Earth's transmission spectrum from lunar eclipse observations

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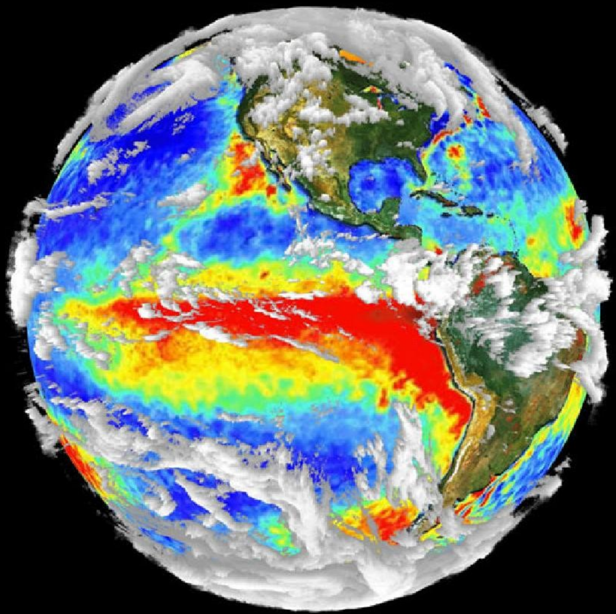
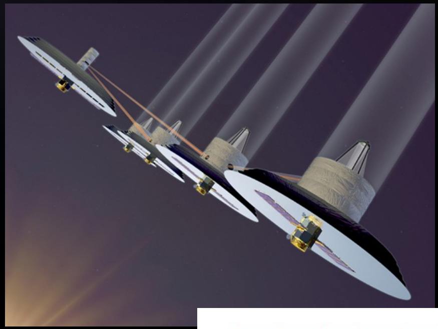
Nowadays we can monitor night lights, atmospheric changes, plankton blooms, forest health, etc...

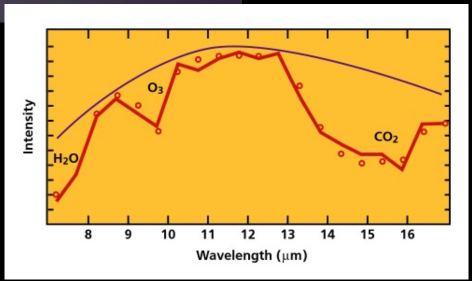


But, how does our planet look like to ET?

When observing an exoplanet, all the light will come from a single point.



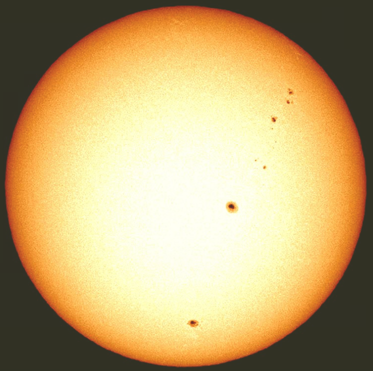
We will need a detailed understanding of the “micro-scale” processes to interpret the observed “macro-scale” properties



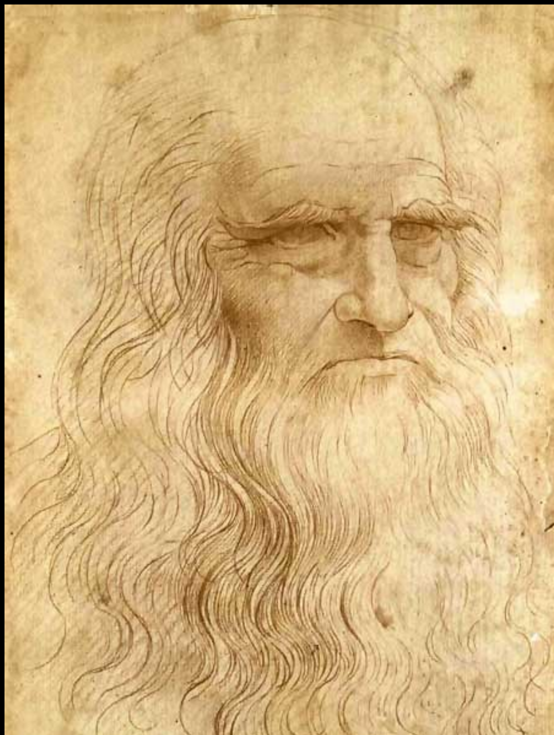
Observing the Earth as a planet (no spatial resolution)

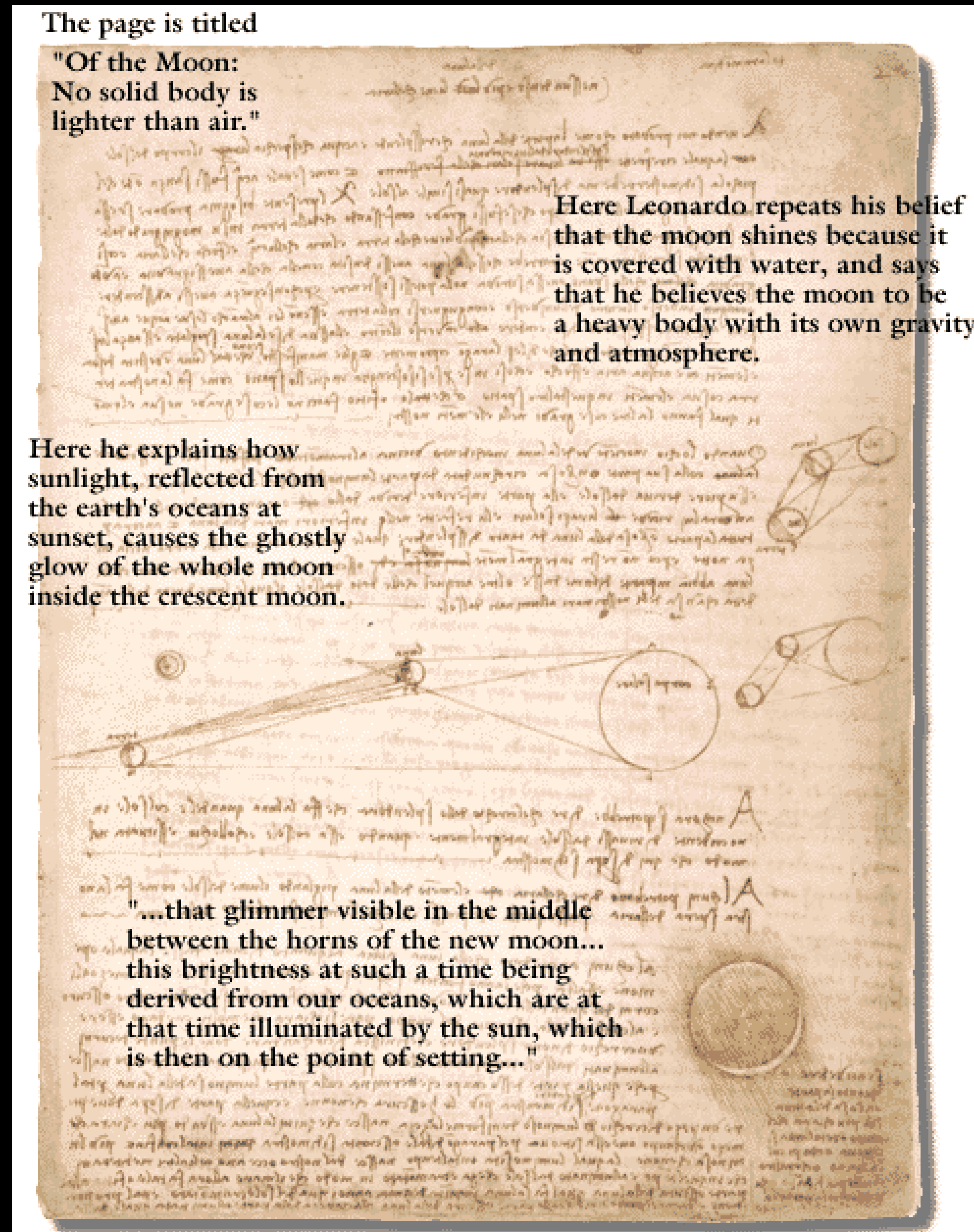
- *Earth–as-a-point observations with a very remote sensor*
- *A compilation of high spatial resolution data into a global spectra or photometry, and modeling*
- *Earthshine Observations: The Earthshine is the ghostly glow on the dark side of the Moon*

The Earthshine on the moon

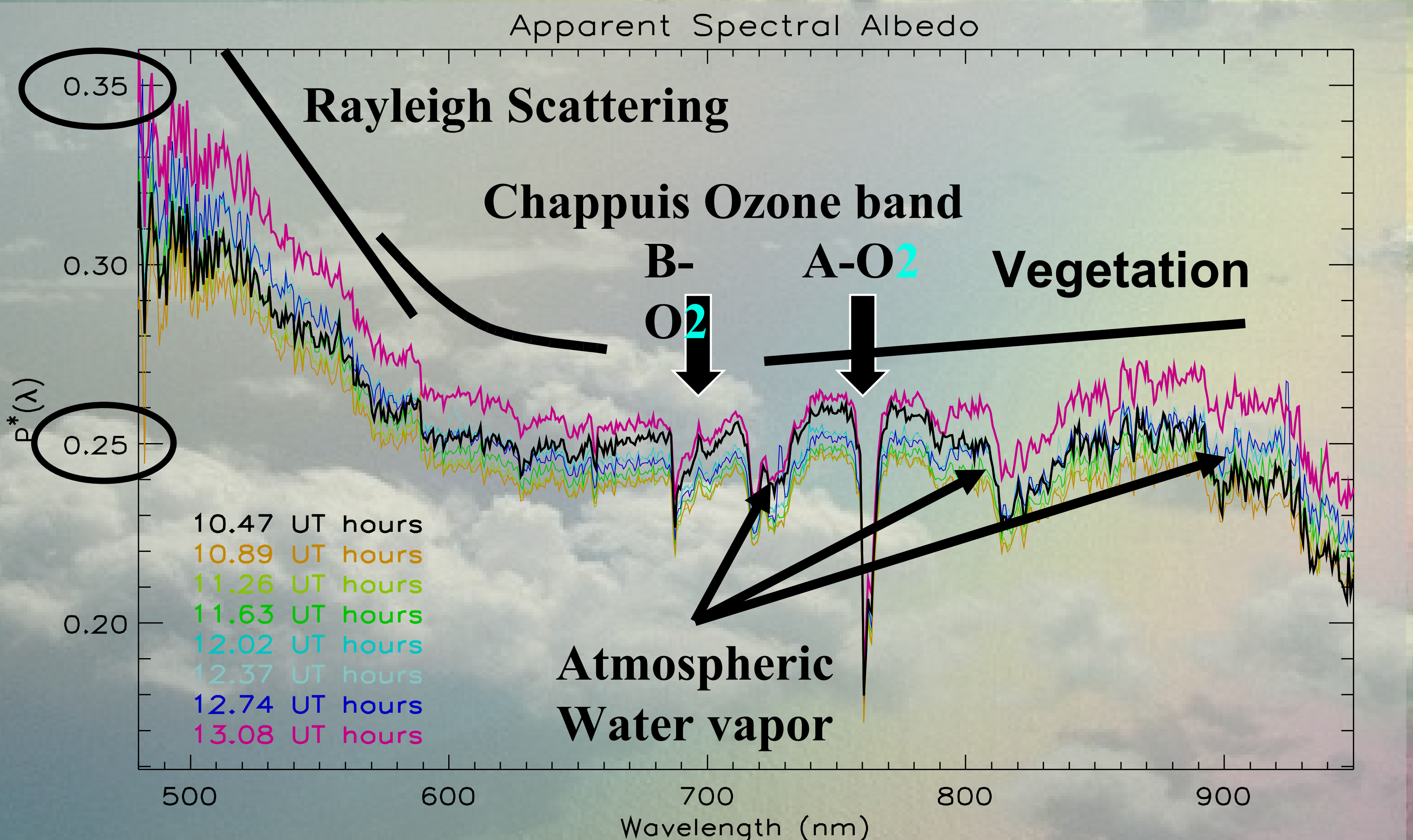


ES/MS = albedo (+ geometry and moon properties)



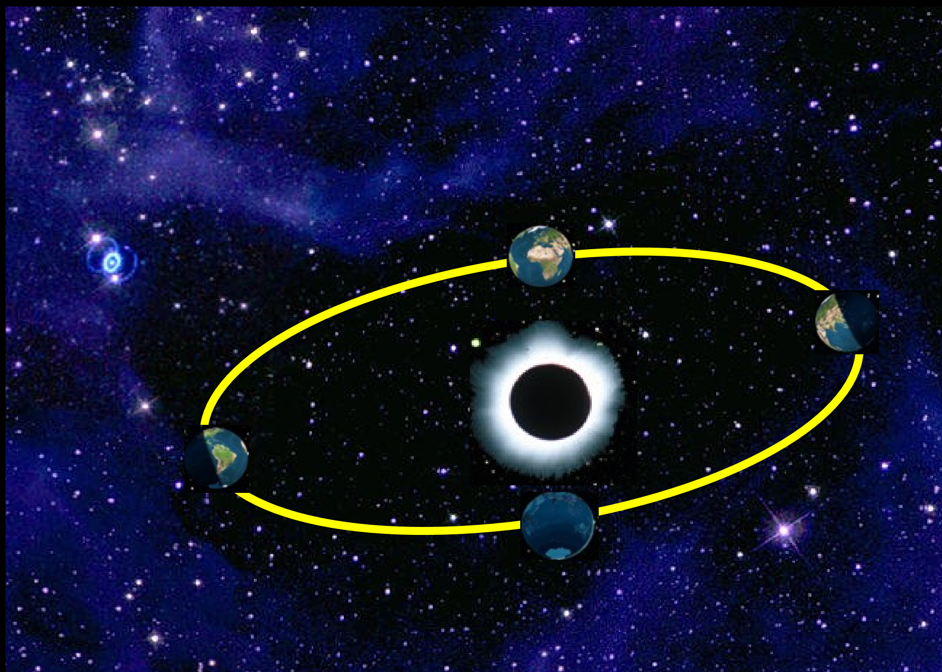

The page is titled
"Of the Moon:
No solid body is
lighter than air."
Here Leonardo repeats his belief that the moon shines because it is covered with water, and says that he believes the moon to be a heavy body with its own gravity and atmosphere.
Here he explains how sunlight, reflected from the earth's oceans at sunset, causes the ghostly glow of the whole moon inside the crescent moon.
"...that glimmer visible in the middle between the horns of the new moon... this brightness at such a time being derived from our oceans, which are at that time illuminated by the sun, which is then on the point of setting..."

Spectral Albedo of the Earth: 2003/11/19



Montañés-Rodriguez et al., ApJ, 2006

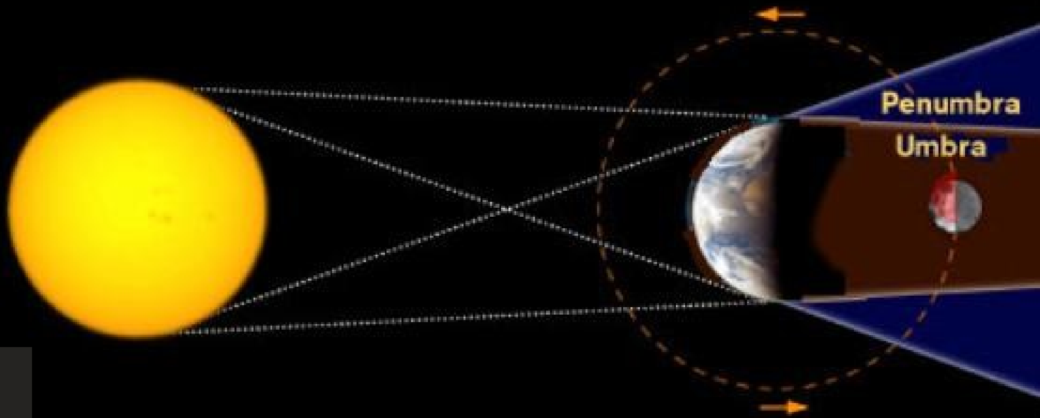
But isolating the light from the planet is *VERY* challenging, what if direct detection is not possible?

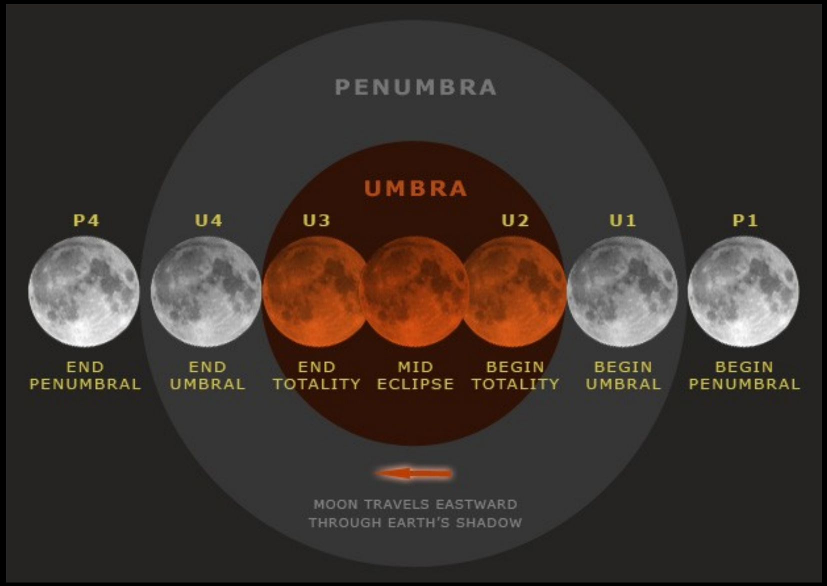


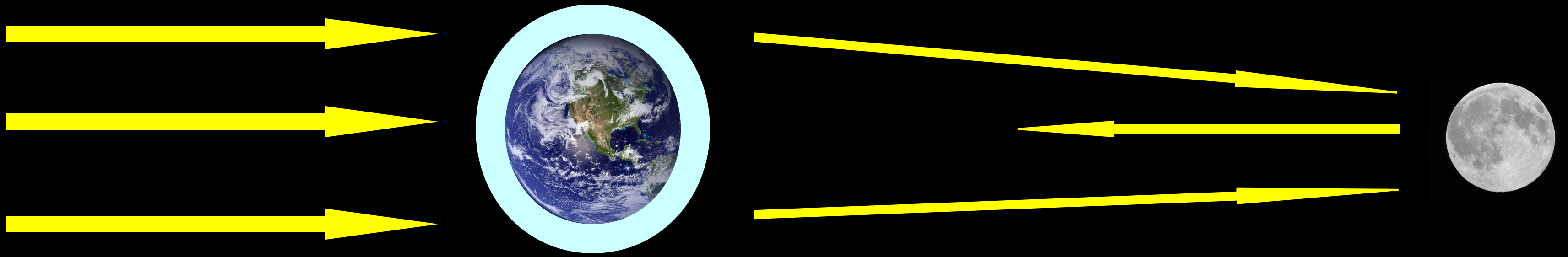
Atmospheric characterization of *Hot Jupiters* has already been achieved trough transit spectroscopy

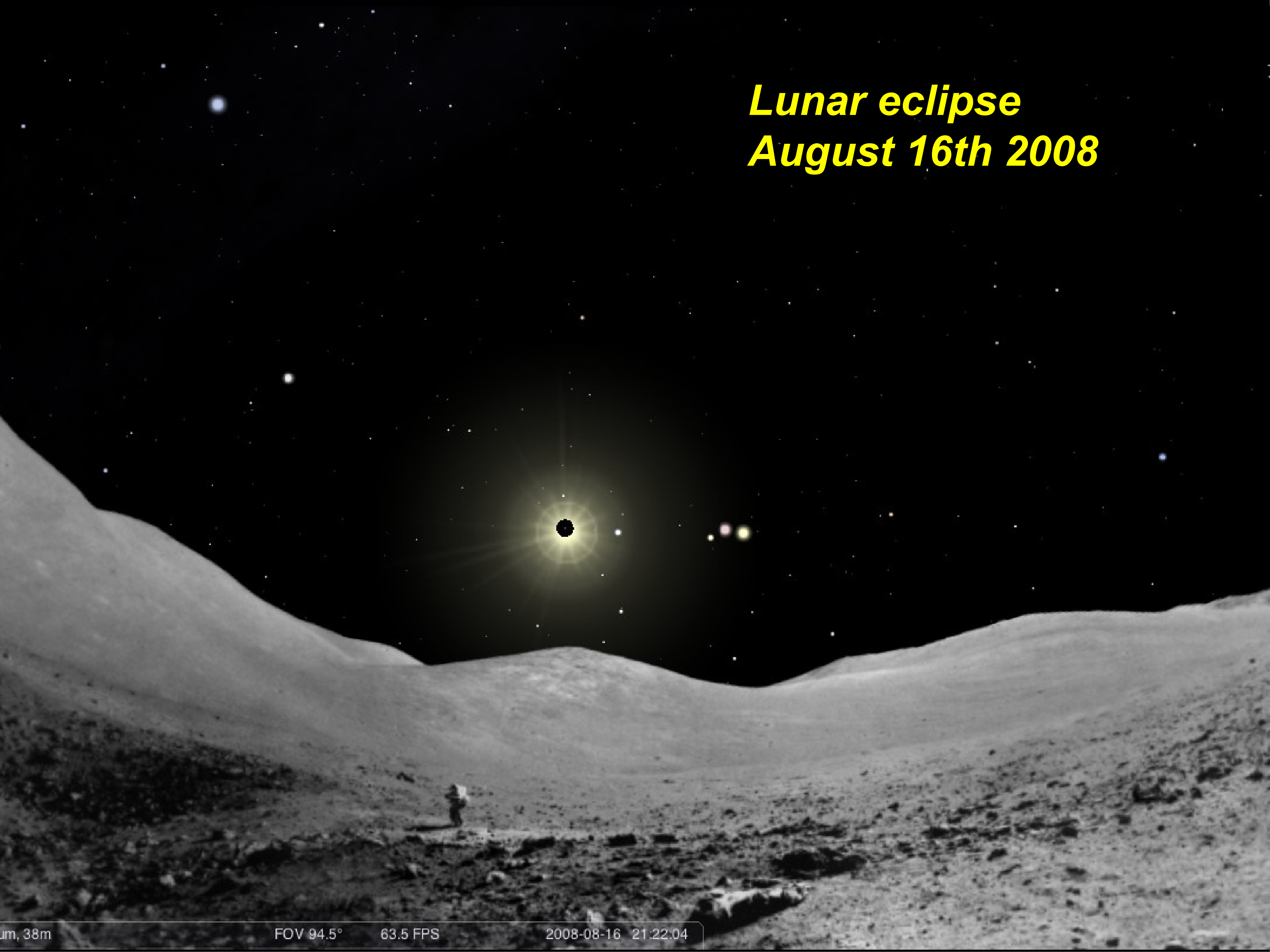
What about transiting Earths?

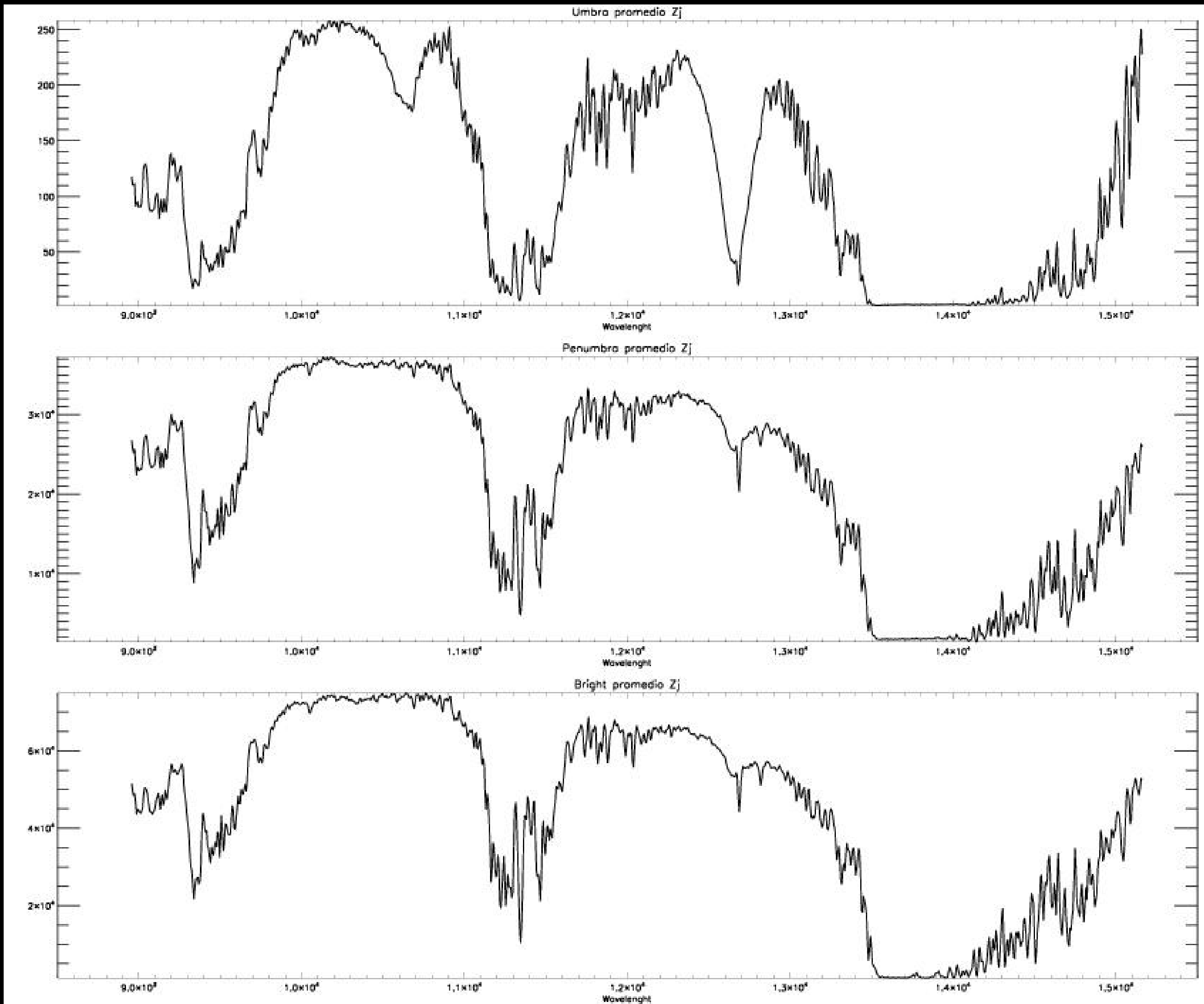
We can observe it during a lunar eclipse







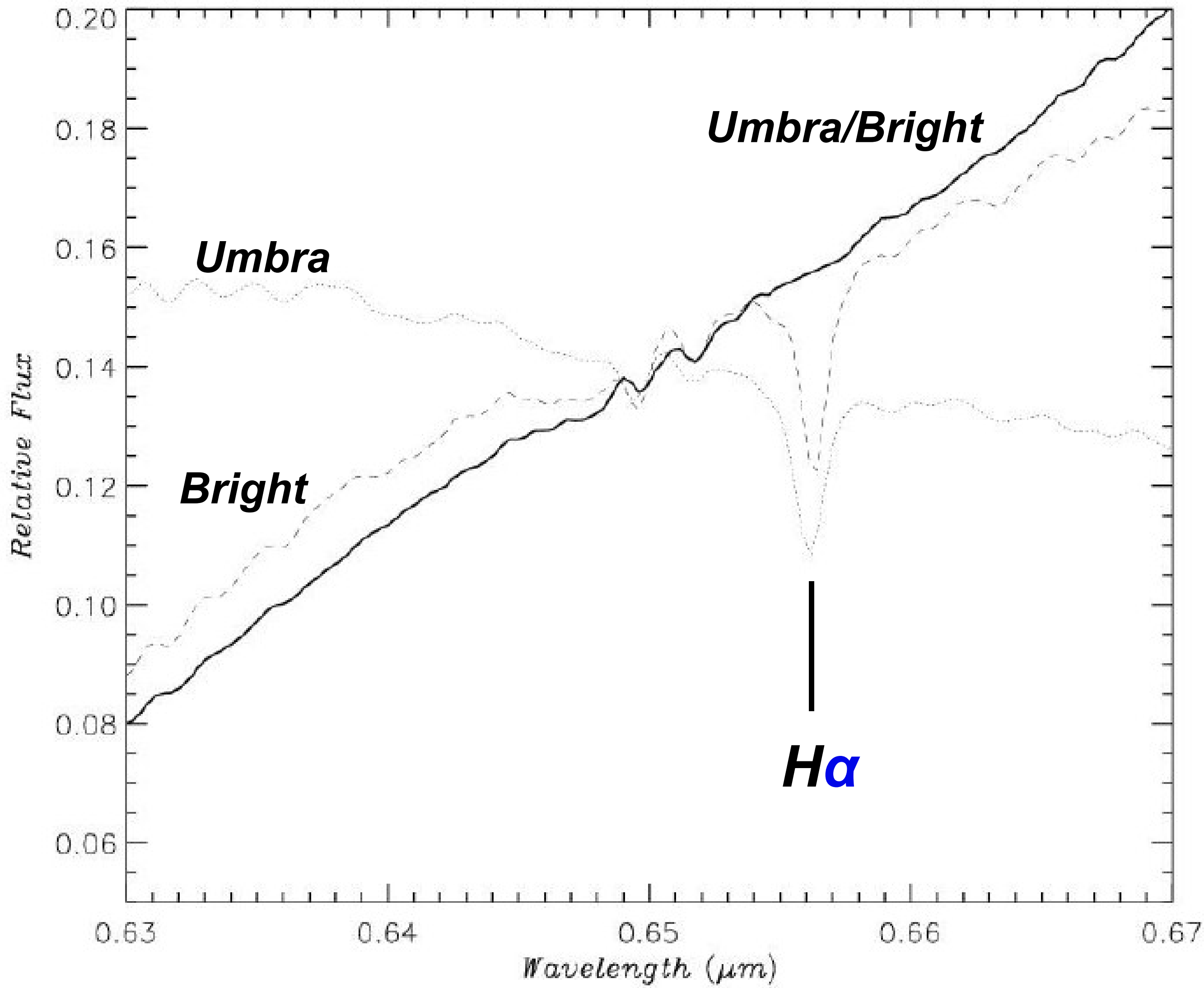

Lunar eclipse
August 16th 2008
um, 38m
FOV 94.5°
63.5 FPS
2008-08-16 21:22:04



Umbra

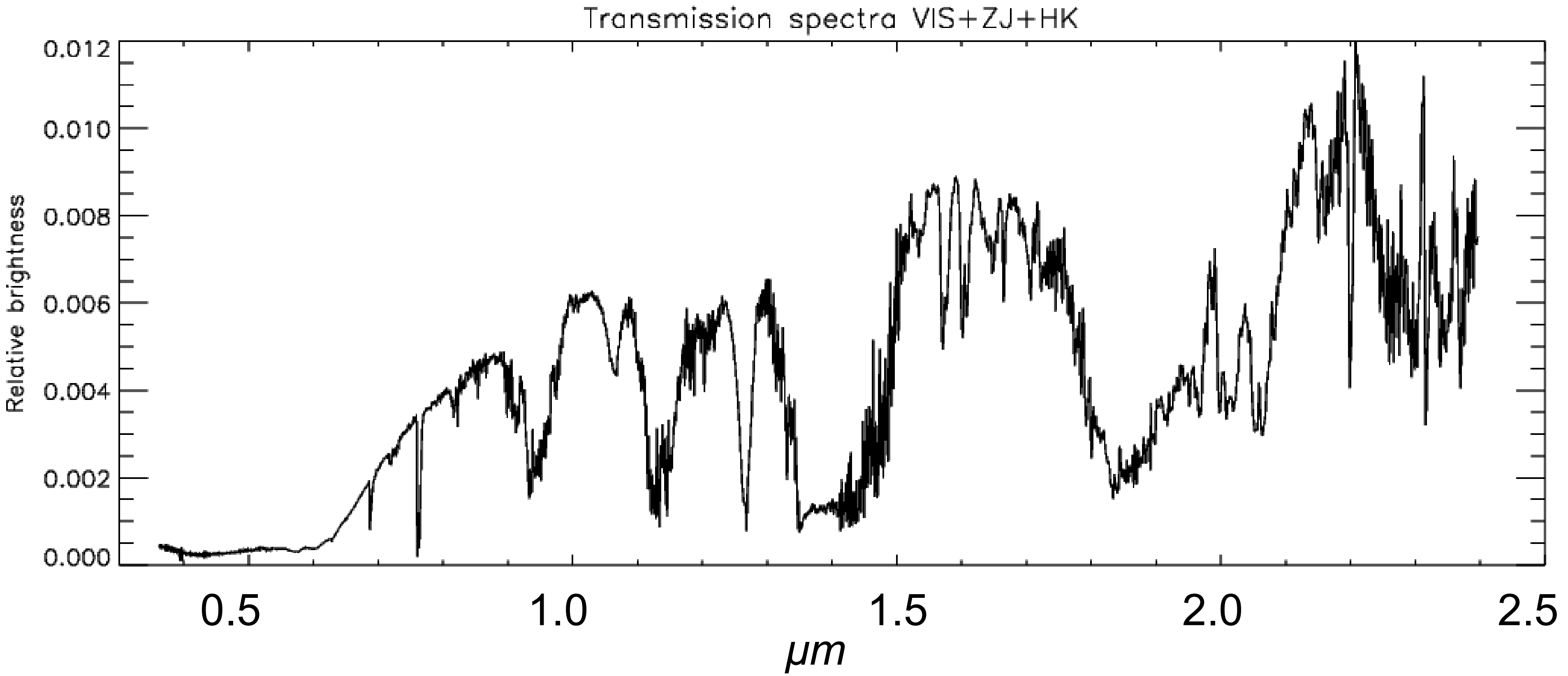
Penumbra

Brigth Moon


Umbra/Bright
Umbra
Bright
Hα
Relative Flux
Wavelength (μm)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.63
0.64
0.65
0.66
0.67

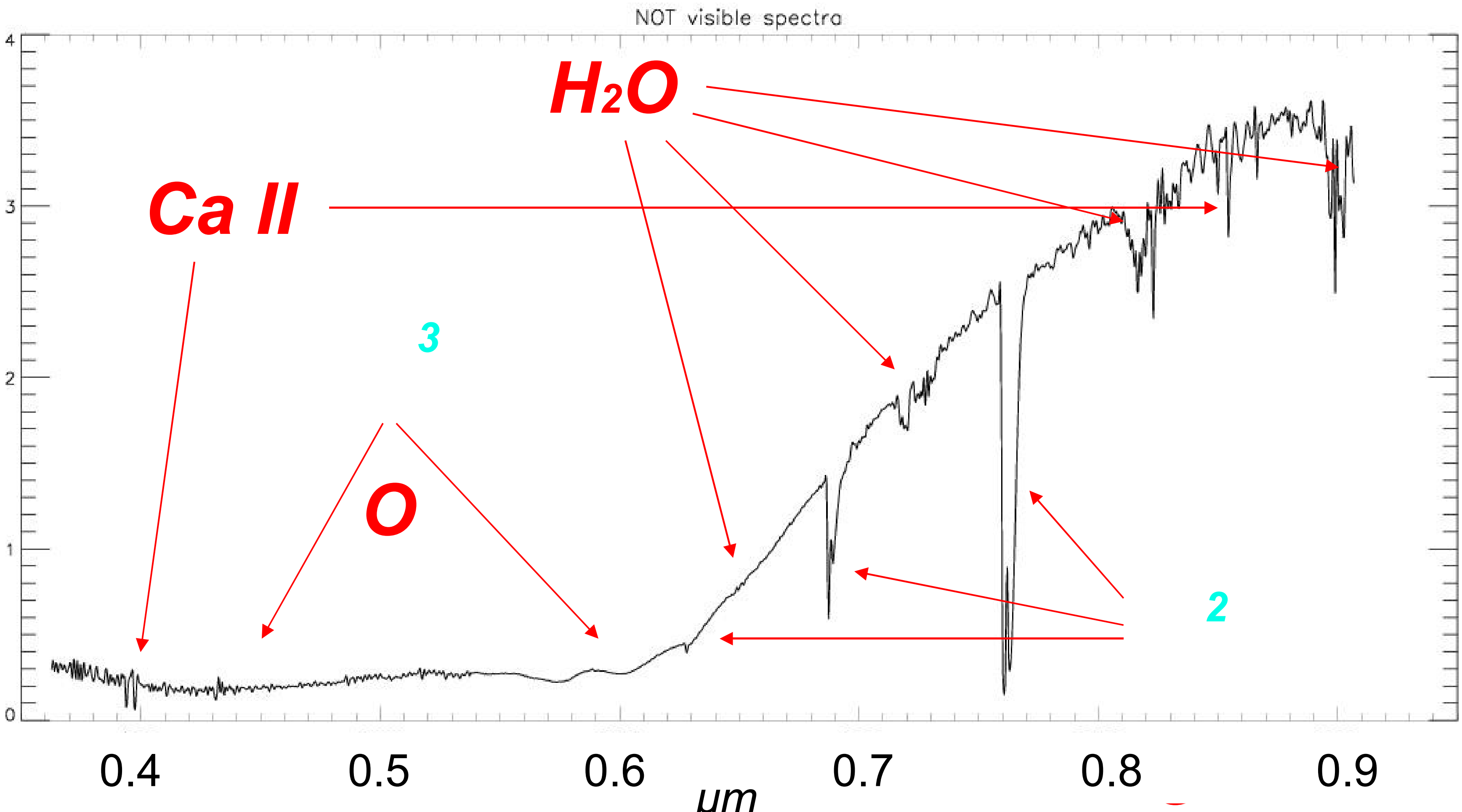
Earth's Transmission Spectrum

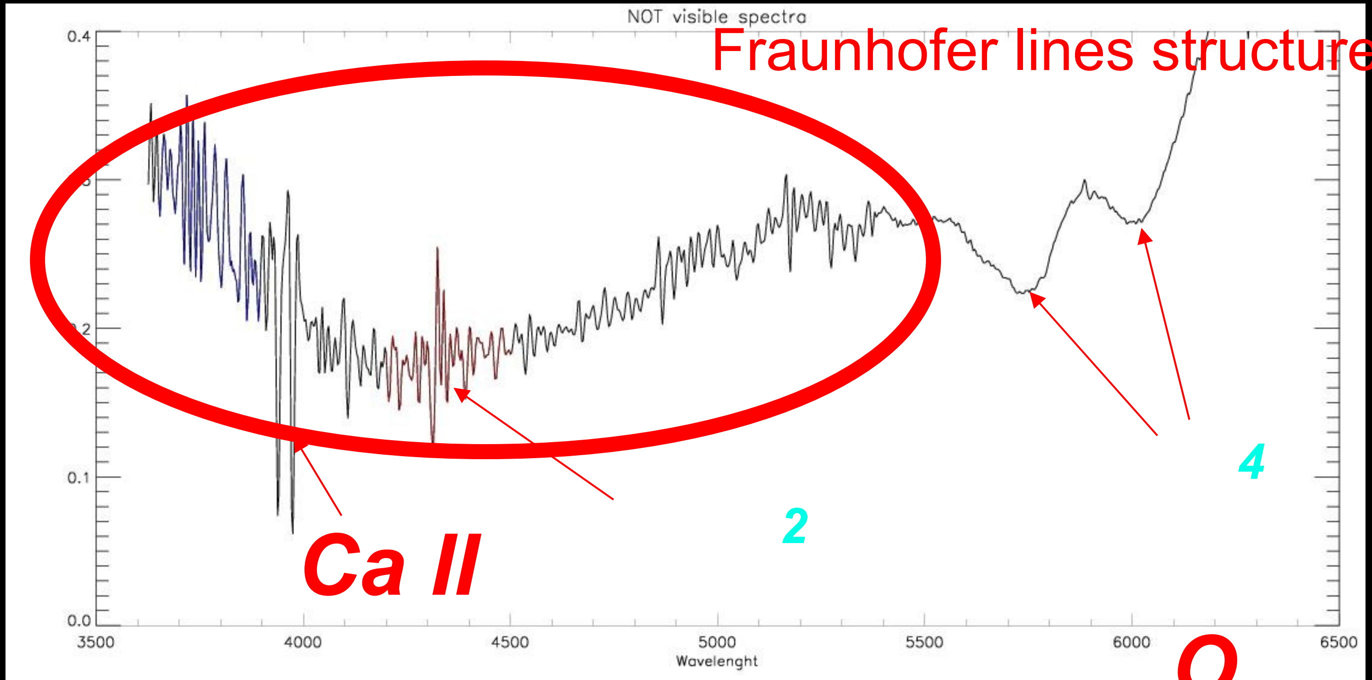
The pale *red* dot

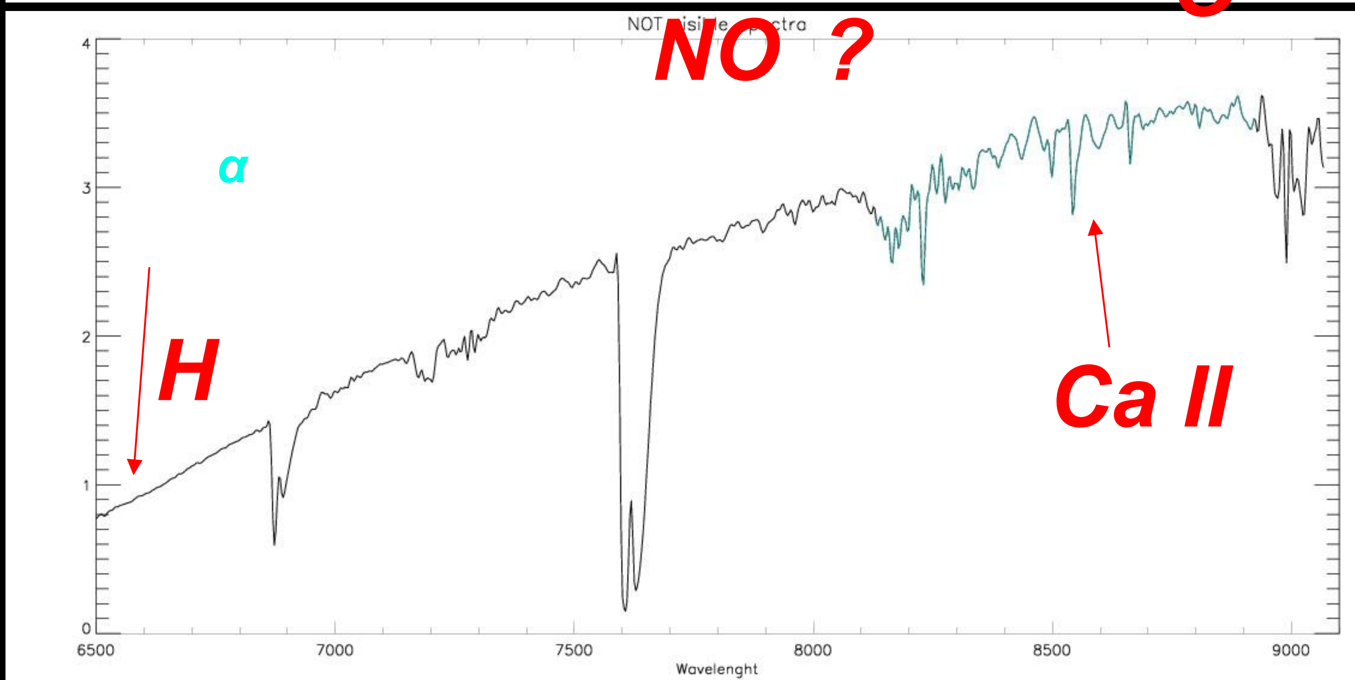


Earth's Transmission Spectrum

Visible

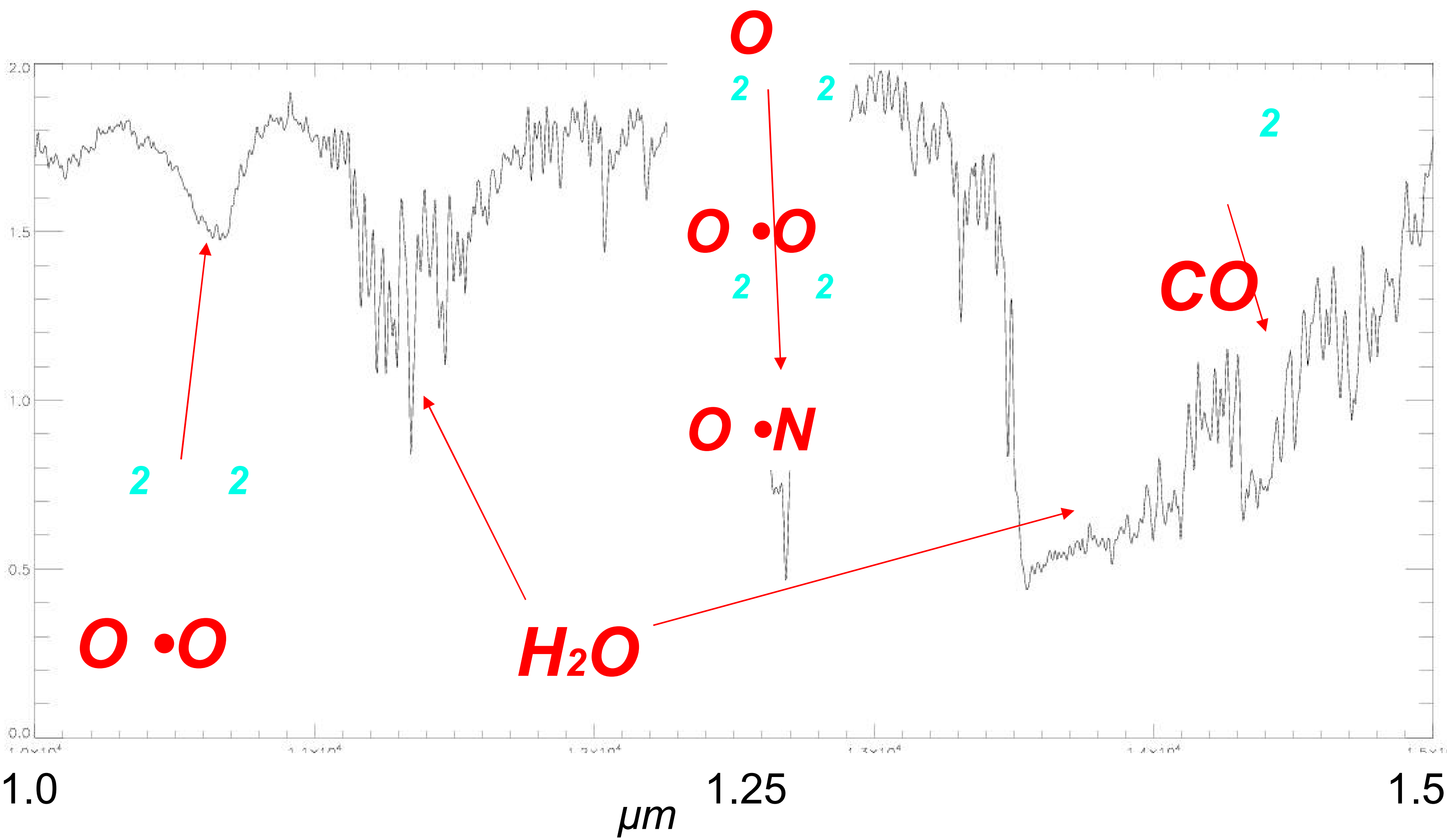



NOT visible spectra
Fraunhofer lines structure
0.4
0.2
0.1
0.0
3500
4000
4500
5000
5500
6000
6500
Wavelenght
Ca II
2
4
O


NOT visible spectra
NO ?
α
H
Ca II
4
3
2
1
0
6500
7000
7500
8000
8500
9000
Wavelenght

Earth's Transmission Spectrum

Near-IR ZJ



Atmospheric Dimers:

Van de Waals molecules: Weakly bound complexes

They are present as *minor* rather than *trace* species.

One likely origin of continuum absorption.

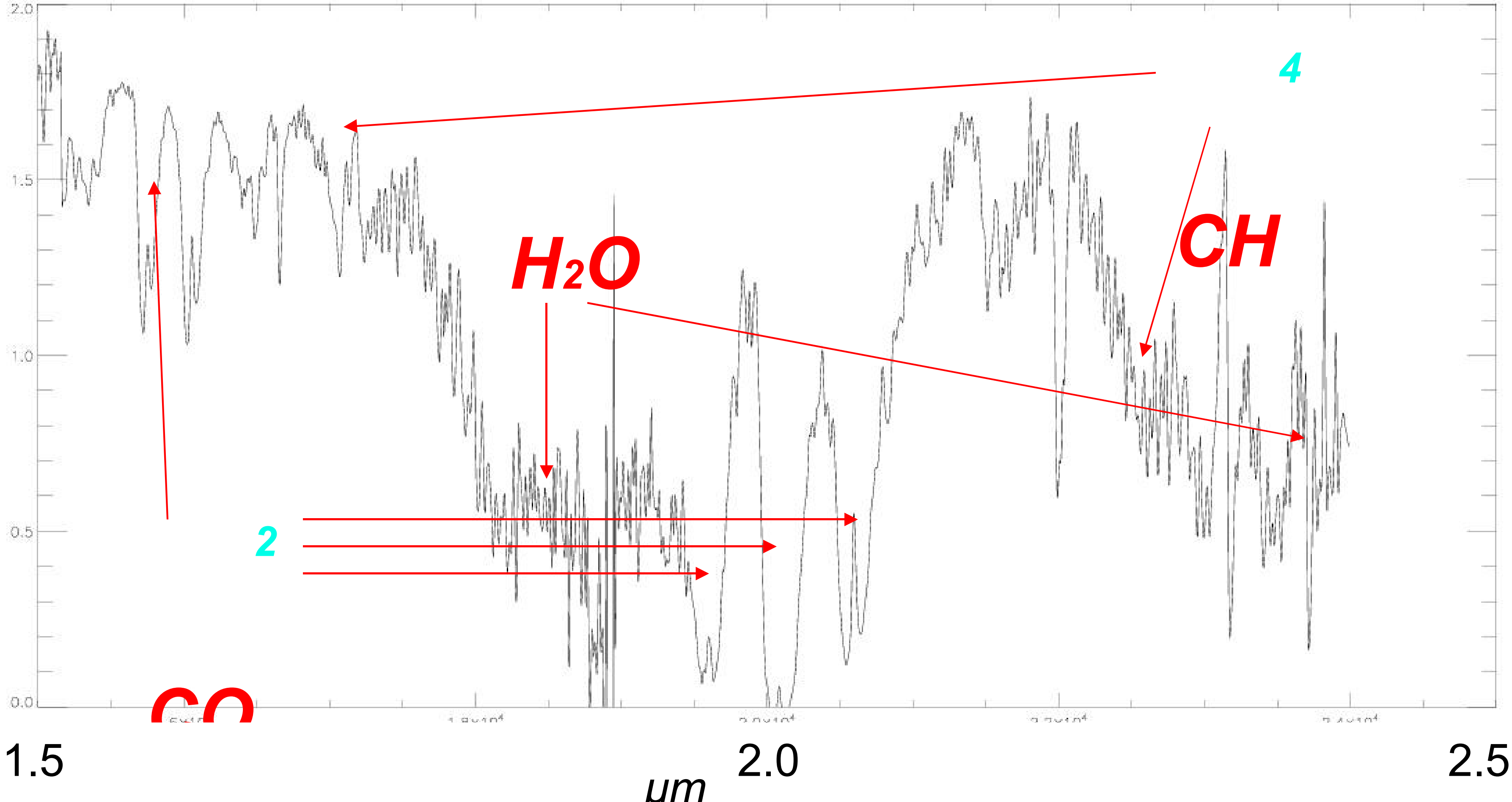
Observed on Earth (gas) and Jupiter (gas; $(H_2)_2$), Ganymede, Europa and Callisto (condensed), and in the laboratory (gas/condensed).

Never on Venus/Mars, where there must be CO_2 – X

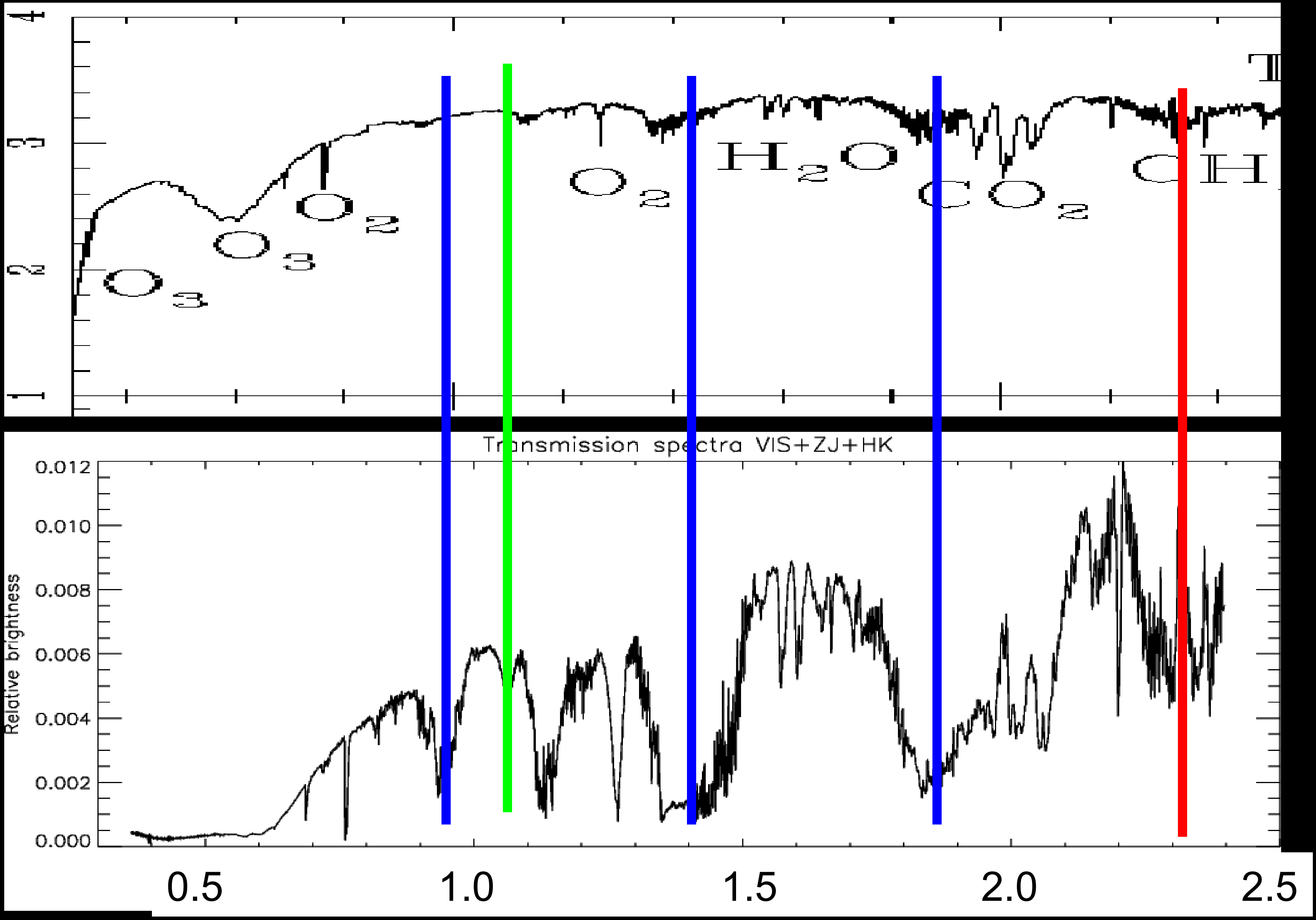
NOT contained in the common spectral libraries

Earth's Transmission Spectrum

Near-IR HK

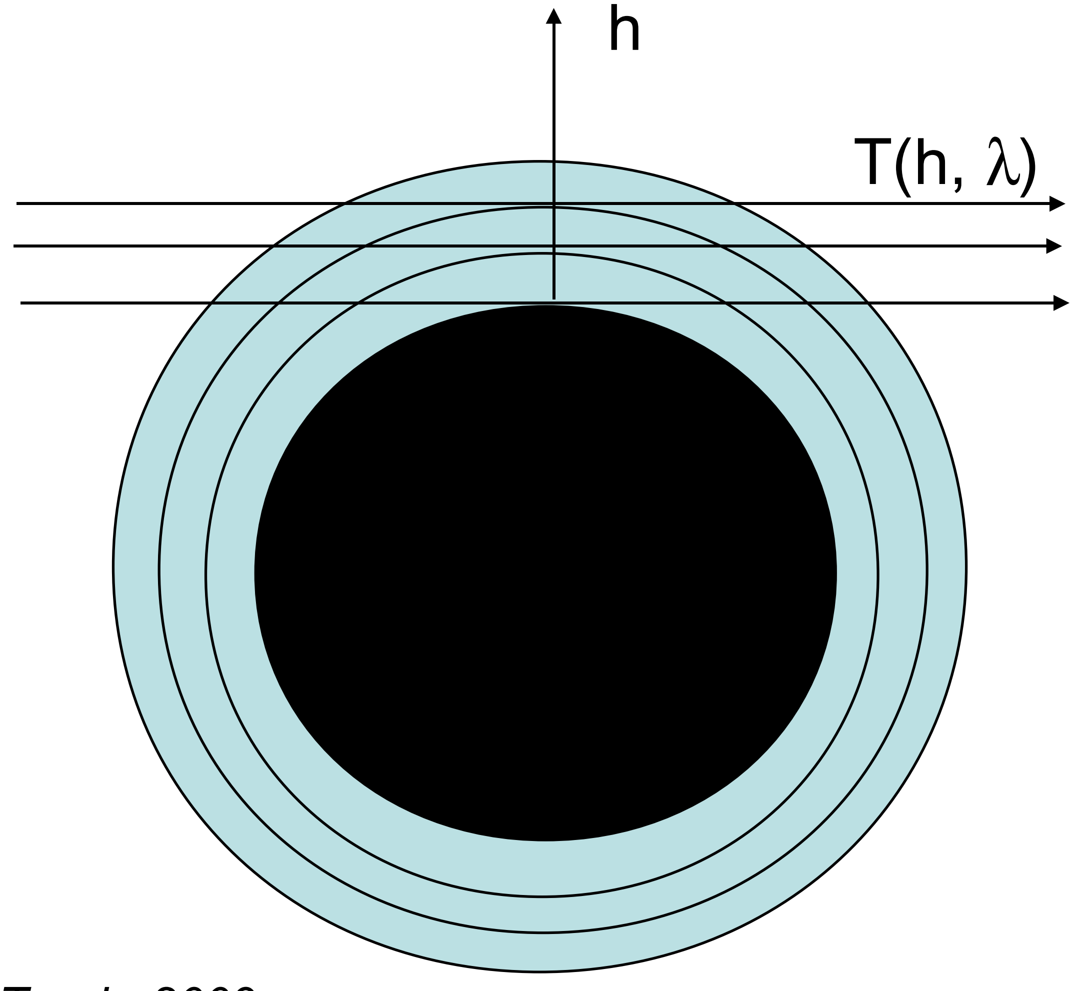


Kaltenegger & Traub 2009



Palle et al, 2009

How deep we see in the planet atmosphere?



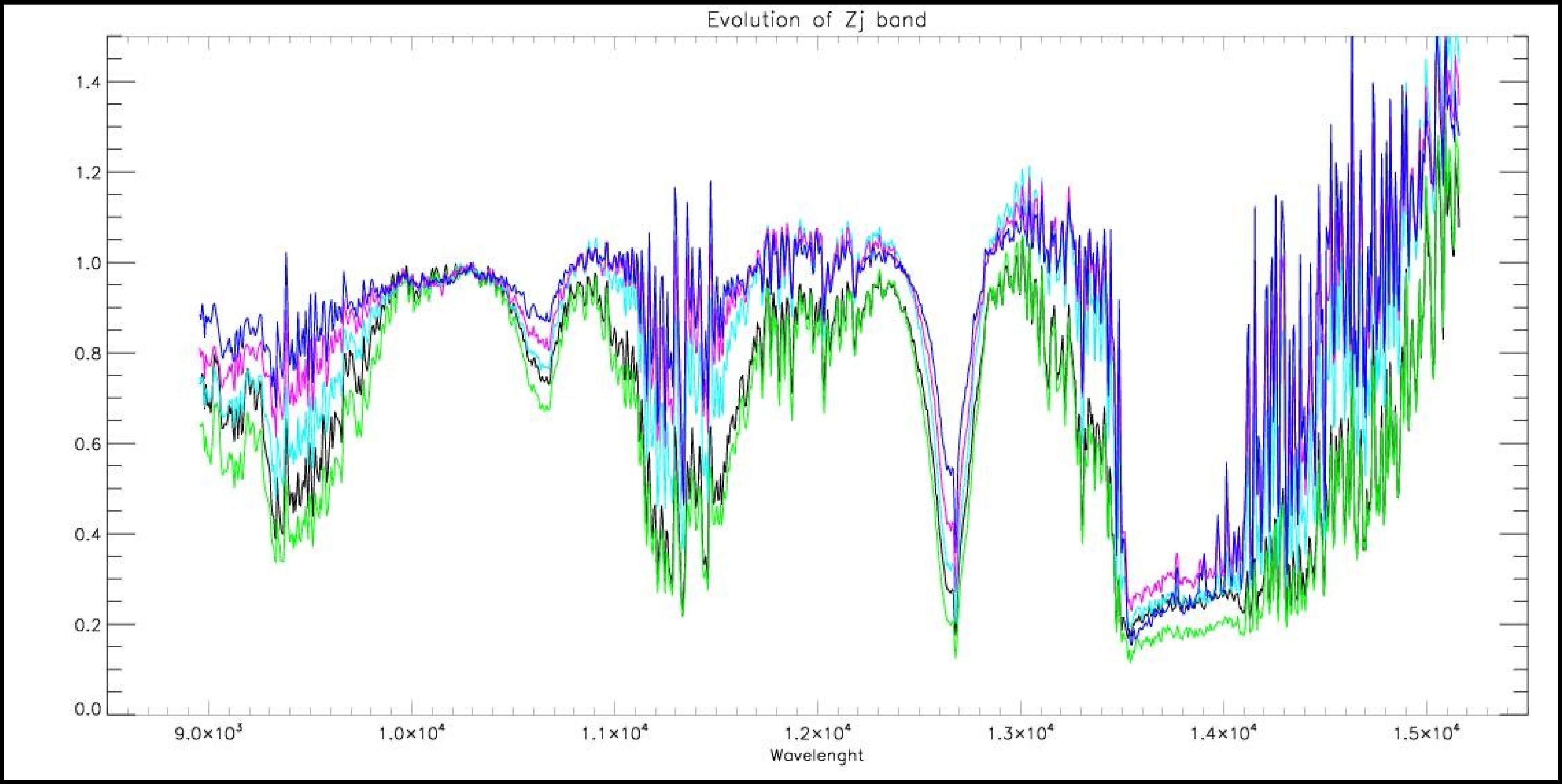
h min ?

- ***Are antropogenic signatures visible in the lower layers?***

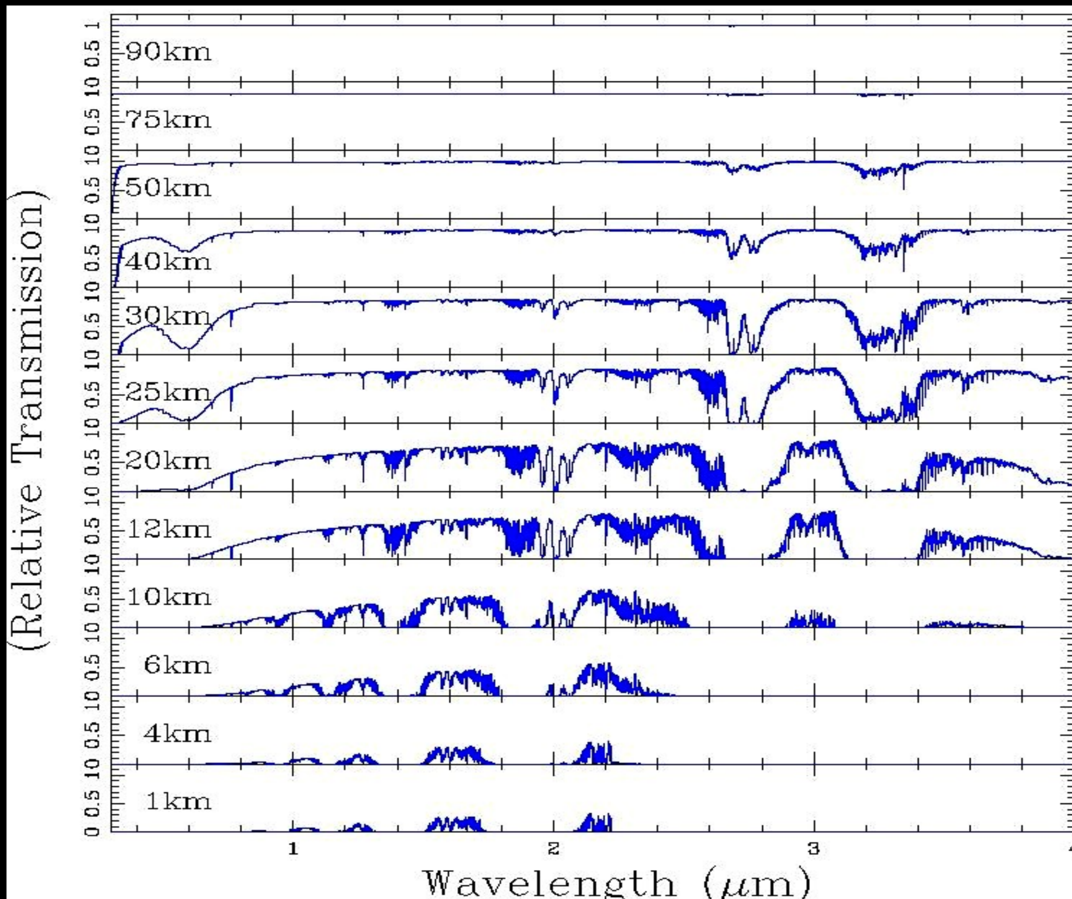
- ***Is there a surface signal?***

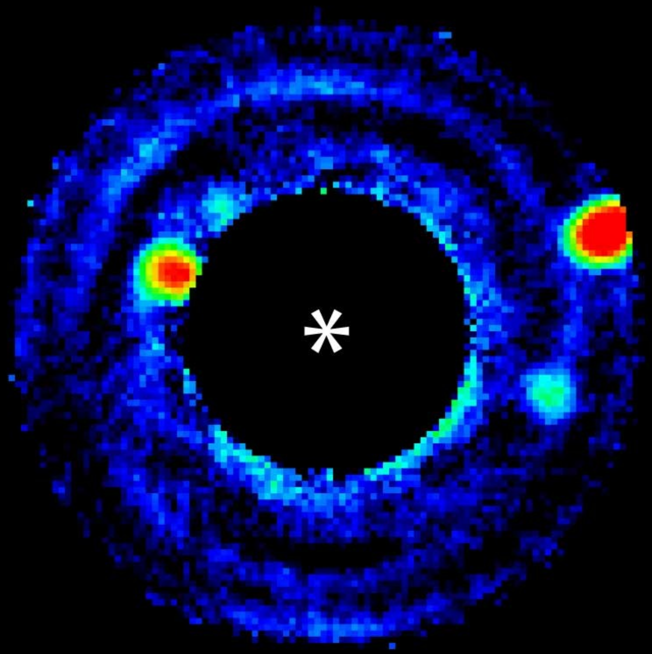
Traub, 2009

Evolution of the Earth’s Transmission Spectrum during the eclipse



How deep we see in the planet atmosphere?

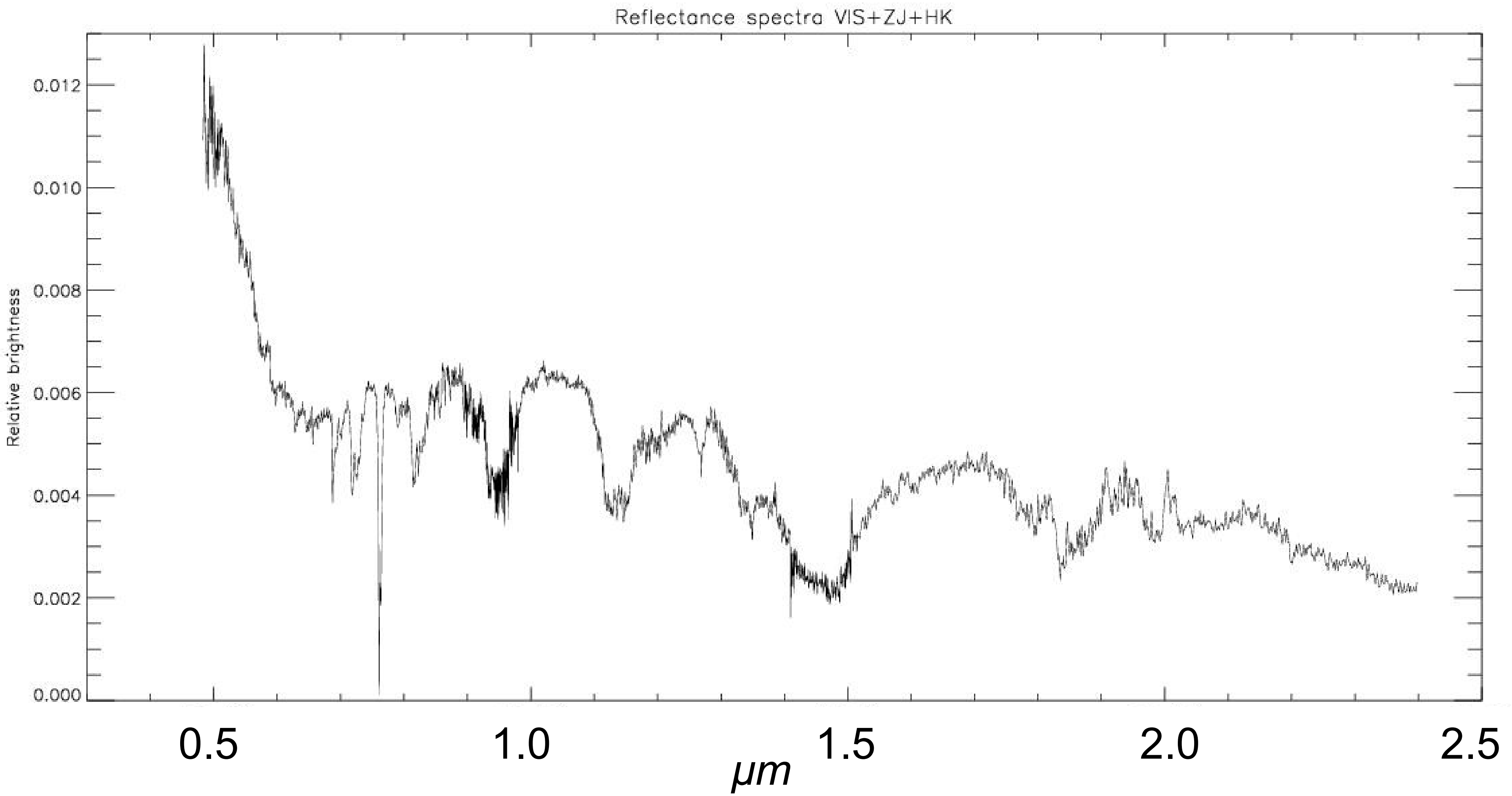


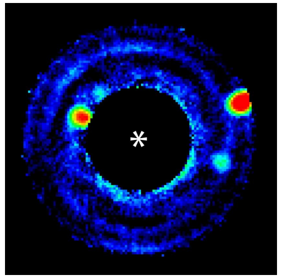


Reflection *vs* *Transmission*

Earth's Reflectance Spectrum: Earthshine

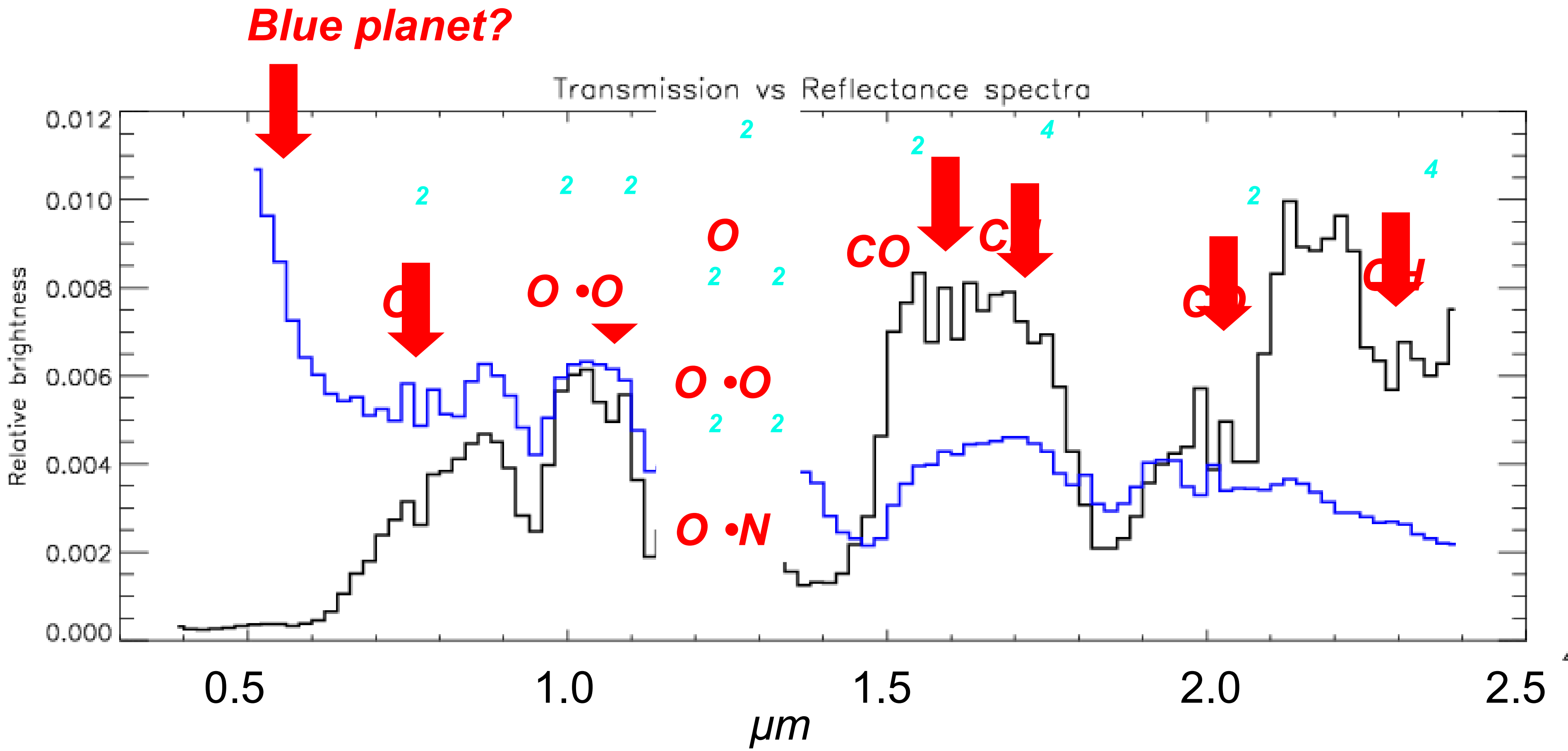
Same instrumentation only two months apart



Reflected spectrum


Transmission Spectrum



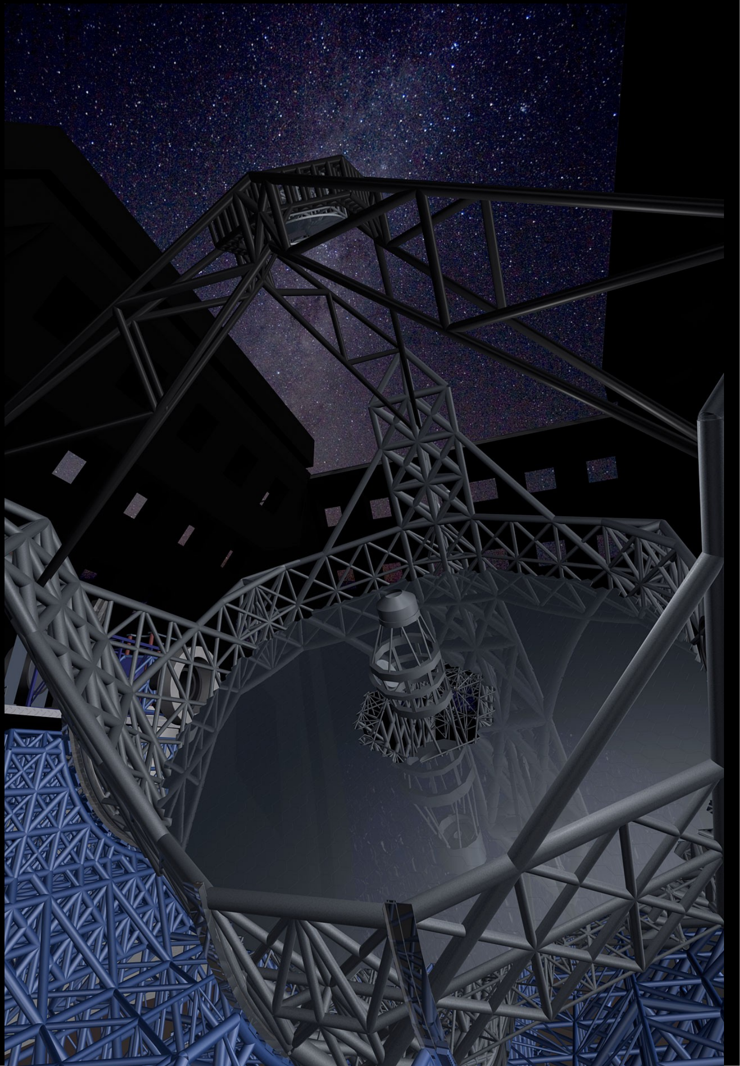
Palle et al, 2009

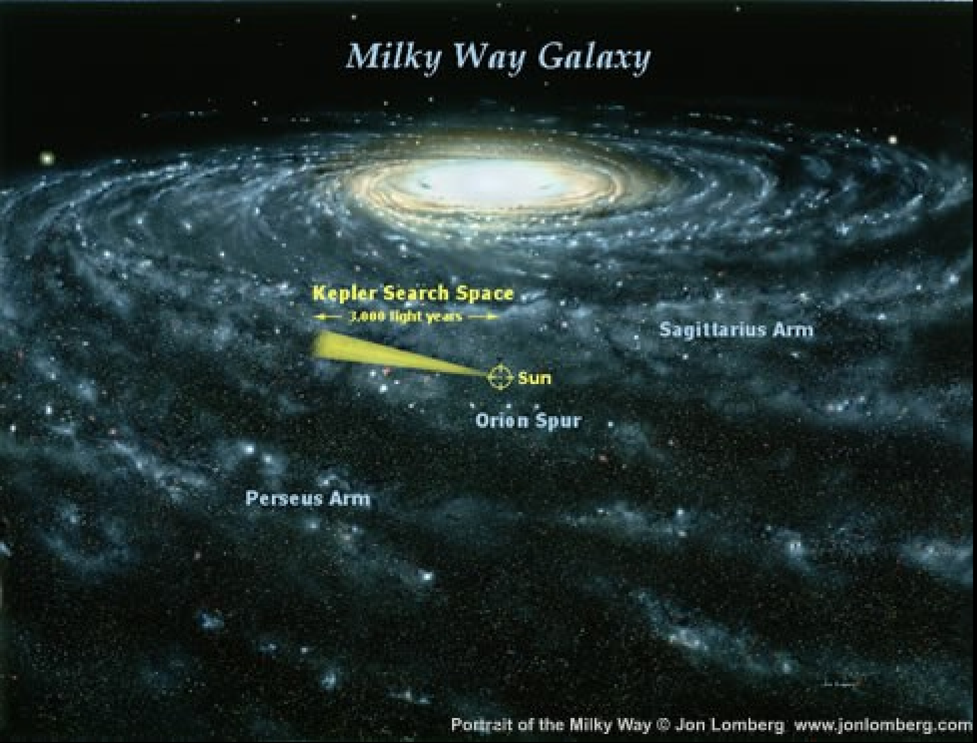
Atmospheric species	Filter wavelengths	Transmission Spectra			Reflection spectra		
		S/N	S/N 10	S/N 5	S/N	S/N 10	S/N 5
H_20	6850 – 6950	2.4	-	-	2.9	-	-
	8100 – 8200	6.0	-	-	9.2	-	-
	9300 – 9400	28.1	2.1	-	8.6	1.6	-
	11200 – 11300	44.0	3.1	1.5	10.0	-	-
	13500 – 13600	53.5	3.8	2.0	6.5	-	-
	18300 – 18400	69.4	4.7	2.3	8.2	1.5	-
O_2	7850 – 7680	26.1	1.5	-	8.0	2.5	-
$O_2 \cdot O_2$	5700 – 5800	12.0	-	-	-	-	-
	10600 – 10700	23.0	-	-	2.0	-	-
	12540 – 12640	29.0	2.4	-	2.6	-	-
$O_2 \cdot O_2$, $O_2 \cdot N_2$	12650 – 12750	35.6	2.8	1.5	5.8	-	-
CO_2	15700 – 15800	23.0	2.1	-	-	-	-
	16000 – 16100	21.8	1.6	-	-	-	-
	20100 – 20200	24.2	5.1	2.3	1.8	-	-
	20600 – 20700	26.1	5.3	2.3	-	-	-
CH_4	16400 – 16500	9.0	-	-	1.7	-	-
	22300 – 22400	2.7	2.2	1.6	-	-	-
	22500 – 22600	5.4	3.4	2.2	2.1	-	-
	22900 – 23000	6.6	4.2	2.7	2.7	-	-

Thus, the transmission spectrum of telluric planets contains more information for the atmospheric characterization than the reflected spectrum.

And it is also less technically challenging

But, how far are we from making the measurements ?





CoRoT & KEPLER can provide this input

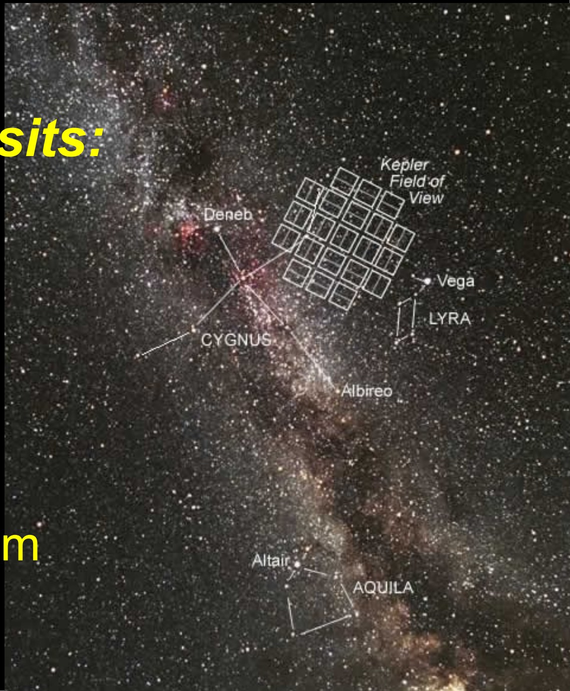
Many other surveys: Plato, TESS, Ground-based searches, ...

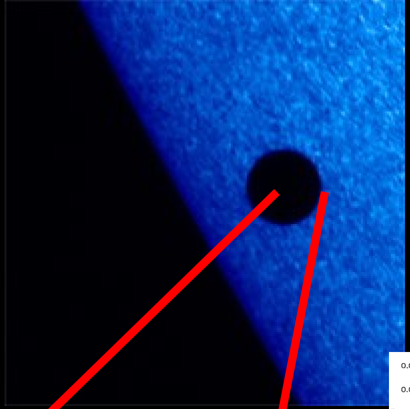
Terrestrial inner-orbit planets based on their transits:

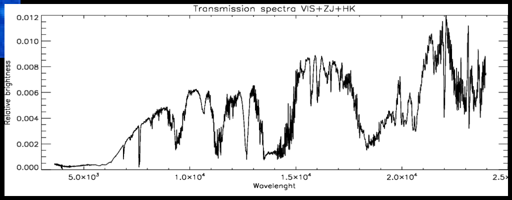
- About planets if most have R ~ 1.0 Re
- About planets if most have R ~ 1.3 Re
- About planets if most have R ~ 2.2 Re

(Or possibly some combination of the above)

About 12% of the cases with two or more planets per system





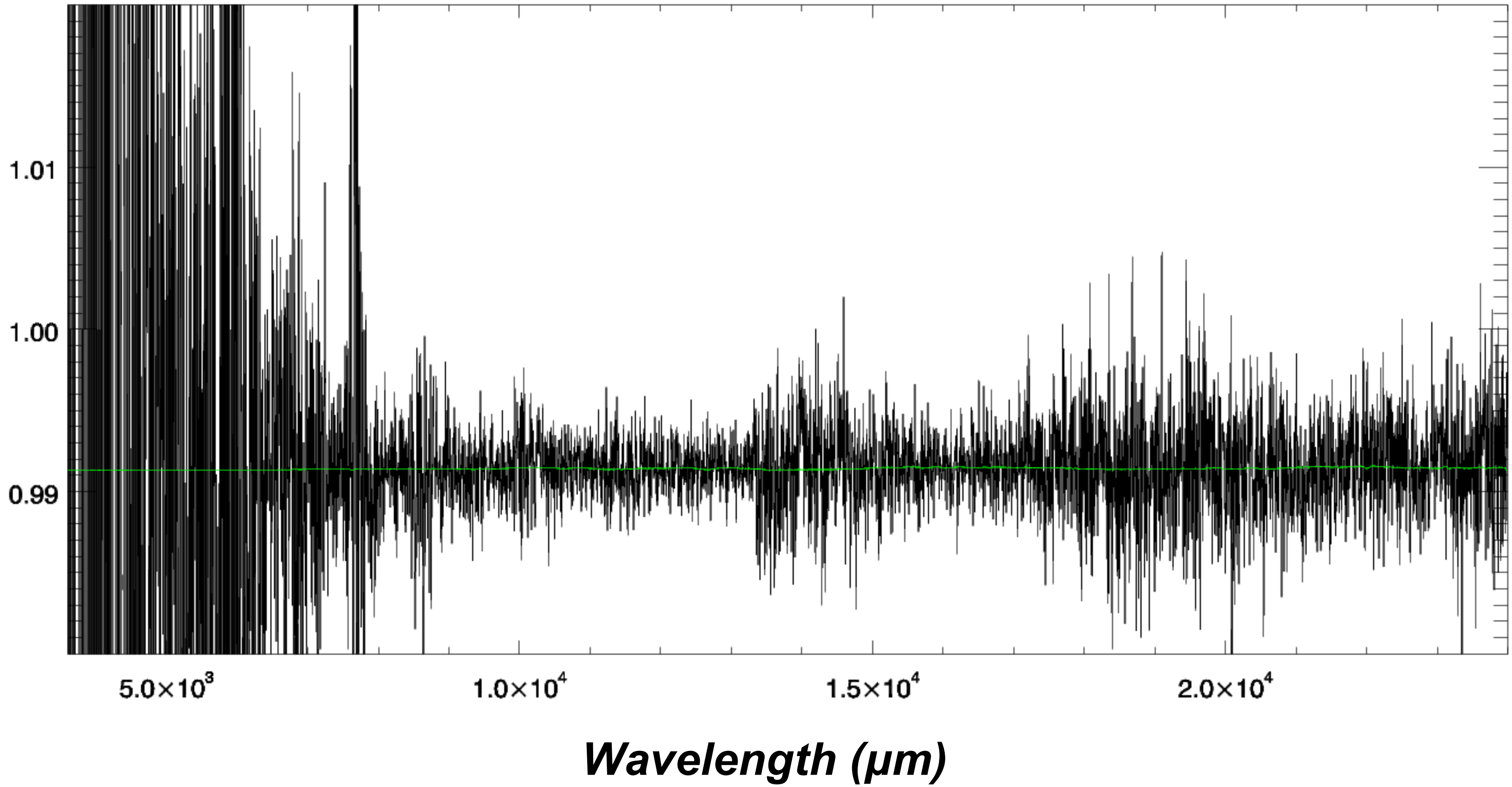

Transmission spectra VIS+ZJ+HK
Relative brightness
Wavelenght
0.012
0.010
0.008
0.006
0.004
0.002
0.000
5.0×10³
1.0×10⁴
1.5×10⁴
2.0×10⁴

+ Noise

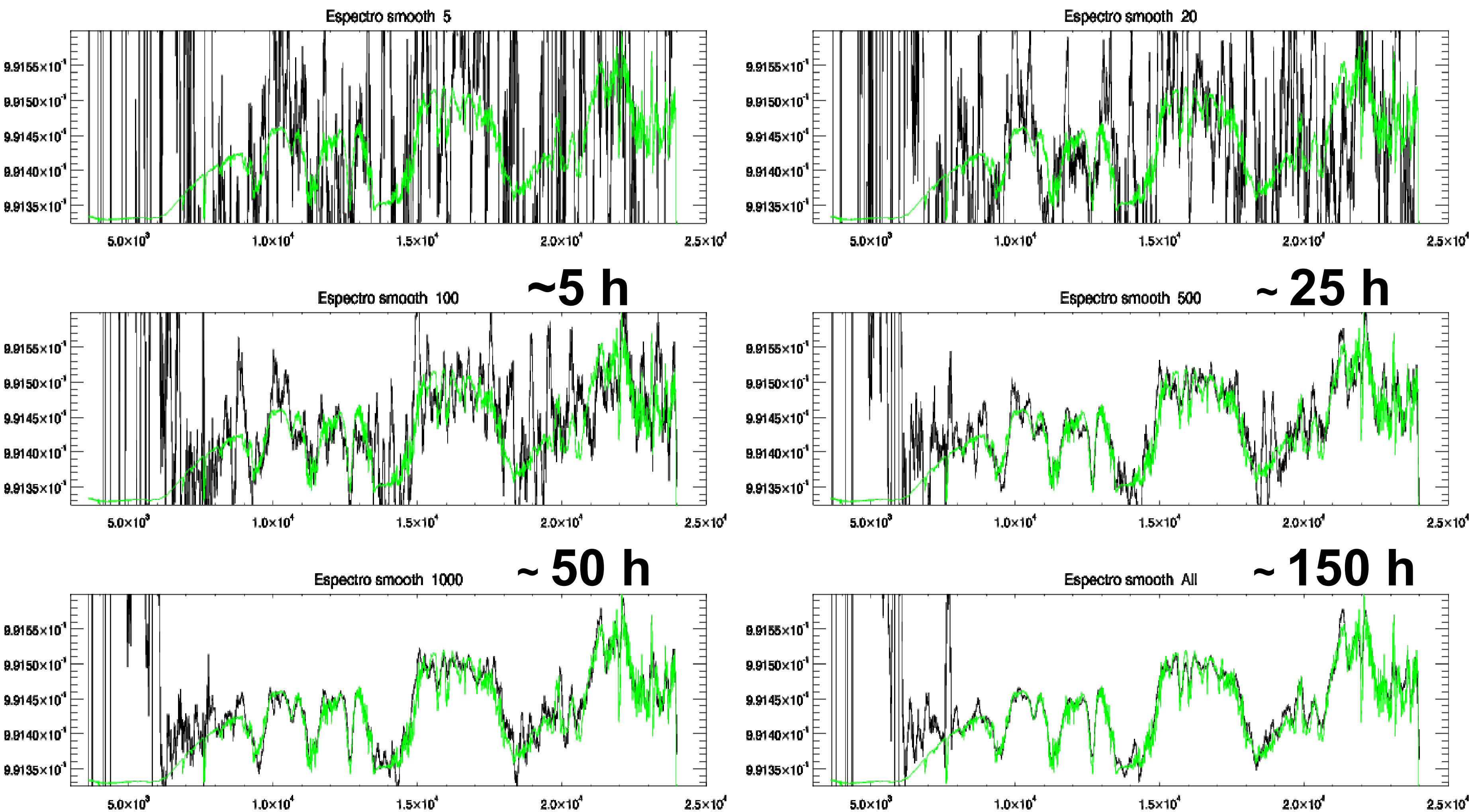
+ Noise

Differential transit spectroscopy M star + Earth : 1 (2) measurement

Ss+p / Sp



M8 star + 1 Earth ... with the E-ELT

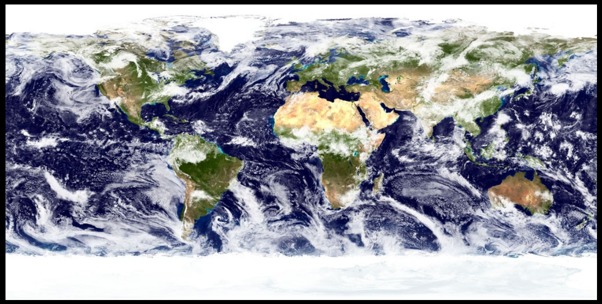


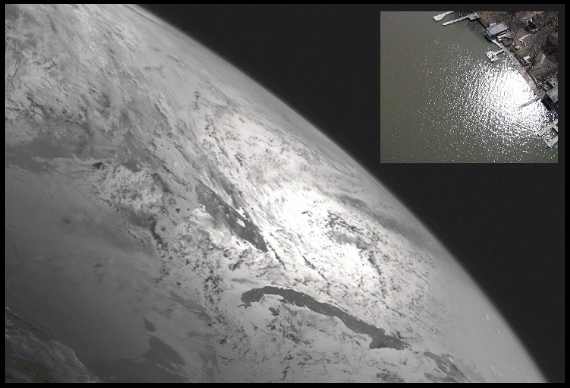
Wavelength (µm) ***Wavelength (µm)***

Work in progress ...

Still, we must pursue the characterization with direct observations

- *Exploration of surface features*
  - *Presence of continents*
  - *Rotational period*
  - *Localized surface biomarkers (vegetation)*
- *Orbital light curve*
- *Ocean glints and polarization effects*





Conclusions

- *We have obtained the Earths transmission spectra 0.4-2.5 μm*
  - *First order detection and characterization of the main constituents of the Earth's atmosphere*
  - *Detection of the Ionosphere : Ca II, (Mg, Fe, ??)*
  - *Detection of $O_2 \bullet O_2$ and $O_2 \bullet N_2$ interactions*
  - *Offers more information than the reflectance spectra*

- *Using the measured Earth transmission spectrum and several stellar spectra, we compute the probability of characterizing a transiting earth with E-ELT*
  - *For a Earth in the habitability zone of an M-star, it is possible to detect H_2O , O_2, CH_4 ,CO_2 (= Life) within a few tens of hours of observations.*


Thank you
© Daniel López


Thank you

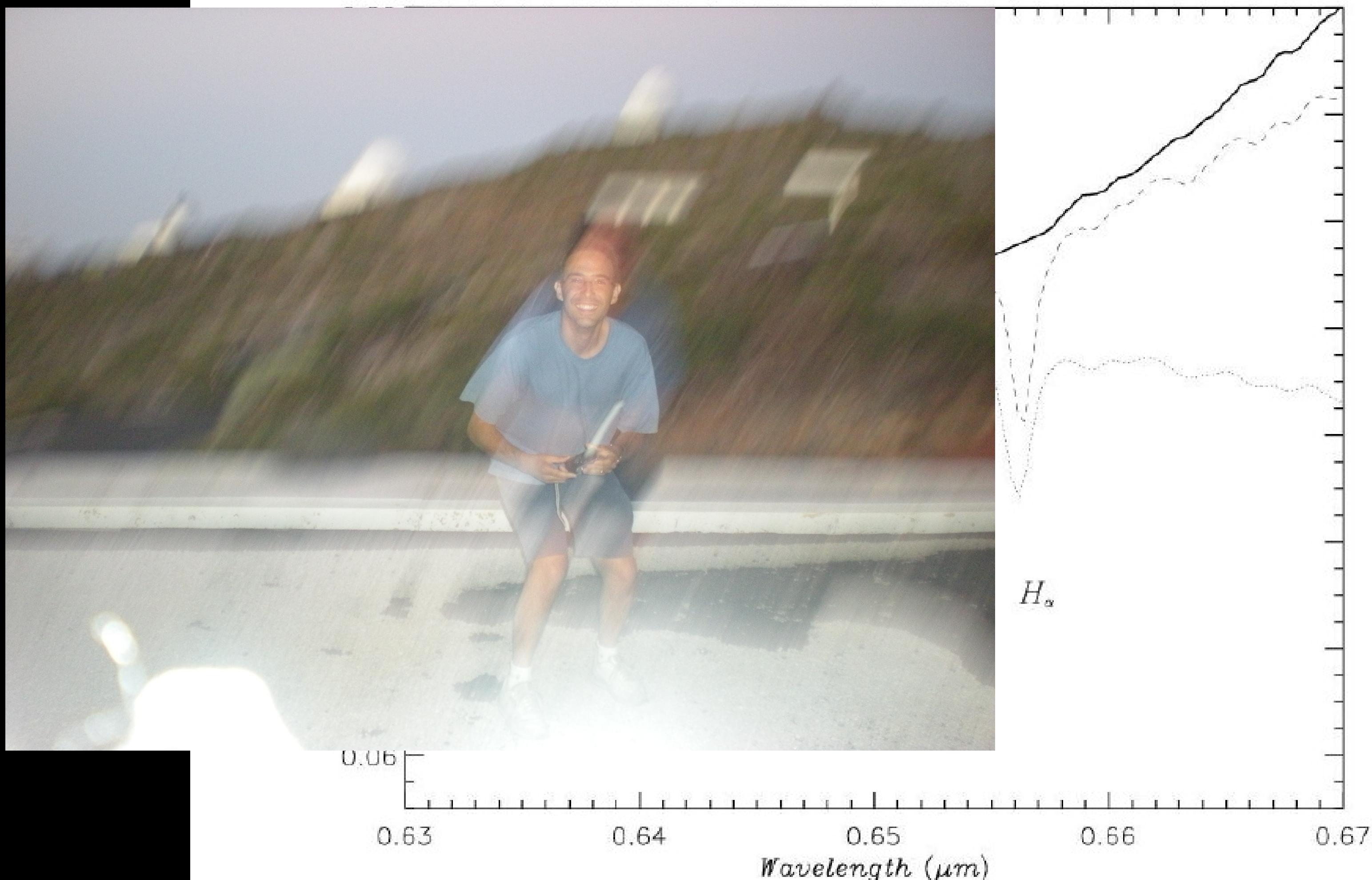


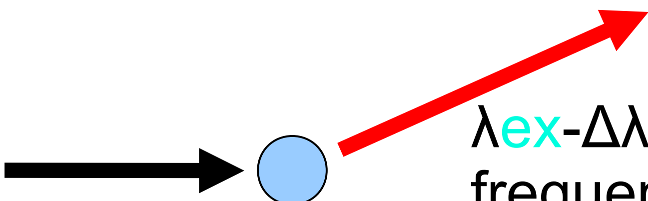
Figure S4: *A detail of the umbra spectrum (broke line), the brigh Moon spectrum (dotted line) and their ratio spectrum (umbra/bright) around the hydrogen alpha (H_α) line (0.6568 μm). The H_α solar line is a great example to illustrate the high S/N of our observations. In this figure, one can see that the H_α is present in the raw spectra of the umbra and the bright Moon, but not in the final transmission spectra. The S/N ratio in all the spectra is so large that the ratio umbra/bright completely removes any contribution from the solar spectrum and the local telluric atmosphere.*

The Ring effect

Rotational Raman Scattering (RRS)

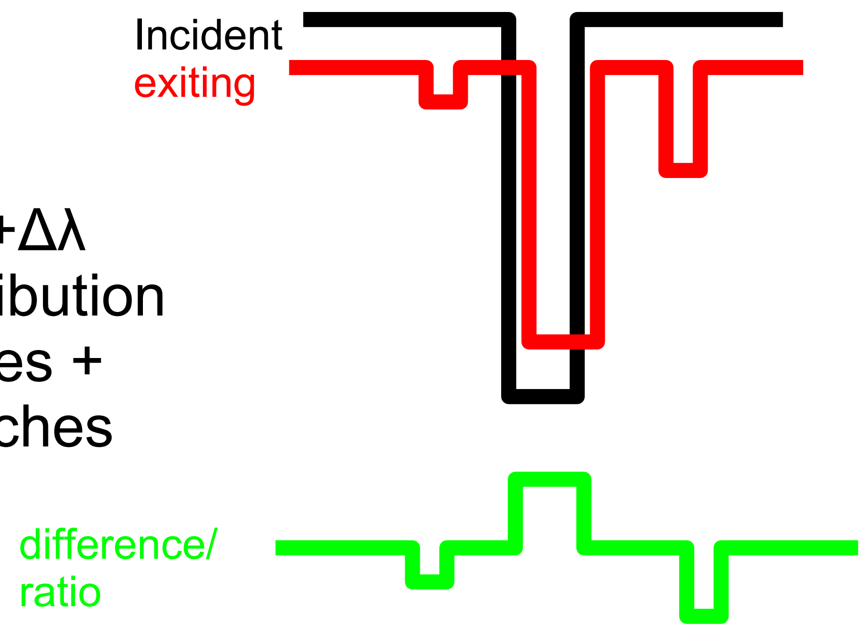
Early evidence:

Sky-scattered Fraunhofer lines were less deep but broader than solar lines

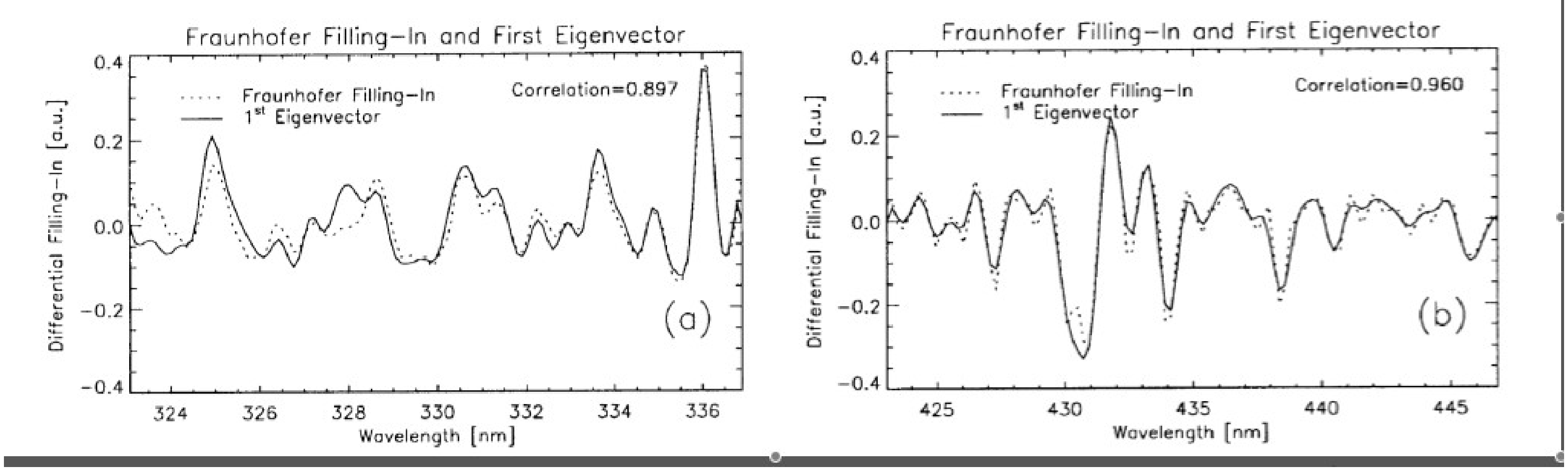


λex
incident photon

λex-Δλ, λex, λex+Δλ
frequency redistribution
Incident λ + Stokes +
Anti-Stokes branches



The Ring effect: Rotational Raman scattering



Vountas et al. (1998)