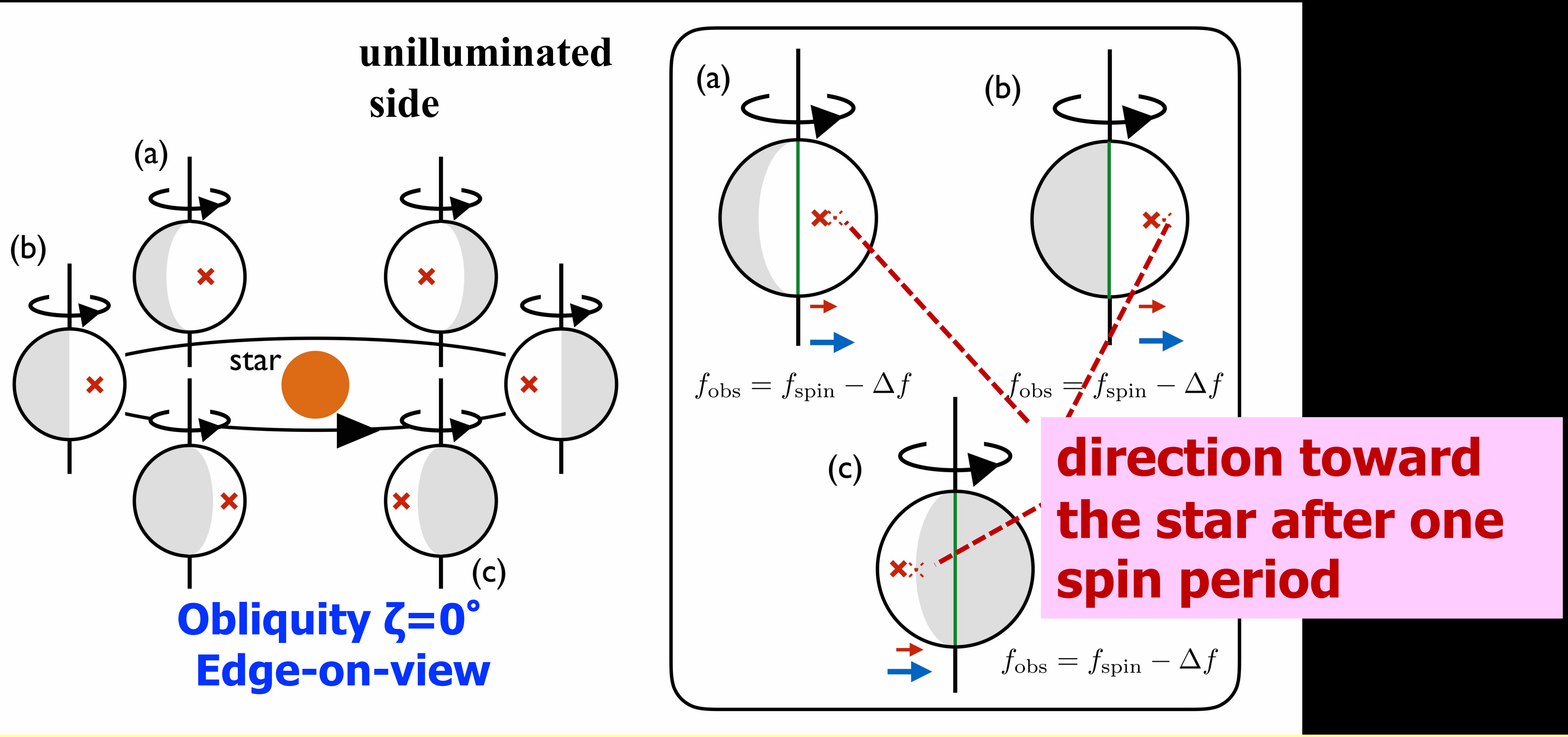
**Yuta Nakagawa**, T.Kodama, M.Ishiwatari, H.Kawahara, Y.Suto, Y.Takahashi, G.Hashimoto, K.Kuramoto, K.Nakajima, S.Takahiro, & Y.Hayashi (2019) in preparation

# Diurnal frequency of the planetary light-curve modulated by the orbital motion



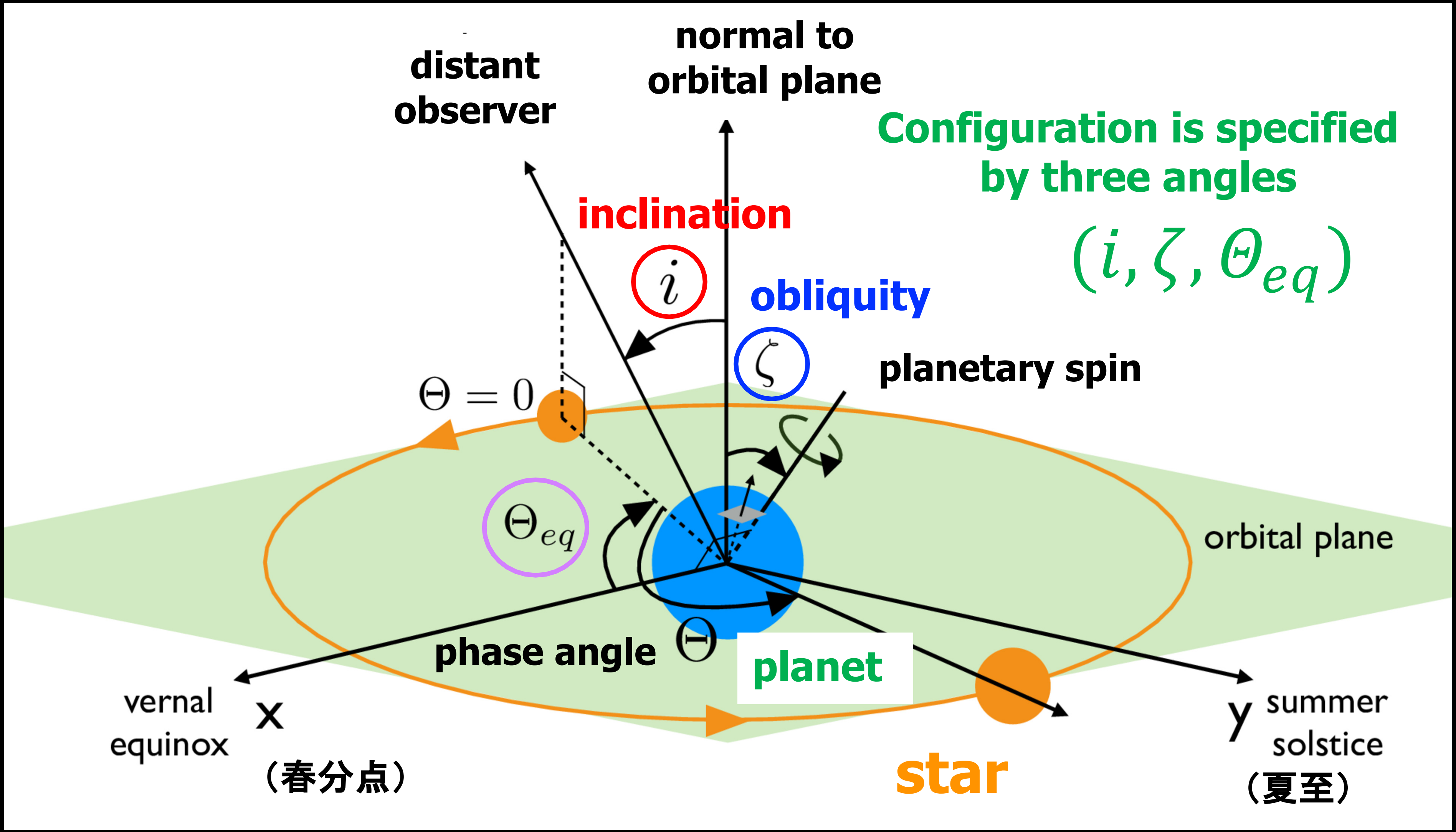

**Planetary spin and obliquity measurement proposed by H.Kawahara, ApJ. 822 (2016) 112**

# Diurnal frequency of the planetary light-curve modulated by the orbital motion




**Planetary spin and obliquity measurement proposed by H.Kawahara, ApJ. 822 (2016) 112**

# Schematic geometry of the system (geocentric frame)



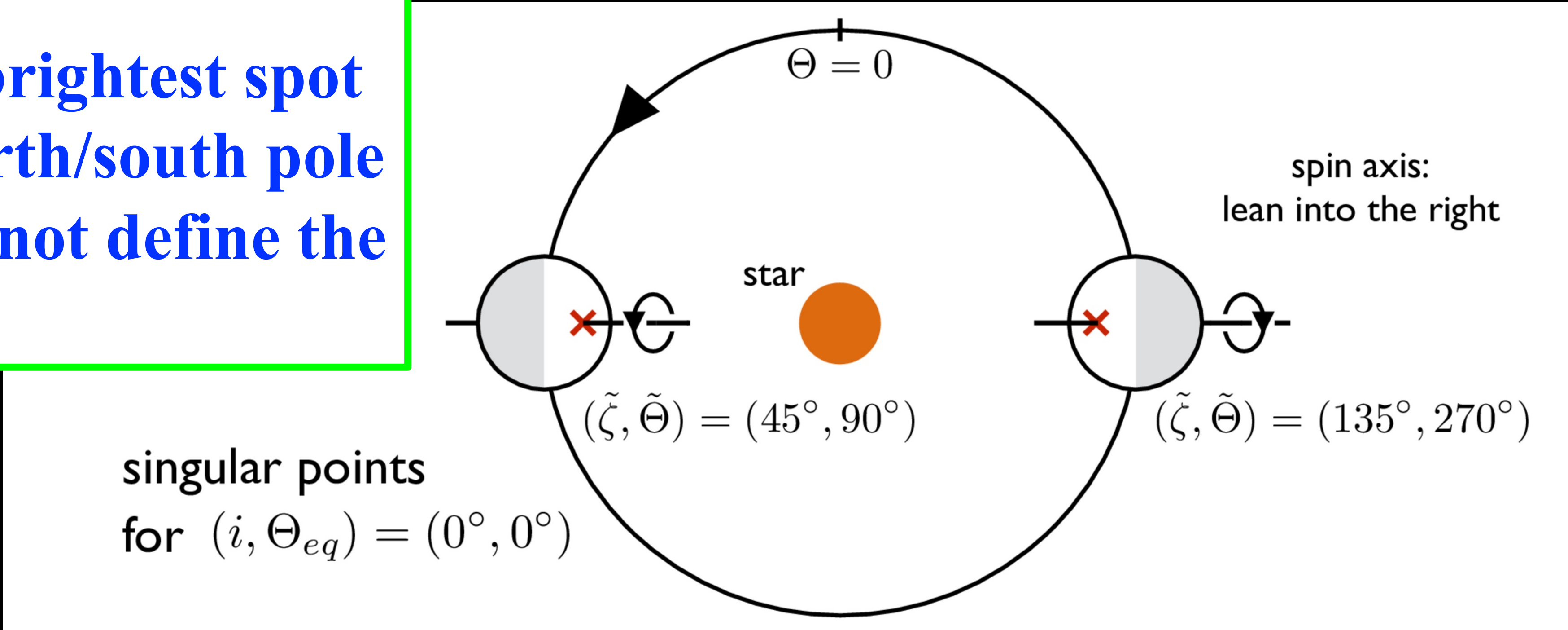
# Modulation factor and singular points

$$
\begin{aligned}
\epsilon_\zeta(\Theta) &= \frac{\kappa'(\Theta)}{1+\kappa^2(\Theta)} \\
&= \{-\cos\zeta + \sin\zeta\cos i\sin(\Theta-\Theta_{eq}) - \cos\zeta\cos\Theta\sin i\} \\
&\quad / \{\cos^2(\Theta-\Theta_{eq}) \\
&\qquad + [-\cos\zeta\sin(\Theta-\Theta_{eq}) + \cos\zeta\sin\Theta_{eq}\sin i + \sin\zeta\cos i]^2 \\
&\qquad\qquad +2\cos\Theta_{eq}\sin i\cos(\Theta-\Theta_{eq}) + \cos^2\Theta_{eq}\sin^2 i\}
\end{aligned}
$$

$$f_{\rm obs} = f_{\rm spin} + \epsilon_\zeta(\Theta) f_{\rm orb}$$

**Singular point $(\tilde{\zeta}, \widetilde{\Theta})$**

**If the instantaneous brightest spot coincides with the north/south pole of the planet, one cannot define the modulation angle.**

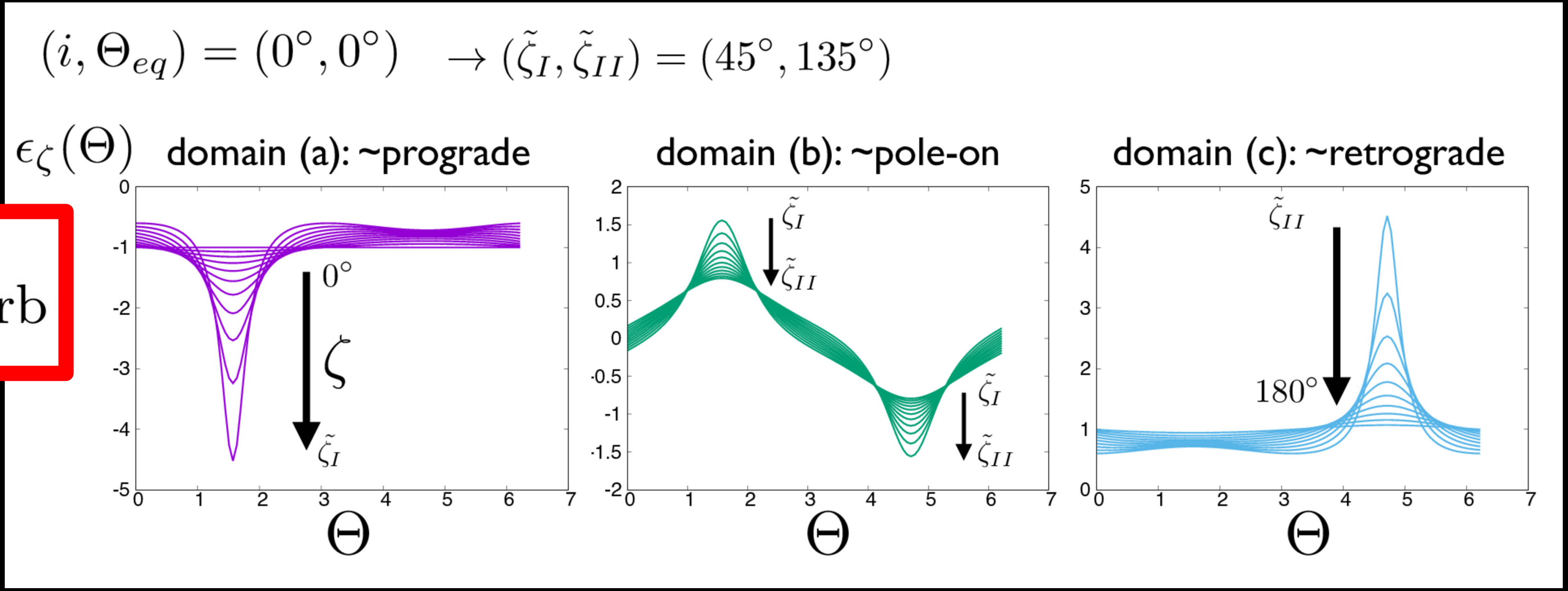


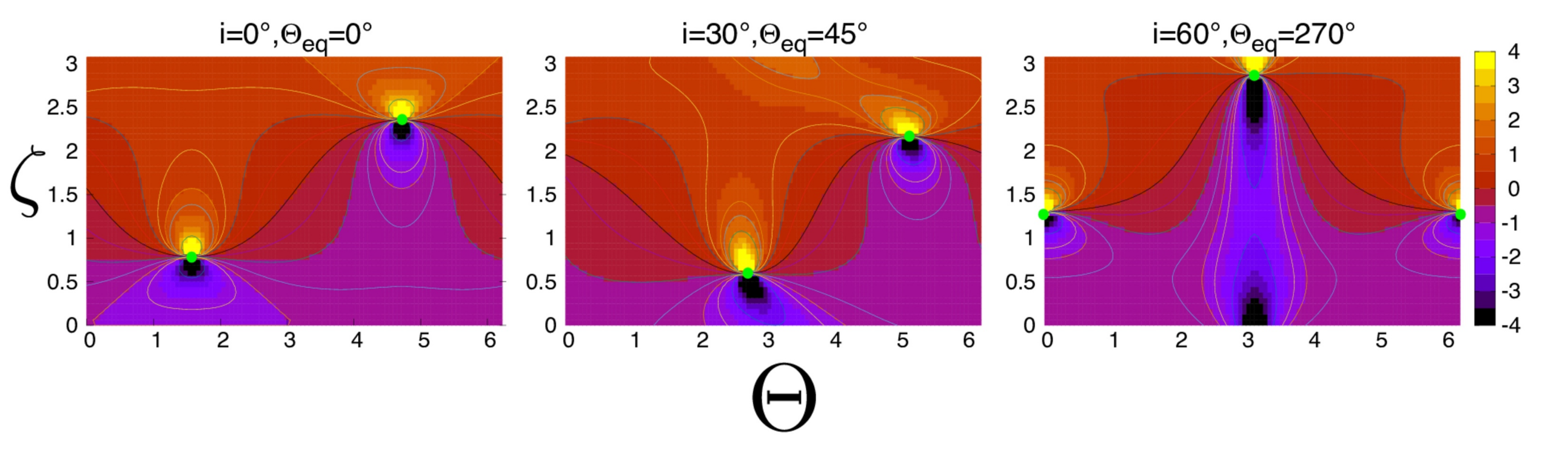

Kawahara (2016)

# The induced frequency modulation

$$f_{\rm obs} = f_{\rm spin} + \epsilon_\zeta(\Theta) f_{\rm orb}$$

Nakagawa (2018)



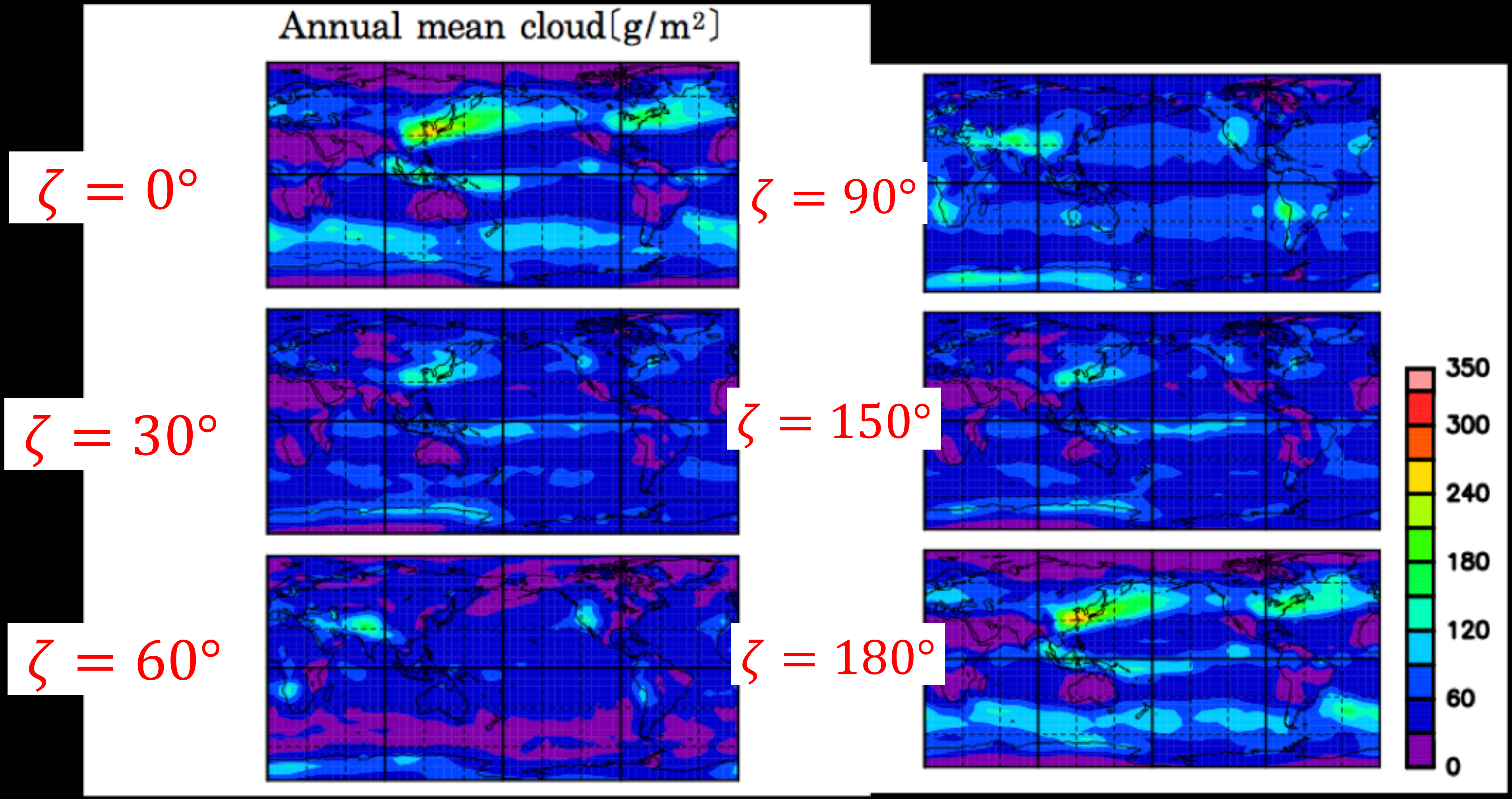
# Mock analysis of "Earth" simulated with GCM (general circulation model)

- GCM code for planetary climate simulatio
  - DCPAM5 (Dennou-Club Planetary Atmosphe
    http://www.gfd-dennou.org
  - (longitude, latitude, pressure altitude)=(32,
  - Surface data from Earth+Obliquity ζ [deg]=
- Radiation transfer code libRadtran to cor
- Frequency modulation computed via pse
  distribution

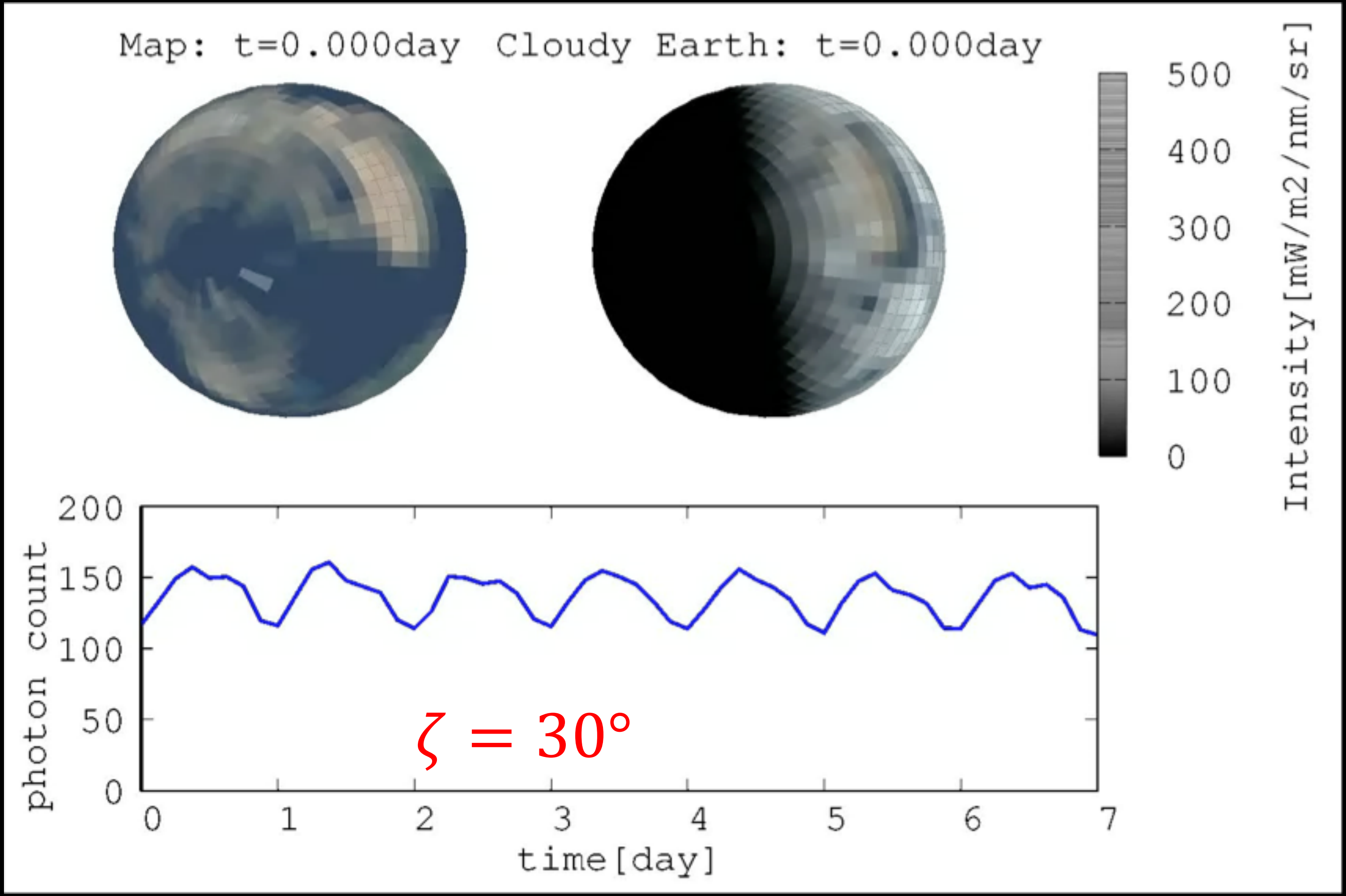
$$g(f,t) = \int_{-\infty}^{\infty} h(\tau) z(t+\tau/2) z$$


Prof. S.Manabe@Princeton, 2019

# Annual mean cloud column density for different obliquities

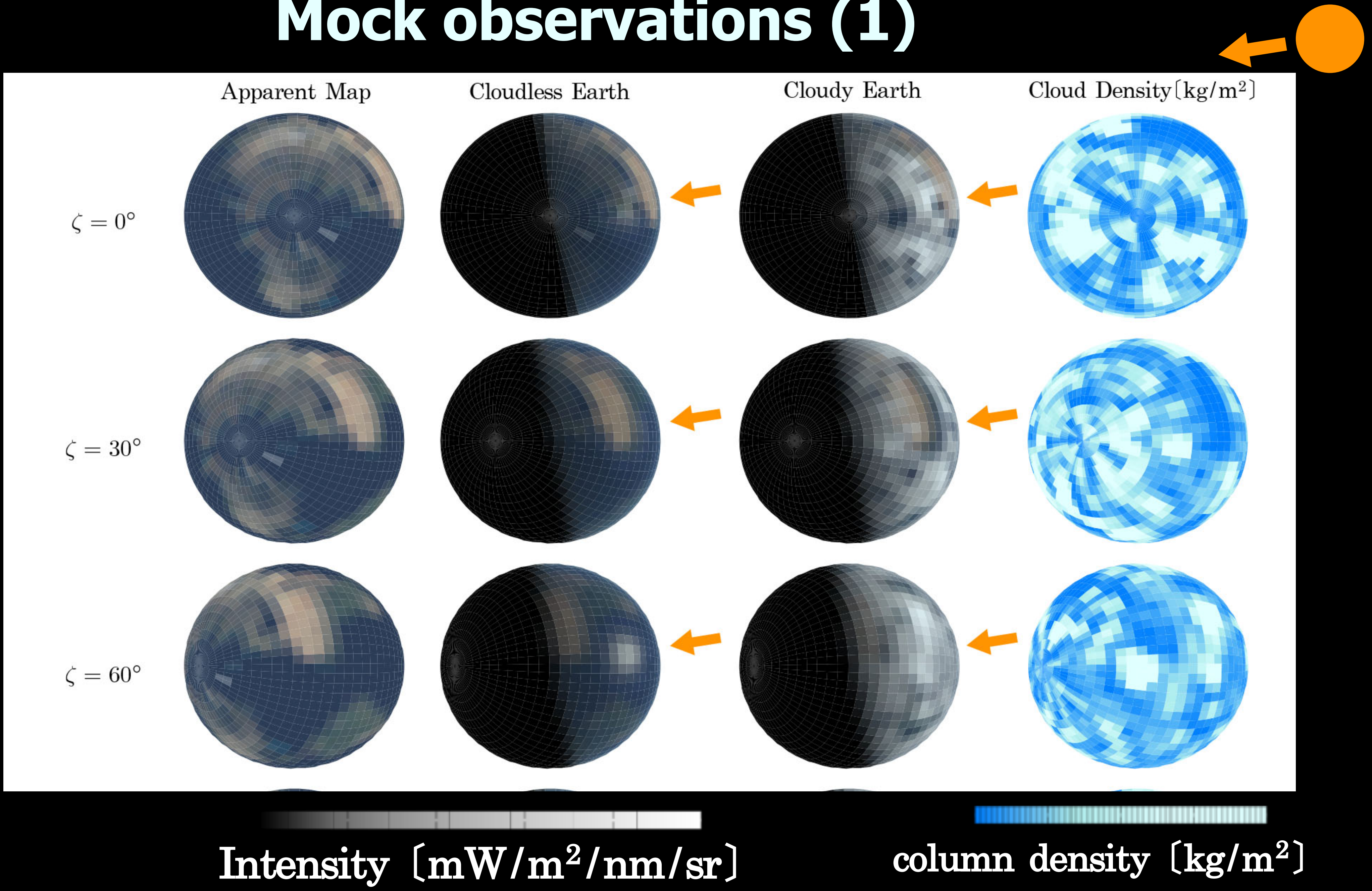


# Photometric variation of oblique Earth simulated with GCM (DCPAM5)

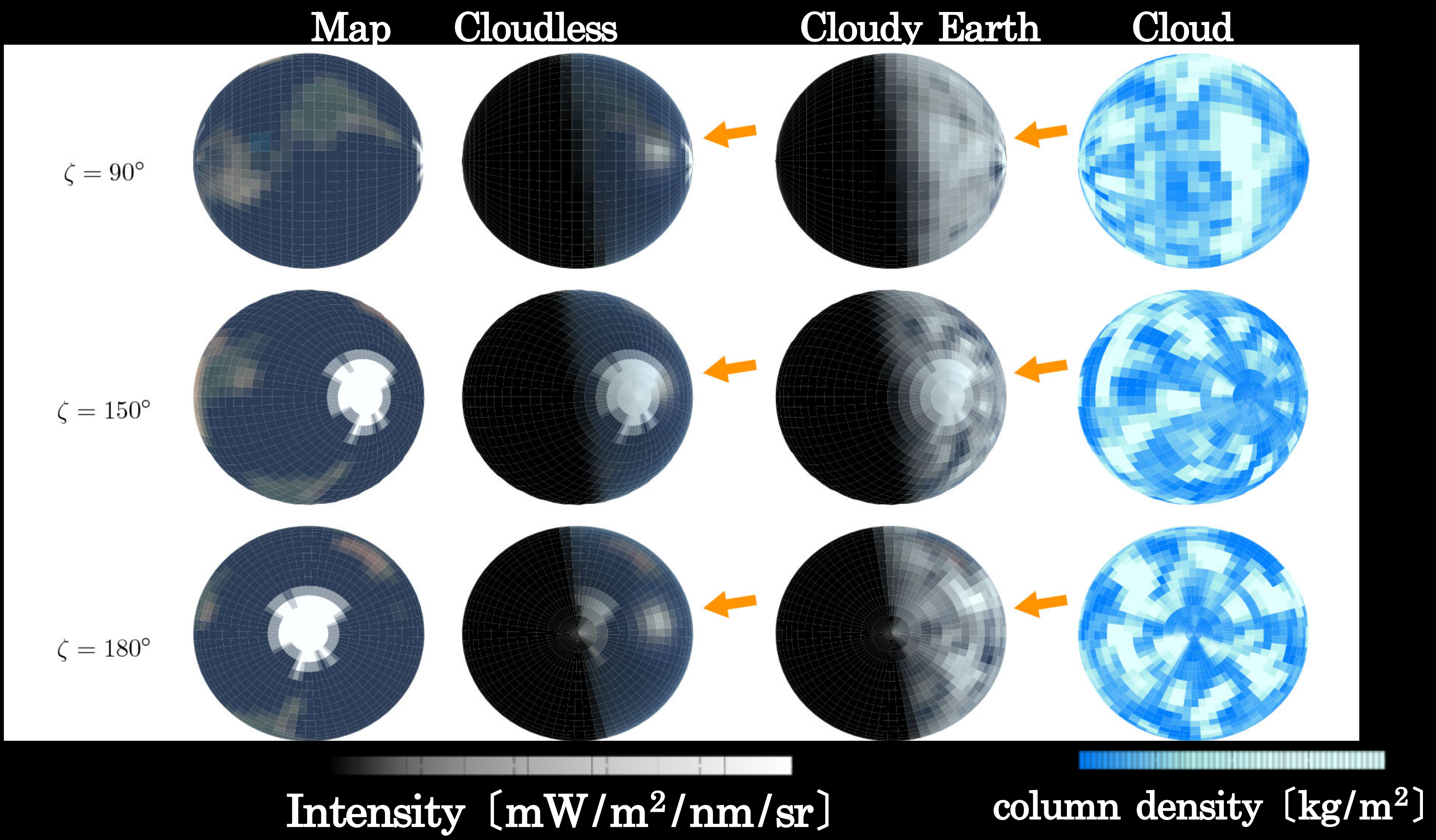



- Mock observation of a second Earth
- Determination of the planetary spin period and obliquity
- Identification of oceans, lands, and vegetation

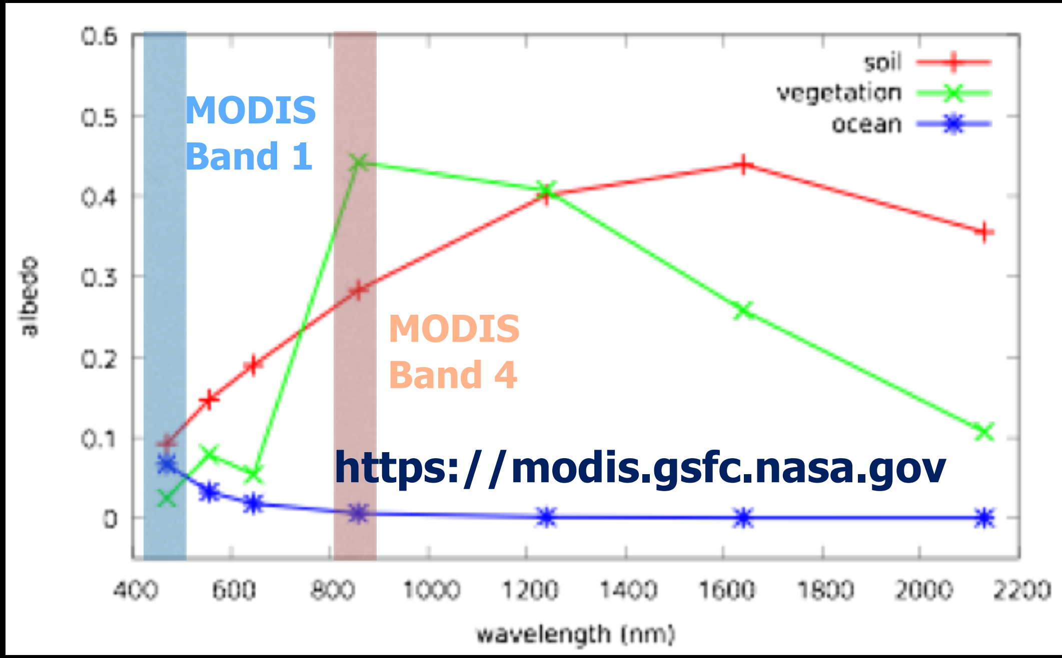
# Mock observations (1)

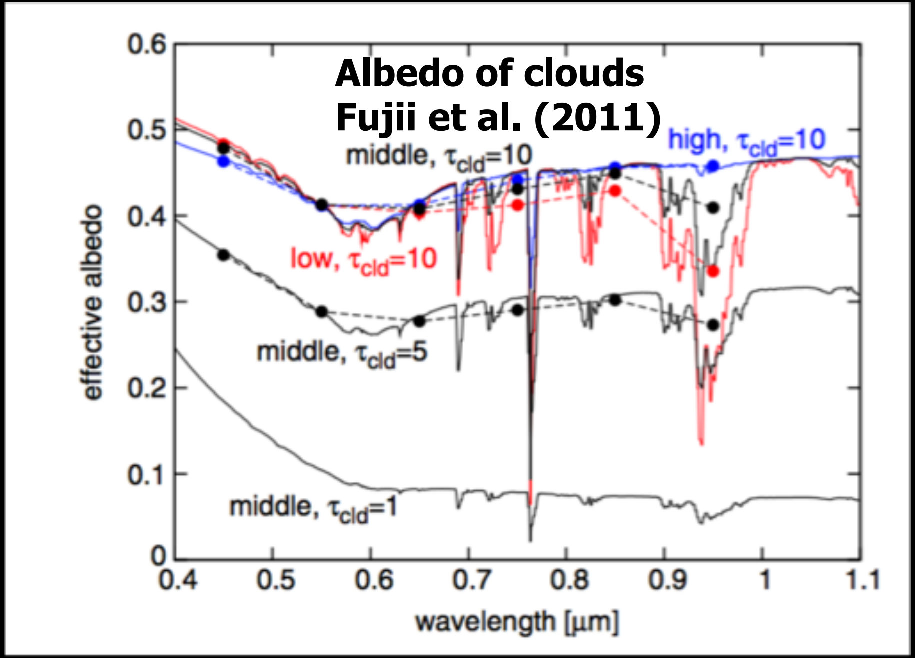


# Mock observations (2)



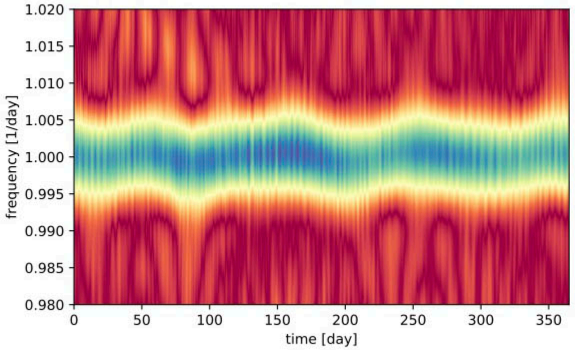
# Idealized mock observations



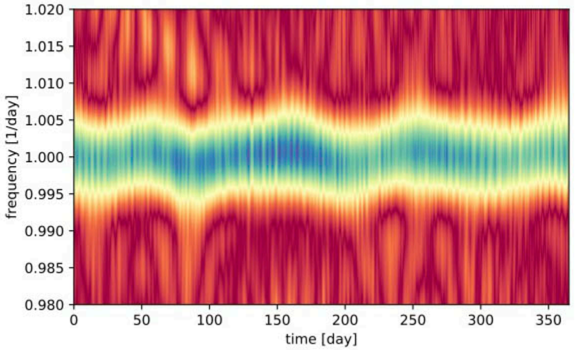




- Stellar flux assumed to be completely blocked
- *Sun-Earth system located at 10 pc away+20m space telescope*
- Photon Poisson errors alone
- MODIS Band1@0.45μm and Band4@0.85μm
- Band1(t) - Band4(t) to remove the effect of time-dependent clouds

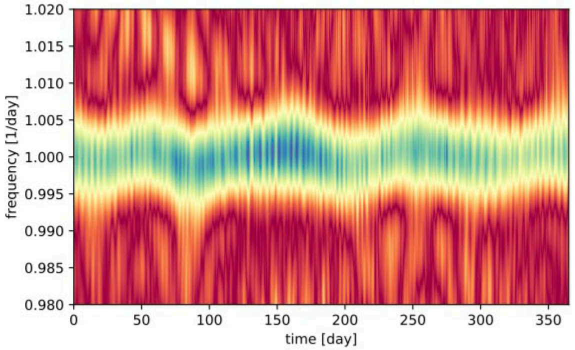
# Frequency modulation of band1 at different photometric bands



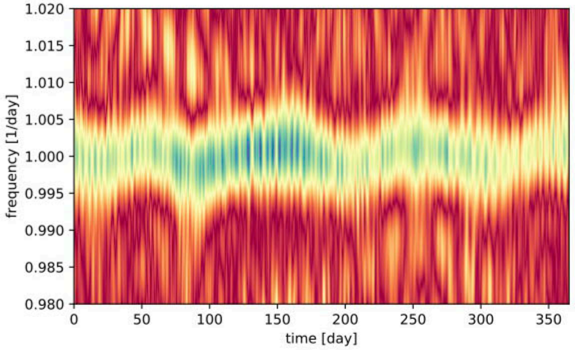

(a) band1$(0.459 - 0.479\mu m)$.



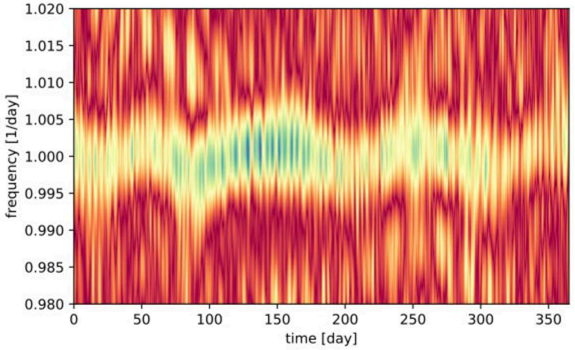

(b) band2$(0.545 - 0.565\mu m)$.



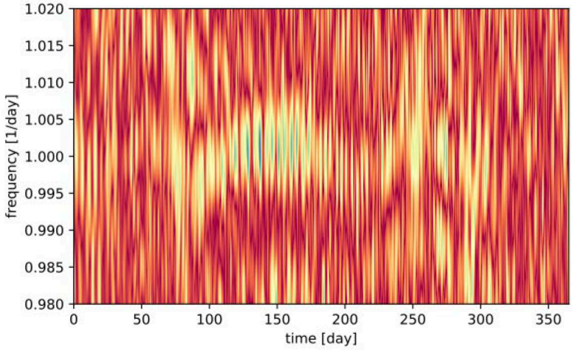

(c) band3$(0.620 - 0.670\mu m)$.




(d) band4$(0.841 - 0.876\mu m)$.

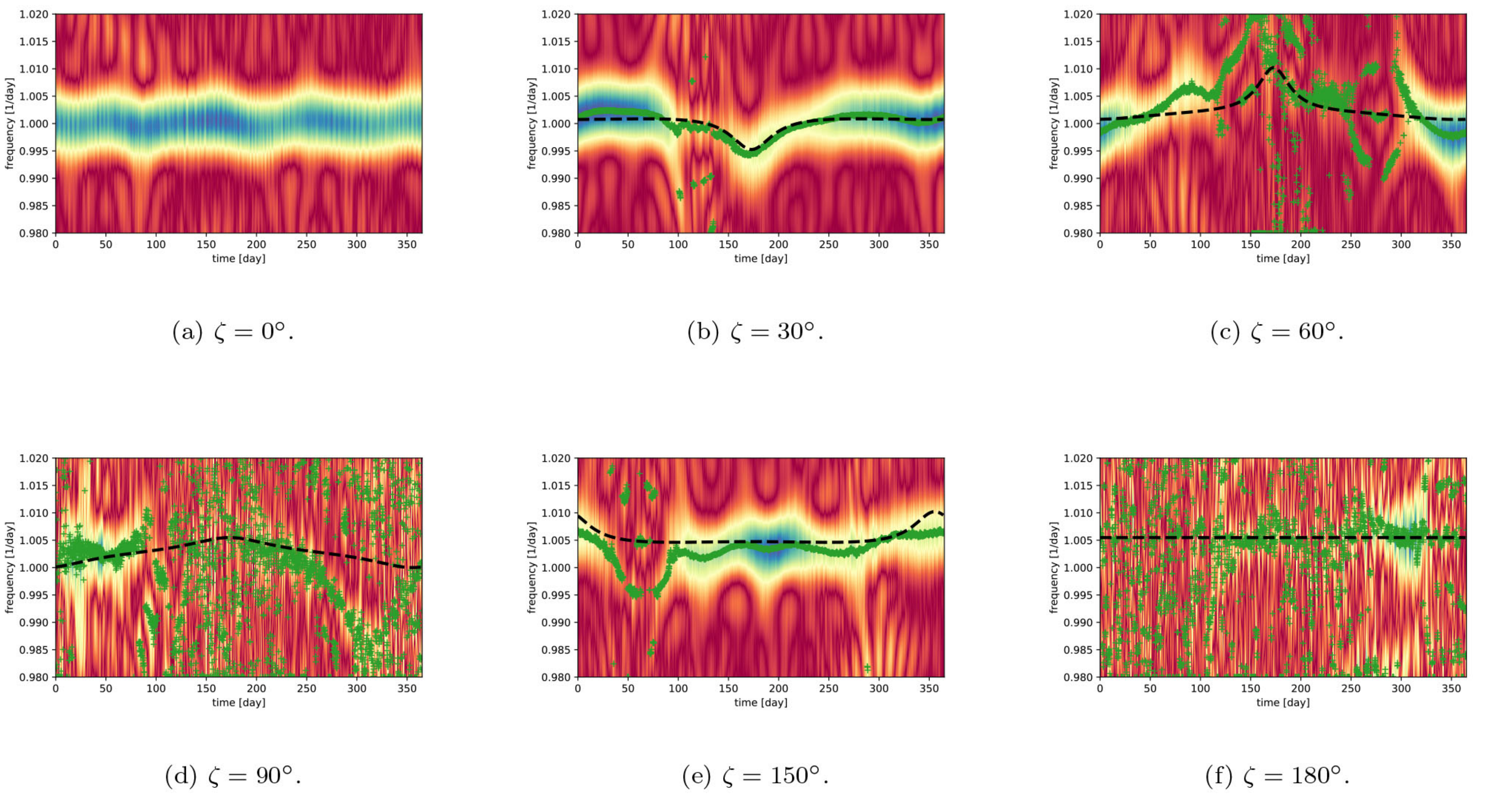



(e) band5$(1.230 - 1.250\mu m)$.




(f) band6$(1.628 - 1.652\mu m)$.

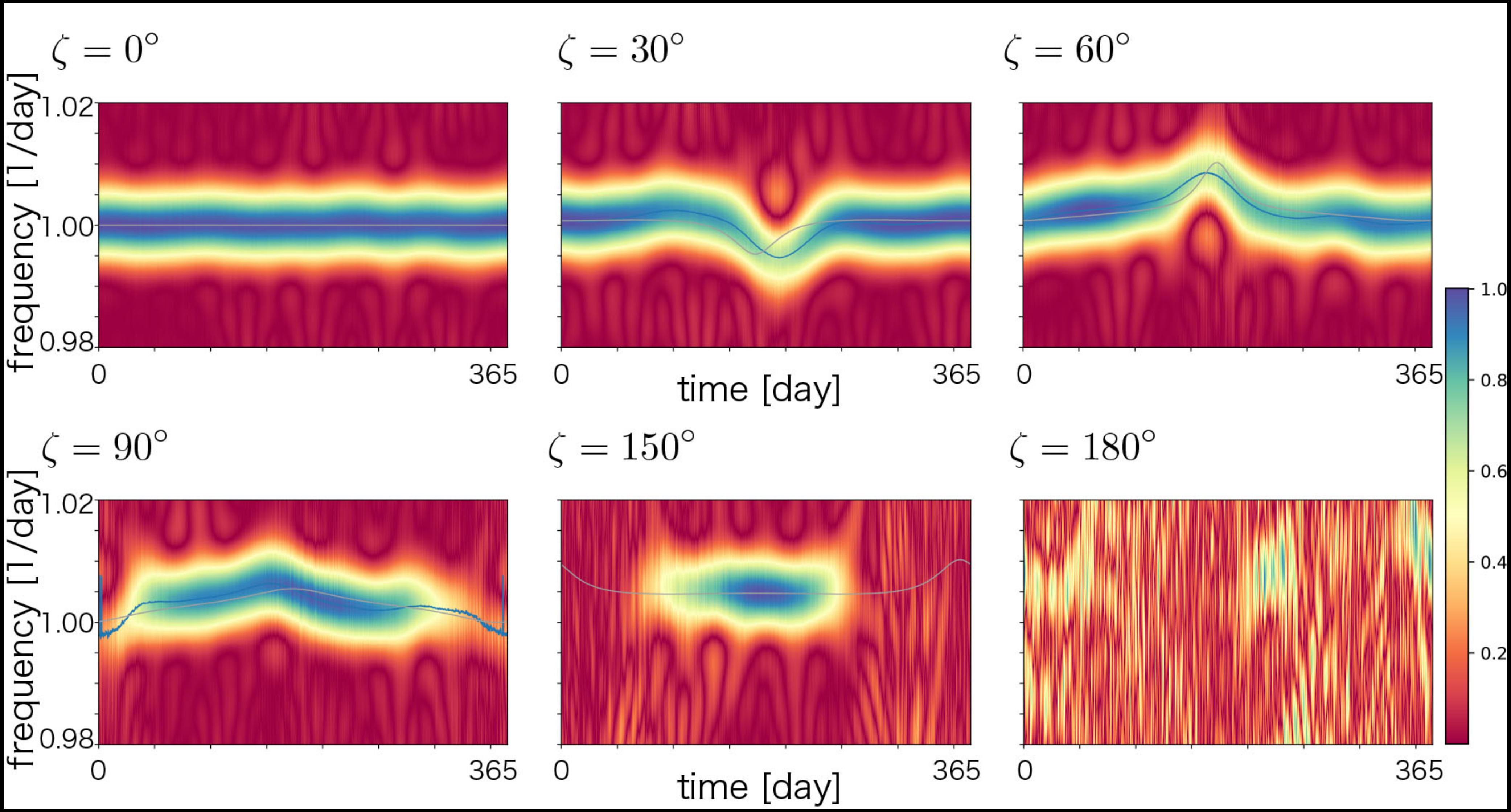
# Frequency modulation of band1 for different obliquities



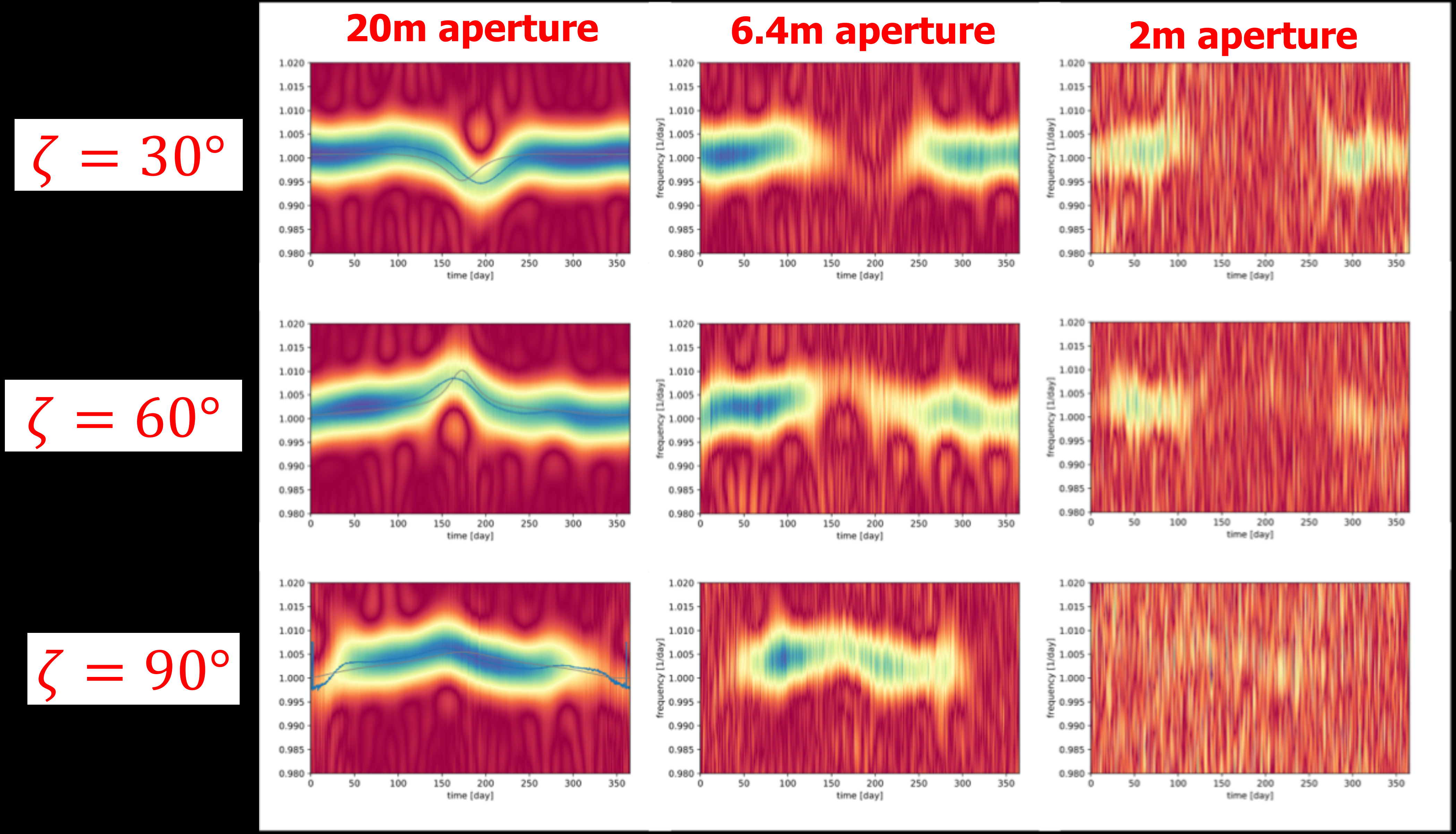

(a) $\zeta = 0°$. (b) $\zeta = 30°$. (c) $\zeta = 60°$.

(d) $\zeta = 90°$. (e) $\zeta = 150°$. (f) $\zeta = 180°$.

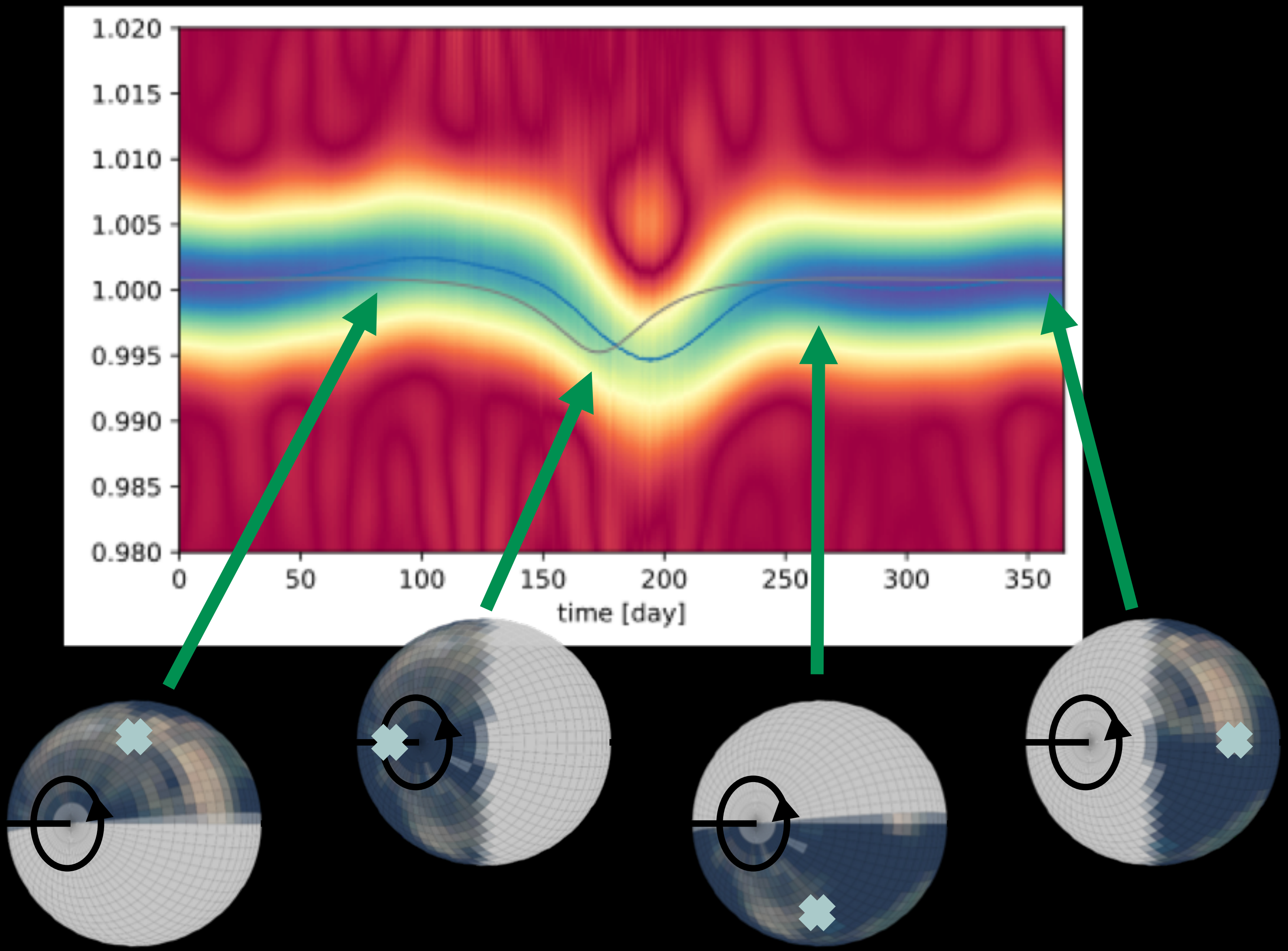
# Frequency modulation of band1- band4 for different obliquities



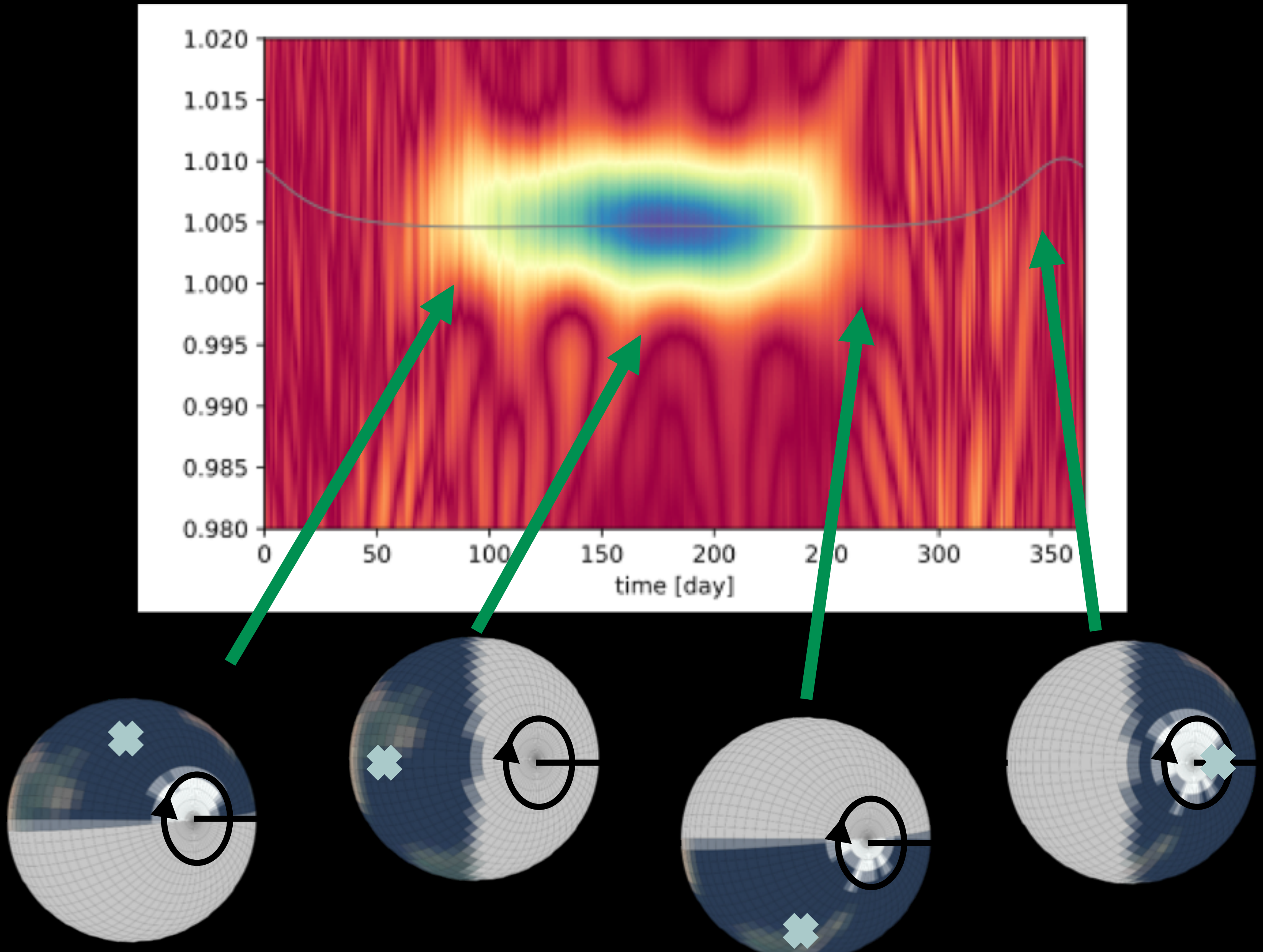
# Dependence on signal-to-noise ratios



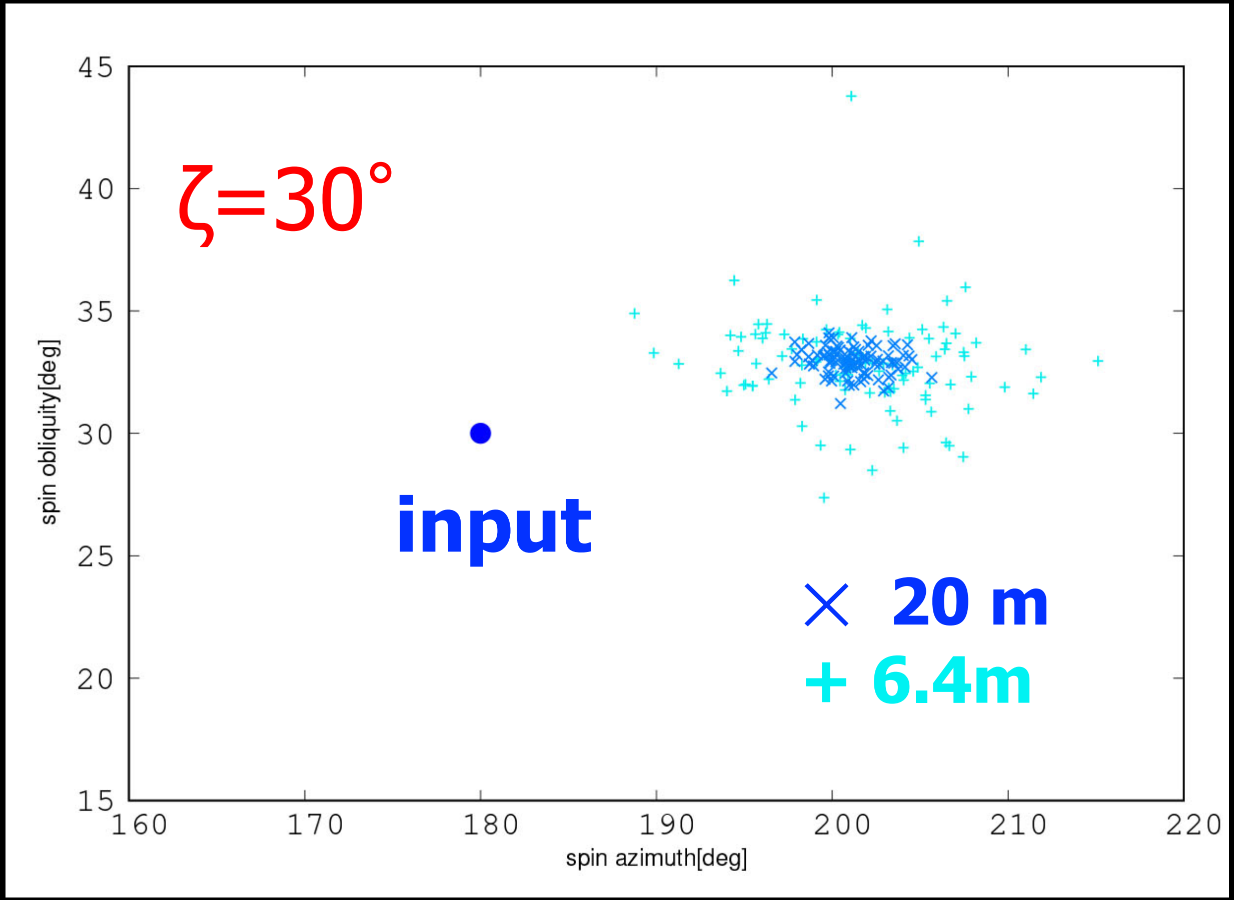
# Frequency modulation for ζ=30°

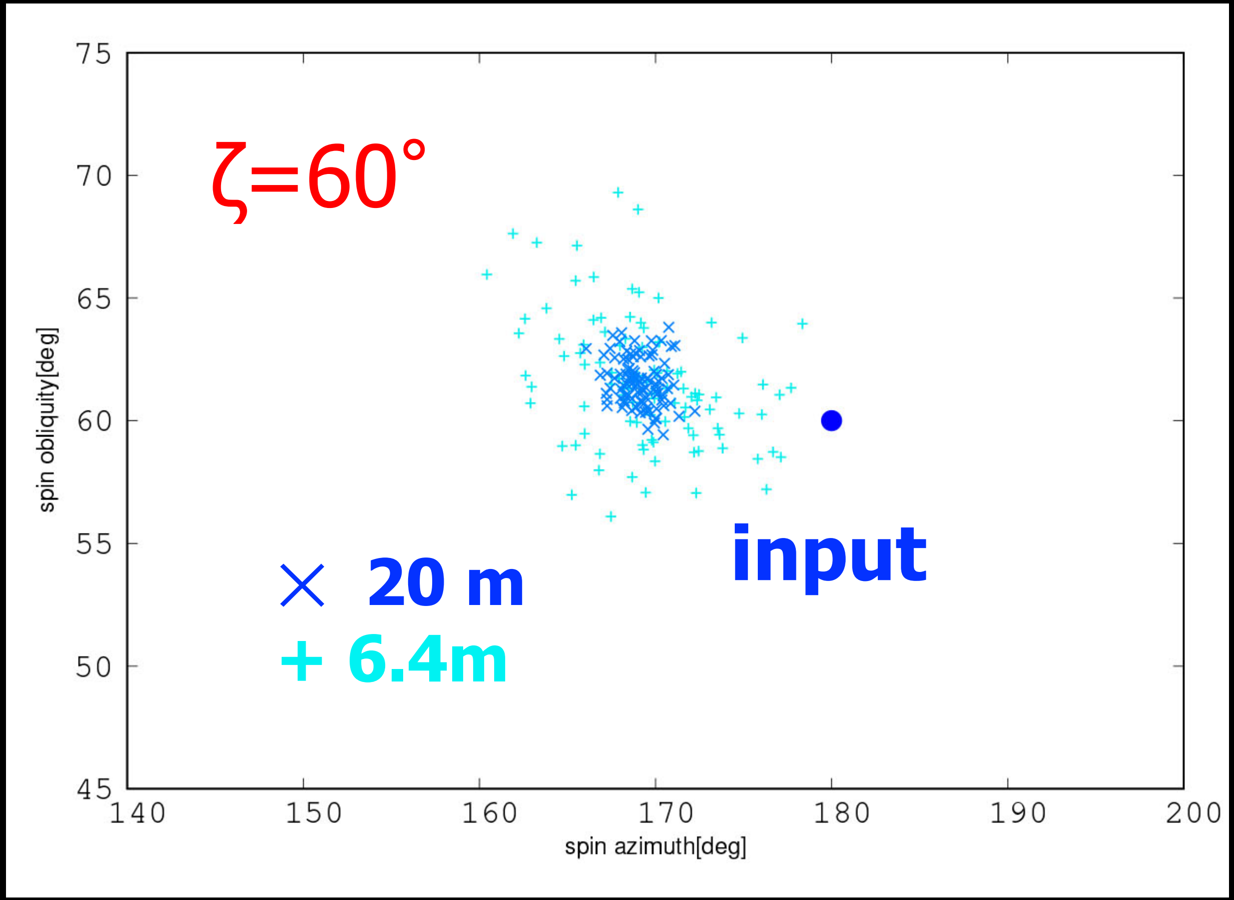


# Frequency modulation for ζ=150°



# Preliminary estimate of the obliquity



# Summary: unveiling a pale blue dot

- Diurnal change of colors of another earth is challenging, but reveals the presence of ocean, land, cloud, and/or even vegetation on their surface
- Spin rate and obliquity of another earth may be also measured through frequency modulation of the photometric variation over the orbital period
- Detection of oxygen, water vapor, and even the red-edge of vegetation may be a promising path towards astrobiology
- Needs more detailed GCM simulation and mock analysis