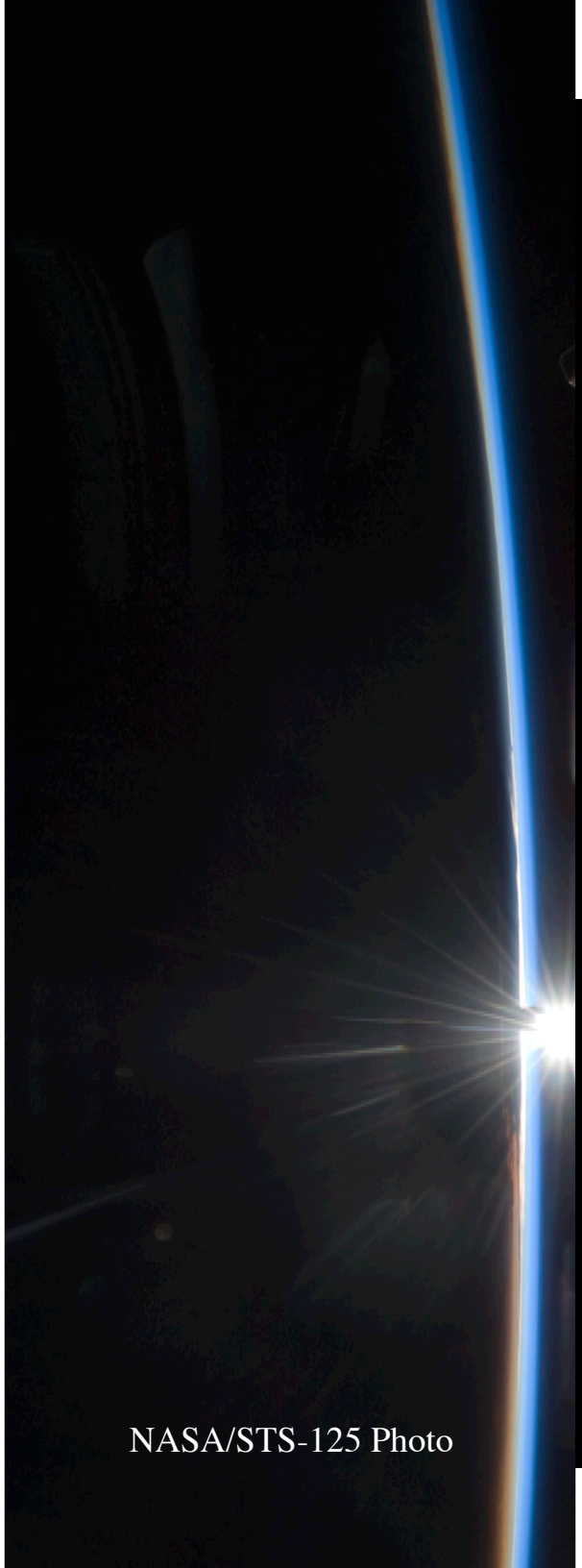


NASA/STS-125 Photo

Super-Earths & Life
A interdisciplinary puzzle

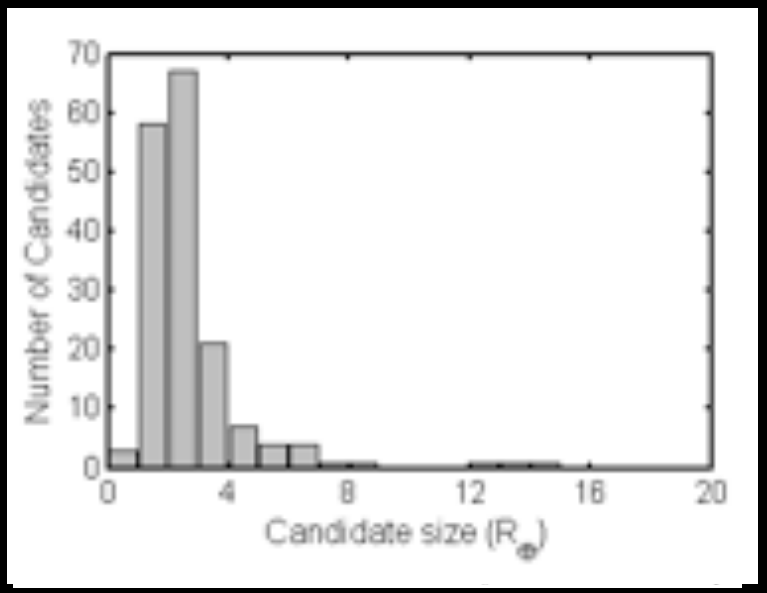
Biomarkers of Habitable Worlds

Lisa Kaltenegger, MPIA/CfA

Bad Honeff, June 8 2011

Planets… 550+ (1235)

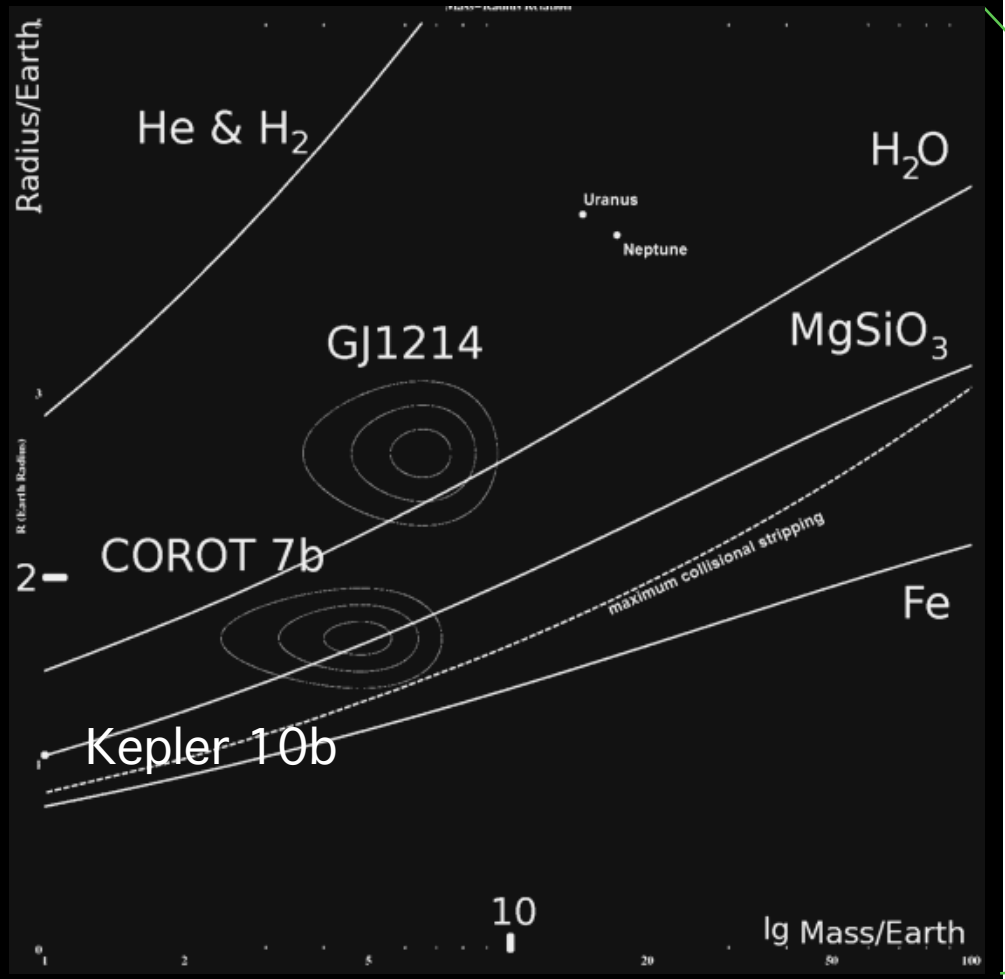
age of statistics

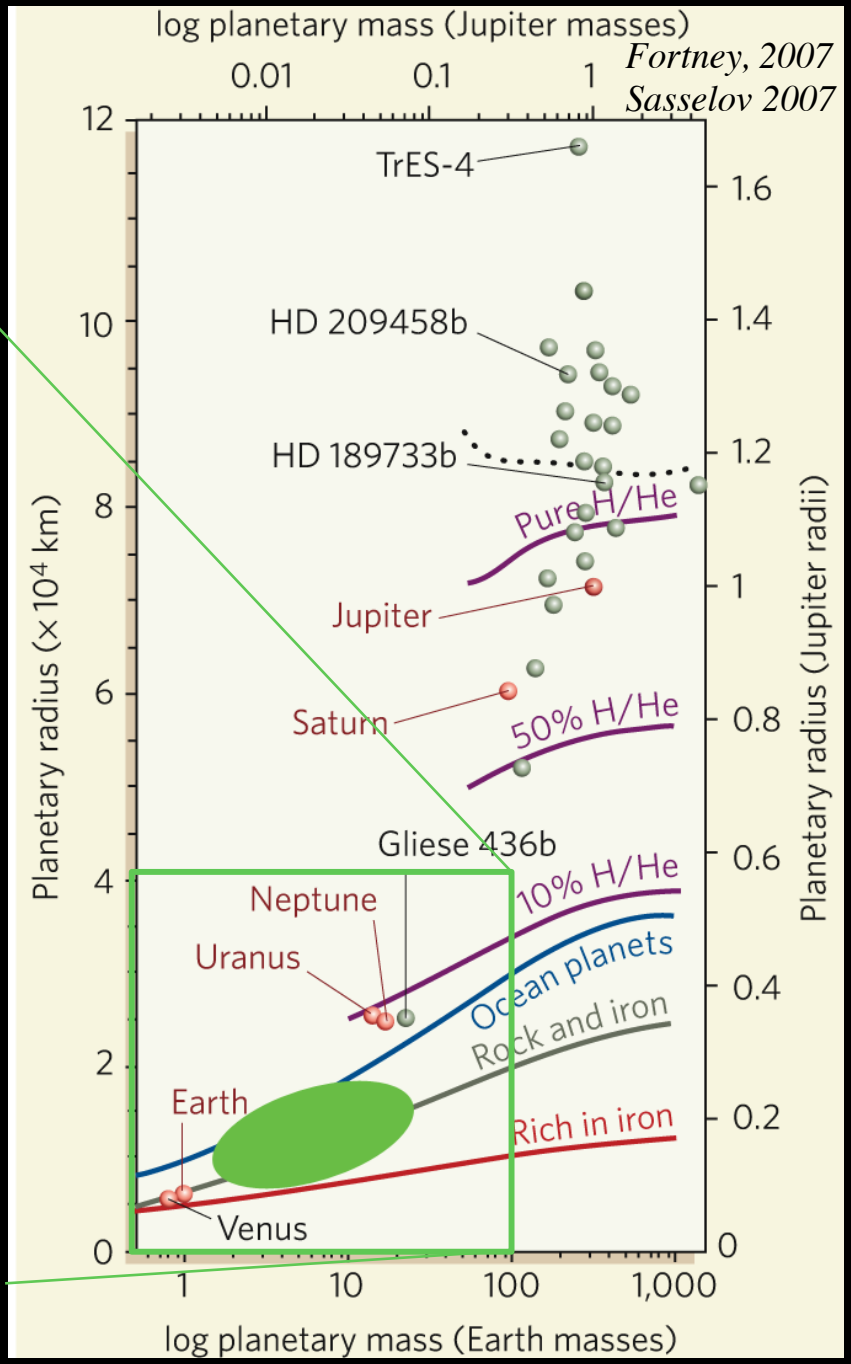


The real question:

What are they like?

RV & Transits: density



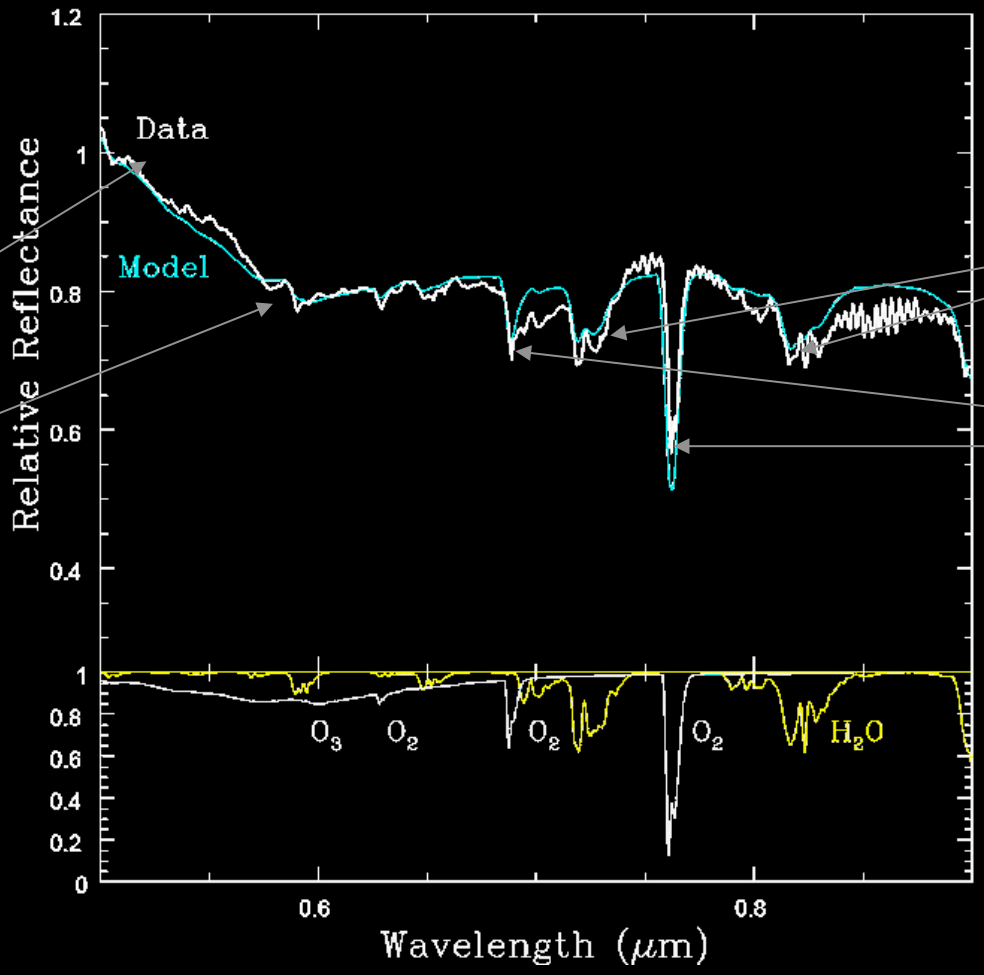


Zeng & Sasselov (in press)

Visible spectrum of Earth

Rayleigh

Ozone O_3



Water H_2O

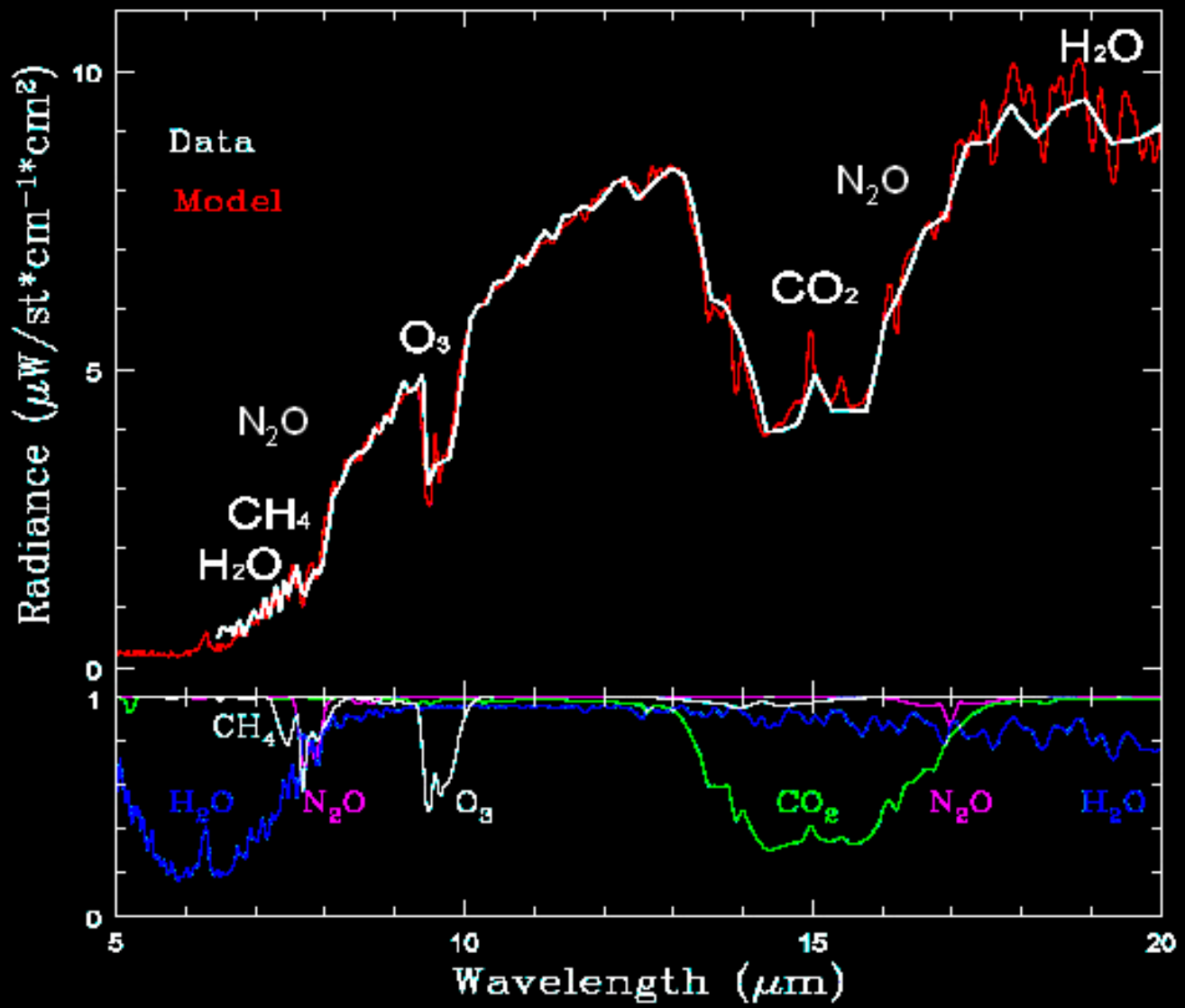
Oxygen O_2

Observed Earthshine, reflected from dark side of moon.

Ref.: Kaltenegger et al 2007, ApJ 574, 2007

see also e.g.: Montanez-Rodrigez 2005, 07, Arnold 2002, 06, 09; Turnbull 06

Earth IR-emission



Kaltenegger, Traub, Jucks 2007 (ApJ)

TES data; Christensen 2004

Signs Of Life On An Earth-like Planet

Ozone & Methane (or other reducing gas) Biomarker
Oxygen

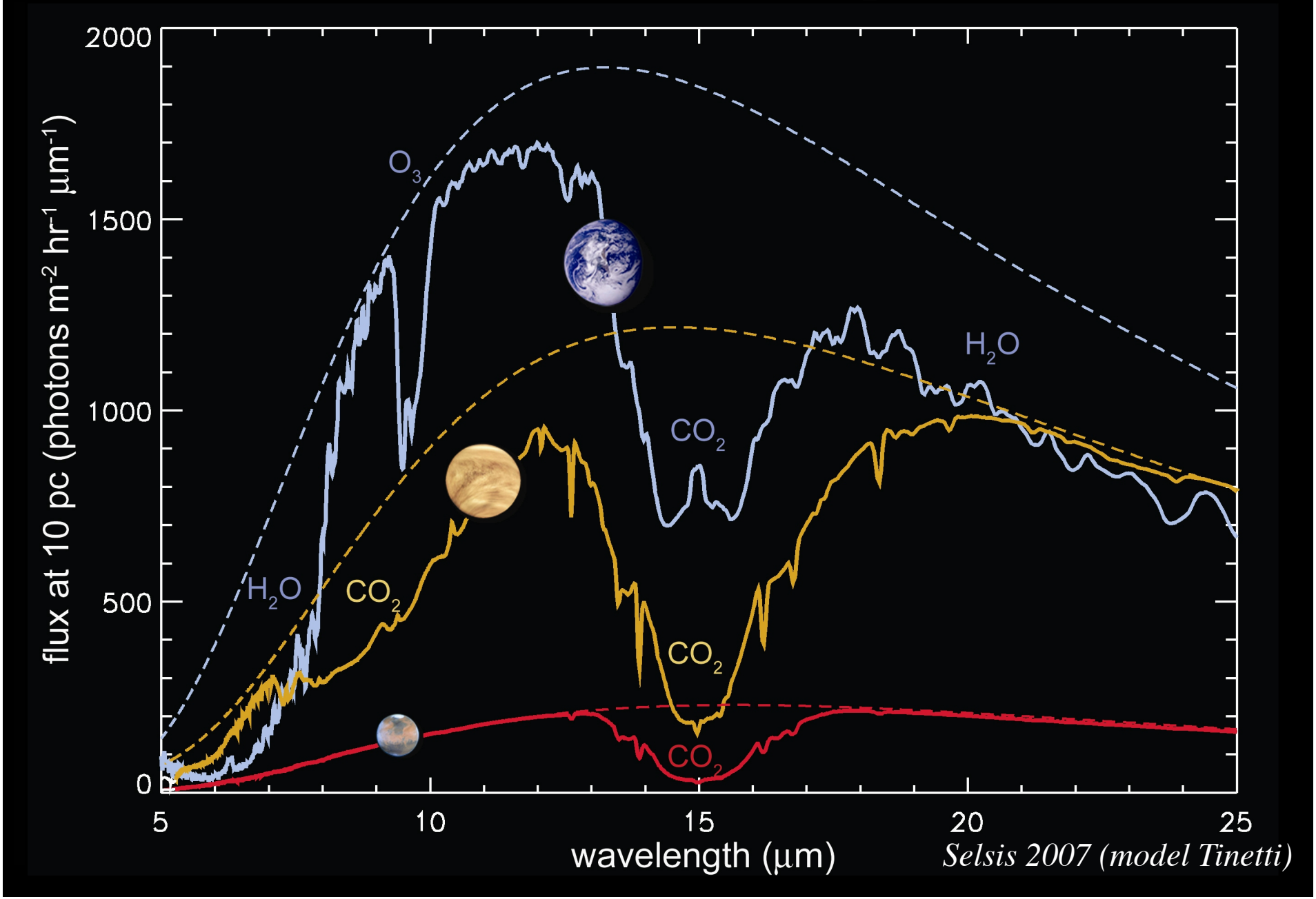
Nitrous oxide ? (see Grenfell's talk)

Water makes Oxygen – WITHOUT life Bio-indicators

Carbon dioxide - greenhouse & HZ extend

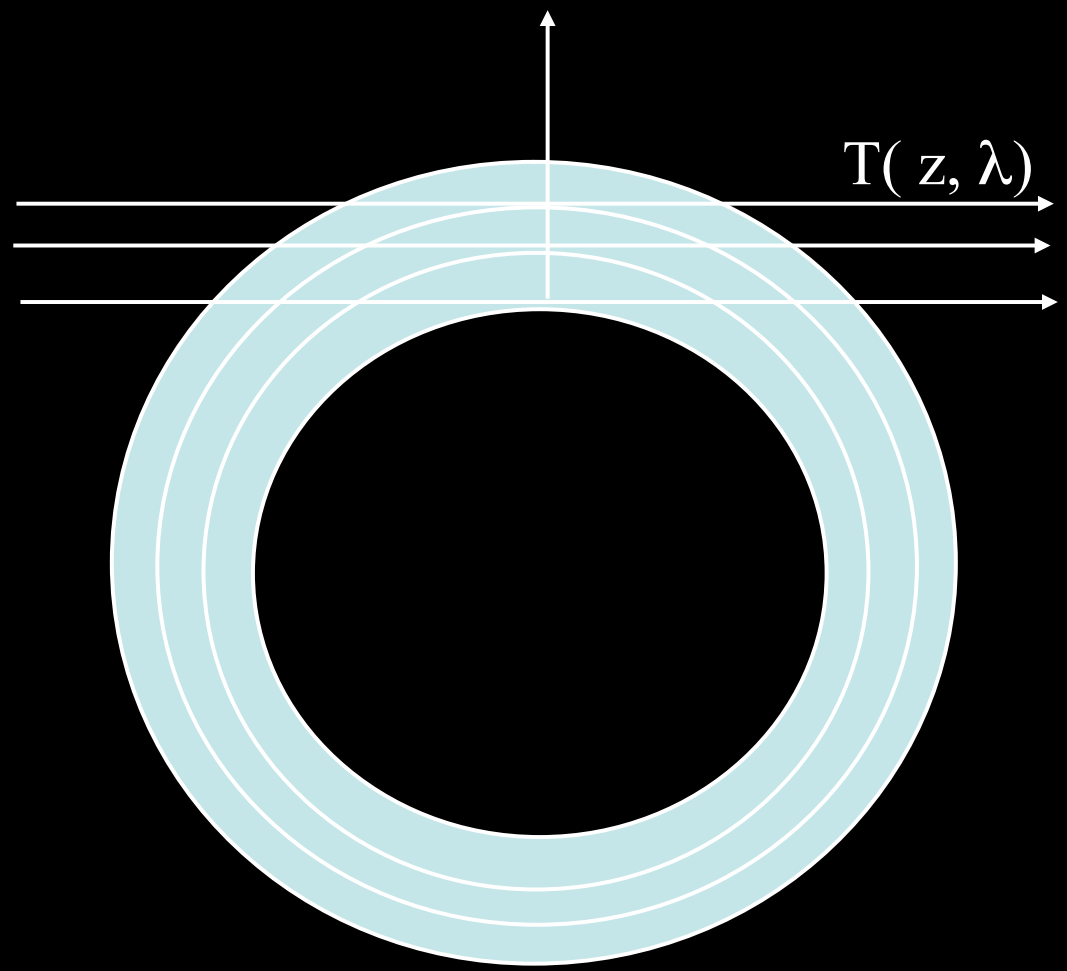
Surface/Vegetation – good enough SNR per 1/20 of planet's rotation to detect surface feature

Features: 1) observables & 2) unique ?



Transit Geometry

$H \approx h \approx T/(g\,\mu)$



h is the effective height of an opaque atmosphere:

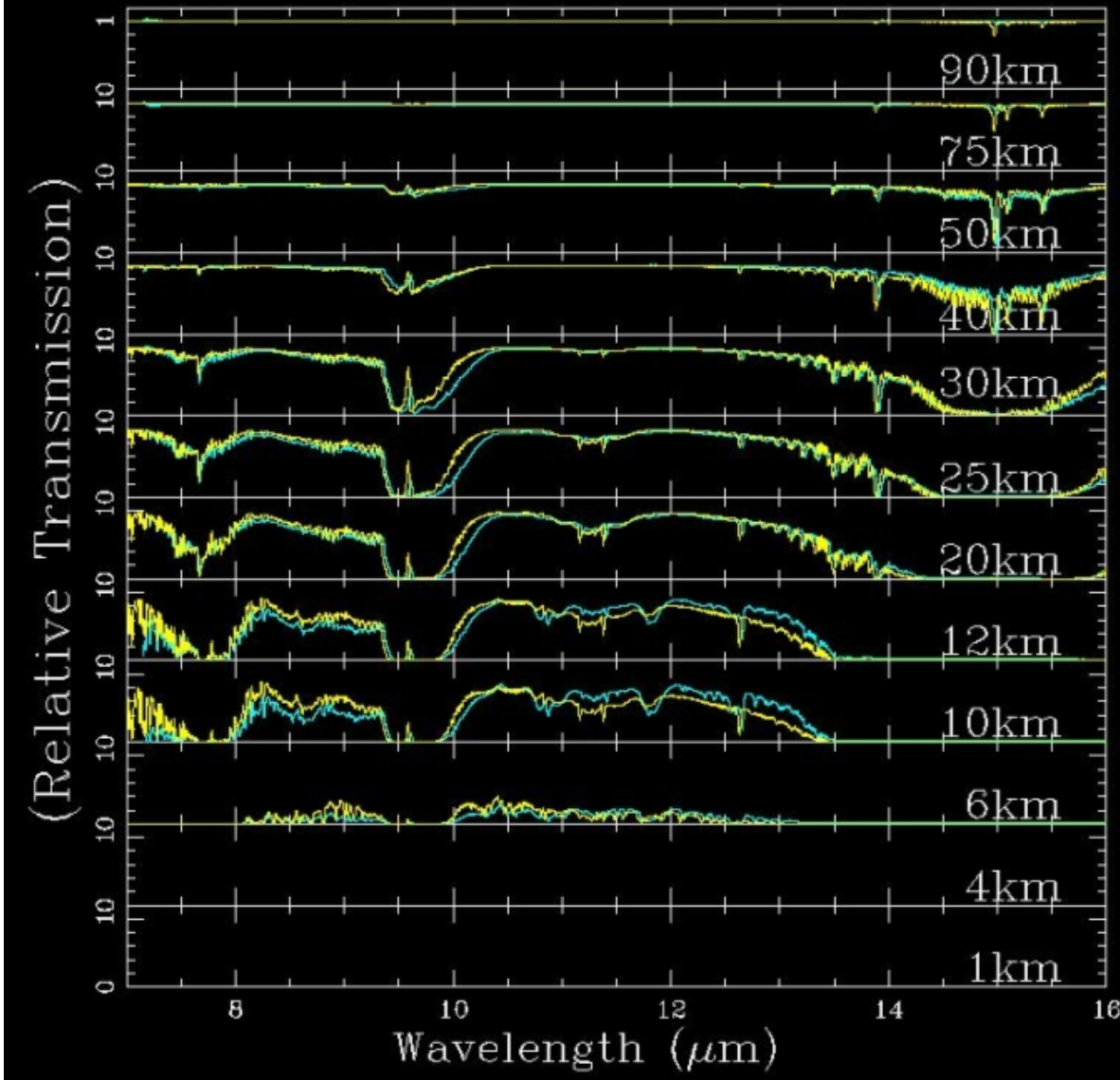
$h(\lambda) = \int (1-T)\, dz$

So

$R(\lambda) = R_0 + h(\lambda)$

$$f_p(\lambda) = 2\pi R_p * h(\lambda) / \pi R_s^2$$

Earth: ATMOS-3:Transmission validation in far-IR



ATMOS-3 transmission of sunlight through Earth's atmosphere, measured with a fast FTS on Shuttle

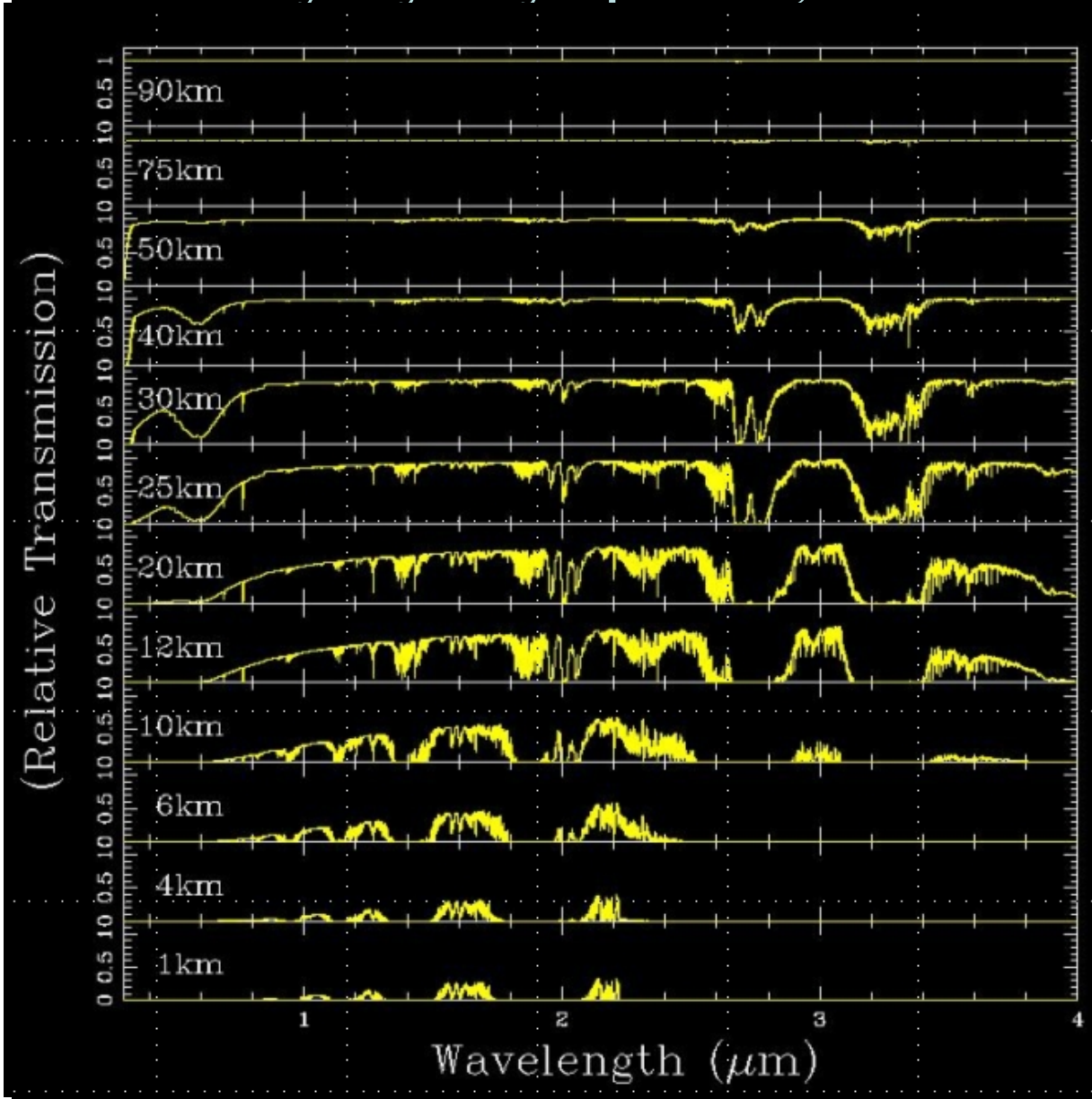
yellow = model

Fit is close, but line wings are not perfect, perhaps owing to line mixing effects in strong bands.

Note low transmission below 10

Kaltenegger & Traub ApJ 2009

Ray-by-ray spectra, visible & near-infrared



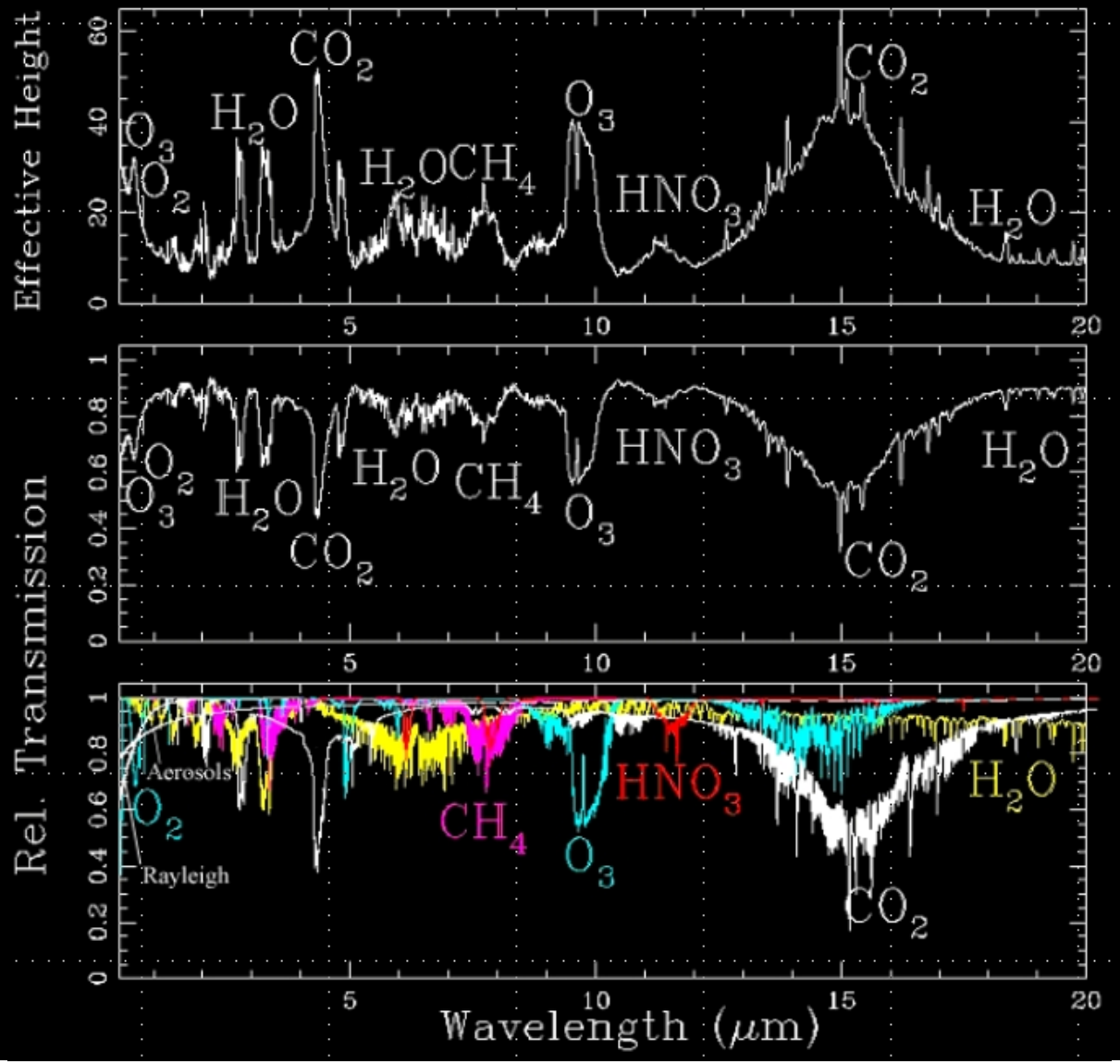
Short wavelength range of transmission spectrum.

Note:

-strong O_3 bands
  - at 0.3 & 0.6 μm,
- weak H_2O bands,
- strong Rayleigh in blue,
- low transmission < 10 km

Kaltenegger & Traub ApJ 2009

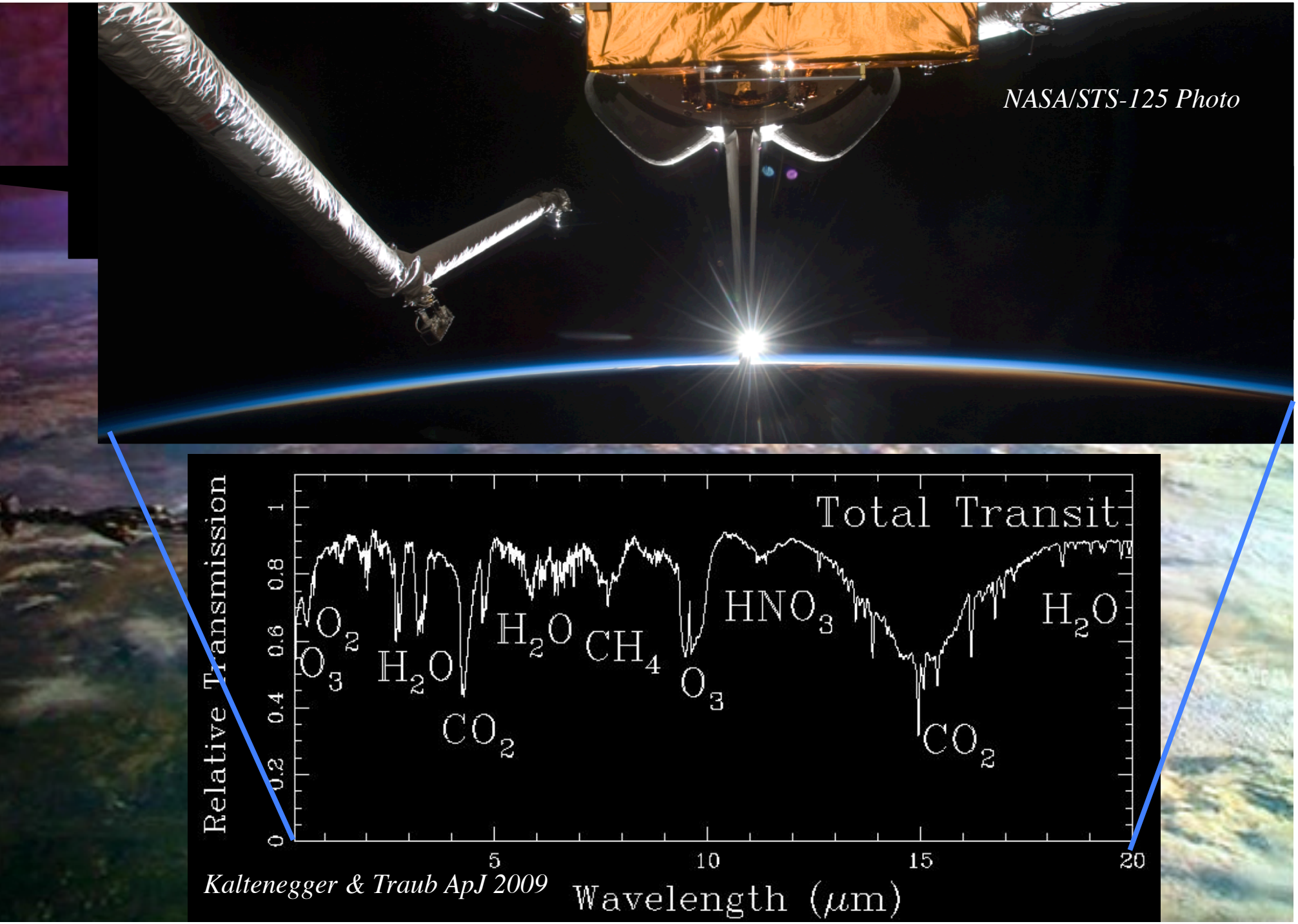
Composite transmission spectrum & effective height



Effective height for spectral range 0.3 – 20 μ

Composite relative transmission.

Individual components


NASA/STS-125 Photo
Total Transit
Relative Transmission
0
0.2
0.4
0.6
0.8
1
5
10
15
20
Wavelength (μm)
O2
O3
H2O
CO2
H2O
CH4
O3
HNO3
CO2
H2O
Kaltenegger & Traub ApJ 2009

JWST Best Case: Closest Stars/Transit, e=0.3

Table 6: Major spectroscopic features and SNR of a transiting Earth for a single transit, for a 6.5-m space based telescope, for the closest stars per stellar subtype (see Table 5). For G2V, we use α centauri A, Gl 559 A at 1.34pc.

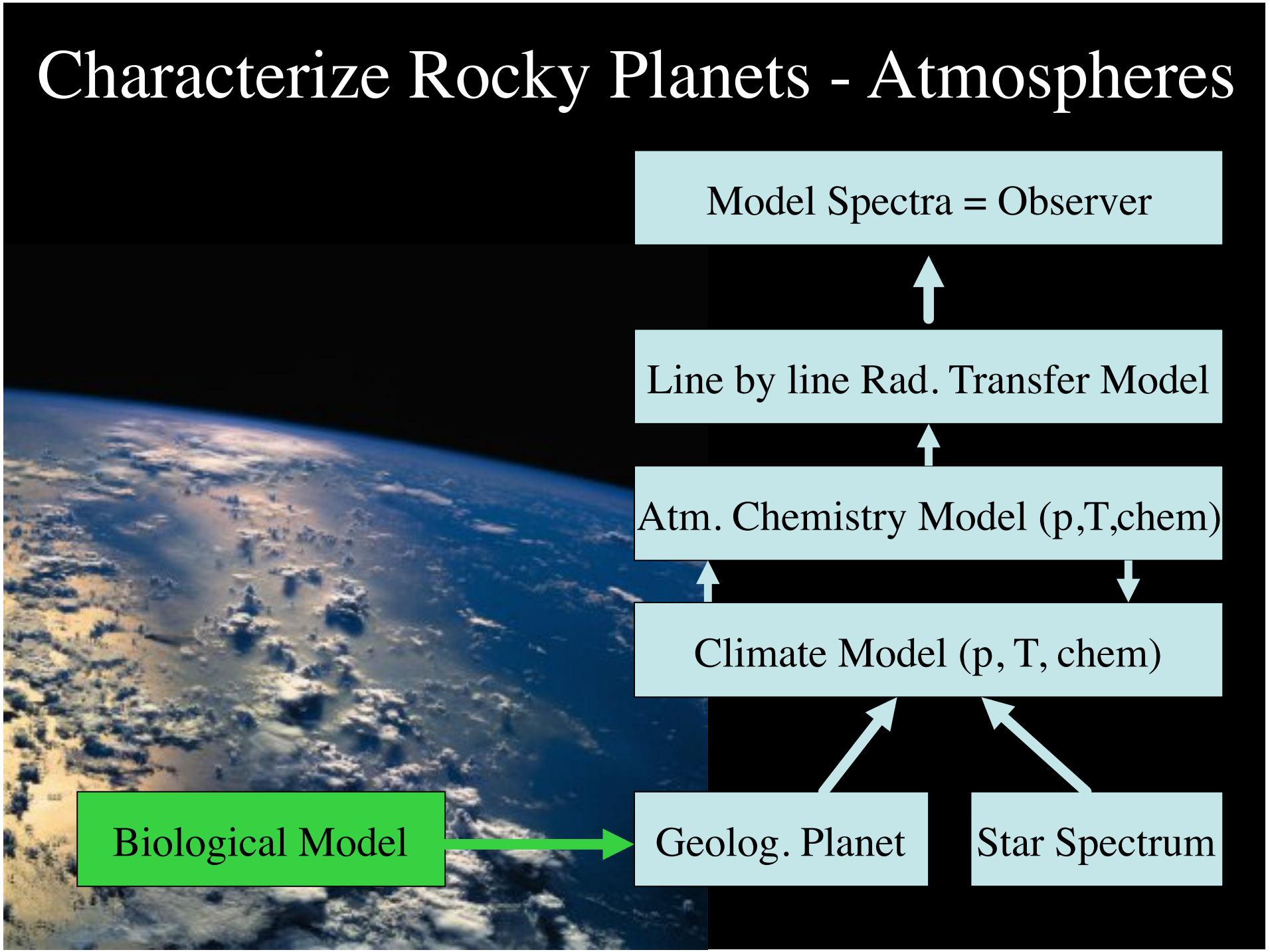
Feature	G2V	M0V	M1V	M2V	M3V	M4V	M5V	M6V	M7V	M8V	M9V
O_3	12.5	1.8	1.5	1.8	1.4	2.1	2.4	1.1	0.5	0.5	0.4
H_2O	3.5	1.0	0.9	1.2	1.0	1.8	2.7	1.5	0.8	0.9	0.9
CO_2	6.3	1.9	1.8	2.4	2.1	3.8	5.8	3.2	1.8	2.0	2.0
H_2O	8.1	2.5	2.4	3.2	2.8	5.1	7.8	4.4	2.5	2.8	2.7
CH_4	1.5	0.5	0.5	0.7	0.6	1.1	1.7	1.0	0.5	0.6	0.6
O_3	4.5	1.5	1.5	2.0	1.8	3.3	5.2	3.0	1.7	1.9	2.0
CO_2	4.3	1.4	1.4	2.0	1.7	3.2	5.0	2.9	1.7	1.9	1.9

Name	d(pc)	Sp Type
Gl 887	3.29	M0.5
Gl 15 A	3.56	M1
Gl 411	2.54	M2
Gl 729	2.97	M3.5
Gl 699	1.83	M4
Gl 551	1.30	M5.5
Gl 406	2.39	M6
Gl 473 B	4.39	M7
SCR1845-63A	3.85	M8.5
Denis1048	4.03	M9

6.5-m telescope			
Feature	λ(μm)	Δλ(μm)	H(λ),km
O_3	0.6	0.15	10
H_2O	1.9	0.2	5
CO_2	2.8	0.1	20
H_2O	3.3	0.25	20
CH_4	7.7	0.7	7
O_3	9.8	0.7	30
CO_2	15.2	3.0	25

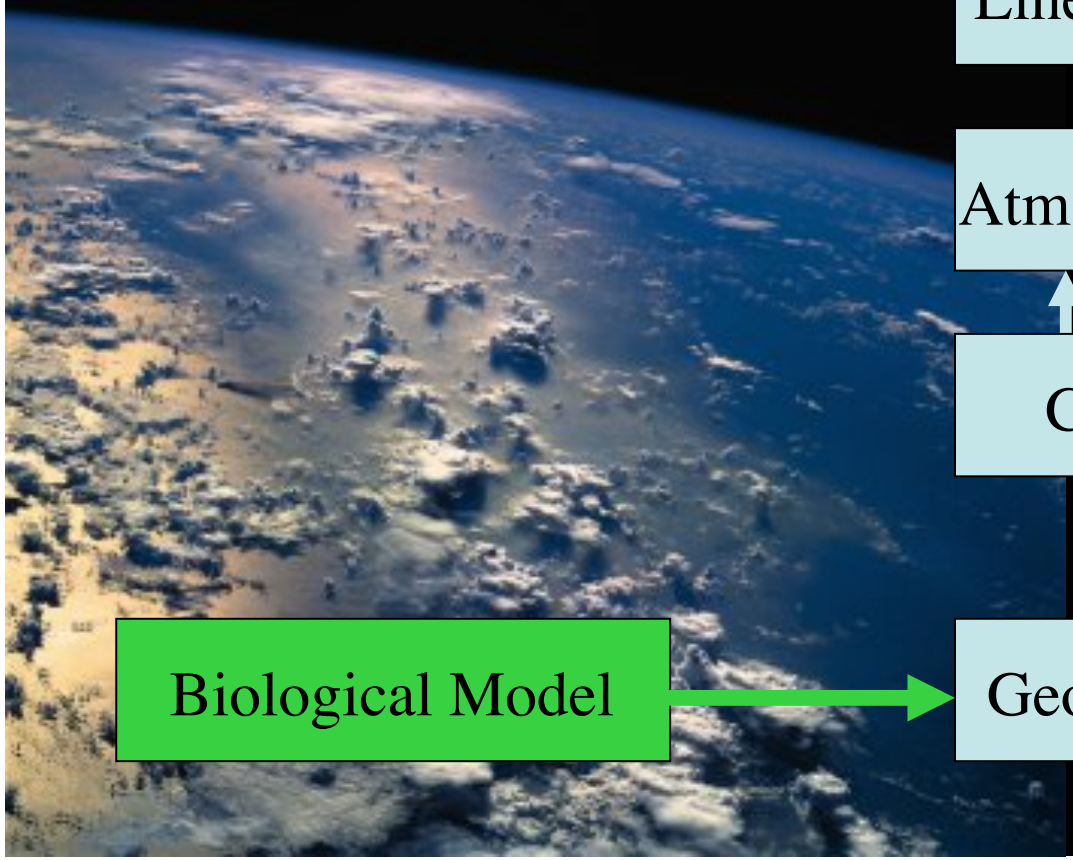
Kaltenegger & Traub ApJ 2009 also Belu et al. 2011, Rauer et al.2011

Characterize Rocky Planets - Atmospheres



“Characterize ” => Spectra UNIQUE?

Andras Zsoms MPIA (Postdoc)
Yamilla Miguel MPIA (Postdoc)
Siddharth Hegde, MPIA (PhD)
Sarah Rugheimer, Harvard (PhD)



Model Spectra = Observer

Line by line Rad. Transfer Model

Atm. Chemistry Model (p,T,chem)

Climate Model (p, T, chem)

Biological Model

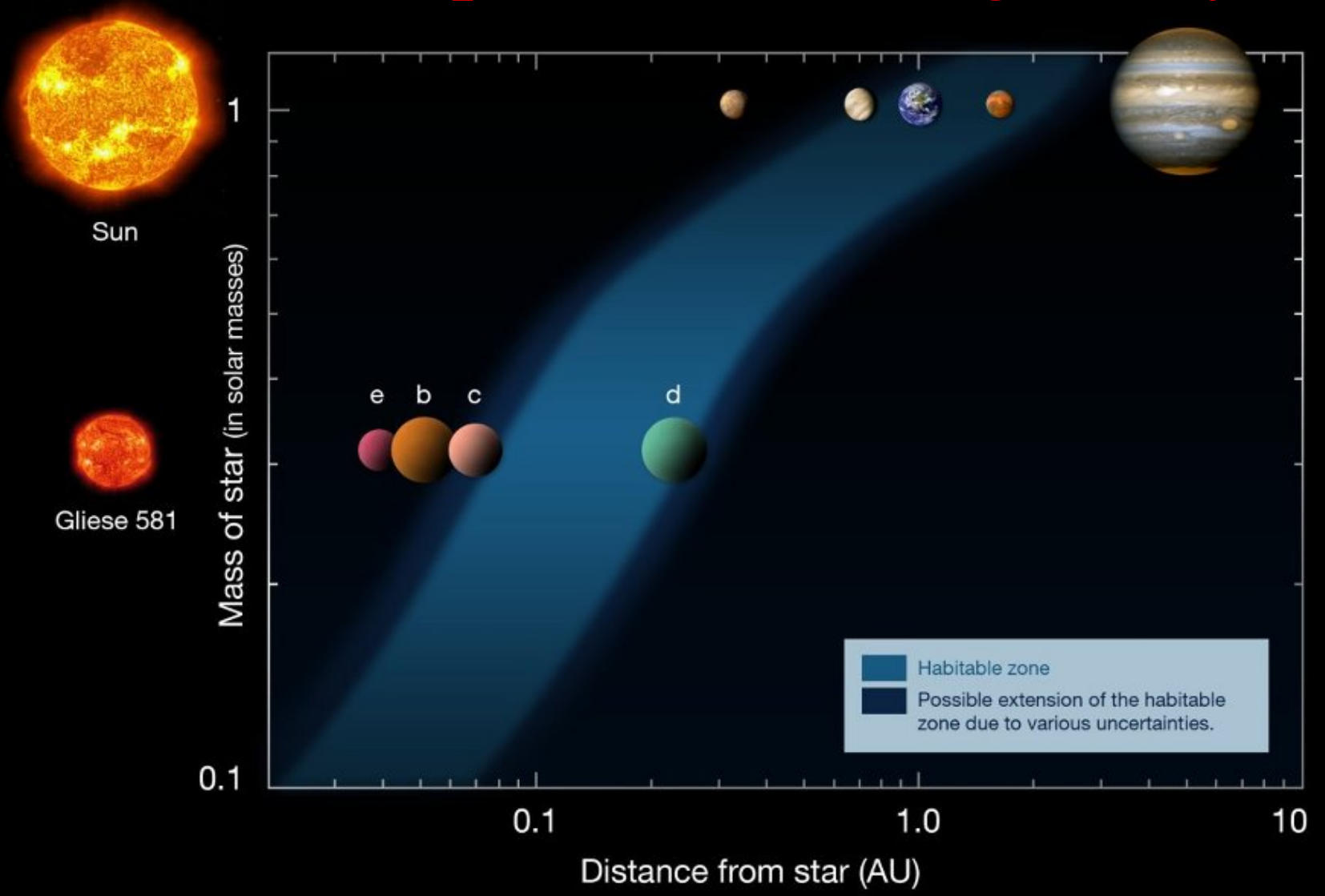
Geolog. Planet

Star Spectrum

Different evolution state / age / mass / etc.

THE TEST:
GRID of Spectra of different planets
– Exoplore underlying physics
- Unique?
- Detectable?
- Inst. requirements
- Retrieval from data?

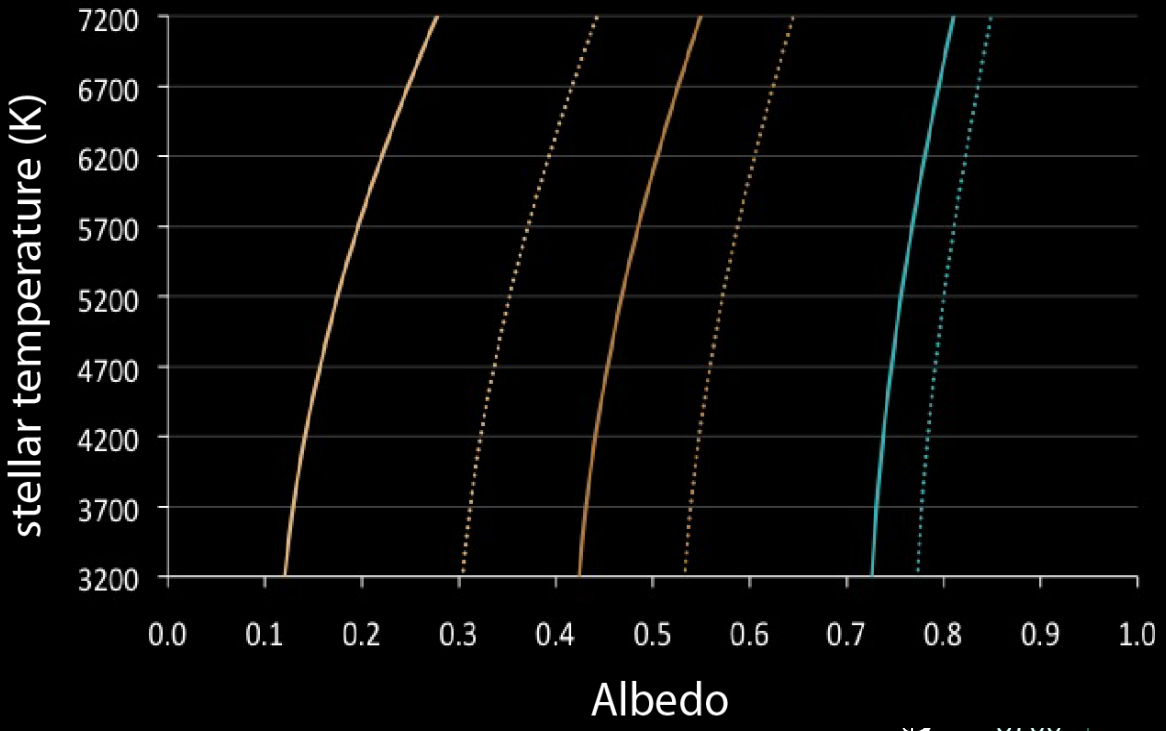
Habitable Zone – water pot.liquid on surface of Earth-like planets (= incl. geol. cycles)



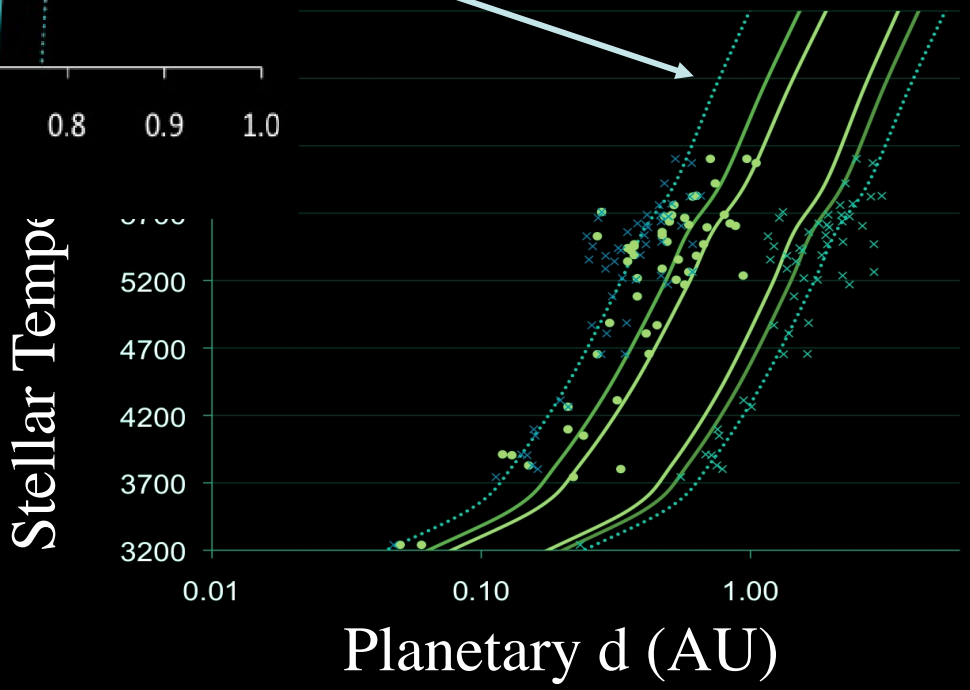
Kaltenegger et al 2011, Wordsworth et al. 2011, von Paris et al 2010, von Bloh et al 2007, Selsis et al 2007, ,...

Habitable Zone: Kepler's pot. habitable planets explored

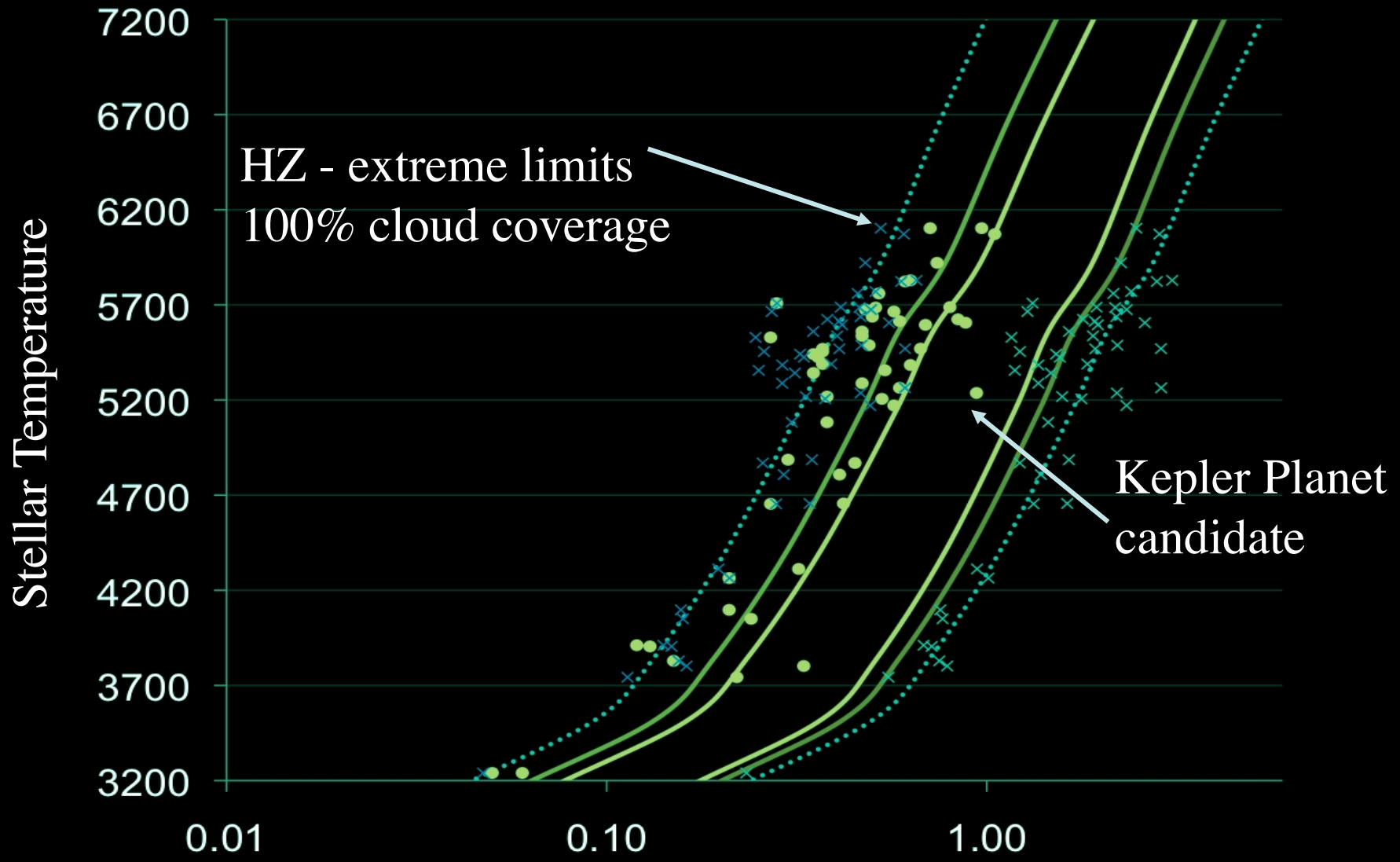
Kaltenegger & Sasselov 2011 ApJL



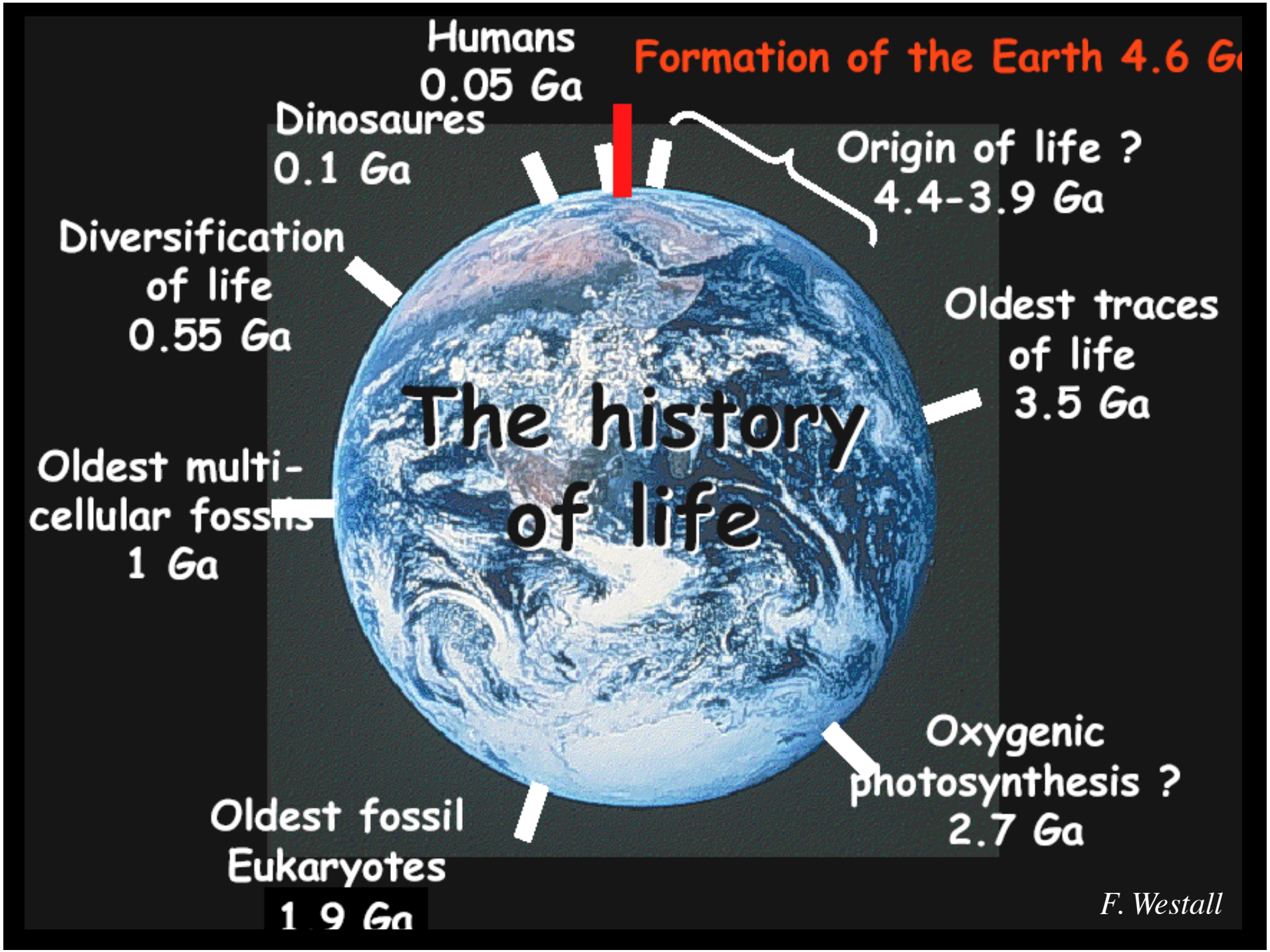
HZ - extreme limits
100% cloud coverage



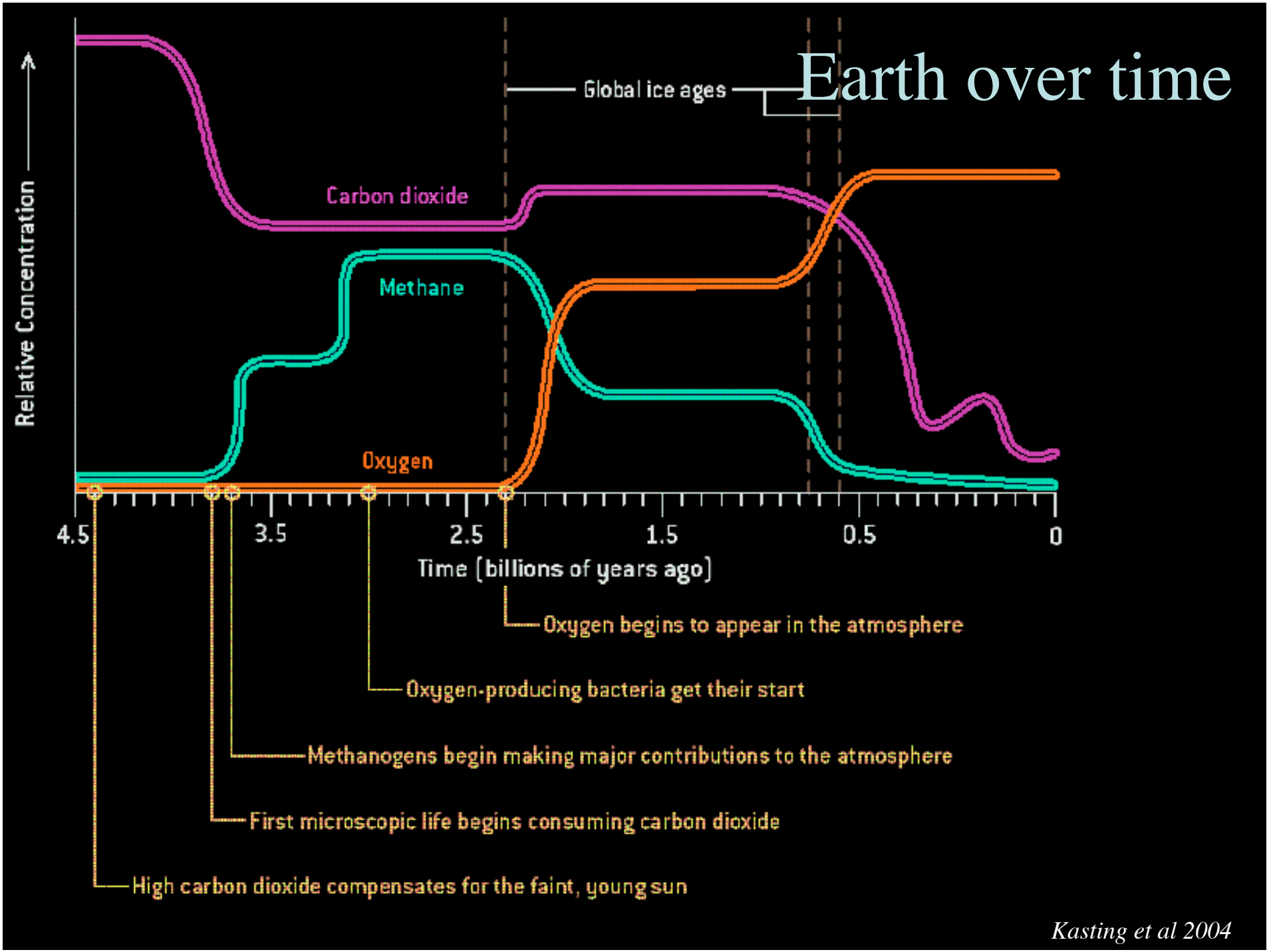
Habitable Zone: Kepler's pot. habitable planets explored



Kaltenegger & Sasselov 2011 ApJL

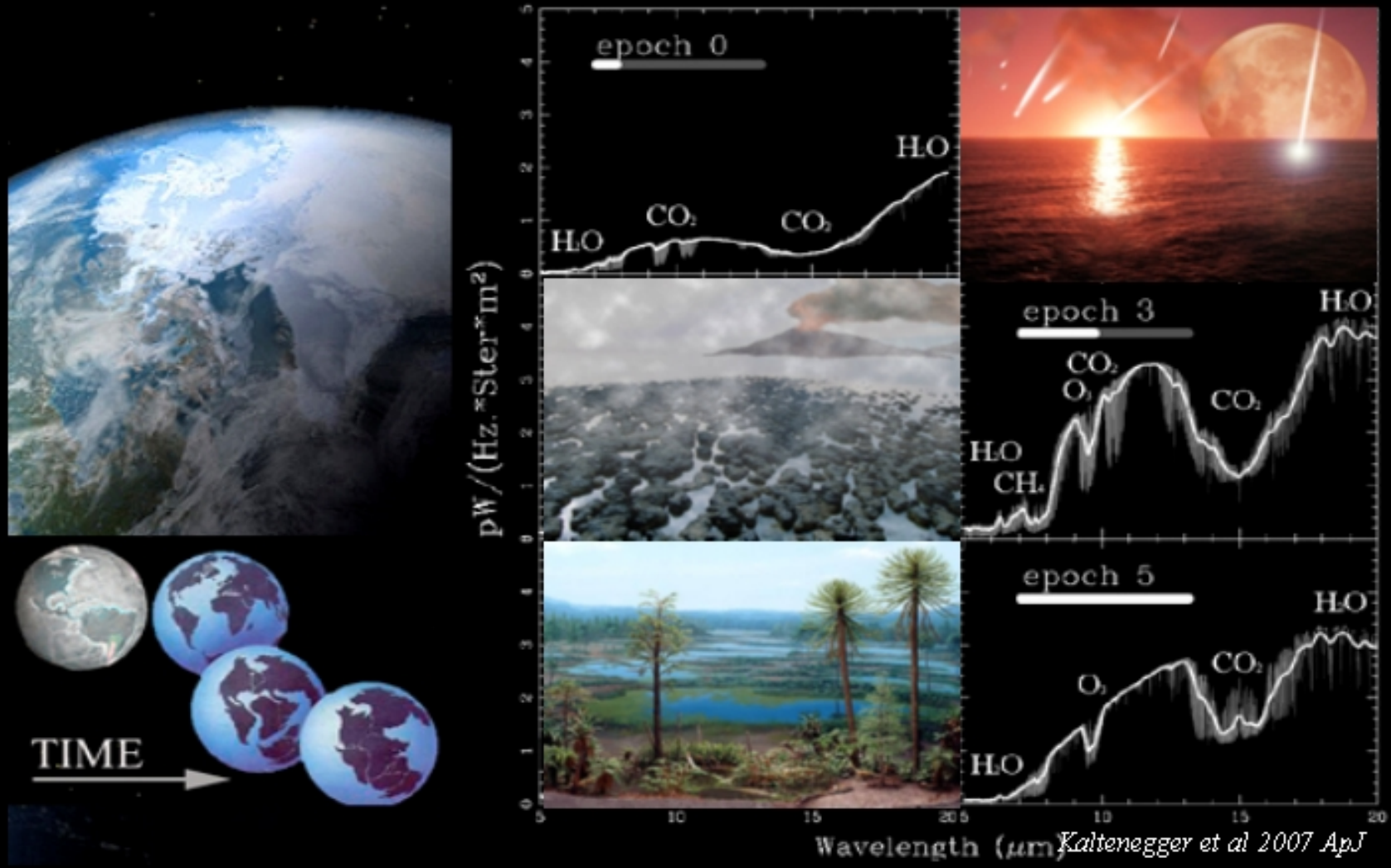

Humans
0.05 Ga
Formation of the Earth 4.6 G
Dinosaures
0.1 Ga
Origin of life ?
4.4-3.9 Ga
Diversification
of life
0.55 Ga
Oldest traces
of life
3.5 Ga
The history
of life
Oldest multi-
cellular fossils
1 Ga
Oxygenic
photosynthesis ?
2.7 Ga
Oldest fossil
Eukaryotes
1.9 Ga
F. Westall

Earth over time



Kasting et al 2004

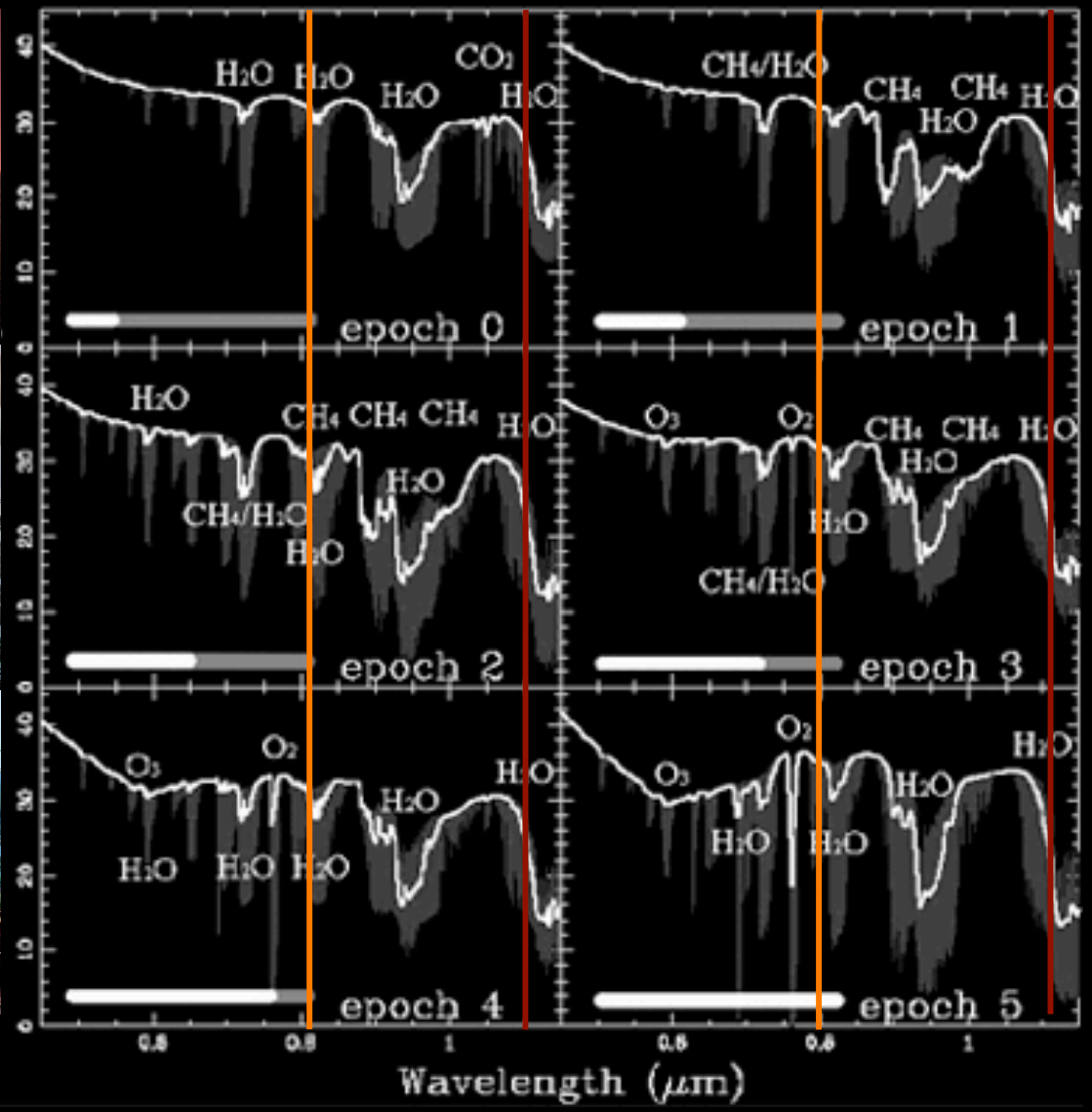
Earth Evolution over geological time - CSI



mid IR (5-20μm): Res = 25

Kaltenegger et al 2007 ApJ

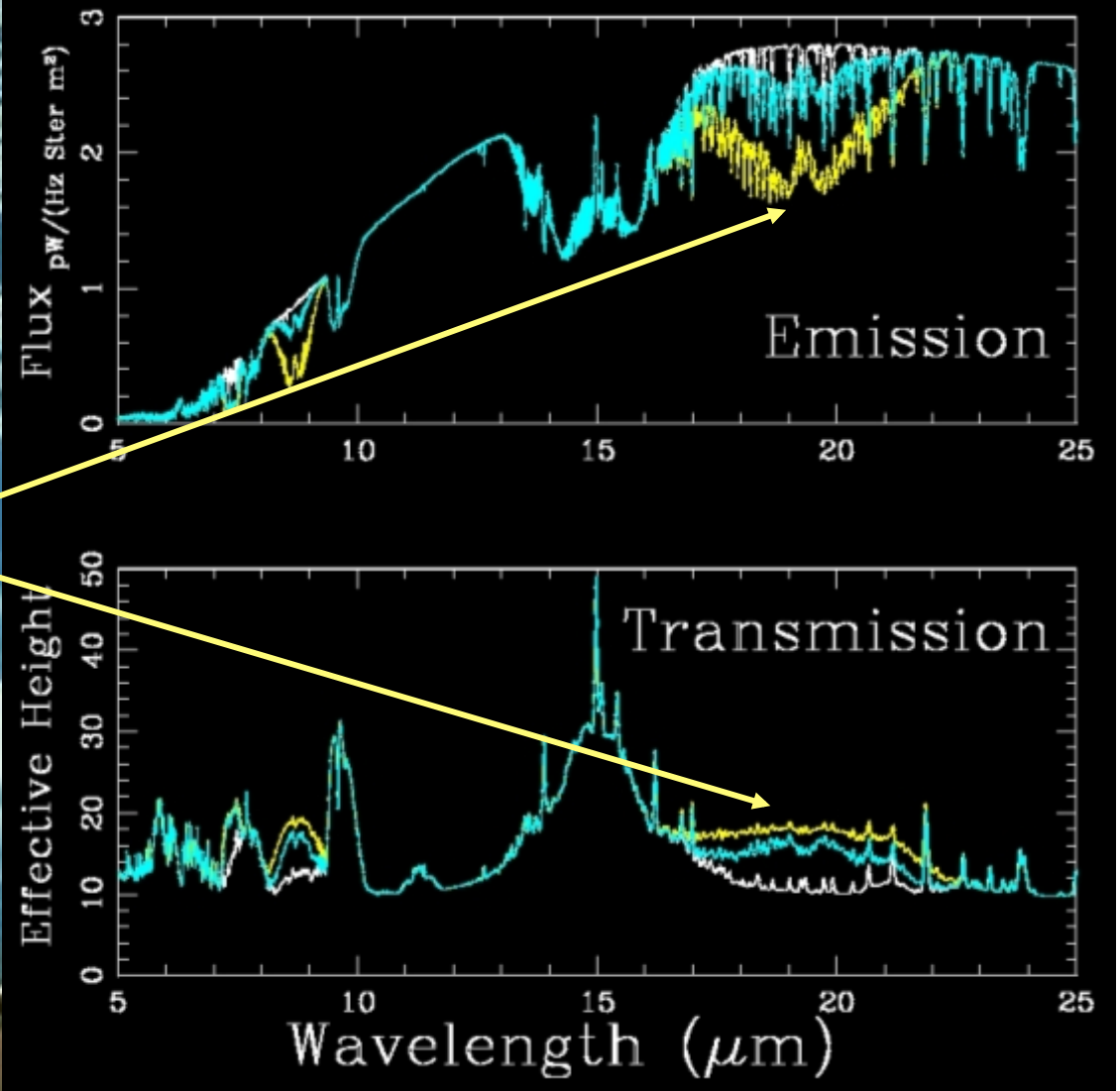
Earth Evolution over geological time - CSI



Kaltenegger, Traub Jucks 2007 ApJ

TEST: GEOLOGY = Exo-Volcanos ?

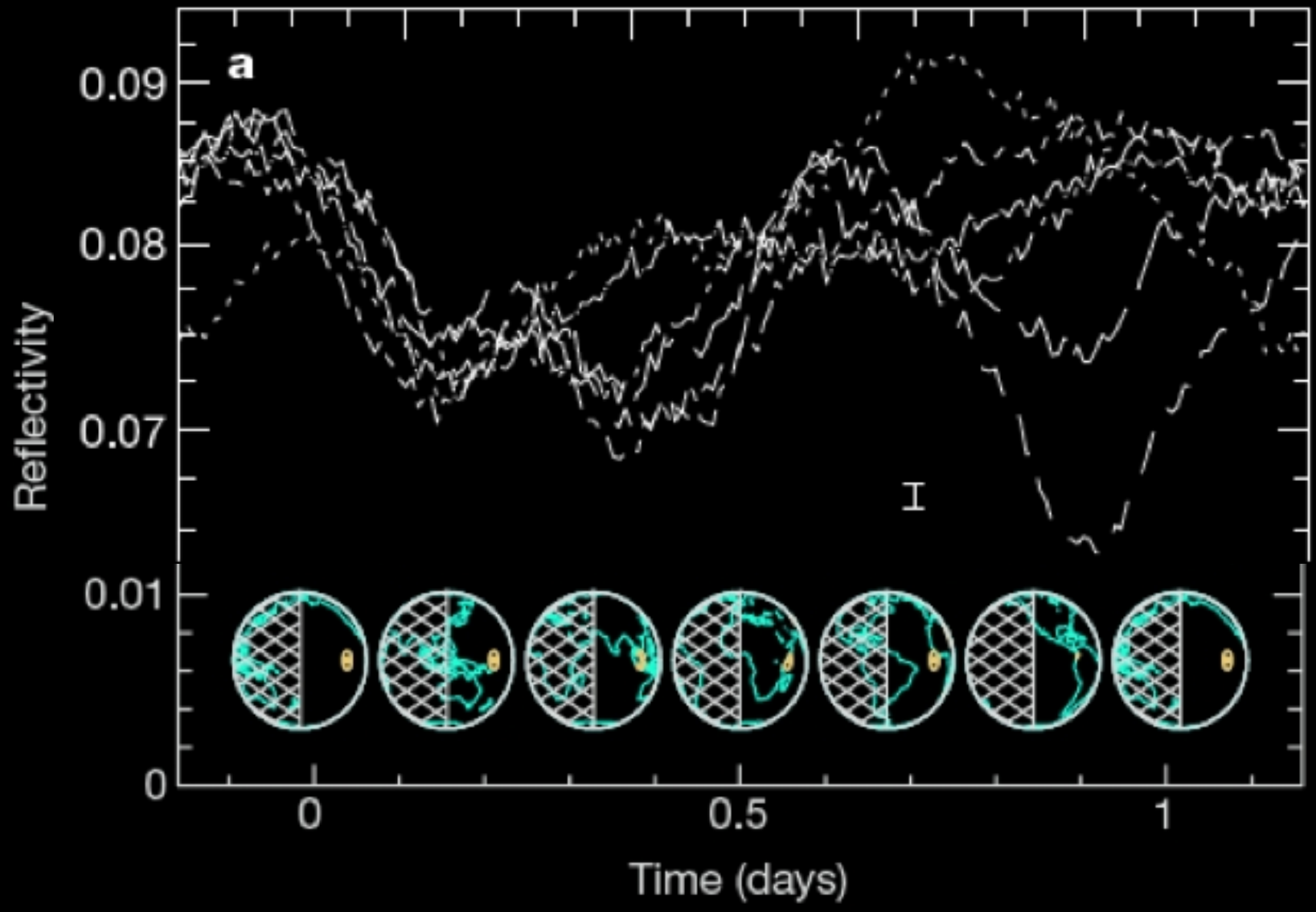
Res = 150, SNR calc. for JWST (pure photon noise, template input for instruments)



Kaltenegger & Sasselov (ApJ 09), Kaltenegger & Henning (ApJ 2010)

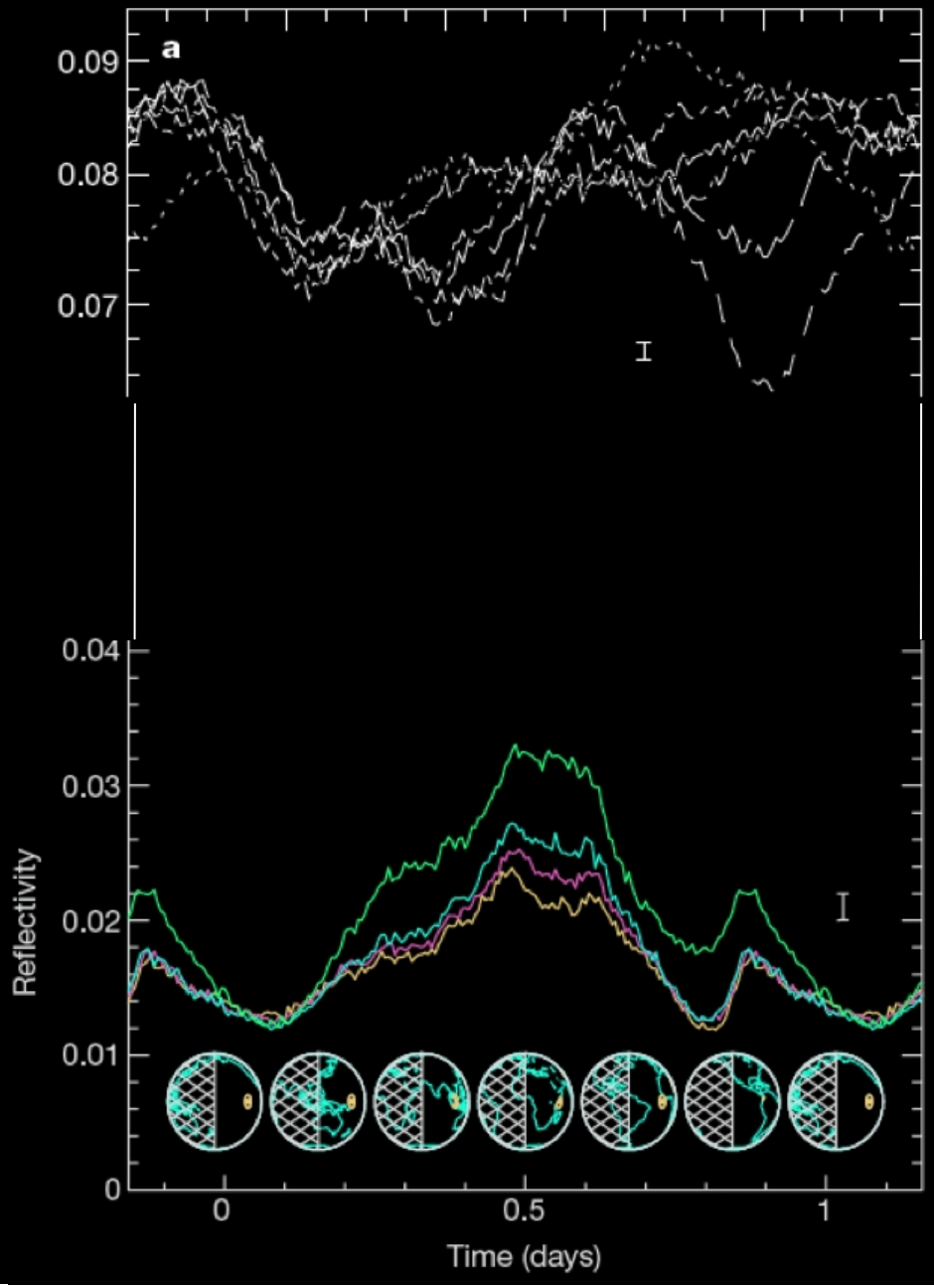
Surface? Measure every 1/20 of rotation period

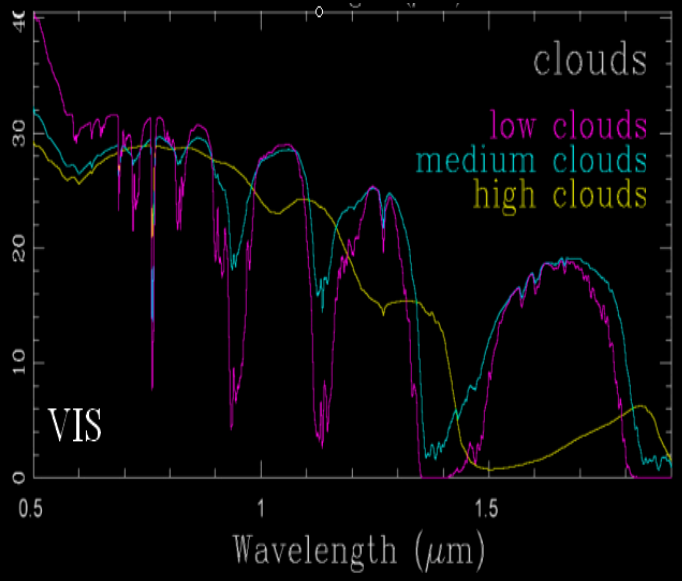
Palle et al. 2008

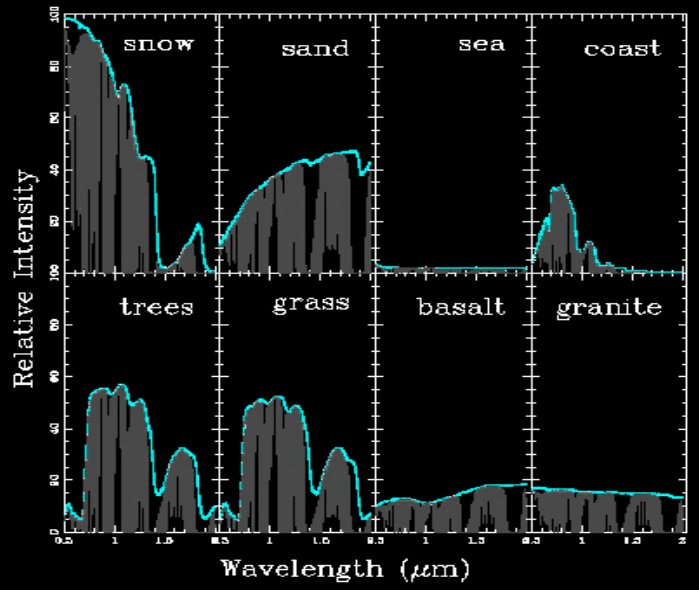


Ford et al. 2001, Cowan et al 2009, Fujii et al 2010

Surface? ONLY if take out clouds SNR

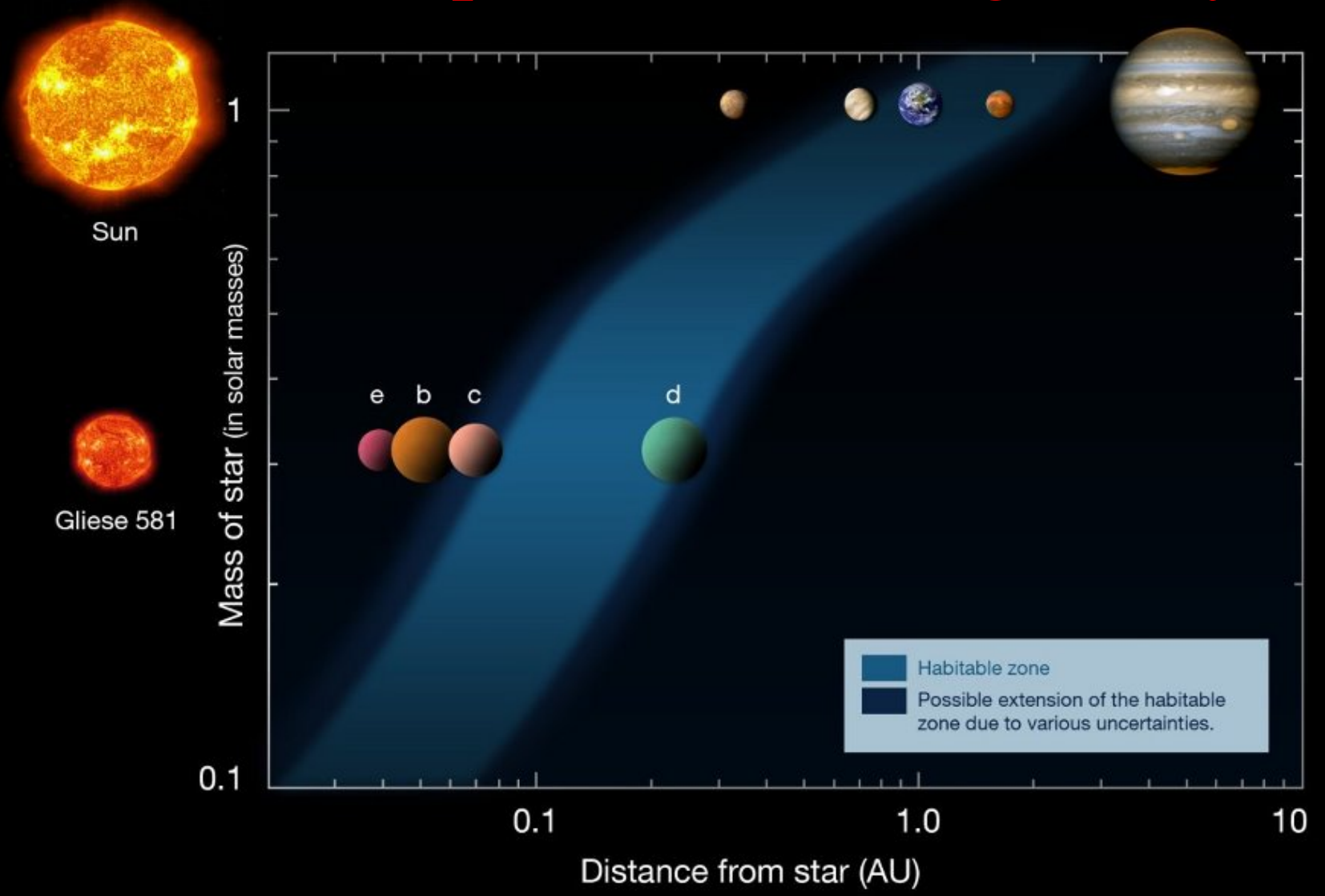




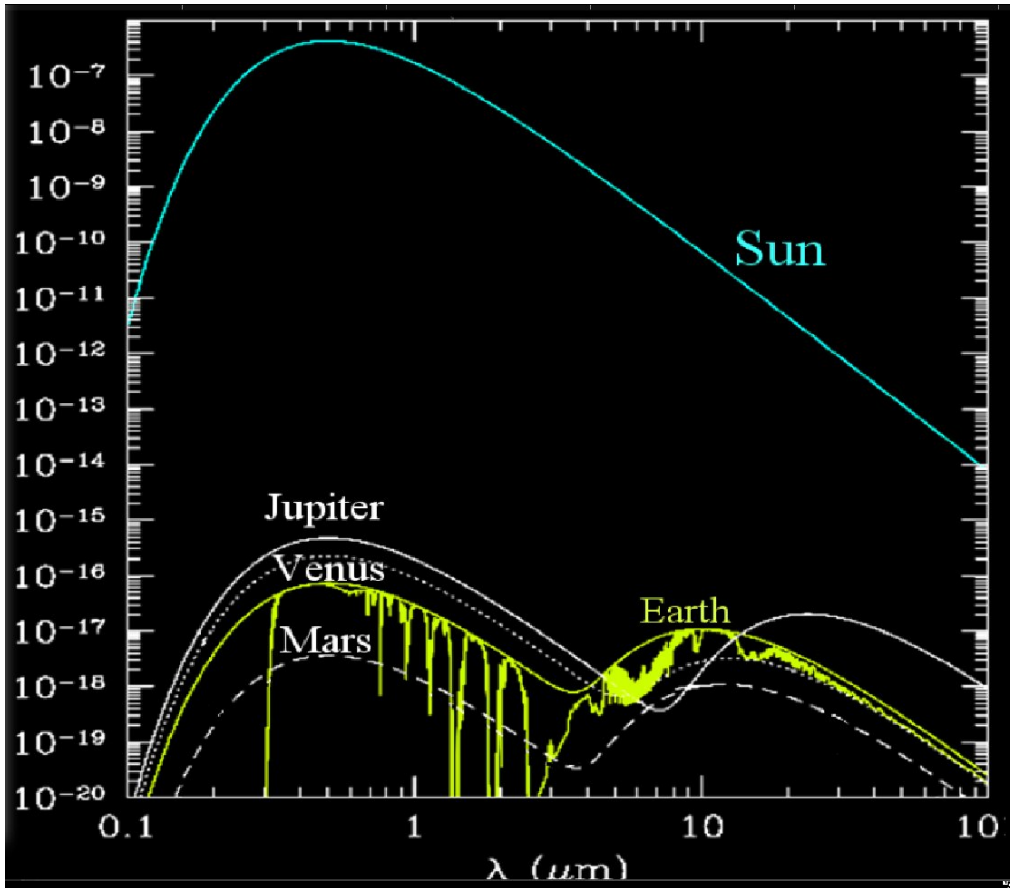


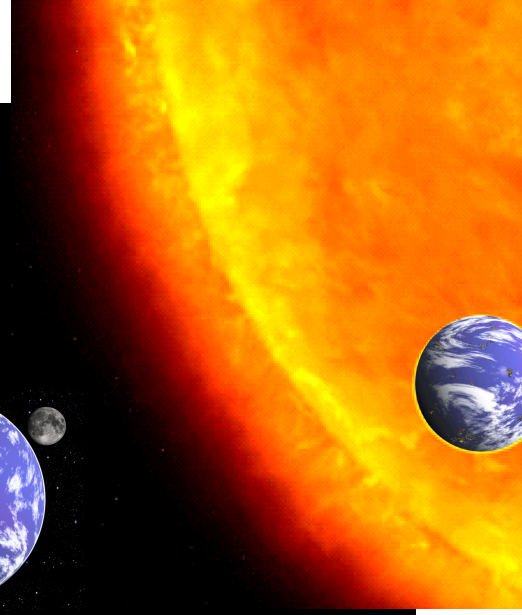
Kaltenegger et al 2007, see also Kitzman poster

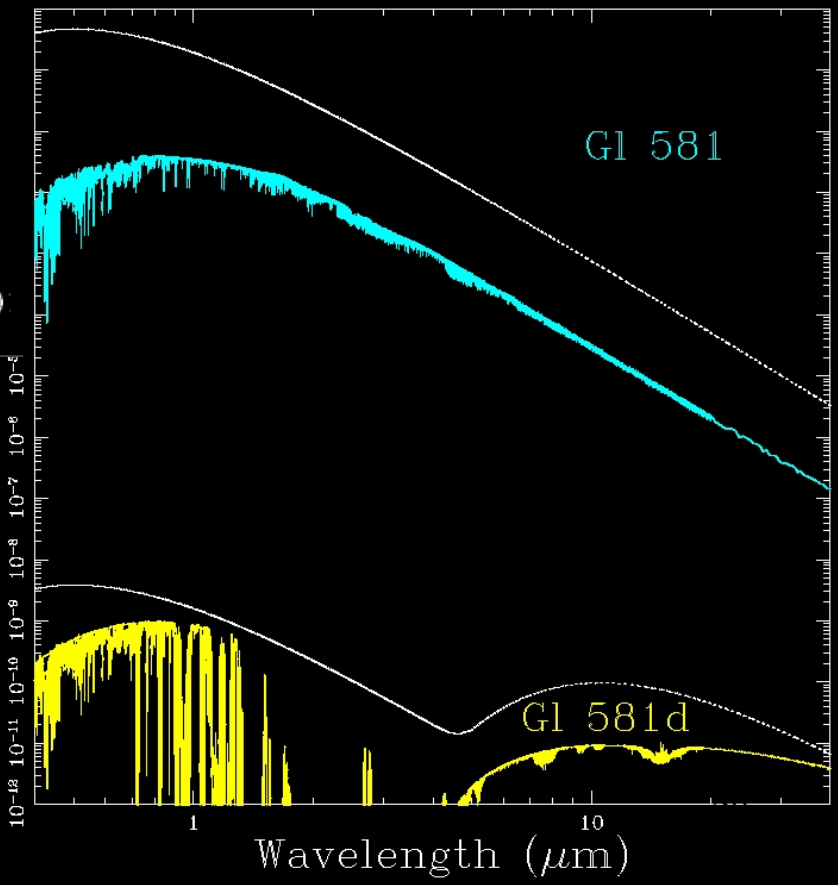
Habitable Zone – water pot.liquid on surface of Earth-like planets (= incl. geol. cycles)



Kaltenegger et al 2011, Wordsworth et al. 2011, von Paris et al 2010, von Bloh et al 2007, Selsis et al 2007, ,...





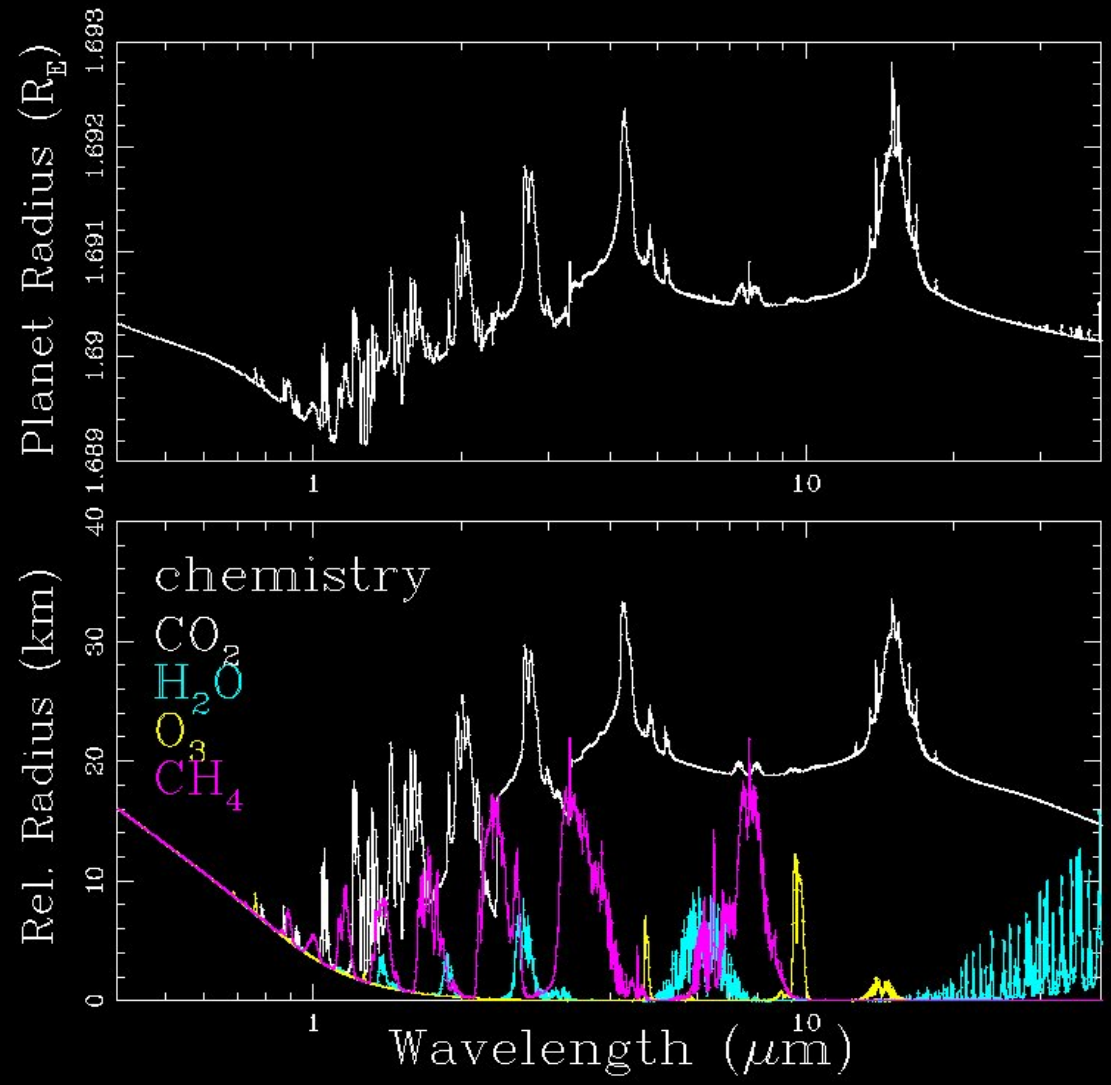


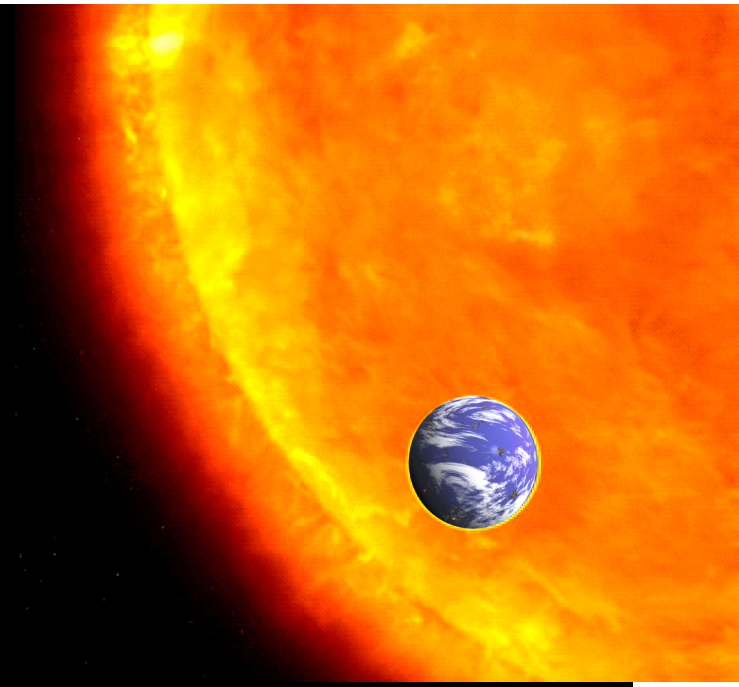
Gl 581d spectra

& star/planet contrast ratio

Kaltenegger, Mohanty & Segura ApJ 2011

Spectra (0.1 - 100 μm): Resolution 150

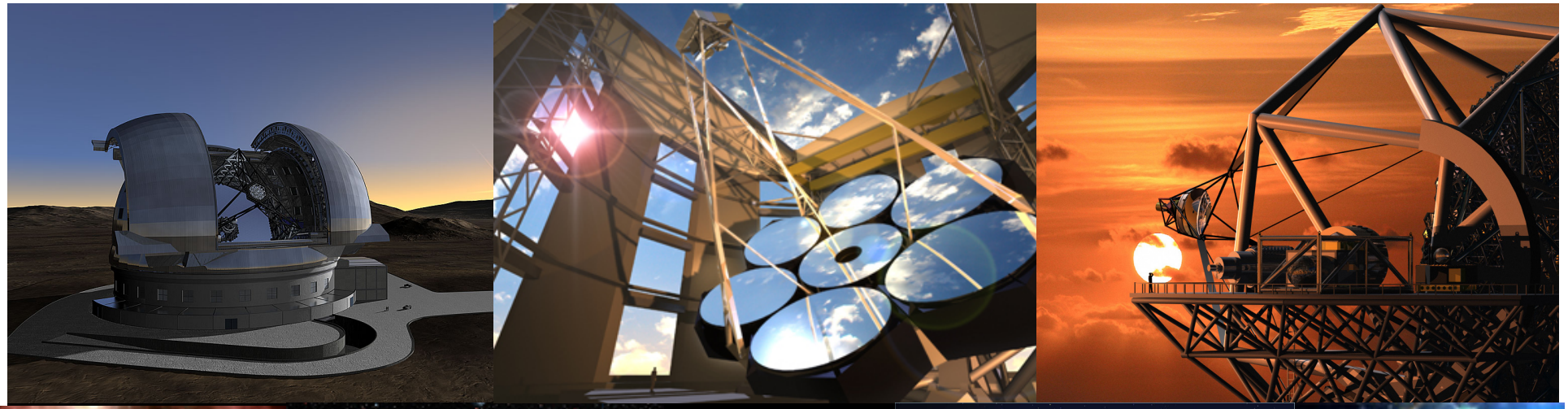




Gl 581d Transit Spectra

in planetary radius *Kaltenegger, Mohanty & Segura ApJ 2011*

Spectra (0.4 - 40 μm): Resolution 150



carmenes

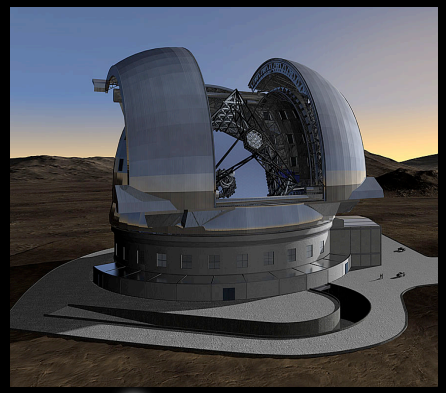
Planetary Search | HARPS

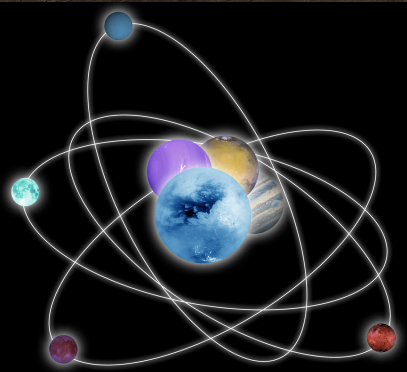
EXOPAG(NASA) – get involved Mtg June 1/2

Exoplanet Exploration Program Analysis Group (Chair: J. Kasting)

Science Case: E-ELT,GMT,TMT, JWST

(SPITZER, SPICA SMALL SPACE MISSIONS (e.g. EChO, TESS))





Not just FIND... (POS VIEW ☺)

Characterize rocky exoplanets

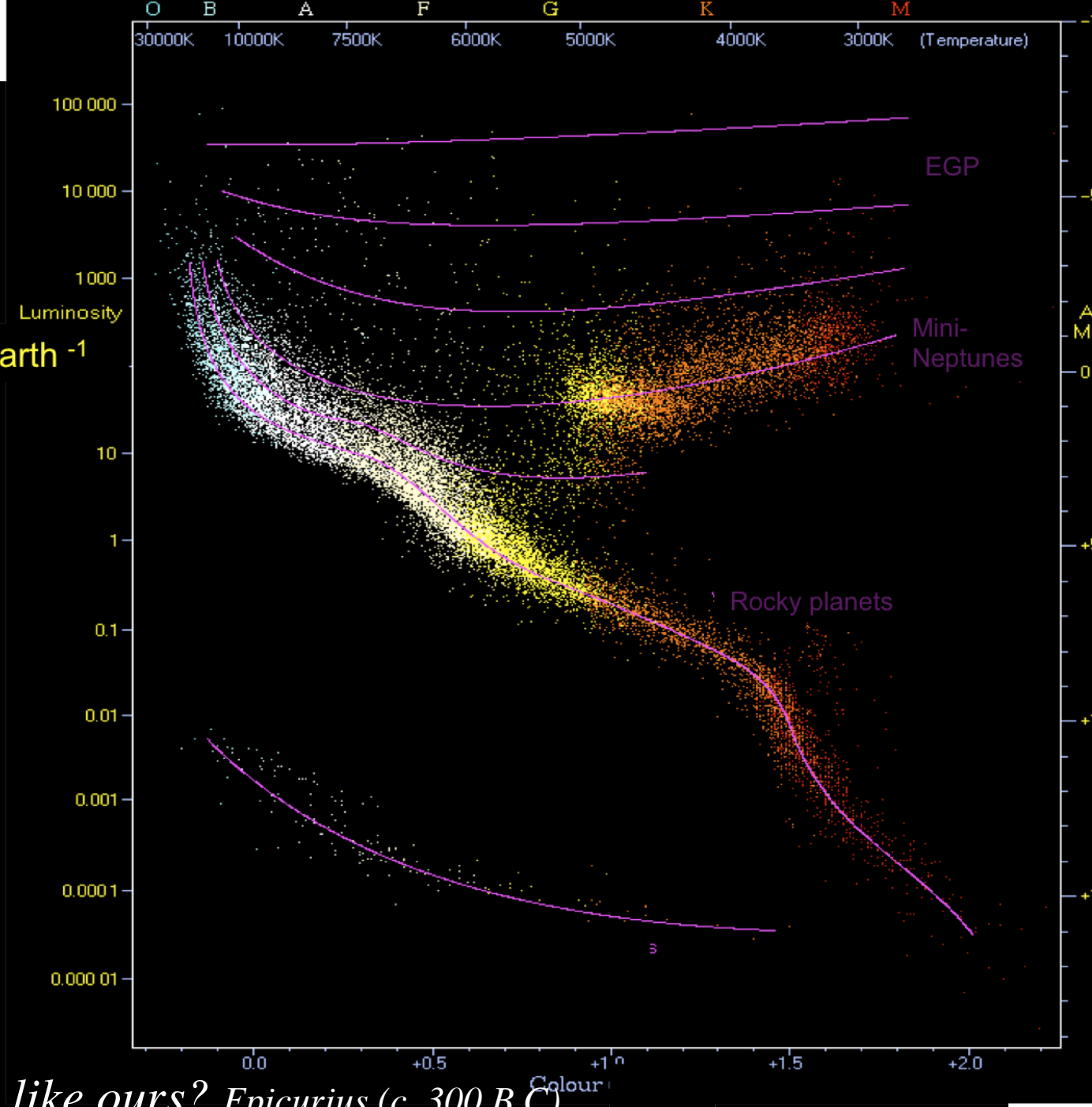
- composition	0 – 50+ years
- habitability	8 – 50+ years
- stage of evolution	8 – 50+ years
- geochemical cycles	8 – 50+ years
- HR Diagram of planets	20 – 50+ years

IAP MPIA ETH INAF IEEC SRON JPL UCL
France Germany Switzerland Italy Spain Netherlands US UK

Are there other worlds like ours? *Epicurius (c. 300 B.C)*

2300 years and counting....

Let‘s find out



Are there other worlds like ours? *Epicurius (c. 300 B.C)*

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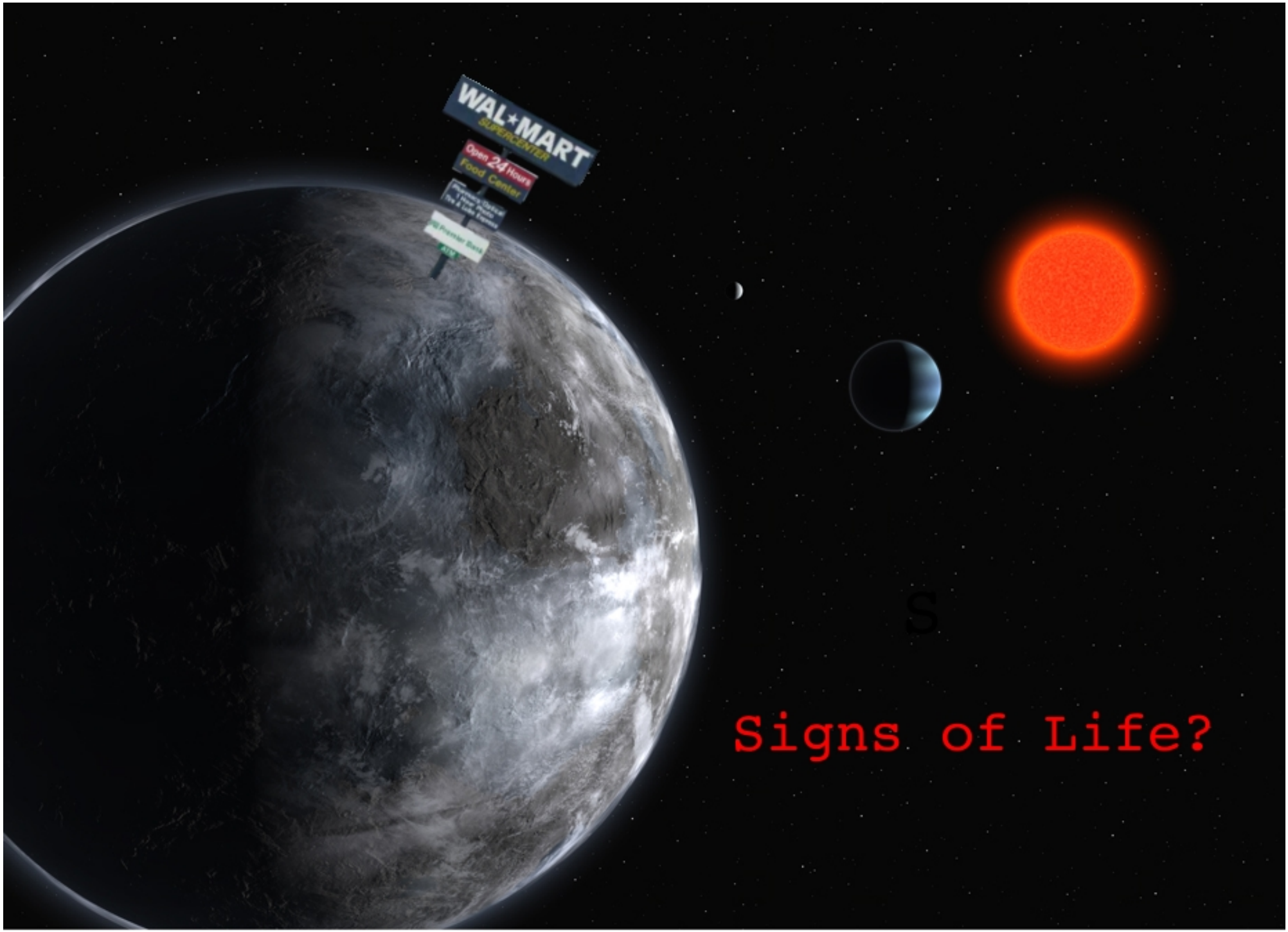

The Planetary System in Gliese 581