GCM simulation of a second earth: cloud pattern and the obliquity determination from future direct imaging

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9:25-9:50, November 6, 2018 @ the 8th KIAS workshop

interview @1st KIAS workshop in 2004

"암흑물질, 에너지에 대한 해답이 우주 푸는 열쇠"

동경 대학교 수토 야수시 우주론 교수

▲ 동경 대학교 수토 야수시 우주론 교수

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"그 동안 우주의 생성과 소멸, 진화 등 우주의 신비를 캐는데 우주론은 상당한 진전을 한 것이 사실이다. 그러나 새로운 문제들이 계속 등장한다. 하지만 머지 않아 우주의 신비도 드러날 것이다".

우주는 얼마나 거대할까. 우주가 그렇게 거대하다면 우리가 살고 있는 지구는 무엇일까. 그리고 한 인간은 불경(佛經)에 인용되는 항하수(恒河水)의 모래보다도 미미한 존재인가. 그러면 인간은 그 거대함 앞에서 무엇을 해야 할까.

그리스 최초의 철학자로 무심한 밤하늘만 바라보면서 걷다가 개울에 빠져 한 노파의 도움을 받고 "당신은 바로 눈앞의 일도 알지 못하면서 어찌 하늘의 일을 알려고 하는가"라며 핀잔을 받은 천문학자이자 수학자인 탈레스(Thales, BC624?-BC546?)의 일화를 보면 천문학의 역사가 학문의 역사만큼 긴 것은 부인할 수 없다.

구름 하나 없이 맑은 밤. 도시의 불빛으로 멀리 떨어진 곳에서 우리는 하늘에 빽빽하게 들어선 수천 개의 별을 볼 수 있다. 이 별들이 인류의 역사와 더불어 계속 존재해 왔다면 그 별들의 본질은 무엇이고 인간에게 어떤 영향을 미쳐 왔는지 알려고 하는 노력은 당연하지 않을까.

"Are we alone ?"

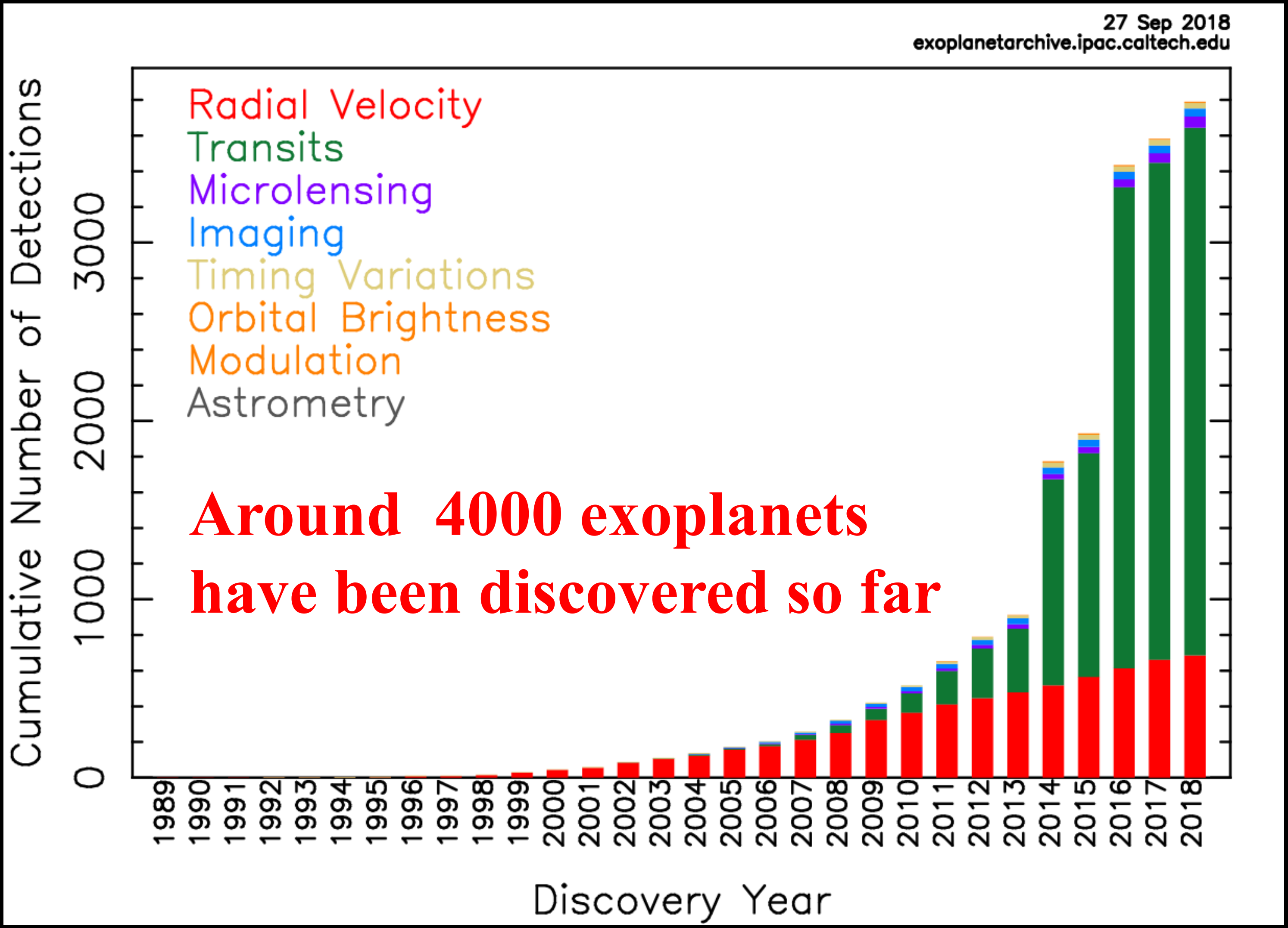
Implications behind the fine-tuned initial conditions ?

- **Question**: The presence of liquid water on our earth comes from the “accidental” fact that it orbits around the Sun within a narrow range called a habitable zone (0.95au<a<1.1au). What is the implication ?

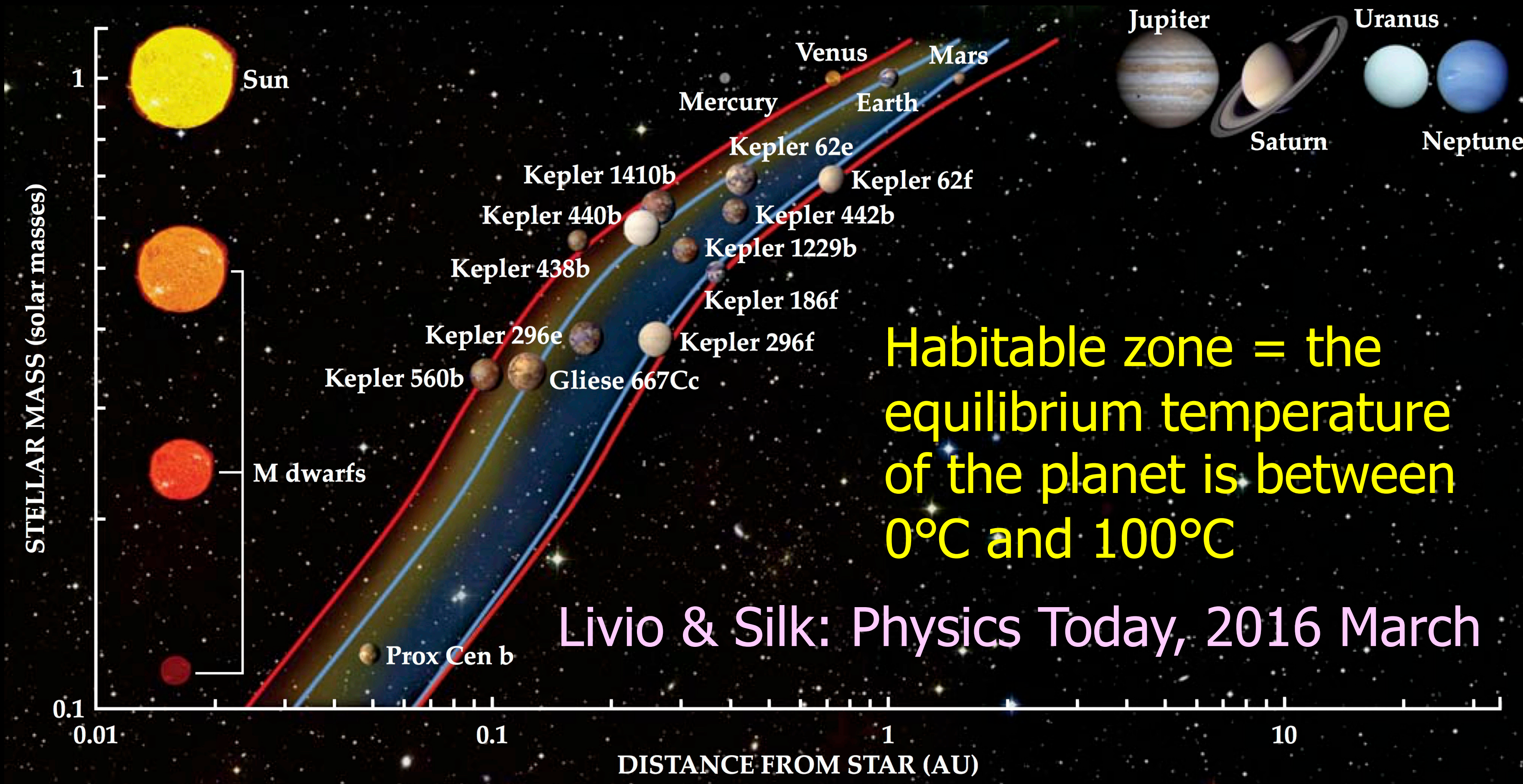
Two opposing view-points

- **Answer1: It is a meaningless question!**
  - The semi-major axis of the Earth-Sun system is simply determined by the initial conditions. It is meaningless to ask why.
- **Answer2: It is a very deep question!**
  - It is true that the fine-tuned initial condition is required for the habitability of the Earth, and should be regarded as completely accidental. If the Solar system is the only planetary system in the universe, it is just a miracle that we live in the system. This is exactly why we should conclude that numerous exoplanetary systems exist.

I do not know which, if any, is the right answer, but we now know



Even a dozen of *habitable* planet *candidates* are identified already



Habitable zone = the equilibrium temperature of the planet is between 0°C and 100°C

Livio & Silk: Physics Today, 2016 March

It is even possible now to *(attempt to)* estimate the occurrent rate of habitable earth-size planets from observations

- **Habitable planets with (1-2)R_{earth} around Sun-like stars corrected for the observational selection effect**
  - **11±4 % (Incident flux is between 1 and times the Solar flux on the Earth)**
  - **$5.7^{+2.2}_{-1.7}$ % (orbital period is between 200 and 400 days)**

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 PNAS 110(2013)19273

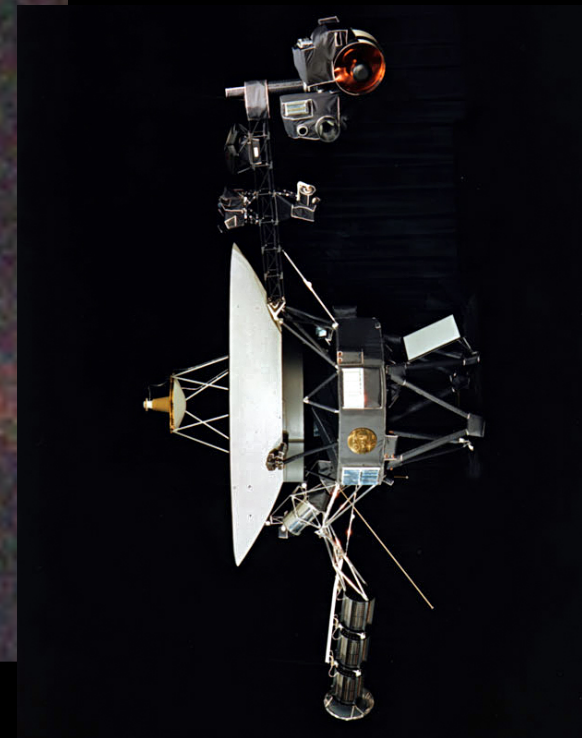
Our universe has numerous ”earths”?

- 10^{11} stars in the Milky Way
  - Their 10% is Sun-like stars (10^{10})
  - Their 10% may have habitable earths
- 10^{9} habitable planets in MW
  - 10^{11} galaxies within the Hubble horizon
- 10^{20} habitable planets within the Hubble horizon !
  - No exoplanet with liquid water is not known (yet)
  - Nobody knows what is the necessary and/or sufficient conditions to harbor life on planets
  - If you are among those scientists who would like to throw away miracles out of our world, however,it is natural to ask

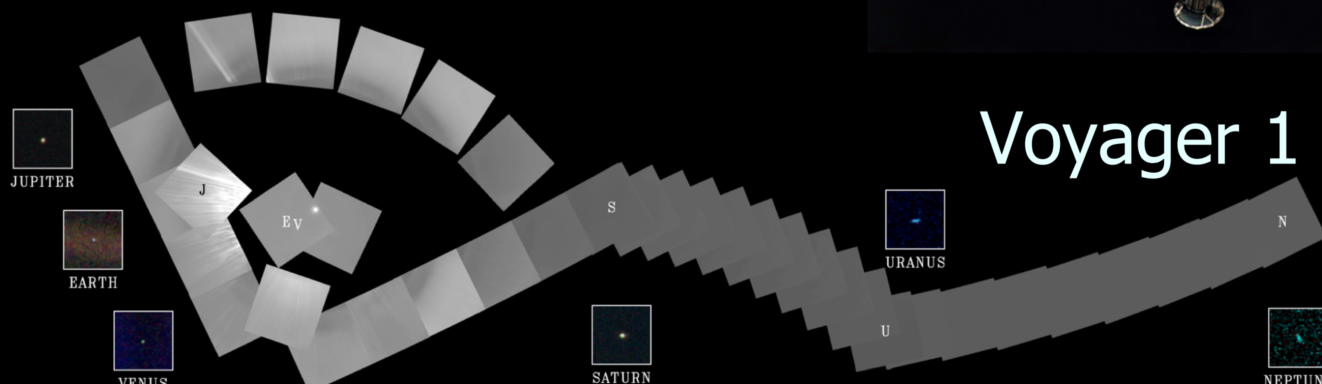
“Where are they ?” E.Fermi (1950)

a pale blue dot

A Pale Blue Dot



Voyager 1



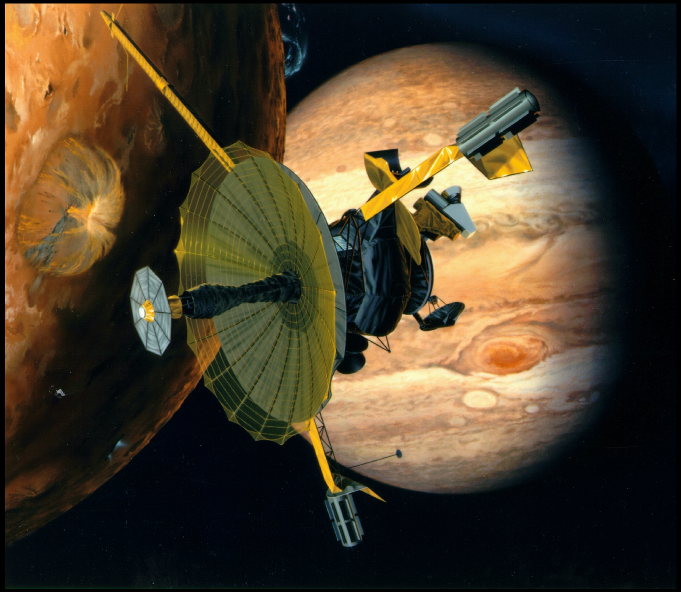
(Carl Sagan, February 4, 1990)

ed 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 ?*

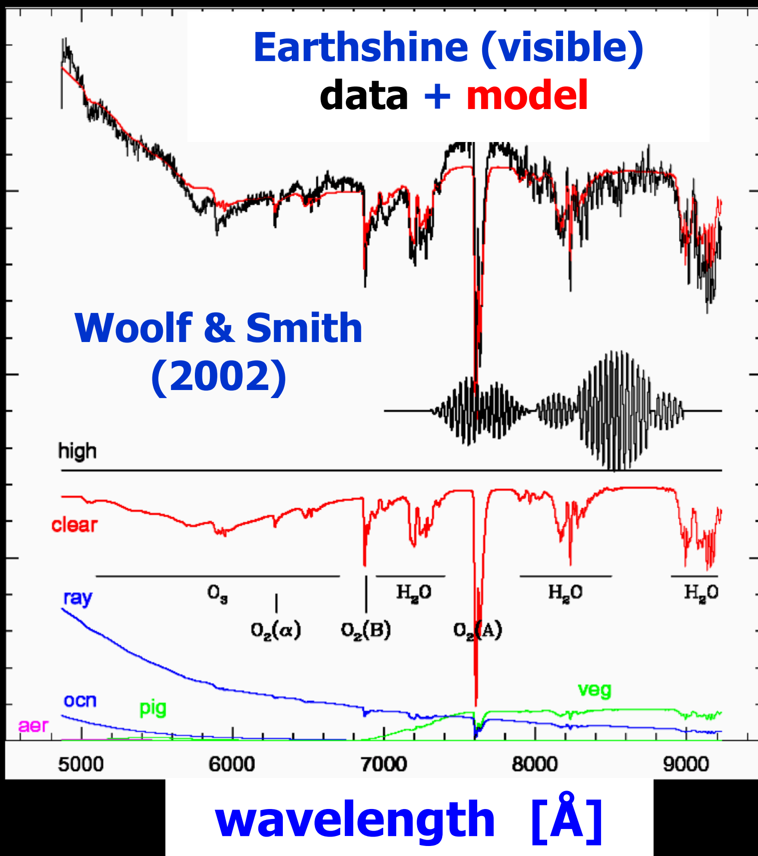
Search for signatures of life on "Earth" with Galileo mission (1990)

- 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

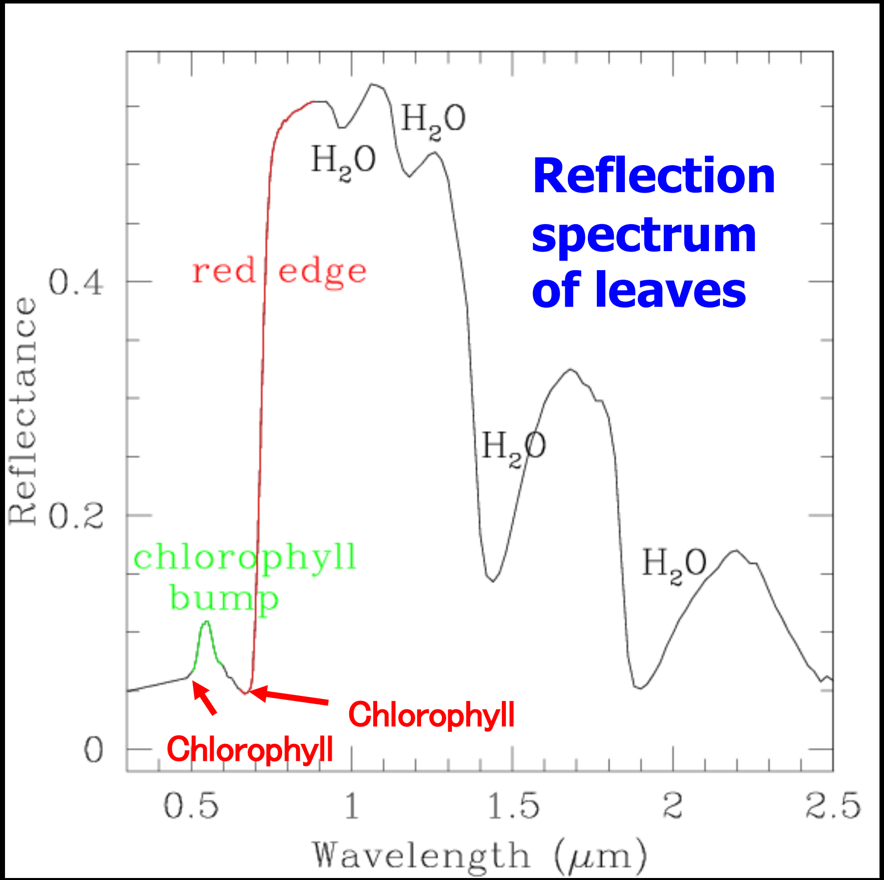


- O_2
  - A-band@0.76μm
  - B-band@0.69μm
- H_2O
  - 0.72, 0.82, 0.94μm
- O_3
  - Chappuis band@(0.5-0.7)μm
  - Hartley band@(0.2-0.3)μm

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

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)

- The Hubble law -> Hubble- Lemaitre -> Hubble-Lemaitre-Slipher ?

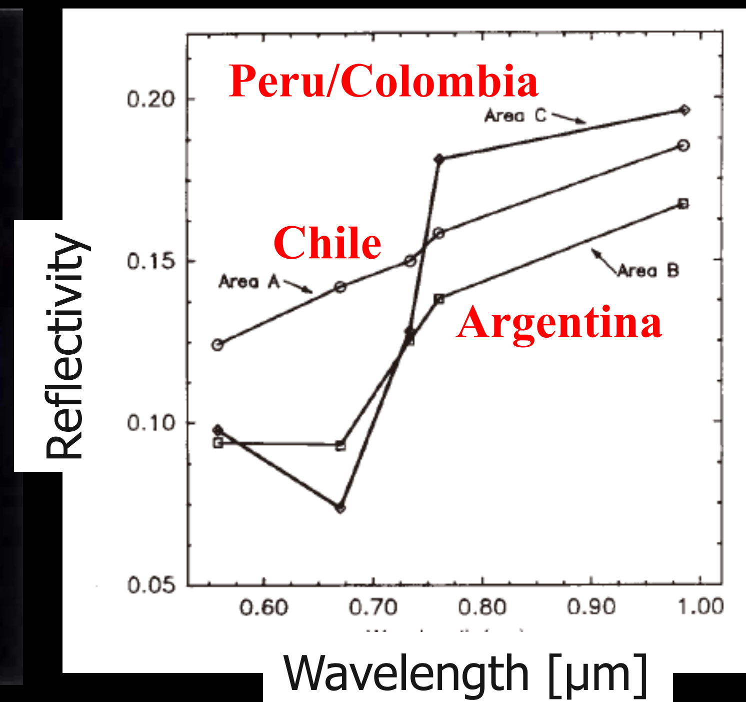
"Observations of Mars in 1924 made at the Lowell Observatory: II spectrum observations of Mars'' **PASP 36(1924)261**

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

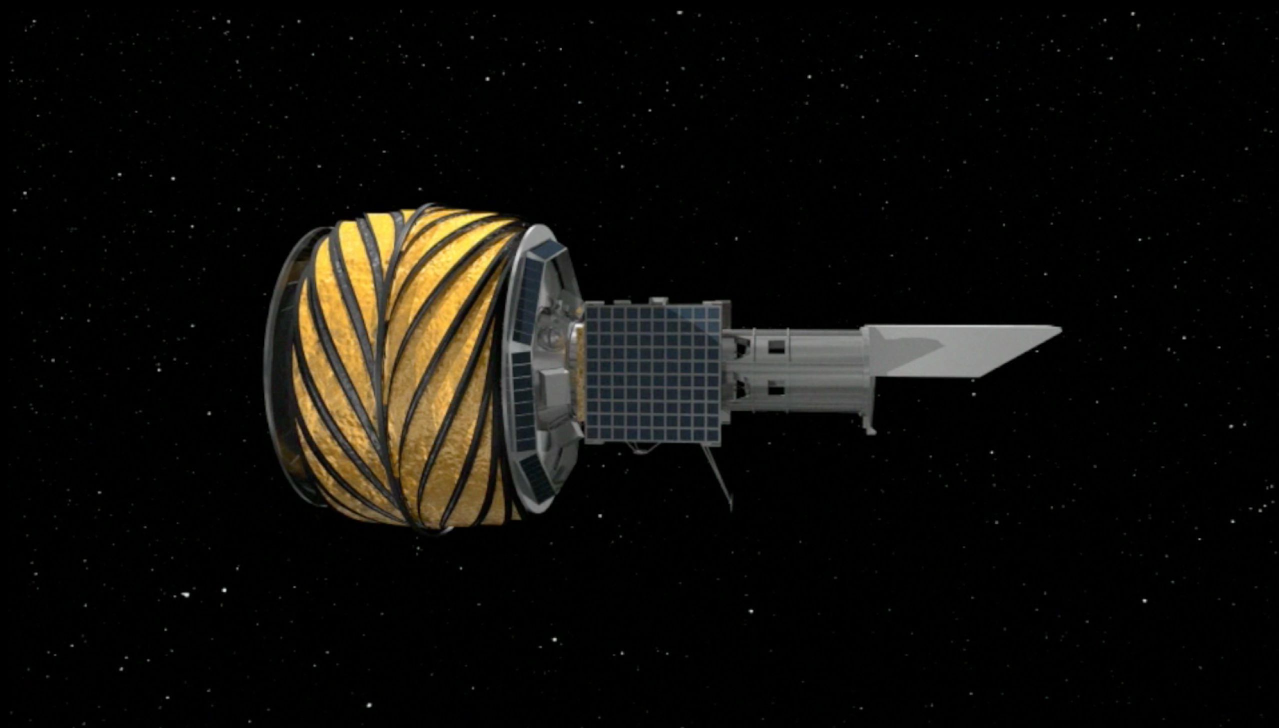
Red-edge of the vegetation on the earth detected by the Galileo mission



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

Simulated Earths observed at 10pc away

Starshade project: direct imaging of a second earth



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

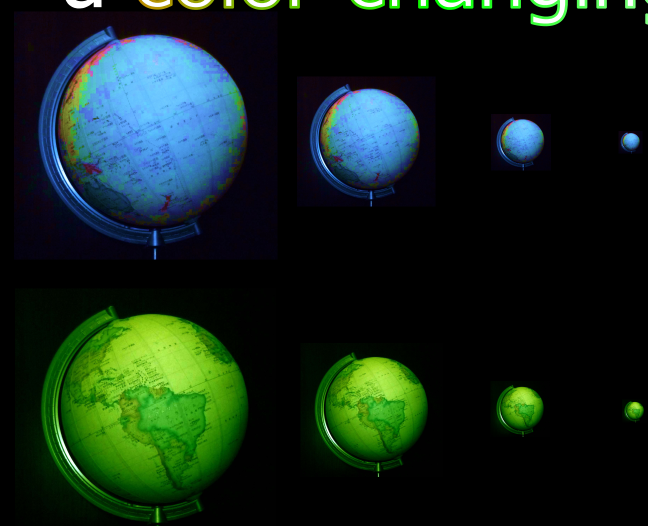
Colors of a Second Earth: estimating the fractional areas of ocean, land and vegetation of Earth-like exoplanets
ApJ. 715(2010)866, arXiv:0911.5621

Colors of a Second Earth. II: Effects of Clouds on Photometric Characterization of Earth-like Exoplanets
ApJ. 738(2011)184, arXiv:1102.3625

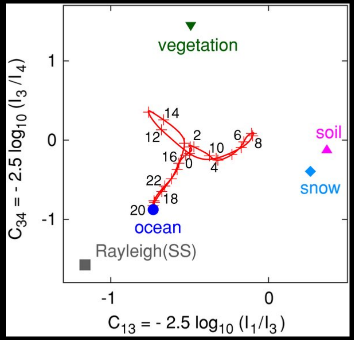
- Yuka Fujii, H.Kawahara, A.Taruya, Y.Suto (Dept. of Phys., Univ. of Tokyo), S.Fukuda, T.Nakajima (Center of climate system research, Univ. of Tokyo), Edwin Turner (Princeton Univ.)

Colors of a second earth

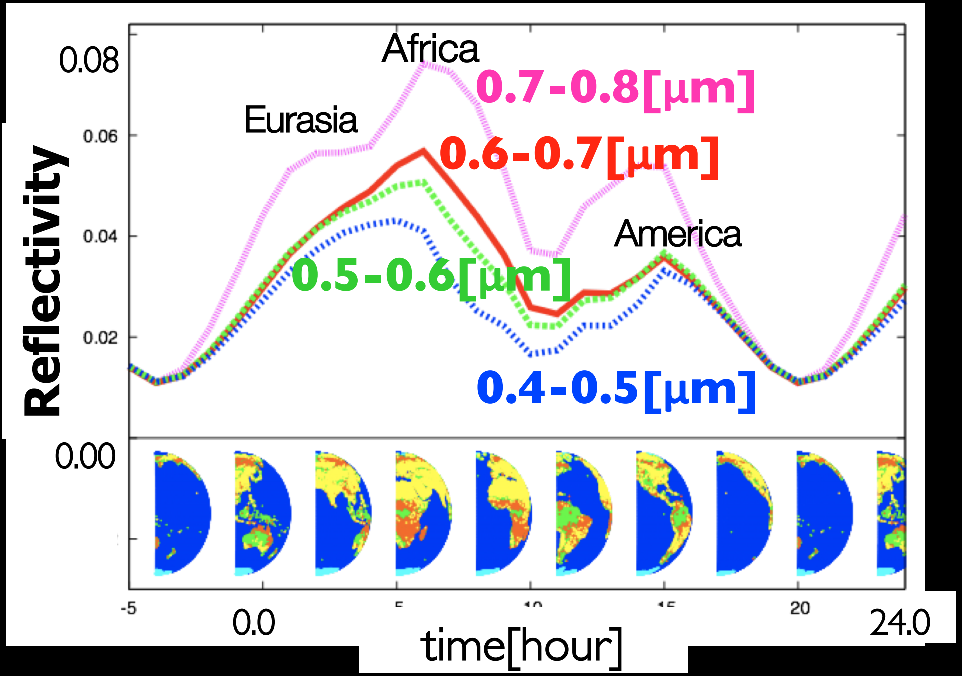
- Beyond a pale blue dot
  - Impossible to spatially resolve the surface of a second earth
  - Color should change due to the rotation
  - A second earth = a color-changing dot



A pale blue dot ? Not really !



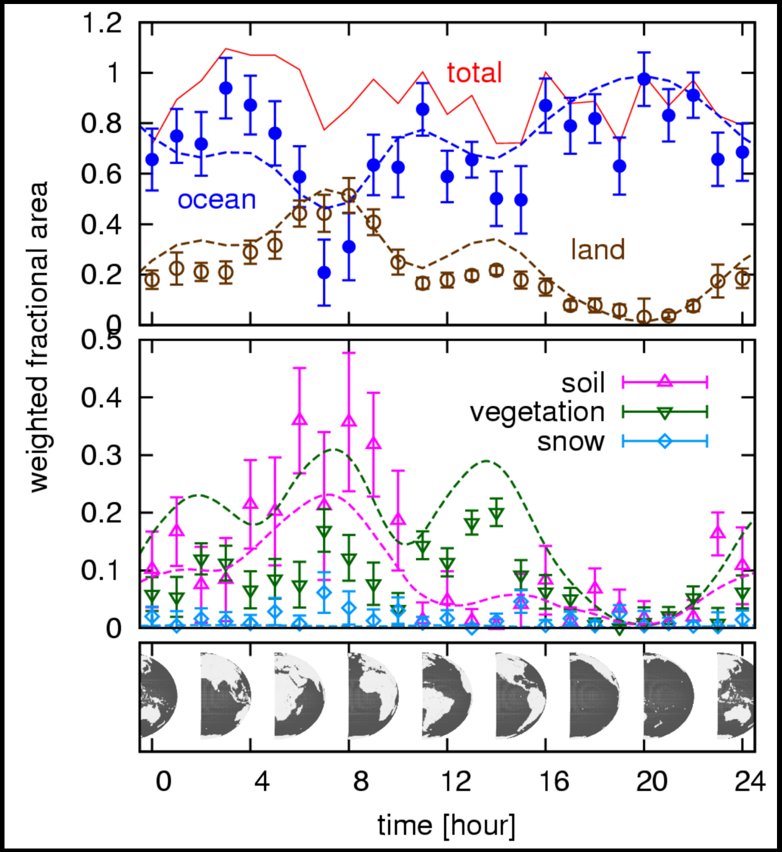
Simulated photometric light-curves of Earth



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

Fujii et al. (2010)

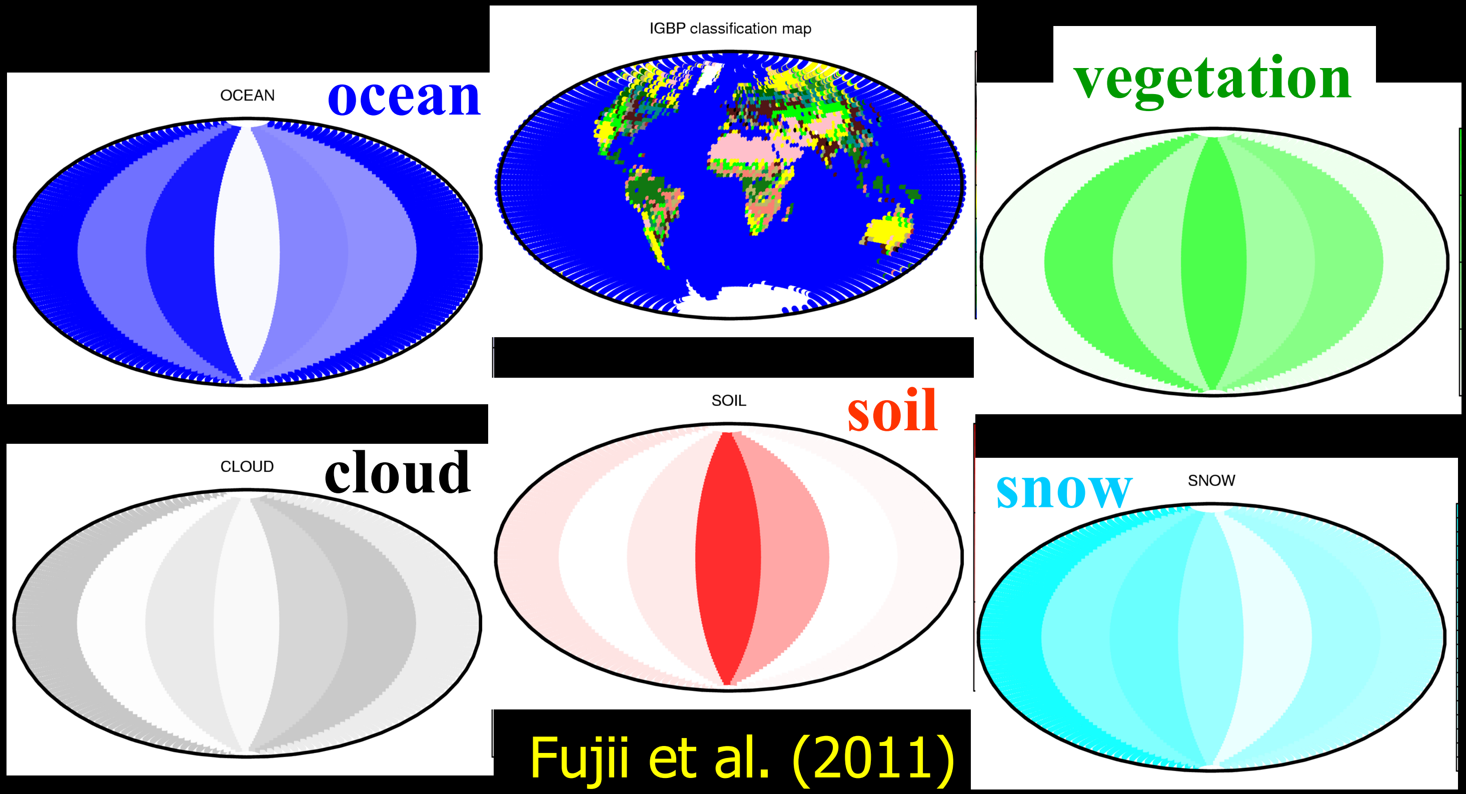
Estimating fractional areas of surface components from colors of a second earth



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

Fujii et al.（2010）

Surface latitude map reproduced from mock simulation and real satellite cloud data



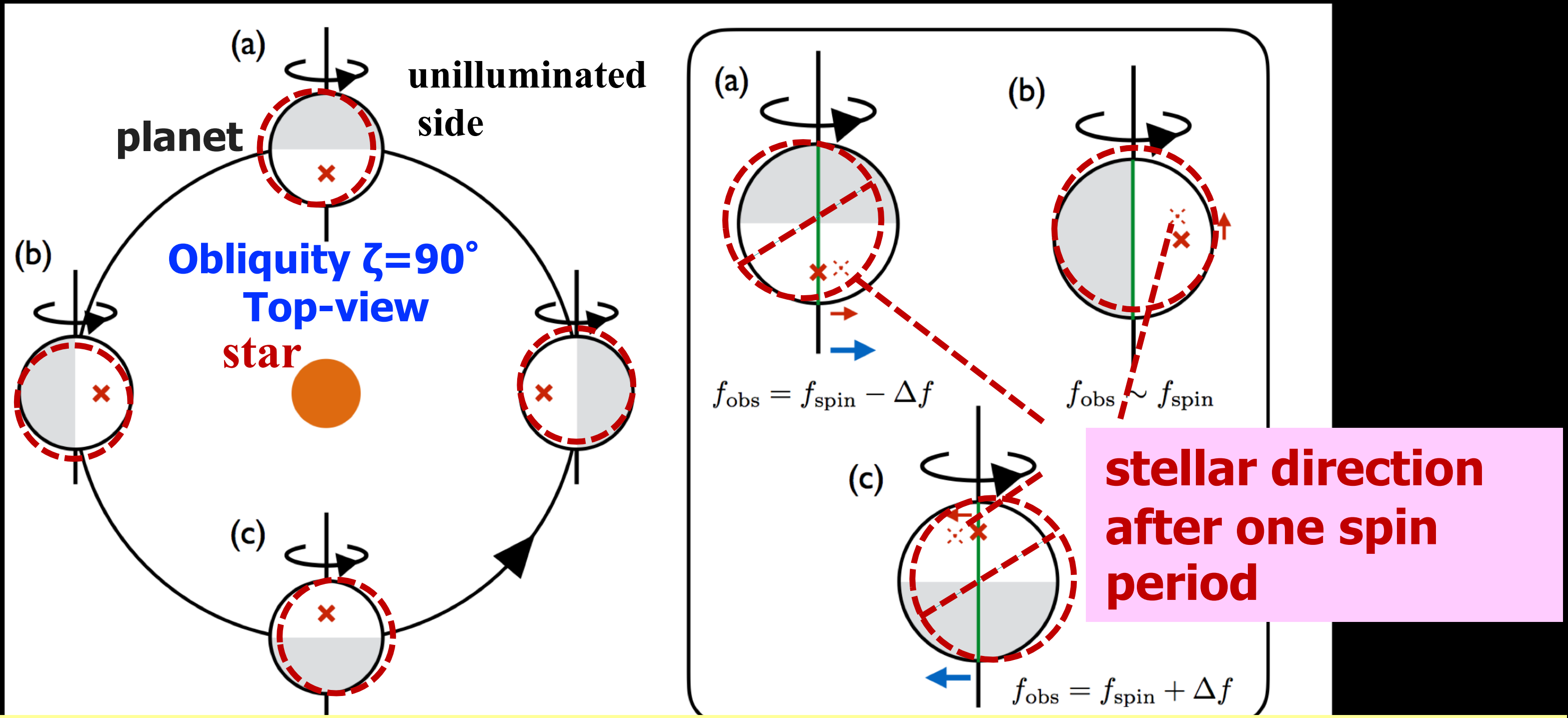
A twin earth at 10 pc away monitored for 2 weeks with 6m space telescope

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 + (2018) 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

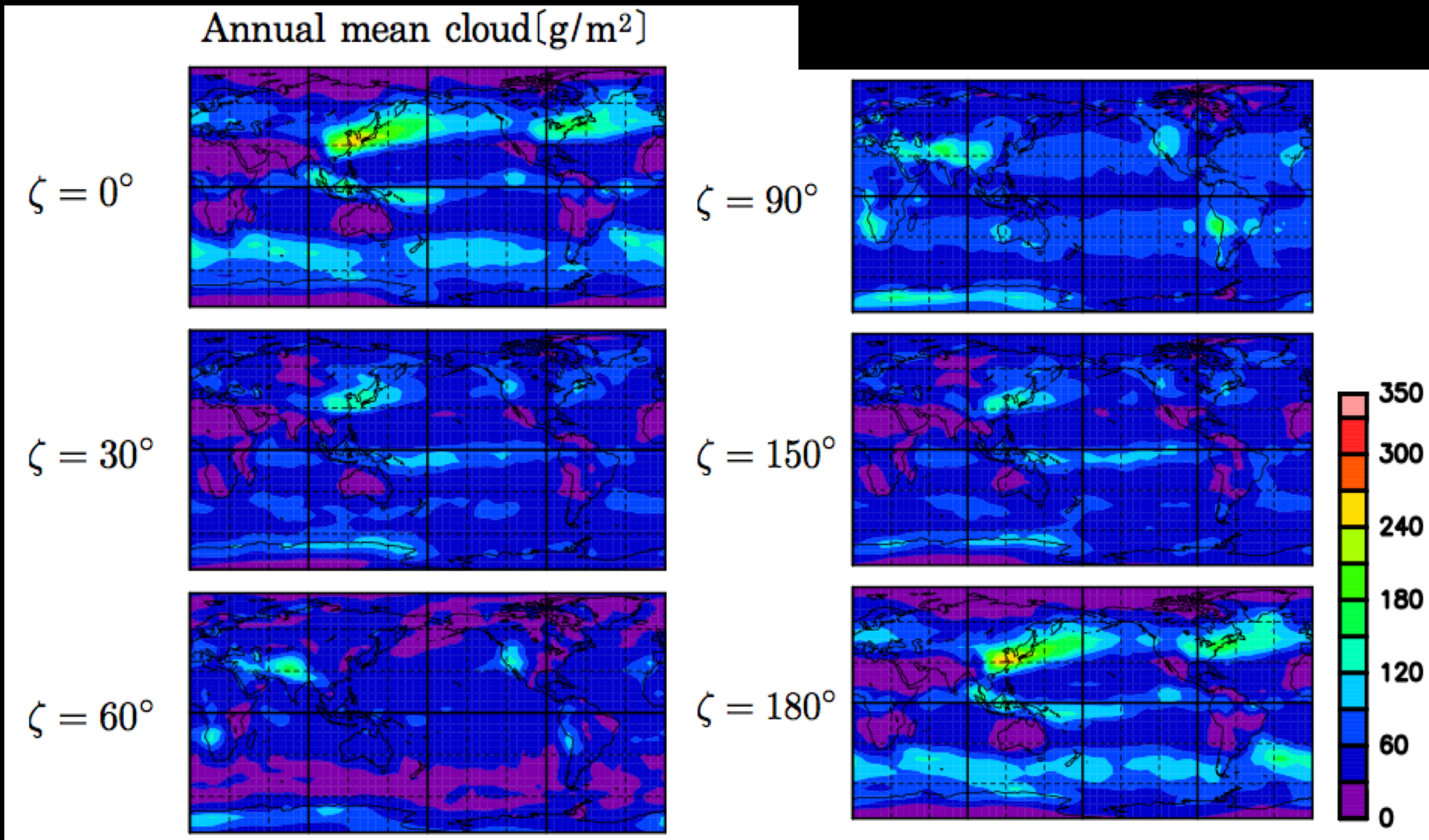
$$f_{\rm obs} = f_{\rm spin} + \epsilon_\zeta(\Theta) f_{\rm orb}$$

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

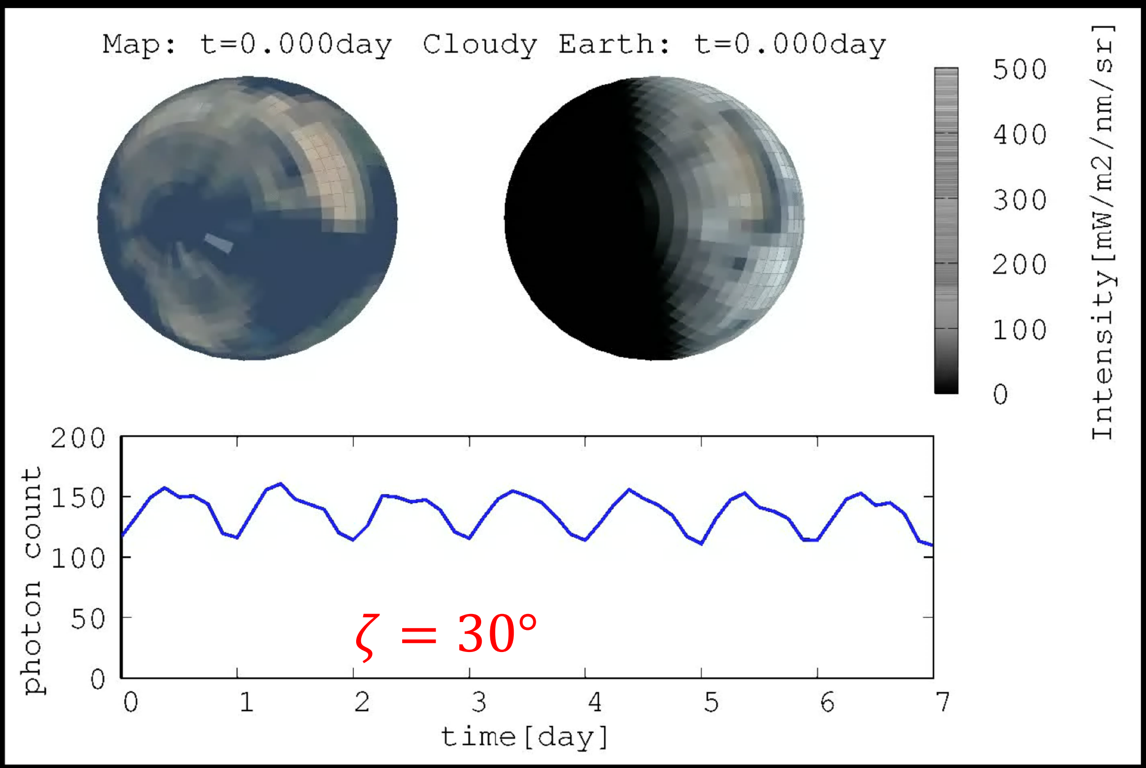
- GCM code for planetary climate simulation
  - DCPAM5 (Dennou-Club Planetary Atmospheric Model) http://www.gfd-dennou.org
  - (longitude, latitude, pressure altitude)=(32,64,26)
  - Surface data from Earth+Obliquity ζ [deg]=0, 30, 60, 90, 150, 180
- Radiation transfer code libRadtran to compute lightcurves
- Frequency modulation computed via pseudo-Wigner distribution

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

Annual mean cloud column density for different obliquities

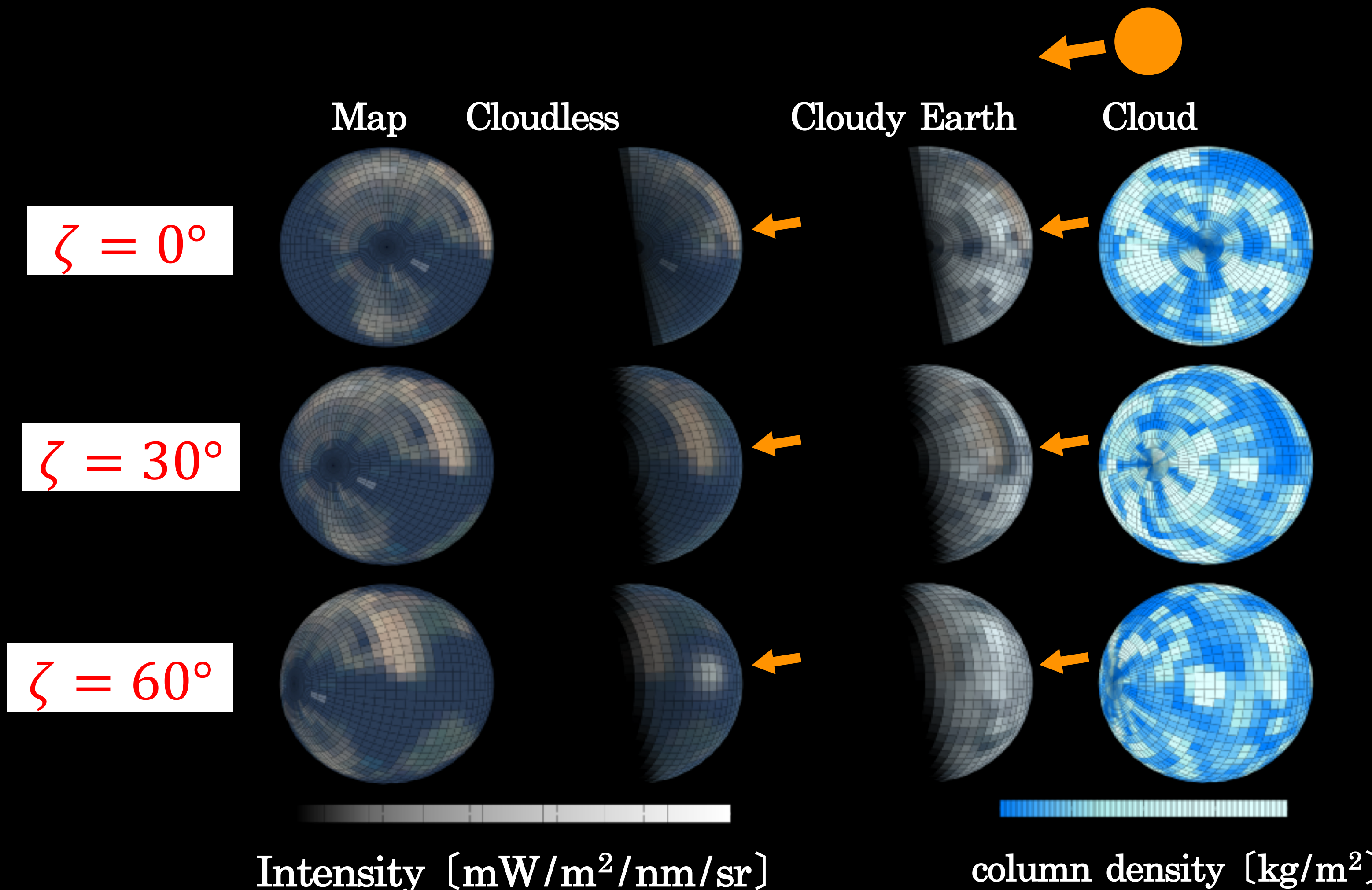


Photometric variation of oblique Earth simulated with GCM

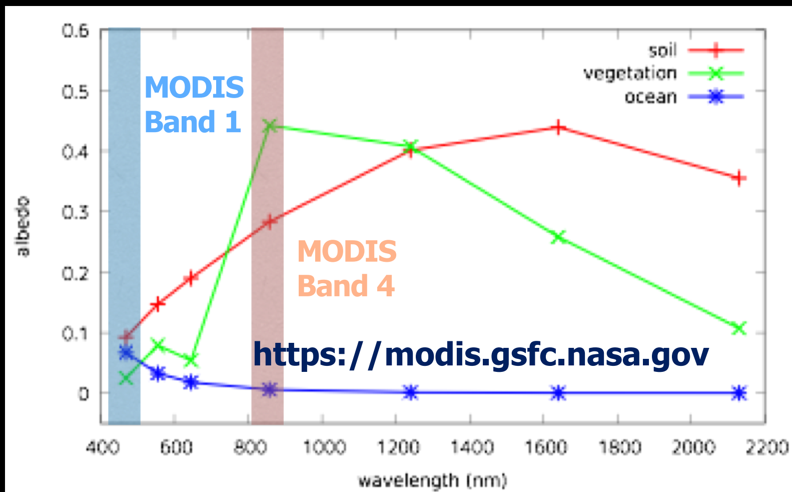


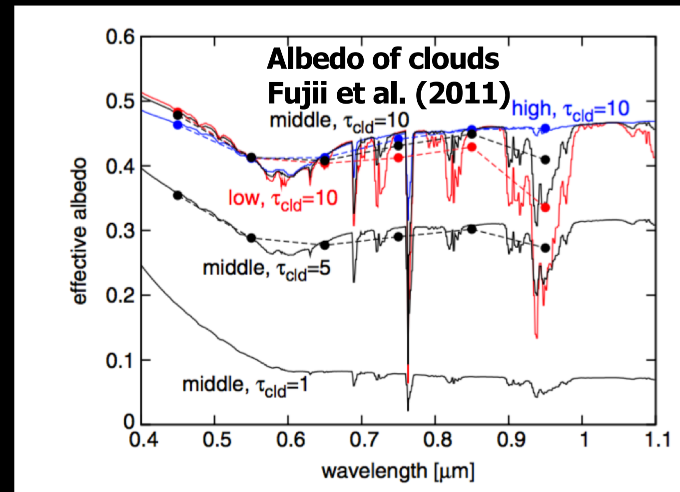
- Mock observation of a second Earth
- Determination of the planetary spin period and obliquity
- Identification of oceans, lands, and vegetation

Mock observations of oblique earths



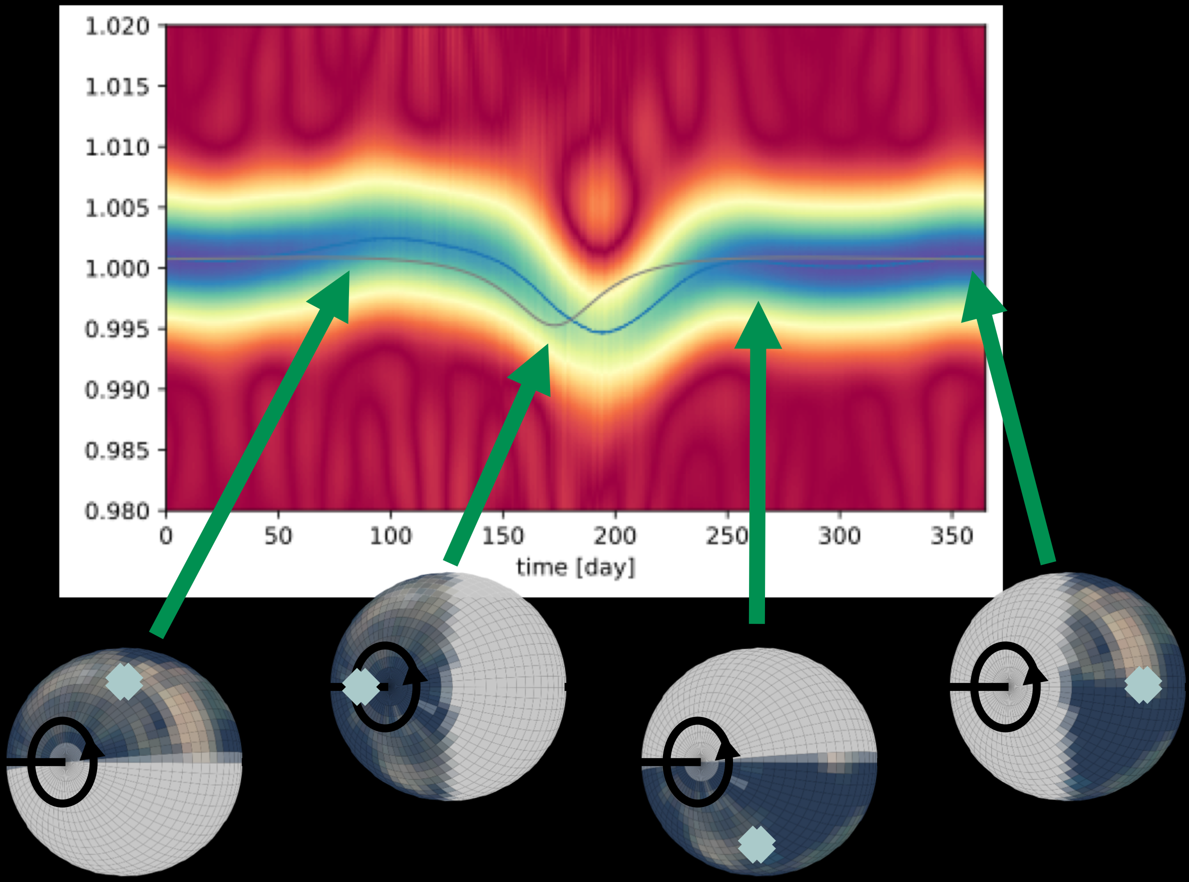
Idealized mock observations of the oblique Earth



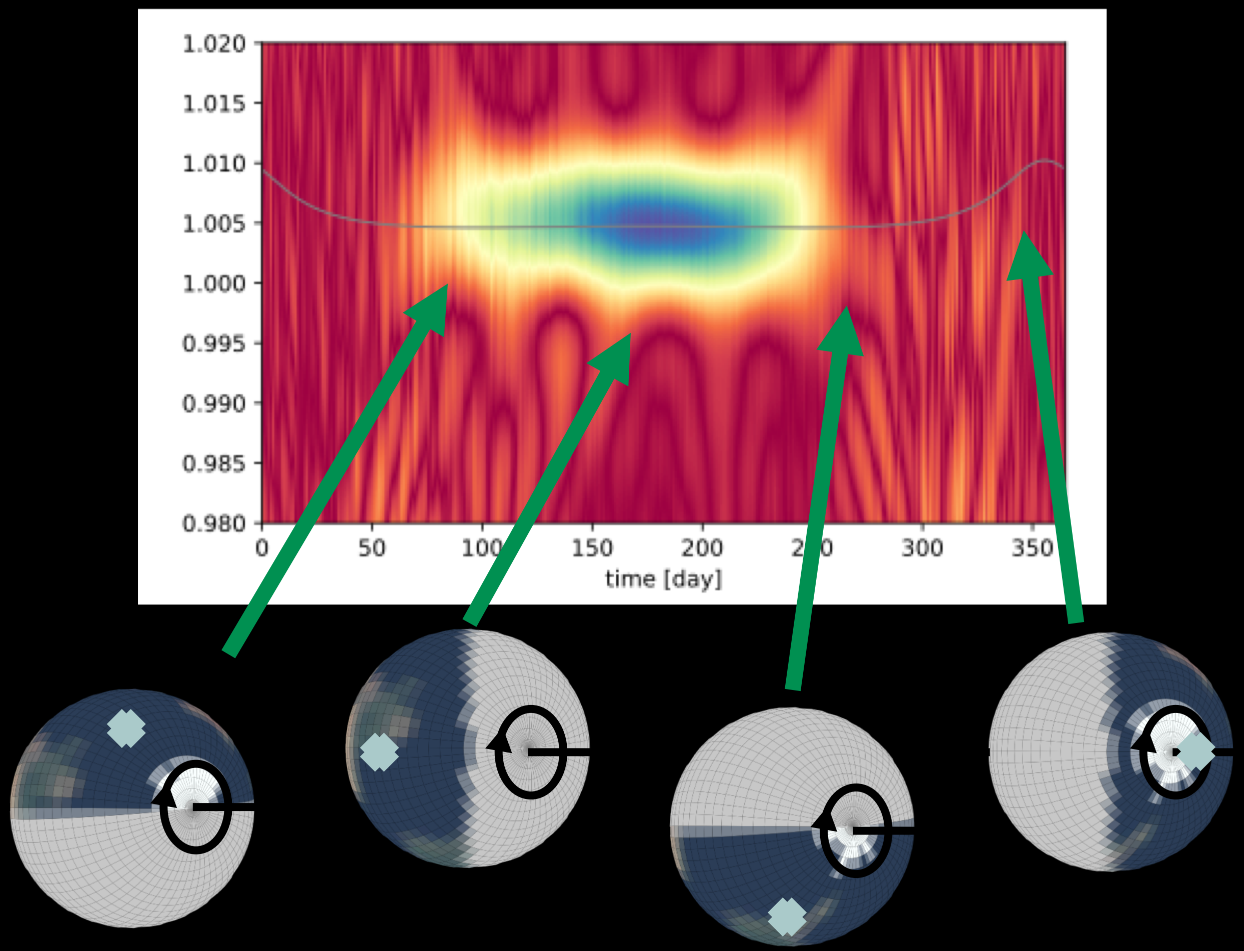


- Stellar flux assumed to be completely blocked
- *Sun-Earth system located at 10 pc away+20m space telescope*
- Photon Poisson errors alone
- MODIS Band1@0.45μm and Band4@0.85μm
- Band1(t) - Band4(t) to remove time-dependent cloud signals

Frequency modulation for ζ=30˚

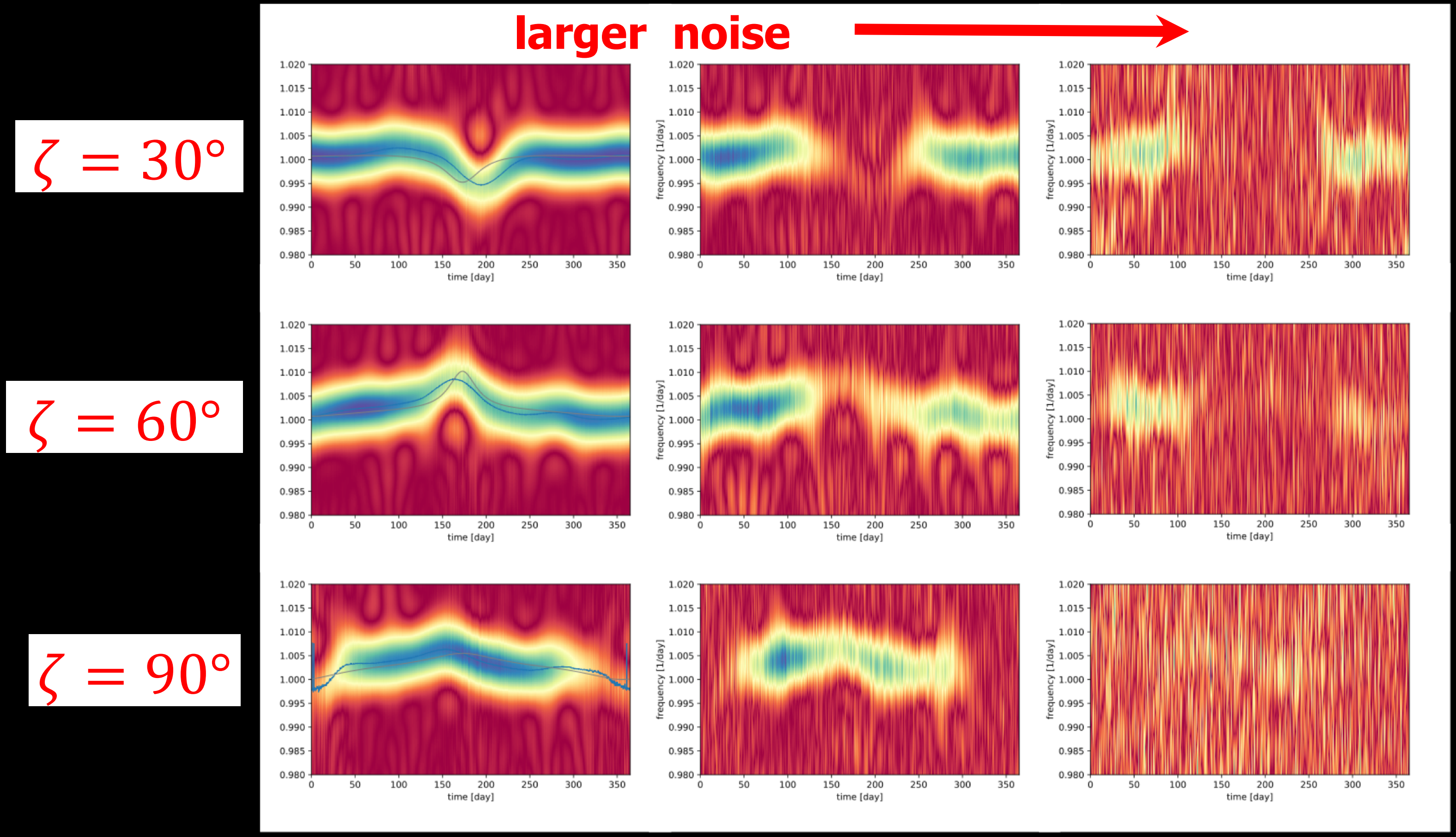


Frequency modulation for ζ=150˚



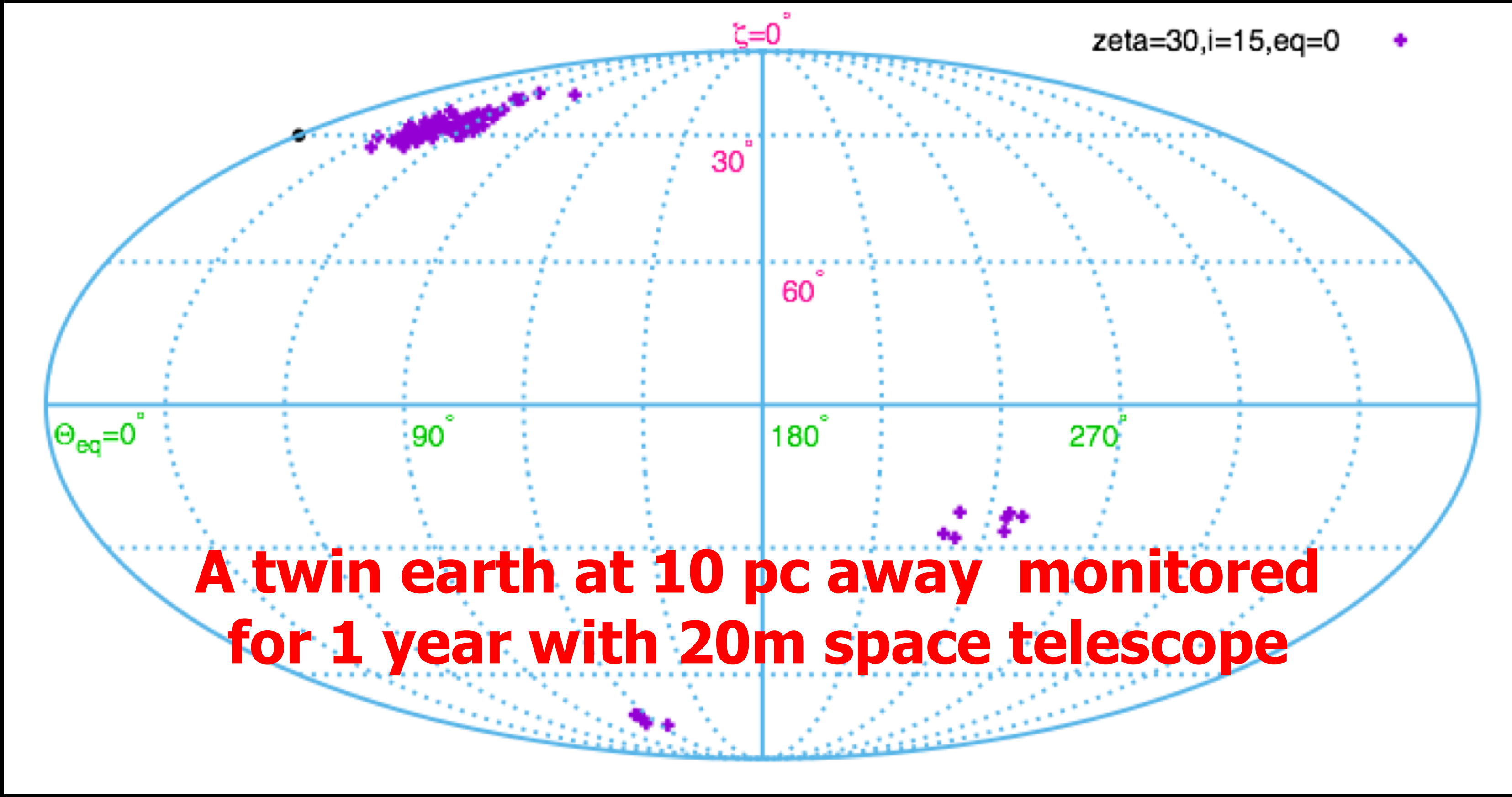
Dependence on obliquity and signal-to-noise ratios

Gray curves: simple model predictions   Blue curves: mean from data



Preliminary attempt of the parameter extraction

input $(i, \zeta, \Theta_{eq}) = (15°, 30°, 0°)$



A twin earth at 10 pc away monitored for 1 year with 20m space telescope

Summary: *unveiling a pale blue dot*

- Detection of diurnal color change of another earth is challenging, but reveals the presence of ocean, land, cloud, and/or even vegetation
- Its spin rate and obliquity 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