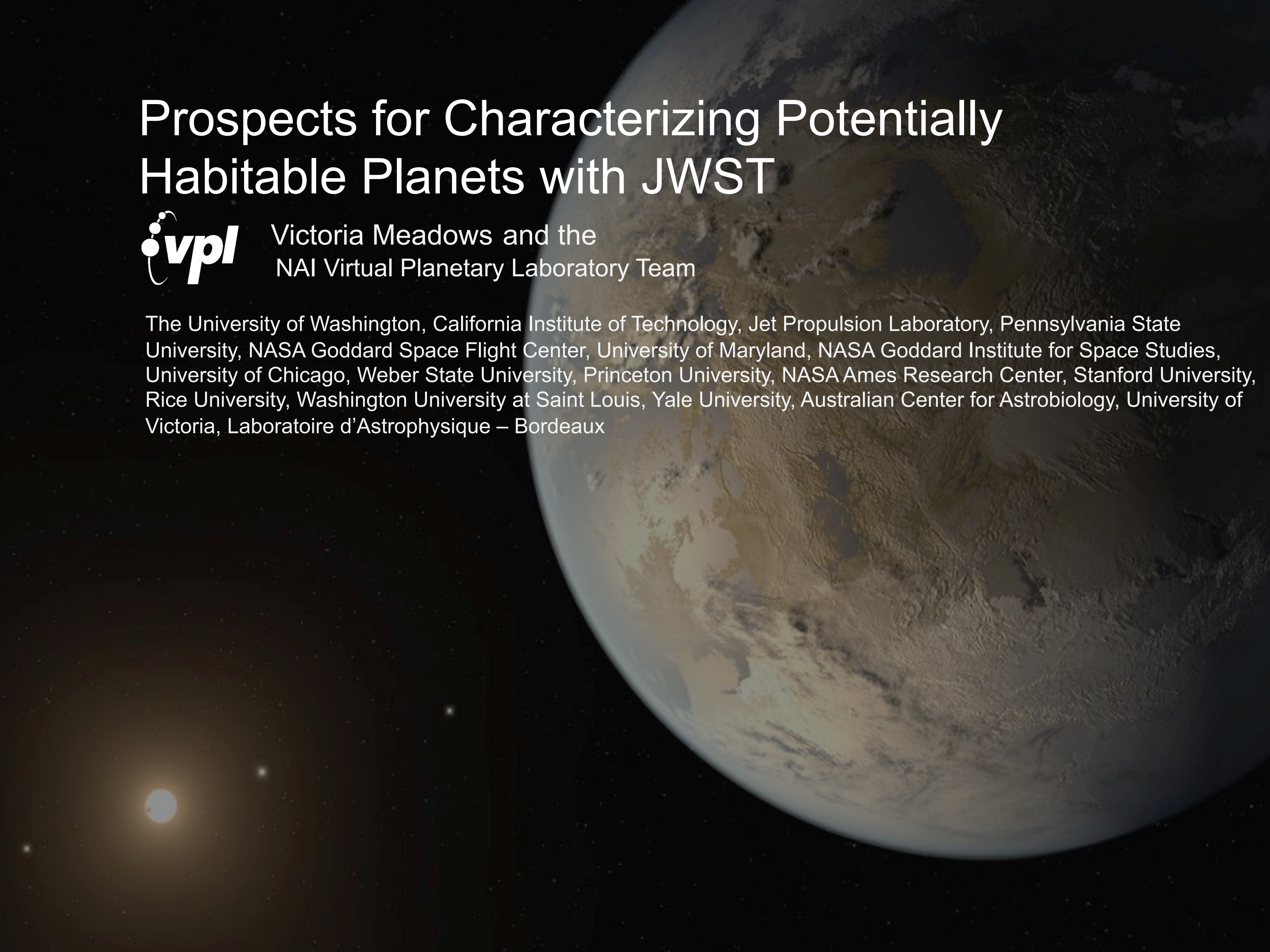
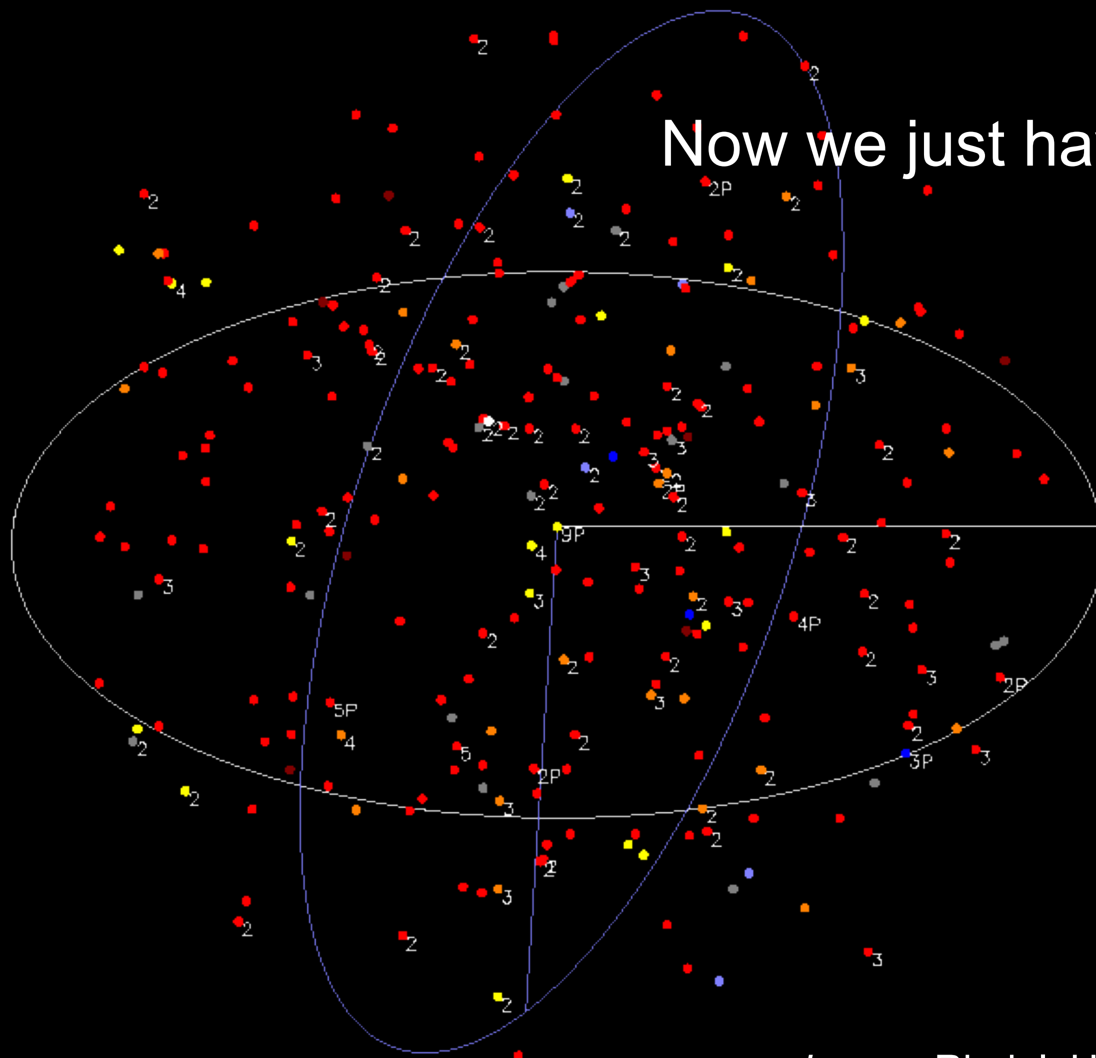


Prospects for Characterizing Potentially Habitable Planets with JWST

Victoria Meadows and the
NAI Virtual Planetary Laboratory Team

The University of Washington, California Institute of Technology, Jet Propulsion Laboratory, Pennsylvania State University, NASA Goddard Space Flight Center, University of Maryland, NASA Goddard Institute for Space Studies, University of Chicago, Weber State University, Princeton University, NASA Ames Research Center, Stanford University, Rice University, Washington University at Saint Louis, Yale University, Australian Center for Astrobiology, University of Victoria, Laboratoire d'Astrophysique – Bordeaux

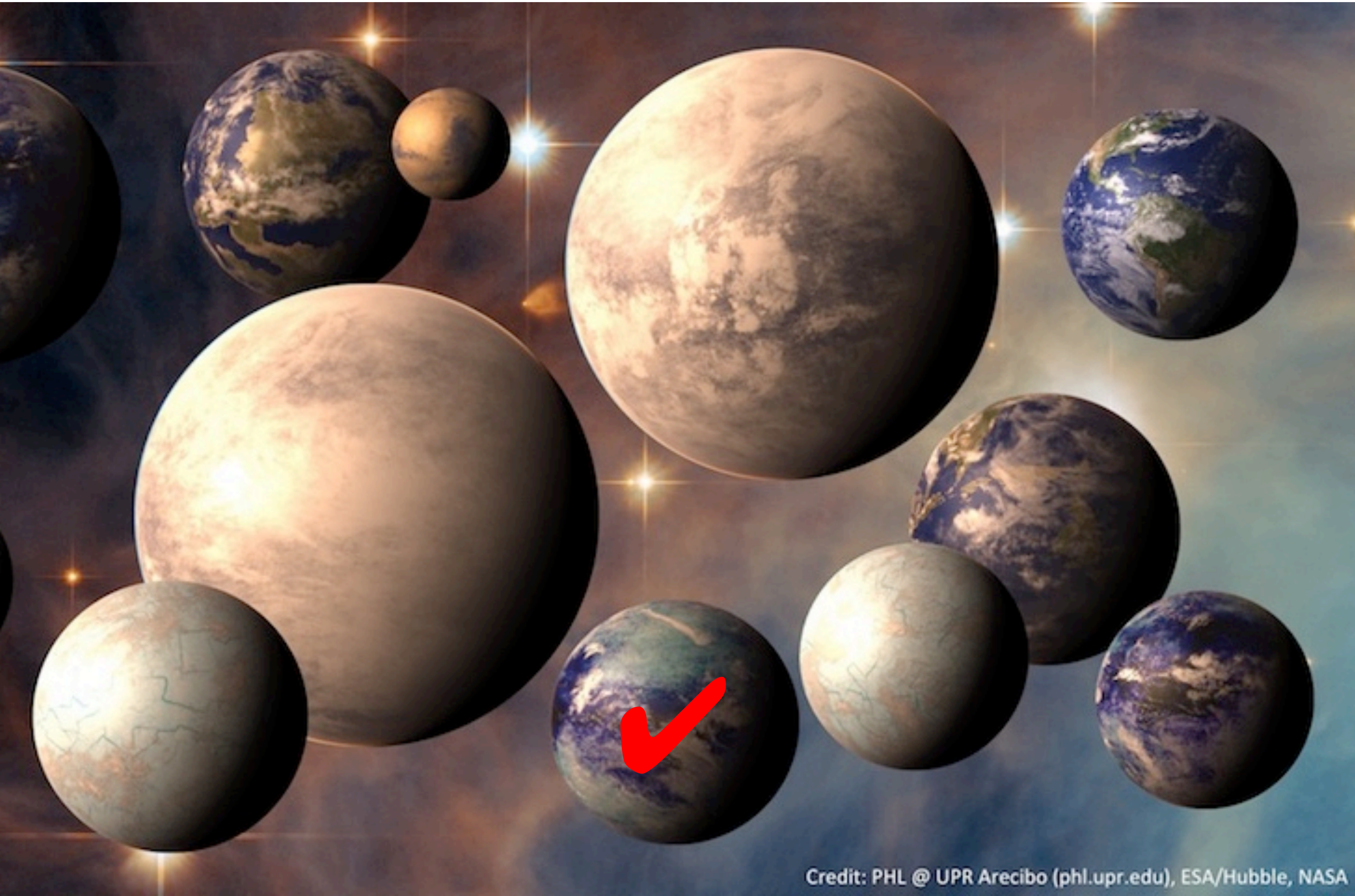
There is a transiting **Earth-sized planet (1-1.5 R_{Earth}) in the habitable zone** of an M dwarf star **within 10.6 pc (Dressing and Charbonneau, 2015).**



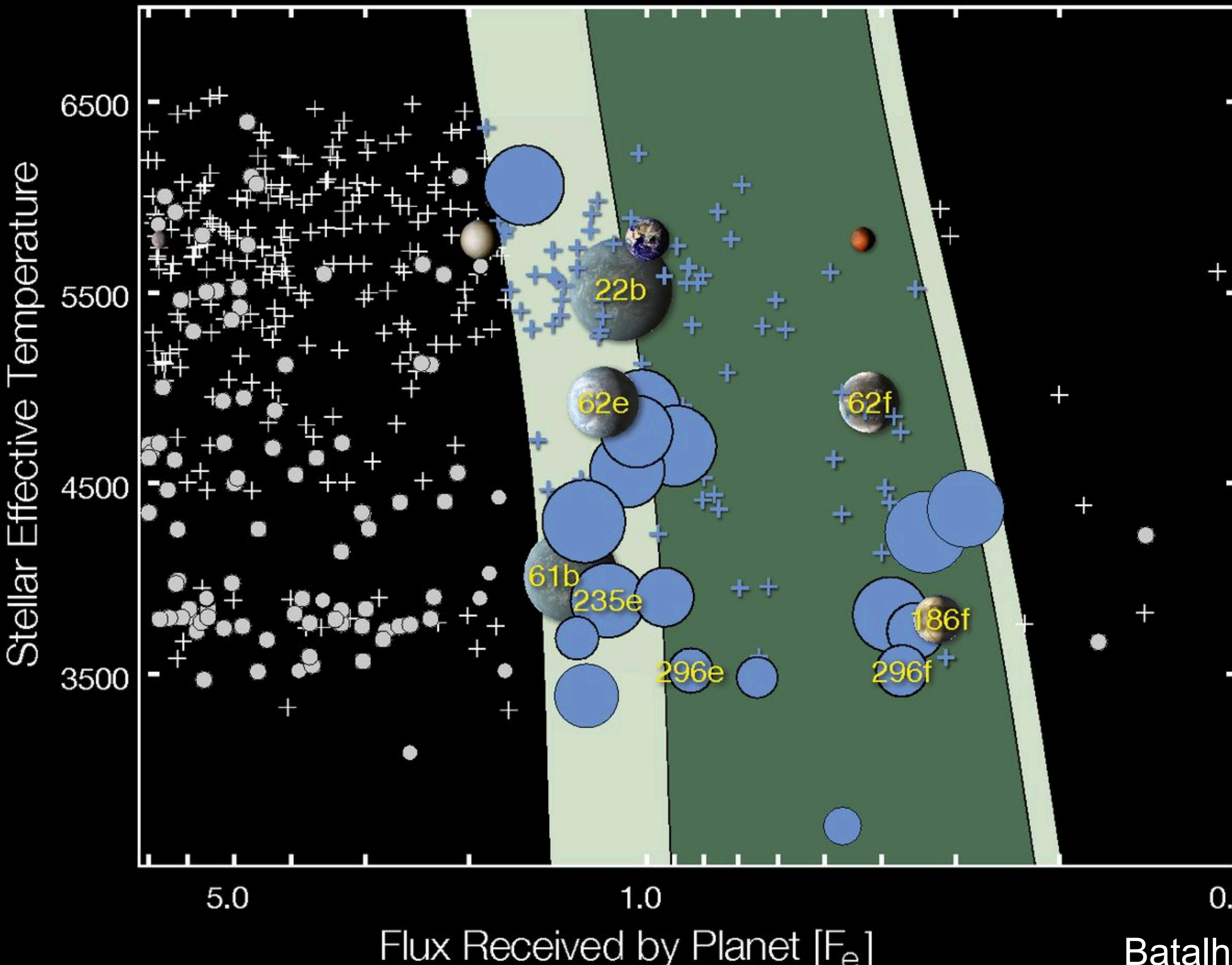
Now we just have to find it!

Image: Riedel, Henry, & RECONS group

How should we pick the right planet to study?

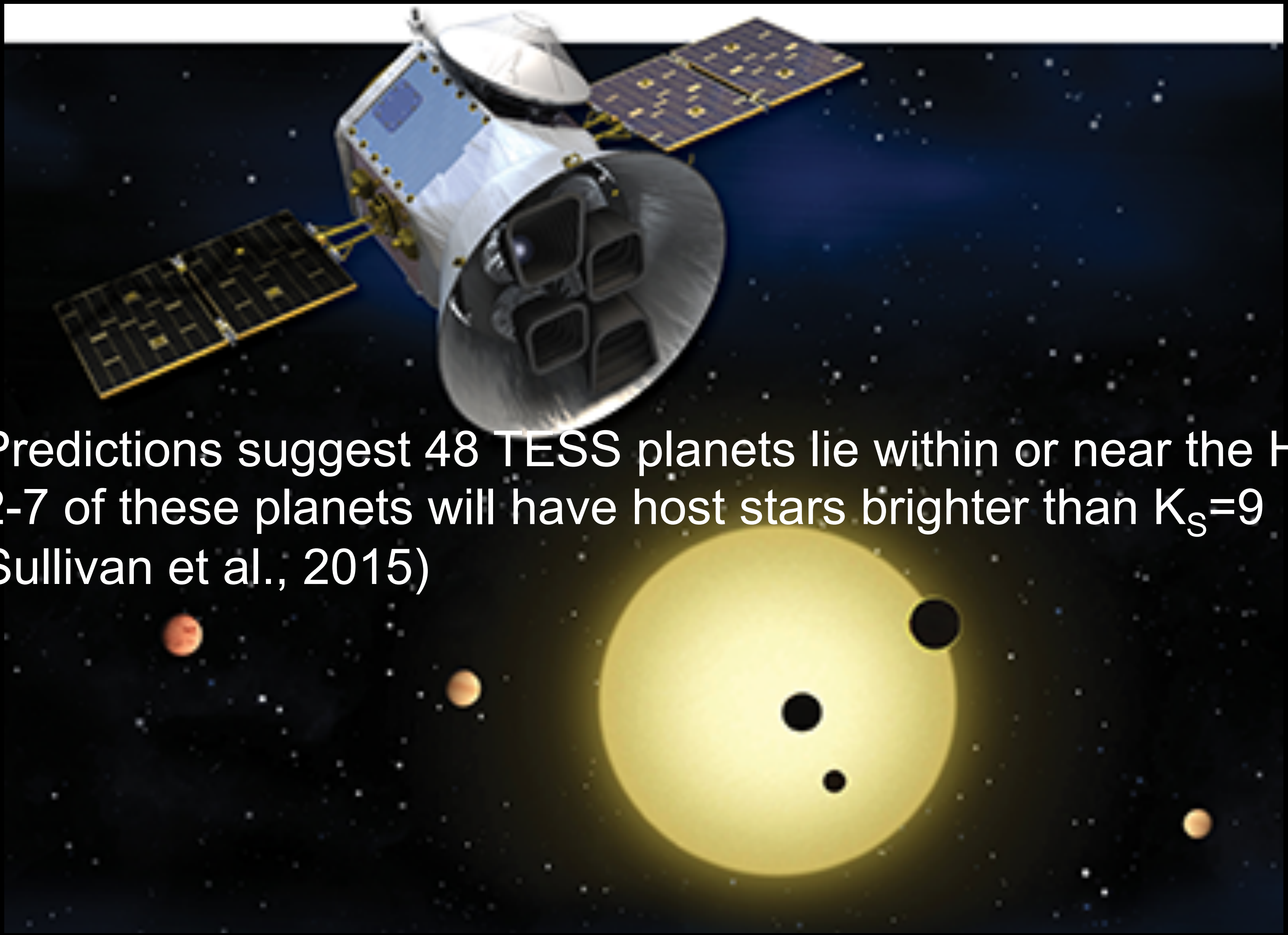


Kepler's Potentially Habitable Planets



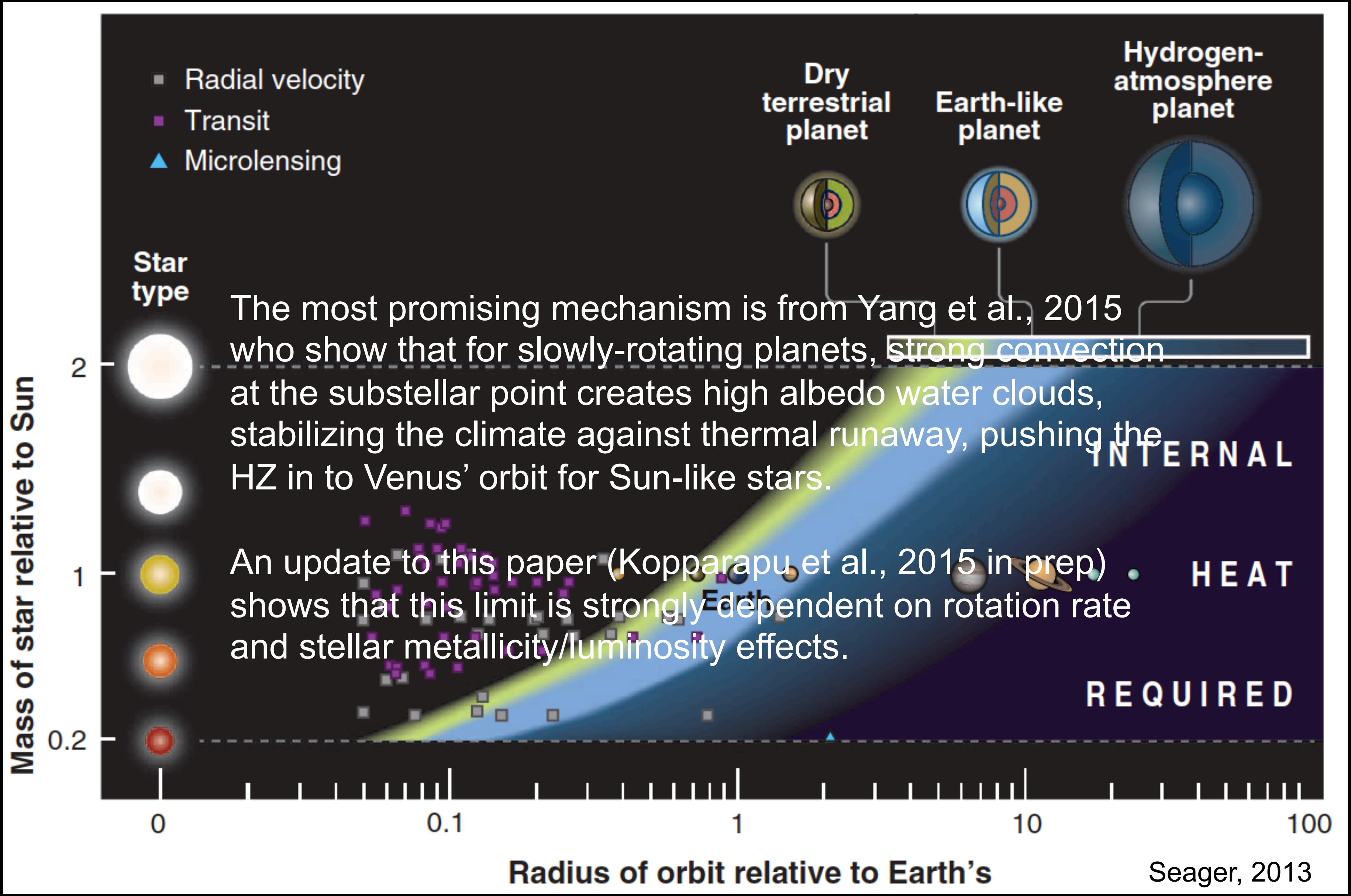
Batalha, 2014

TESS will most likely find JWST targets



- Predictions suggest 48 TESS planets lie within or near the HZ
- 2-7 of these planets will have host stars brighter than K_S=9 (Sullivan et al., 2015)

Extreme Habitability?



The most promising mechanism is from Yang et al., 2015 who show that for slowly-rotating planets, strong convection at the substellar point creates high albedo water clouds, stabilizing the climate against thermal runaway, pushing the HZ in to Venus' orbit for Sun-like stars.

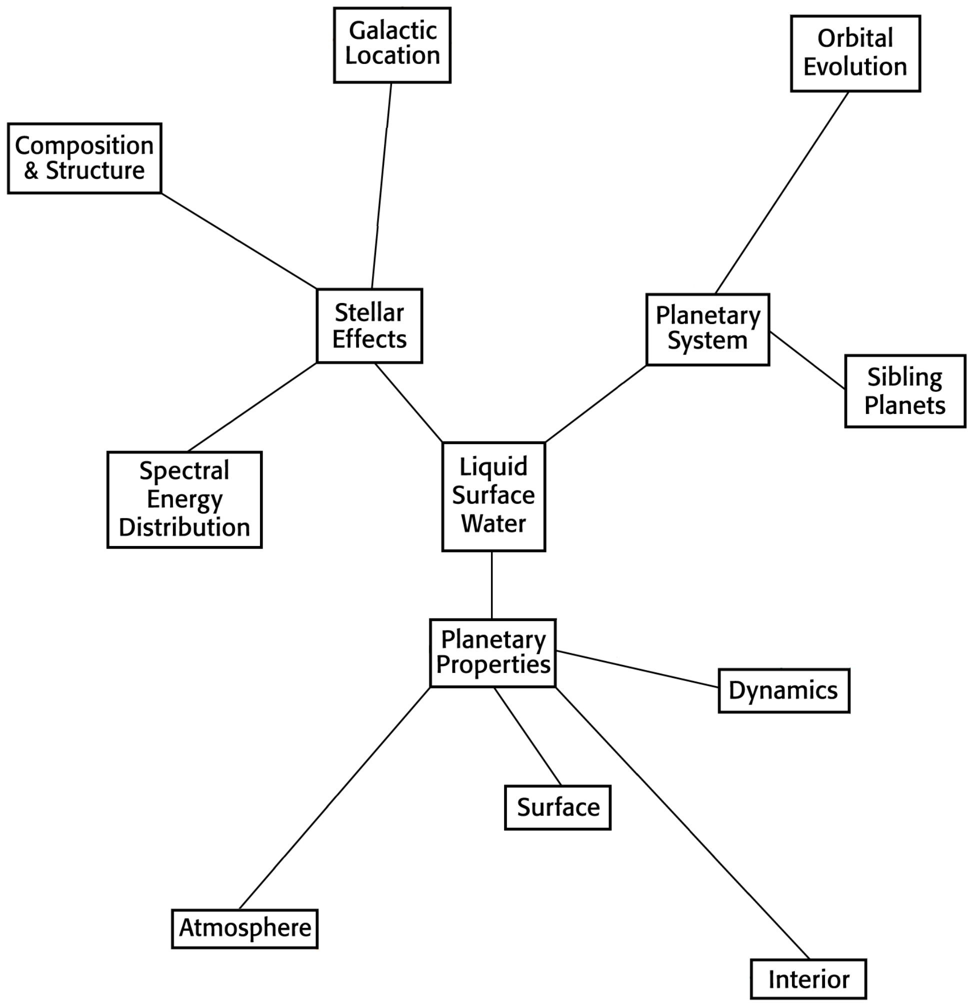
An update to this paper (Kopparapu et al., 2015 in prep) shows that this limit is strongly dependent on rotation rate and stellar metallicity/luminosity effects.

Seager, 2013

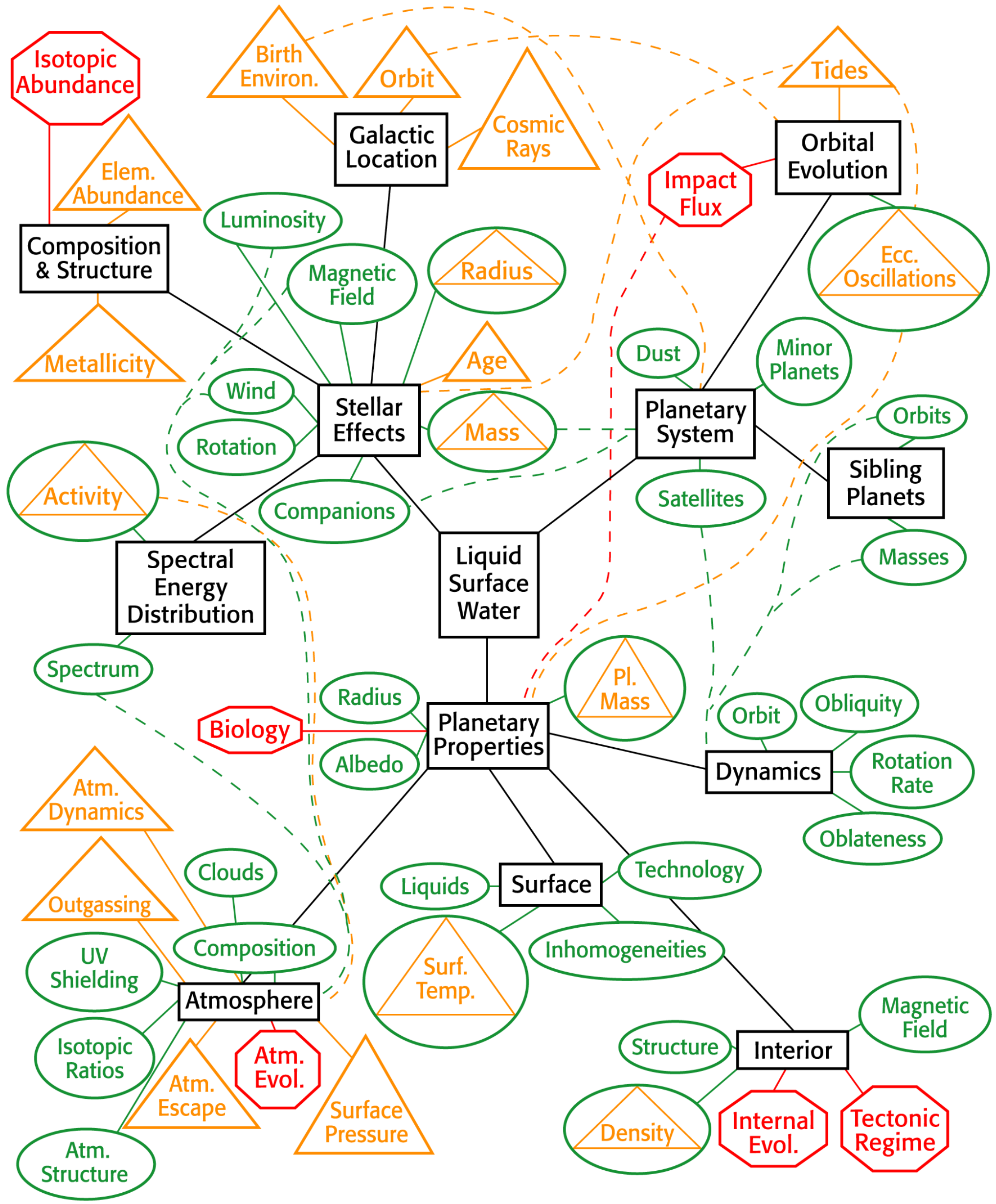
Assessing Potential Habitability

Liquid
Surface
Water

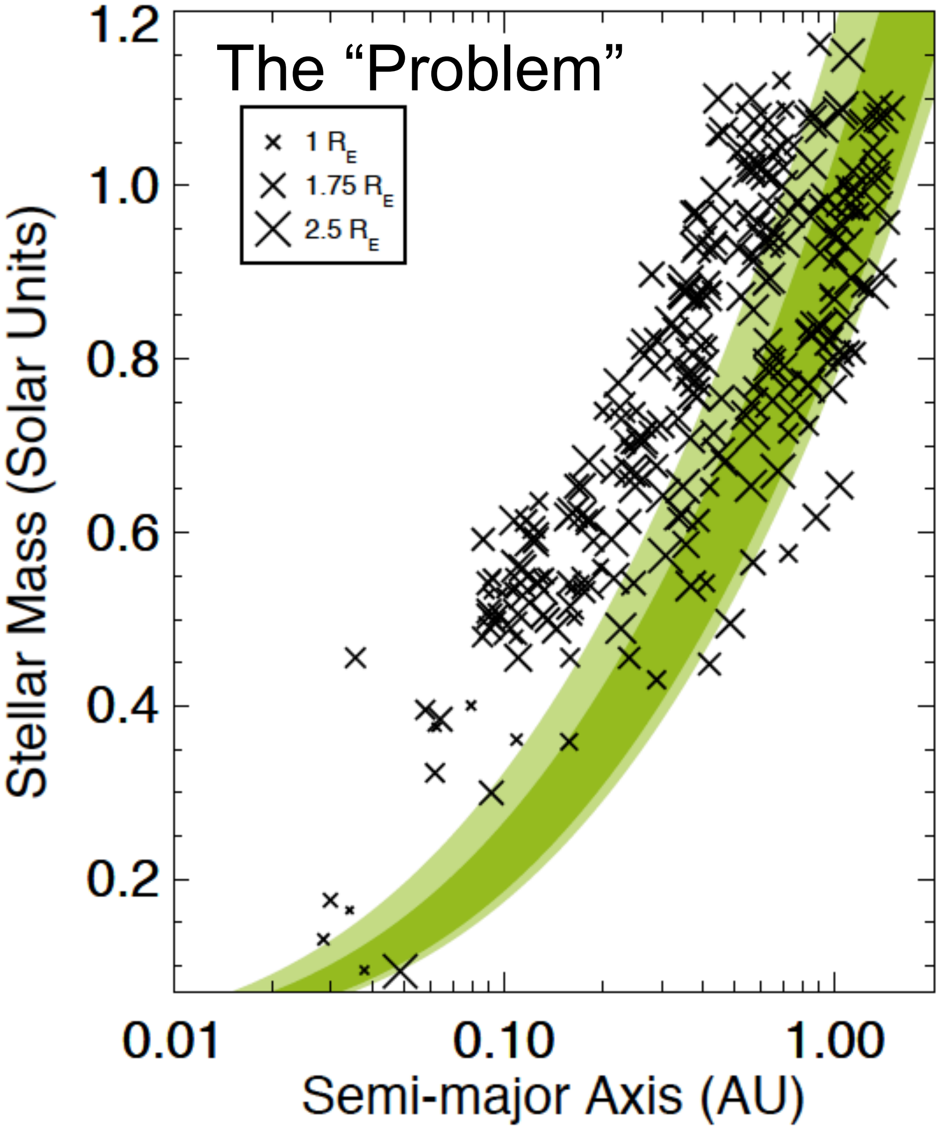
Assessing Potential Habitability

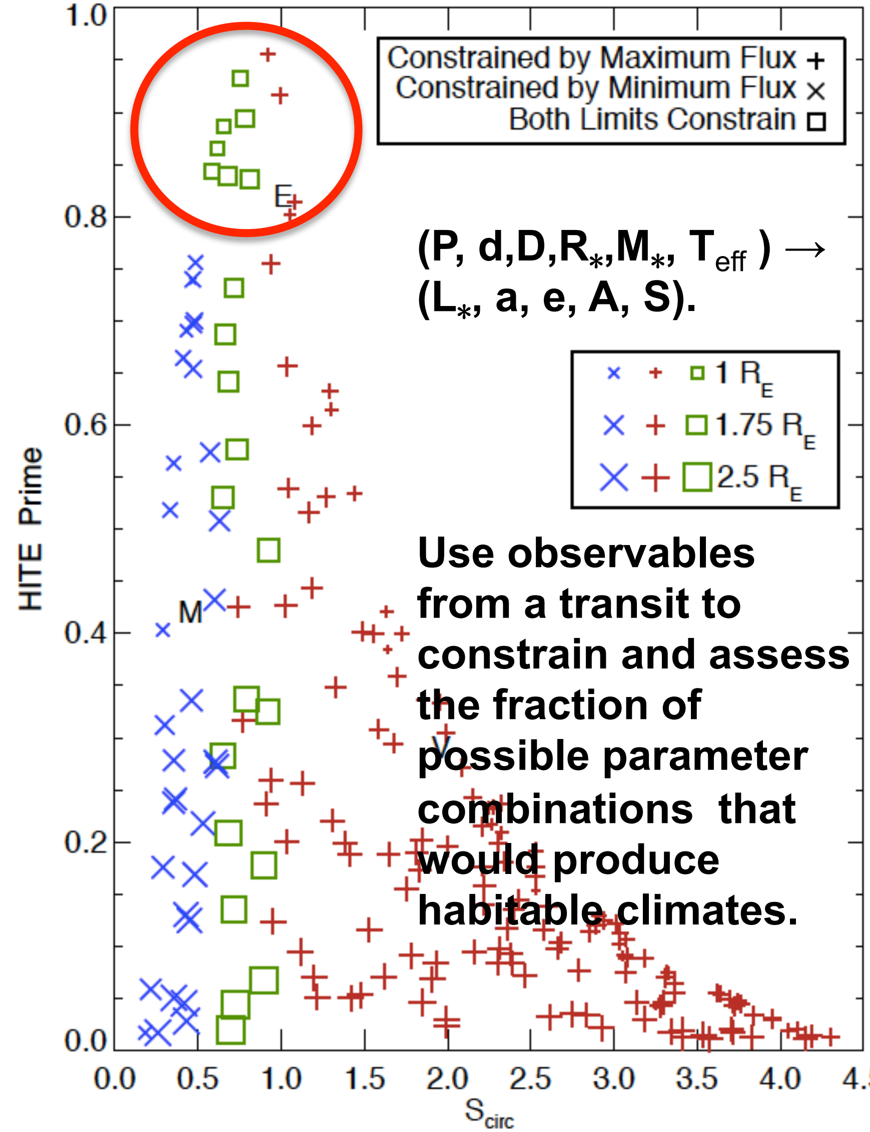


Assessing Potential Habitability



The Habitability Index





$(P, d, D, R_*, M_*, T_{eff}) \rightarrow (L_*, a, e, A, S)$.

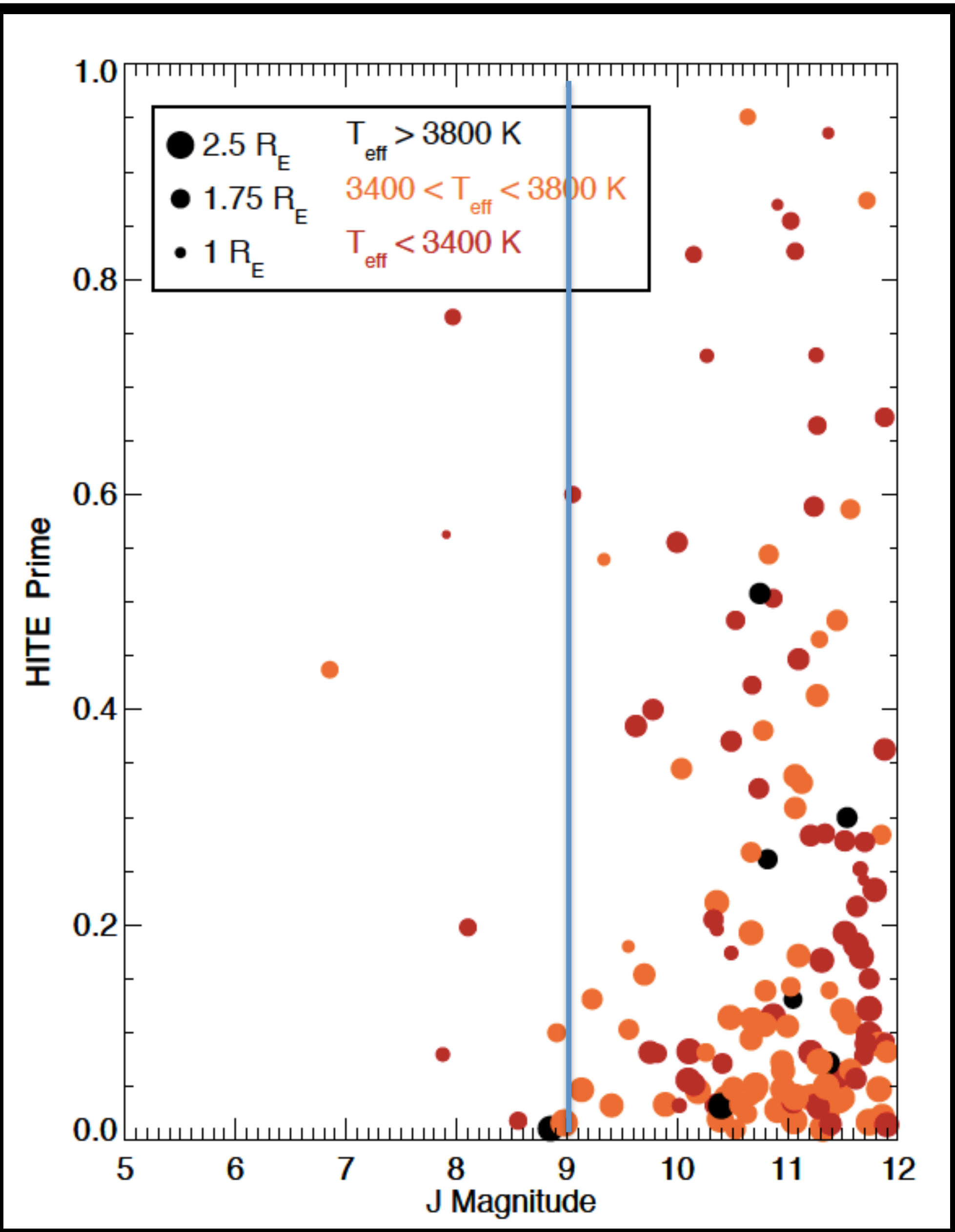
Use observables from a transit to constrain and assess the fraction of possible parameter combinations that would produce habitable climates.

Barnes, Meadows & Evans, 2015

Habitability Index for TESS Planets

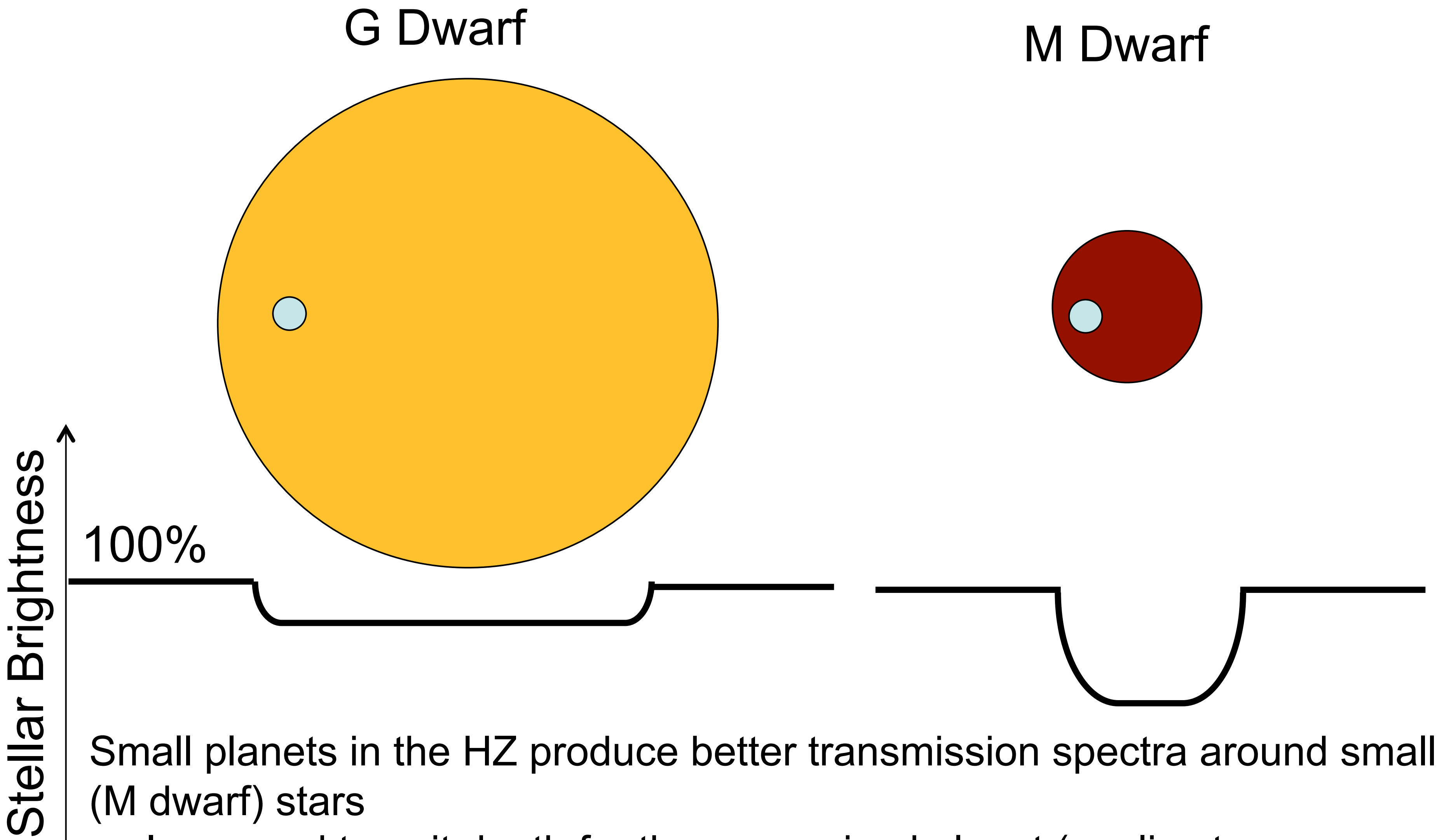
From Barnes, Meadows & Evans, (2015), *in press*

Based on a the Sullivan et al. (2015) study to predict the exoplanet yield from TESS.



Limitations on Probing Exoplanet Environments with Transmission Spectra

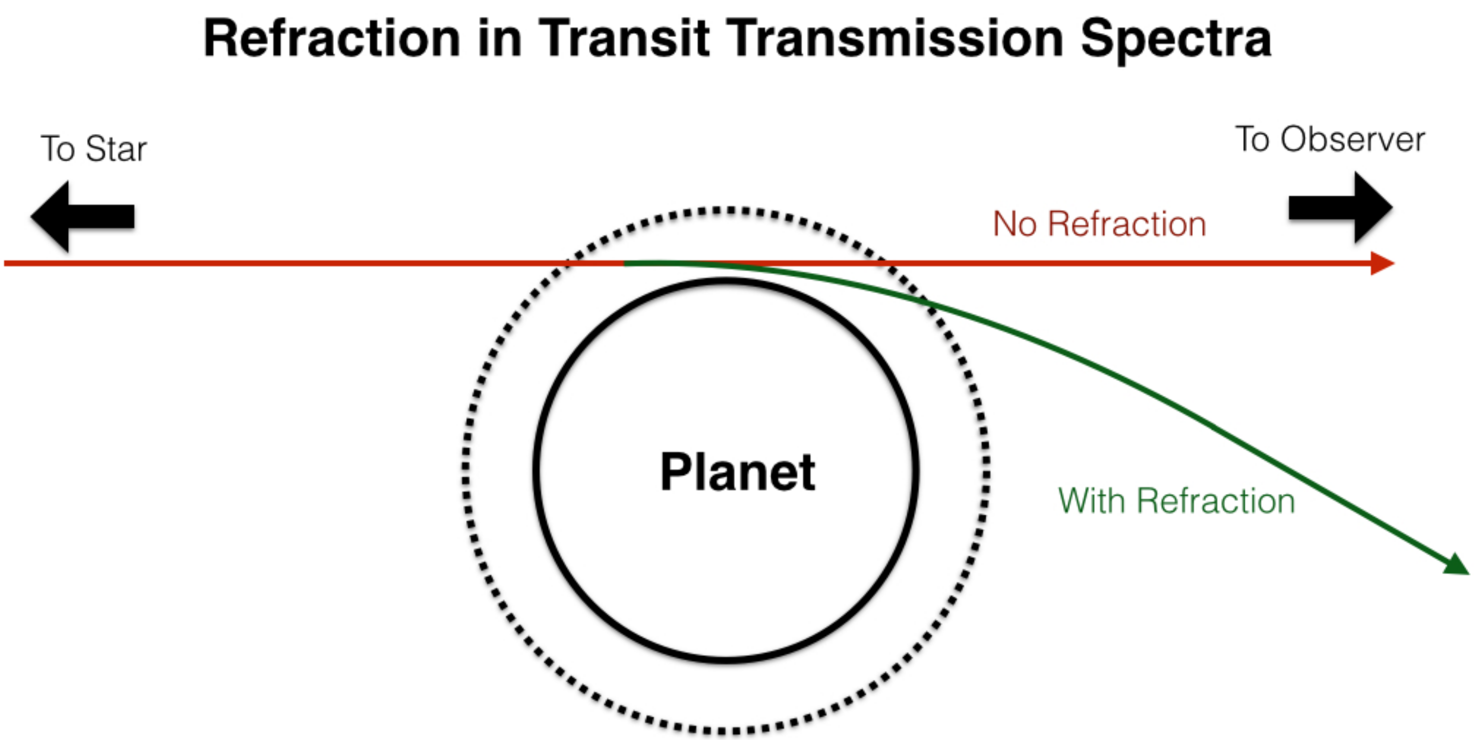
Better Signal for Planets Orbiting M Dwarfs



Small planets in the HZ produce better transmission spectra around small (M dwarf) stars

- Increased transit depth for the same-sized planet (applies to atmospheric absorption too)

Refraction Also Limits Altitudes Probed

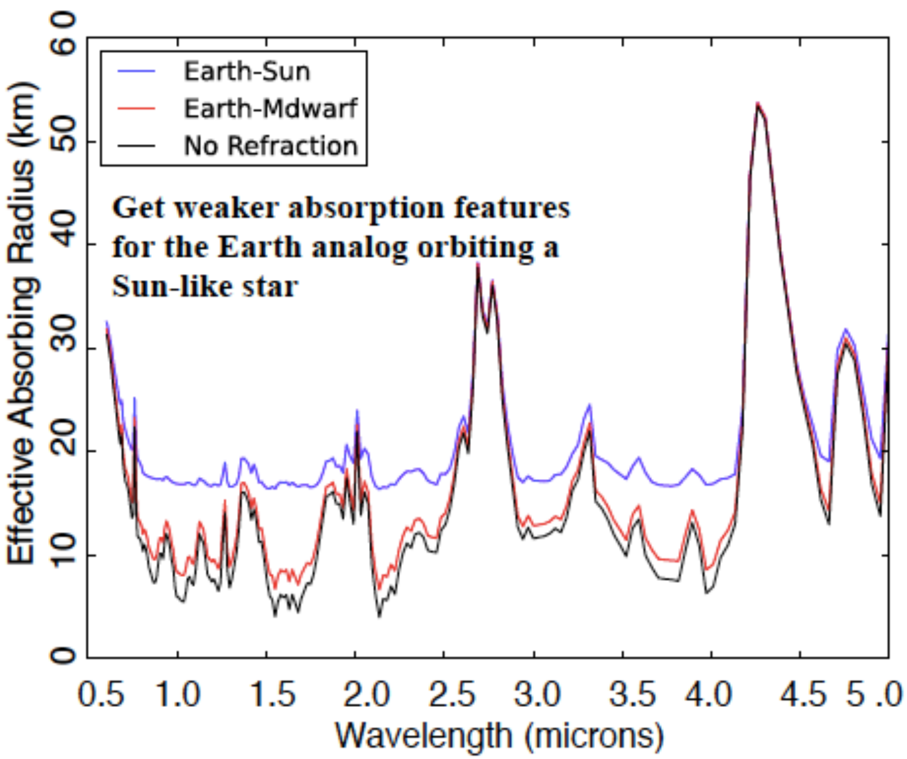


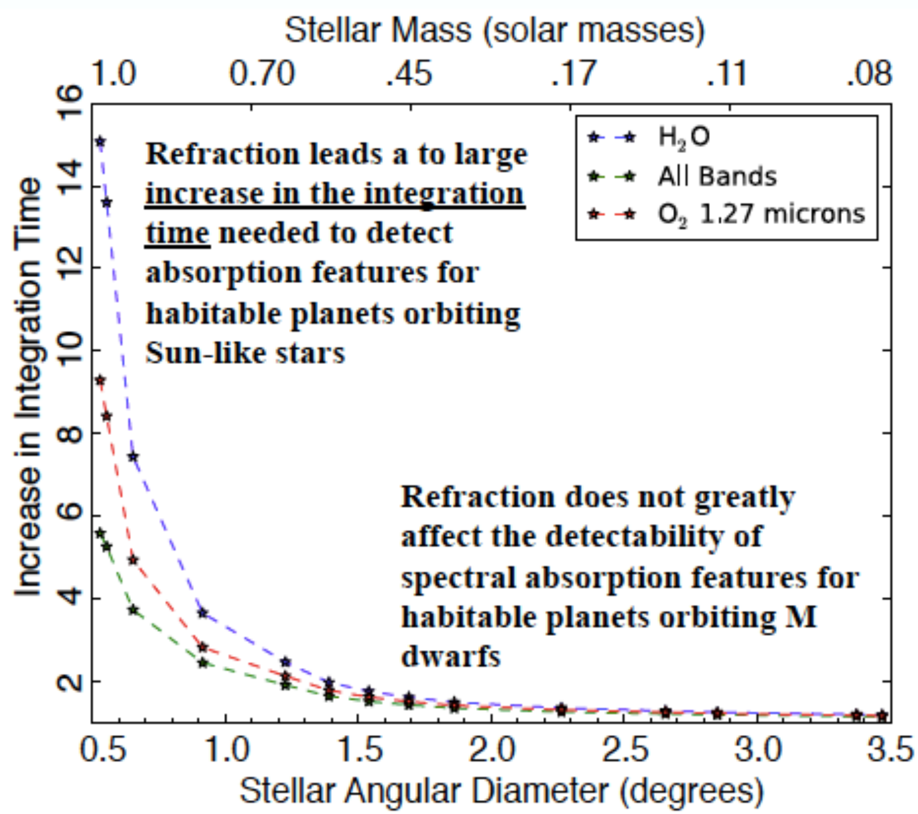
Transit transmission will not allow us to learn about the planetary surface

For every planet/star system there will be a maximum pressure (or minimum altitude) that can be probed. At deeper levels the refracted starlight is at too high an angle to be intercepted by the observer.

Garcia-Muñoz et al., 2012; Misra, Meadows and Crisp., 2014; Bertremieux & Kaltenegger, 2013, 2014

Refraction Reduces Spectral Features

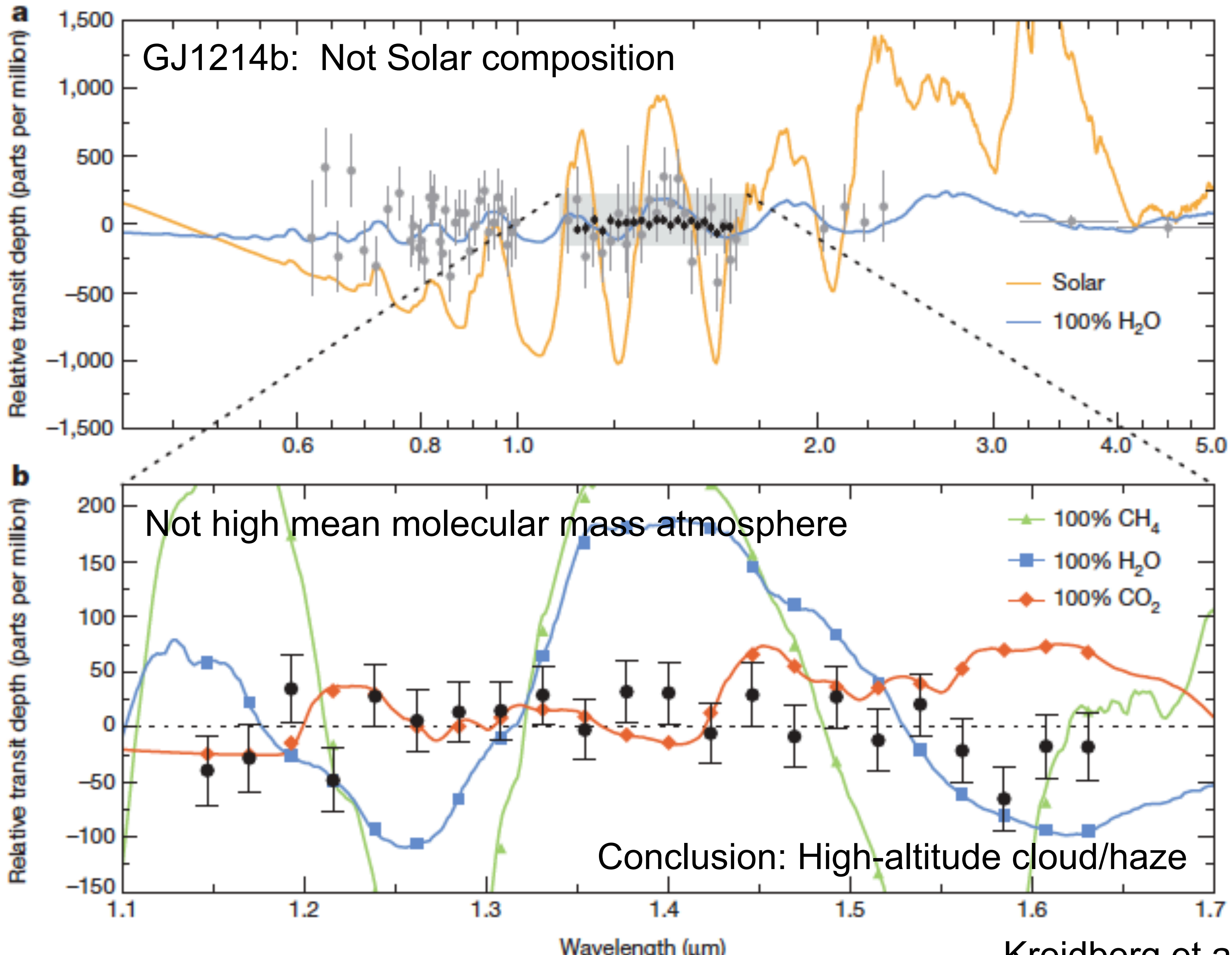




For planets in the habitable zone of their parent stars refraction has less of an effect on detectability of spectral absorption for M dwarf planets, with a larger effect for G dwarf planets.

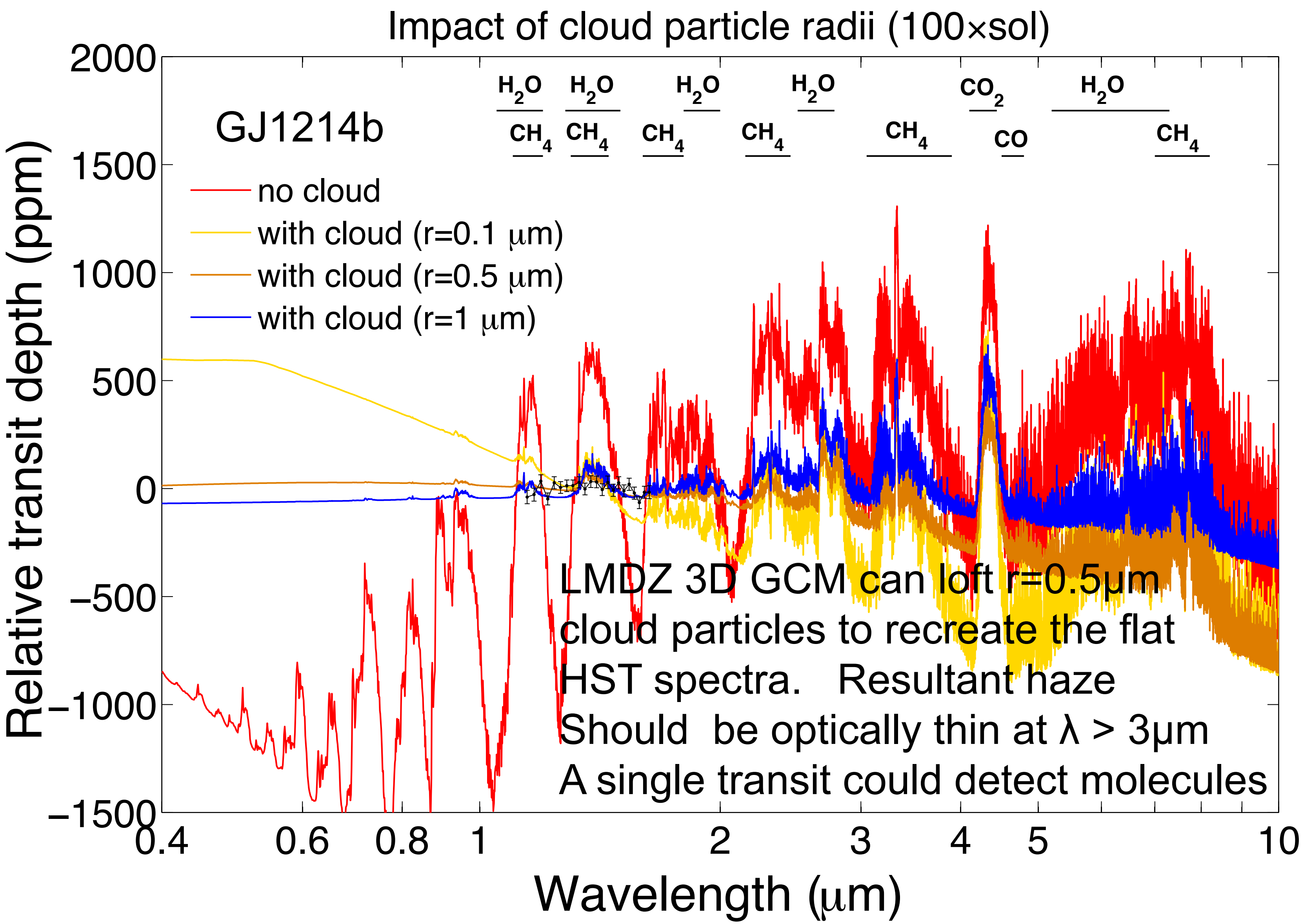
Misra, Meadows and Crisp, 2014

Haze can severely limit transmission spectra



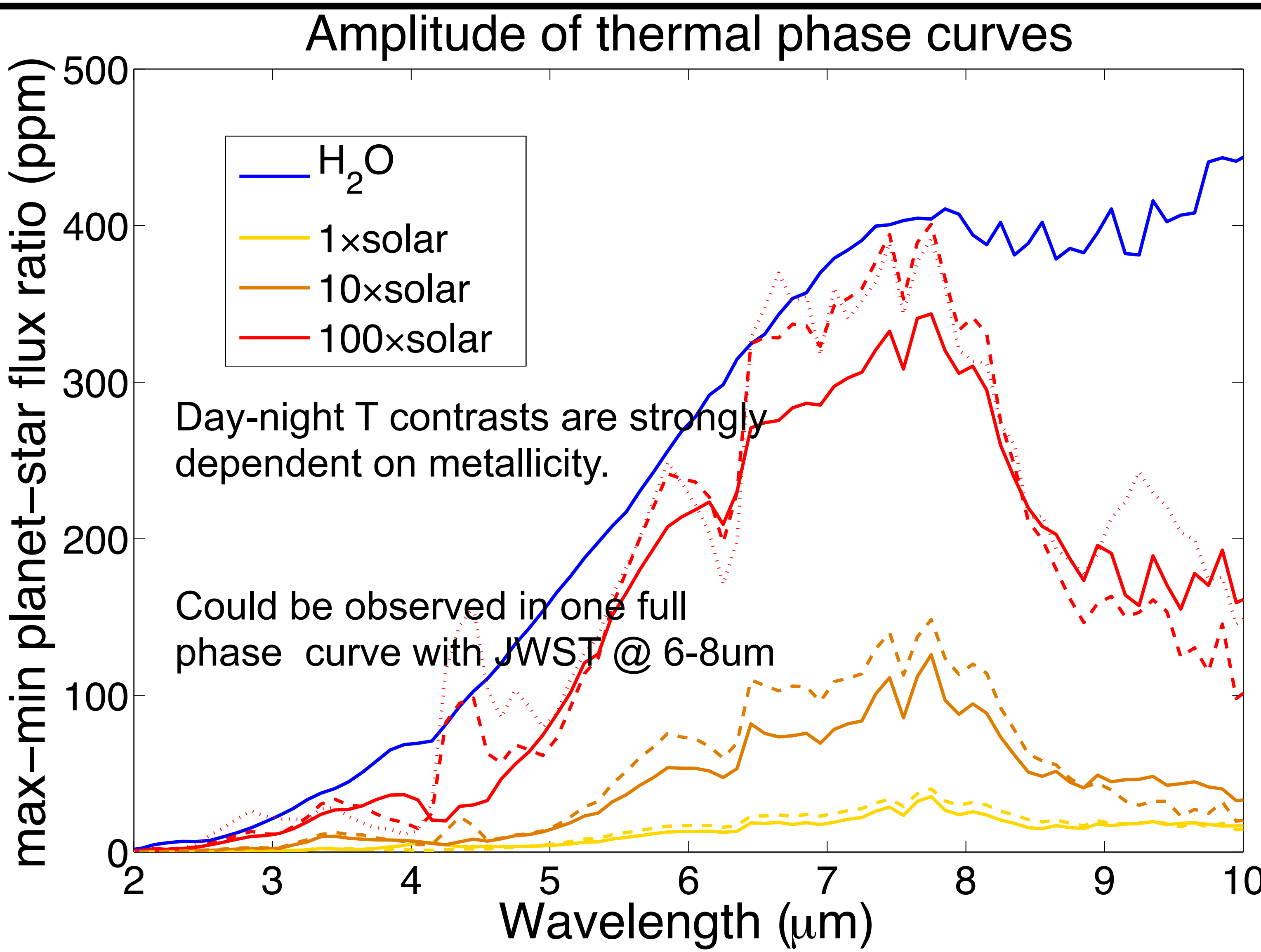
Kreidberg et al., 2014

JWST will get us beyond "the flat zone" for mini-Neptunes



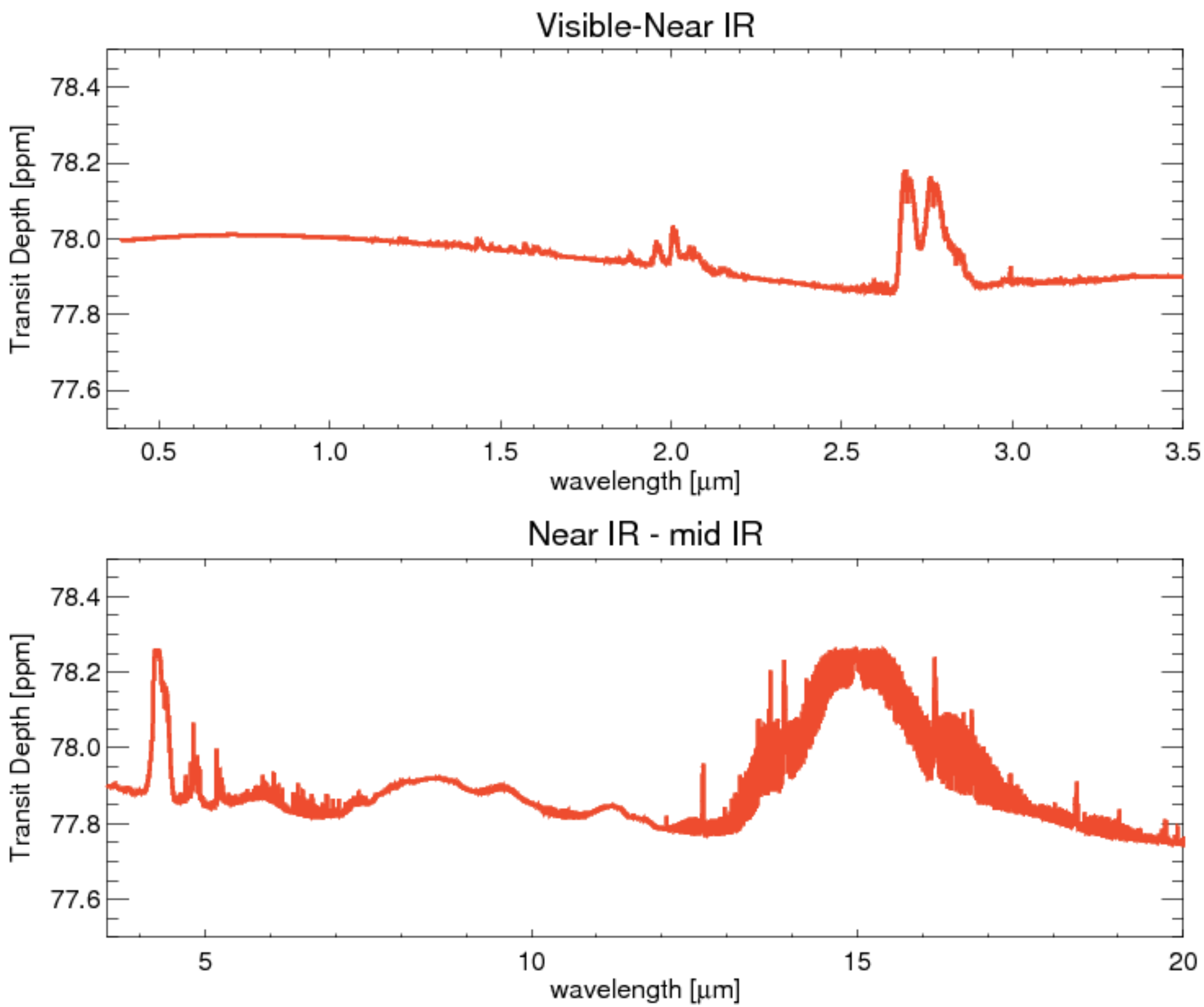
Charnay, Meadows, Misra, Leconte, Arney (2015) in press

Thermal Phase Curves May Reveal Metallicity



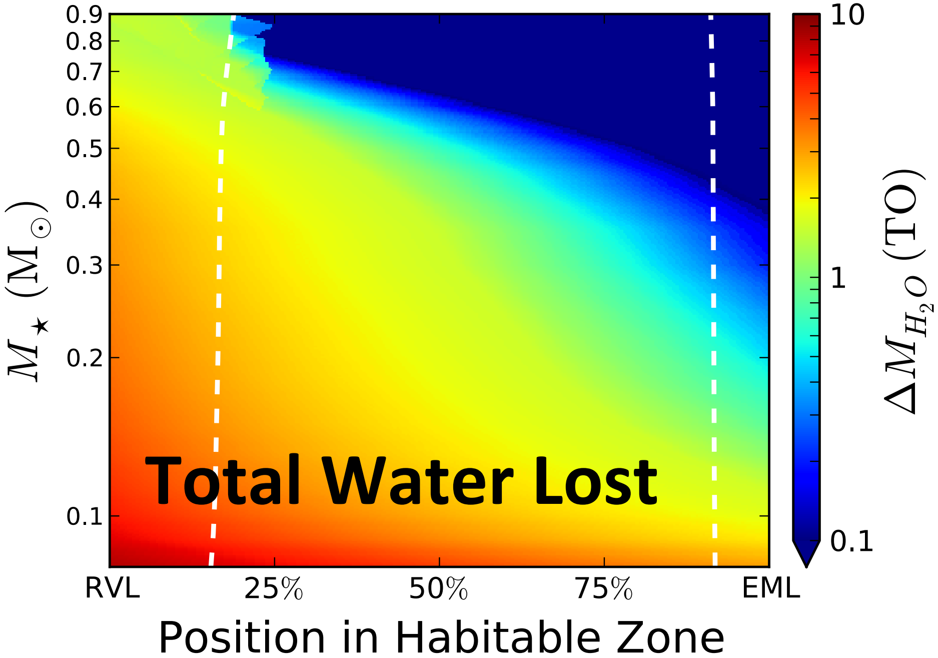
Charnay, Meadows, Misra, Leconte, Arney (2015) in press

Venus in Transit



Giada Arney

M Dwarf Planets May Make Their Own O_2!

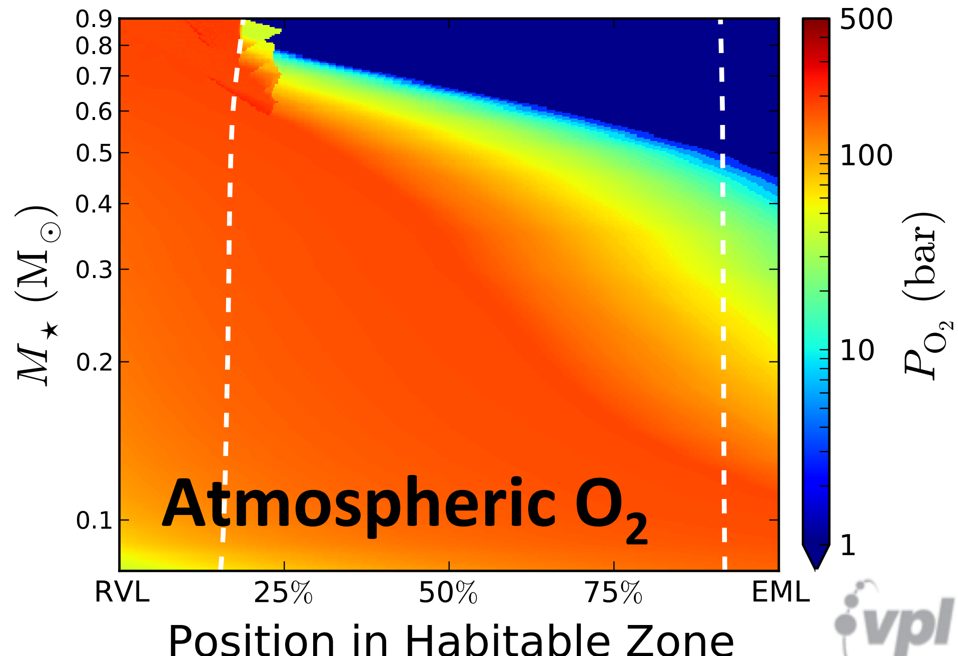


Terrestrial planets can lose several Earth oceans of water via hydrodynamic escape during the PMS phase of M dwarfs.

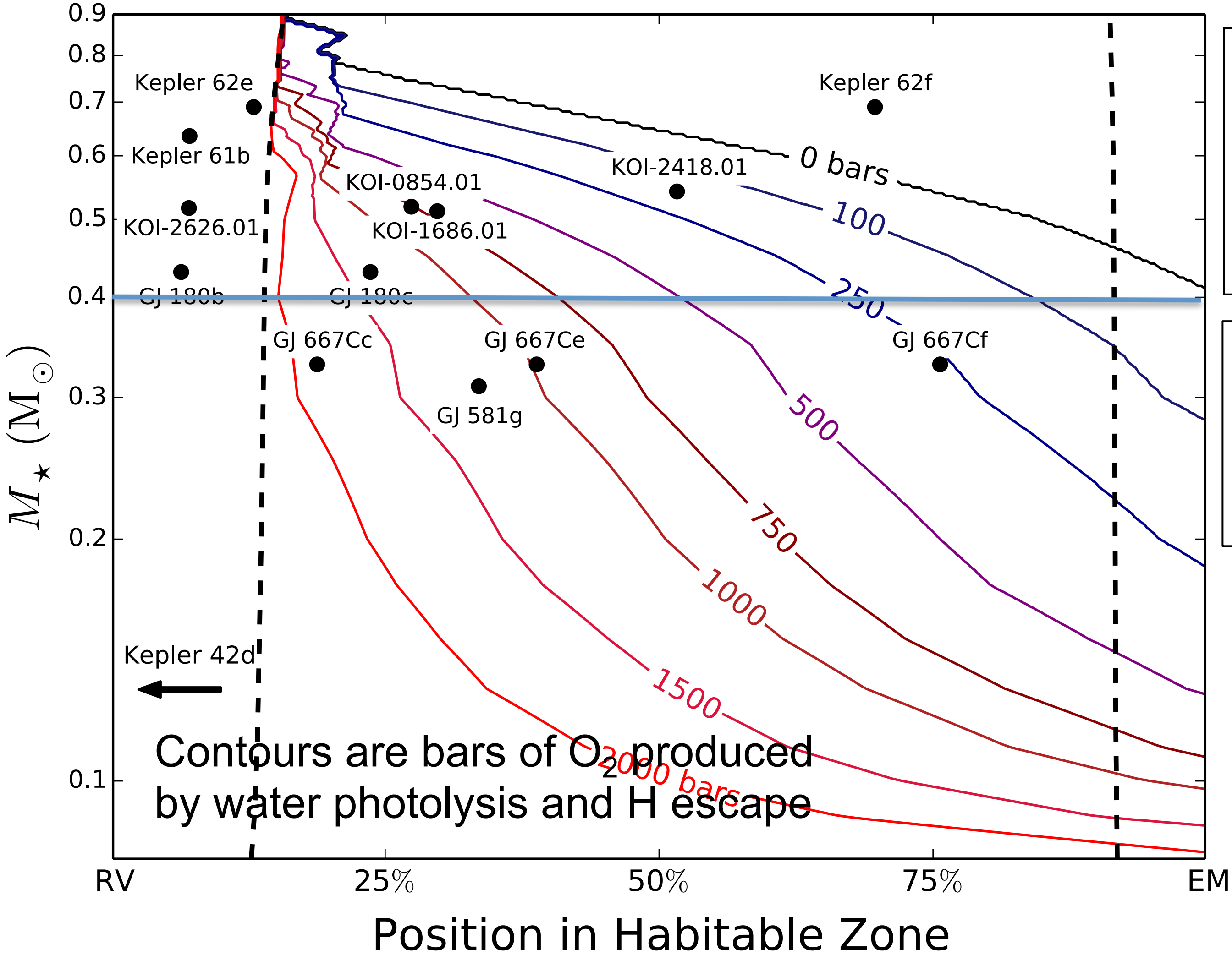
Luger & Barnes (2015)

Depending on surface sinks, up to several hundreds of bars of photolytically-produced O_2 can potentially build up in the atmospheres of these planets.

Luger & Barnes (2015)



Early Atmospheric Loss for M dwarf planets



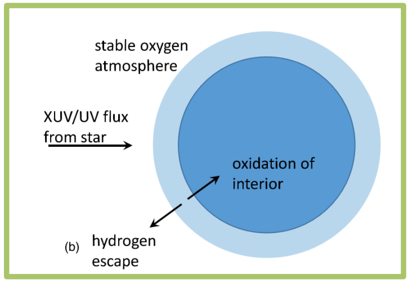
This extra pre-MS luminosity can last for up to a billion years and could dessicate planets formed in the habitable zone of low mass stars within the first 100 Myr

THE PUNCHLINE: Planets orbiting stars above a stellar mass of ~ 0.4 are less likely to experience this phenomenon, especially towards the outer edge of the HZ.

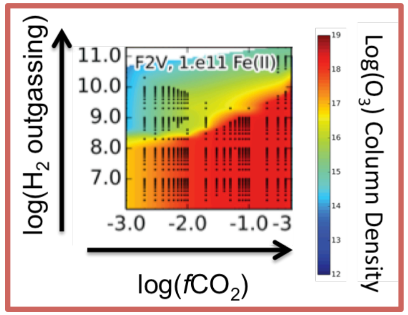
Luger and Barnes, 2015

Abundant O_2 may not indicate habitability

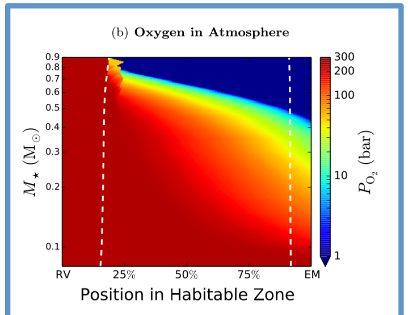
1. H Escape from Thin N-Depleted Atmospheres
(Wordsworth & Pierrehumbert 2014)



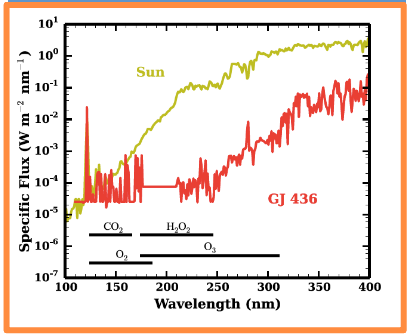
2. Photochemical Production of O_2/O_3 (Domagal-Goldman, Segura, Claire, Robinson, Meadows 2014)



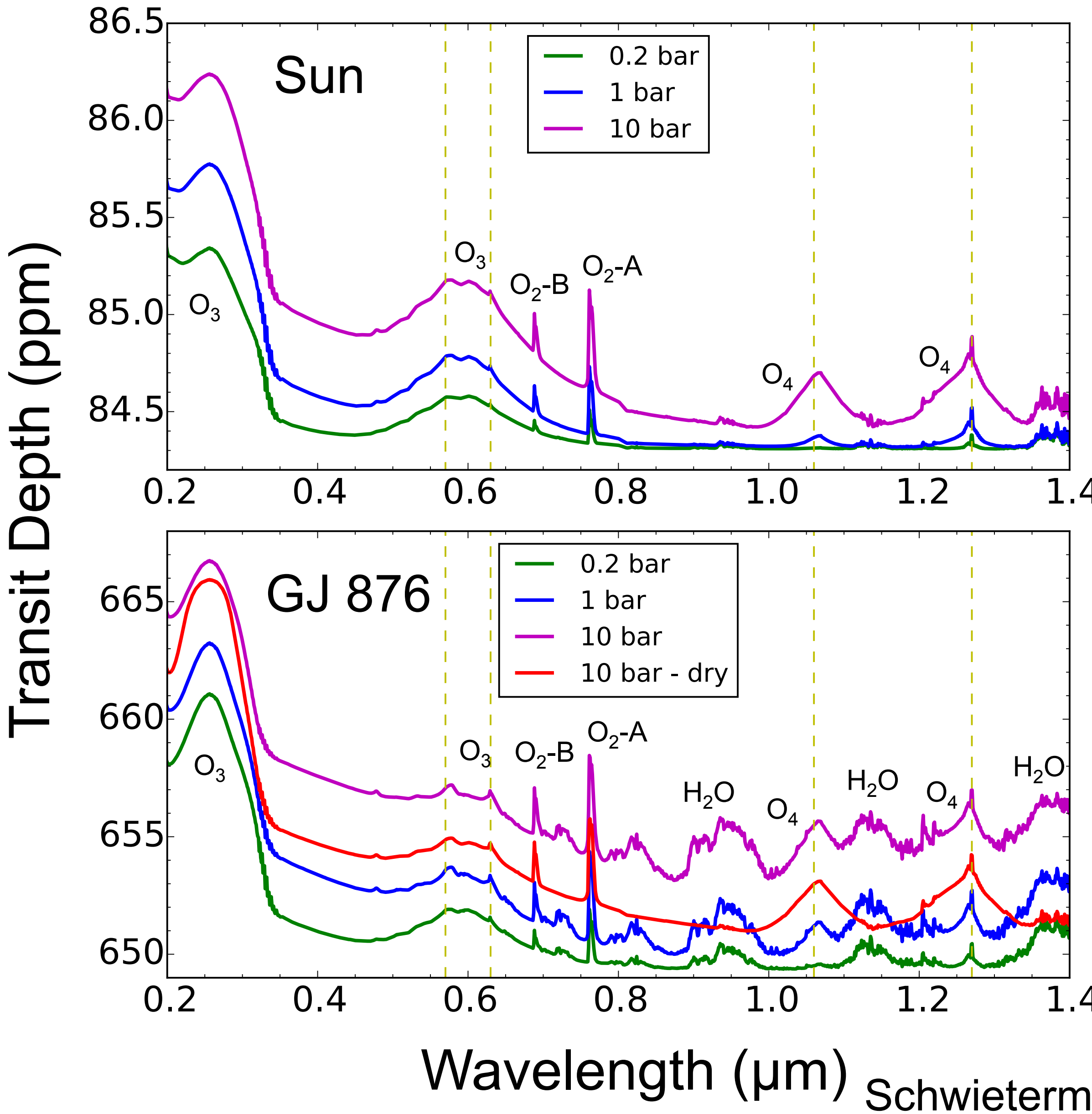
3. O_2-Dominated Post-Runaway Atmospheres from XUV-driven H Loss (Luger & Barnes 2014)



4. CO_2 Photolysis in Dessicated Atmospheres
(Gao, Hu, Robinson, Li, Yung, 2015)

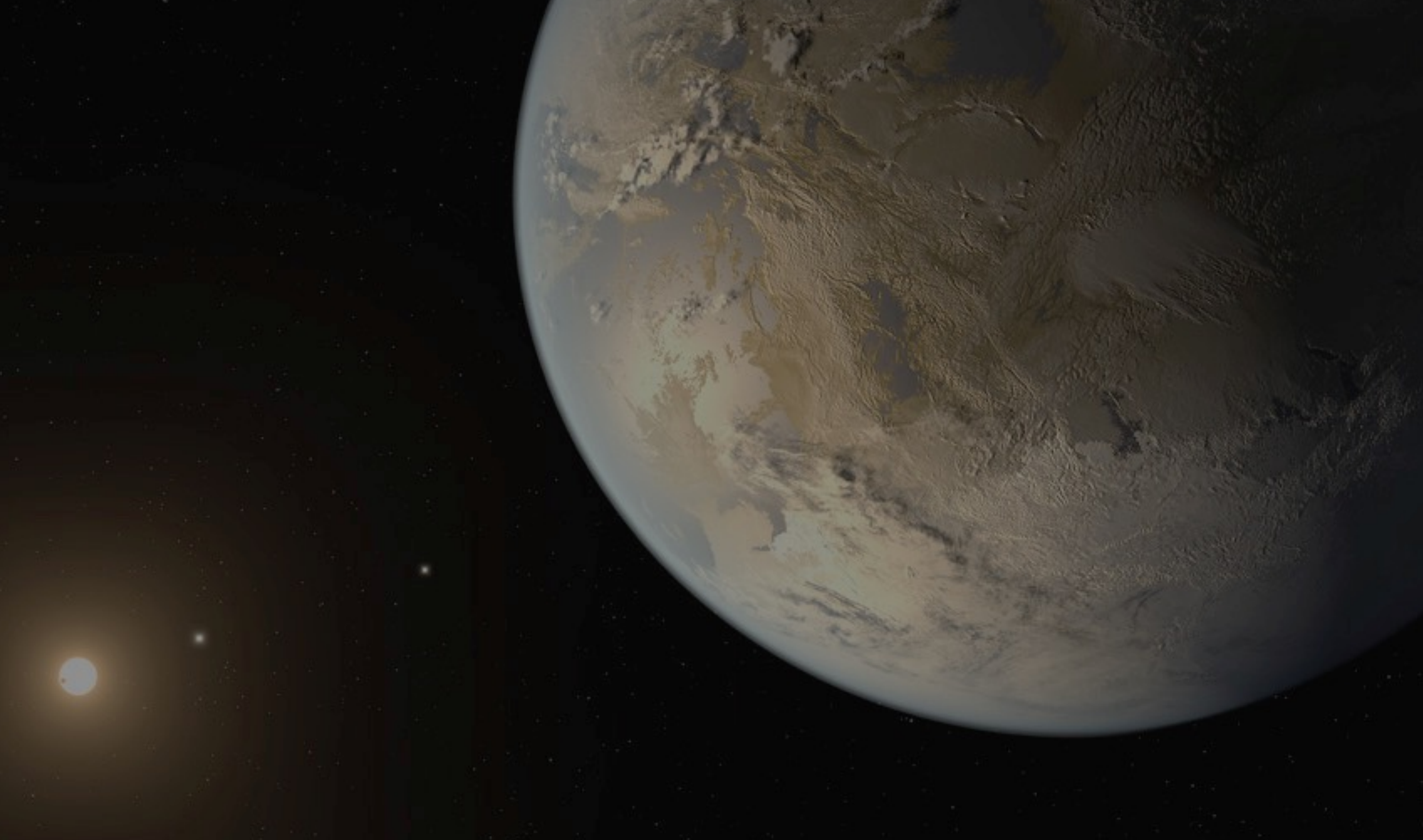


Massive O_2 atmospheres may have O_4 features

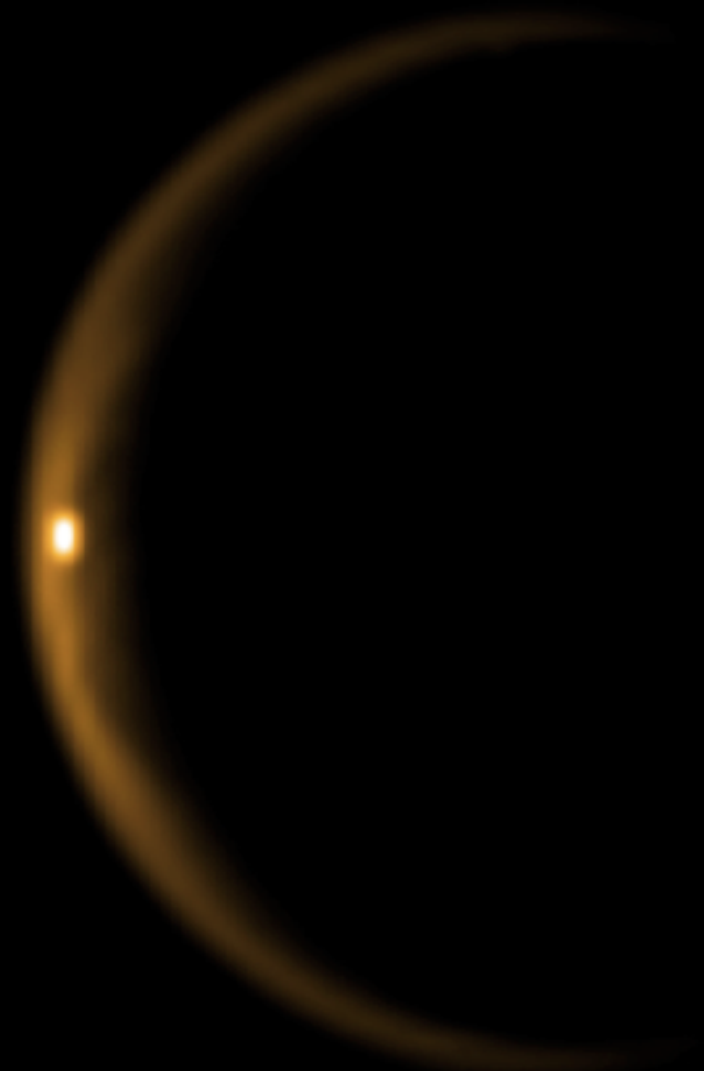


Schwieterman et al., in prep

Measurements We Would Like to Make for Terrestrials

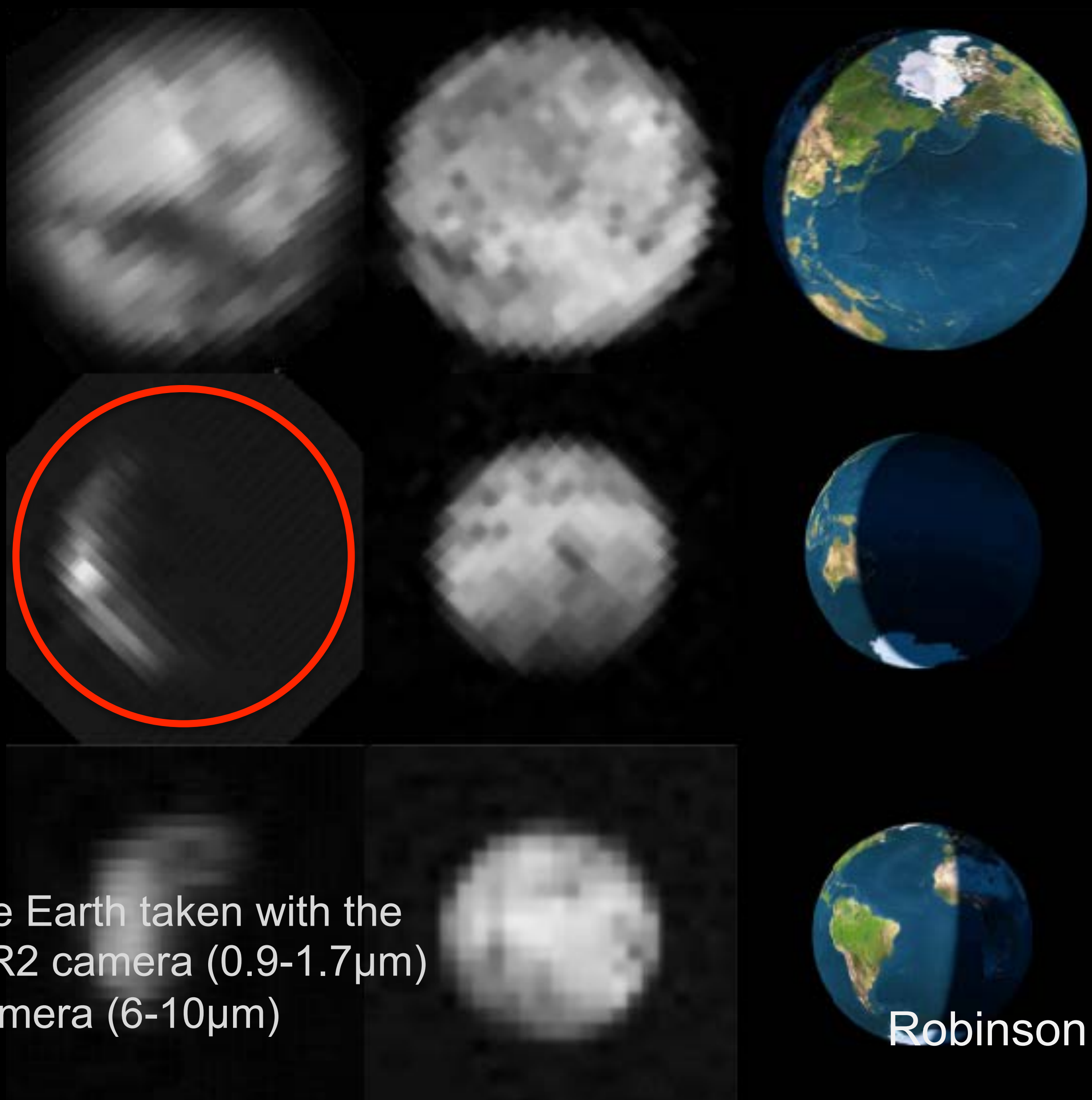


Detecting Surface Liquid



Stephan et al., 2010

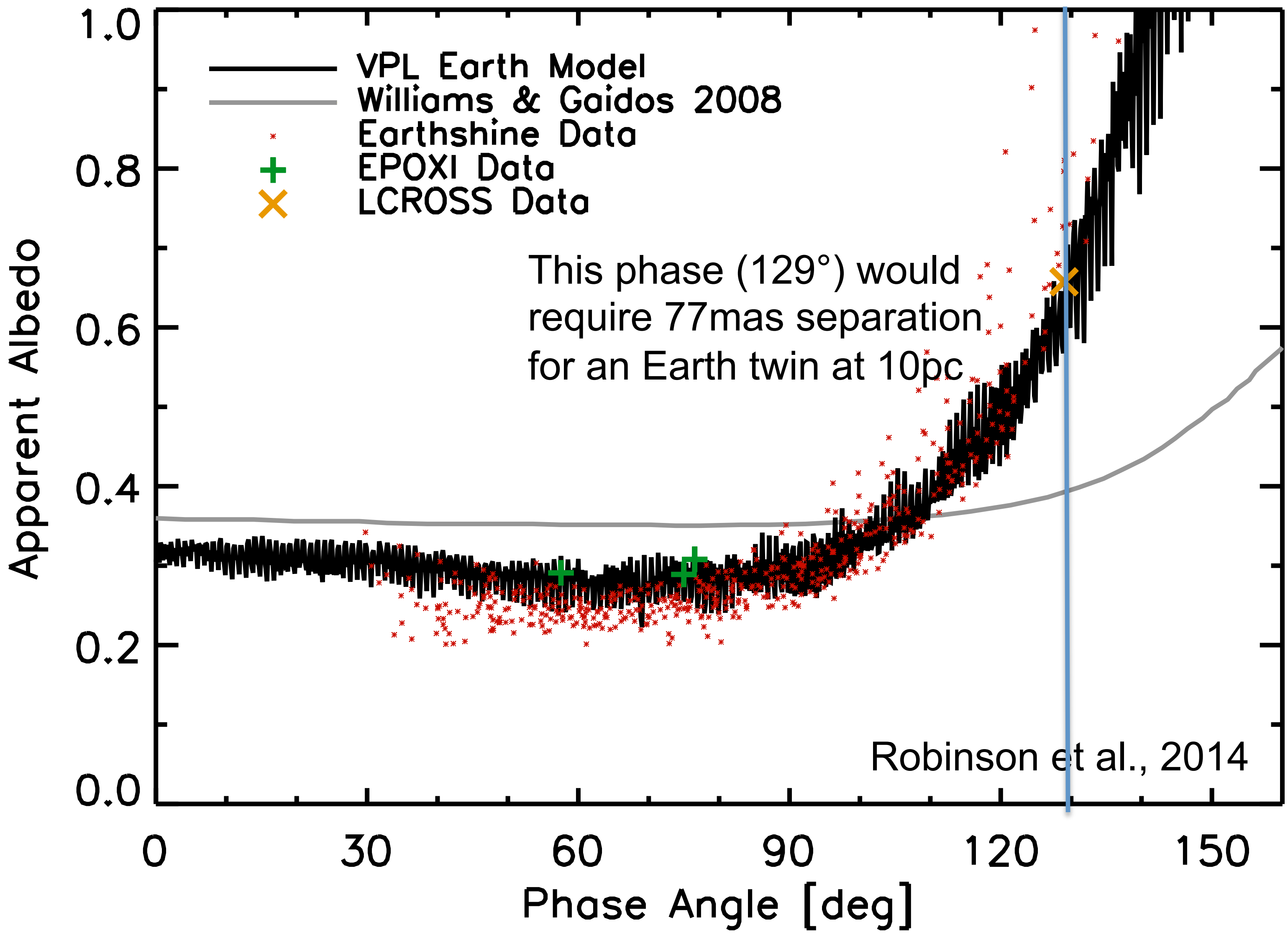
LCROSS Observations of Earth Glint



Images of the Earth taken with the LCROSS NIR2 camera (0.9-1.7μm) and MIR1 camera (6-10μm)

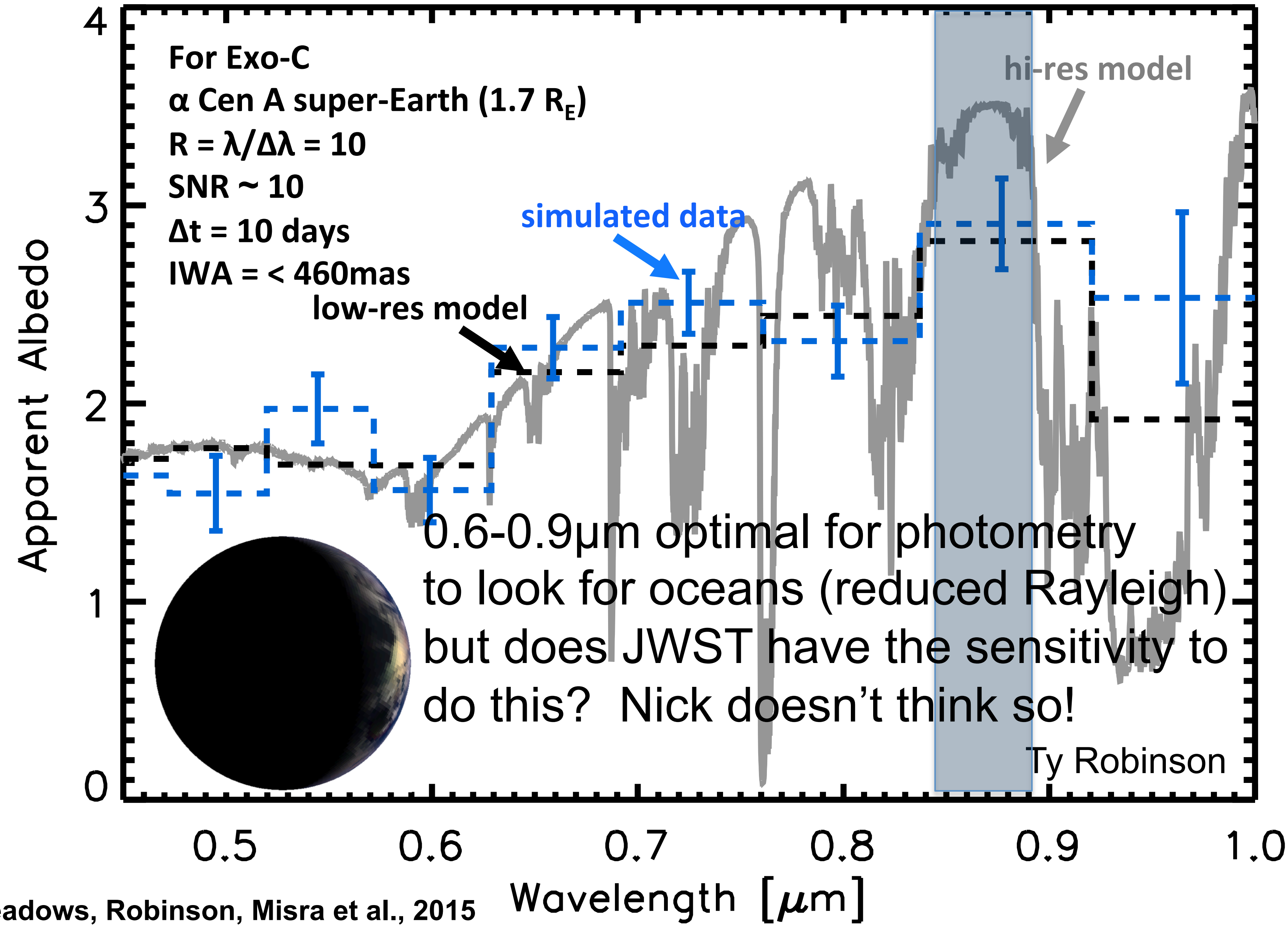
Robinson et al., 2014

LCROSS Data Confirm Glint Predictions



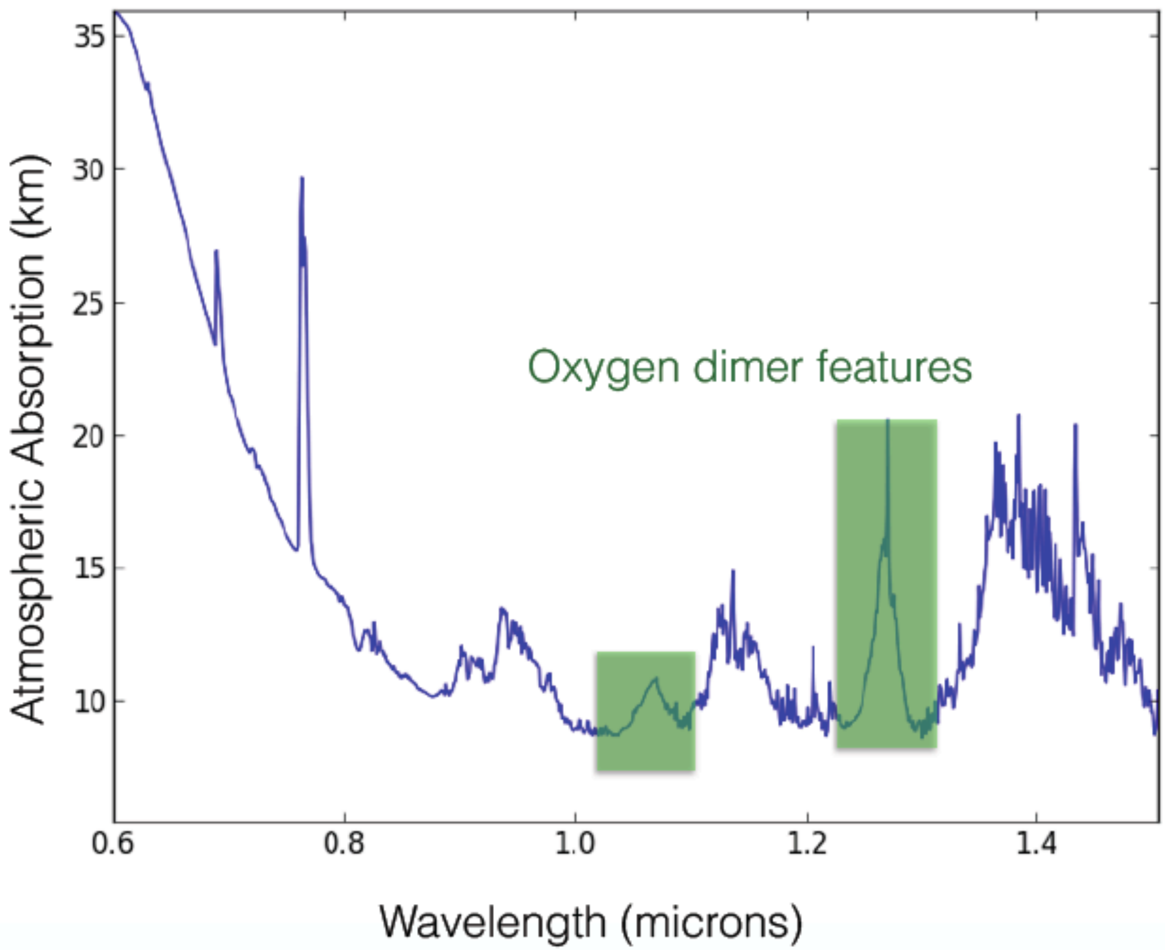
Robinson et al., 11:30am Today in Salon A1!

Detecting Glint for an Exo-Earth



Meadows, Robinson, Misra et al., 2015

O_4 in Transit Transmission



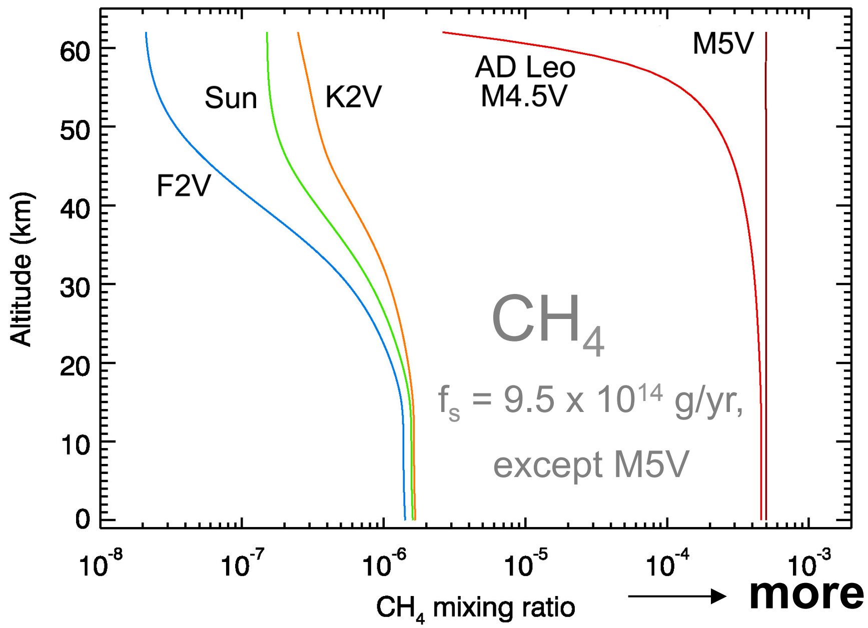
JWST may be able to detect (SNR > 3) the 1.06um O_4 and 1.27um O_2 features for an Earth-like planet orbiting an M5 dwarf 5pc away.

IF we can get every transit in the mission lifetime or IF the sensitivity is better than expected!

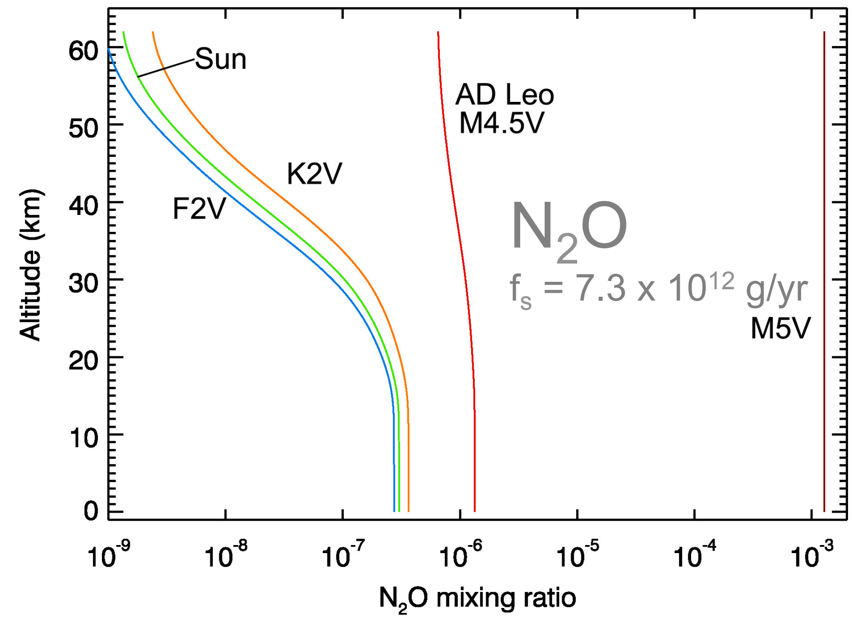
The oxygen A band would likely not be detectable (1.1-sigma), even in the cloud-free case.

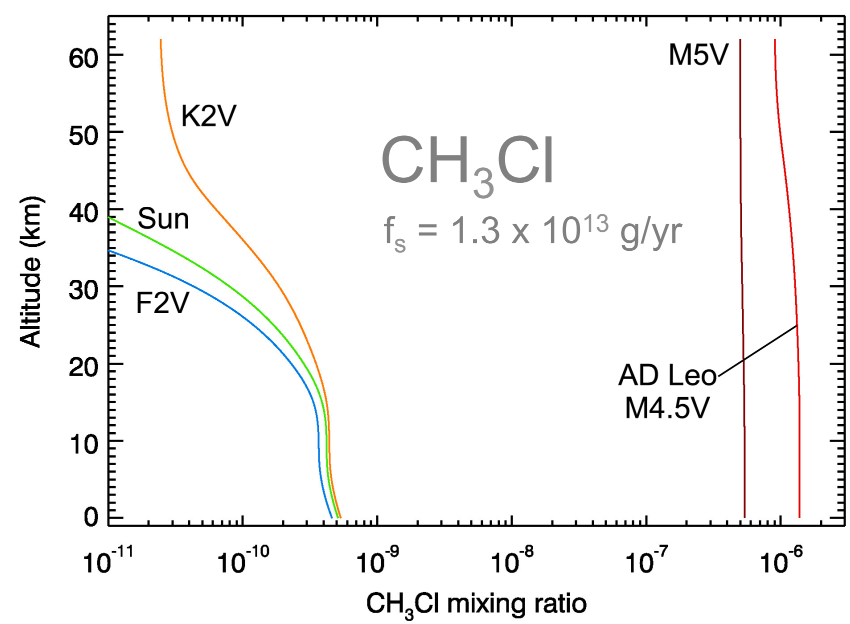
Misra, Meadows, Crisp, Claire (2014)

Atmospheric Chemistry Around M Dwarfs



Segura et al., 2003, 2005

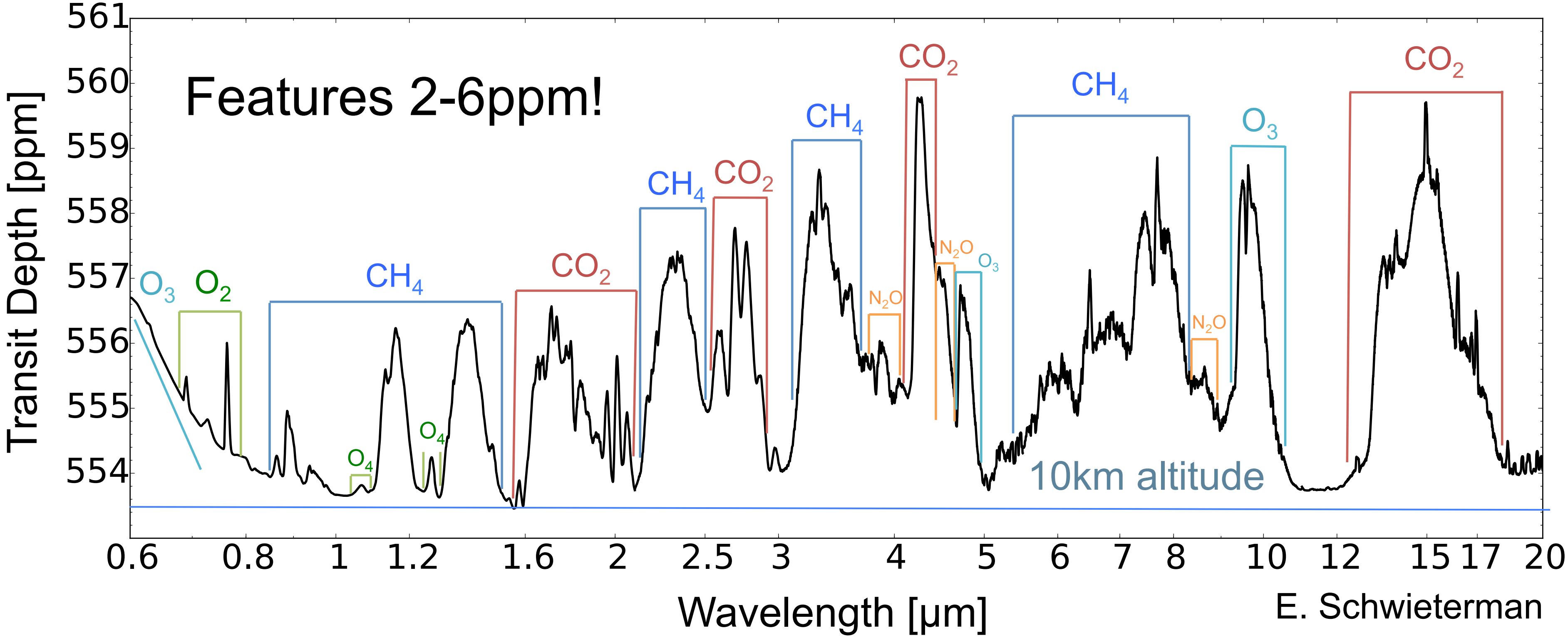




- Earth-like planets around cooler stars show enhanced biosignature abundances (Segura et al., 2003, 2005)
    - M stars less effective at O_3 photolysis.

- Enhancements in biosignatures, (including O_3), are *also* seen when an Earth-like planet is moved towards the outer edge of its habitable zone (Grenfell et al., 2006, 2007)

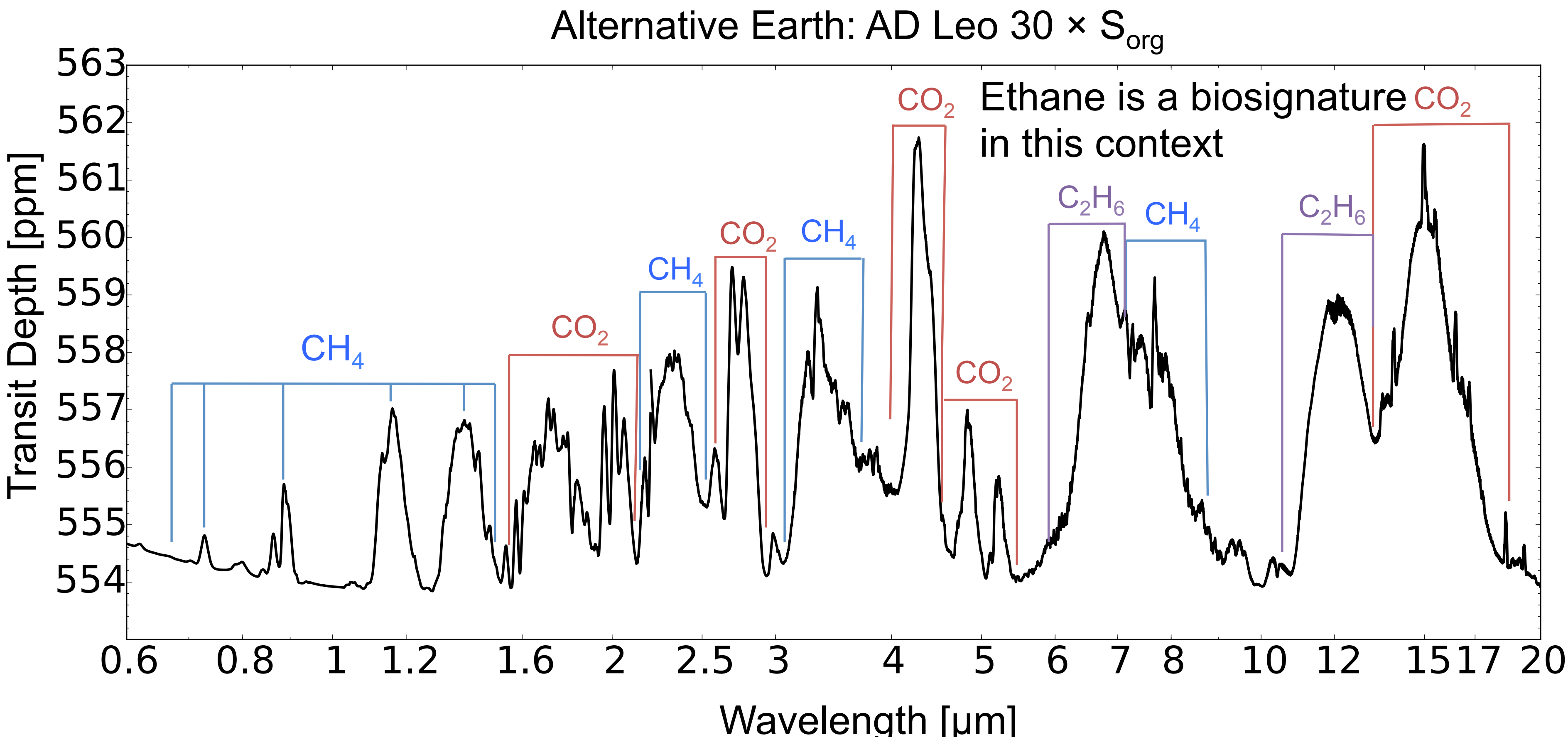
Transmission Spectrum of Earth Orbiting an M Dwarf



Spectrum of self-consistent Earth around an M3.5V from Segura et al. (2005)
Transmisson model (includes refraction) from Misra et al., (2014)

Model is cloud-free, however the deepest altitude reached is 10km, likely above any actual cloud deck. This also explains the lack of water vapor.

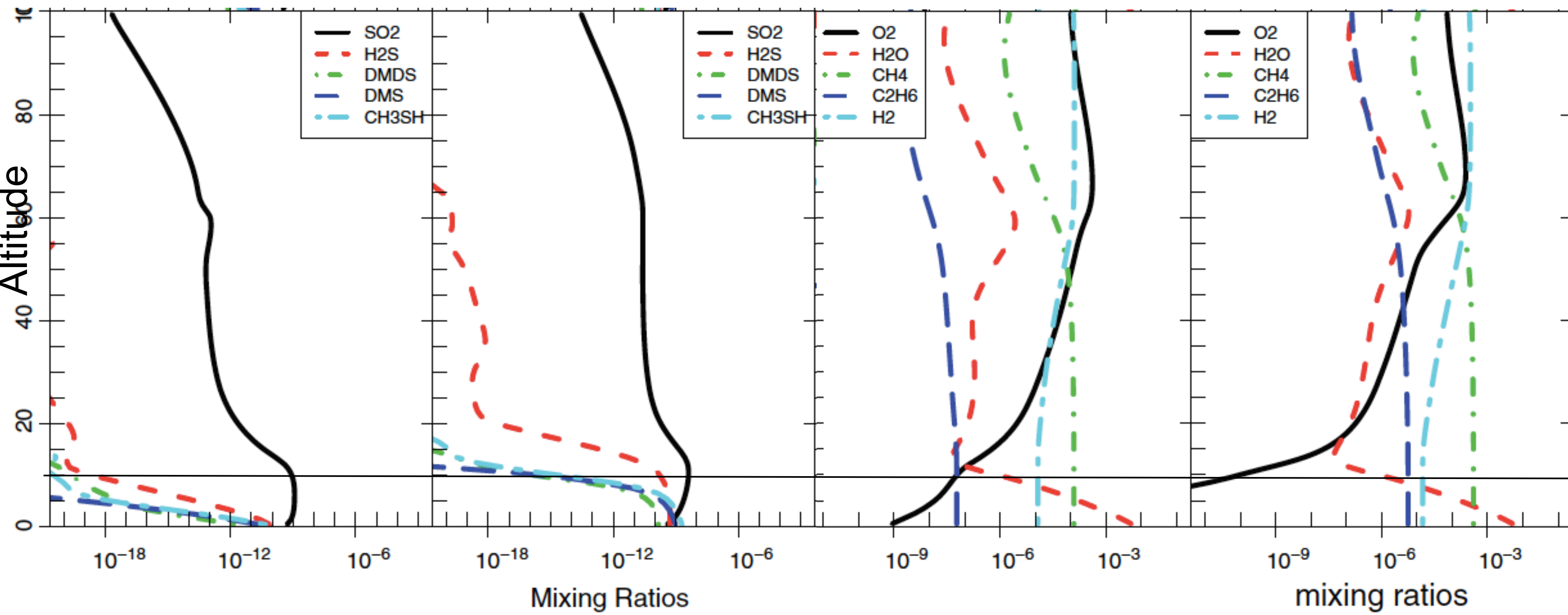
Transmission Spectrum of Early Earth Orbiting an M Dwarf



E. Schwieterman

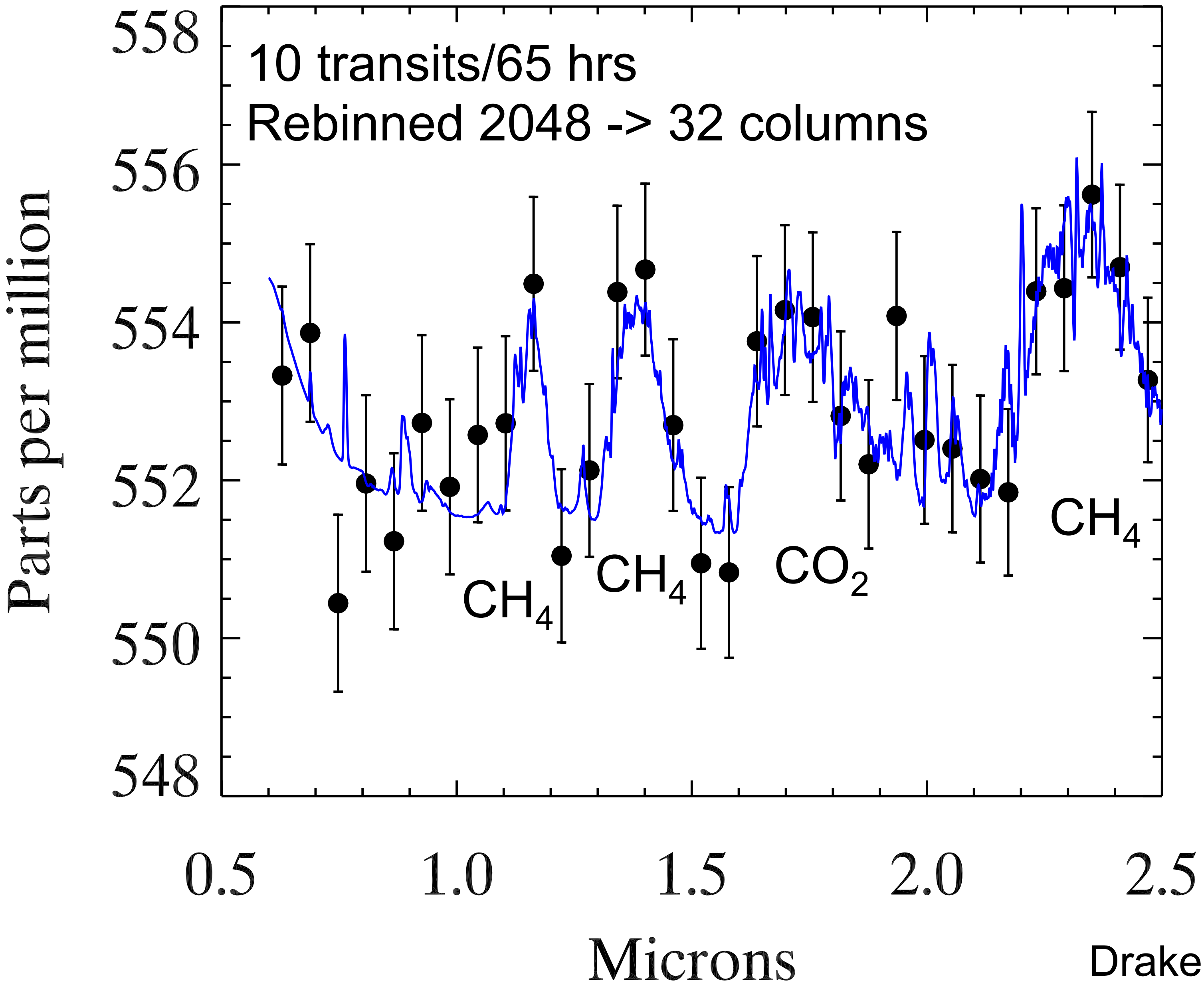
- Self-consistent early Earth (anoxic atmosphere/sulfur biosphere) around M3.5V from Domagal-Goldman et al., (2011)
- Model is cloud and haze-free, and the deepest altitude reached is 10km, likely above any actual cloud deck.
- Distinctive sulfur gases in the troposphere are not seen in the spectrum.

Early Earth Orbiting an M Dwarf



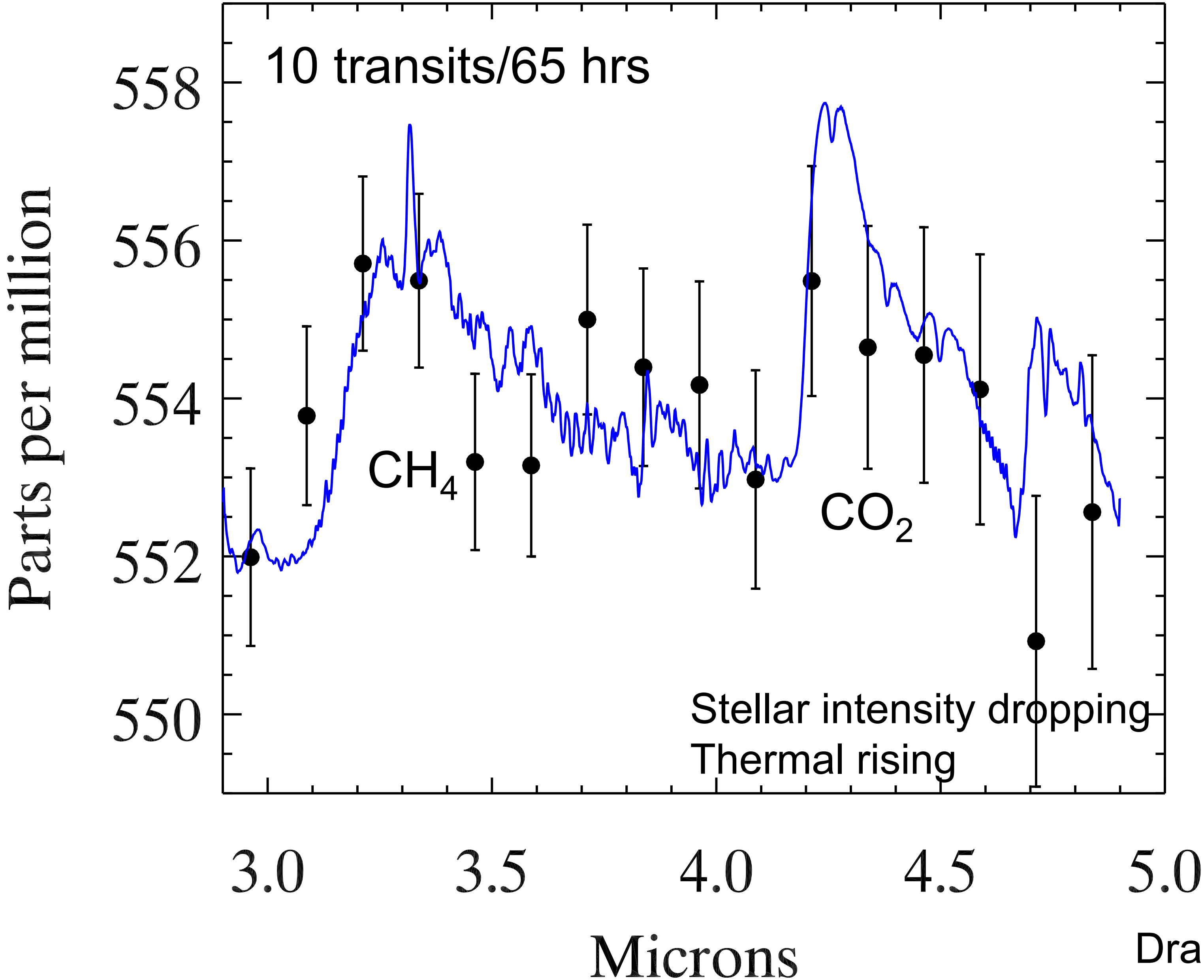
Domagal-Goldman, Meadows et al., 2011

NIRISS Spectrum of M Dwarf Earth



Drake Deming

NIRSPEC Spectrum of M Dwarf Earth



Drake Deming

Summary

- Warm mini-Neptunes (e.g. GJ1214b) should be straightforward targets for JWST, which has the potential to characterize their cloud and atmospheric composition using transmission spectra, secondary eclipse and phase curve measurements.

- JWST will be our first chance to characterize terrestrial planets, including those in the habitable zone of their parent star.

- For HZ planets observations will require ppm sensitivity
  - Refraction may limit observations to the stratospheres
  - Water and tropospheric biosignatures may be difficult to detect.

- Transit observations coadded over several years may be necessary.
  - Systematic noise sources will need to be characterized

- Target selection will be important, as features for these targets will take many transits to appear.

The Virtual Planetary Laboratory

PI: Victoria Meadows (UW)

With Thanks To…

Eric Agol (UW)
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Giada Arney (UW)
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Peter Driscoll (CIW)
Peter Gao (Caltech)
Colin Goldblatt (U. Victoria)
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Suzanne Hawley (UW)
Tori Hoehler (NASA-Ames)
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Ravi Kopparapu (PSU)
Monika Kress (SJSU)
Andrew Lincowski (UW)
Rodrigo Luger (UW)
Jacob Lustig-Yaeger (UW)
Amit Misra (UW)
Niki Parenteau (NASA-Ames)
Ray Pierrehumbert (U. Chicago)
Tom Quinn (UW)
Sean Raymond (Lab. Astrophysique de Bordeaux)
Tyler Robinson (Sagan Fellow – UC Santa Cruz)
Eddie Schwieterman (UW)
Antigona Segura (UNAM)
Janet Seifert (Rice U.)
Holly Sheets (U. Maryland)
Aomawa Shields (NSF/UCLA/Harvard)
Eva Stüeken (UW)
Lucianne Walkowicz (Adler Planetarium)
Robin Wordsworth (Harvard)
Yuk Yung (Caltech)
Kevin Zahnle (NASA-Ames)

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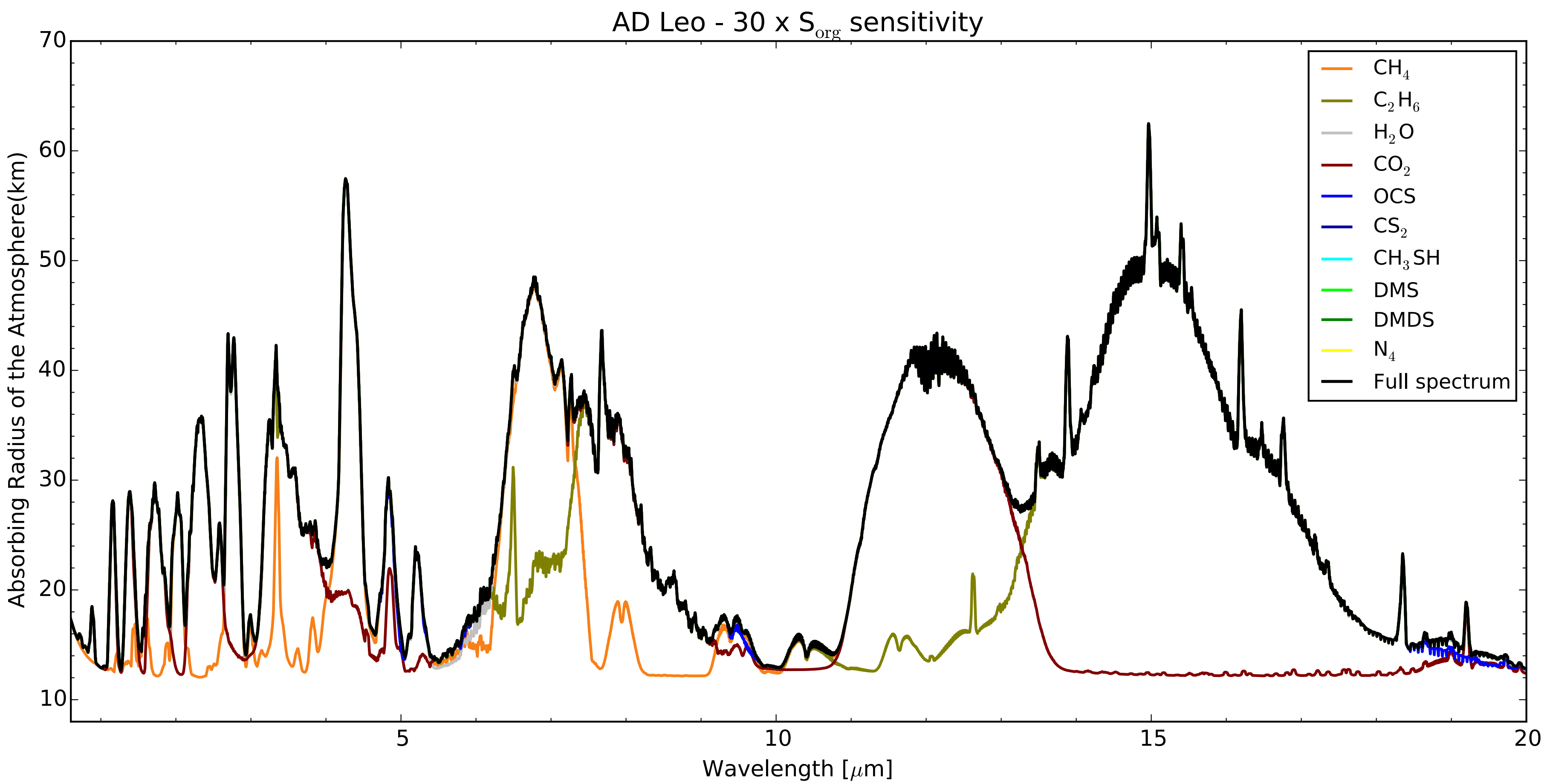
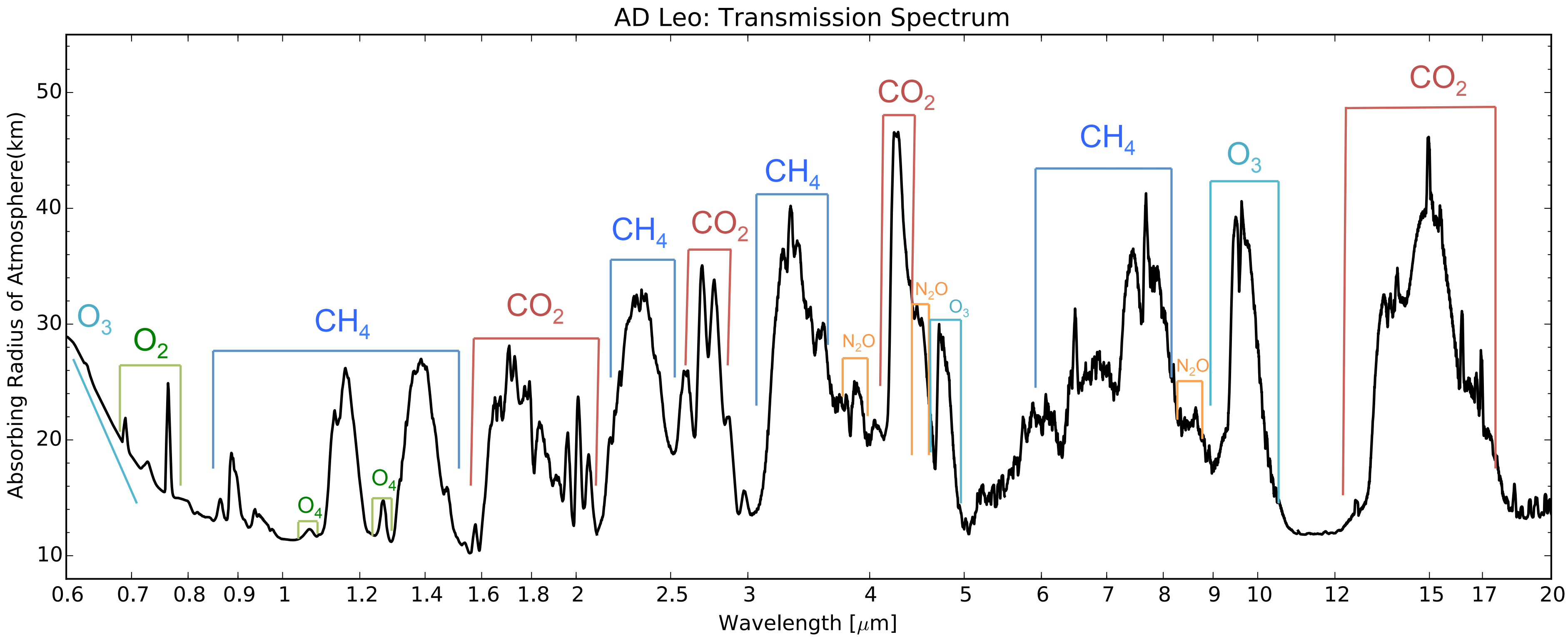
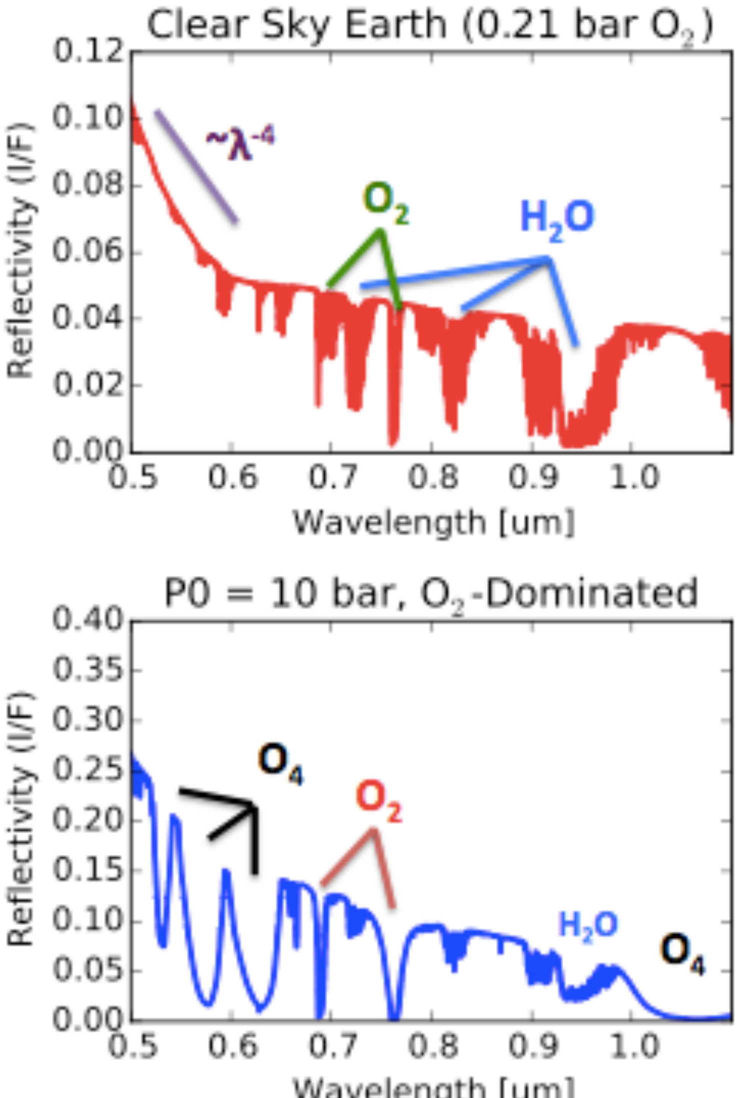
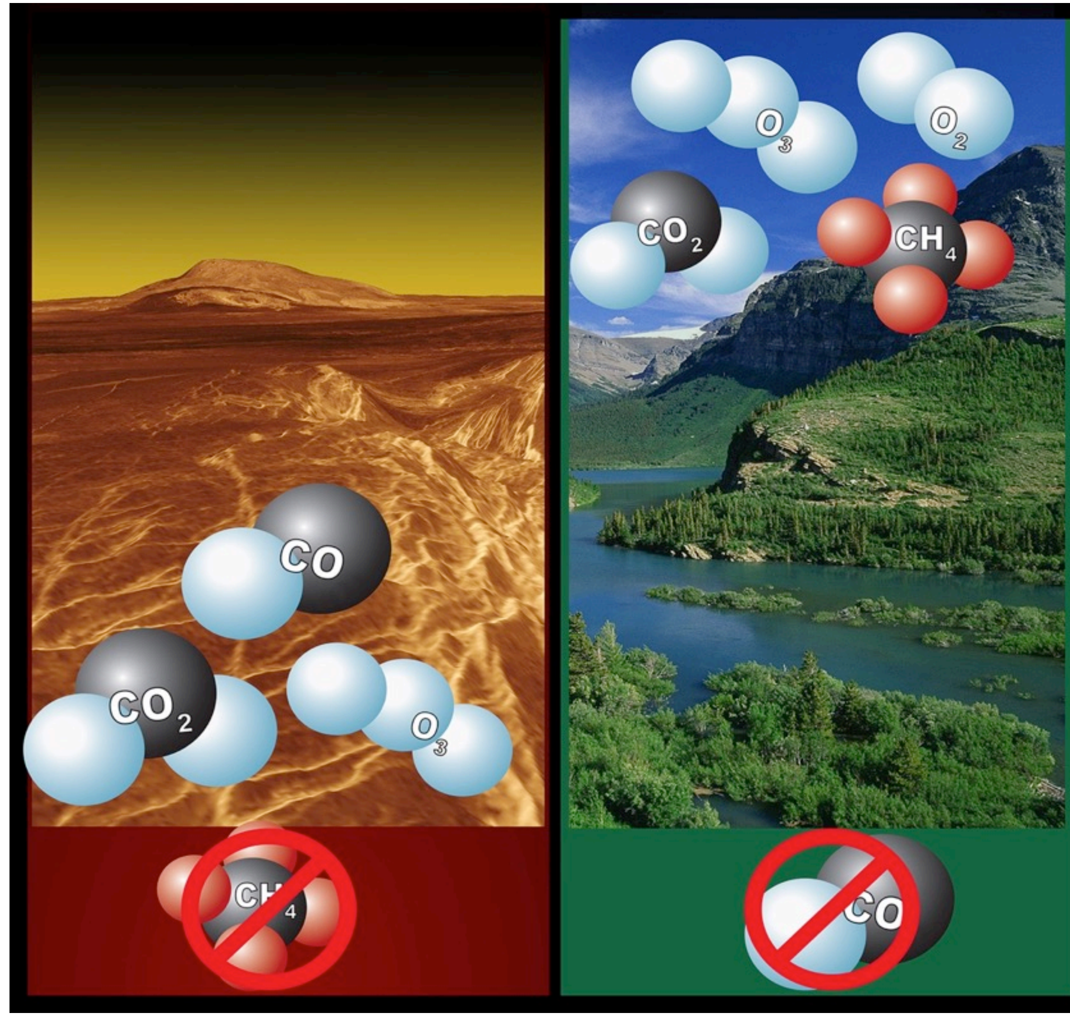


AD Leo - 30 x S_{org} sensitivity
Absorbing Radius of the Atmosphere(km)
70
60
50
40
30
20
10
5
10
15
20
Wavelength [μm]
CH_4
C_2H_6
H_2O
CO_2
OCS
CS_2
CH_3SH
DMS
DMDS
N_4
Full spectrum


AD Leo: Transmission Spectrum
Absorbing Radius of Atmosphere(km)
Wavelength [μm]
O_3
O_2
CH_4
O_4
O_4
CO_2
CH_4
CO_2
CH_4
N_2O
CO_2
N_2O
O_3
CH_4
N_2O
O_3
CO_2

Other gases may show up false positives for life





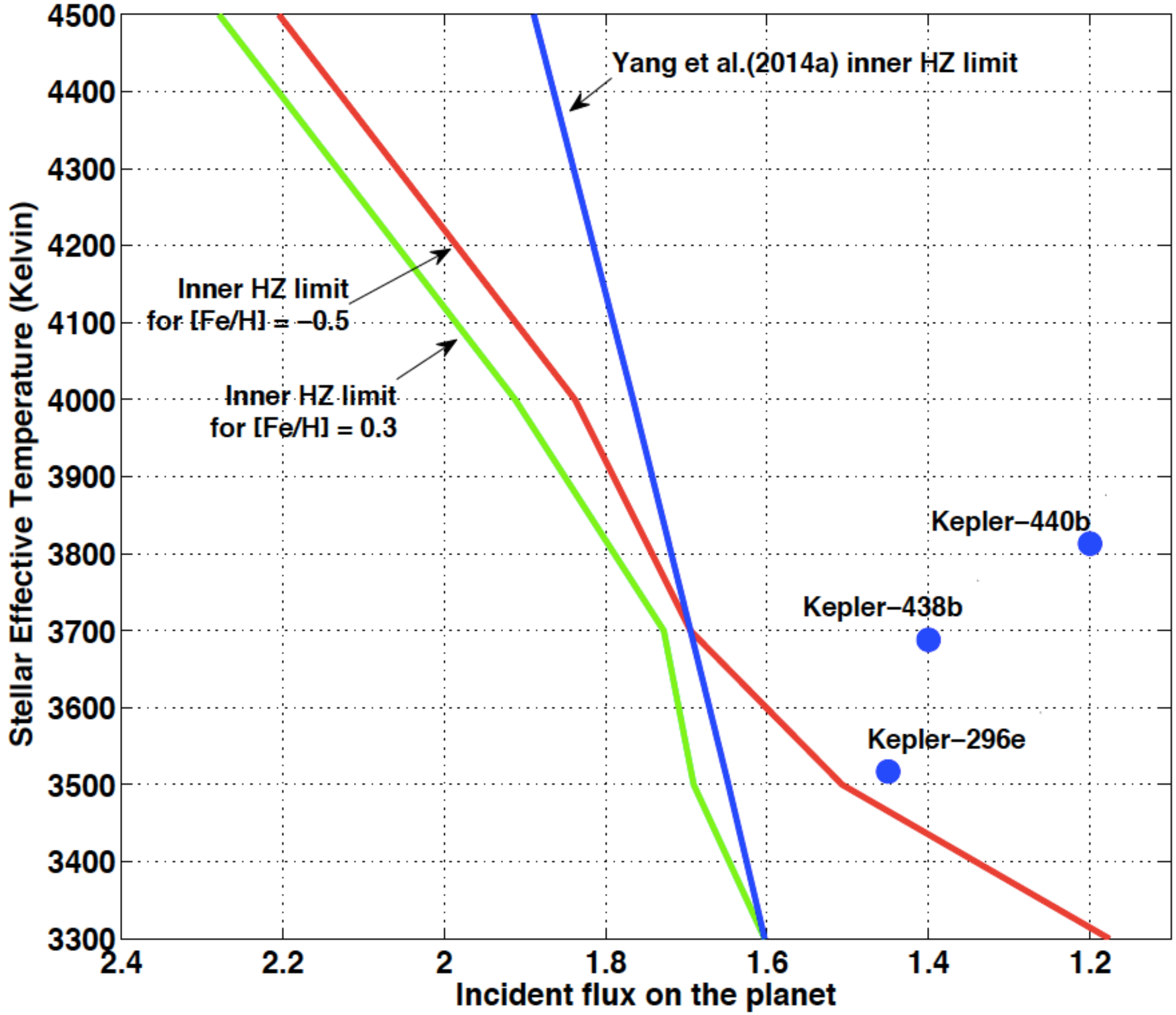
Domagal-Goldman et al., 2014

Schwieterman et al., in prep

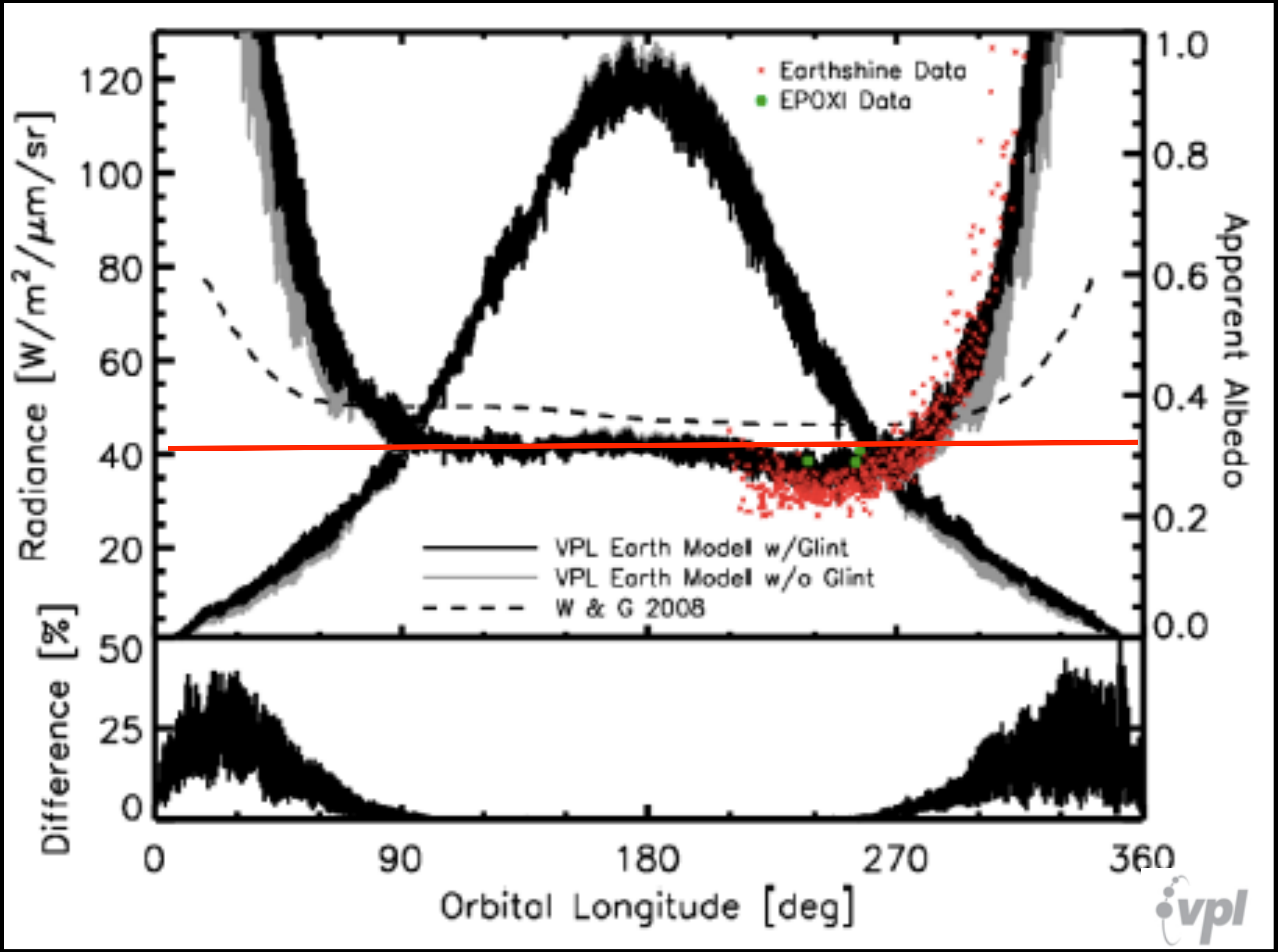
Dimers may indicate High-O_2 from atmospheric escape

Lack of methane or presence of CO may indicate O_2 from photolysis

Extreme Habitability



Glint Predictions From The VPL Earth Model



http://vpl.astro.washington.edu/spectra/planetary/earth_orbit.htm

Robinson, Meadows, & Crisp (2010)