An inconvenient truth about biosignatures on Earth-like exoplanets

Hanno Rein, University of Toronto

IAS, 2011

“There are infinite worlds both like and unlike this world of ours.”

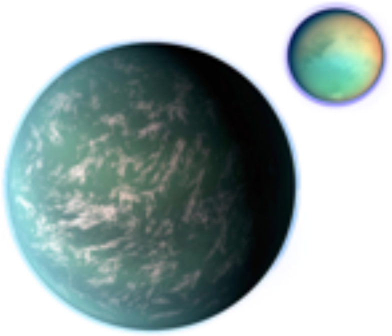
Epicurus (341-270 B.C.)

Demo

The Exoplanet App is available
for free on the AppStore.

Biosignatures

Spectral resolution



Planet/moon false positive

Biosignatures

Biosignature

Life

Yellowstone National Park, 2011

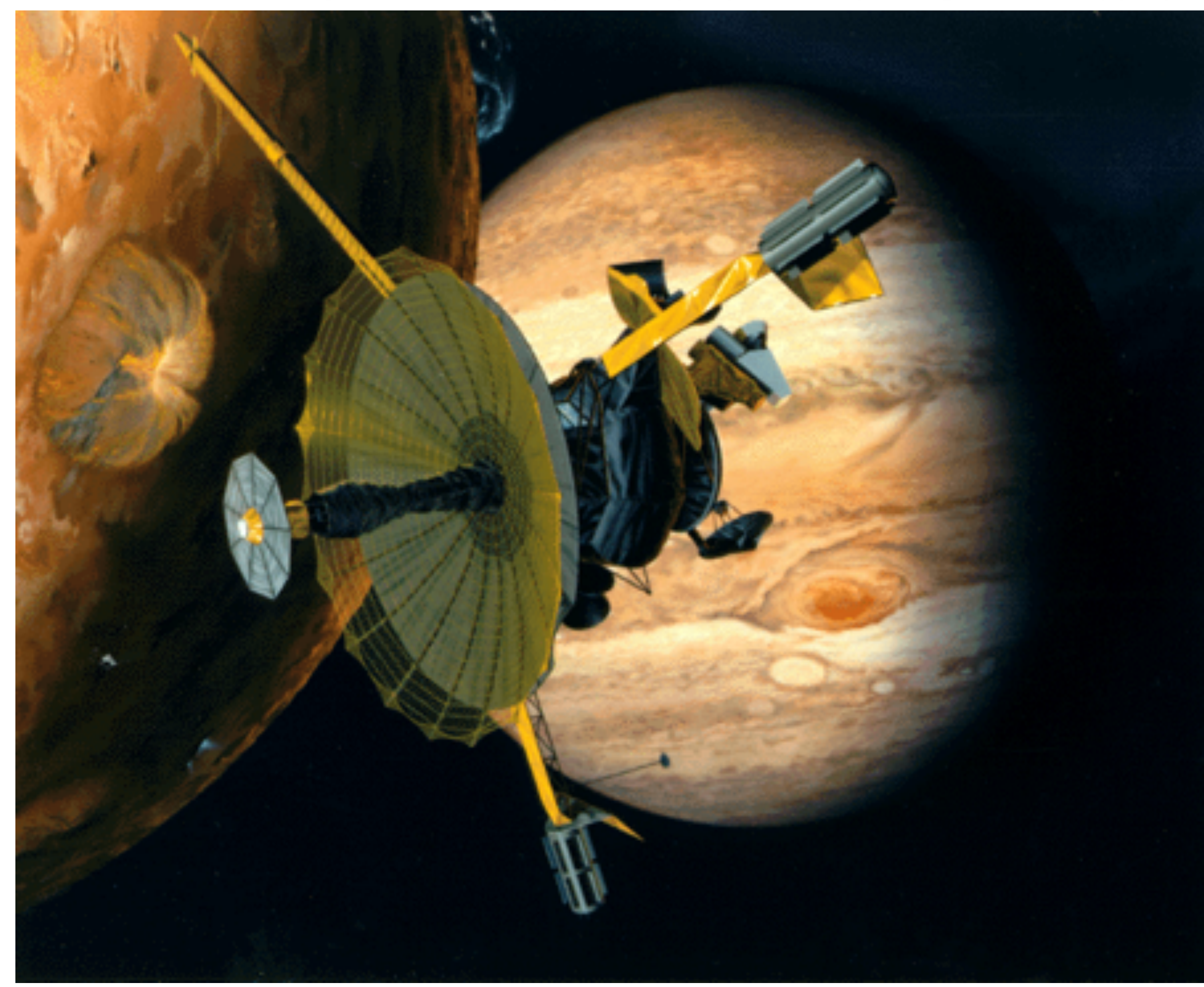
Carl Sagan

A search for life on Earth from the Galileo spacecraft

Carl Sagan[*], W. Reid Thompson[*], Robert Carlson[†], Donald Gurnett[‡] & Charles Hord[§]

[*] Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853, USA
[†] Atmospheric and Cometary Sciences Section, Jet Propulsion Laboratory, Pasadena, California 91109, USA
[‡] Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242-1479, USA
[§] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309, USA

In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.



Biosignature 1: Deficiency in the red colours

IAS, 2011

Biosignature 2: Traces of individual molecules

O_2 / CH_4

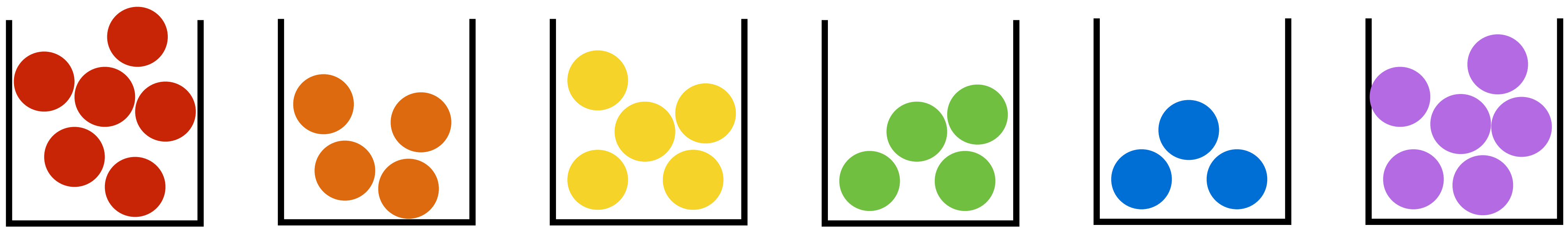
Biosignature 3: Traces of multiple molecules

$$O_2 + CH_4$$

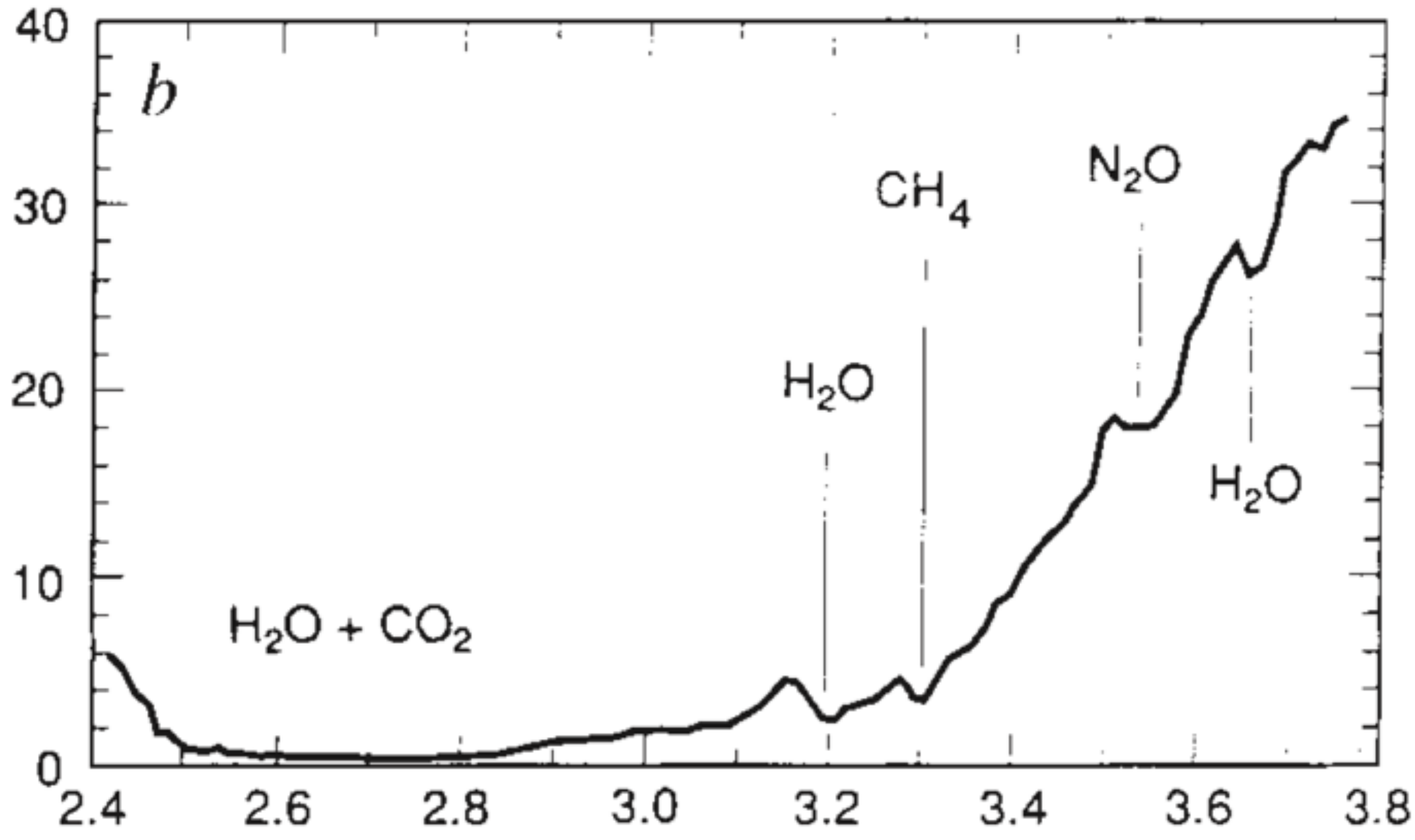
Spectral resolution

What is a spectrum?

Collecting photons, sorting them by colour



The spectrum of Earth

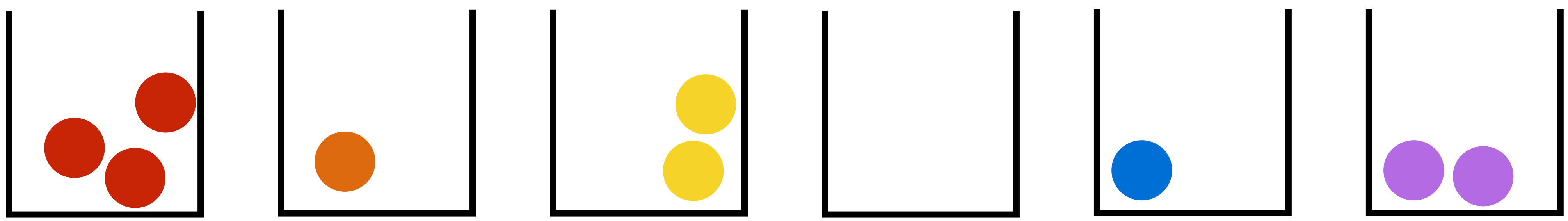


Number of photons

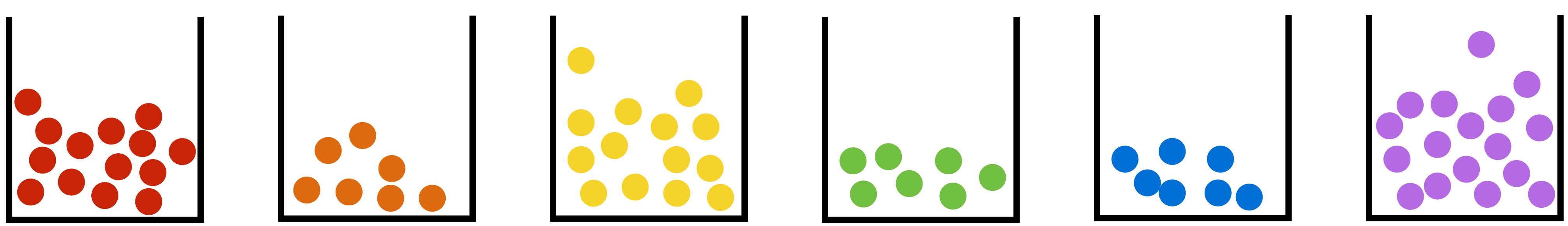
Colour

Sagan et al (1993).

Spectral resolution



Low spectral resolution

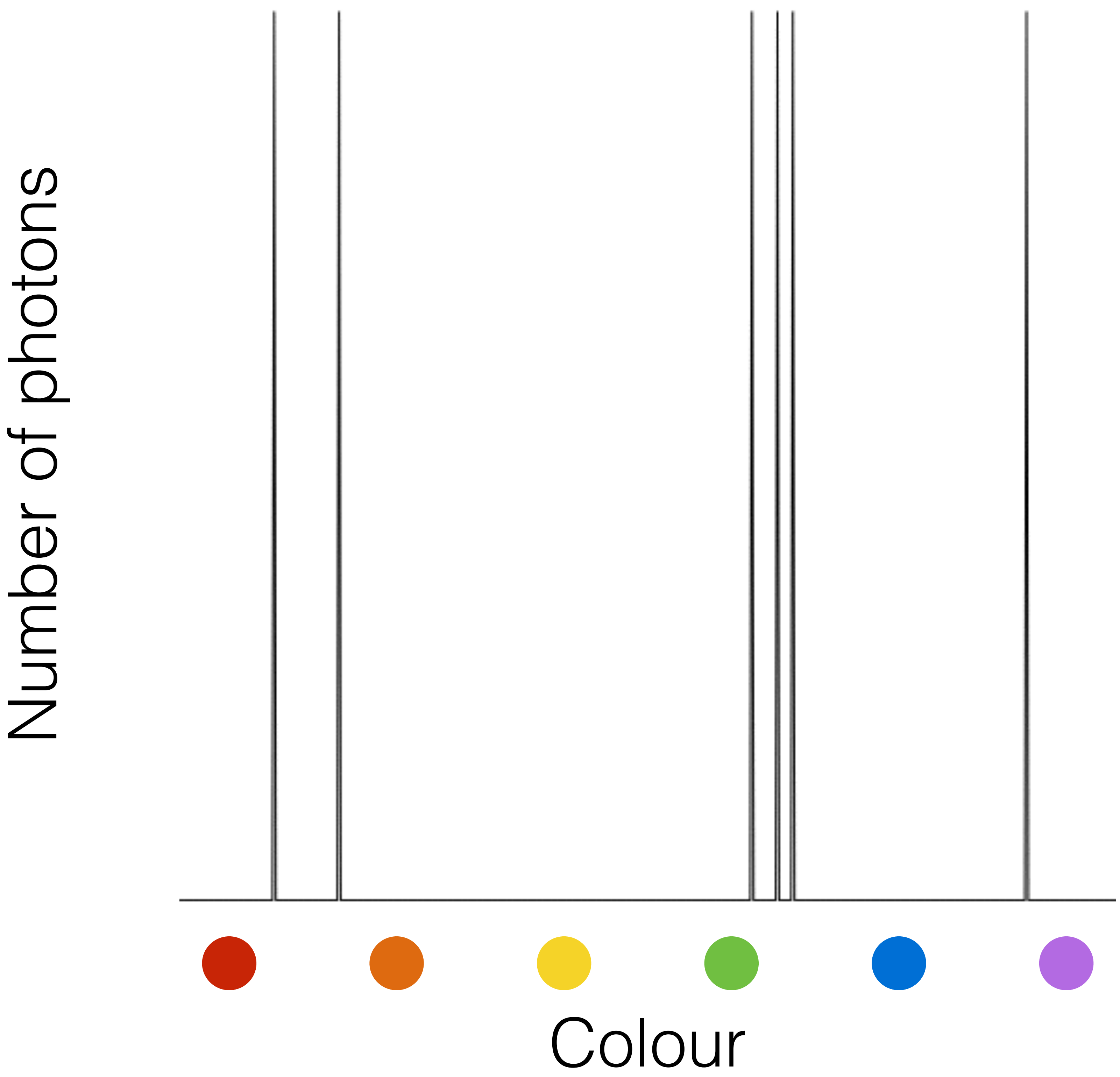


High spectral resolution

Spectral resolution

Spectral resolution is
ultimately photon noise limited.

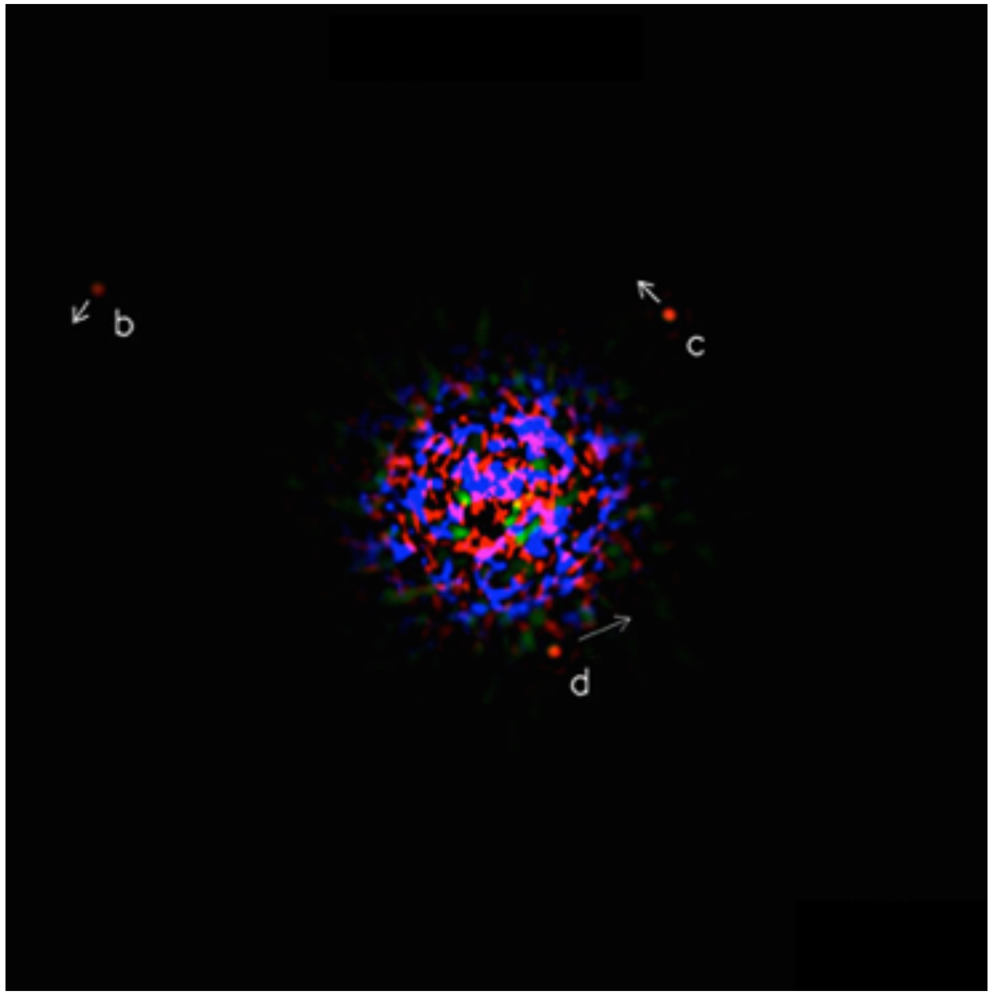
Spectral resolution



Spectral resolution

Taking spectra of exoplanets

Directly imaged planets



Transiting planets

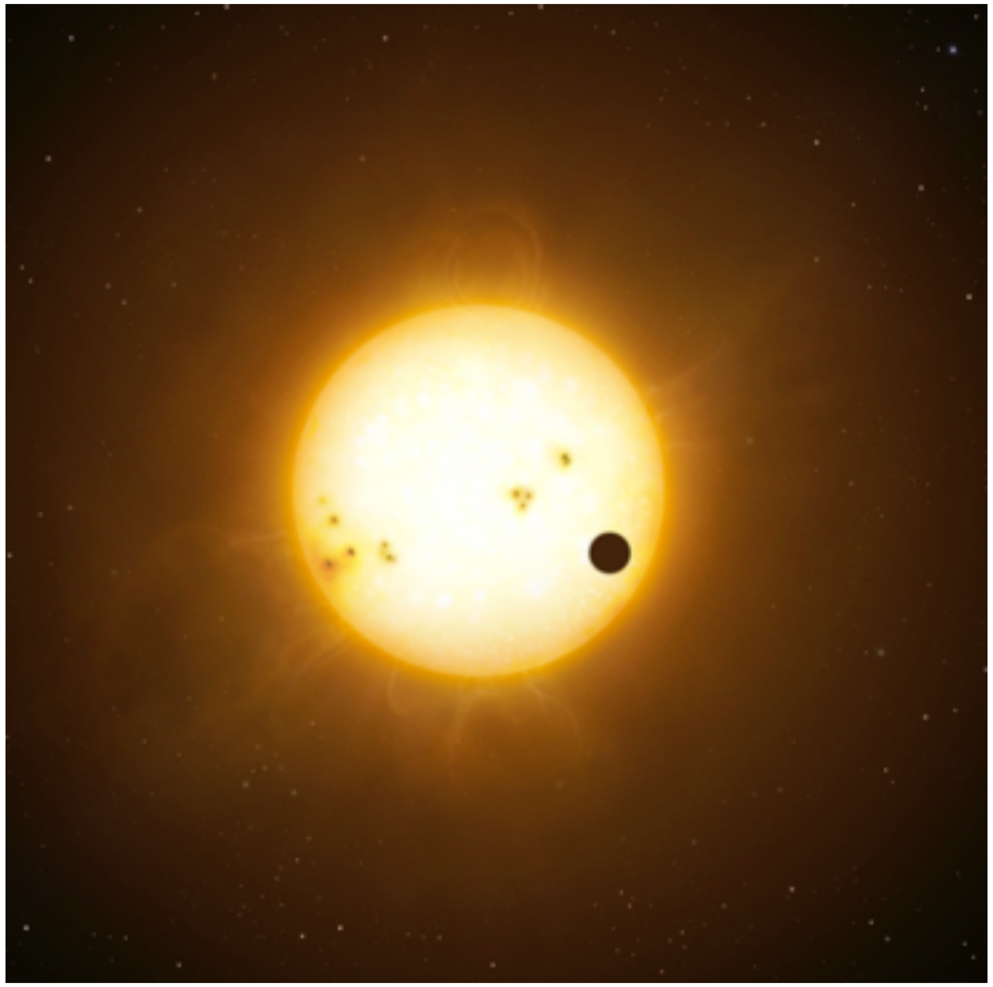
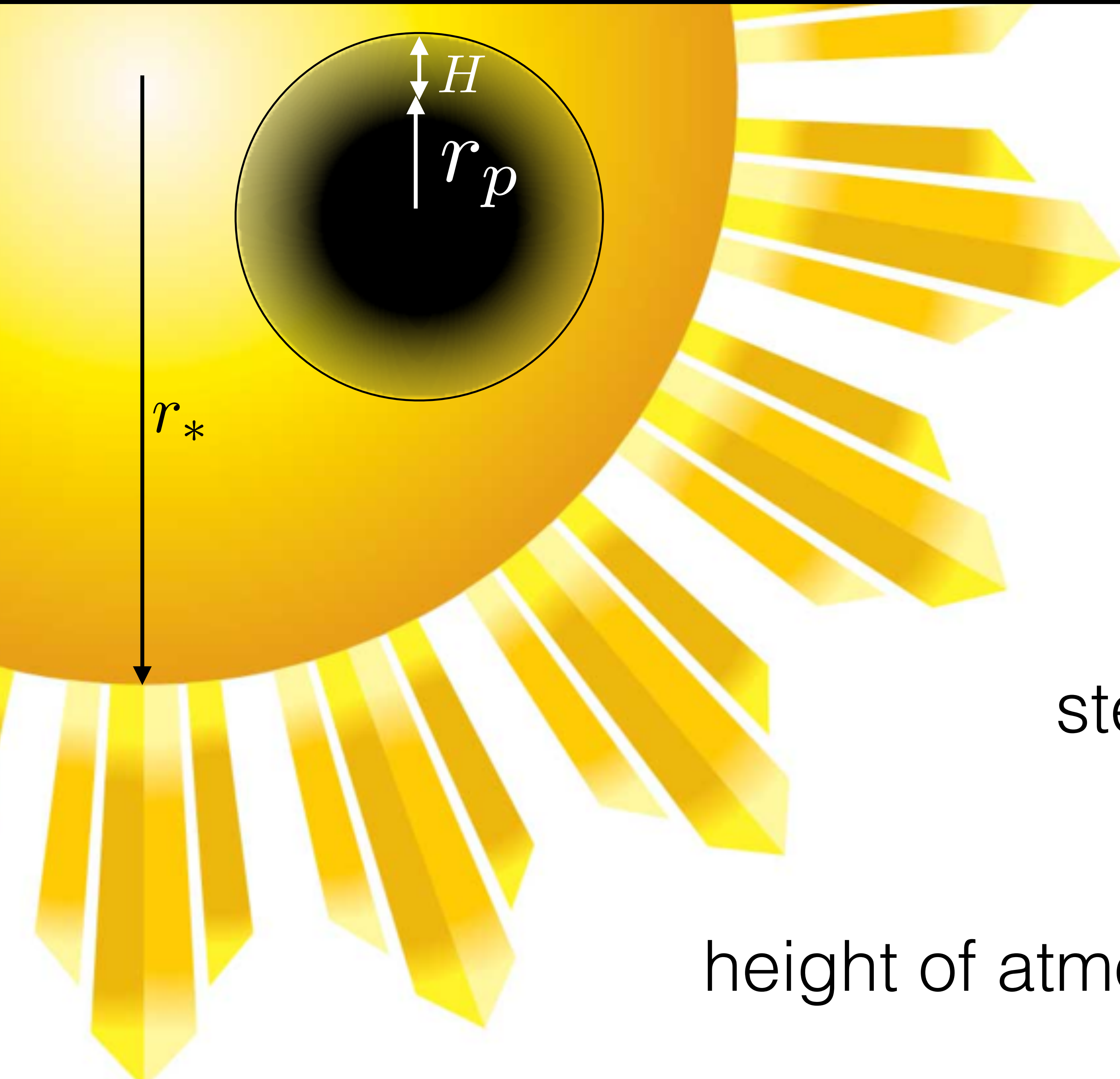


Image credit: STSCI, Keck Observatory, Ben Zuckerman

Transiting planet

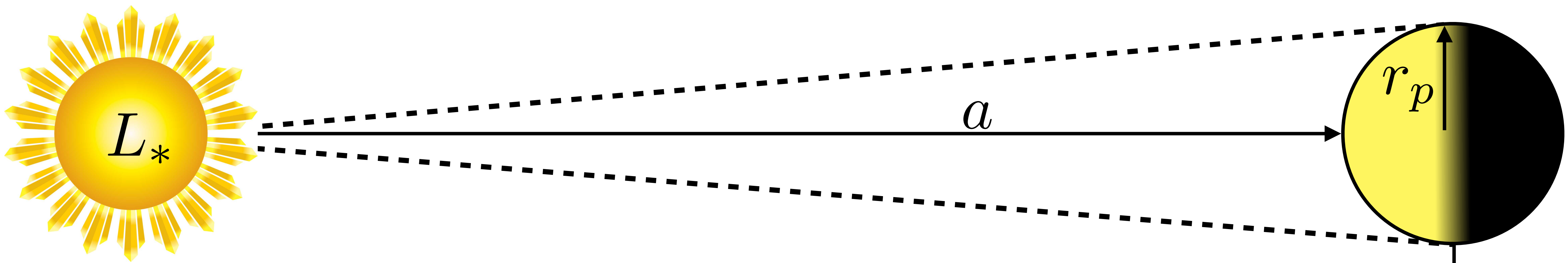


stellar flux $$F_* = \frac{L_*}{4\pi d^2}$$

height of atmosphere $$H \sim 39 \text{ km}$$

flux through atmosphere $$F_{\text{transit}} = \frac{(r_p + H)^2 - r_p^2}{r_*^2} F_*$$

Directly imaged planet



stellar flux $$F_* = \frac{L_*}{4\pi d^2}$$

luminosity of planet $$L_{\mathrm{reflected}} = \frac{L_* \pi A r_p^2}{4\pi a^2}$$

planetary flux $$F_{\mathrm{reflected}} = \frac{L_{\mathrm{reflected}}}{4\pi d^2} = \frac{L_* A r_p^2}{16\pi a^2 d^2}$$

Fundamental upper limit on resolution

Directly imaged planet

$$R^{\text{max}}_{\text{reflected}} = \frac{\lambda}{d\lambda} = \frac{\lambda}{d\lambda}\,\frac{\dot{N}_{\text{reflected}}\Delta t}{\text{SNR}^2}$$

$$= \underbrace{\frac{\pi}{64\sigma hc}}_{\text{constants}}\ \underbrace{\frac{A\,r_p^2}{a^2}}_{\text{planet}}\ \underbrace{\frac{L_*\lambda^2\,B_\lambda[T_*]}{T_*^4}}_{\text{star/band}}\ \underbrace{\Delta t\,\frac{D^2}{d^2}\,\text{SNR}^{-2}}_{\text{telescope}}$$

$$= 1683\left(\frac{d}{10\text{pc}}\right)^{-2}\left(\frac{D}{6.5\text{m}}\right)^{2}\left(\frac{\Delta t}{12\text{hrs}}\right)\left(\frac{\text{SNR}}{10}\right)^{-2}.$$

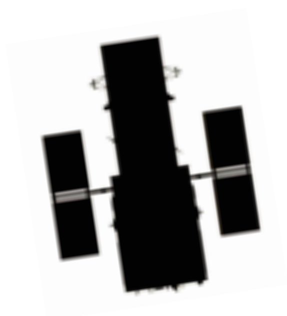
Transiting planet

$$R^{\text{max}}_{\text{transit}} = \frac{\lambda}{d\lambda} = \frac{\lambda}{d\lambda}\,\frac{\dot{N}^2_{\text{transit}}/\dot{N}_*}{\text{SNR}^2}\Delta t$$

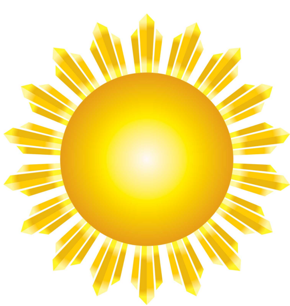
$$= \underbrace{\frac{\pi}{4\sigma hc}}_{\text{constants}}\ \underbrace{r_p^2 H^2}_{\text{planet}}\ \underbrace{\frac{L_*\lambda^2\,B_\lambda[T_*]}{r_*^4 T_*^4}}_{\text{star/band}}\ \underbrace{\Delta t\,\frac{D^2}{d^2}\,\text{SNR}^{-2}}_{\text{telescope}}$$

$$= 12.2\left(\frac{d}{10\text{pc}}\right)^{-2}\left(\frac{D}{6.5\text{m}}\right)^{2}\left(\frac{\Delta t}{12\text{hrs}}\right)\left(\frac{\text{SNR}}{10}\right)^{-2}.$$

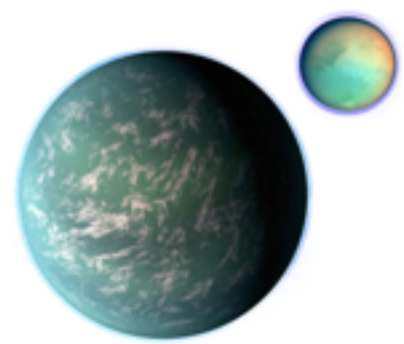
Problems beyond the fundamental limit



- Telescope photon efficiency
- Spectrograph photon efficiency
- Systematic instrumental error

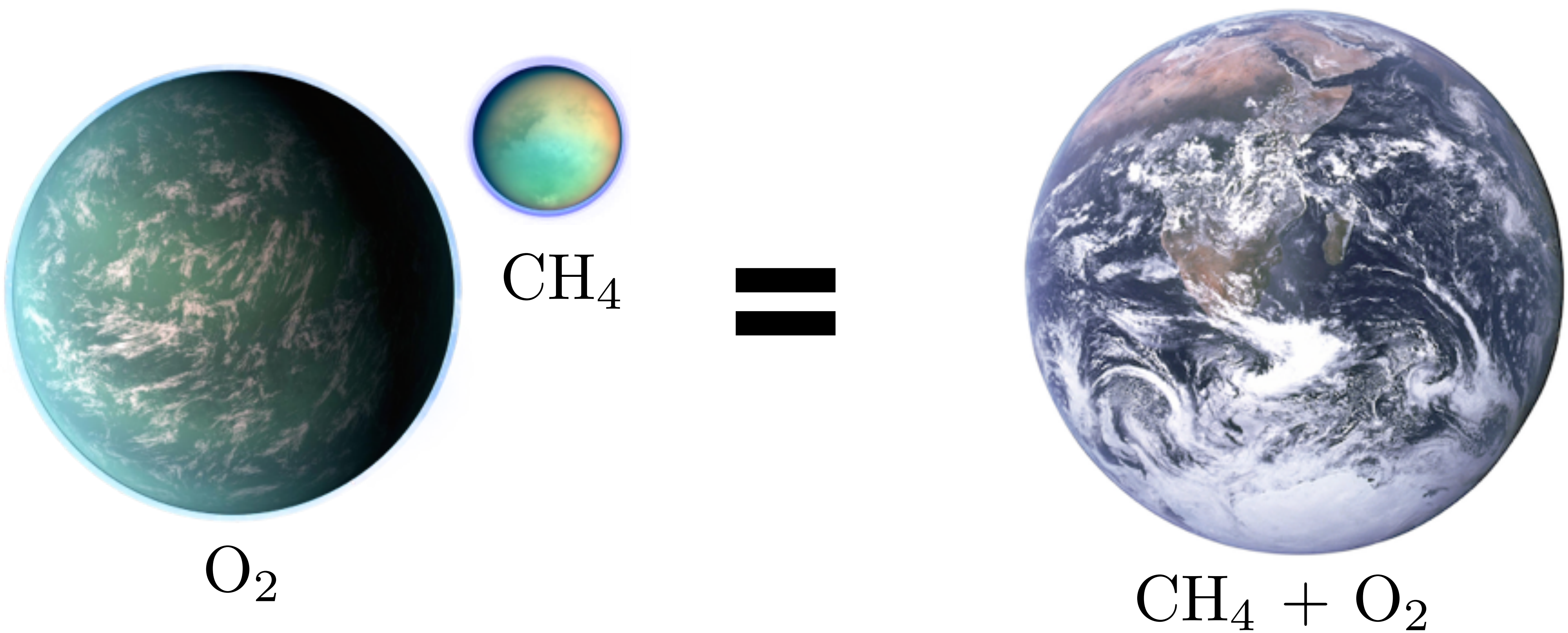


- Zodiacal light
- Exozodiacal light
- Star spots
- Background sources
- Upper limit on integration time
- Transiting planets on average 6 times further away

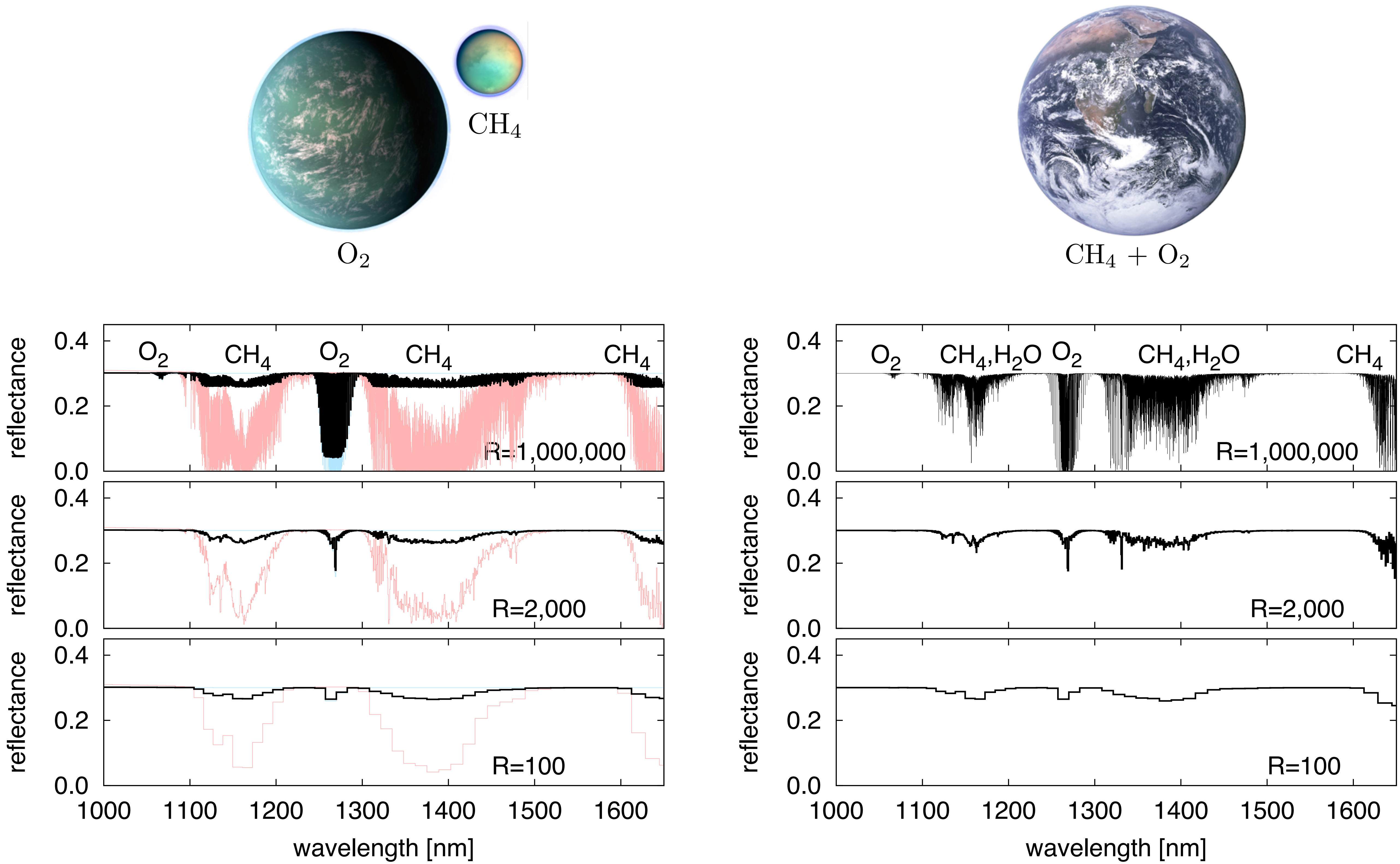


Planet/moon false positive

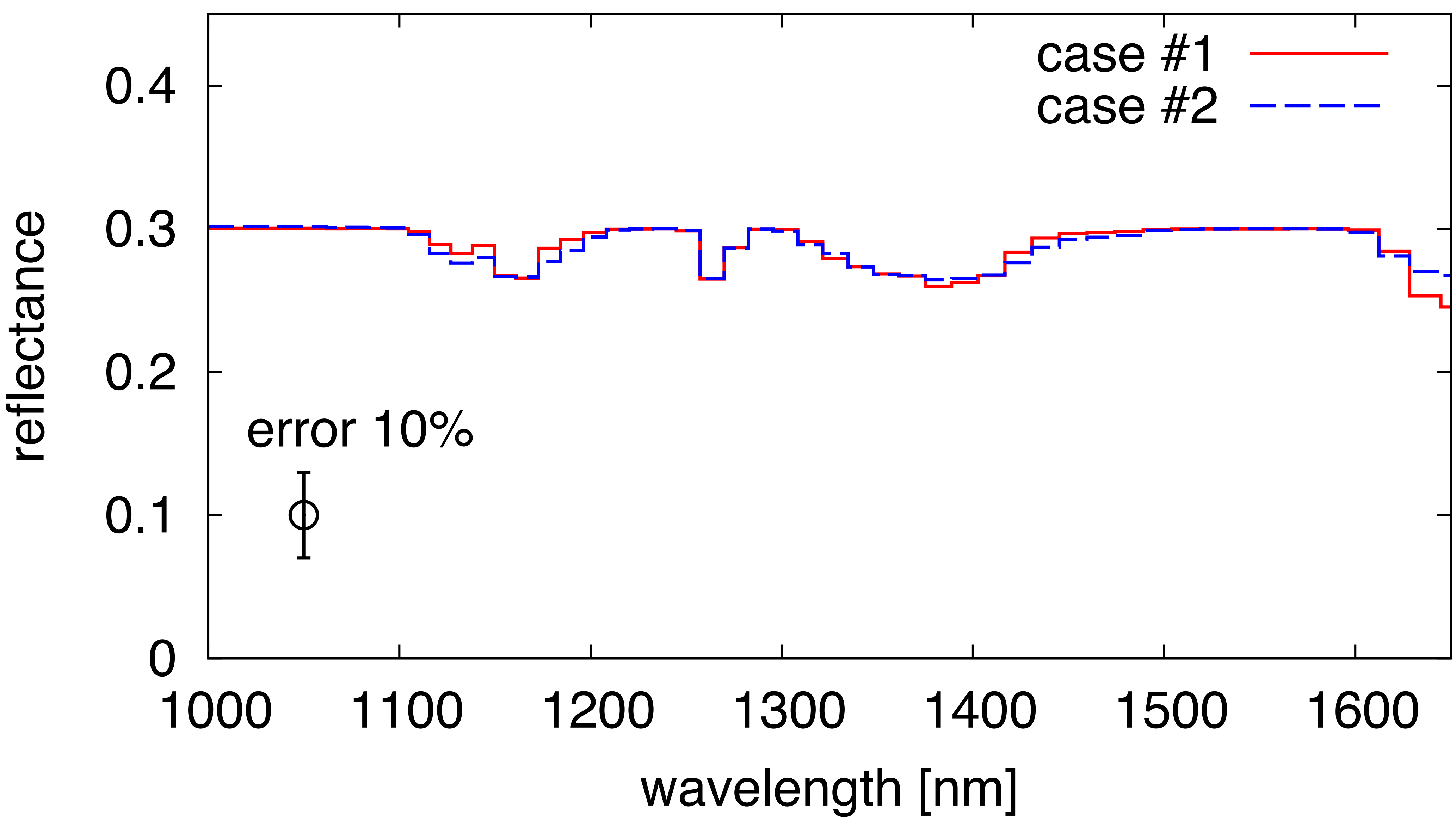
The basic idea

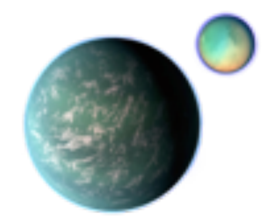


Model spectra



Model spectra



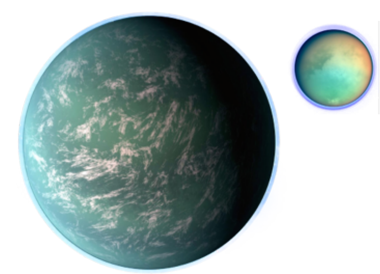
This is not the end of the story. 

Possible ways to break degeneracy

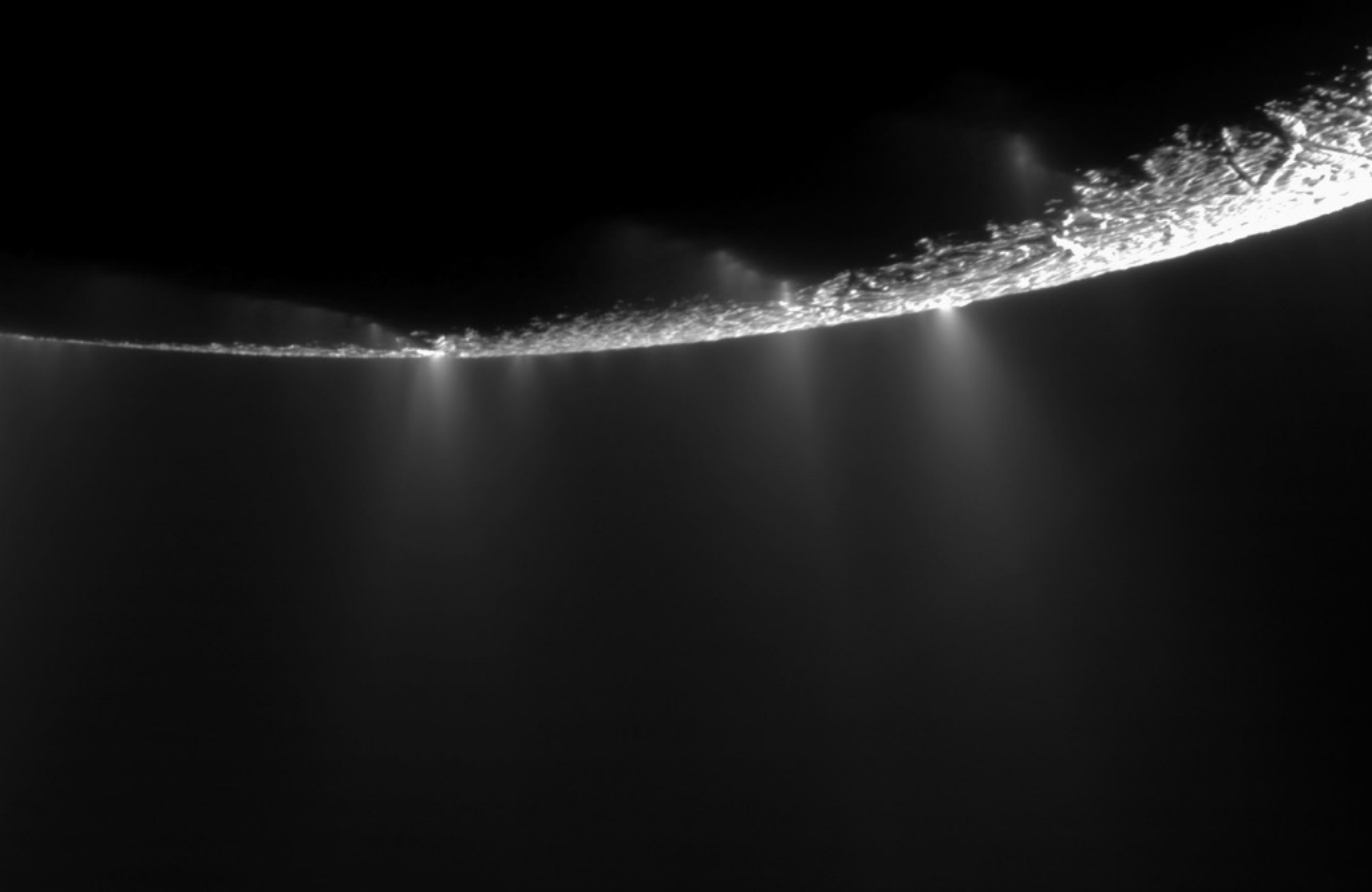
Very close-by planet $R \sim d^{-2}$

Single molecule biosignature O_2/CH_4

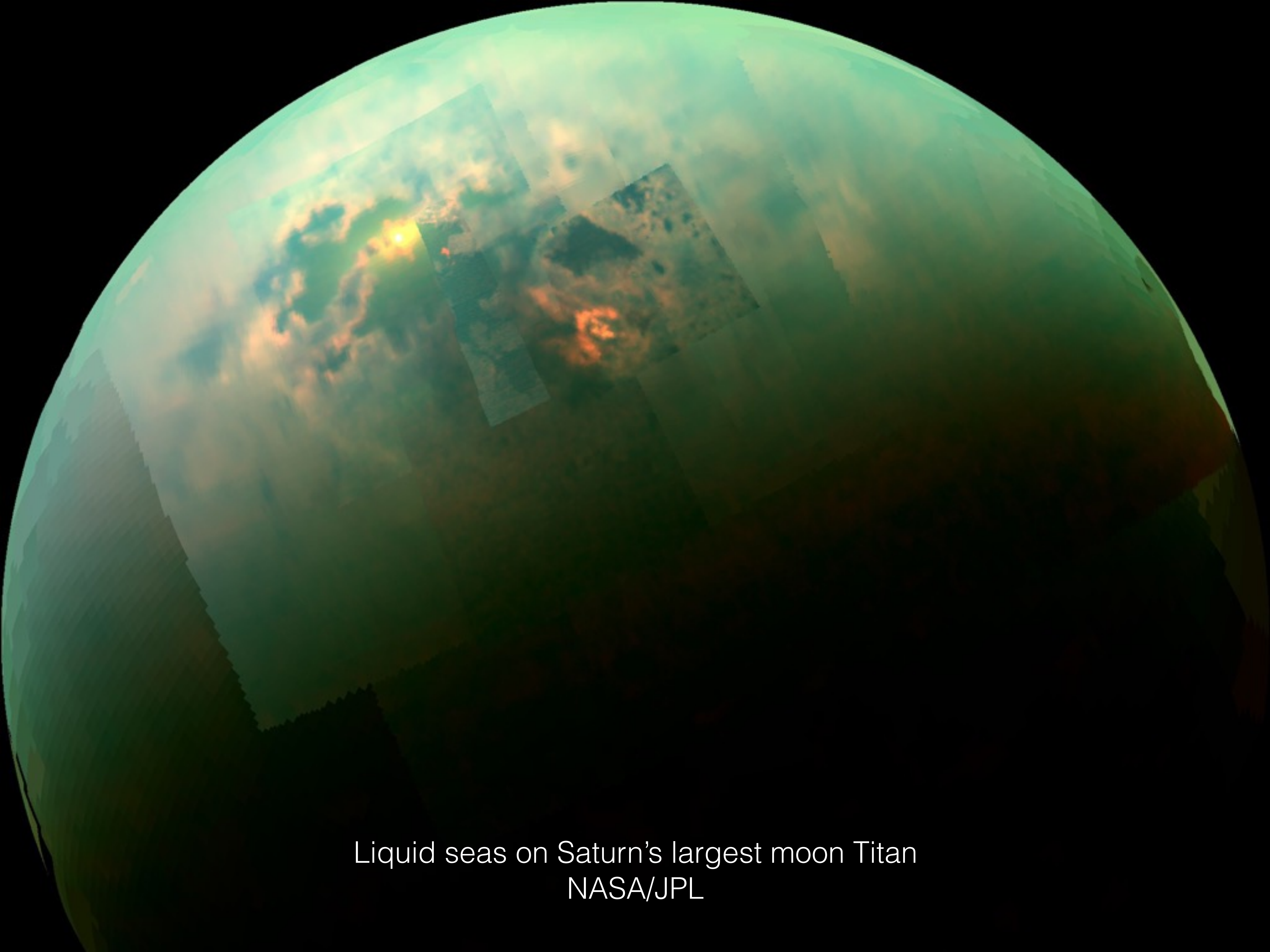
Time variability



Relax Earth-Sun twin



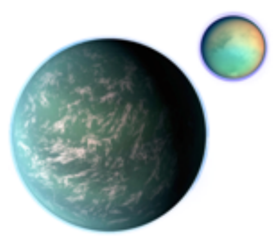
Enceladus geysers
NASA/JPL/Space Science Institute



Liquid seas on Saturn’s largest moon Titan
NASA/JPL

Summary

It’s very hard to take a spectrum of an Earth-like planet.



A new false positive: planet + moon. Impossible to distinguish in low resolution spectra.

Forget about Earth-Sun analogues. Search elsewhere.