

A blue-tinted image of Earth from space, showing the curvature of the planet and the atmosphere. The Moon is visible in the upper right corner. A bright star with a lens flare is in the lower left corner. The background is a dark, starry space.

SAG 4 – a lot of great work  
currently done...

L. Kaltenegger, J. Kasting: For SAG 4

# SAG 4 Team Members

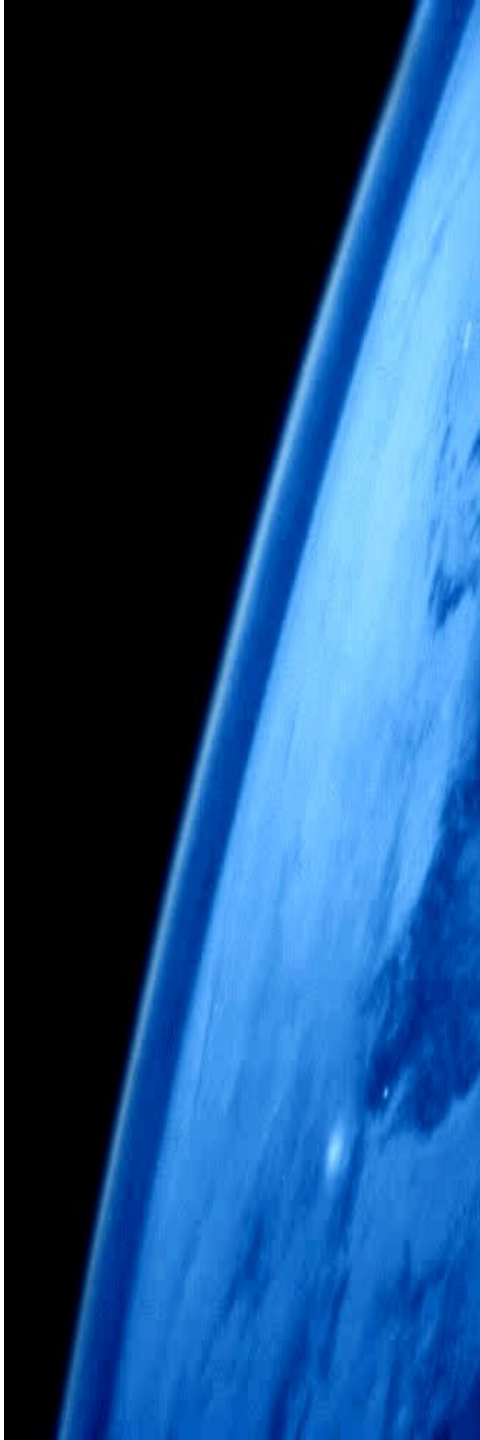
- D. Abbot (Chicago)
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- S. Domagal-Goldman (Goddard)
- C. Dressing (Harvard)
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- S. Rugheimer (Harvard)
- D. Sasselov (Harvard)
- S. Seager (MIT)
- A. Segura (Mexico)
- F. Selsis (Bordeaux)
- W. Traub (JPL)
- E. Turner (Princeton)
- P. van Paris (Bordeaux)
- R. Wordsworth (Chicago)
- A. Zsom (MIT)

**Let me know if YOU want to join the discussions 😊**

# Motivation (Earth-like planets)

SAG 10 – all planets – Giants-rocky

- Why?
  - what science for what observations
- What can you learn/explore
  - at different wavelengths?
  - at different resolution?
  - at different time intervals ?
- Feeds into
  - instrument design (SAG 5, SAG 10)
  - observation strategy (SAG 5, SAG 10)



# GOAL: Planetary Measurements needed for Exoplanet Characterization (Jim's slide)

**Which measurements** are needed to characterize exoplanets ?

- how accurate they must be,
- how difficult they are to obtain, and
- which might be done from the ground

**Products:**

- List of measurements and required precisions needed to understand a planet's state to different levels of completeness
- List of measurement techniques that look over different time frames, and which of these can only be done from space

**Participants:** Atmospheric and surface modelers, ground and space observers, and exoplanet mission teams

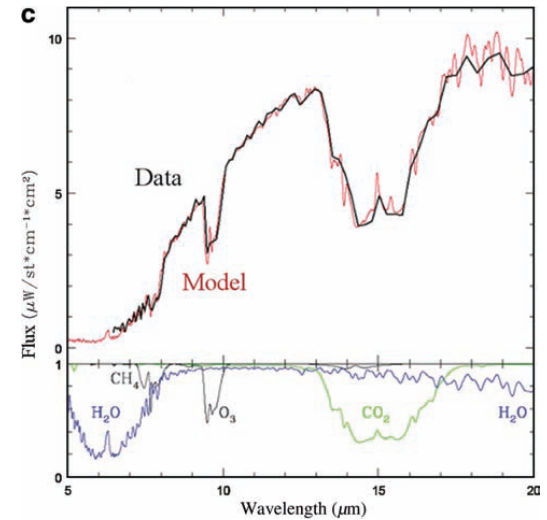
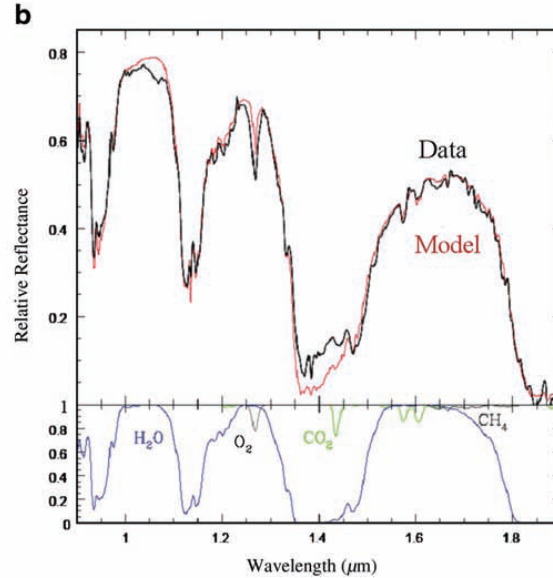
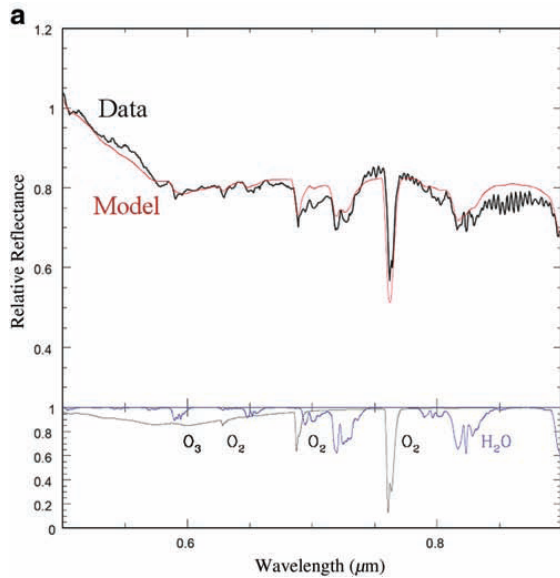
# Summary & Timeline

- **Products:**
  - List of measurements and required precisions needed to understand a planet's state to different levels of completeness
  - List of measurement techniques that look over different time frames, and which of these can only be done from space
- **Timeline**
  - Report draft (LK & JK) send to team - mid Feb
  - Comments due - mid March (team)
  - Report sent to ExoPAG EC - mid April
  - Report available on ExoPAG website - end May
- **SAG4 team:** Abbot, Betremieux, Cowen, Domagal-Goldman, Forget, Green, Kaltenegger, Kasting, Kopparapu, Meadows, Pierrehumbert, Rauer, Roberge, Robinson, Rugheimer, Sasselov, Seager, Segura, Selsis, Traub
- **WELCOME TO THE TEAM e-mail: [kaltenegger@mpia.de](mailto:kaltenegger@mpia.de)**

# An overview of topics covered

- Biosignatures
  - Earth-centric, non Earth-centric, false positives
- Thought on the HZ borders (Observable biosignatures)
  - Inner & outer borders, 3D versus 1D, dry, wet, pressure
- Observing geometry influence
  - Lightcurves, Color-color diagrams, transit, direct imaging
- Observables at different parts of the HZ
- Change in observables for diff. kind of planets
  - High density atm, water worlds, Earths, mini-Earths, super-Earths, dessert worlds, extreme worlds

# Spectra & wavelength: start = Earth

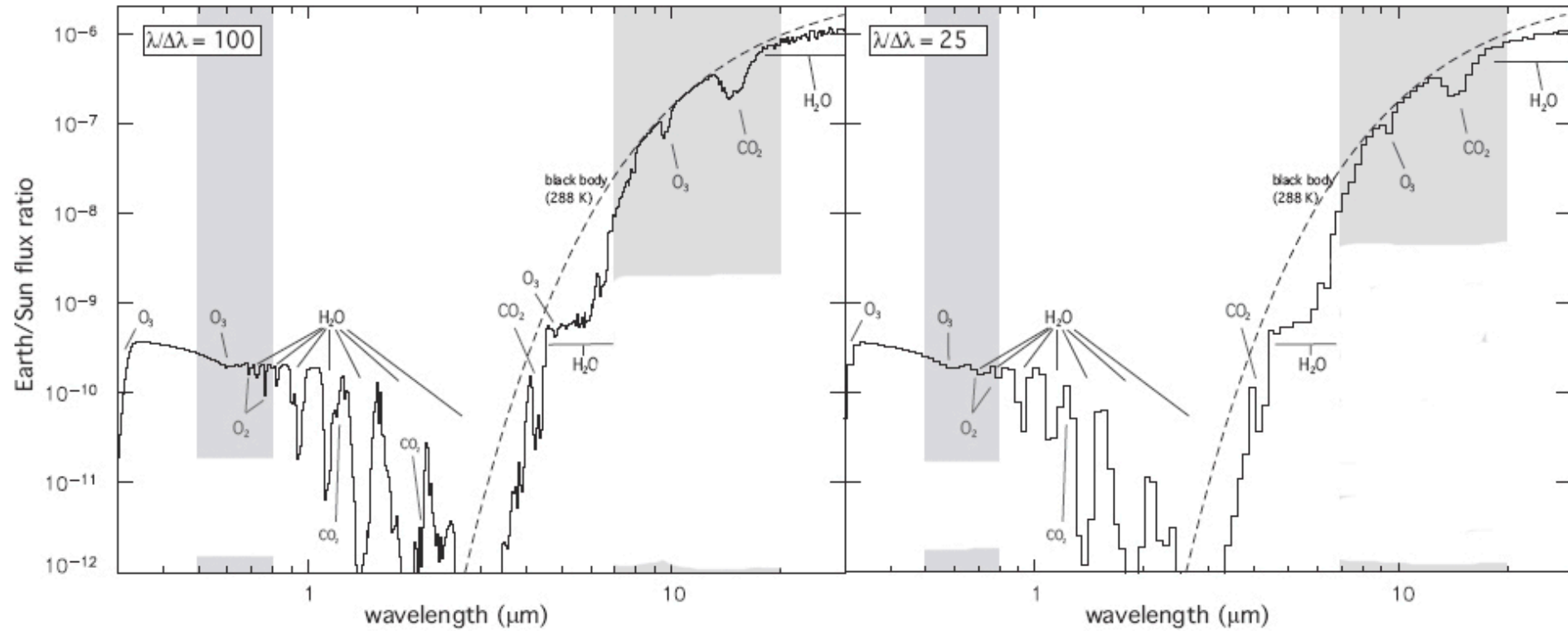


*Kaltenegger et al. 2007*



*See extensive work by Kaltenegger, Meadows, Robinson, Segura, Selsis, Traub, and others*

# Spectra & wavelength: start = Earth



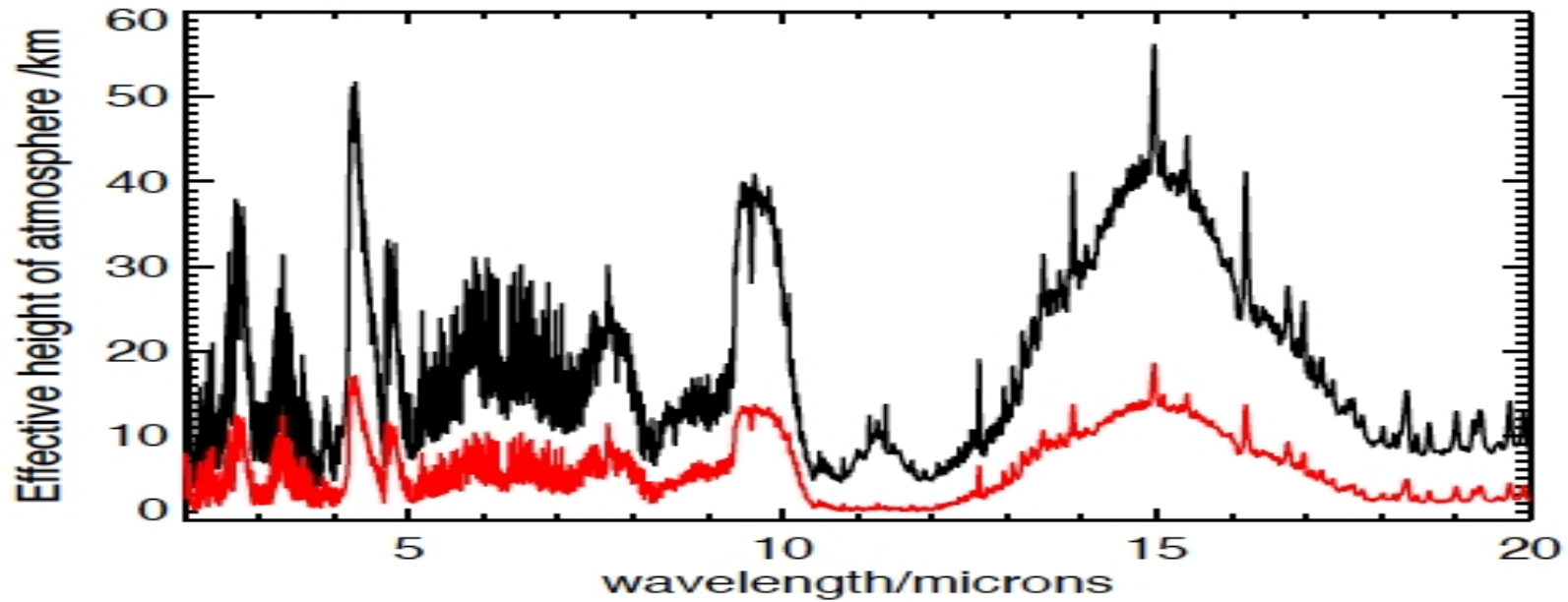
*Selsis et al. 2007*



*What resolution is needed to detect features ?*



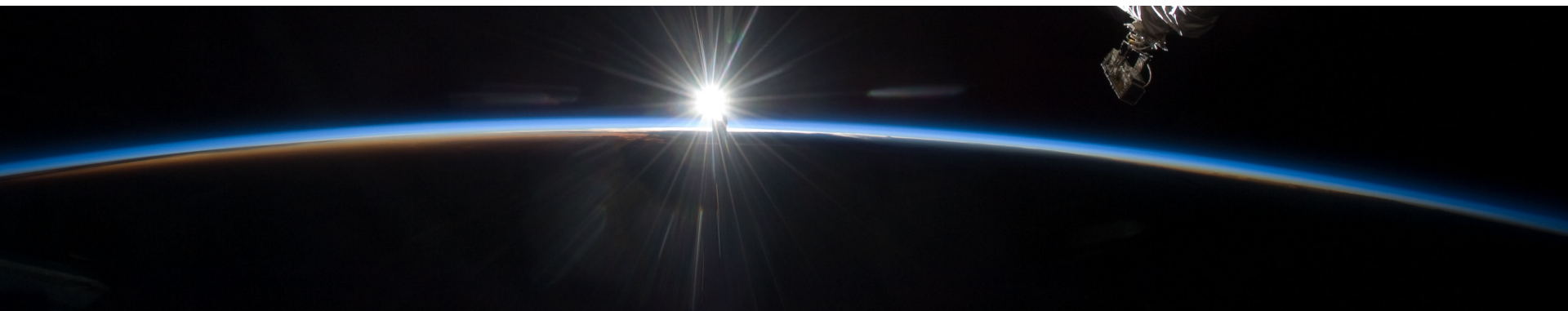
# Spectra & wavelength: start = Earth



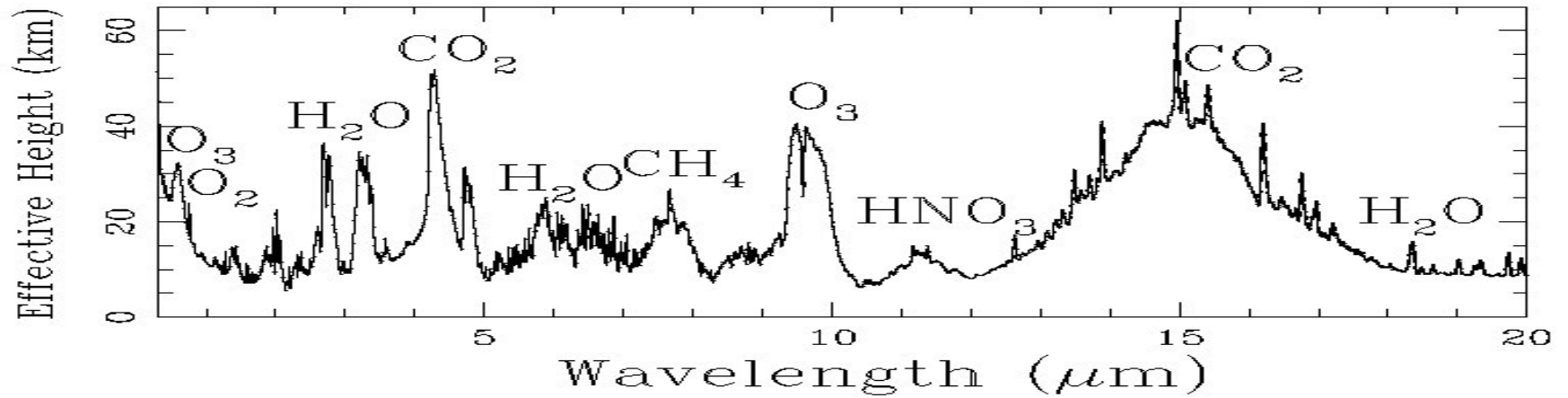
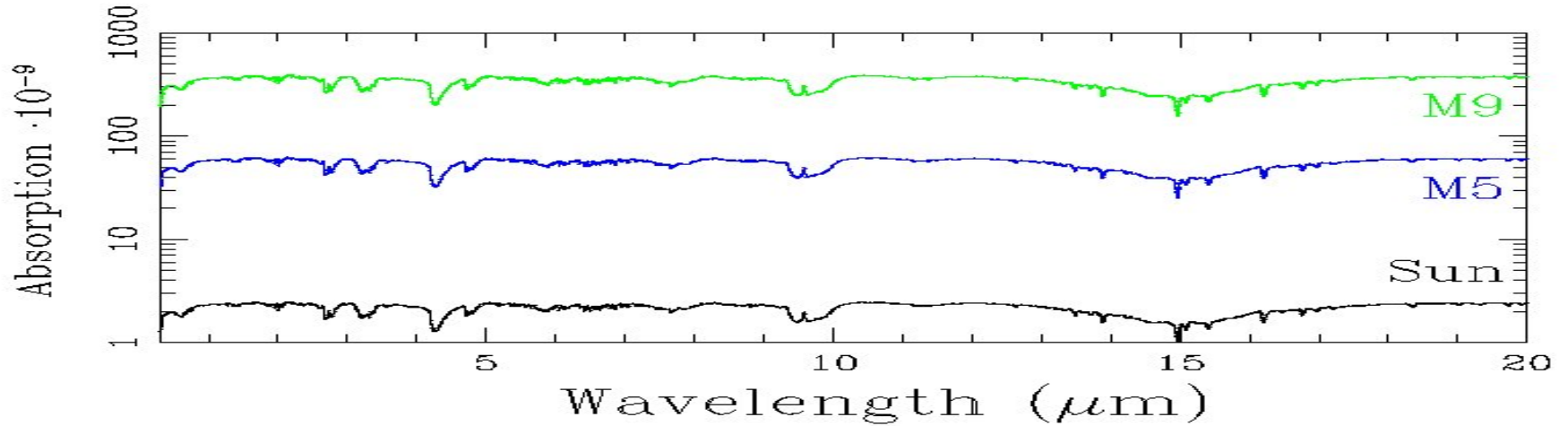
*Rauer et al. 2010*

Effective heights: Earth and 3g super-Earth (red) around Sun.

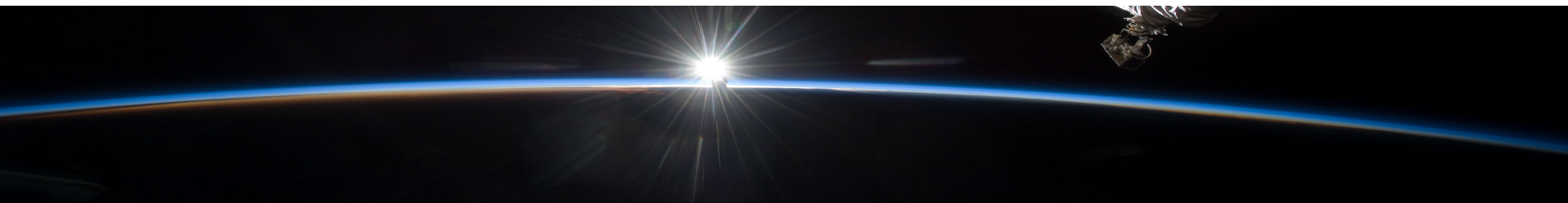
*Kaltenegger & Traub 2009, Rauer et al. 2010, Palle et al 2012 and others*



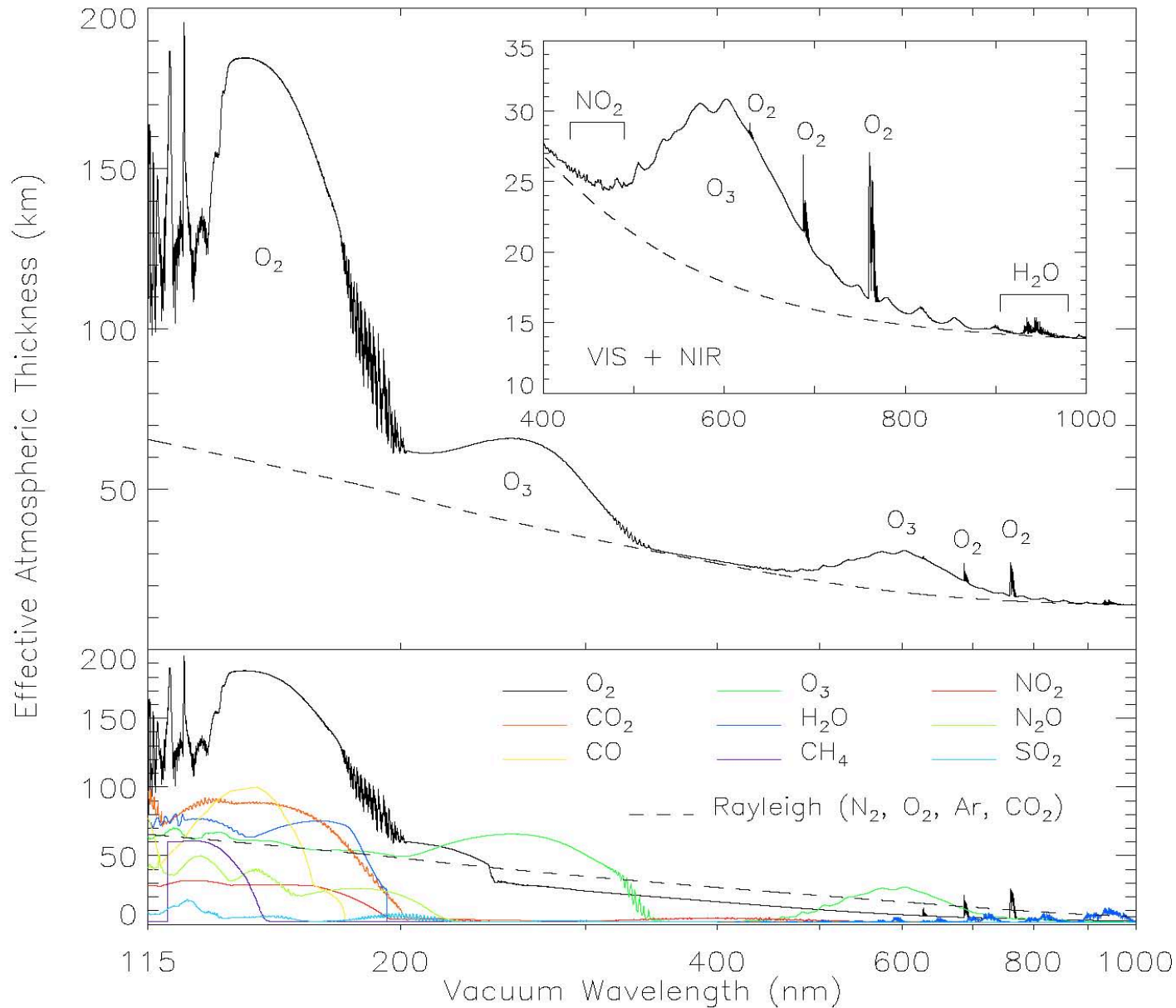
# Spectra & wavelength: contrast ratio



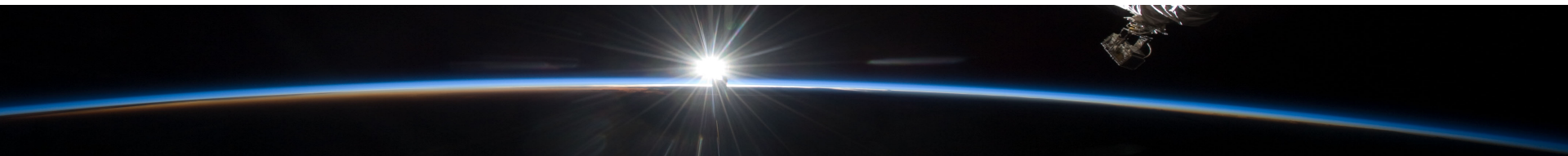
Kaltenegger 2010



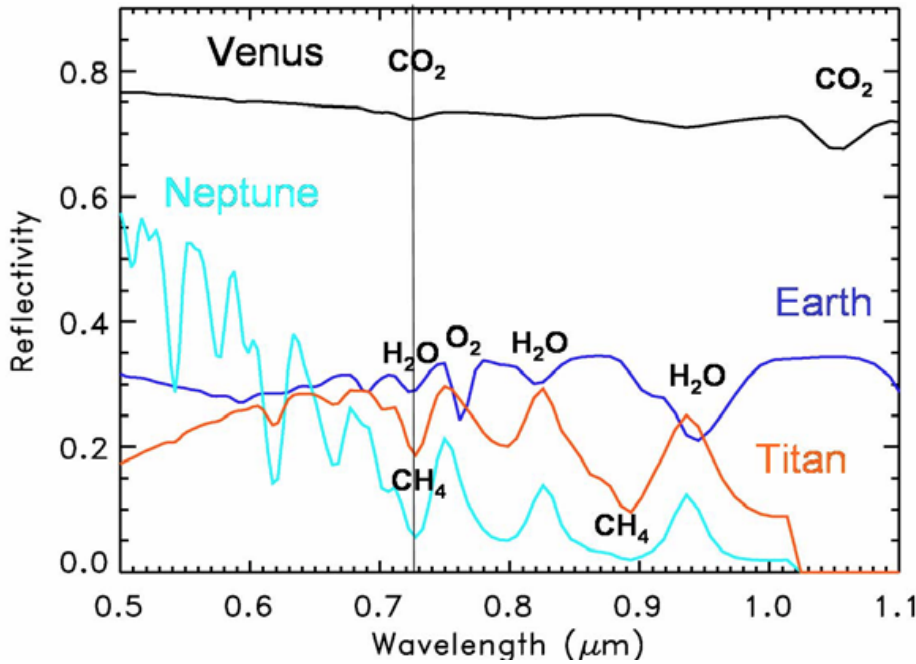
# Spectra & wave= length: SNR



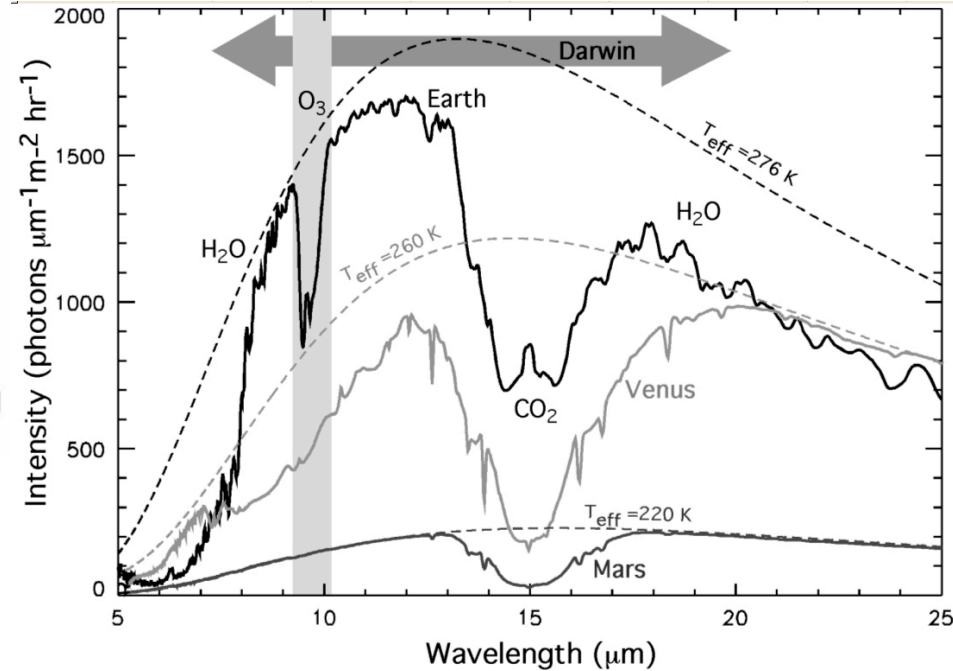
Betremieux&Kaltenegger 2013



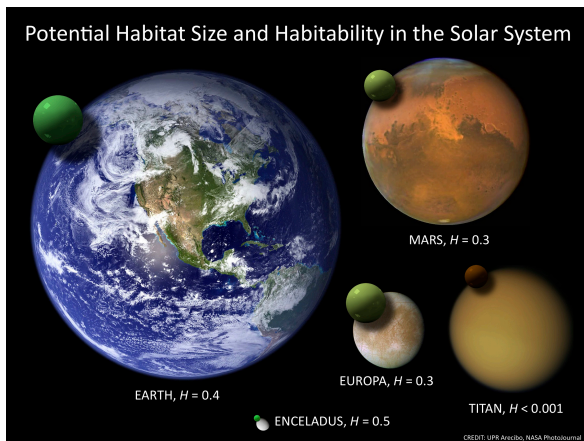
# Spectra & wavelength: comparison



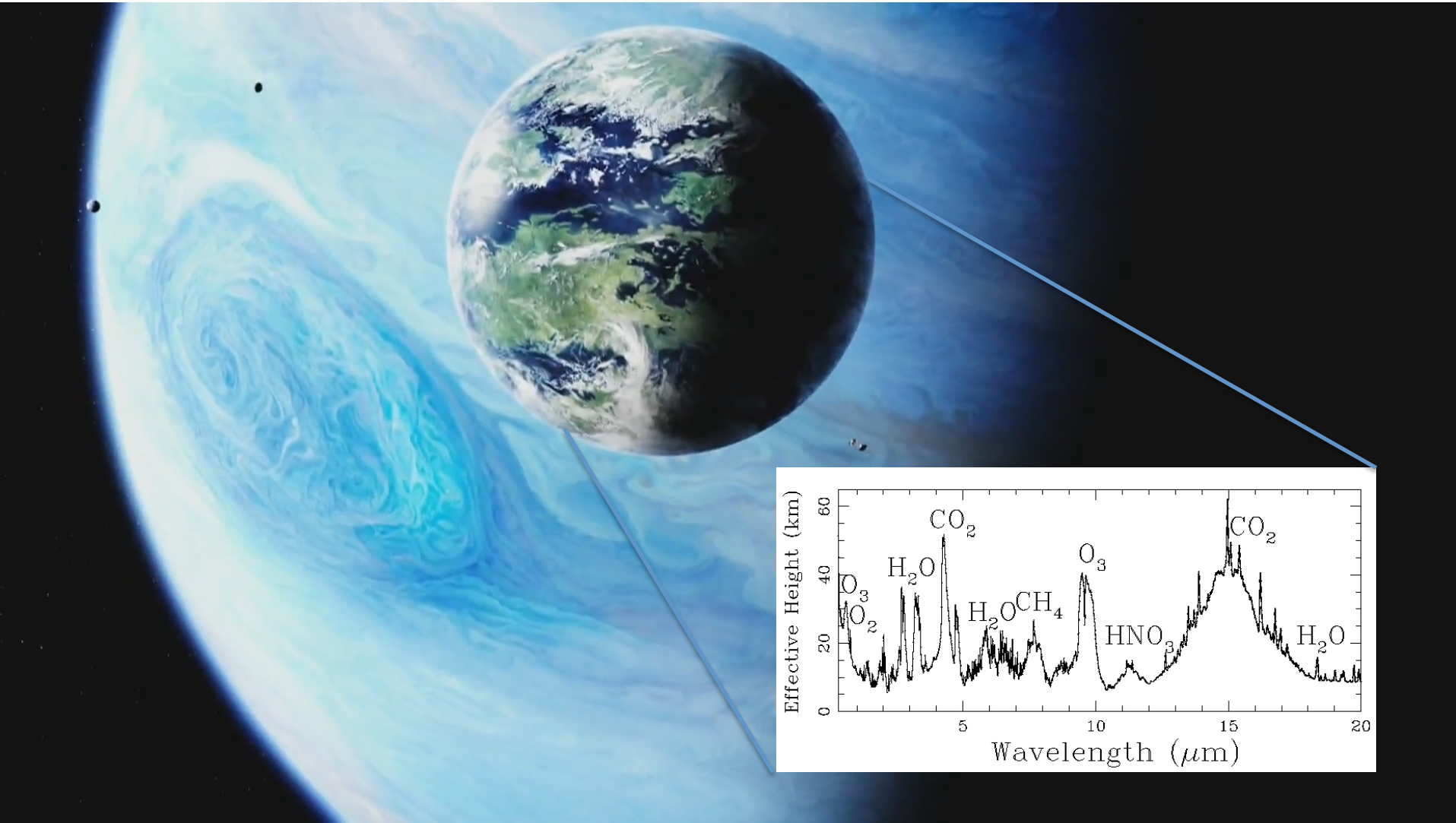
Meadows 2006



Selsis et al. 2007

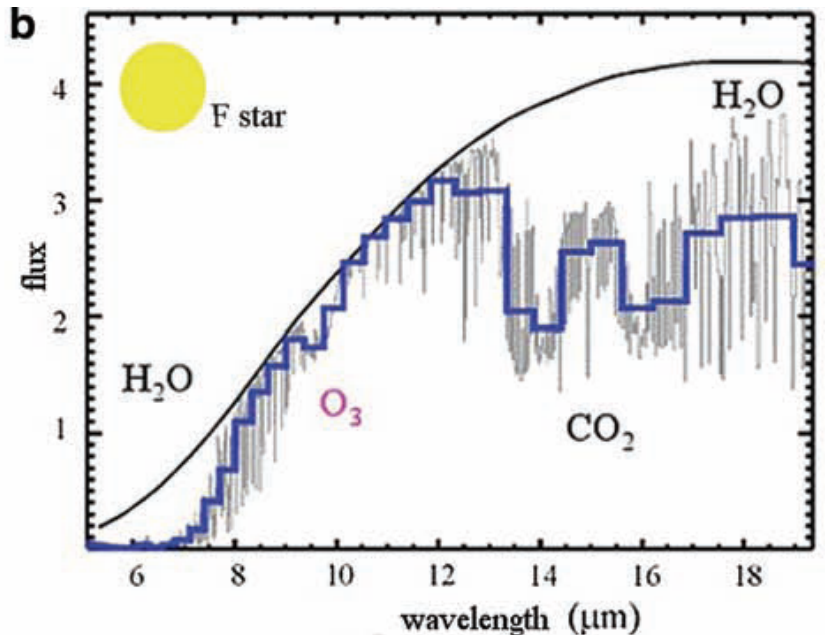
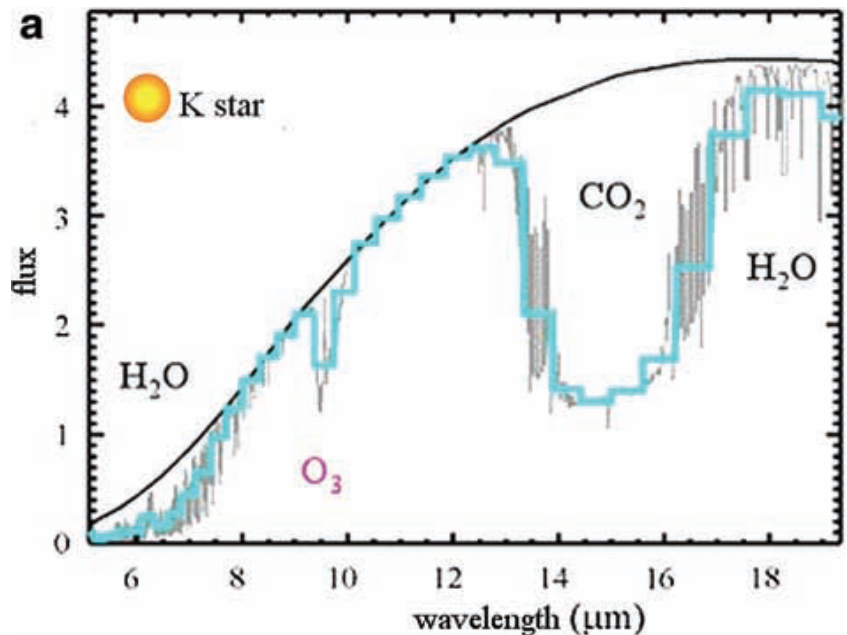


# Habitable Exomoons? - geometry



see e.g. Williams & Kasting 1997, Kaltenegger 2010, Heller & Barnes 2012

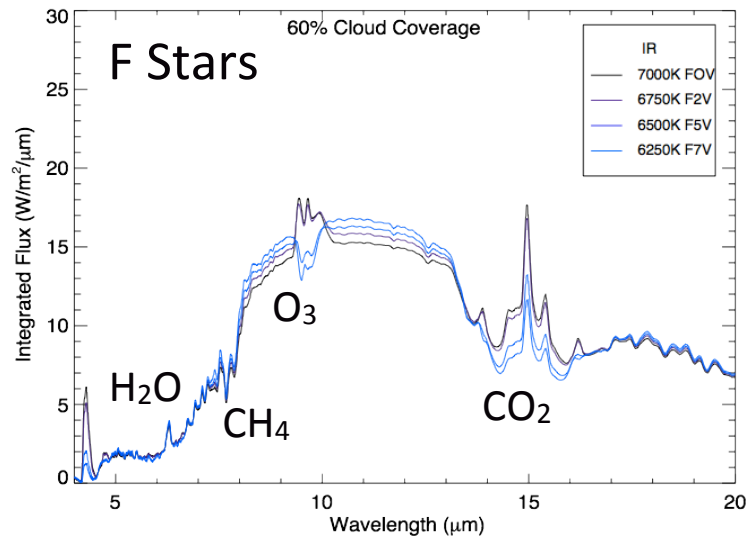
# Earth spectra & wavelength (vary stars)



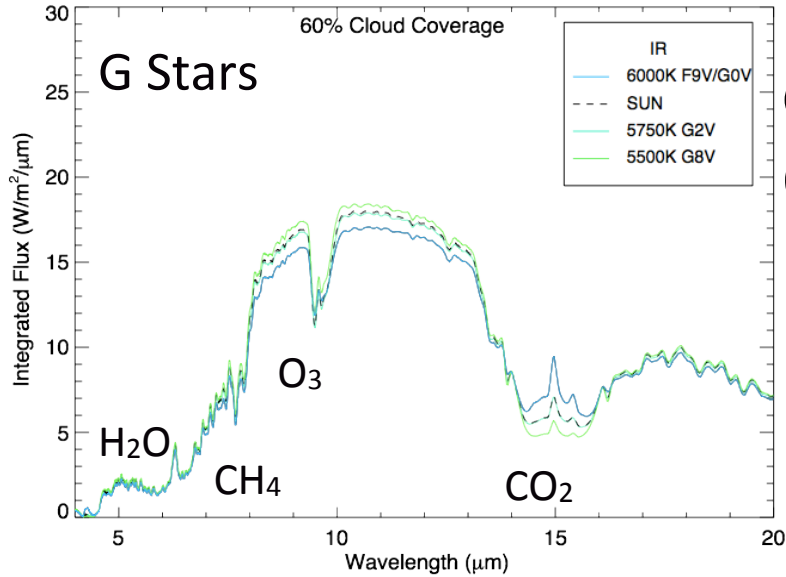
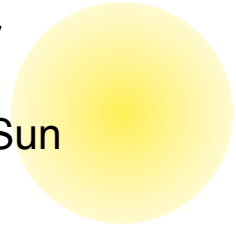
Selsis et al. 2002

see e.g. Selsis et al 2002, Segura et al 2003, Rugheimer et al 2012

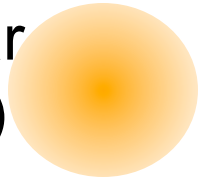
# IR Spectra for Target Star types SNR & Resolution needed ?



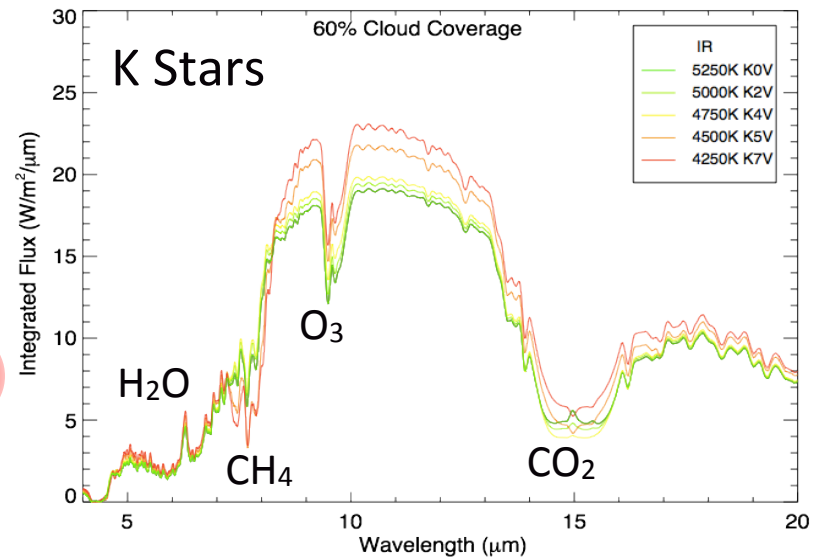
F star  
 $T > T_{Sun}$



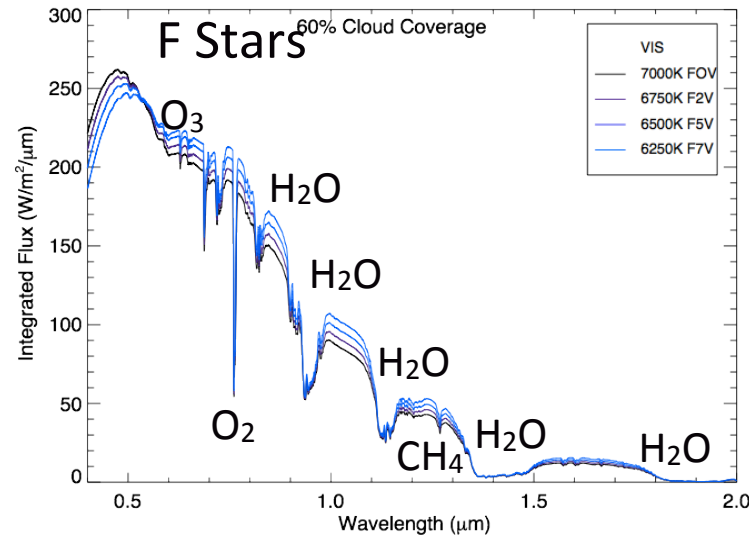
G star  
(Sun)



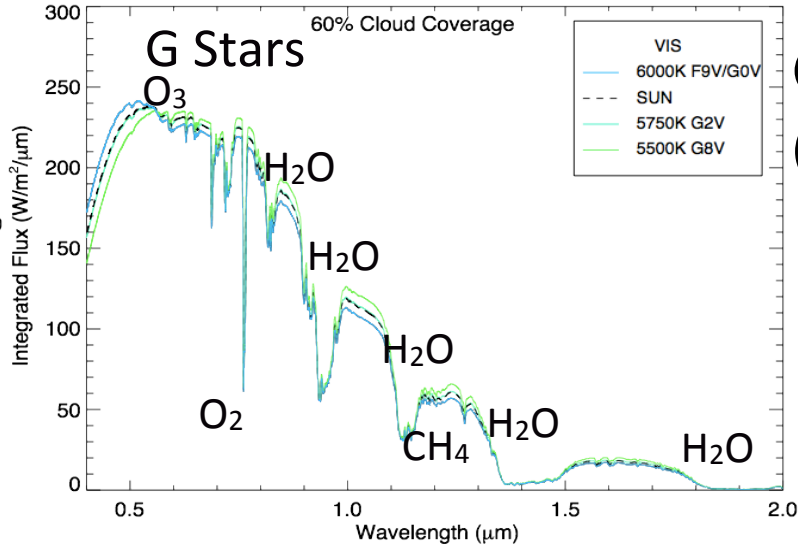
K star  
 $T < T_{Sun}$



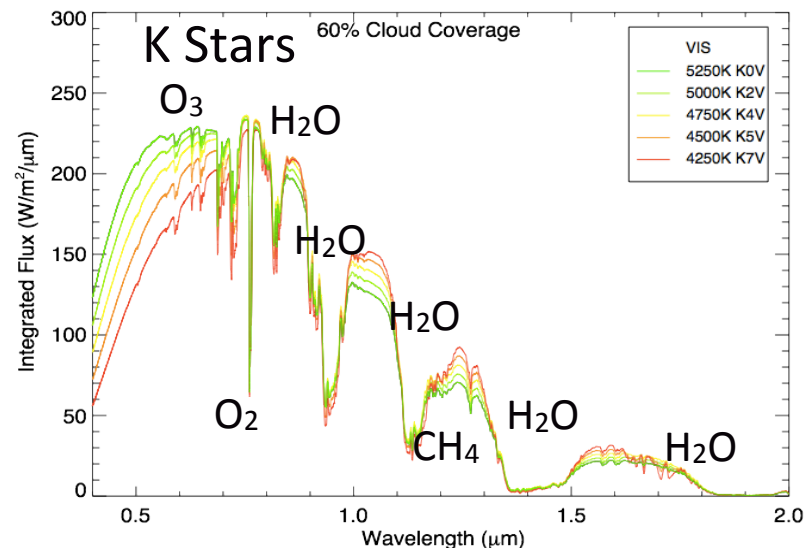
# VIS Spectra for Target Star types SNR & Resolution needed ?




F star  
 $T > T_{Sun}$

G star  
(Sun)

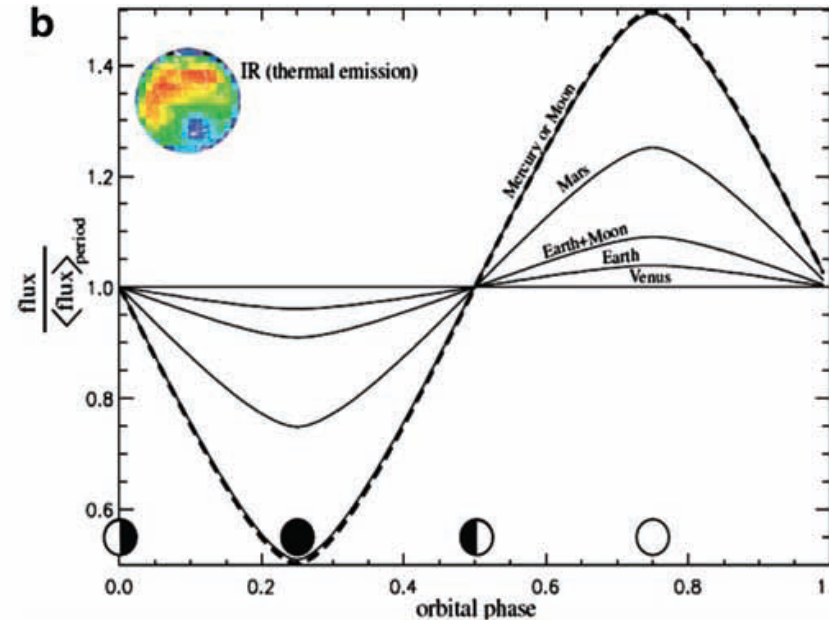
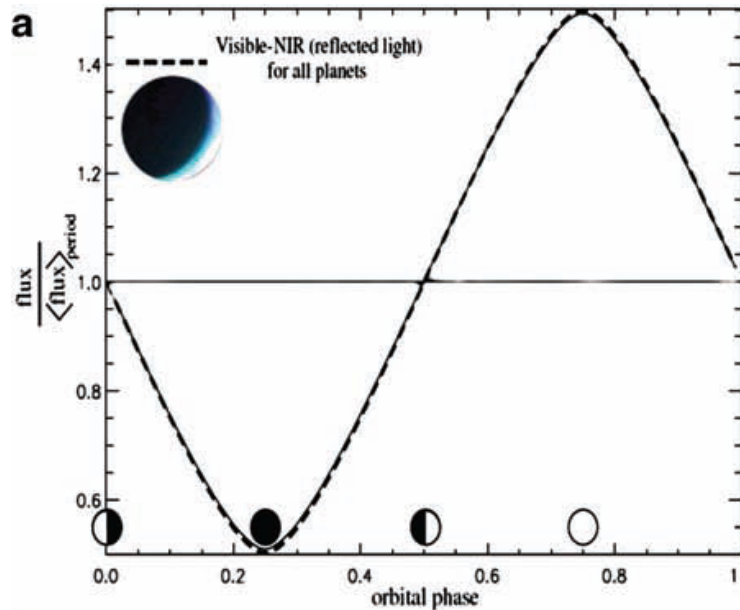



K star  
 $T < T_{Sun}$





# Lightcurves to characterize planets



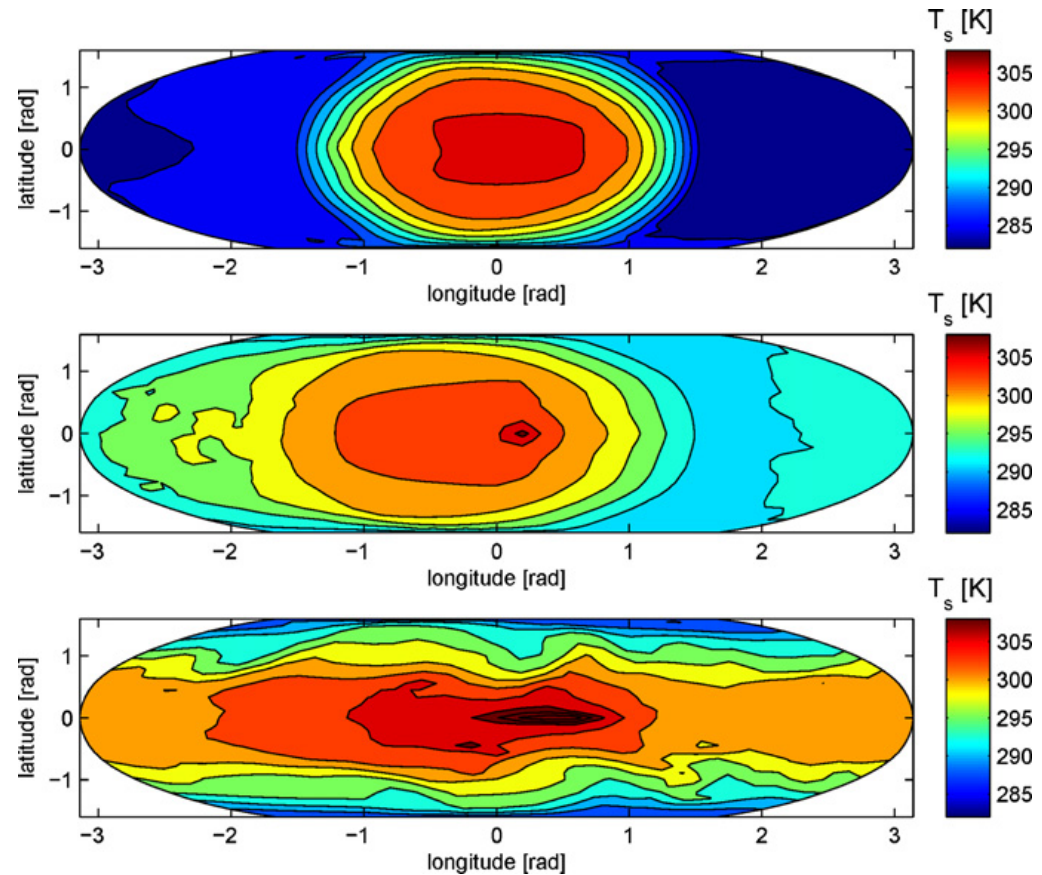
*Selsis et al. 2003, Gaidos et al 2004*

## Distinction between atmospheres

- Density/pressure
- Effect of moons

# Cool stars – new insights

- Few very interesting papers still in review (soon)
- Key questions:
  - Tidal locking
    - Dynamics of atm?
    - 1D vs 3D models?
    - habitability as fct of surface pressure

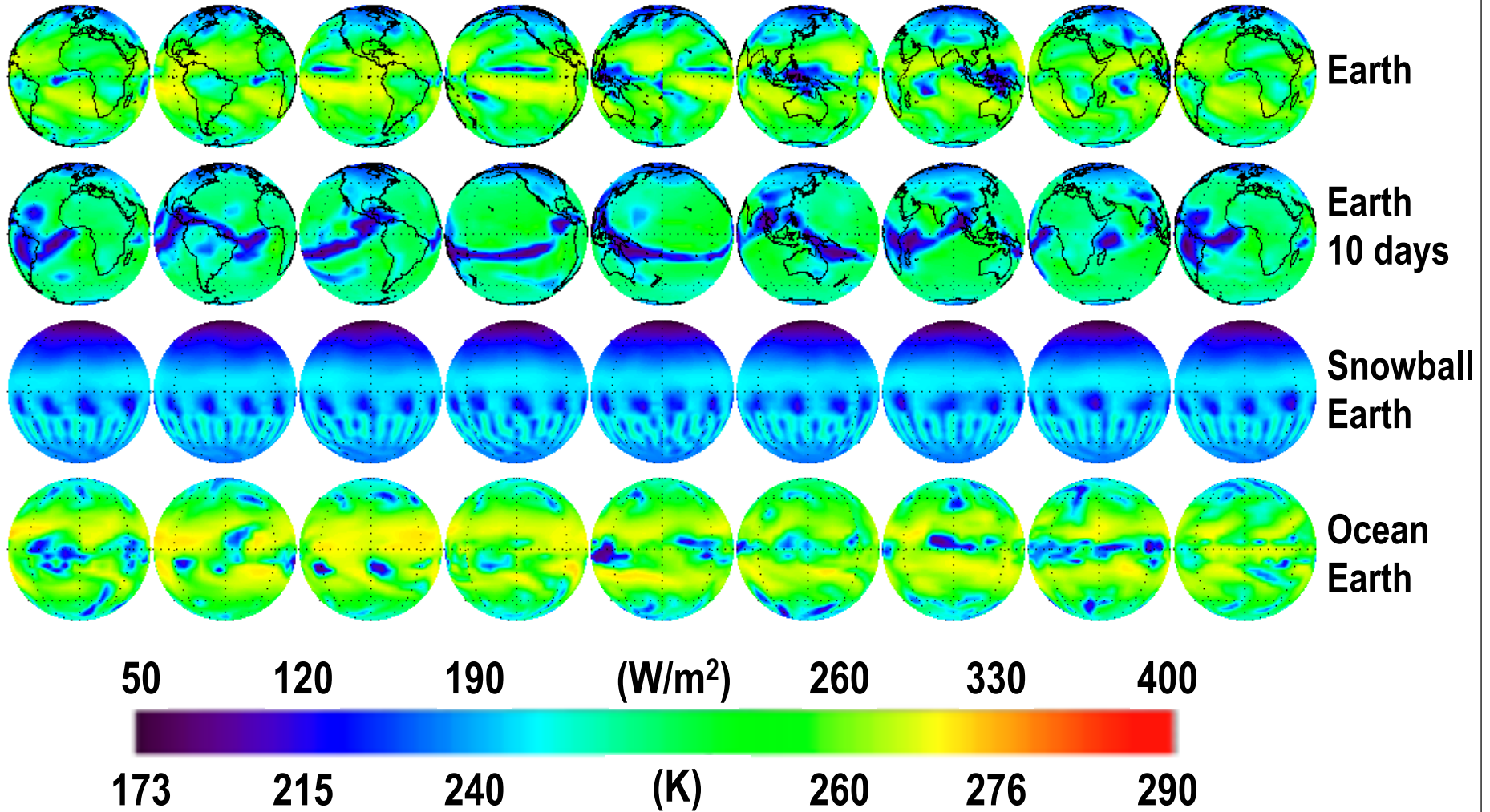


**Fig:** Surface Temp (60 orbits) rocky planet (20bar  $\text{CO}_2$ -atm) (a) 1:1, (b) 1:2, (c) 1:10 tidal resonance

(e.g. Wordsworth et al. 2011,13, Kaltenegger et al. 2011, vanParis et al. 2010, Leconte et al 2013)

# Earth-like planets with GCM

*Gomez-Leal, Codron et al., in prep*



*see e.g. new work by Gomez-Leal, Forget, Read, Selsis, Wordsworth*

# Cool stars – new insights

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- Key questions:

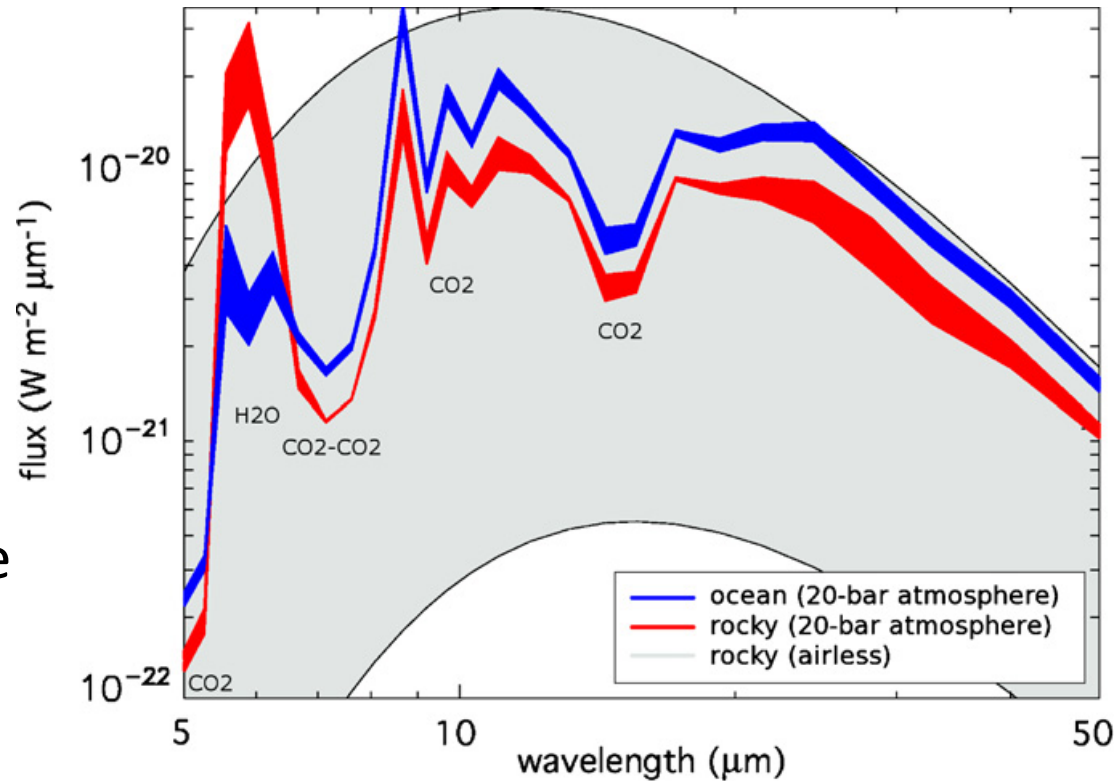
- Tidal locking

- Dynamics of atm?
- 1D vs 3D models?
- habitability as fct

of surface pressure

- Bio-signatures

- Changes (UV & SED)



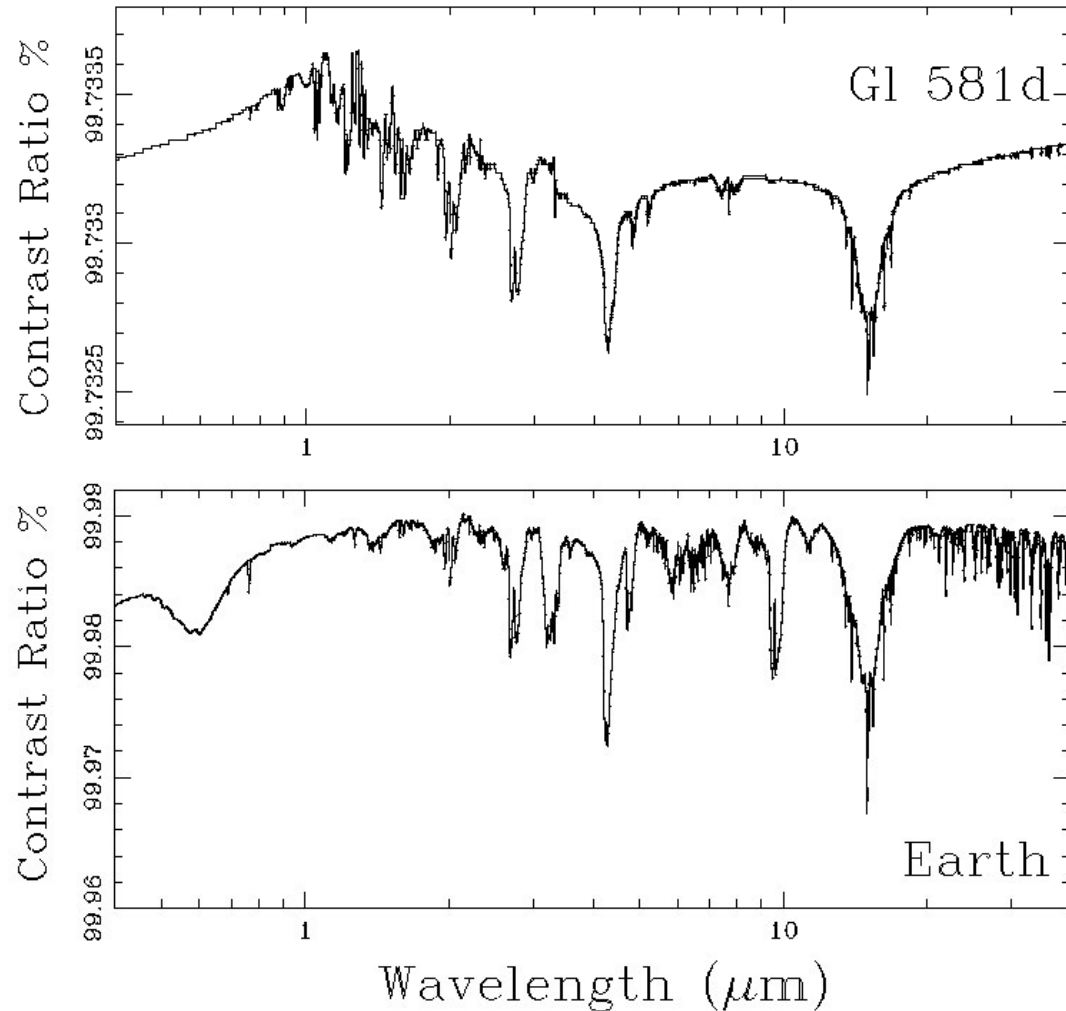
Wordsworth et al. 2011

# Cool stars – new insights

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- Key questions:

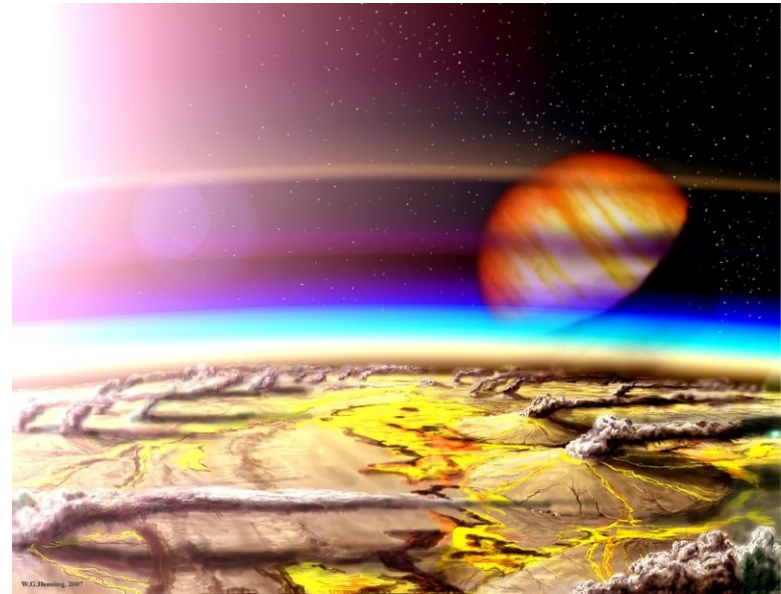
- Tidal locking
  - Dynamics of atm?
  - 1D vs 3D models?
  - habitability as fct of surface pressure
- Bio-signatures
  - Changes (UV & SED)
- New information
  - Papers in review



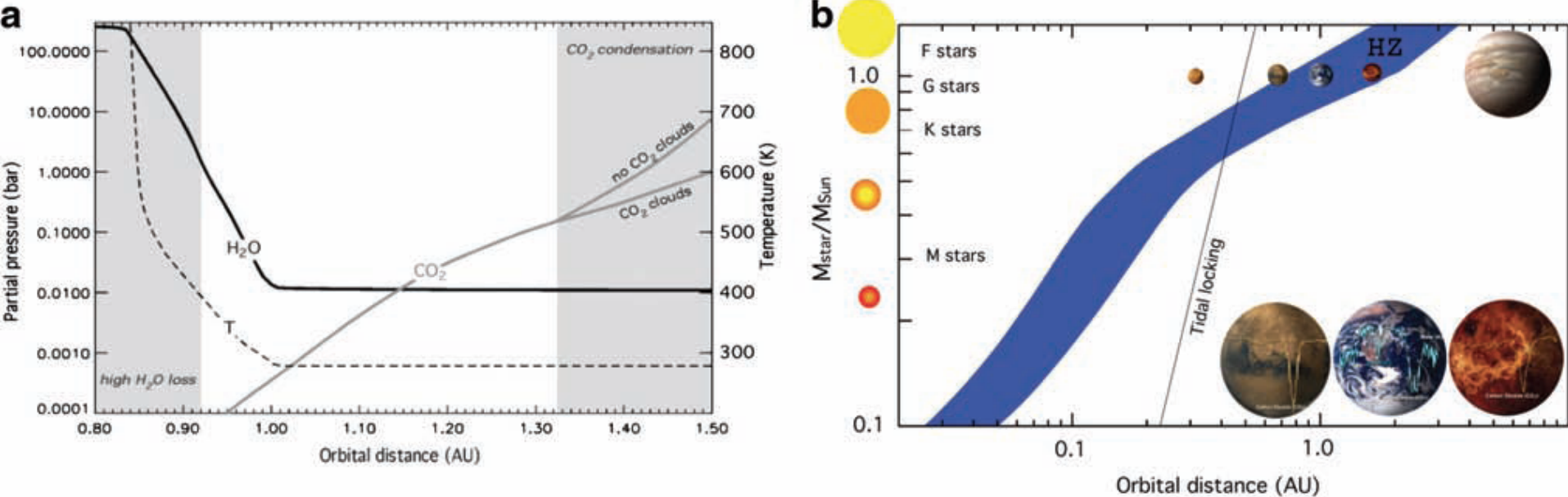
# First answers to fundamental questions...

- Insensitivity of weathering behavior and habitability to planetary land fraction
- Tectonics & geological cycles on Super-Earths
- Detectability of different geological cycles
- Simple 1D (self-consistent) cloud models

*see e.g. Abbot et al 2012, Goldblatt et al 2011,  
Kaltenegger & Sasselov 2011, Cowan et al 2013,  
Zsom et al. 2012, etc.*

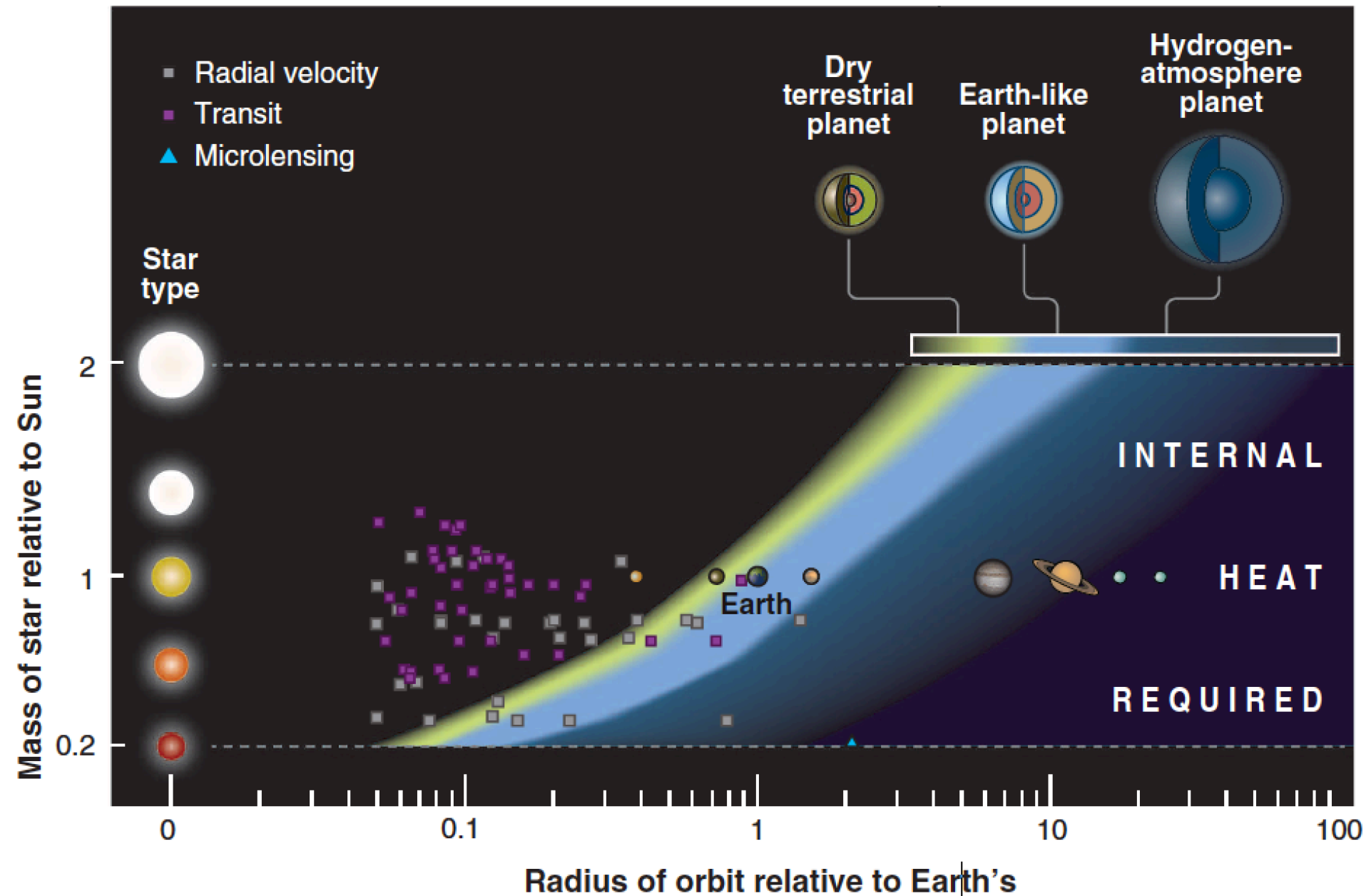


# Update: The concept of the HZ



- HZ of Dry planets
- HZ of binaries
- HZ different atmospheric composition? (e.g. dominated by  $SO_2$ ,  $CH_4$ , or other gases?)
- Very interesting new papers coming up.... (e.g. 3D vs 1D)

*See extensive work by Kasting, Selsis, Kopparapu, Domagal-Goldman, Kaltenegger, Zsom, Pierrehumbert, Mischna, etc*

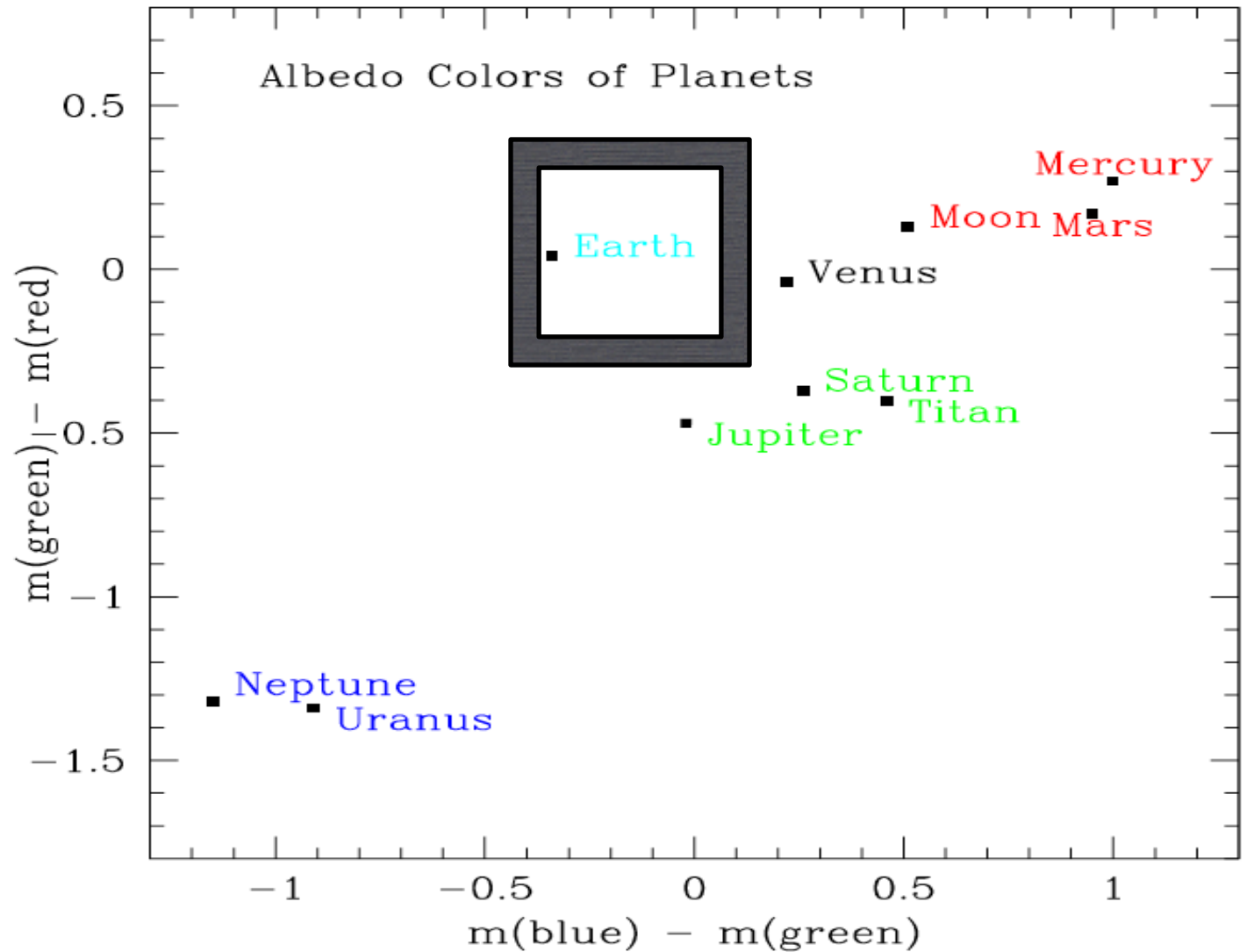


*Seager et al. 2013 review Science*

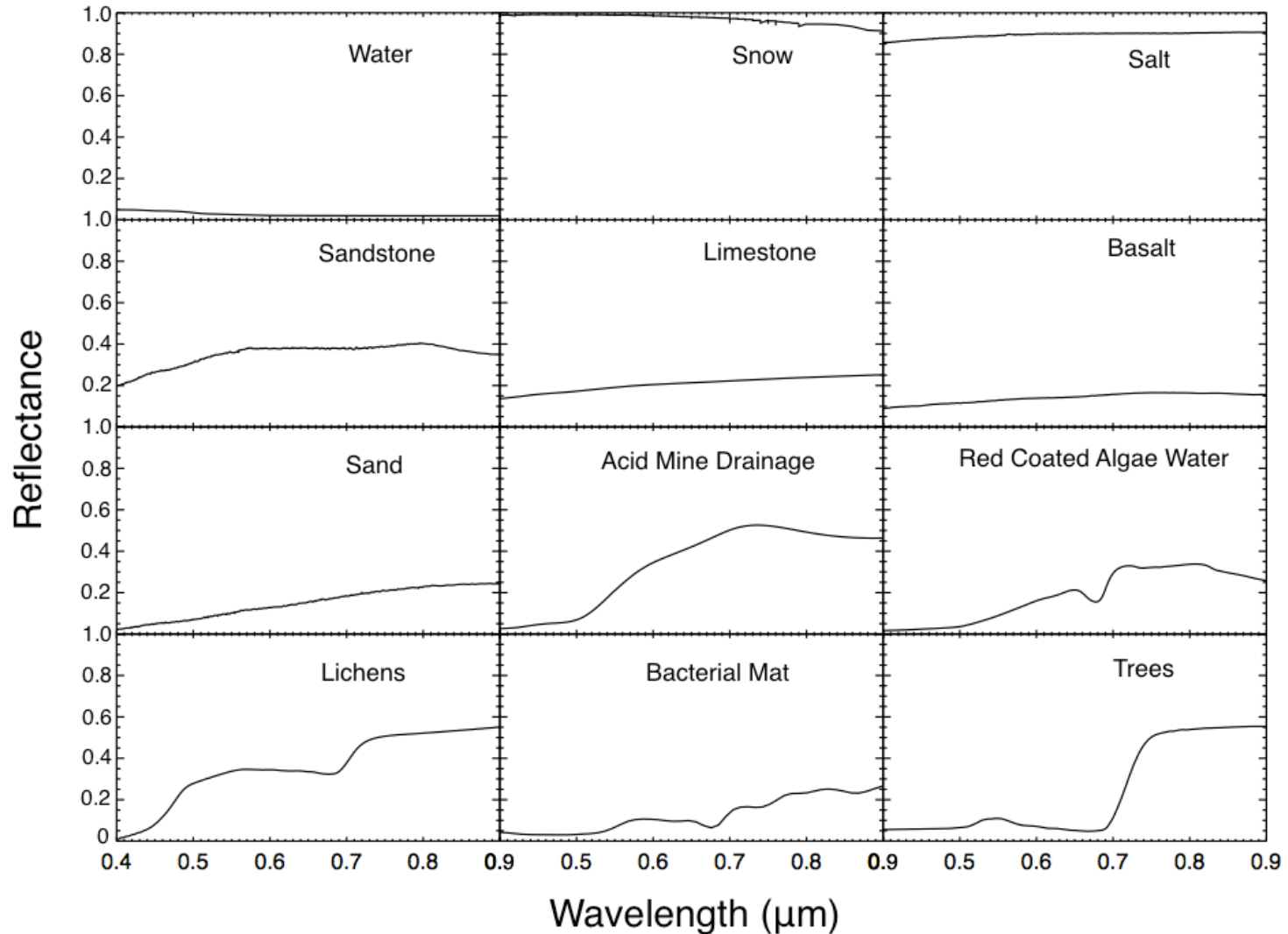
*Graphic based on work by Abe et al 2011, Zsom et al. 2013, Pierrehumbert & Gaidos 2010, and many others*



# Color of worlds – prioritize targets

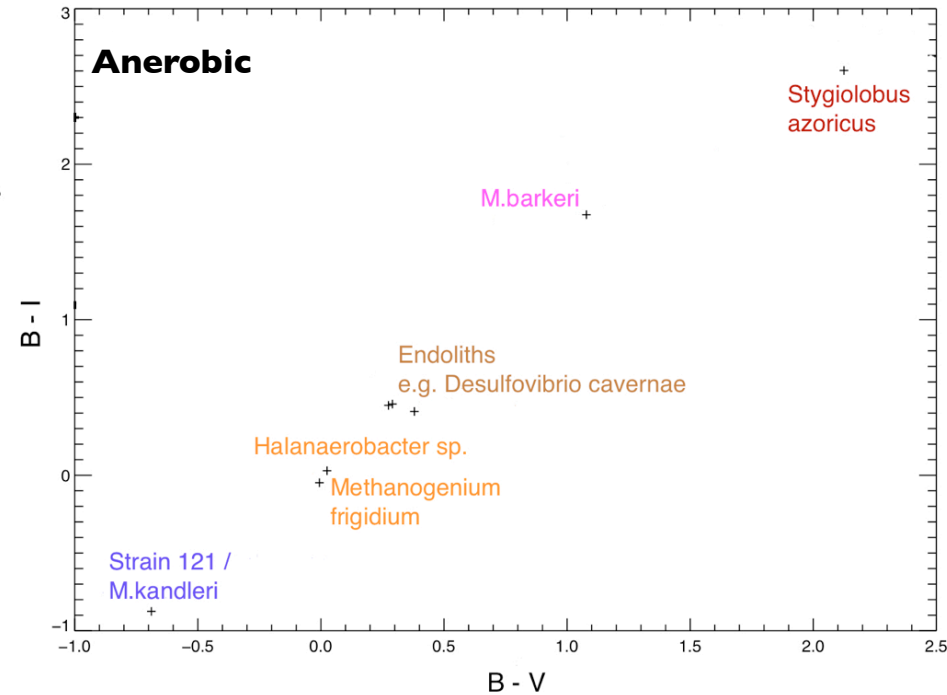
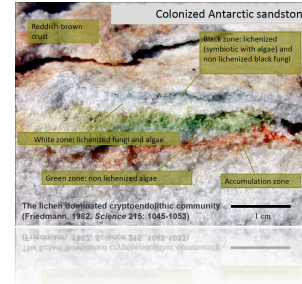
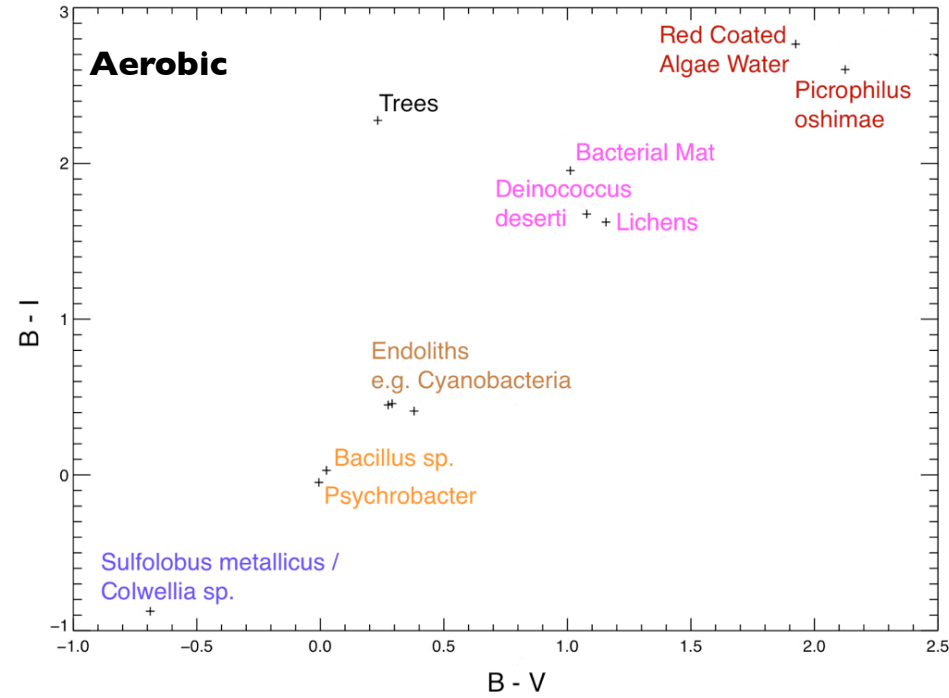


# Spectra of different surfaces



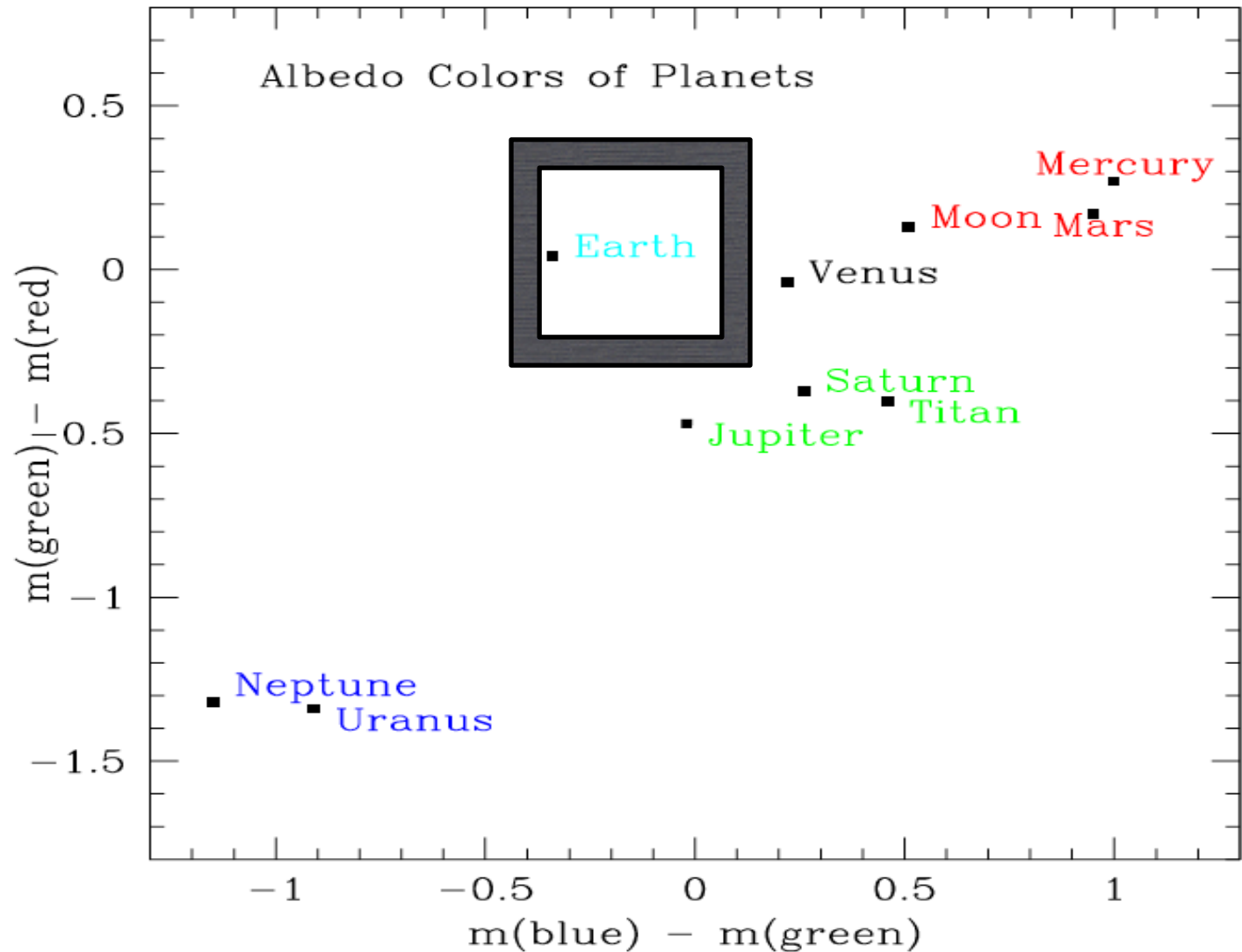
Data obtained from ASTER spectral library and USGS digital spectral library

# Diff. environments support diff. extremophiles on Earth



# Color of extreme worlds – prioritize targets

- ▲ Complete coverage
- Mixed surface
- ▲ VRE: complete coverage
- VRE: partial coverage
- + Present-day Earth



# THANK YOU to SAG 4 Team Members

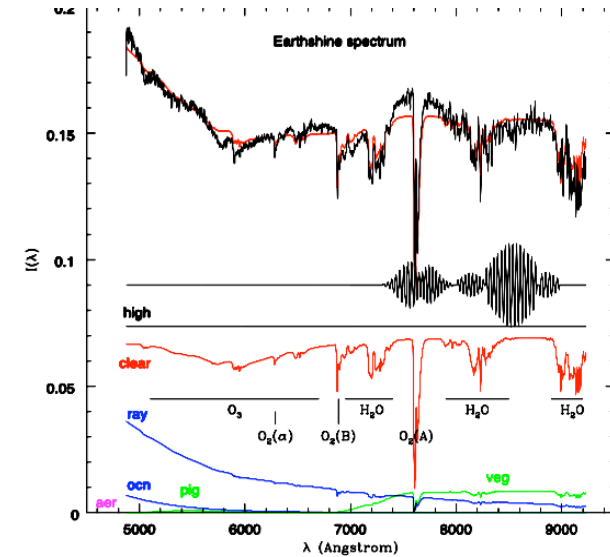
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- E. Turner (Princeton)
- P. van Paris (Bordeaux)
- R. Wordsworth (Chicago)
- A. Zsom (MIT)
- And you ? 😊

**Let me know if YOU want  
to join the discussions 😊**

- [kaltenegger@mpia.de](mailto:kaltenegger@mpia.de)

# SAG 4. Planetary Measurements Needed for Exoplanet Characterization

- **Objective:** Determine
  - which measurements are needed to characterize large and small exoplanets,
  - how accurate they must be,
  - how difficult they are to obtain, and
  - which might be done from the ground
- **Participants:** Atmospheric and surface modelers, ground and space observers, and exoplanet mission teams



Woolf et al., Ap.J. 2002

- SAG4 team: Abbot, Betremieux, Cowen, Domagal-Goldman, Forget, Green, Kaltenegger, Kasting, Kopparapu, Meadows, Pierrehumbert, Rauer, Robinson, Rugheimer, Sasselov, Seager, Segura, Selsis, Traub (& you!)<sub>30</sub>