Colors of a Second Earth:

a Future Path Towards Astrobiology From Space

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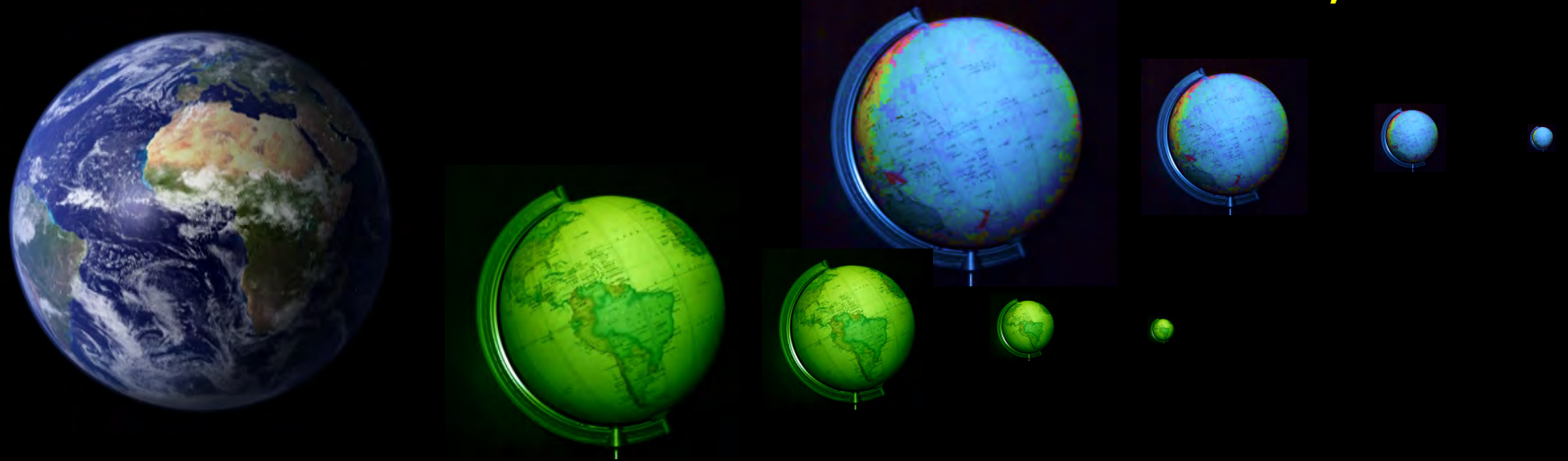
2016 Inter-Academy Seoul Science Forum
17:00-17:30 November 3 @ The Plaza Hotel, Seoul

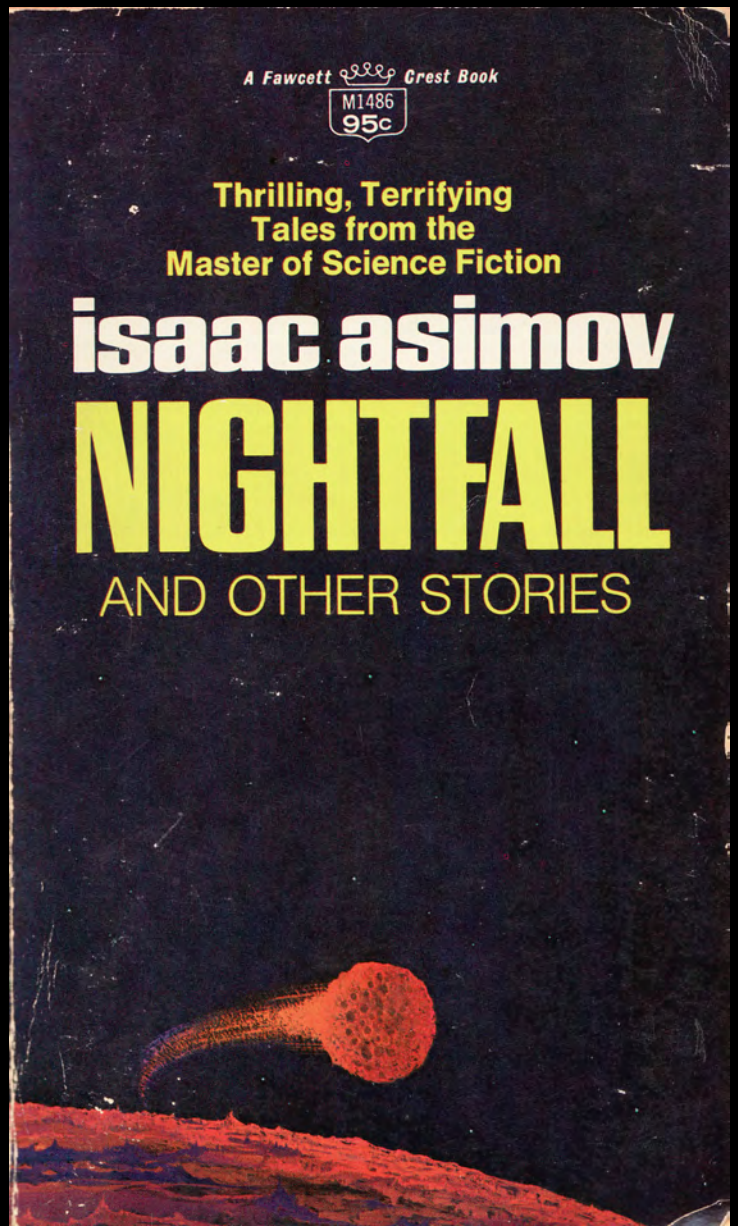


Issac Asimov (1941): Nightfall

(illustration: Alisa Haba)

- Planet "Lagash" has no "night" except the total eclipse due to an inner planet every 2049 years
- People understood the true world for the first time

Nightfall: We didn't know anything

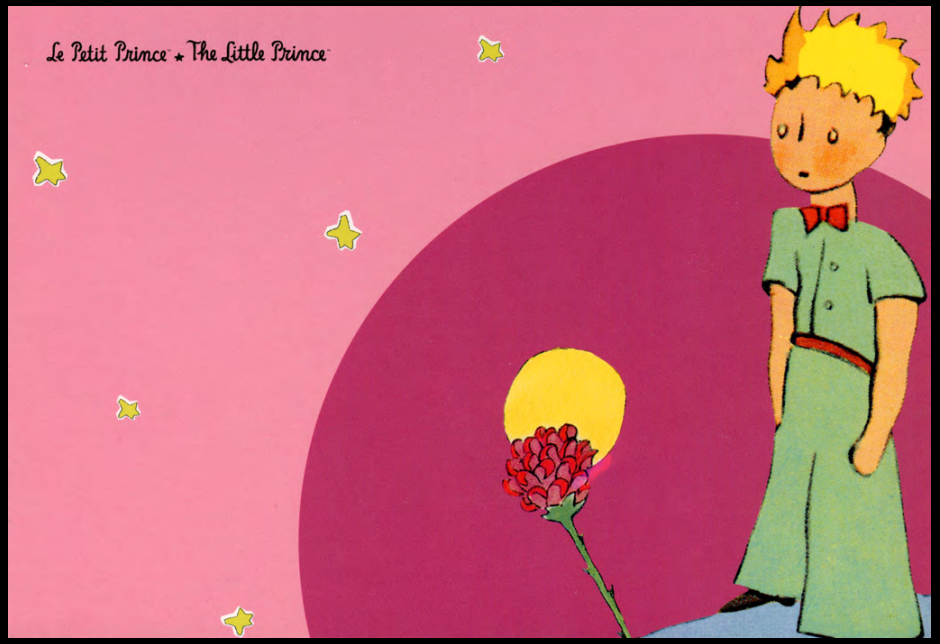


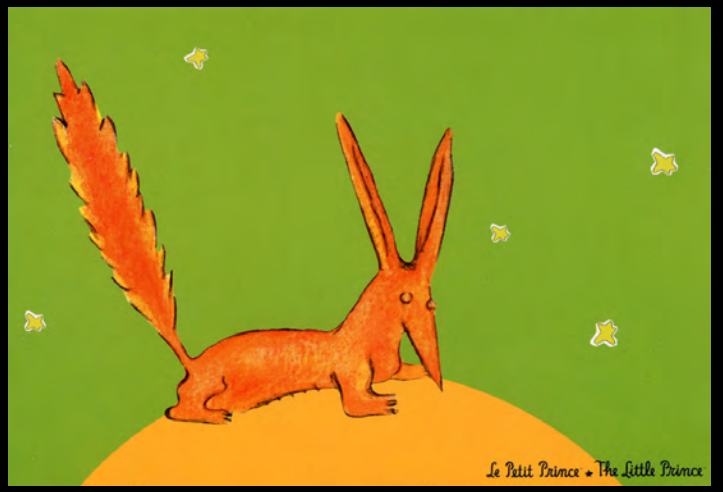
- "Light !" he screamed. Aton, somewhere, was crying, whimpering horribly like a terribly frightened child.
  "Stars -- all the Stars -- we didn't know at all. We didn't know anything."

The essential is invisible for the eyes

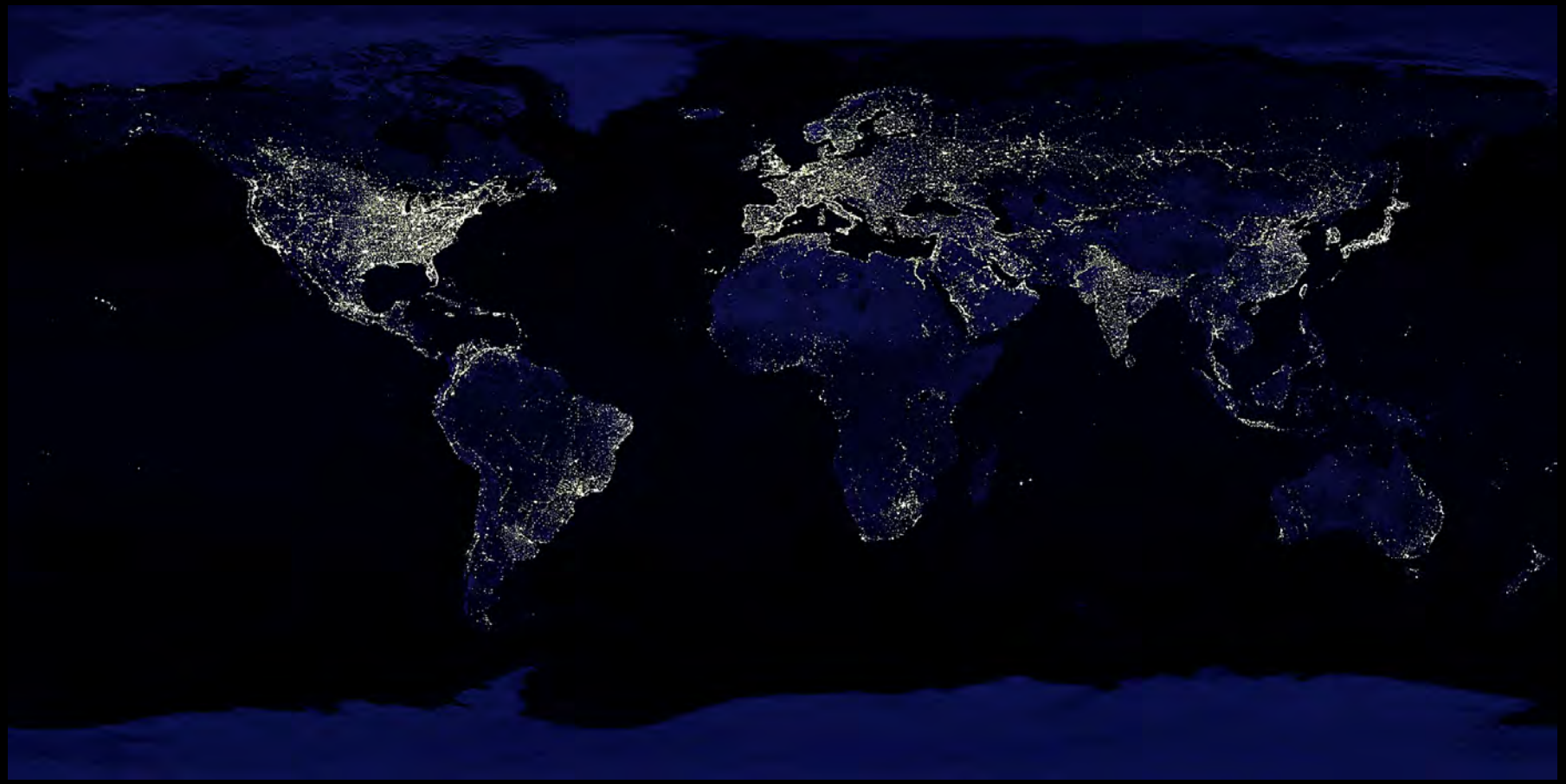
Adieu, dit le renard. Voici mon secret. Il est très simple : on ne voit bien qu'avec le coeur. L'essentiel est invisible pour les yeux.

Le Petit Prince:
Antoine de Saint Exupéry





Don’t assume that everything in the world is bright

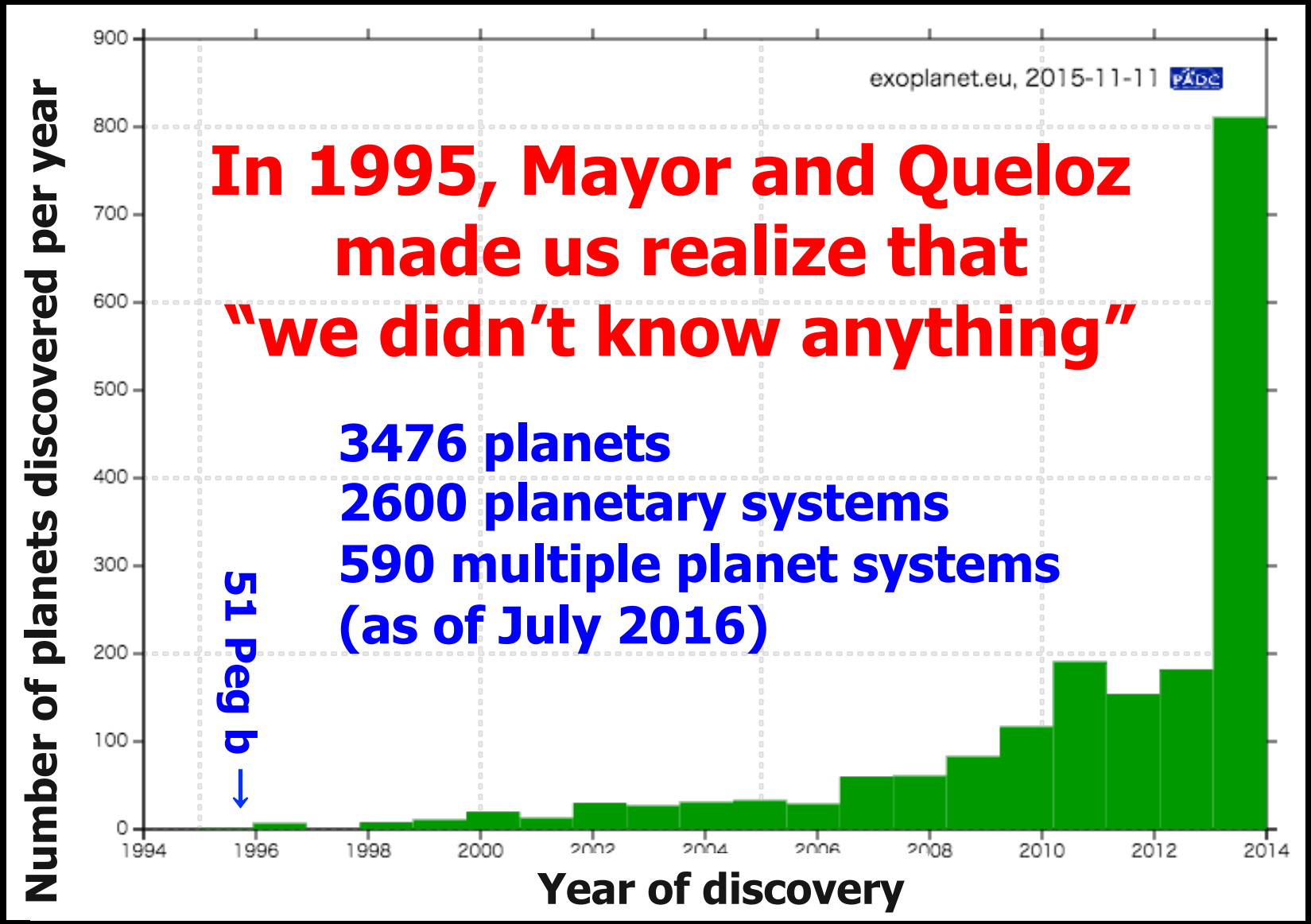


http://earthobservatory.nasa.gov/Features/NightLights/page3.php

L'essentiel est invisible pour les yeux

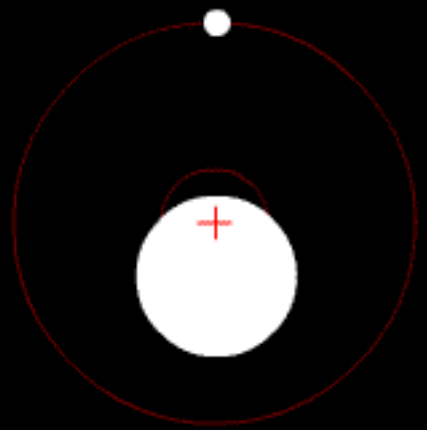
Even more important and surprising things may be hidden somewhere in dark regions of the universe

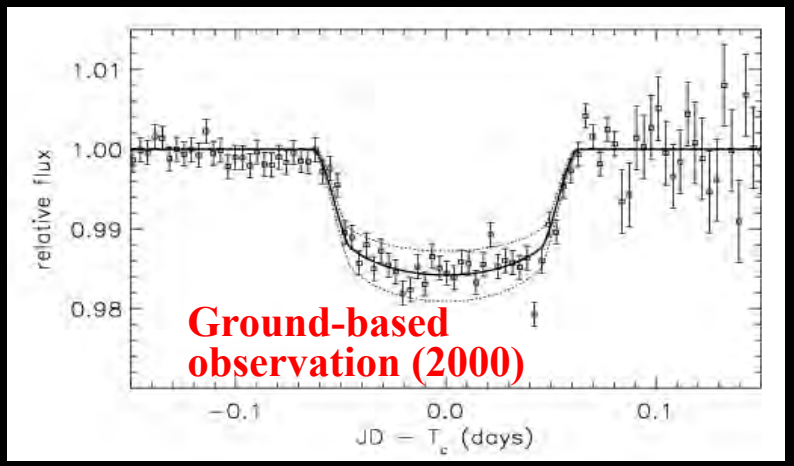
Yes, our universe is full of planets



http://exoplanet.eu/

How to find planets ?





- Radial velocity
  - Periodic modulation of the velocity of star due to the presence of planets
- Transit
  - Periodic dimming of the stellar light due to the occultation of planets in front of the star
- Direct imaging
  - Separate the light from the star and planets

Kepler mission (March 6, 2009 launch)

Photometric survey of transiting planets

Searching for terrestrial/habitable planets

http://kepler.nasa.gov/

Are we alone ?

a Pale Blue Dot ?
or pale blue dots ?

Science with exoplanets

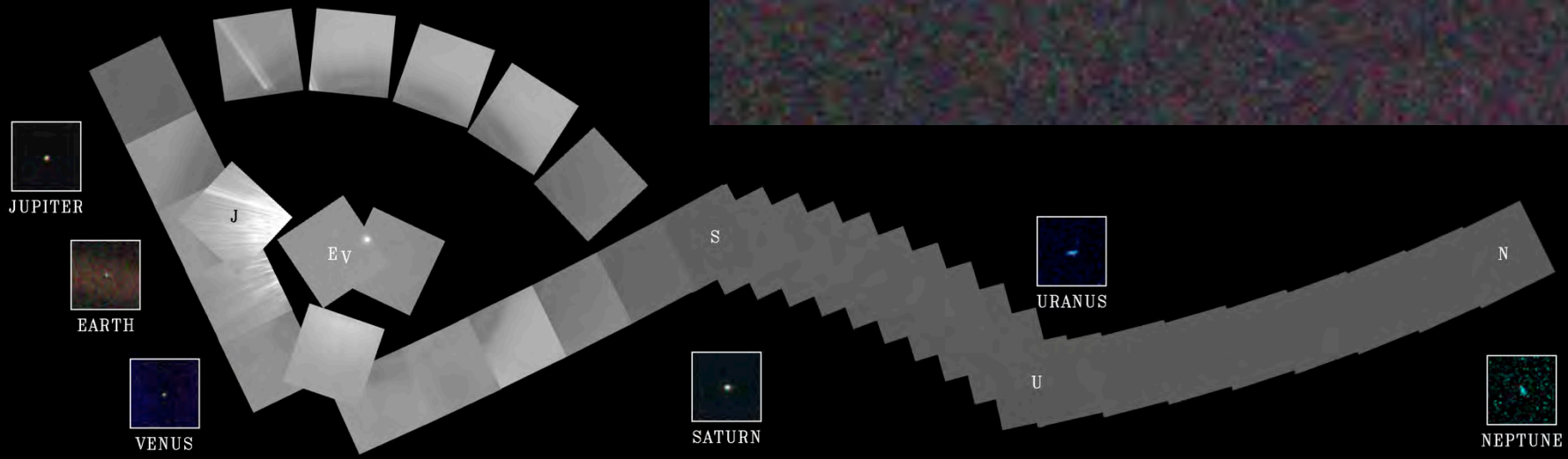
- the ***final*** question: ***Are we alone ?***
  - origin of the earth
  - origin of the Solar System
  - ***habitable*** planets ⇒ origin of life
  - signature of extra-terrestrial life ?

    ⇒ extra-terrestrial intelligence ?

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

Earth imaged by Voyager 1 (February 4, 1990)

- Image from 40 AU away
- A Pale Blue Dot (Carl Segan)



Earth and Moon from Saturn (2013)

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

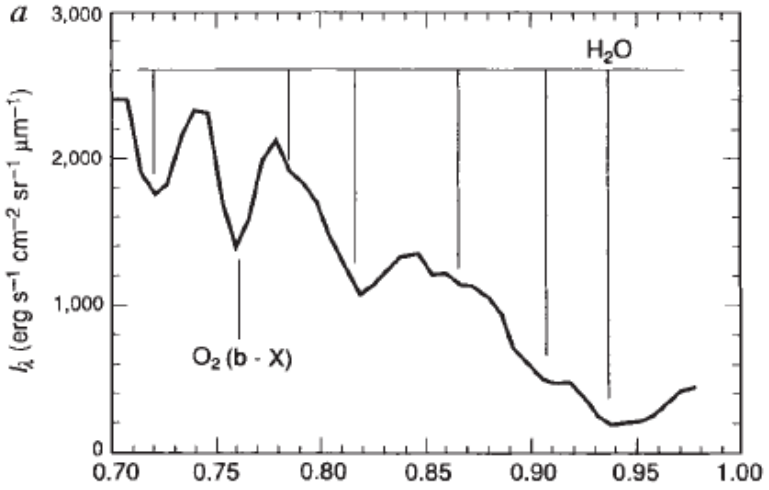
Can we detect signatures of life on our Earth ?

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

Sagan et al. (1993): spectrum of atmosphere



Strong O_2 absorption @A-band(0.76μm)

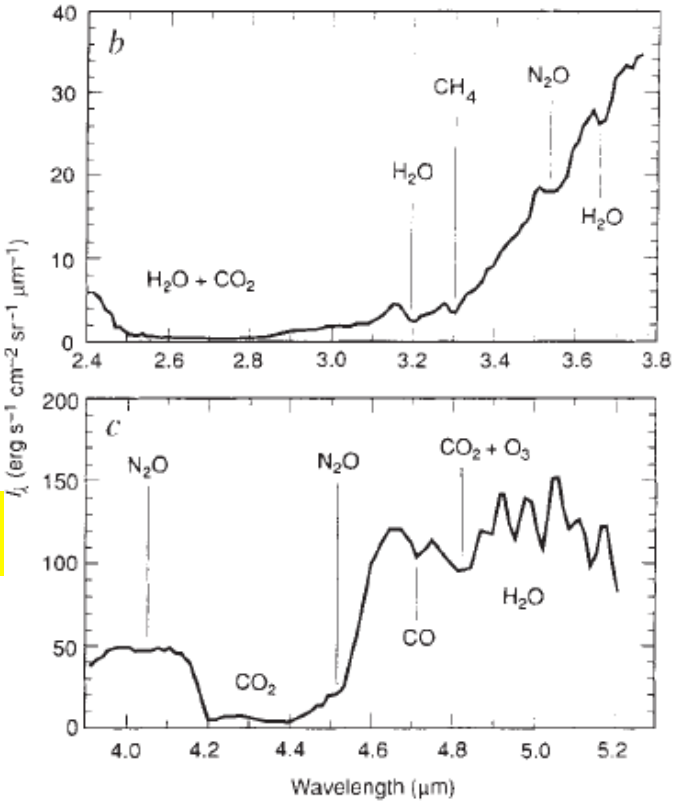
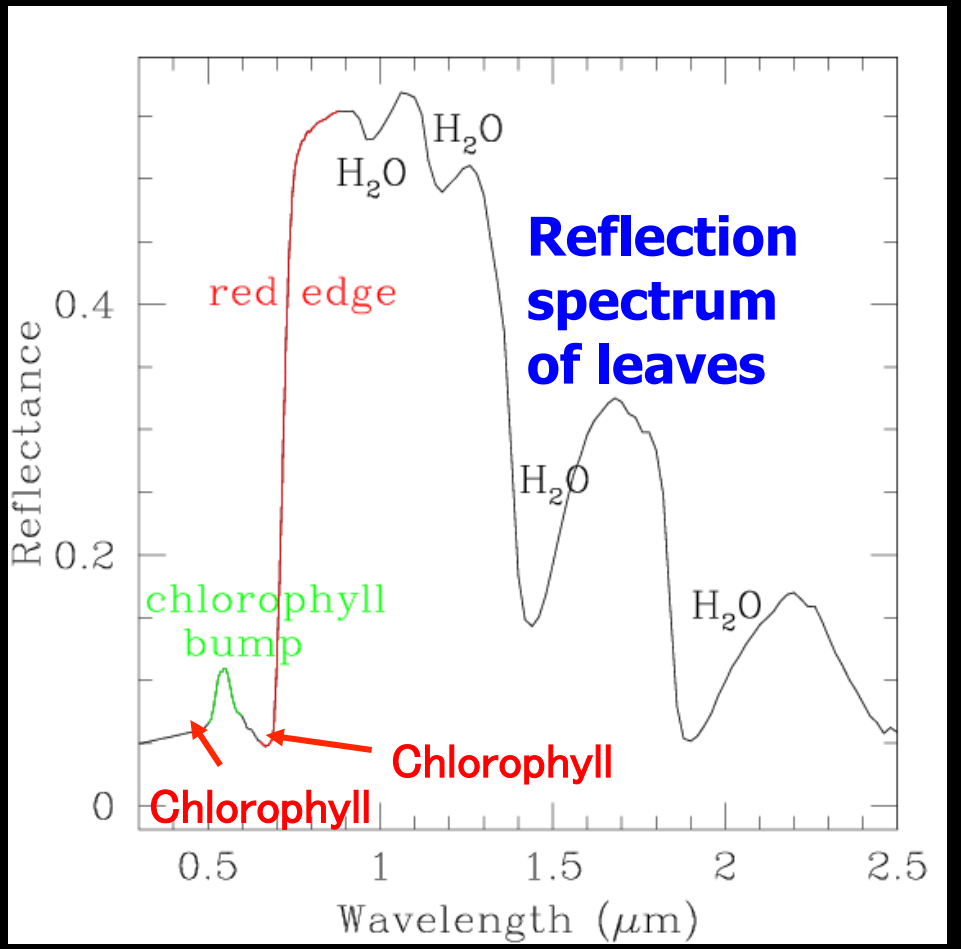


FIG. 1 *a*, Galileo long-wavelength-visible and near-infrared spectra of the Earth over a relatively cloud-free region of the Pacific Ocean, north of Borneo. The incidence and emission angles are 77° and 57° respectively. The ($b'\Sigma_g^+$—$X^3\Sigma_g^-$) 0–0 band of O_2 at 0.76 μm is evident, along 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 υ_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 υ_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 biosignature in *exoplanets*

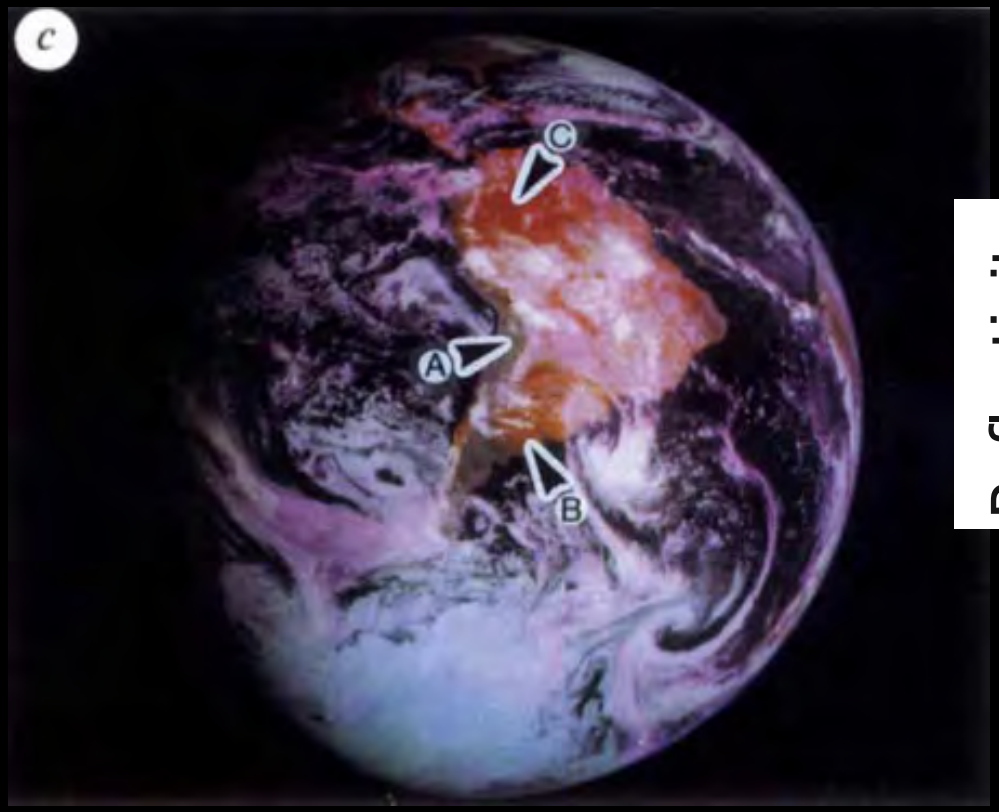
- Red-edge
  - Significant increase of reflectivity of leaves on Earth (terrestrial planets) for λ>7000Å
- Widely used in the remote-sensing of our Earth

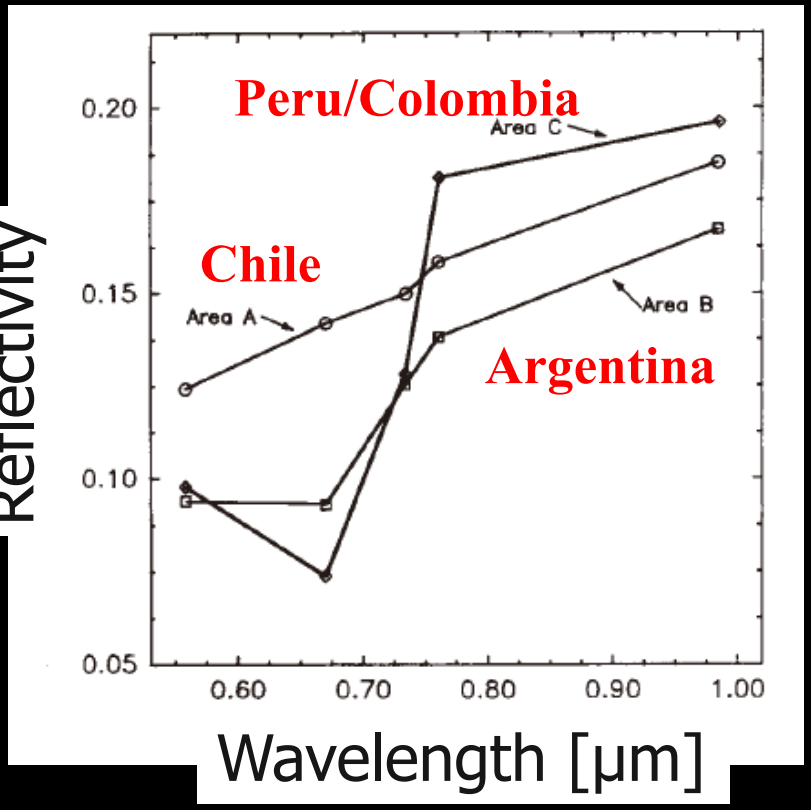


Seager, Ford & Turner astro-ph/0210277

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

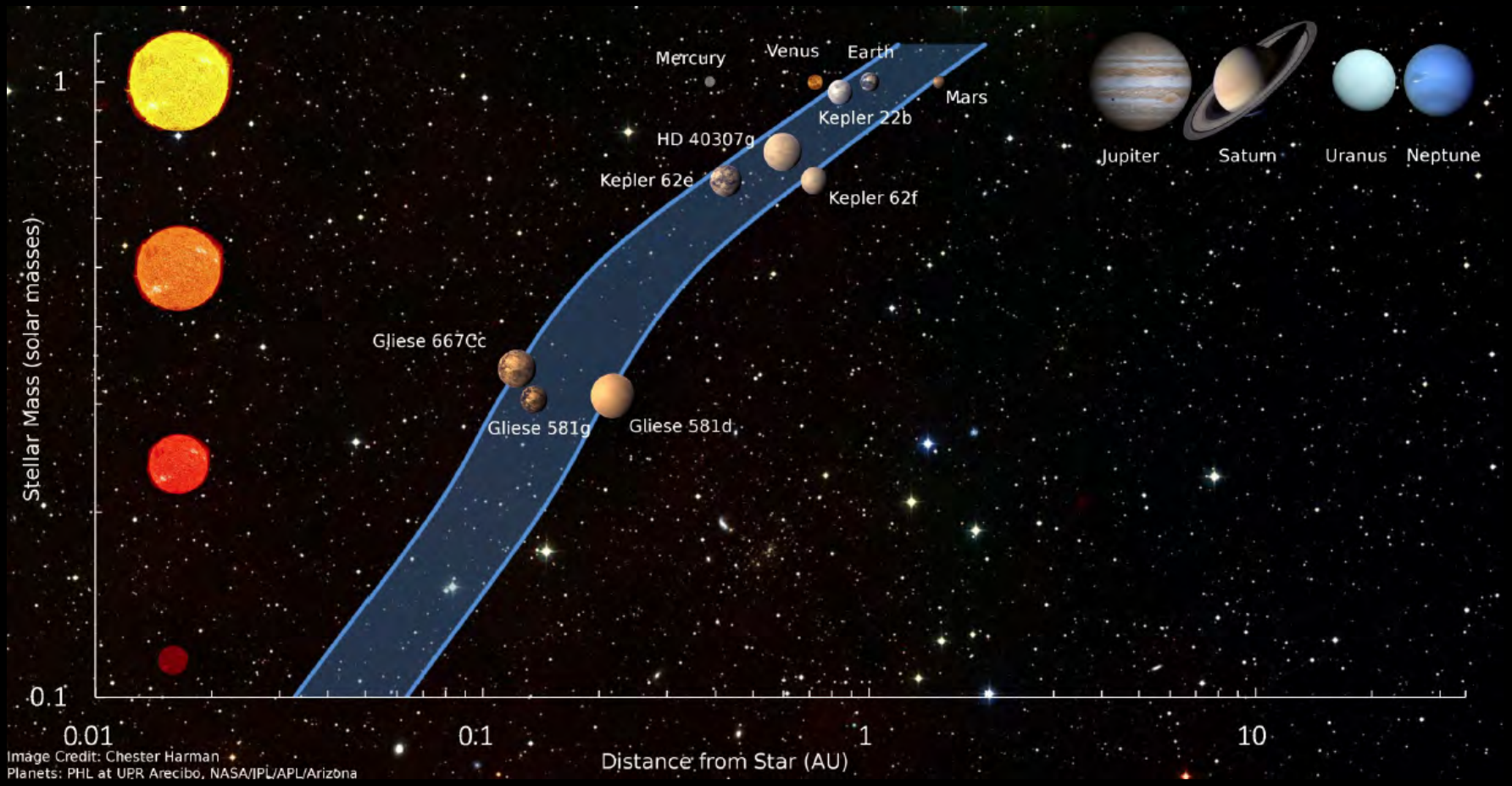
Red-edge of the vegetation on the earth detected by the Galileo mission





Simulated Earth observed at 10pc away

Habitable zone around host stars



Kasting, Kopparapu, Raminez & Harman: arXiv:1312.1328

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

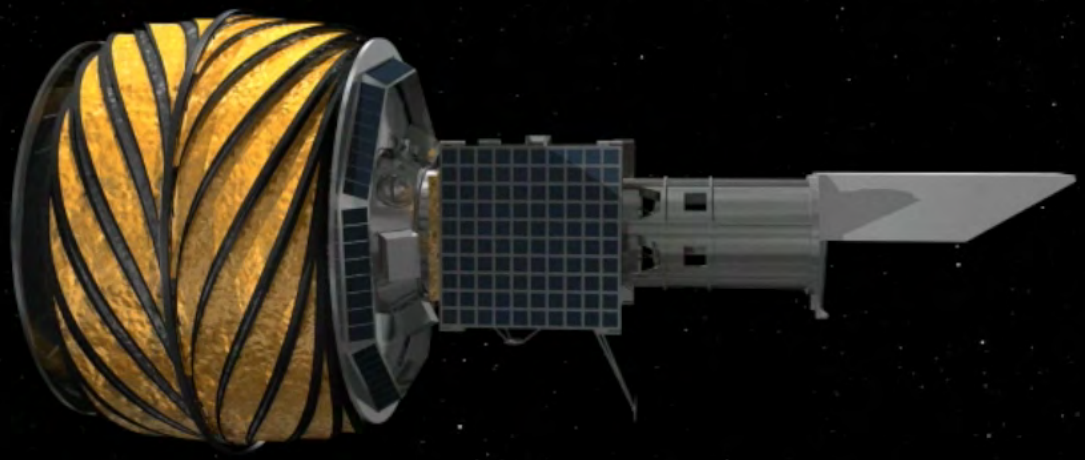
- Planets with (1-2) Earth radius around GKstars
  - Kepler Transit planets corrected for selection effect
  - 11±4 % (1-4 times the Solar flux on the earth)
  - 5.7+2.2-1.7 % (orbital period of 200-400days)

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)

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

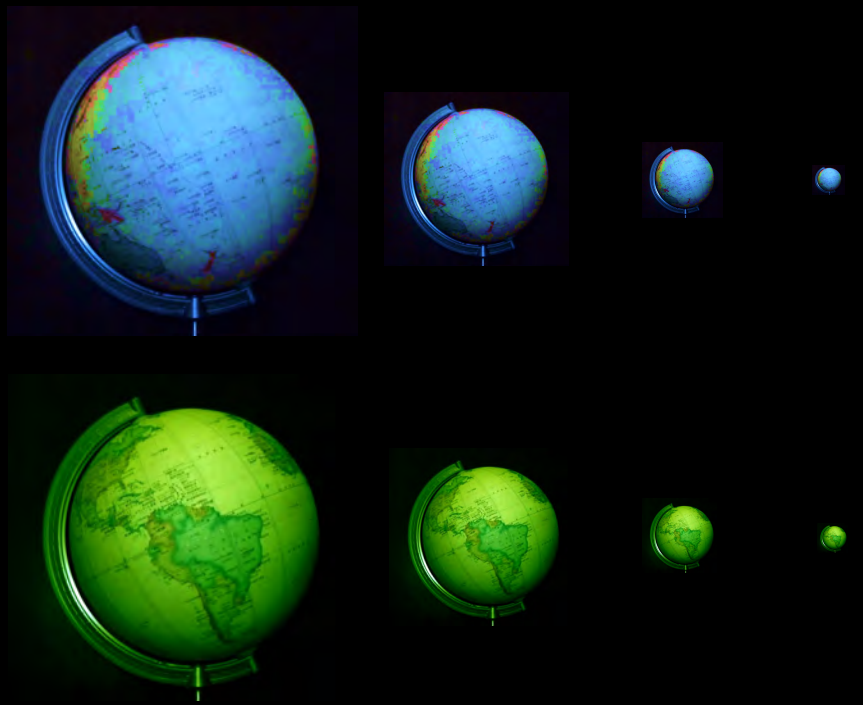
ApJ. 738(2011)184, arXiv:1102.3625

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

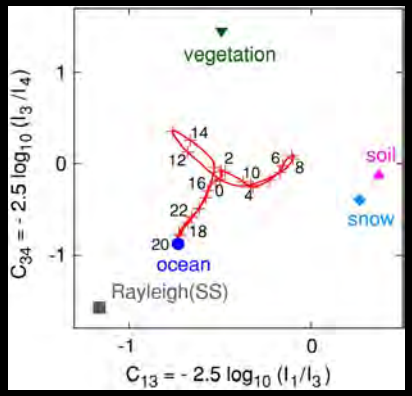
http://www.space.com/scienceastronomy/color-changing-planets-alien-life-100513.html

Colors of a second earth

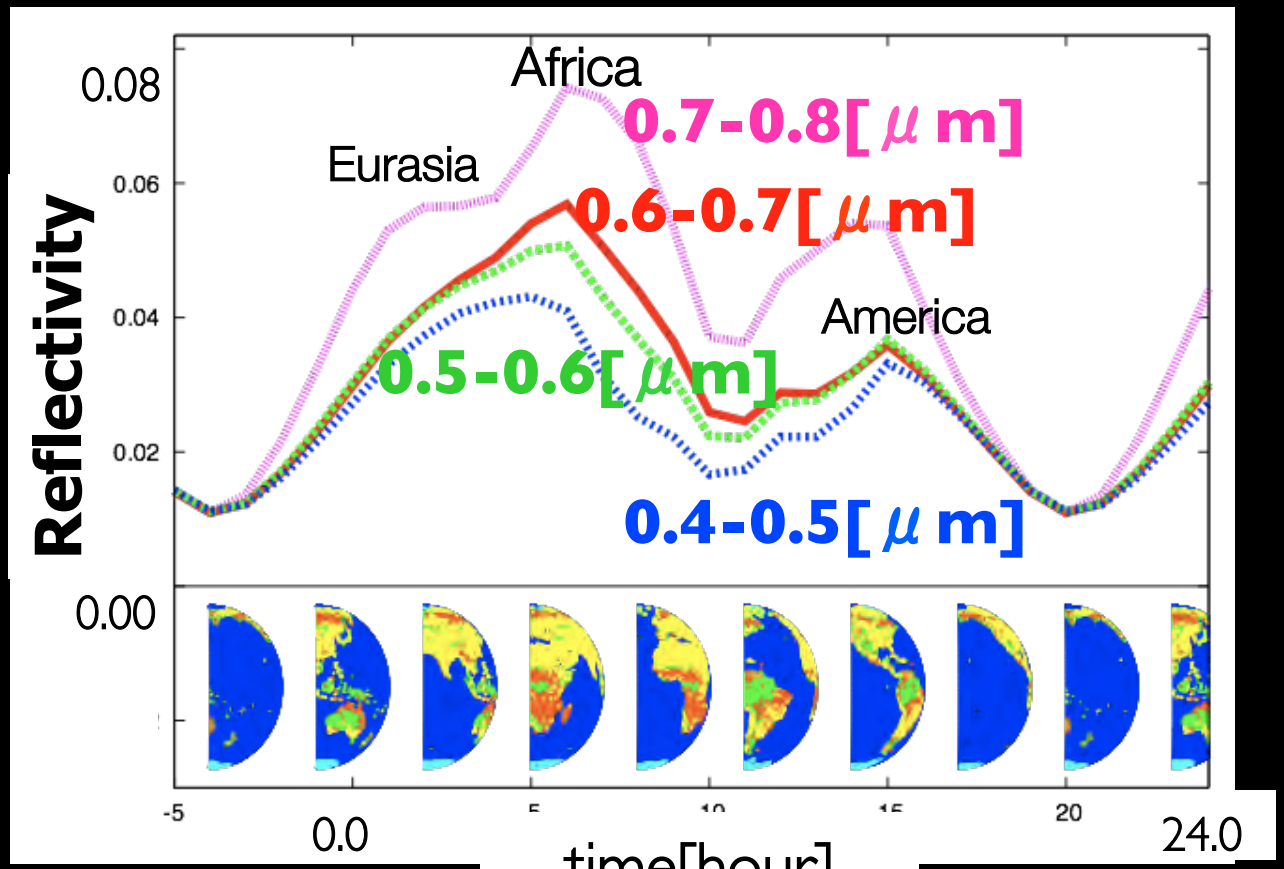
- Beyond a pale blue dot
  - Impossible to spatially resolve the surface of a second earth
  - Color should change due to the rotation
  - A second earth = a color-changing dot



A pale blue dot ? Not really



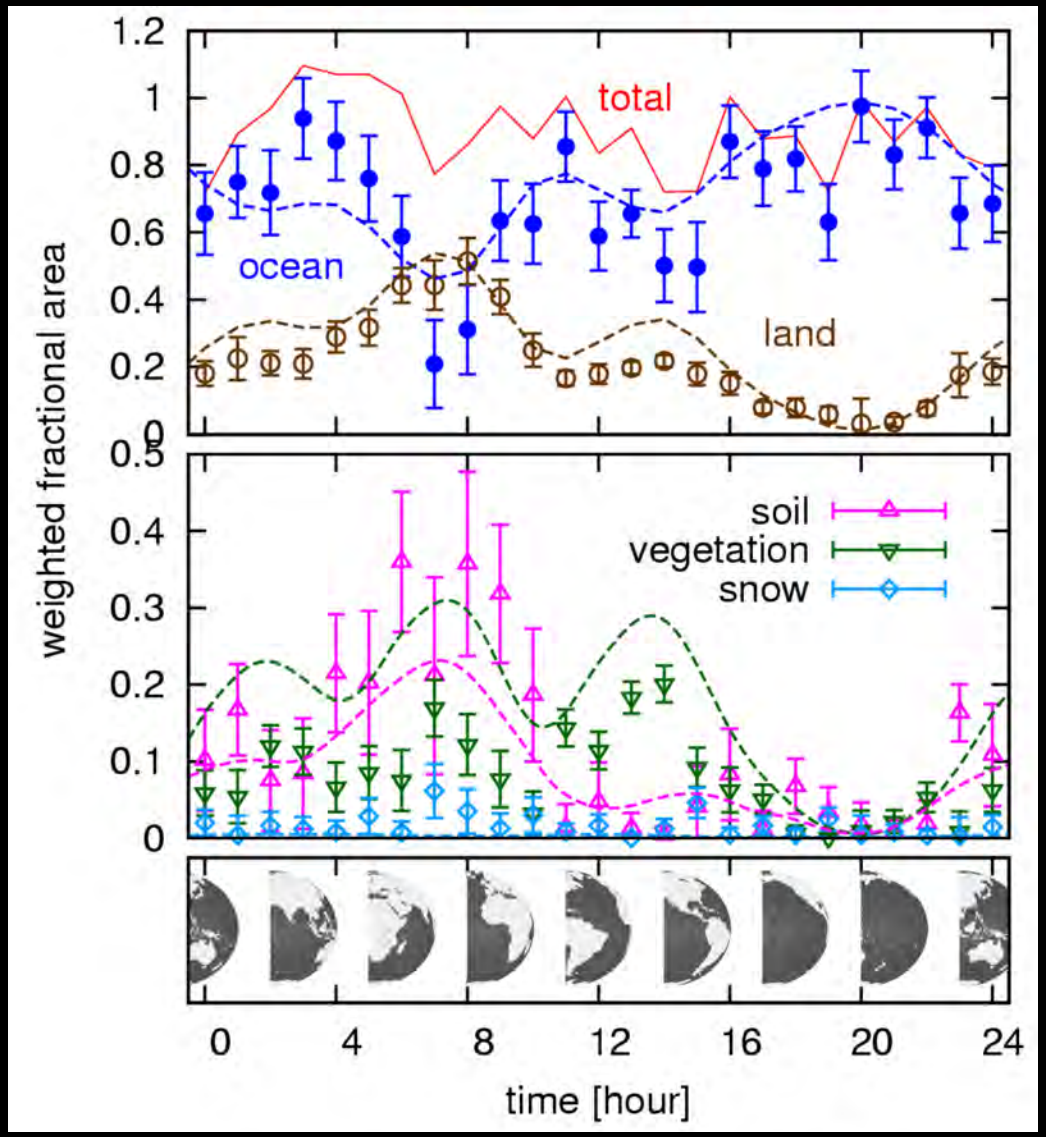
Simulated photometric light-curves of Earth



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

Fujii et al. (2010)

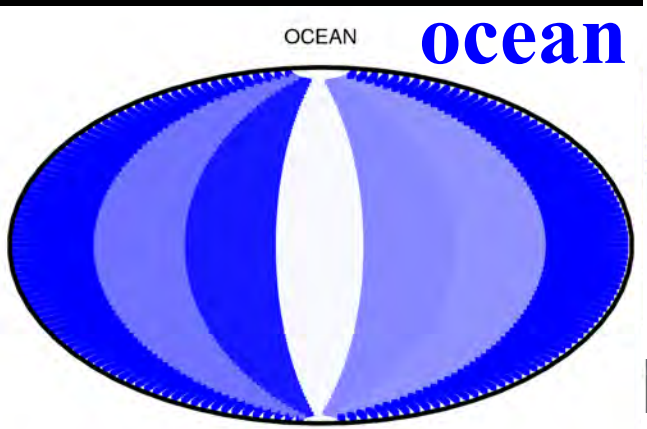
Estimating fractional areas of surface components from colors of a second earth



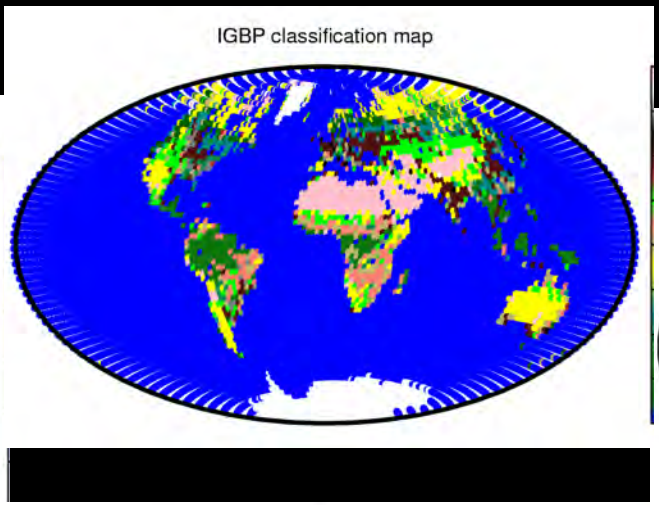
- 2 week observation of a cloudless Earth at 10 pc away
- Reasonably well reproduced
- possible to identify vegetation !

Fujii et al.（2010）

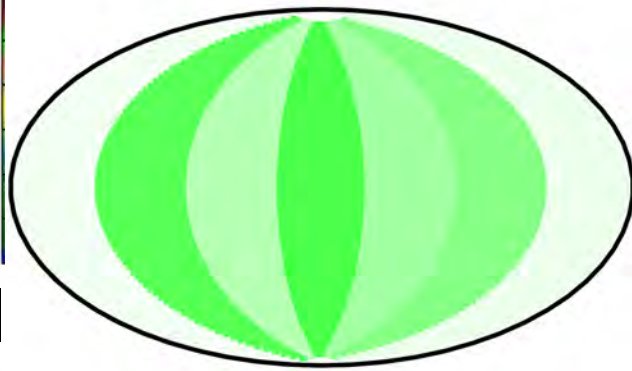
Surface latitude map estimated from real satellite data with cloud model

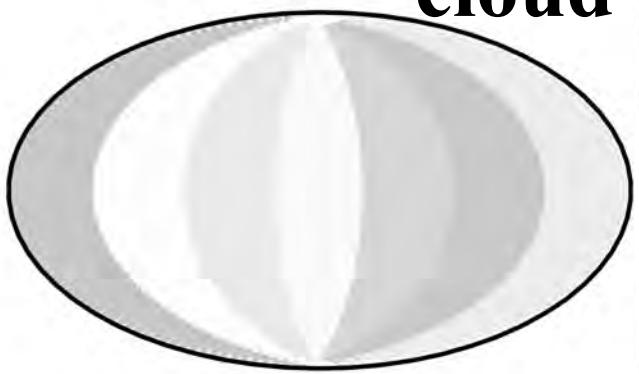


ocean

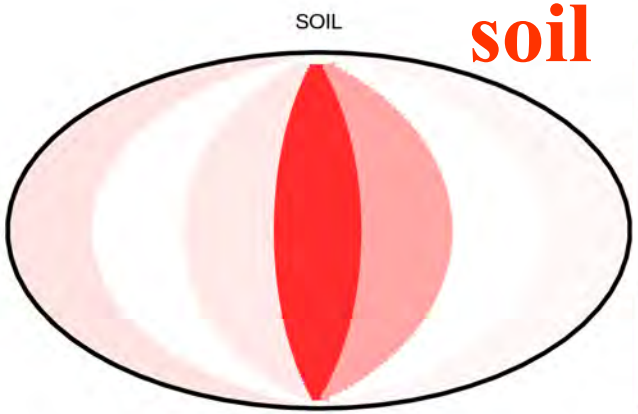


vegetation



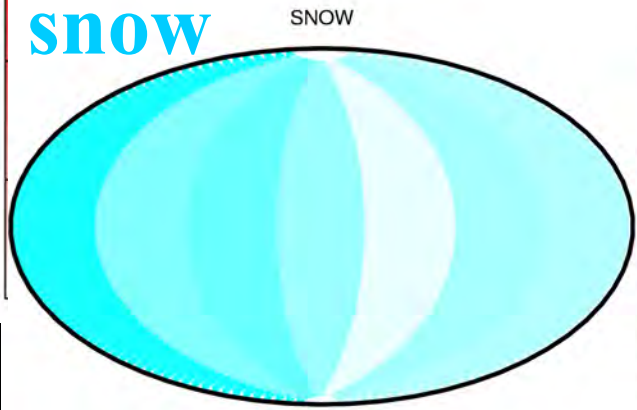


cloud



soil

snow

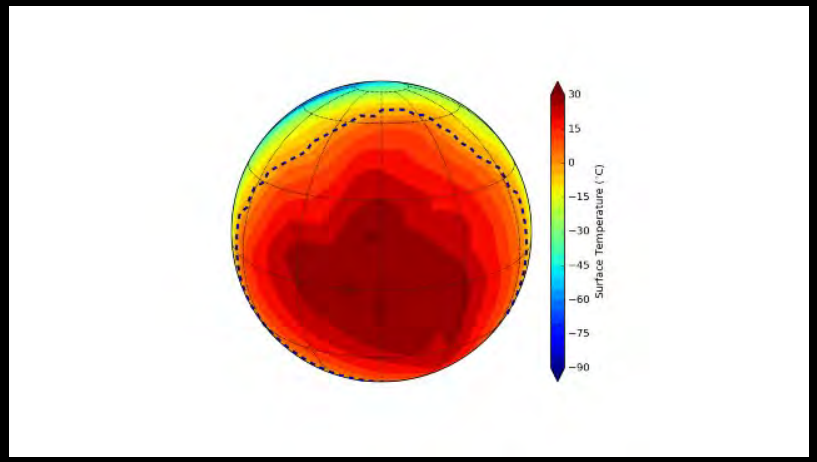


Fujii et al. (2011)

Proxima Centauri b

A terrestrial planet candidate in a temperate orbit around Proxima Centauri

- G.Anglada-Escude et al.
  Nature 25 August 2016 issue, 536(2016)437
- Proxima Centauri b
  - Orbital period 11days
  - M_p sin i =1.3 M_{earth}
  - Eccentricity < 0.35
  - Semi-major axis = 0.05 AU
  - Equilibrium temperature = 230 K



http://www.eso.org/public/usa/news/eso1629/

Breakthrough Initiatives

http://breakthroughinitiatives.org/Initiative

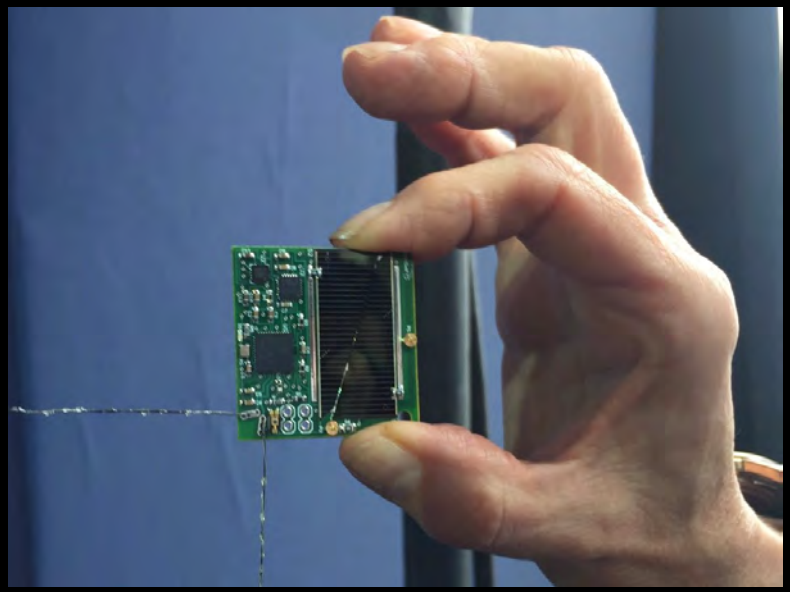
- A program founded on July 20, 2015 by a Russian internet investor Yuri Milner to search for extraterrestrial intelligence
  - Breakthrough Listen to discover signs of extraterrestrial civilizations through radio and laser transmissions
  - Breakthrough Message to study the ethics of sending messages into deep space
  - Breakthrough Starshot to develop a proof-of-concept light sail spacecraft fleet capable of making the journey to Alpha Centauri

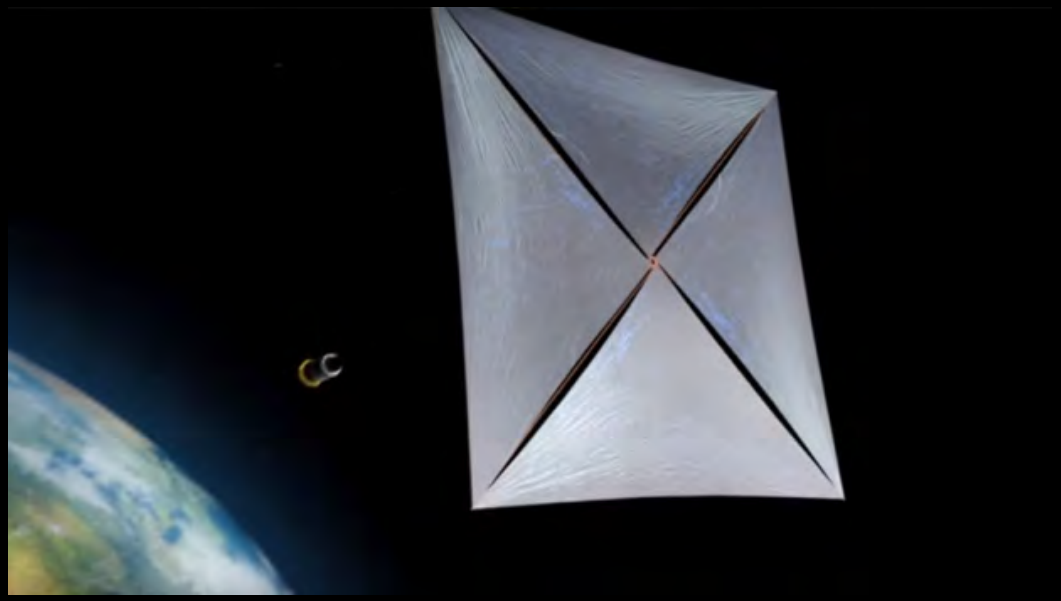
Breakthrough Starshot

http://breakthroughinitiatives.org/Initiative/3

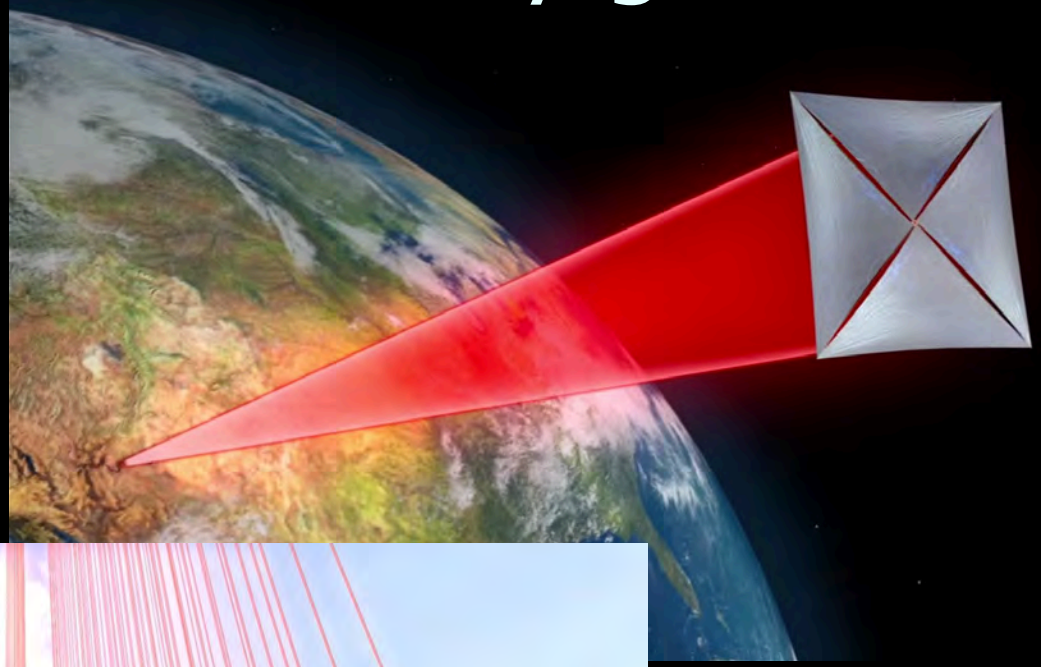
- StarChip
  - A cm-sized nano-spacecraft of several grams
  - With camera, computer, communication laser, plutonium power source, and light sail
  - A 4m×4m light sail for each spacecraft is accelerated by the focused ground-based lasers
  - 0.2c in 10 minutes
- A fleet of 1000 StarChips to Proxima Centauri in 20 years
- Technology not available yet, but in 20 years

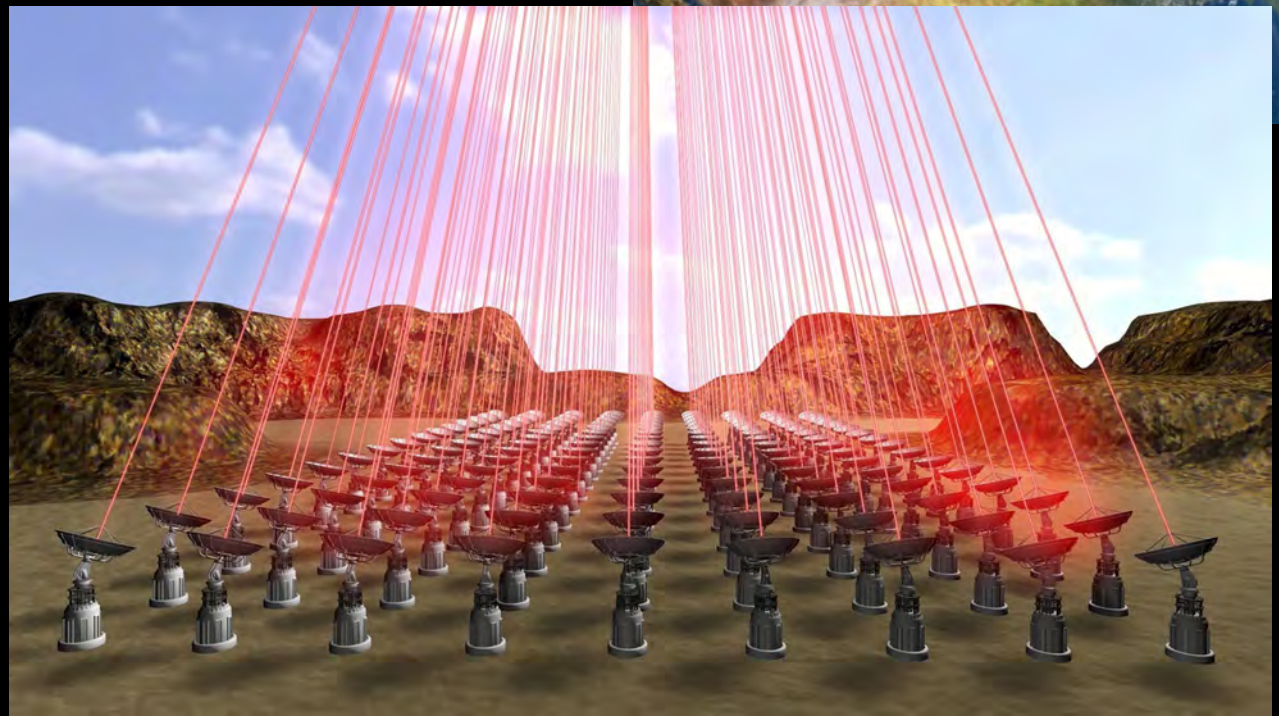
StarChip





Light sail accelerated by ground lasers





Summary

a second earth ≠ a pale blue dot !

- Future direct imaging of daily change of colors of another earth is challenging, but may reveal the presence of ocean, land, cloud, and/or even vegetation on their surface
- Detection of a second Earth may not be a mere fairly tale nor a science fiction any more
- Detection of oxygen, water vapor, and even the red-edge should be a promising path towards astrobiology from space

Take-home message

Exoplanets are very faint,
but
the future of exoplanetary science is amazingly bright.

"We didn't know anything"
(Issac Asimov 1941)
"Where are they ?"
(Enrico Fermi 1950)