SAG 4 – Measure what how good to characterize rocky exoplanets

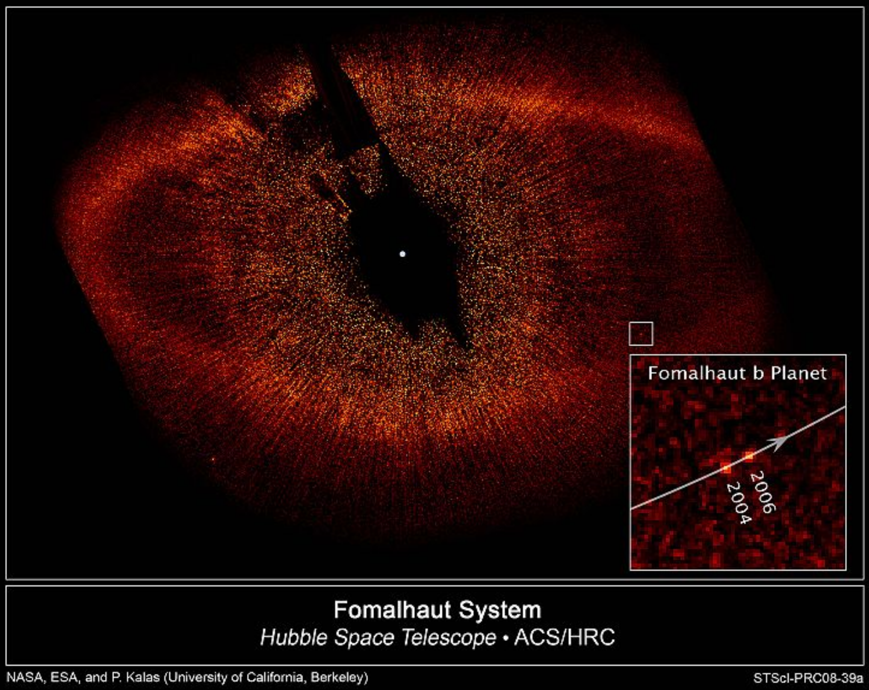
a fascinating cross-disciplinary puzzle

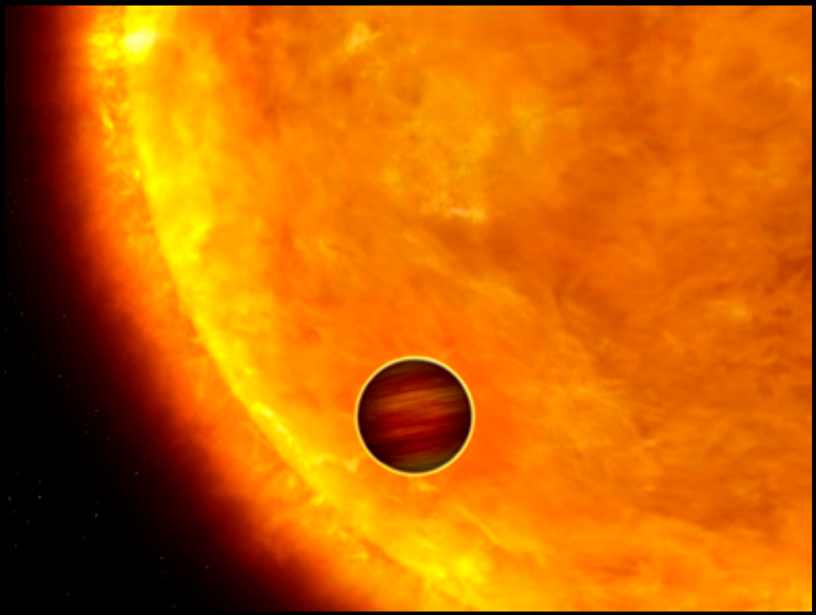
need to work it out together

L. Kaltenegger (for SAG 4)
Harvard University
AbGradCon 2010, June 17, 2010

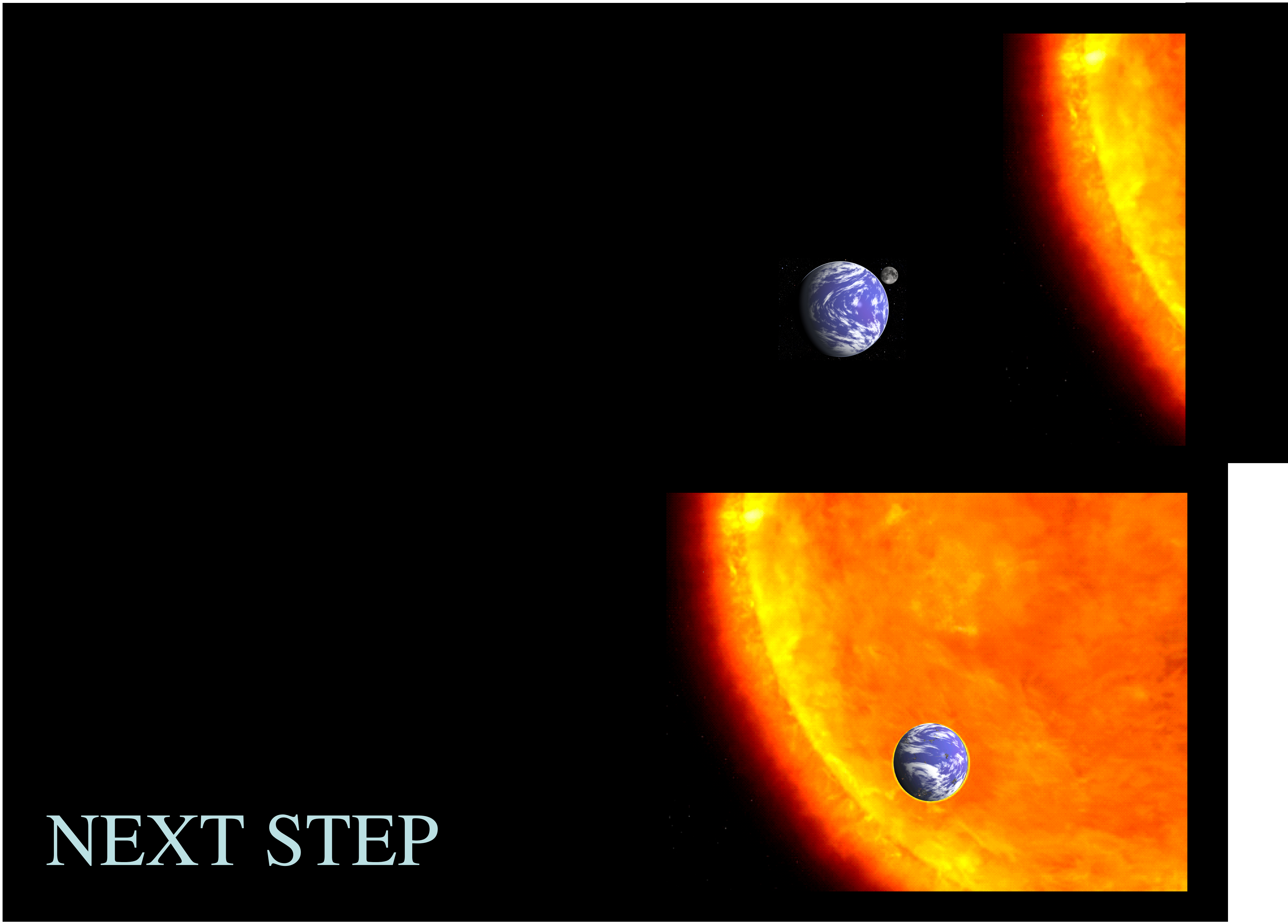
SAG 4 – exoplanet Characterizations

- measurements (R, M, T, chem. comp)
  - needed to characterize exoplanets
- what accuracy needed ?
- what can be done from the ground ?


Fomalhaut b Planet
2004
2006
Fomalhaut System
Hubble Space Telescope • ACS/HRC
NASA, ESA, and P. Kalas (University of California, Berkeley)
STScI-PRC08-39a



NOW


NEXT STEP

Characterising ROCKY exoplanets

Why should you care!

What biota?

↑

What chemistry?

What star ? HZ ?

↑

Plate tectonics?

Ocean/land?

↓

Density ?

(radius/mass)

↓

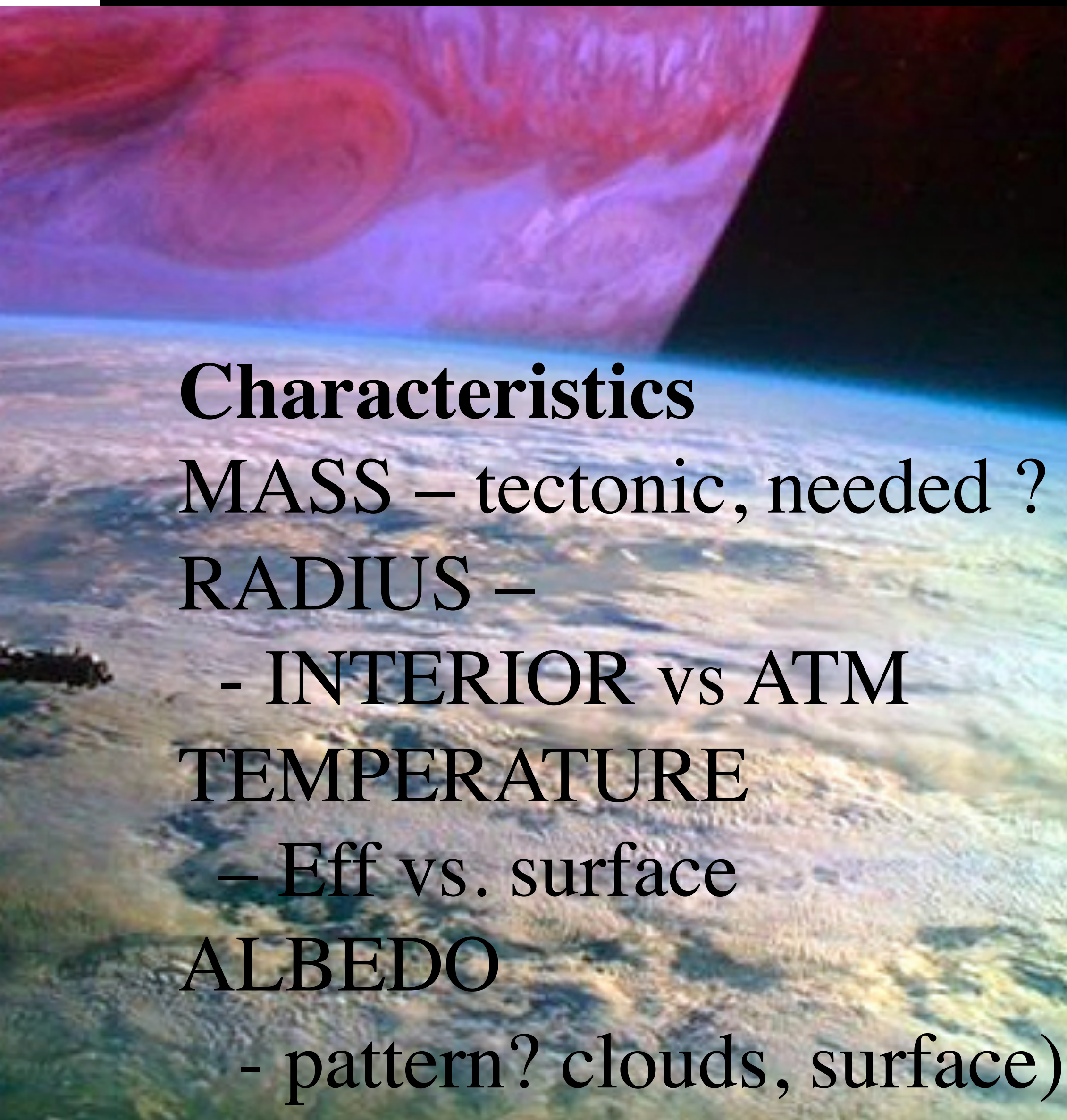
Formation Models

WHAT KIND

↑

FORMATION

Mini-Neptunes



Characteristics

MASS – tectonic, needed ?

RADIUS –

- INTERIOR vs ATM

TEMPERATURE

– Eff vs. surface

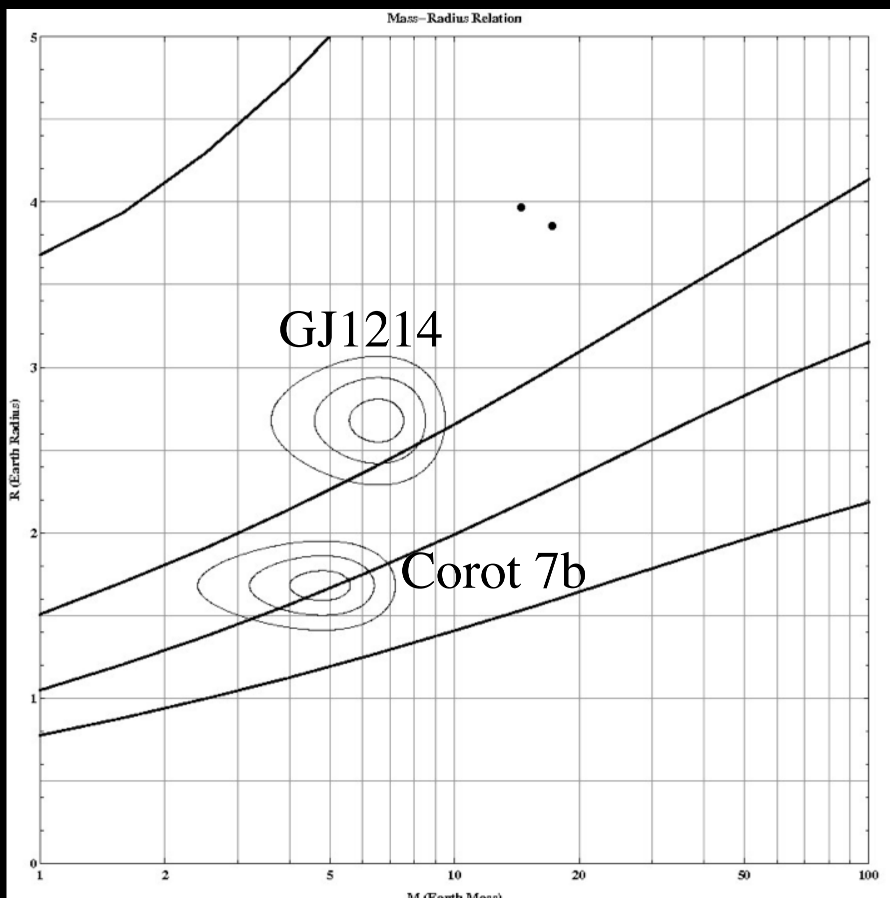
ALBEDO

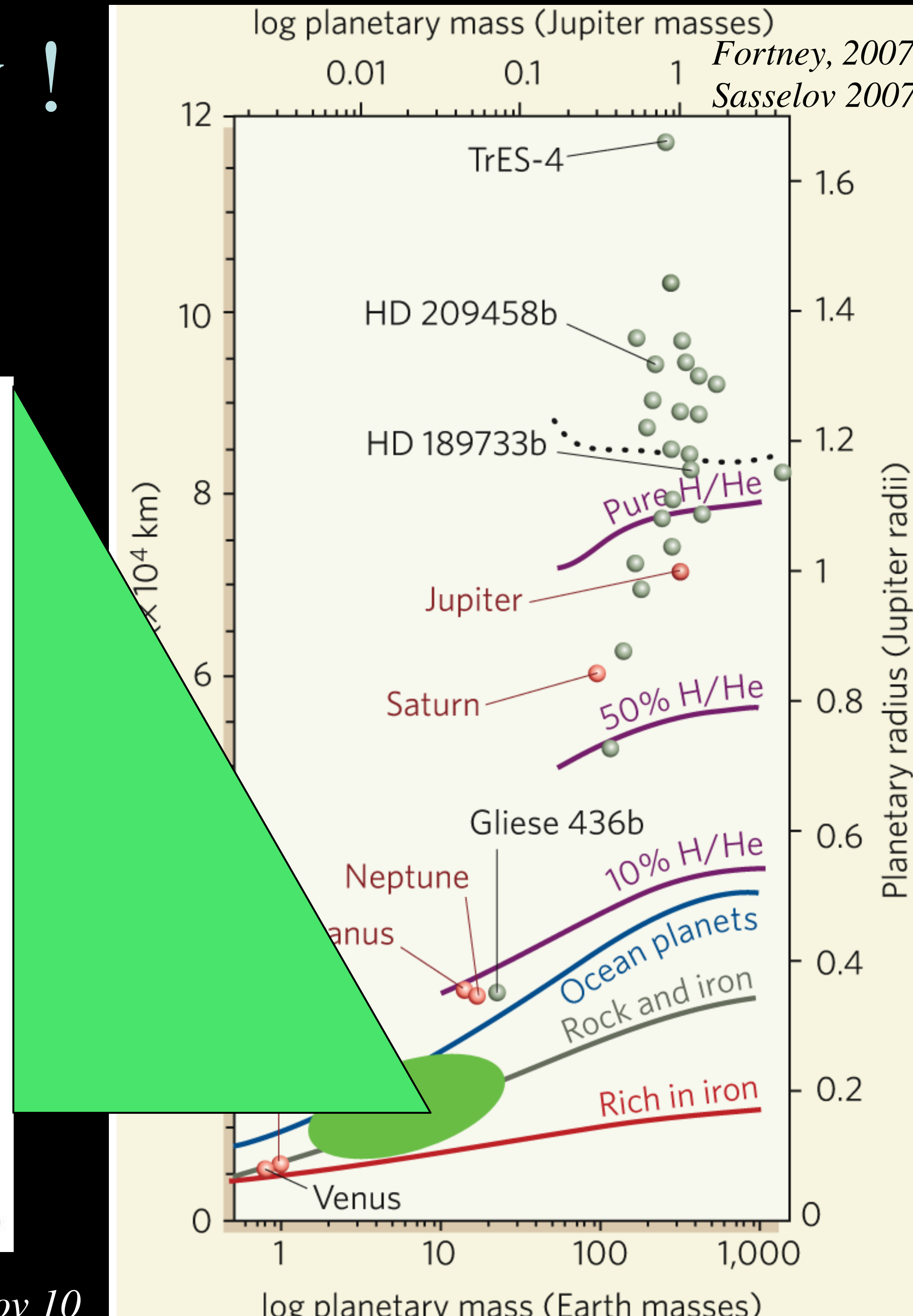
- pattern? clouds, surface)

8 - 15 M_E

Super-Earths

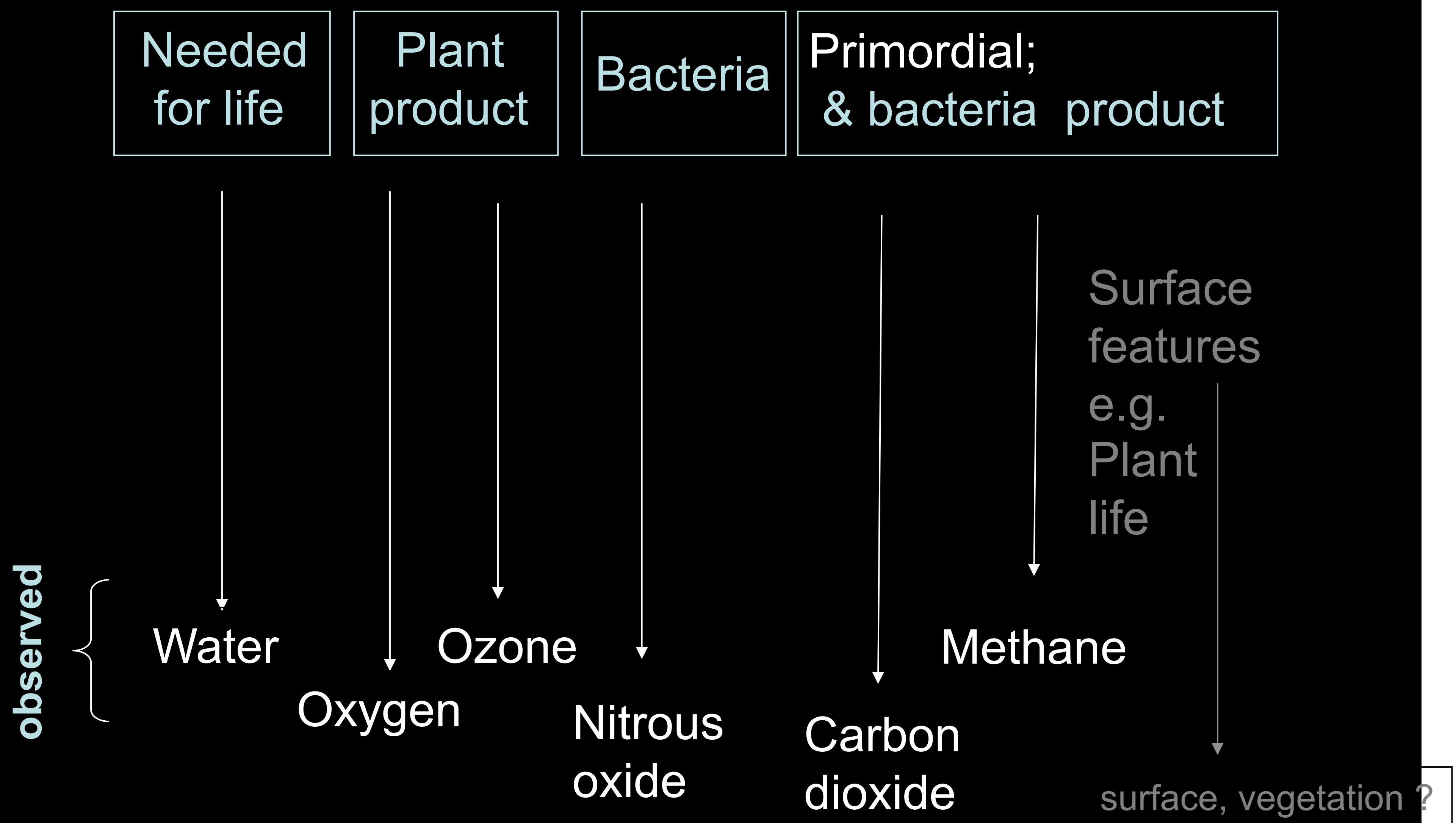
M & R = av. Density !
Degeneracy (= atm.)

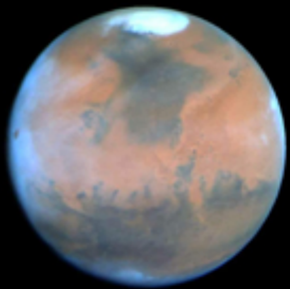
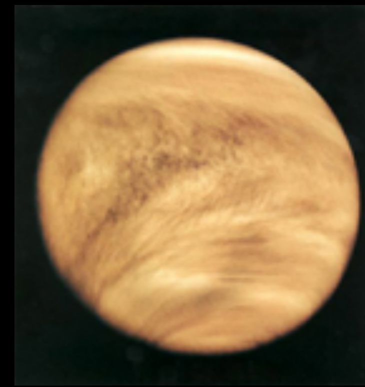




e.g. Seager et al 07, Adams et al. 09, Zeng &Sasselov 10

Signs Of Life On An Earth-like Planet



Reflected light

$$I_{VIS/NIR}(t) \propto \phi(t) \times A \times 2\pi R^2$$

The reflected light (visible-NIR) is modulated by $\phi(t)$ with or without a dense atmosphere

Thermal emission

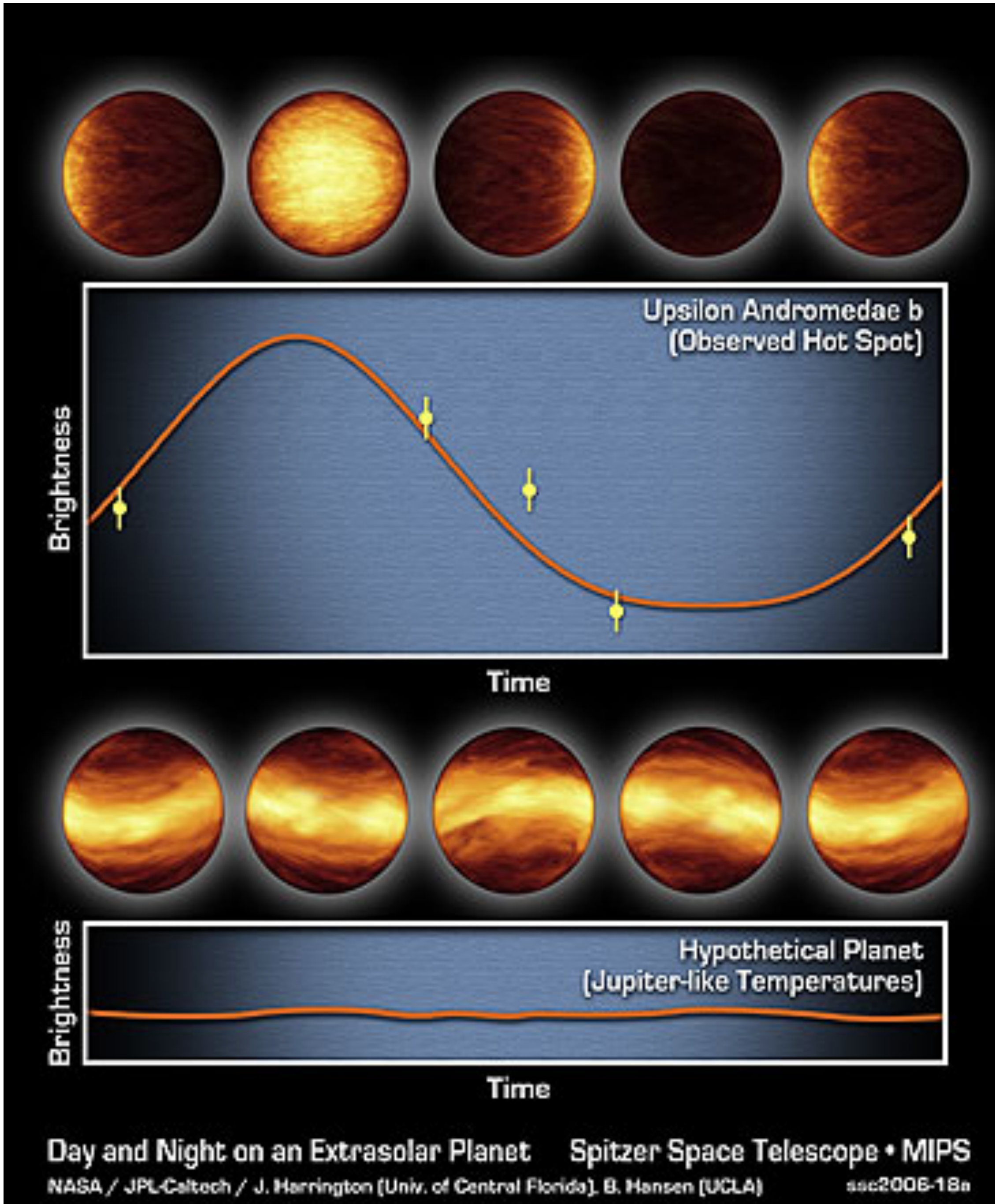
$$I_{IR}(t) \propto \phi(t) \times BB(T) \times 2\pi R^2$$

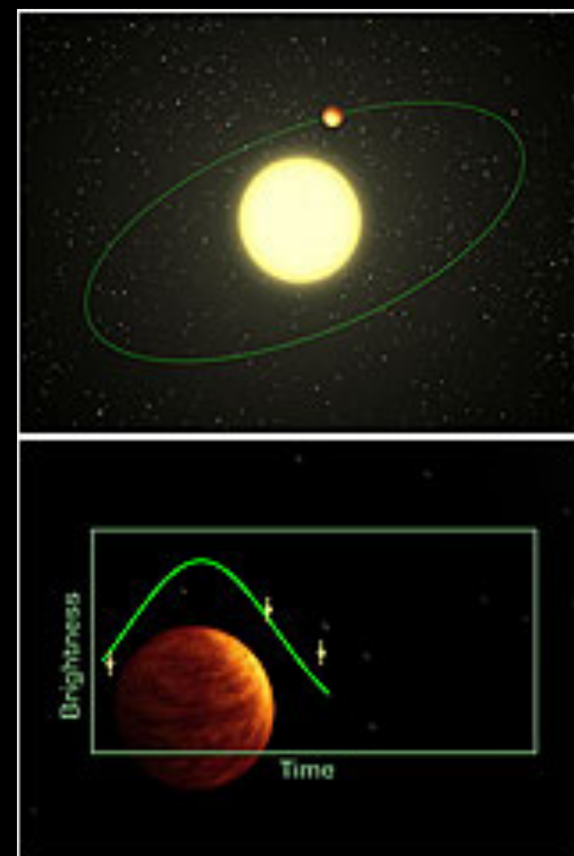
$$I_{IR}(t) \propto \cancel{\phi(t)} \times BB(T) \times 2\pi R^2$$

The thermal emission is modulated by $\phi(t)$ <u>only</u> when there is no (or a thin) atmosphere

Selsis

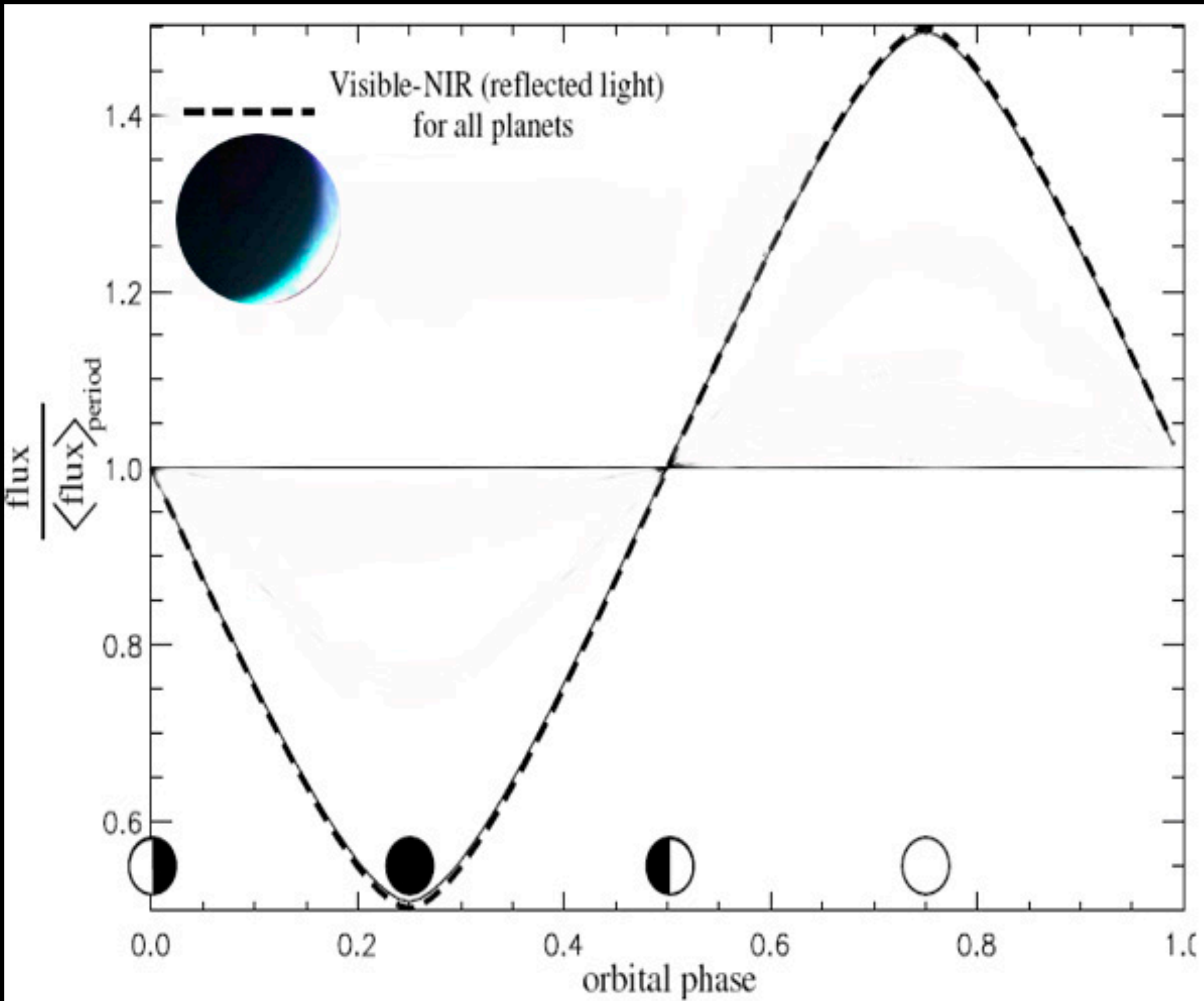
SPITZER





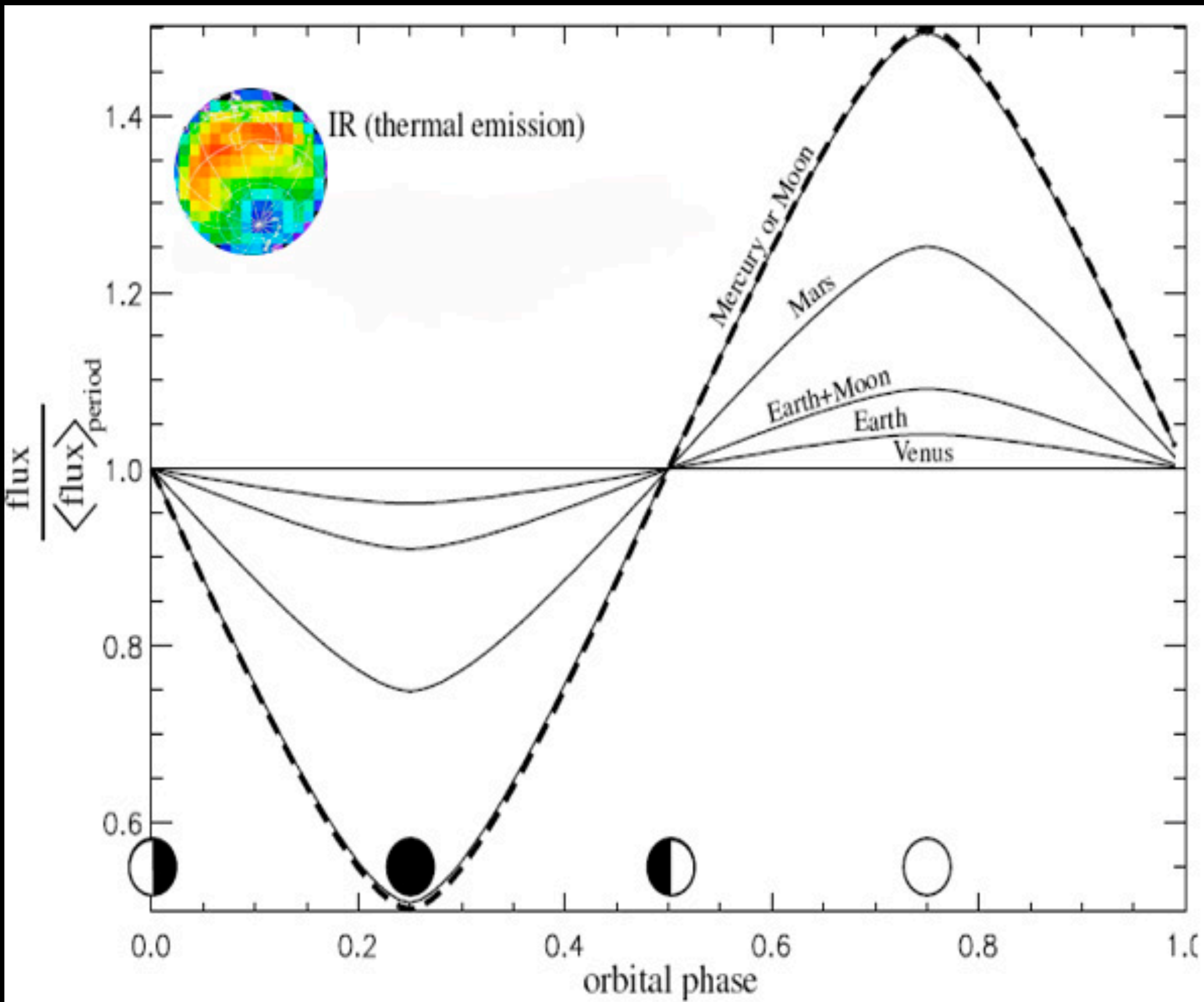
Knutson 2009

Steps to characterize – CONTEXT



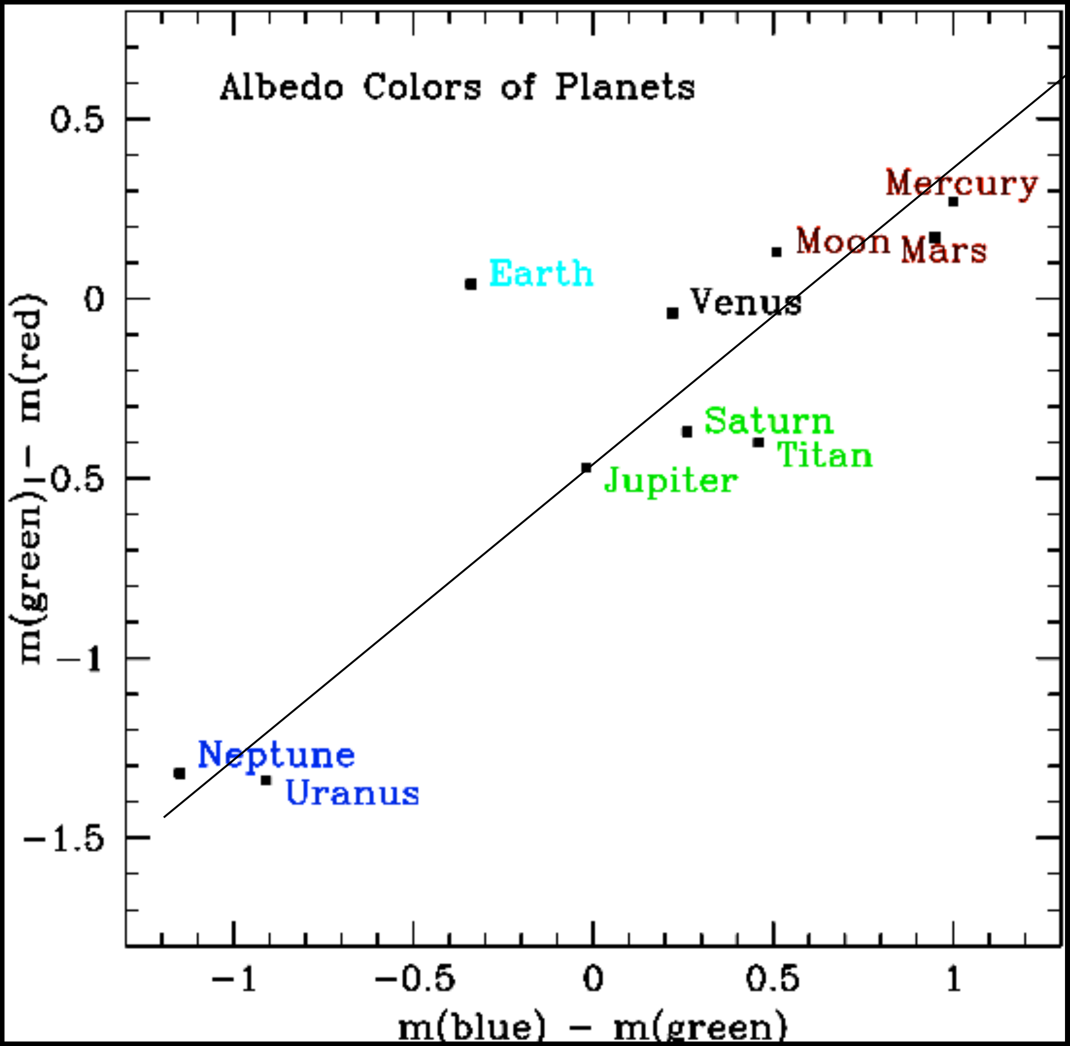
Selsis 2004, Gaidos 2004

Steps to characterize – CONTEXT

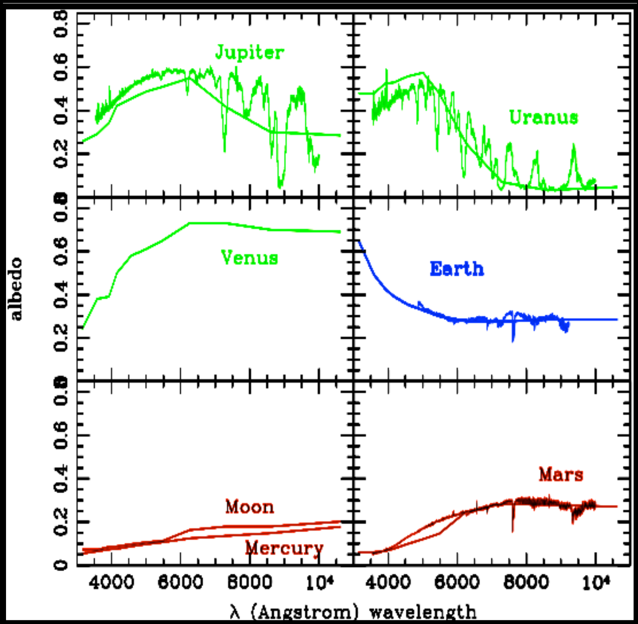


Selsis 2004, Gaidos 2004

Colors of our planets – low spectral res
What about exoplanet ?



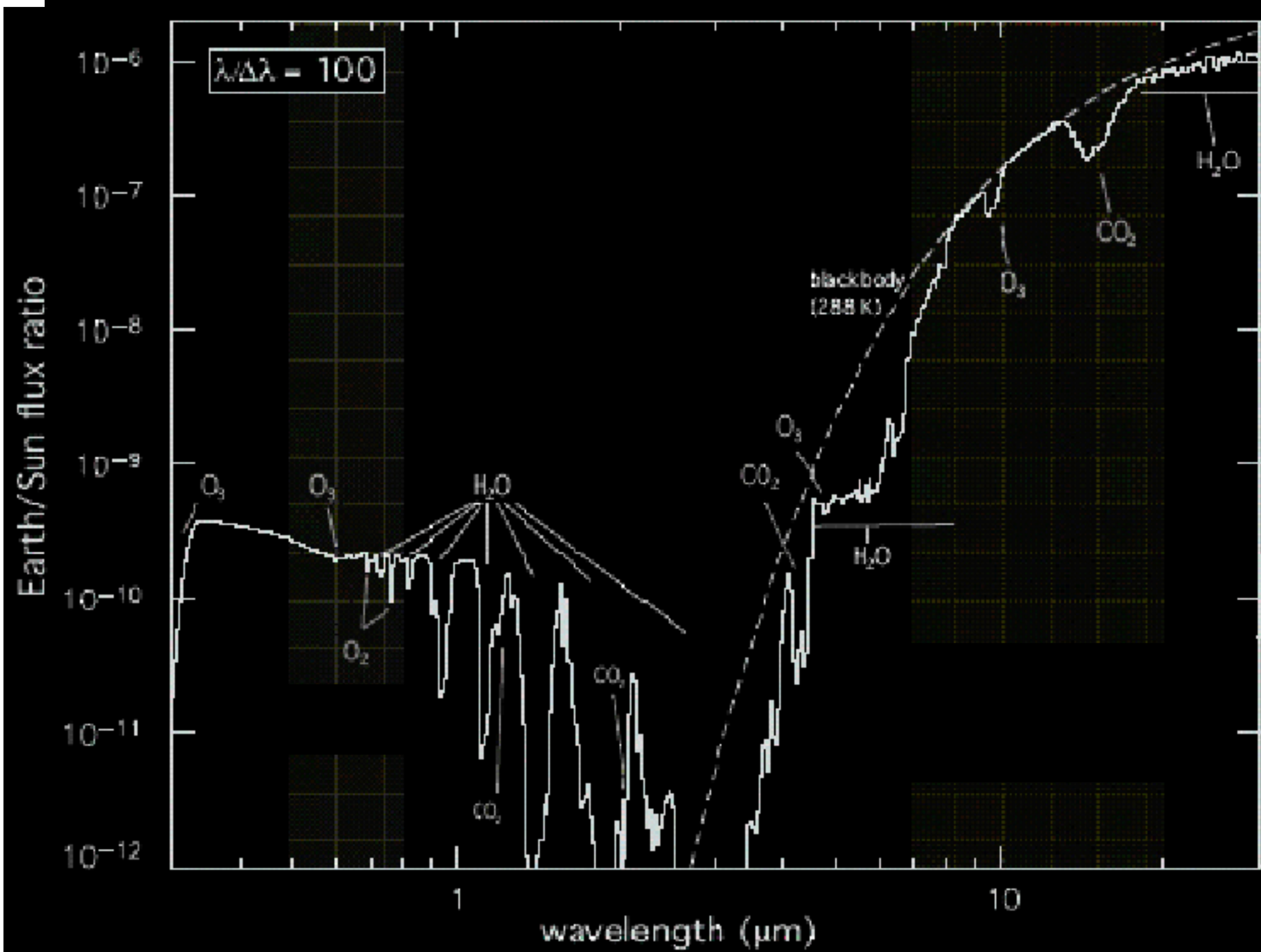
Planets have colors
Label them by type?

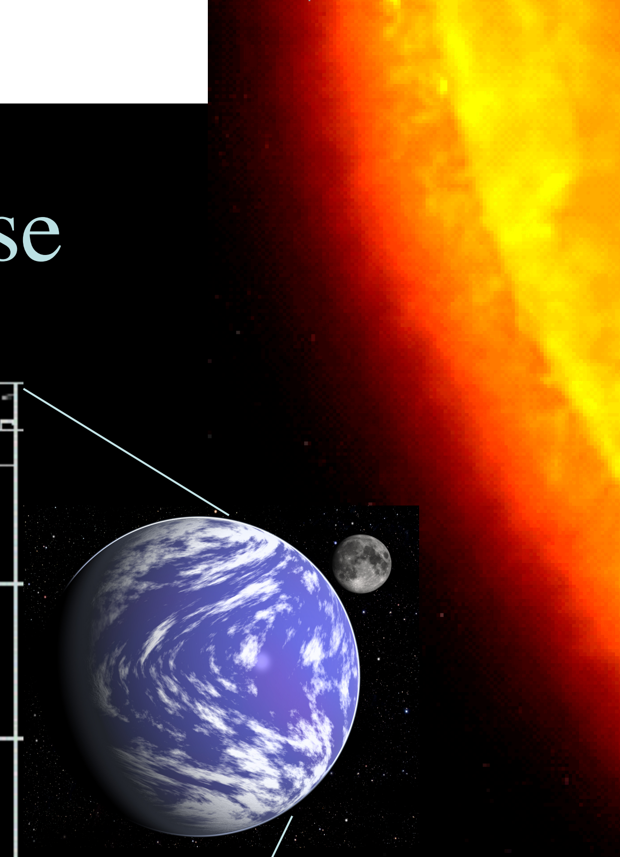


Traub 2002, & new papers sub.

Blue (0.4-0.6 μm), Green (0.6-0.8 μm), Red (0.8-1.0 μm)

Direct Imaging & **Secondary** Eclipse

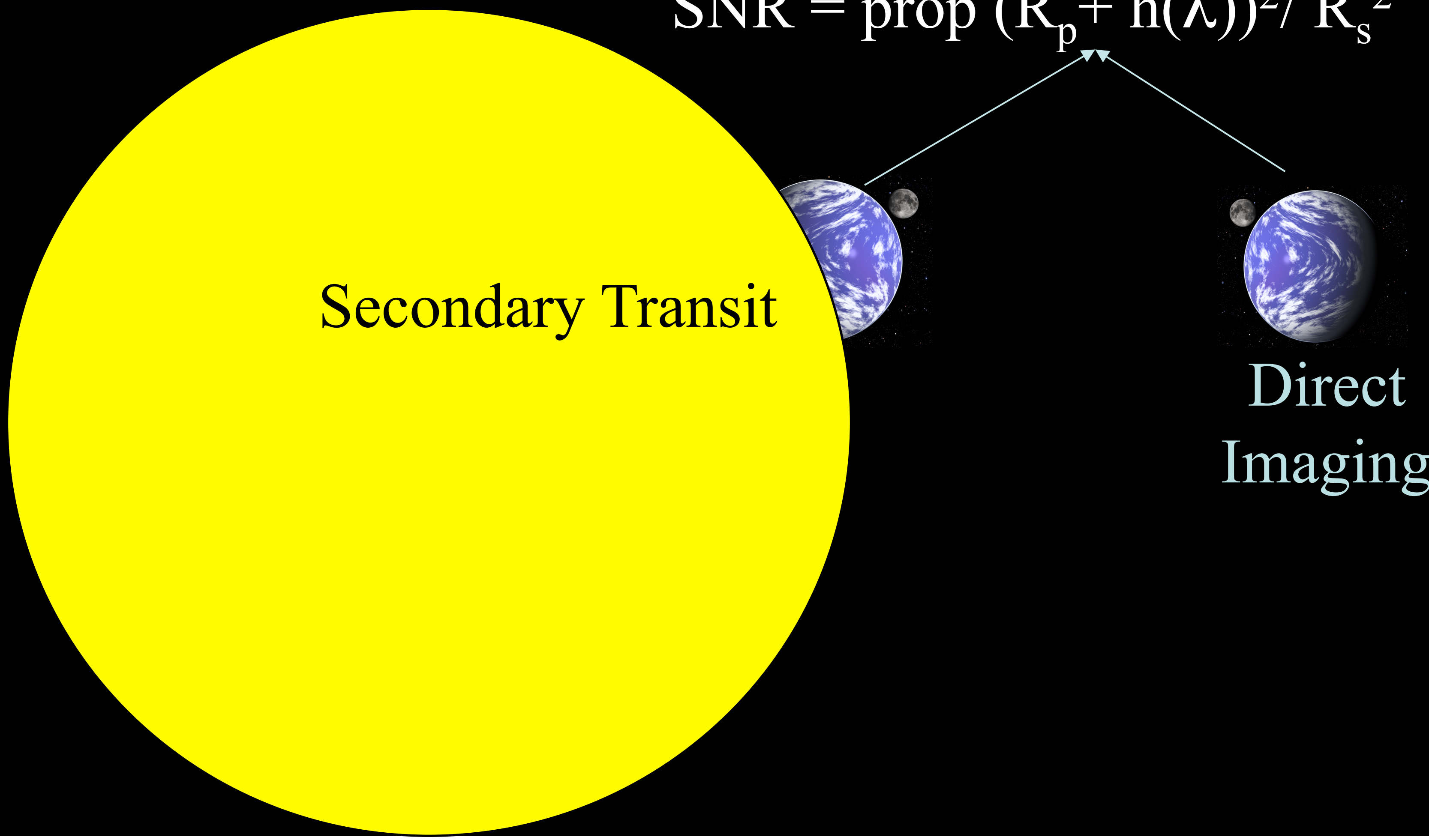




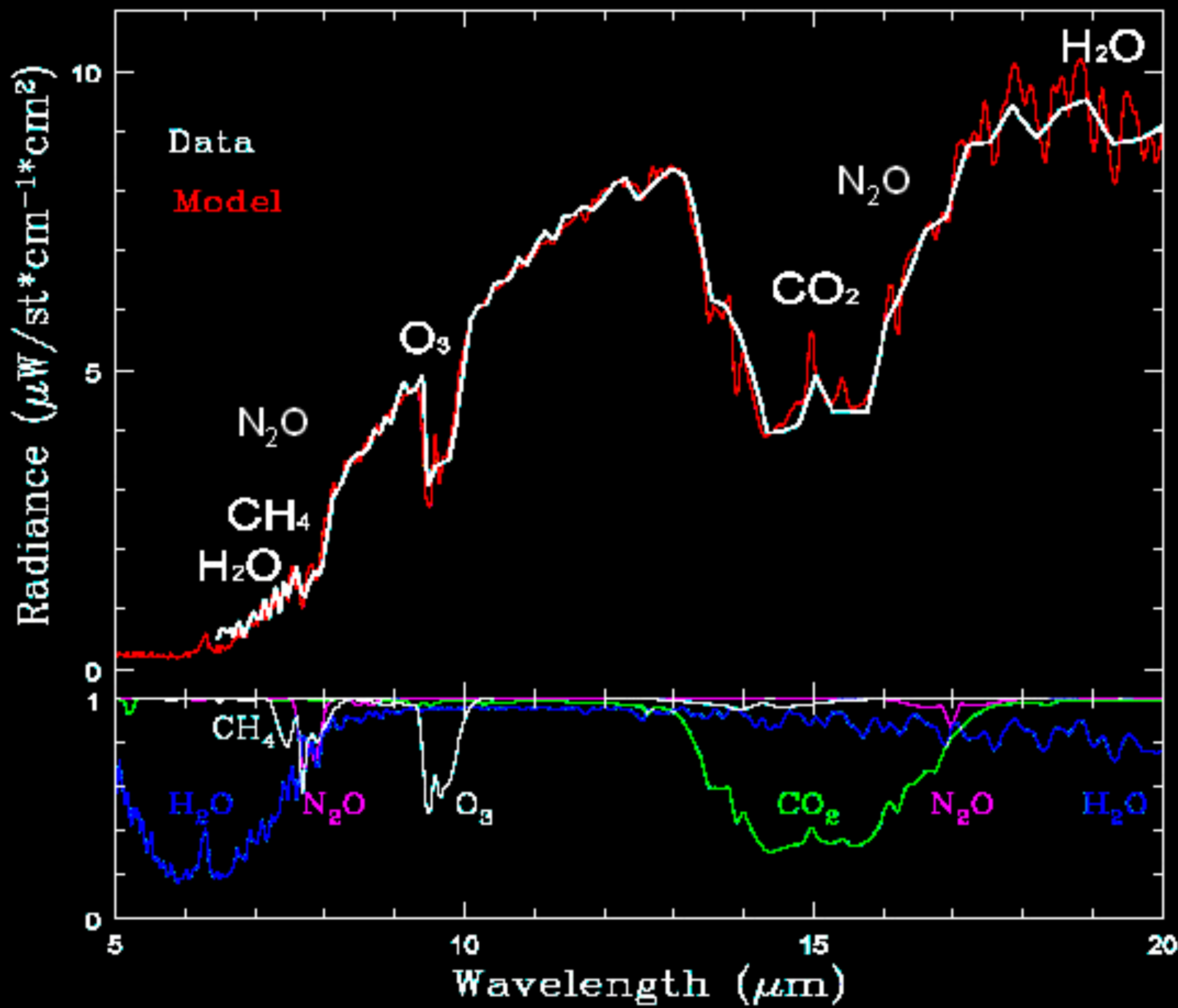
e.g. Kaltenegger & Selsis 2010

Characterizations – spectral res. f (λ) - I

$$SNR = prop\ (R_p + h(\lambda))^2 / R_s^2$$



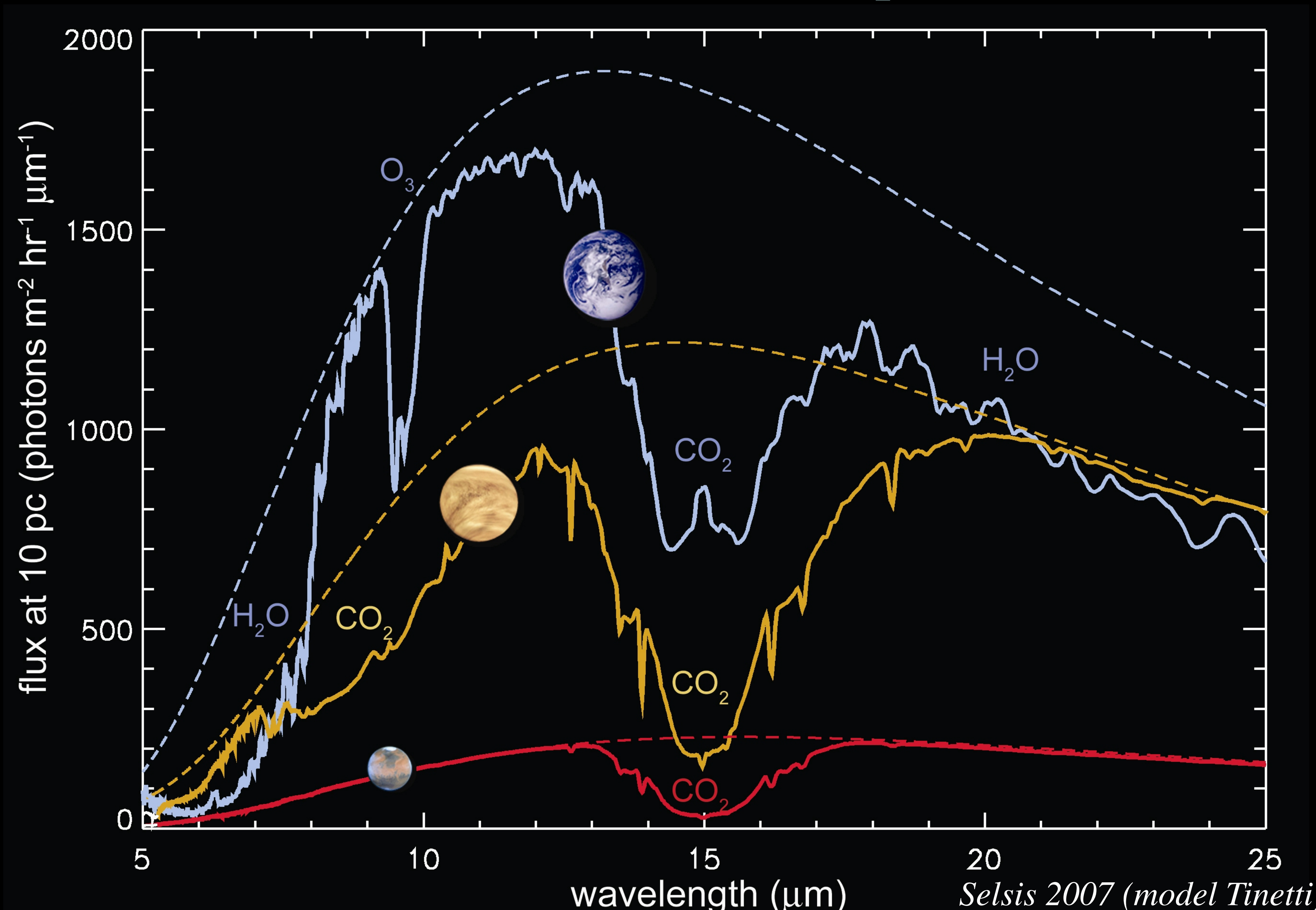
Earth IR-emission



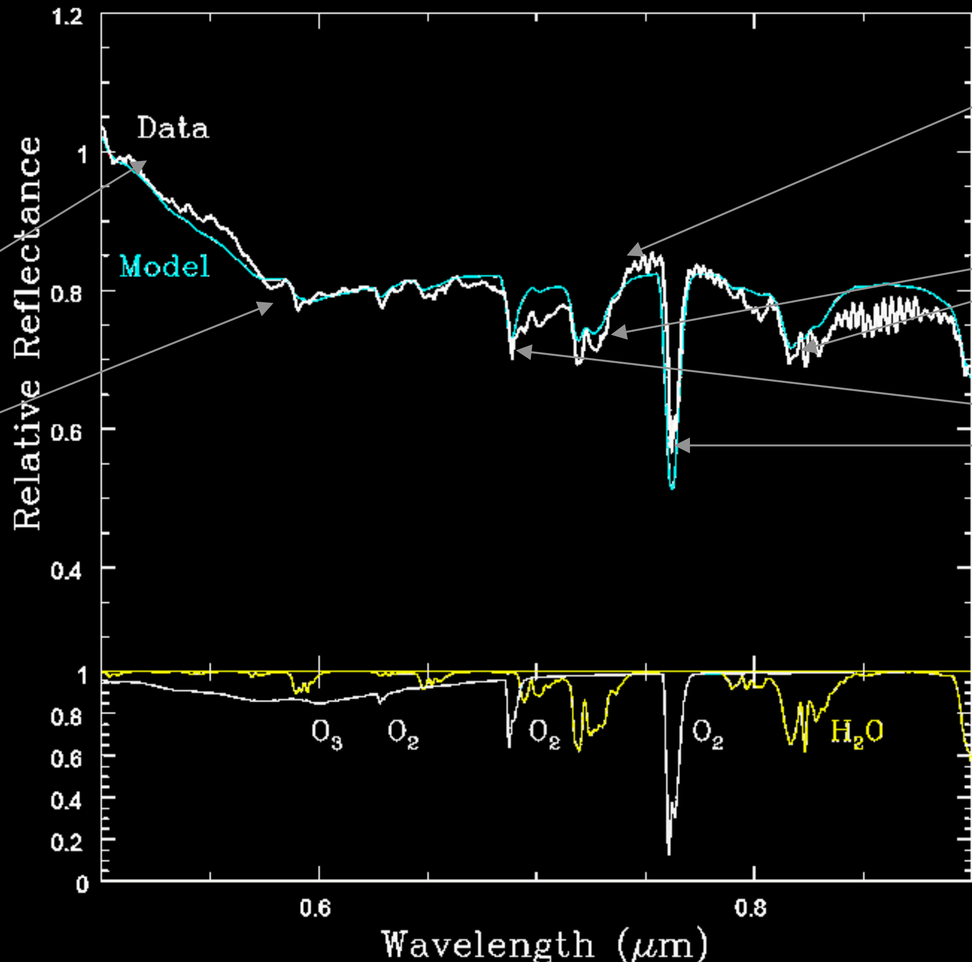
Kaltenegger, Traub, Jucks 2007 (ApJ)

TES data; Christensen 2004

Features: 1) observables & 2) unique ?



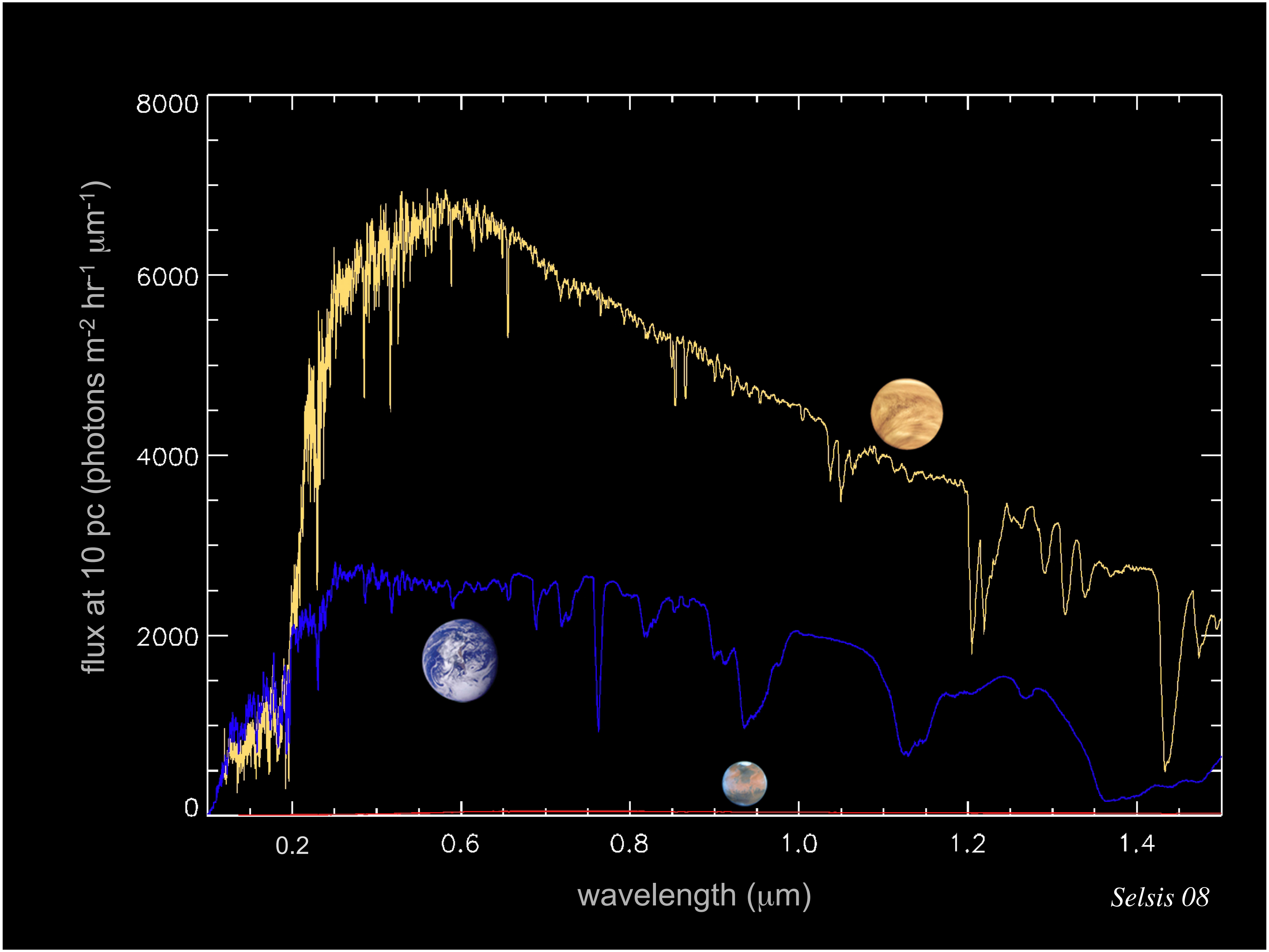
Visible spectrum of Earth



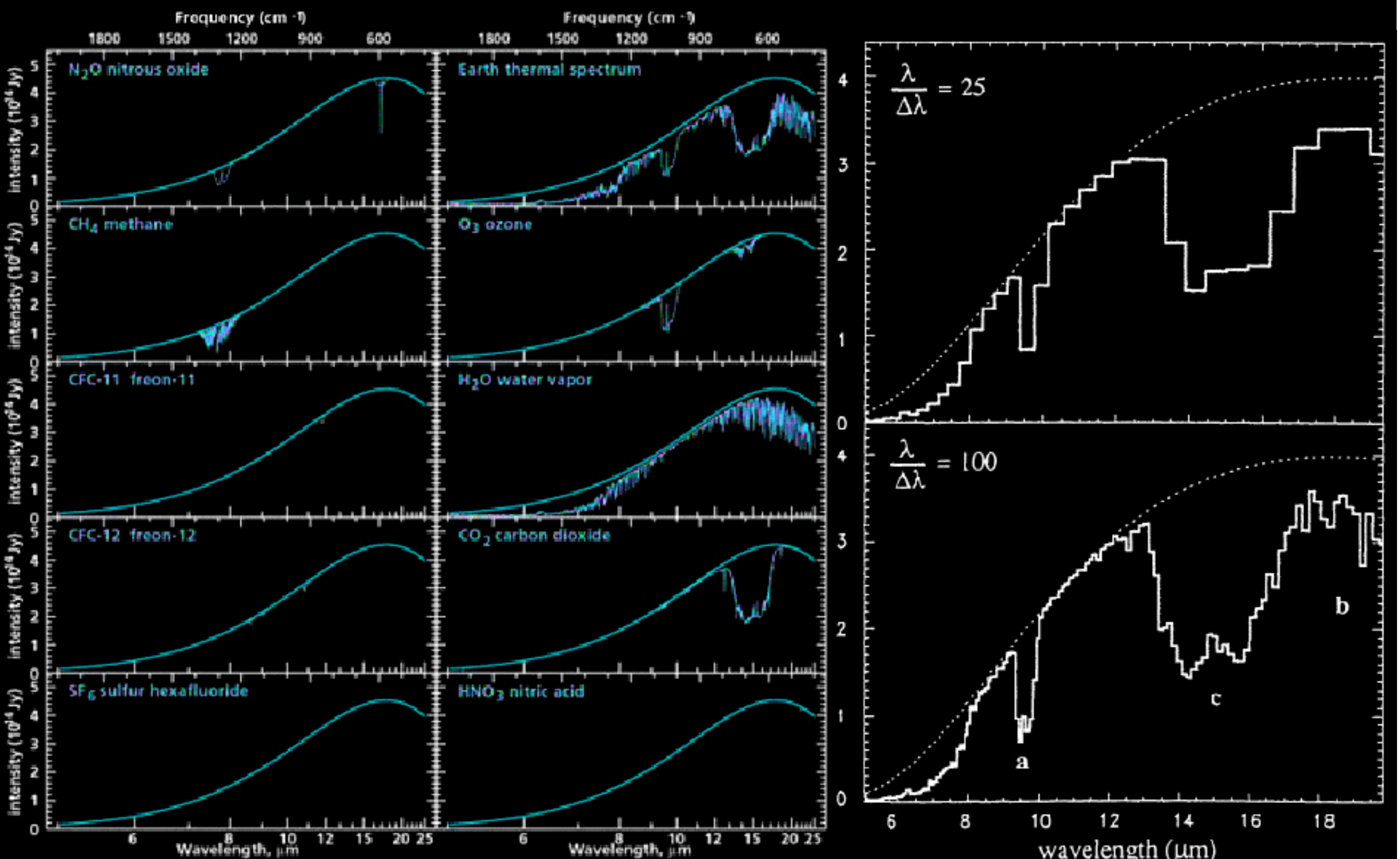
Observed Earthshine, reflected from dark side of moon.

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

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


8000
6000
4000
2000
0
flux at 10 pc (photons m-2 hr-1 μm-1)
0.2
0.6
0.8
1.0
1.2
1.4
wavelength (μm)
Selsis 08

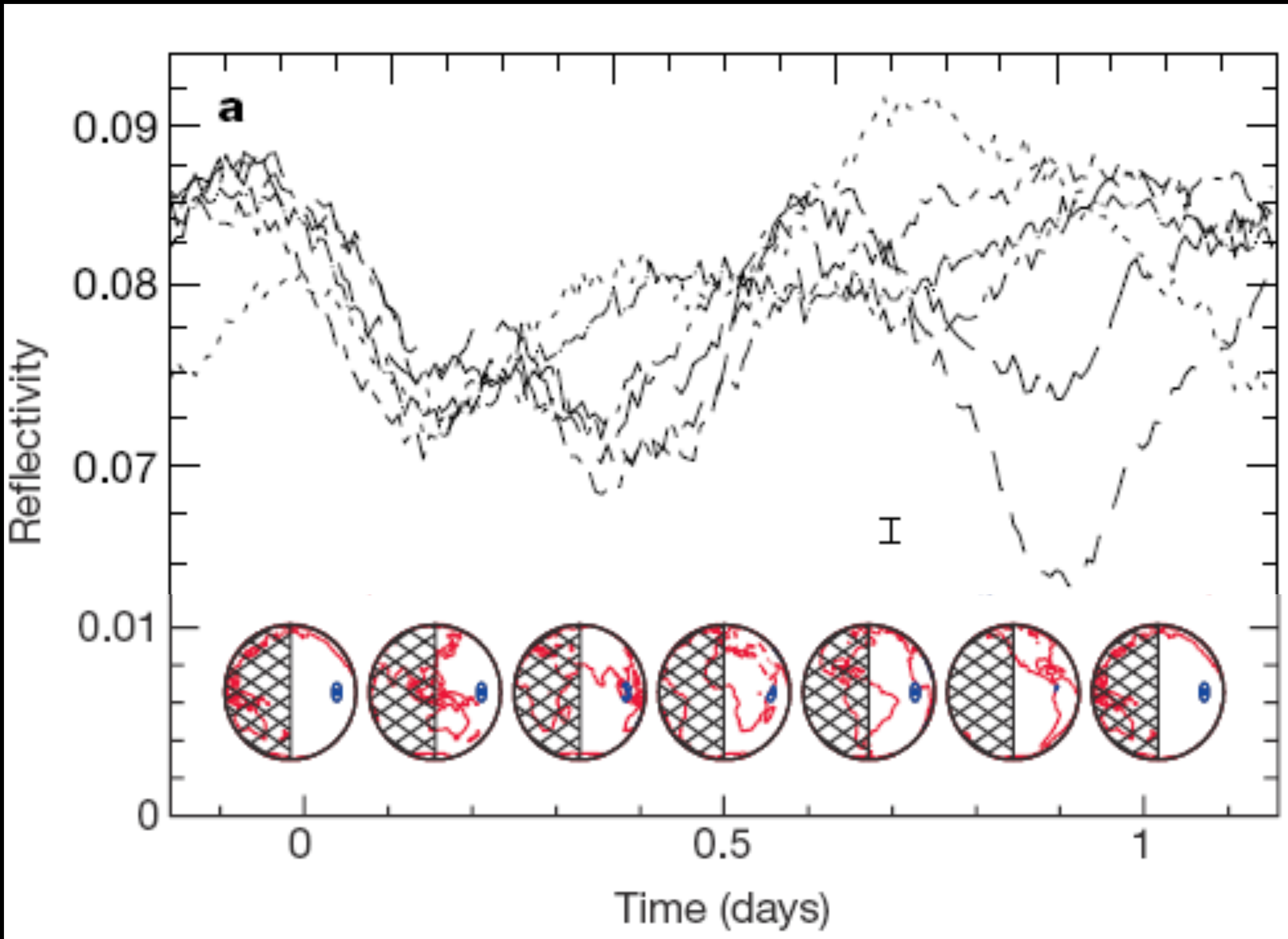
Spectral features IR & Is there Take out ?



Traub & Jucks, AGU, 2002; Des Marais et al. 2002, Selsis 2003

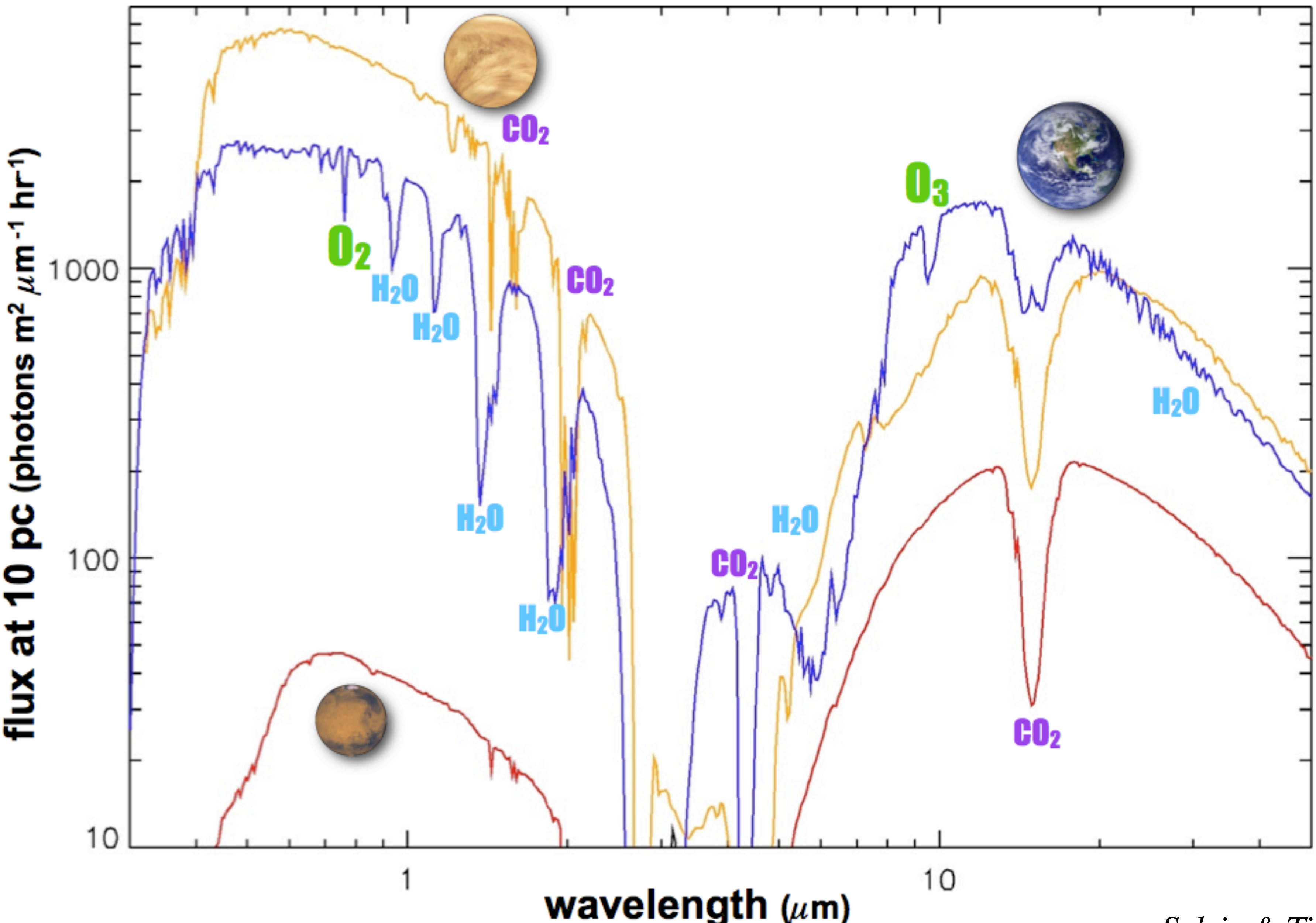
Surface? Measure every 1/20 of rotation period

Palle et al. 2008



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

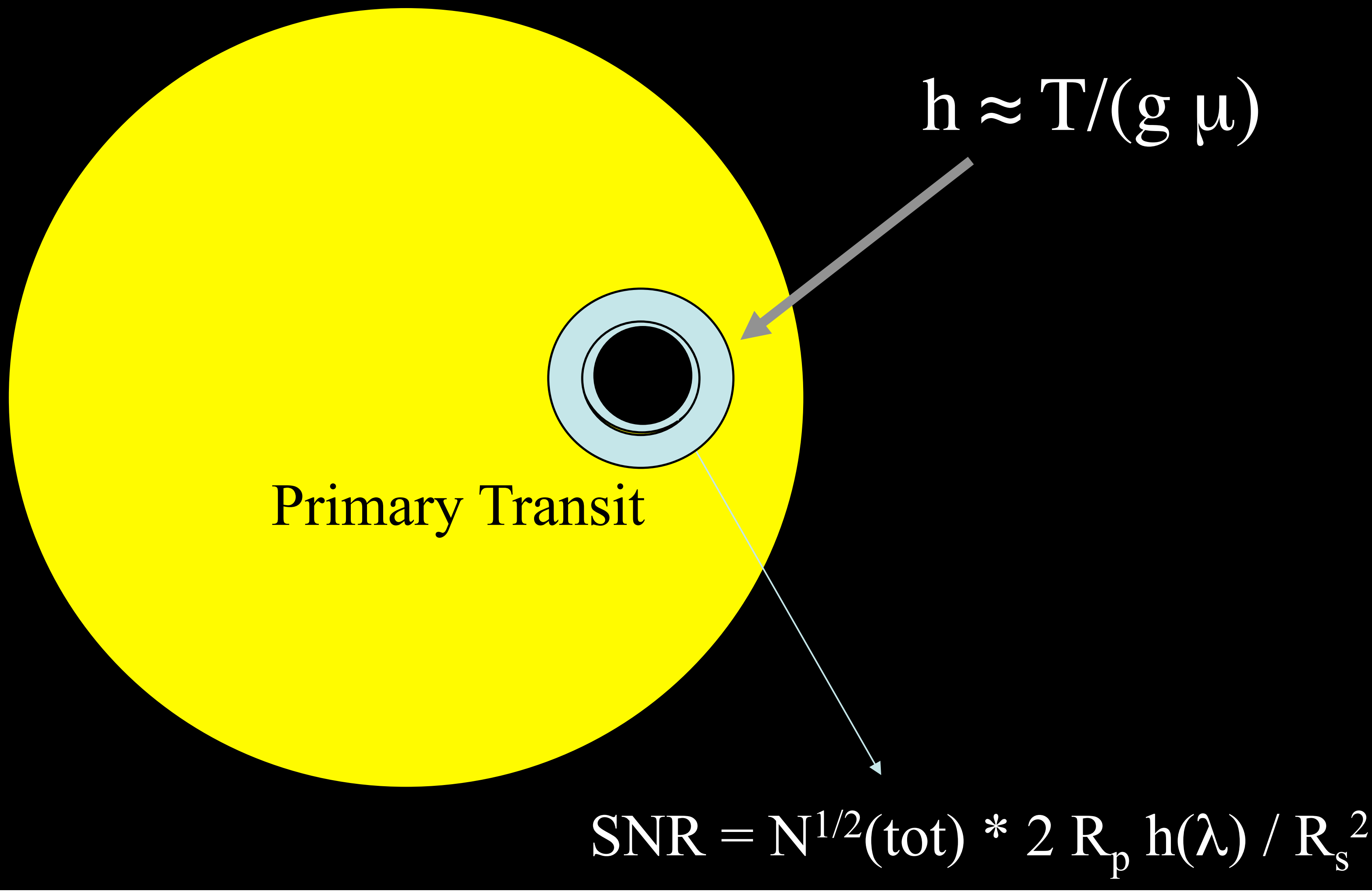
SNR vs diameter (λ) TPF, Darwin, NWO (etc) performance reports



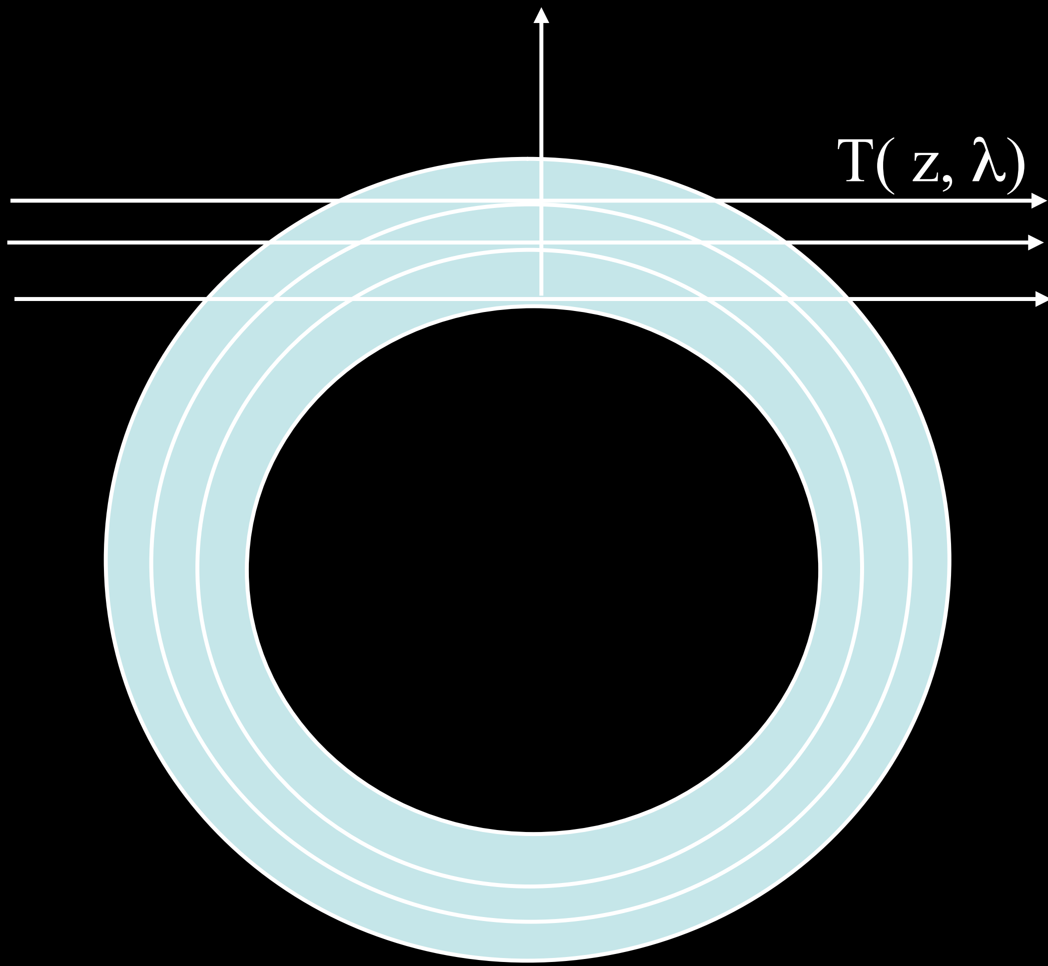
Selsis & Tinetti

Characterizations – spectral res. f (λ) – II

apparent radius



Transit Geometry



h is the effective height of an opaque atmosphere:

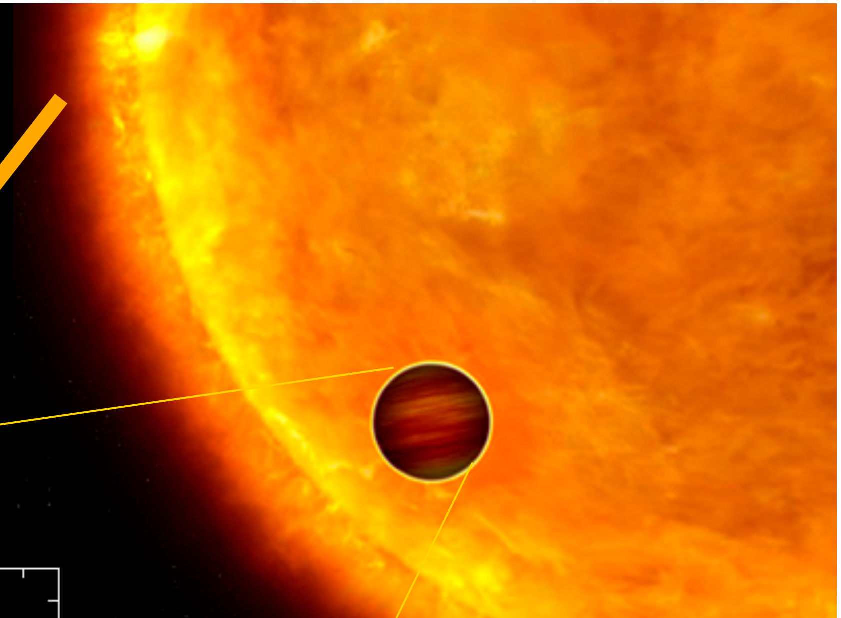
$$h(\lambda) = \int (1\text{-}T)\, dz$$

So

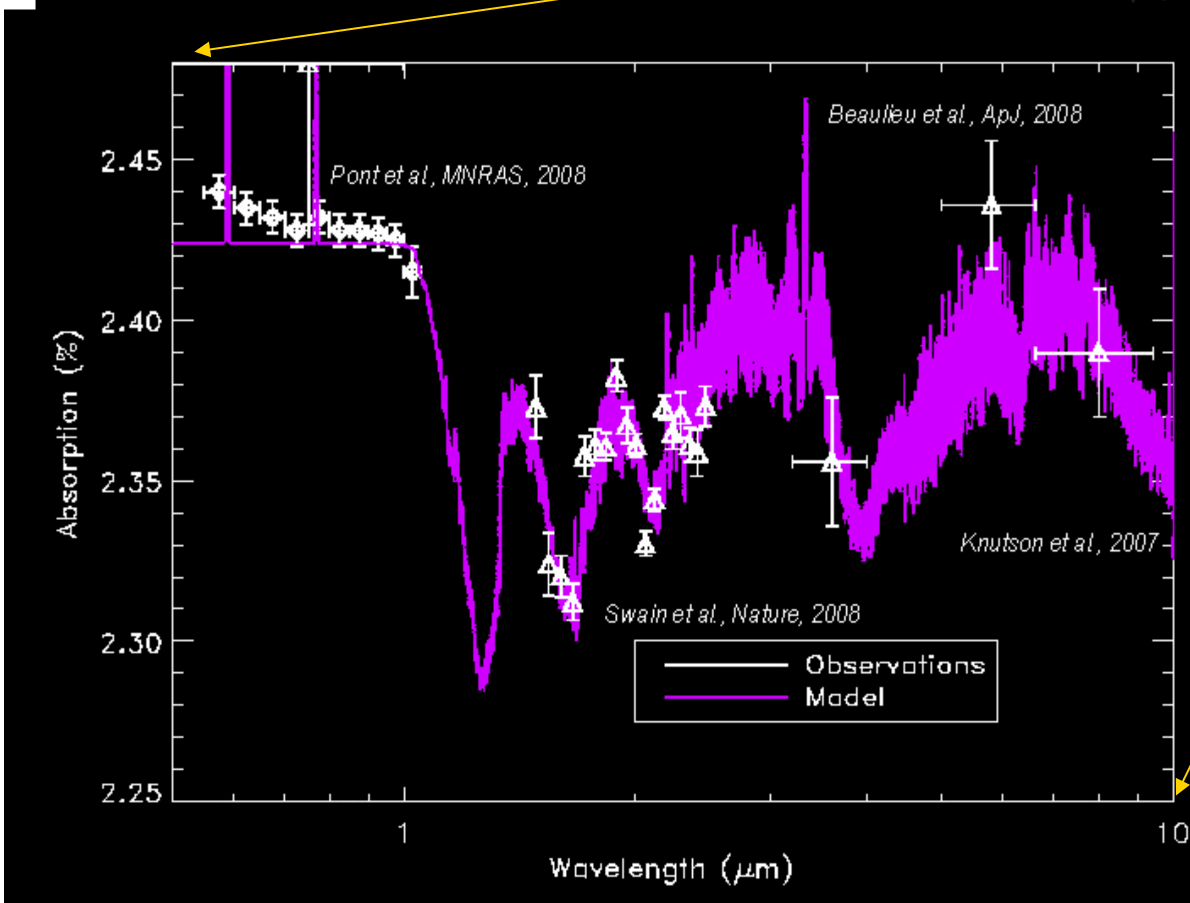
$$R(\lambda) = R_0 + h(\lambda)$$

Traub

Explore Planets - EGP ✓



2007 +

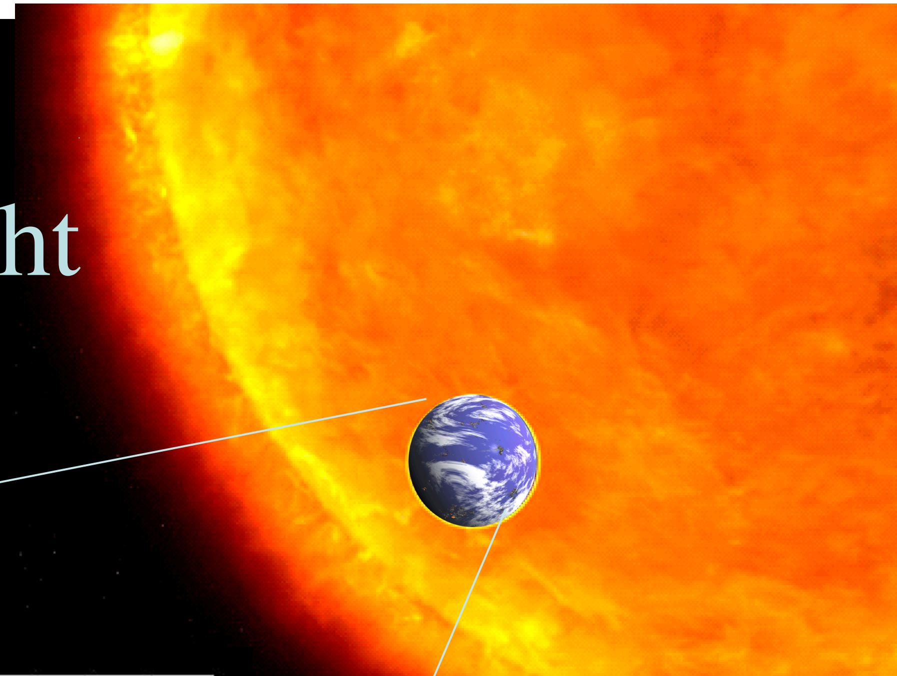


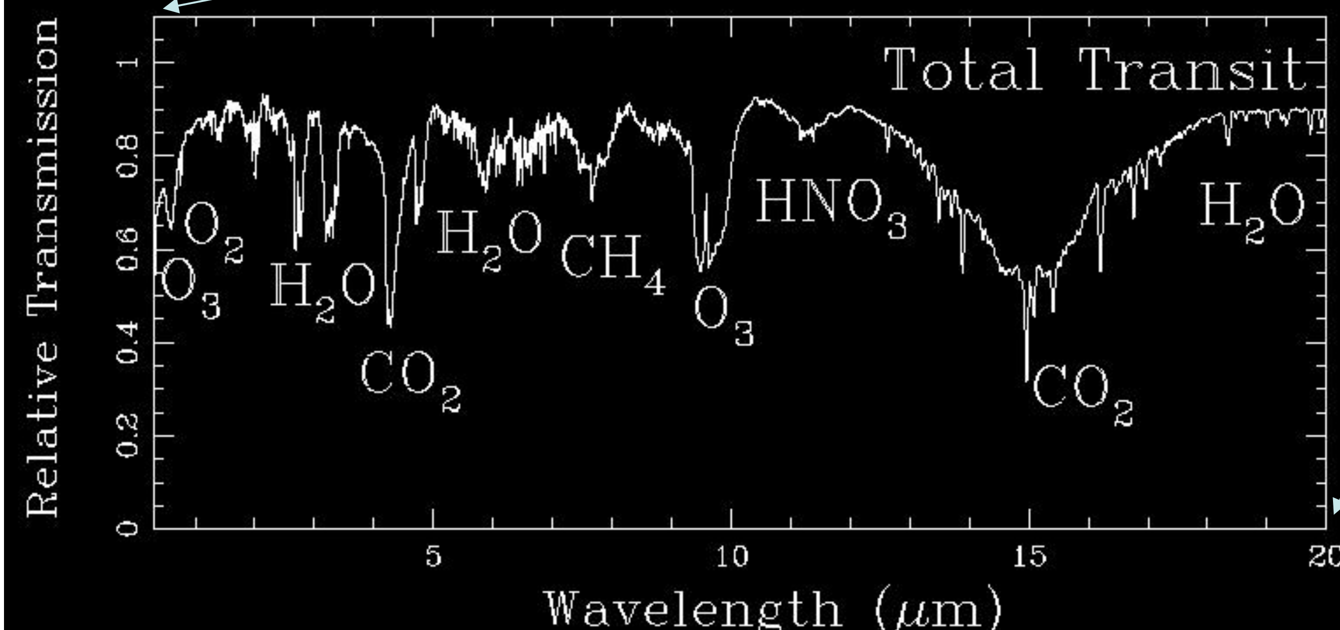
Atmosphere by transits…

HD189733b *(Tinetti07, Swain08)*

Earth *(Palle 09, Kaltenegger 09)*

Earth Primary Transit: collect transmitted starlight



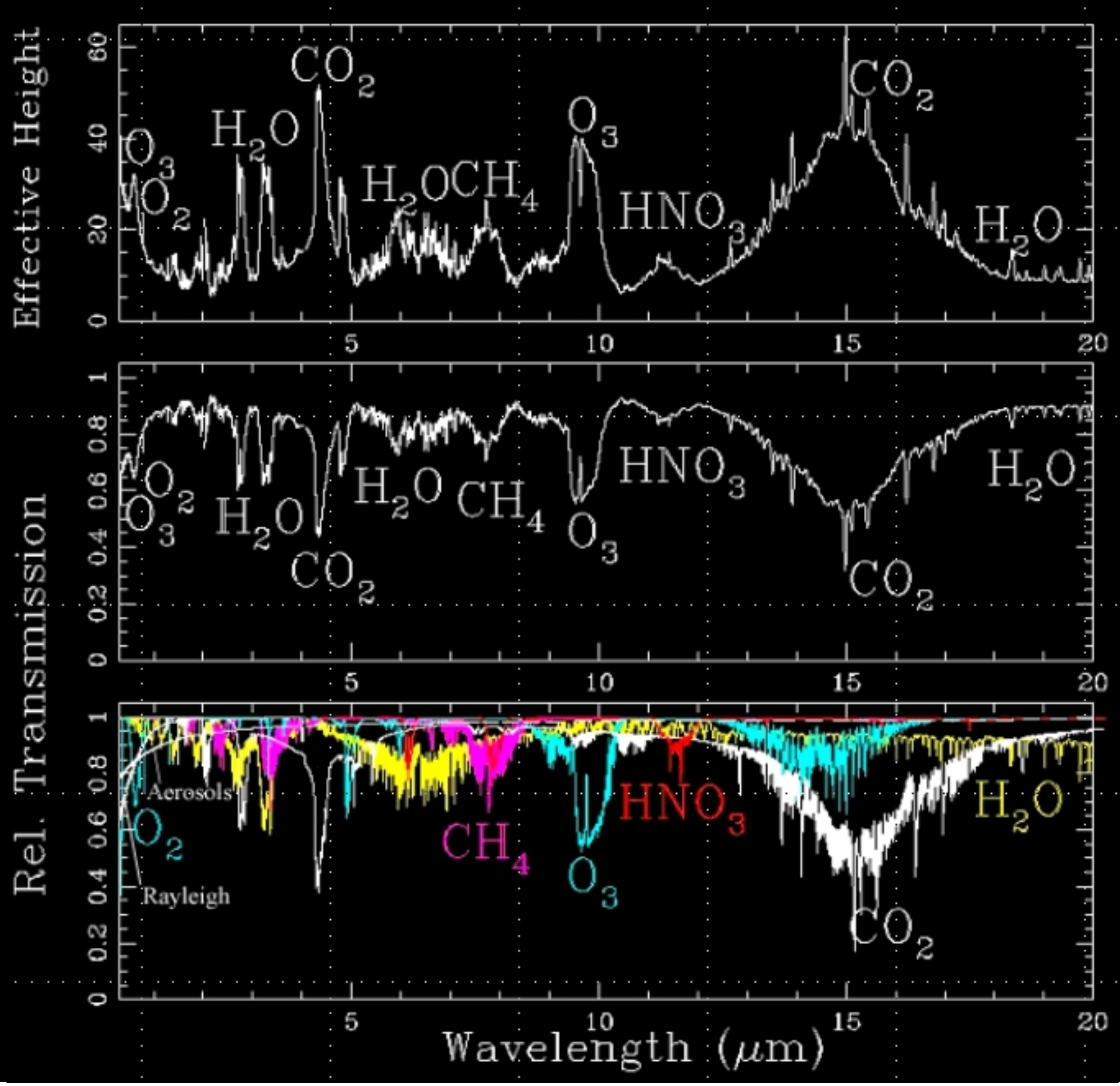


2002/2014+ ?

$$SNR = N^{1/2}(tot) * 2\pi R_p\ h / \pi R_s^2$$

Kaltenegger & Traub ApJ 2009
Palle et al. Nature 2009
Data: ATMOS B. Irion 2002

Composite transmission spectrum & effective height



Effective height for spectral range 0.3 – 20 μ

Composite relative transmission.

Individual components

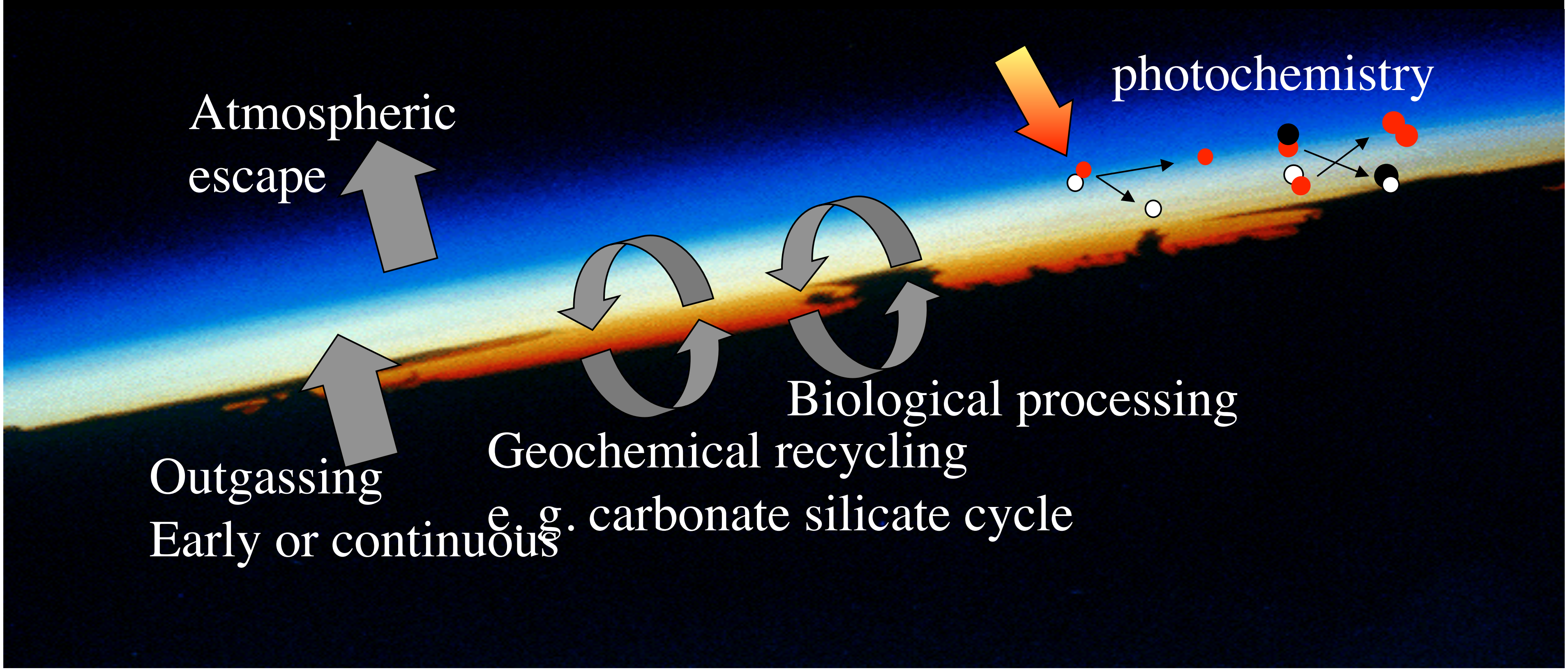
SNRs for M-stars, 1 transit, BETTER contrast, LESS time/transit

6.5-m telescope				SNR (E, Star) 10 pc					
Feature	**λ(μm)**	**Δλ(μm)**	**h(λ).km**	**G2V**	**M0V**	**M2V**	**M5V**	**M8V**	**M9V**
O_3	0.6	0.15	10	1.67	**0.45**	**0.30**	**0.12**	**0.06**	**0.05**
H_2O	1.9	0.2	5	0.47	**0.25**	**0.21**	**0.13**	**0.10**	**0.09**
CO_2	2.8	0.1	20	0.84	**0.48**	**0.41**	**0.28**	**0.22**	**0.22**
H_2O	3.3	0.25	20	1.08	**0.63**	**0.55**	**0.38**	**0.30**	**0.30**
CH_4	7.7	0.7	7	0.20	**0.13**	**0.11**	**0.08**	**0.07**	**0.07**
O_3	9.8	0.7	30	0.61	**0.38**	**0.34**	**0.25**	**0.21**	**0.22**
CO_2	15.2	3.0	25	0.58	**0.37**	**0.33**	**0.24**	**0.21**	**0.21**

Kaltenegger & Traub ApJ 2009

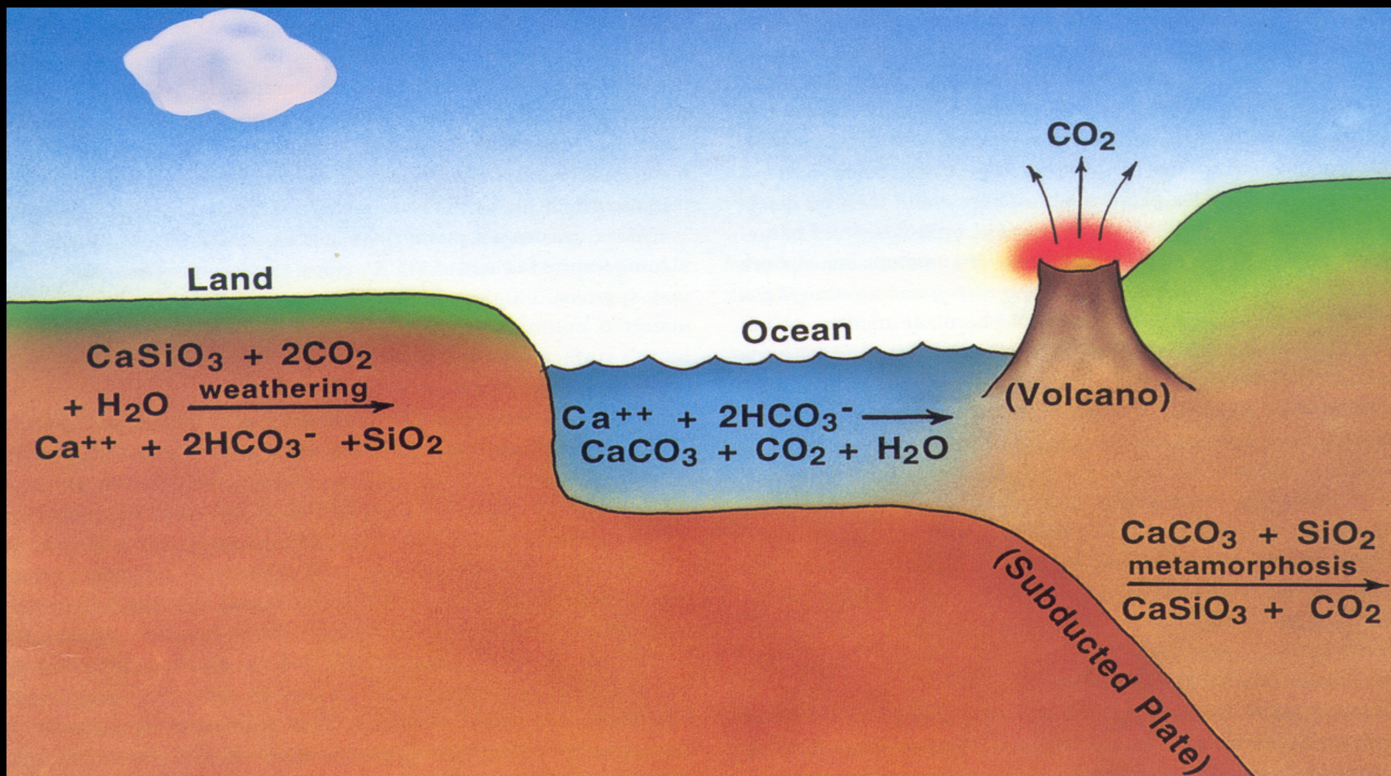
INFLUENCE NEEDED ACCURACY

- Outgassing vs loss as f(t)
- Different geochem cycles ? (e.g. S)
- Biological processing ?



Climate Stabilization : Carbonate – Silicate Cycle

Walker et al. 1981



Ts ↓ ⇒ water cycle ↓ ⇒ weathering ↓

⇓

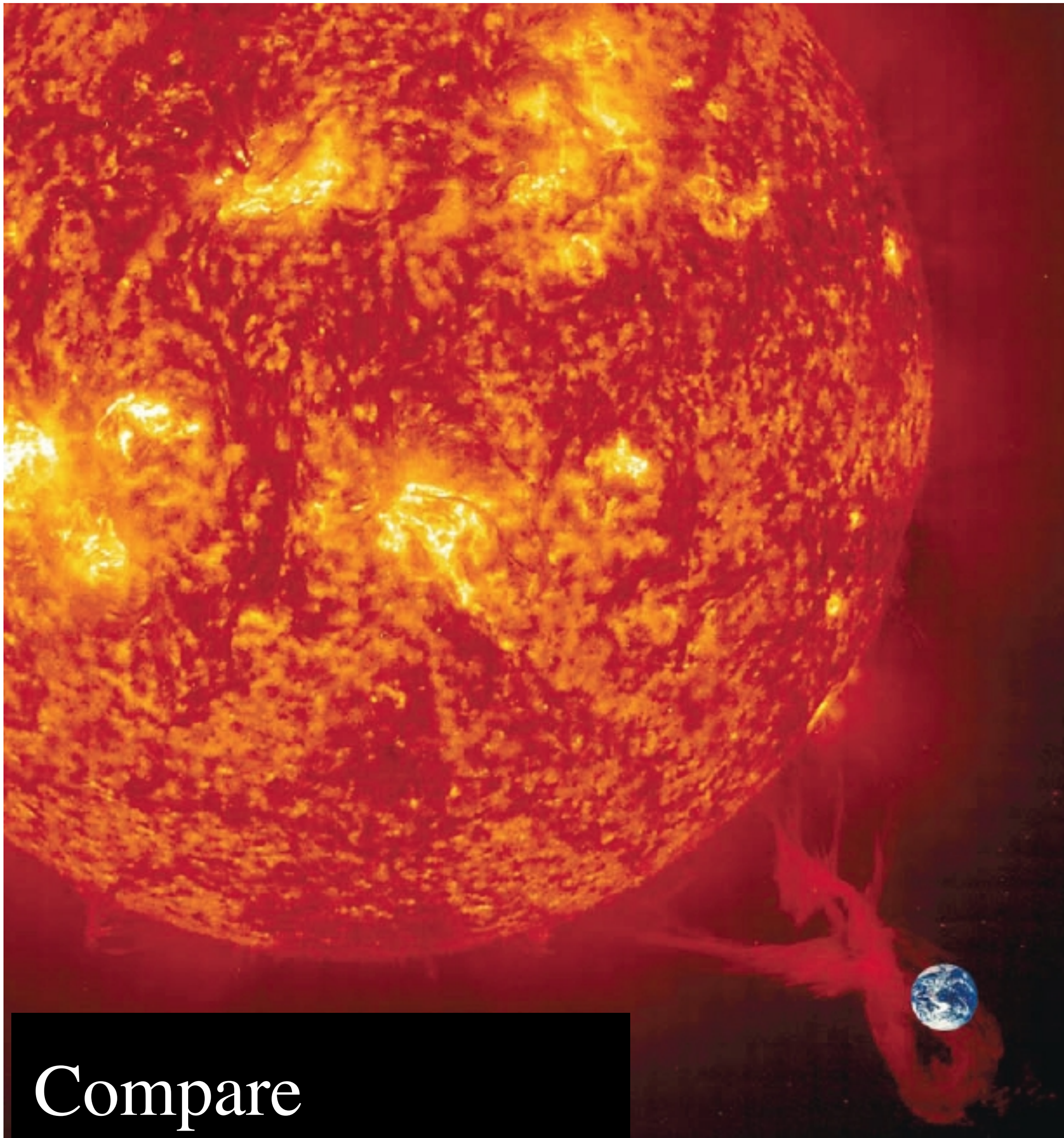
Ts ↑ ⇐ Greenhouse effect ↑ ⇐ P_{CO2} ↑

Mass – what is the upper limit on rocky pl? plate tectonics = habitability? Open

- Mass – SuperEarth & tectonic ?
  - ongoing discussions (cross-disciplinary)
  - $< 15\ M_{earth}$ rocky, habitats? MANY

- what accuracy needed
  - Mass degeneracy for diff. compositions
  – atm & interior split?

- See panel discussion



Compare
standard models

MODEL

↓ ↑

STAR: Flux

PLANET:

- Composition
- Water delivery
- Outgassing
- Tectonic
- Geoch. Cycle
- Magnetosphere

↓ ↑

= ATMOSPHERES

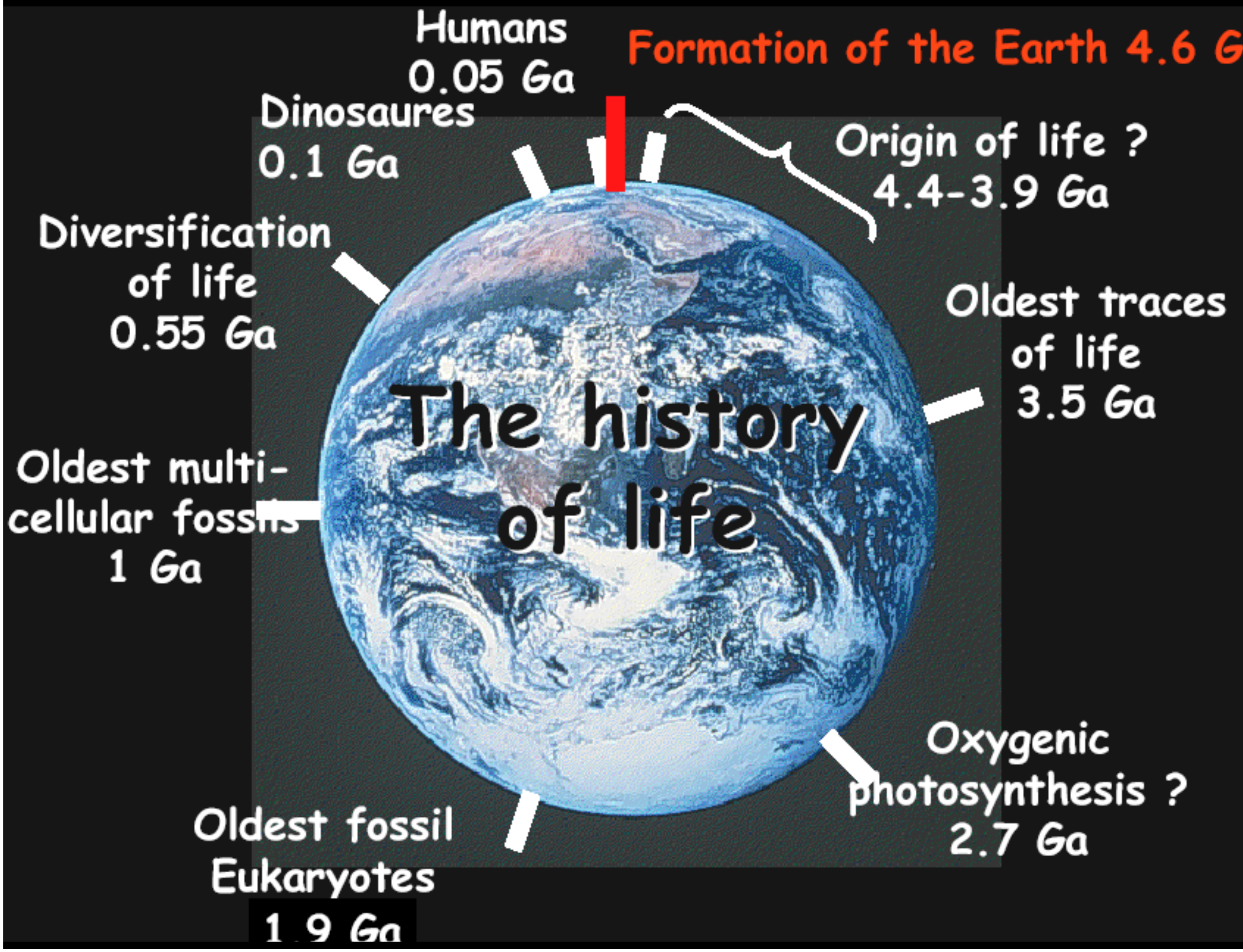
↓ ↑

SPECTRAL Fingerprint

↓ ↑

DATA

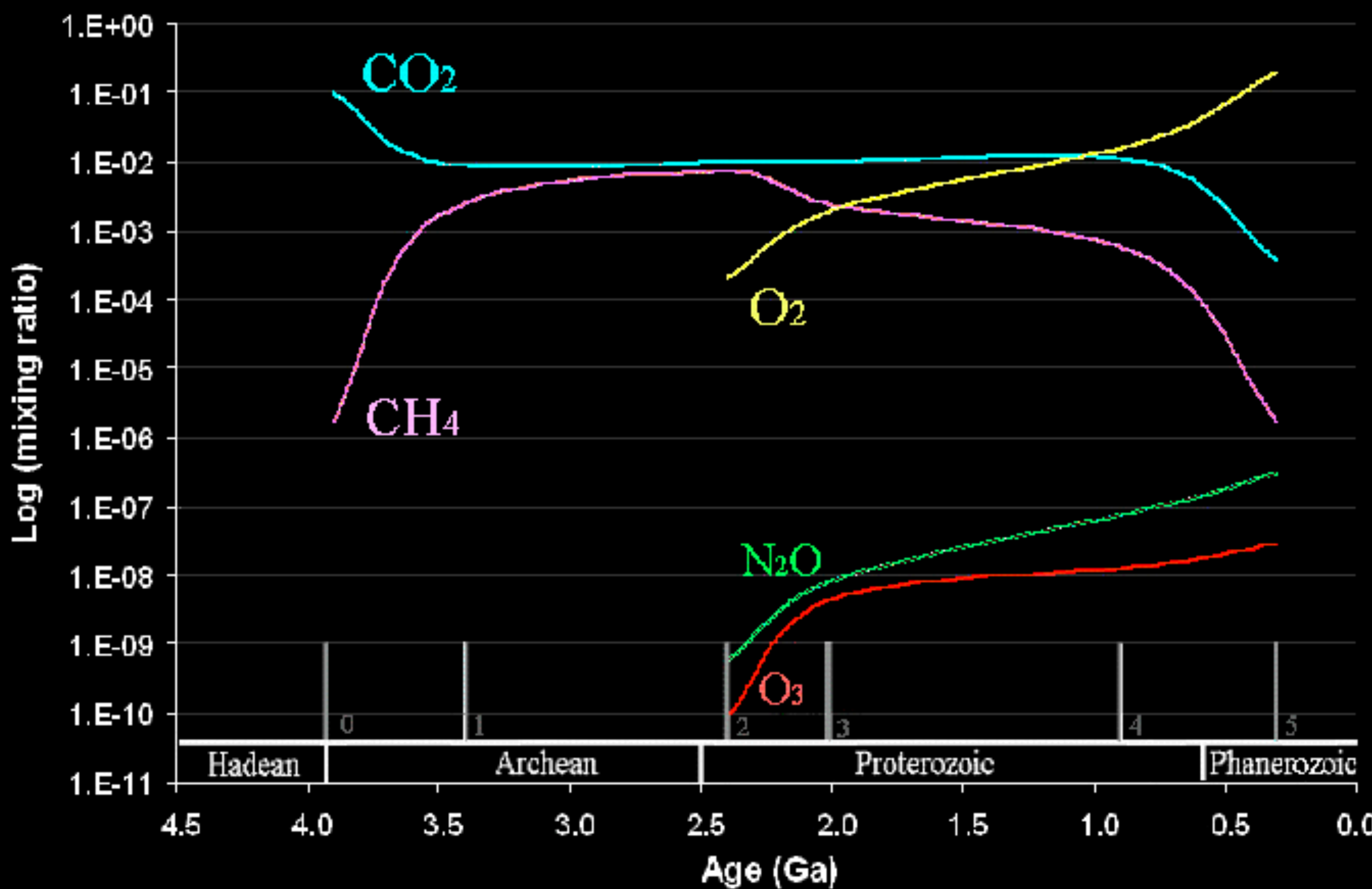
Exo-planets = time machine ?



F. Westall

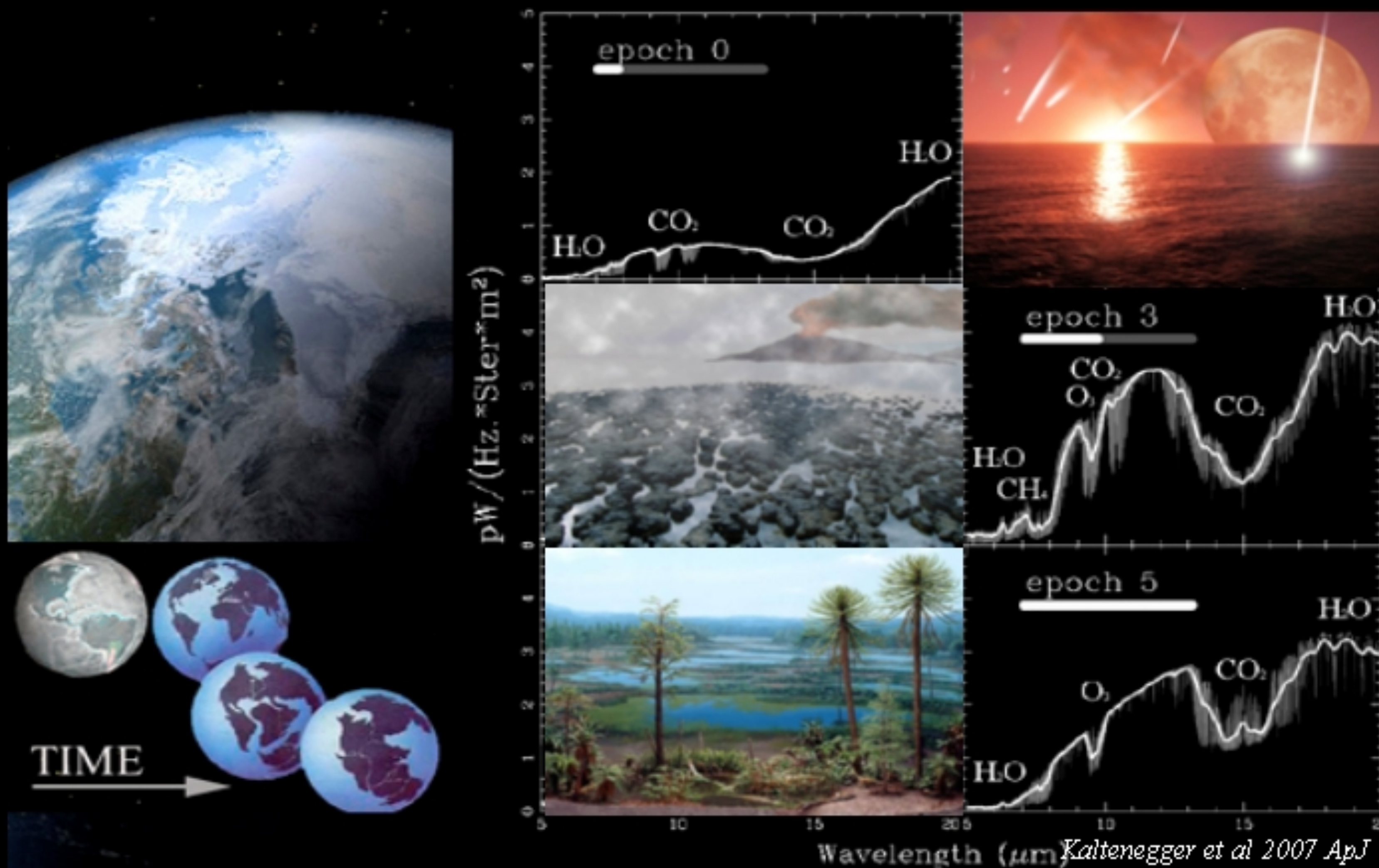
Biomarkers & spectra change over time

IMPORTANT: e.g: Surface temp change, cloud! coverage



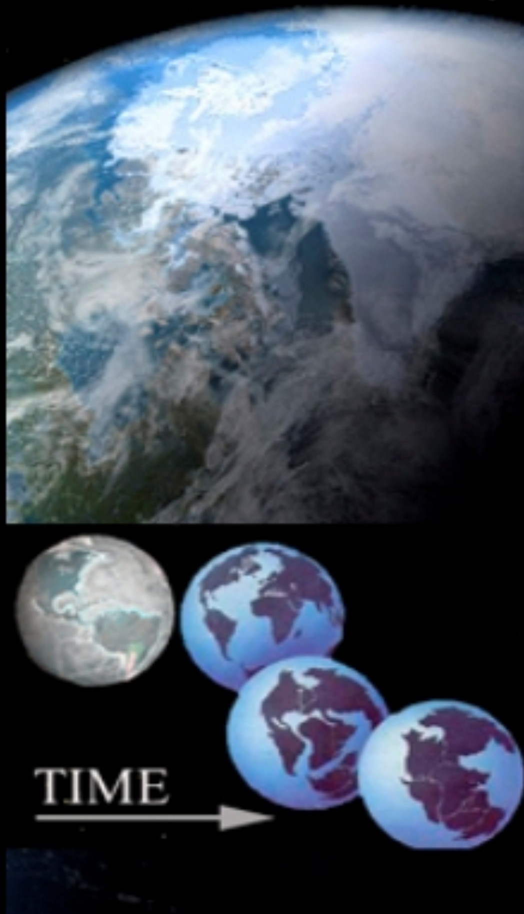
Kasting et al 2004 Kaltenegger et al ApJ 2007

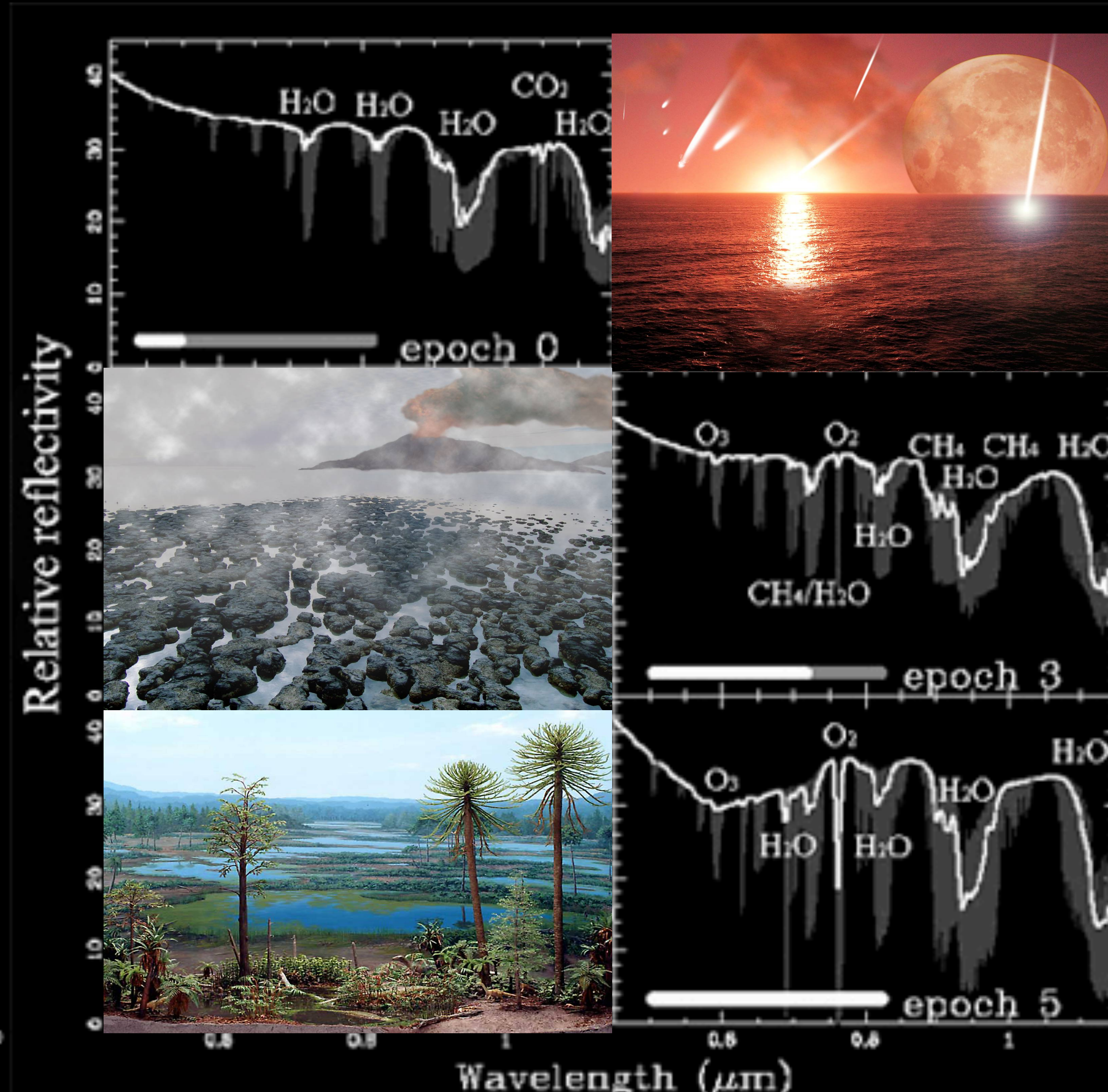
Earth Evolution over geological time - CSI



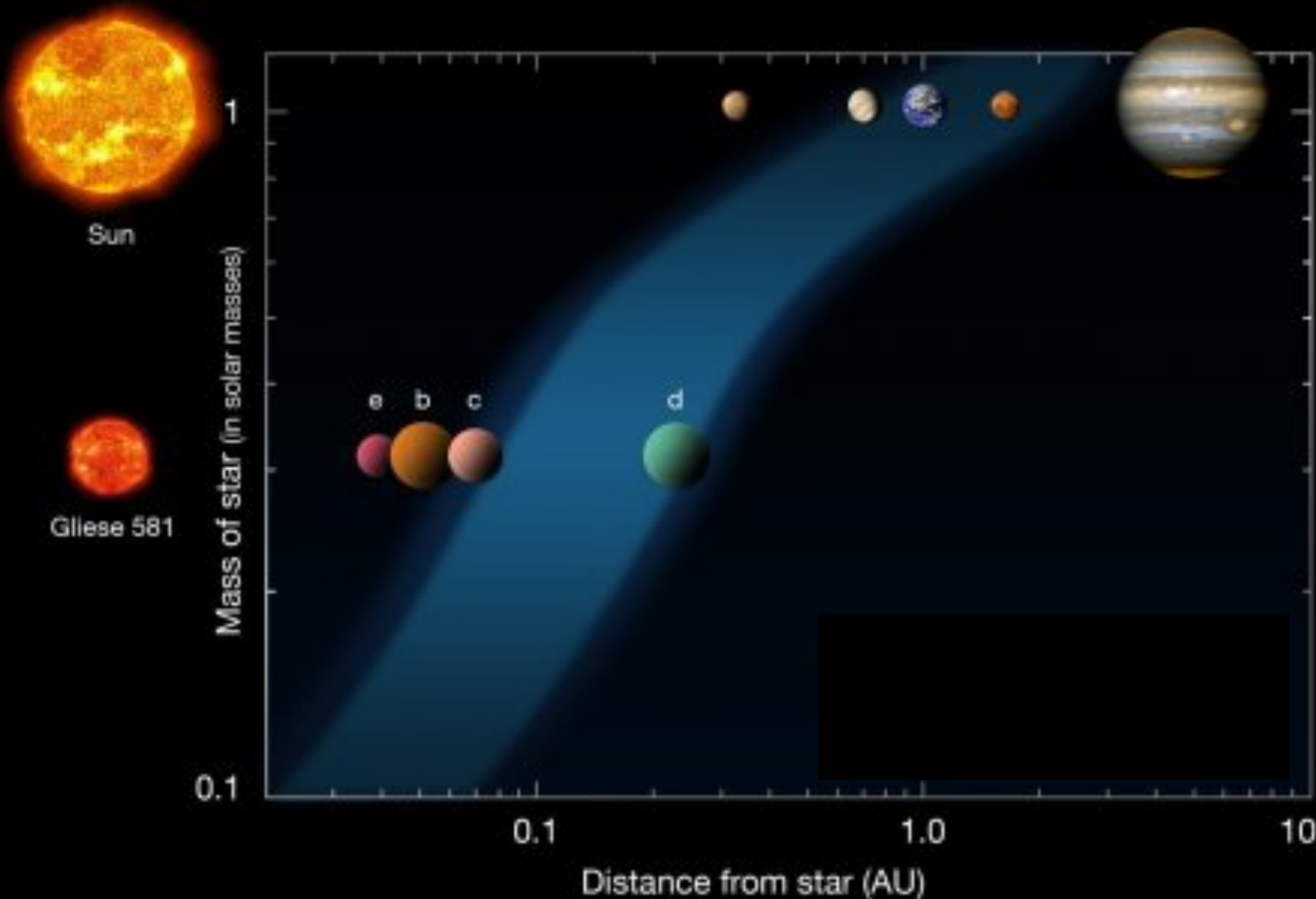
Kaltenegger et al 2007 ApJ

Earth Evolution over geological time - CSI



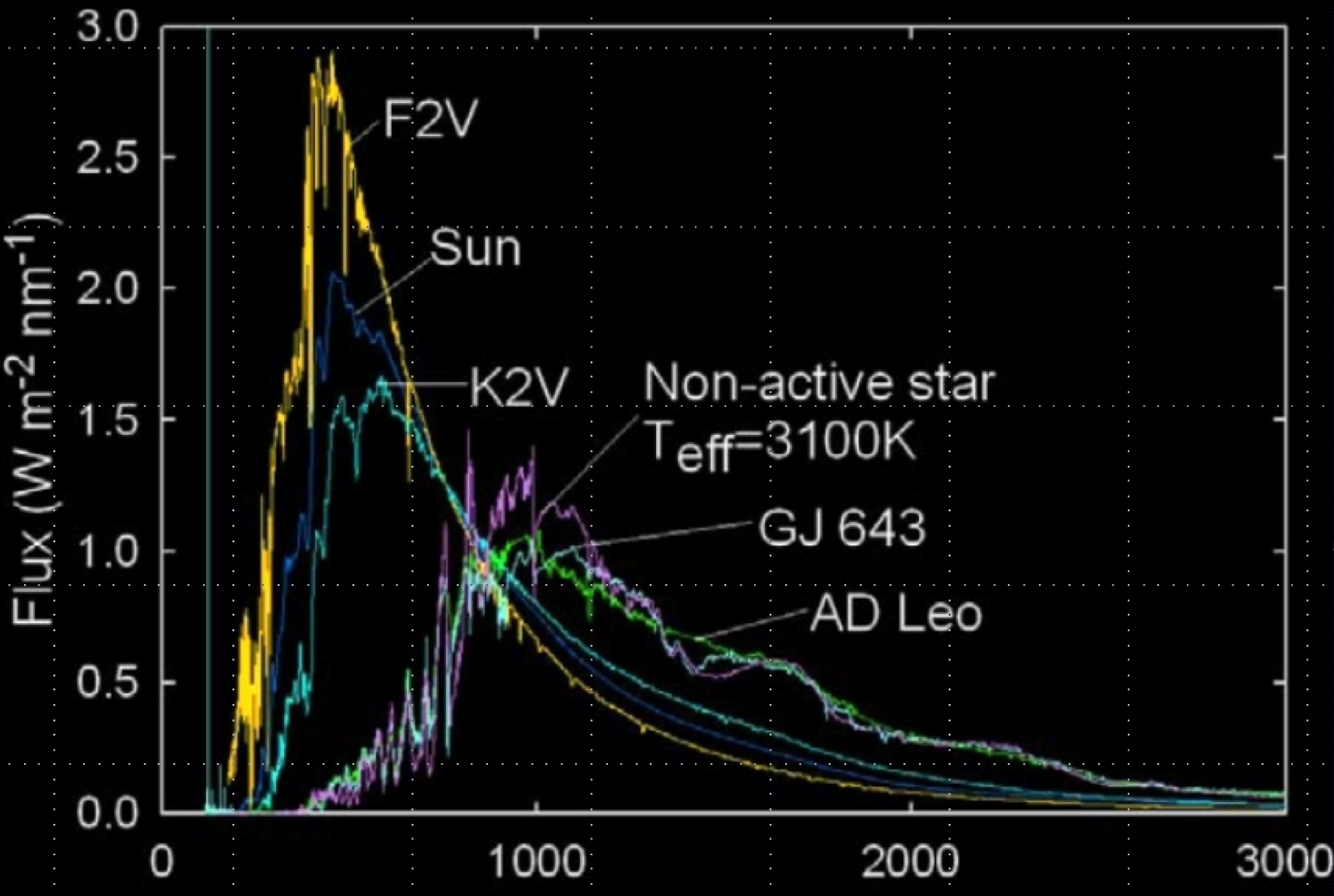


Kaltenegger et al 2007 ApJ

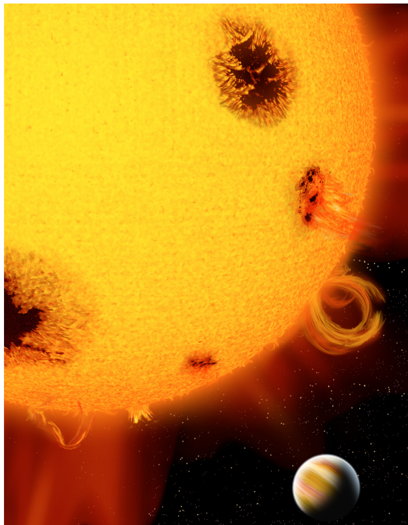


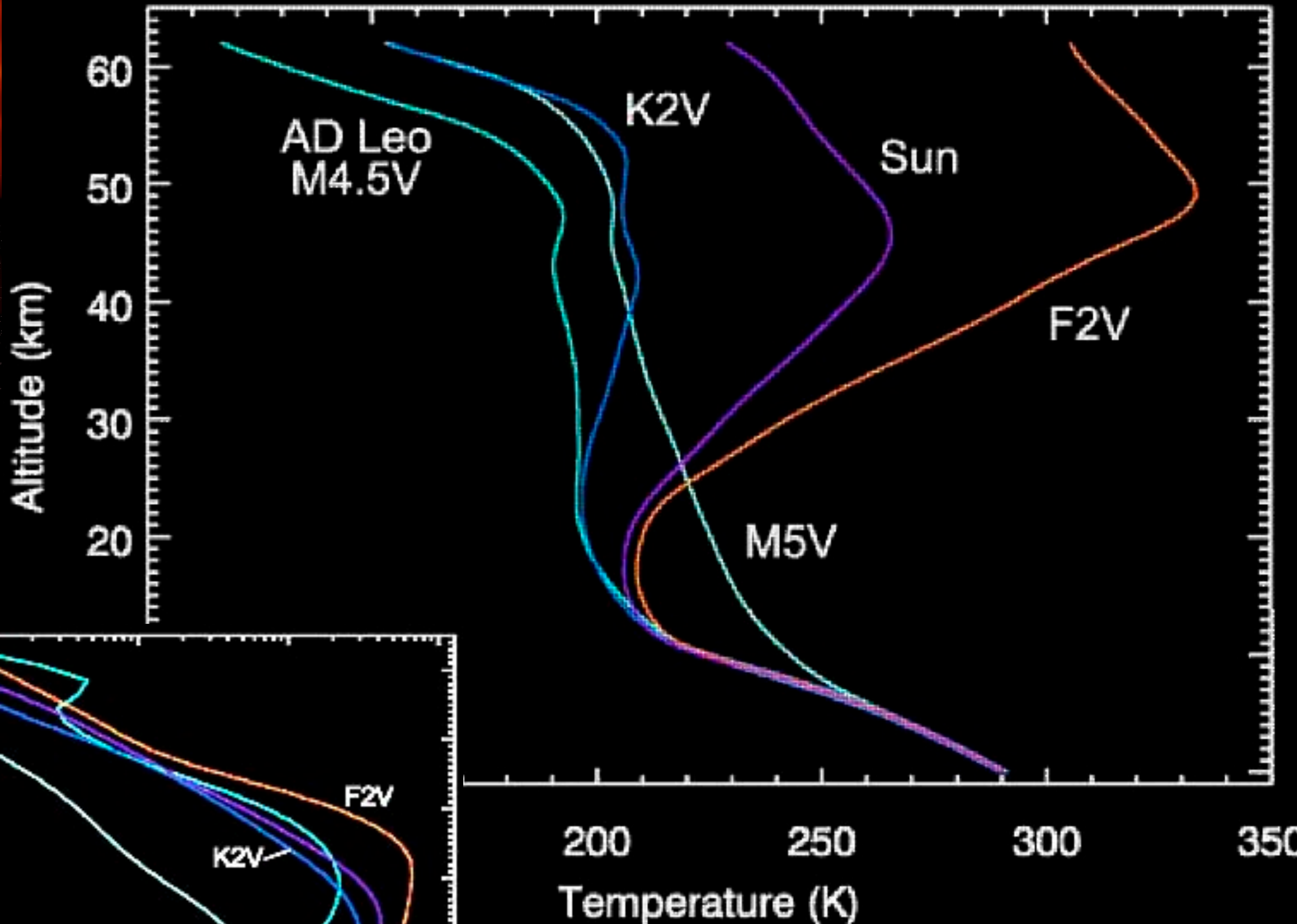
Udry et al 2007, Selsis et al 2007, van Braun et al 2007, Kaltenegger et al 2010, ….

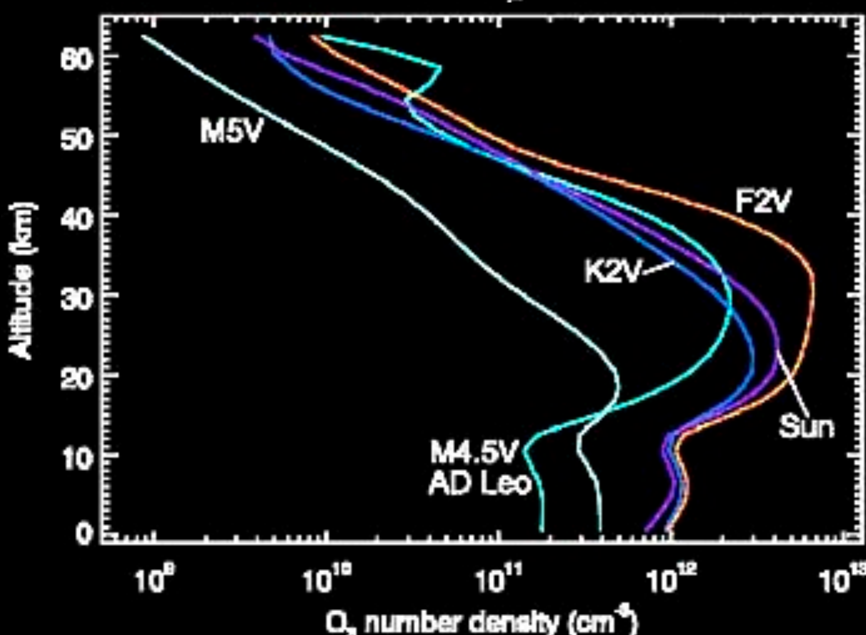
Host stars



Segura et al 2005; Kaltenegger & Segura 2010



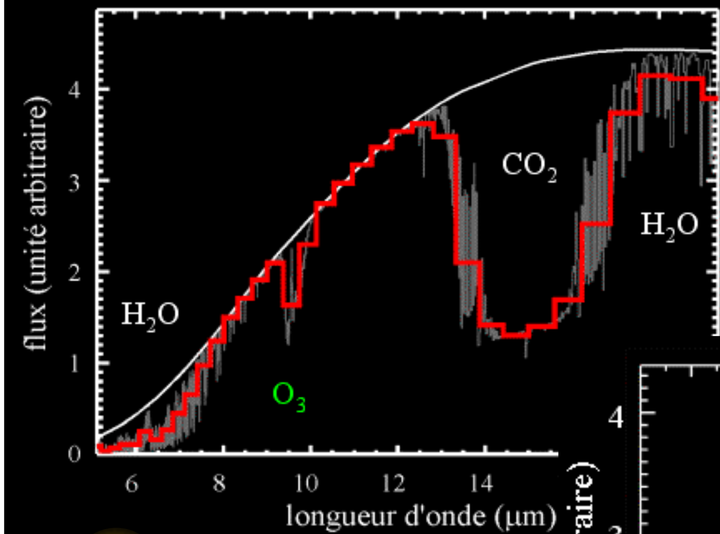




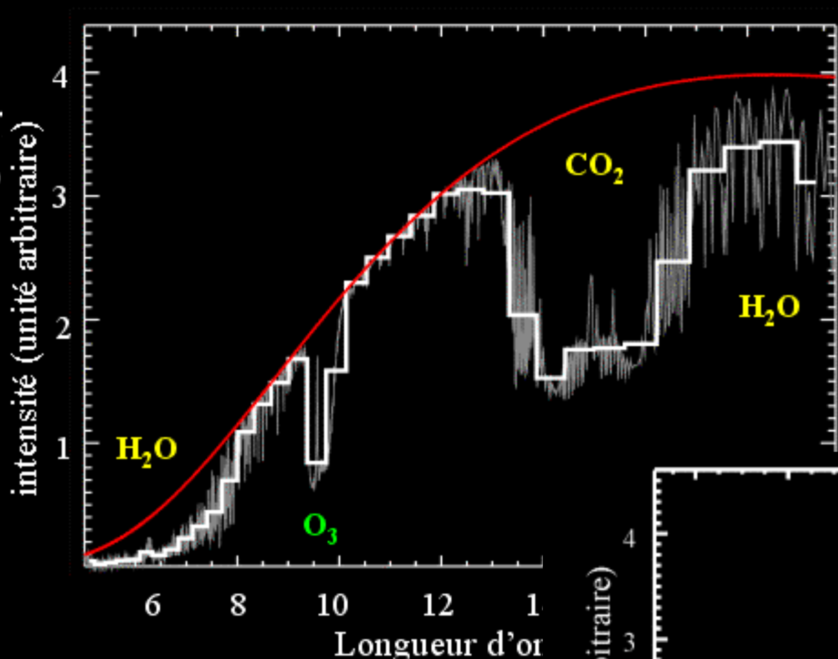
Stellar Type = Flux = Chemistry

Segura et al 2005

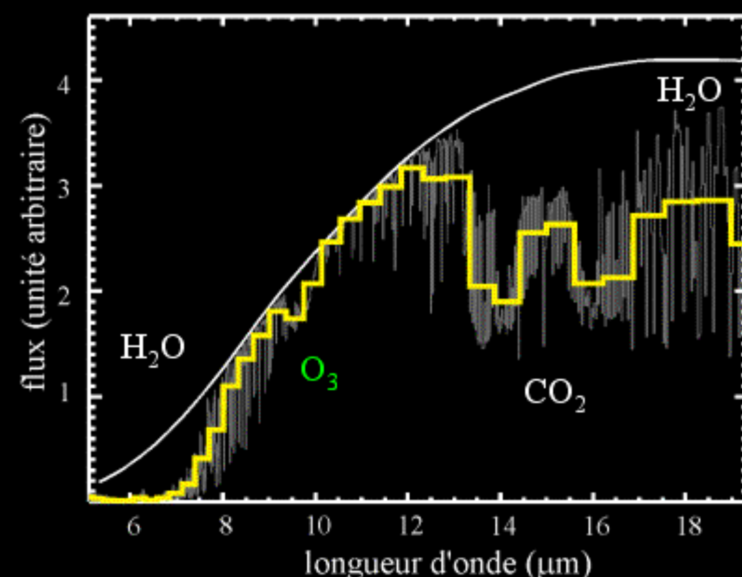
Target Star types



K star
T < T_{Sun}



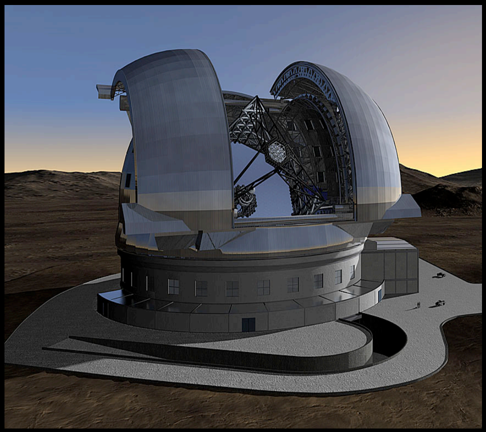
G star
(Sun)



F star
T > T_{Sun}

Selsis et al. 2002
See also Segura et al. 2004
Kaltenegger et al. 2010

Science Case: ELT,GMT,TMT, JWST (SPITZER, SPICA, SMALL SPACE MISSIONS)



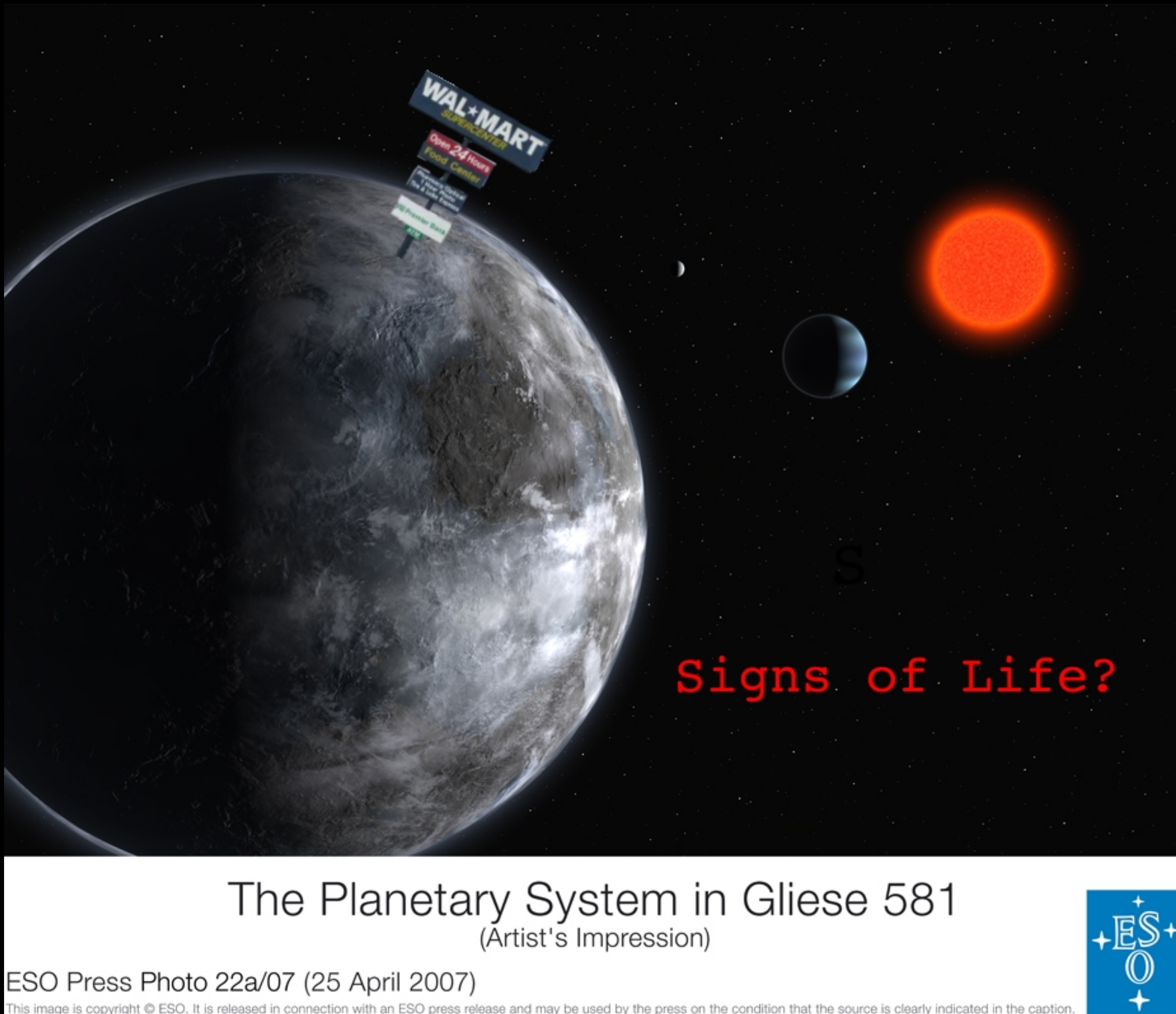
Not just FIND...

Characterize rocky exoplanets

- composition	0 – ... years
- habitability	5 – ... years
- stage of evolution	5 – ... years
- geochemical cycles	5 – ... years
- HR Diagram of planets	5 – ... years

2300 years and counting….

Let‘s find out


WAL★MART
SUPERCENTER
Open 24 Hours
Food Center
S
Signs of Life?
The Planetary System in Gliese 581
(Artist's Impression)
ESO Press Photo 22a/07 (25 April 2007)
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ESO

SAG 4 – your input needed

- measurements (R, M, T, chem.)
    - needed to characterize exoplanets

- what accuracy needed ?
    - Earth: R = 10-30km, EGP 100 – 1000km, compare models

- which models as standard for rocky planets?

WELCOME TO THE TEAM !!!

e-mail: lkaltene@cfa.harvard.edu