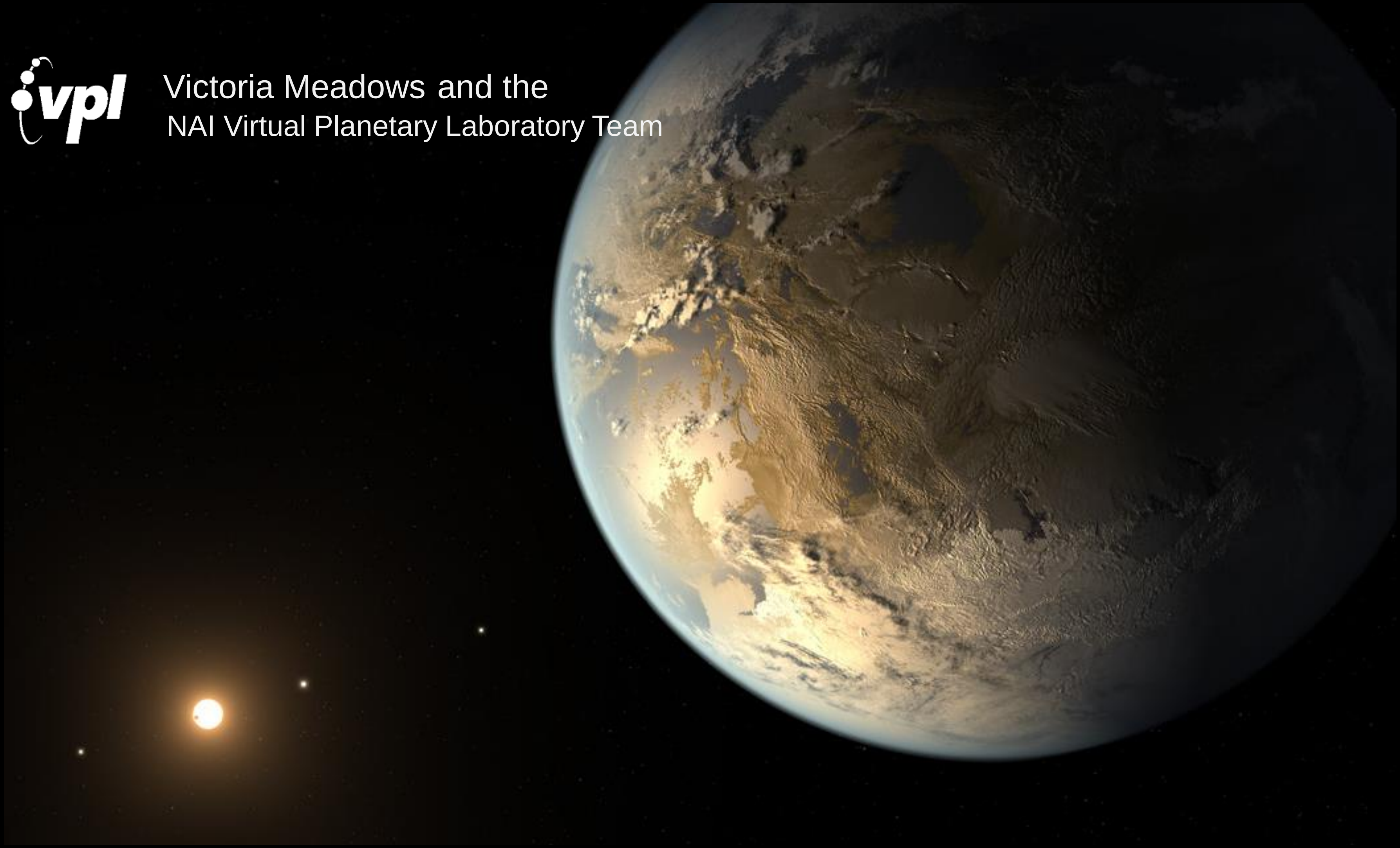
Reflections on Oxygen as a Biosignature

Victoria Meadows and the
NAI Virtual Planetary Laboratory Team



Photosynthesis is Earth's Dominant Metabolism

The first photosynthesizers likely evolved 3.8-3.4 Gya.
Cyanobacteria - oxygenic photosynthesizers - may have evolved < 2.7Gya.
Cyanobacteria are responsible for the large O_2 fraction in our atmosphere
Our abundant O_2 is the most detectable sign of life on this planet
It is also considered the most robust against false positives
It's likely to be the first biosignature we try to detect.

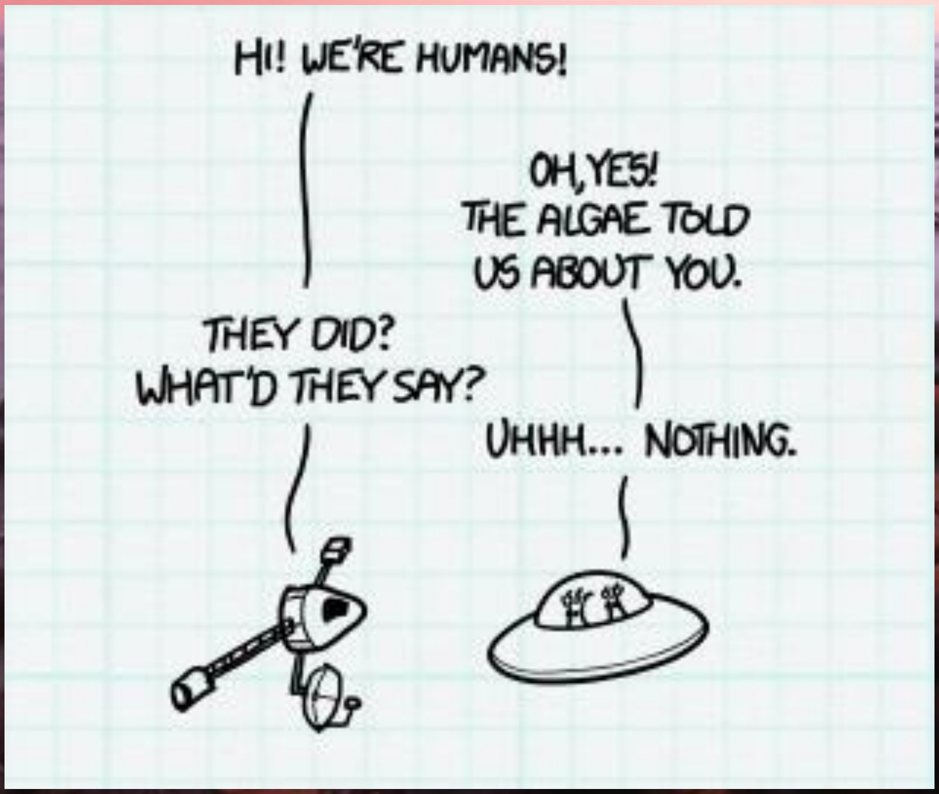
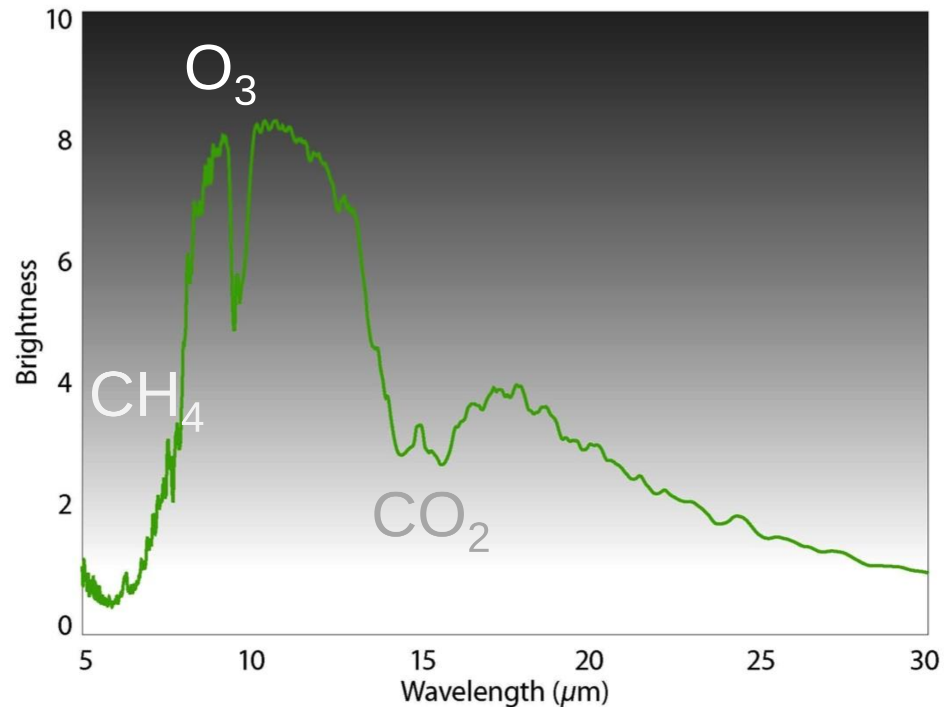


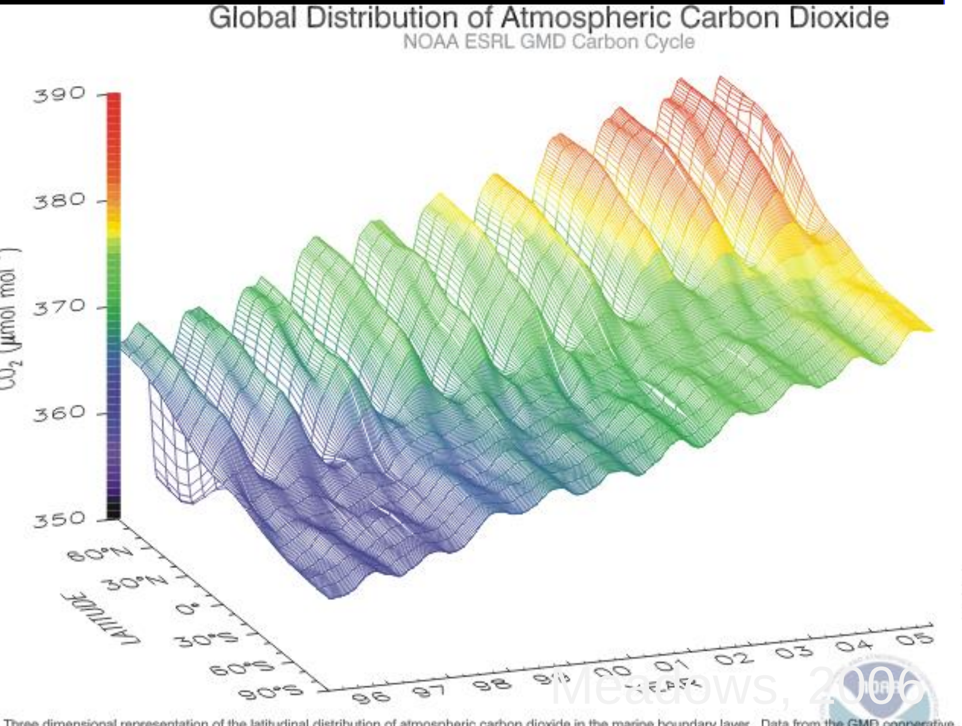
Photo: Frans Lanting

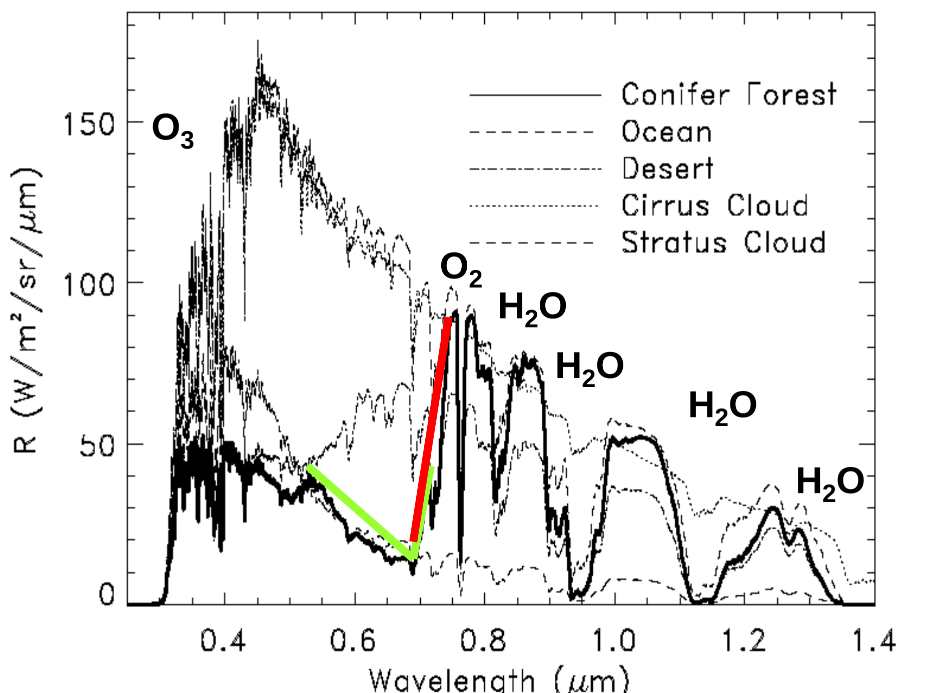
Photosynthetic Biosignatures

- Photosynthesis has globally modified the Earth's:
  - Atmosphere: Abundant O_2 (and O_3) in the presence of N_2 and an ocean.
  - Surface: Reflectivity red edge from vegetation.
  - Temporal behavior: Seasonal CO_2 cycle, seasonal surface albedo changes.

Meadows, 2006

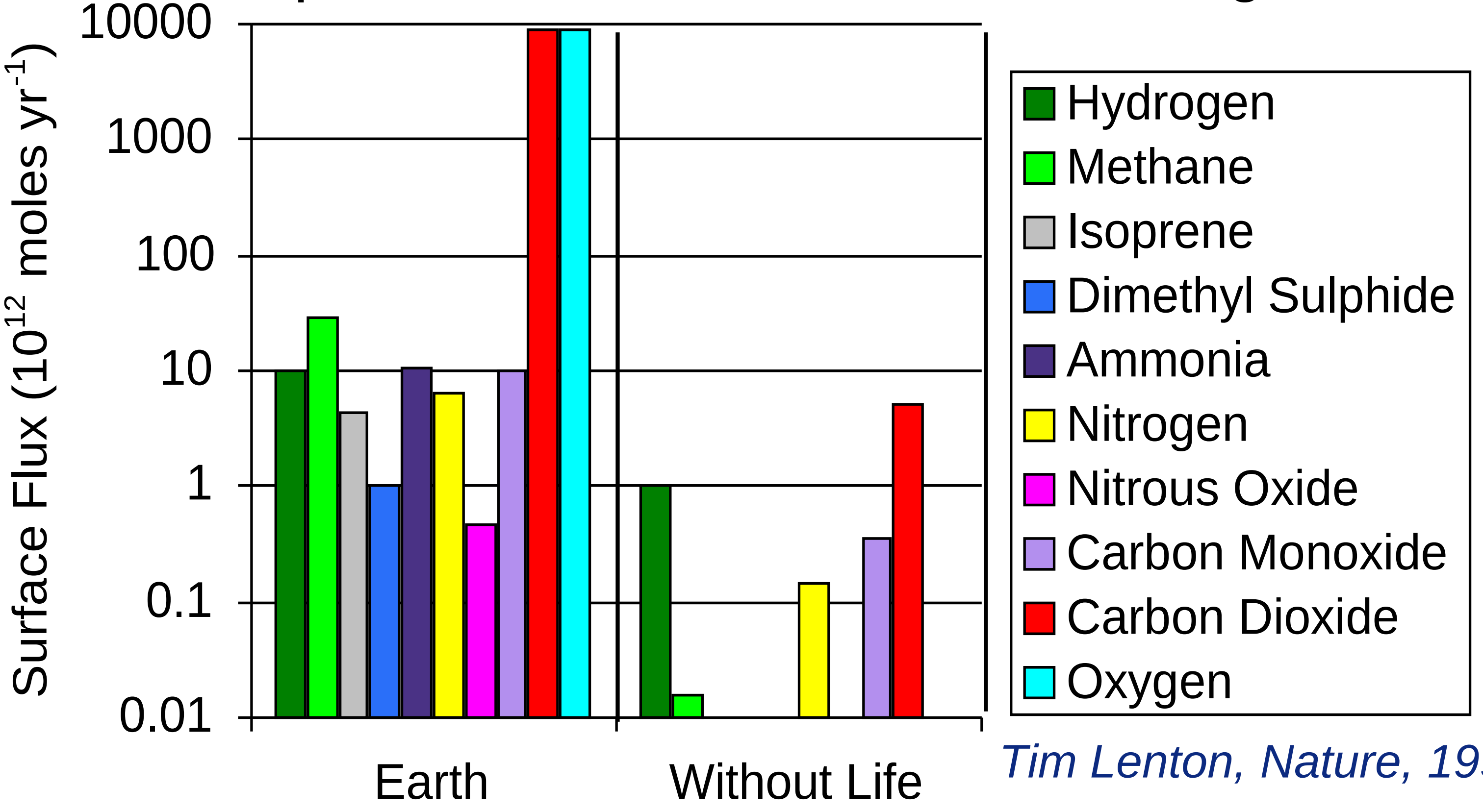






Biological Modification of the Atmosphere

Life is responsible for a LOT of our surface gas fluxes



Tim Lenton, Nature, 1998

- Life can modify the atmosphere via production of gaseous by-products of metabolism (e.g. O_2 from photosynthesis).
- Because there is an active source, life's gases are often seen in the atmosphere in *chemical disequilibrium.*

Earth’s Disequilibrium Biosignatures

TABLE 1 Constituents of the Earth’s atmosphere (volume mixing ratios)

Molecule	Standard abundance (ground-truth Earth)	Galileo value*	Thermodynamic equilibrium value Estimate 1†	Estimate 2‡
N_2	0.78		0.78	
O_2	0.21	0.19 ± 0.05	0.21§	
H_2O	0.03–0.001	0.01–0.001	0.03–0.001	
Ar	9×10^{-3}		9×10^{-3}	
CO_2	3.5×10^{-4}	$5 \pm 2.5 \times 10^{-4}$	3.5×10^{-4}	
CH_4	1.6×10^{-6}	$3 \pm 1.5 \times 10^{-6}$	$< 10^{-35}$	10^{-145}
N_2O	3×10^{-7}	$\sim 10^{-6}$	2×10^{-20}	2×10^{-19}
O_3	10^{-7}–10^{-8}	$> 10^{-8}$	6×10^{-32}	3×10^{-30}

* Galileo values for O_2, CH_4 and N_2O from NIMS data; O_3 estimate from UVS data.

† From ref. 16 (P, 1 bar; T, 280 K).

‡ From ref. 17 (P, 1 bar; T, 298 K).

§ The observed value; it is in thermodynamic equilibrium only if the under-oxidized state of the Earth’s crust is neglected.

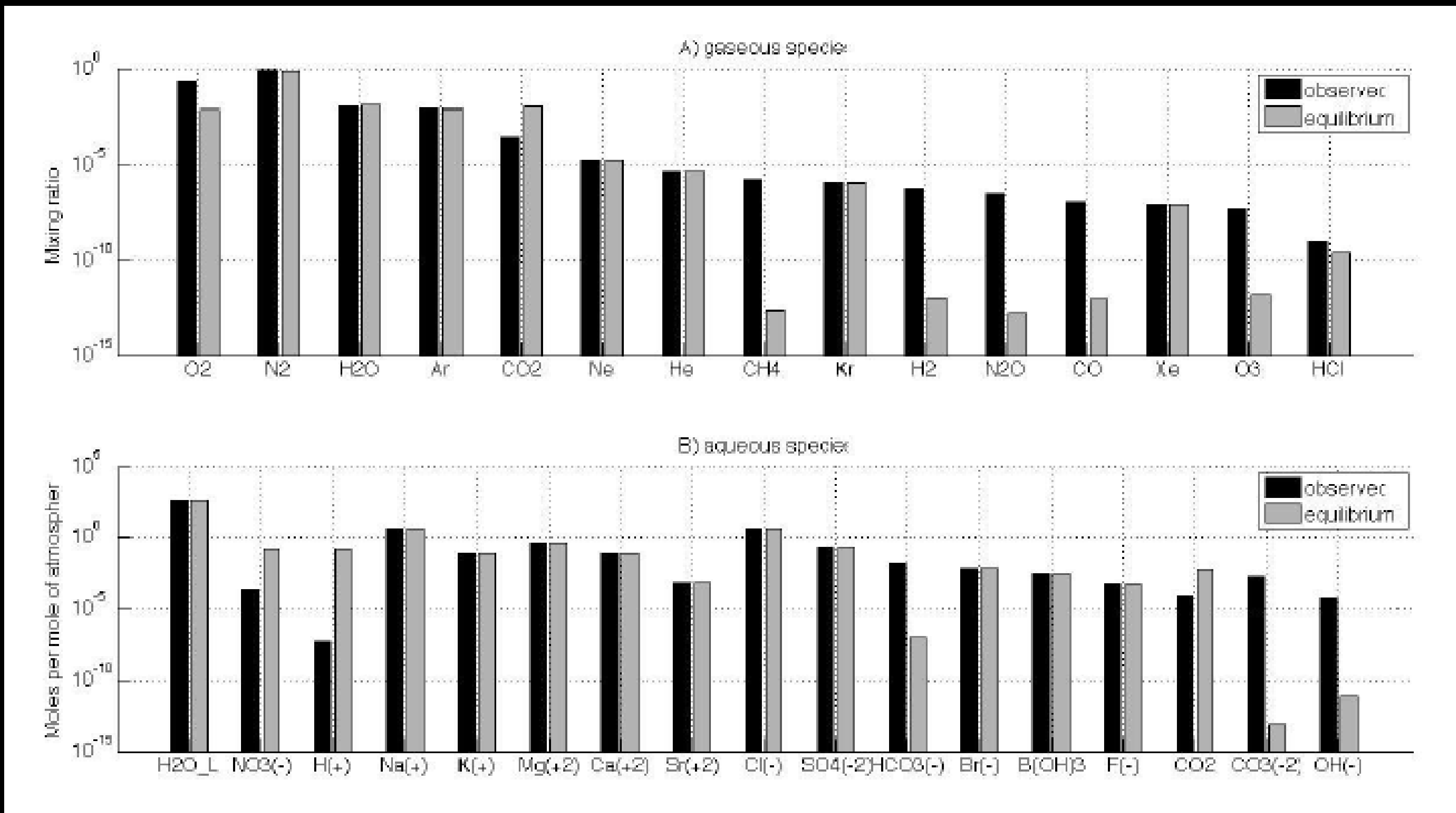
Sagan et al., 1993

Methane observed in our oxygen rich atmosphere is out of thermodynamic equilibrium by many orders of magnitude.

Earth's Disequilibrium Biosignatures

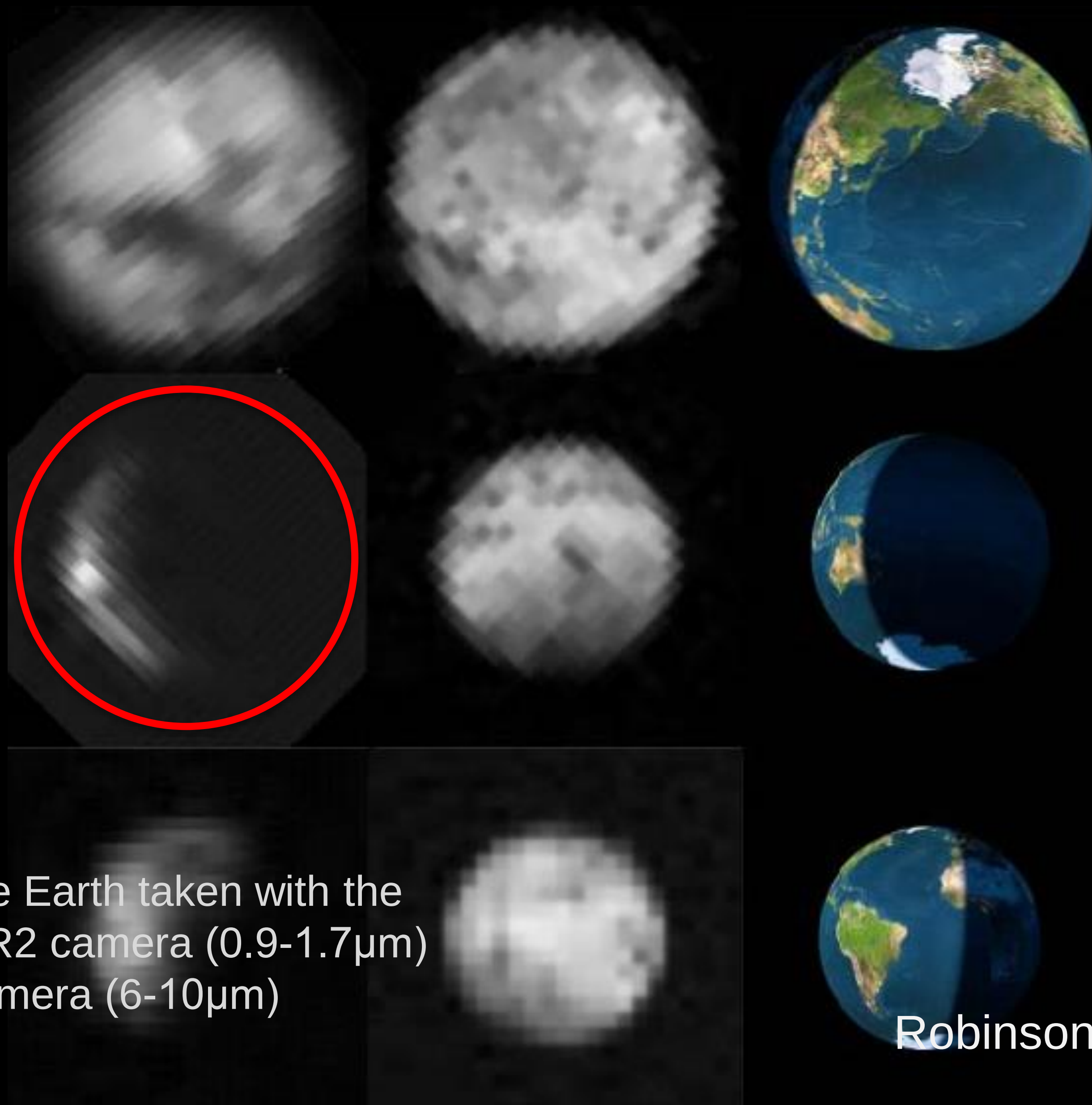
Earth's thermodynamic disequilibrium is biogenic in origin, and the main contribution is the coexistence of N_2, O_2 and liquid water instead of more stable nitrate.

$$2N_2(g) + 5O_2(g) + H_2O(l) \rightleftharpoons 4H^+(aq) + 4NO_3^-(aq)$$



Krissansen-Totton et al., in review

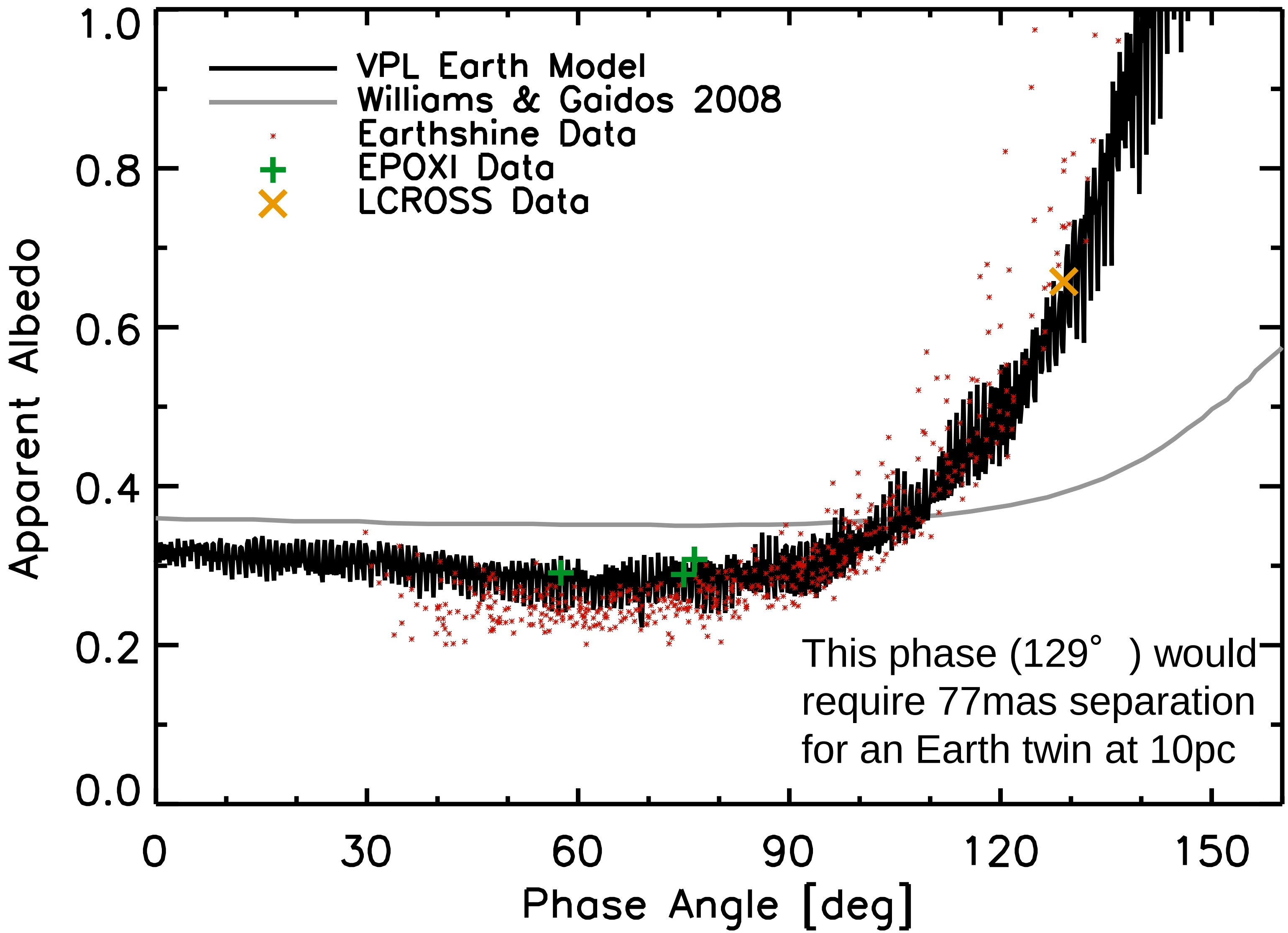
Detecting Earth's Ocean via Glint



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

Robinson et al., 2014

Earth's Glint Most Detectable at Phases > 90°

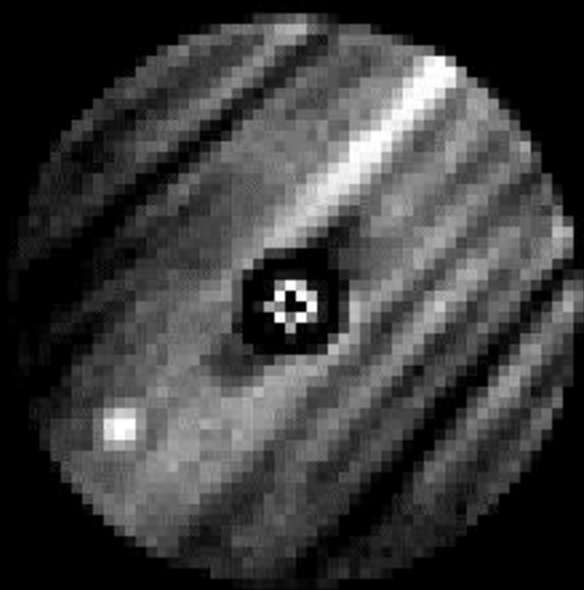


Robinson et al., 2014.

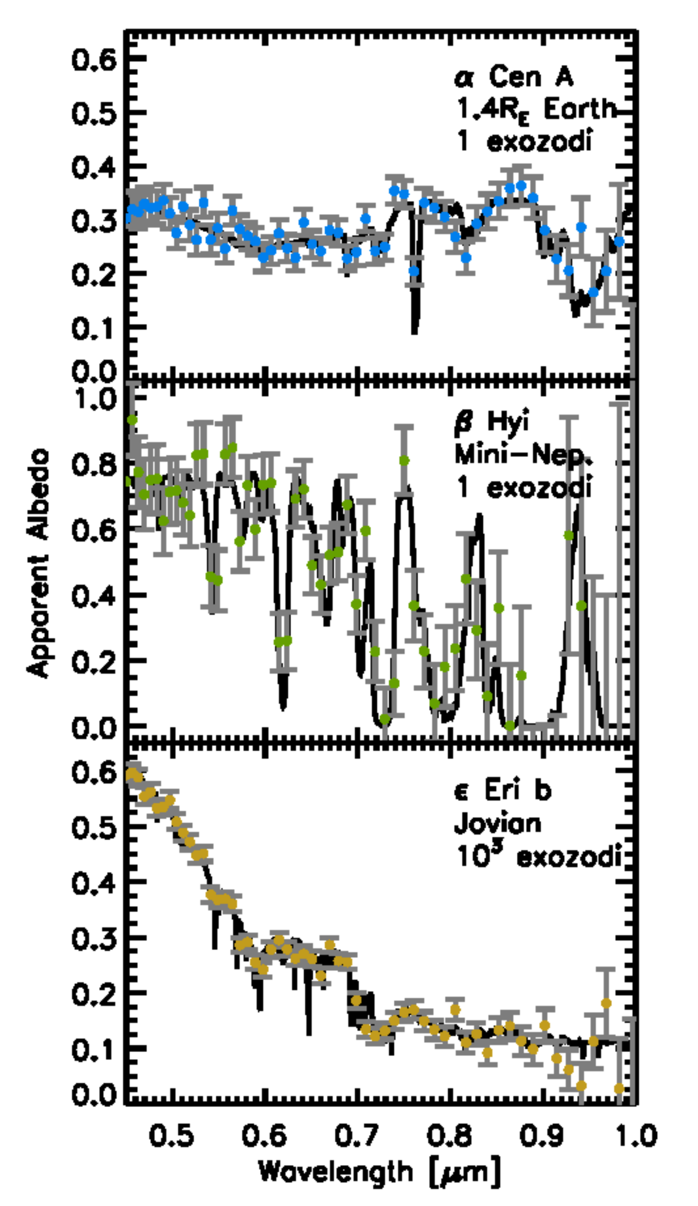
Earthshine data courtesy E. Palle

Exo-C and Alpha Cen A

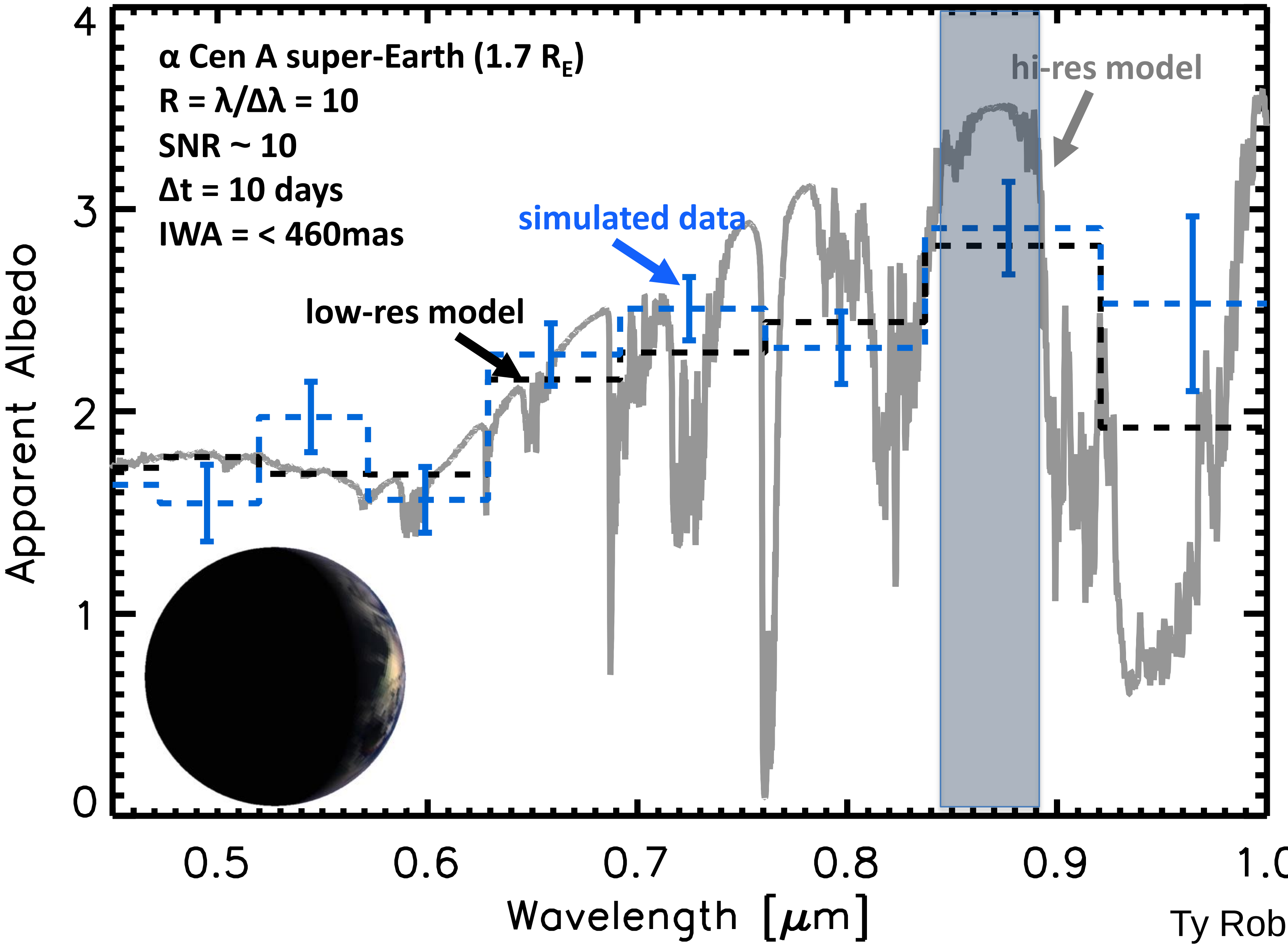
Simulated 5-day V band Exo-C exposure of an Earth analog in the habitable zone of Cen A



In 660 hrs of integration time we can get a spectrum

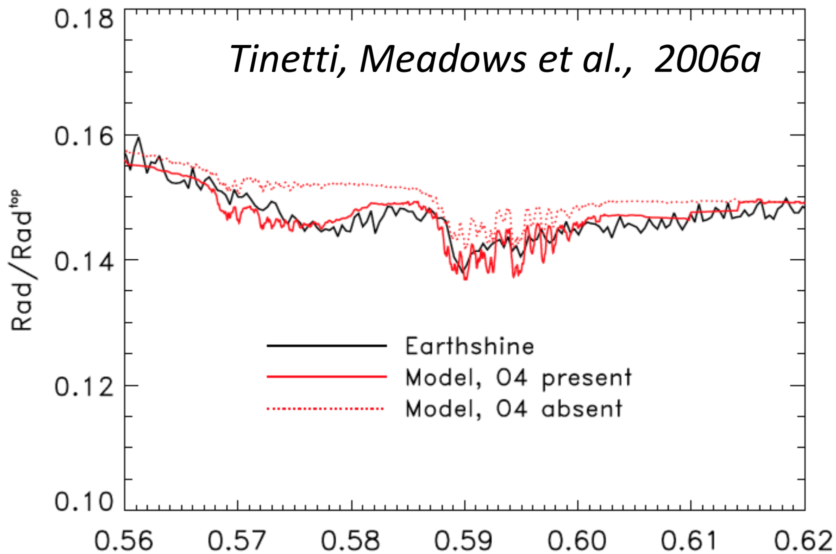


Detecting Glint for Earth orbiting α-Cen A

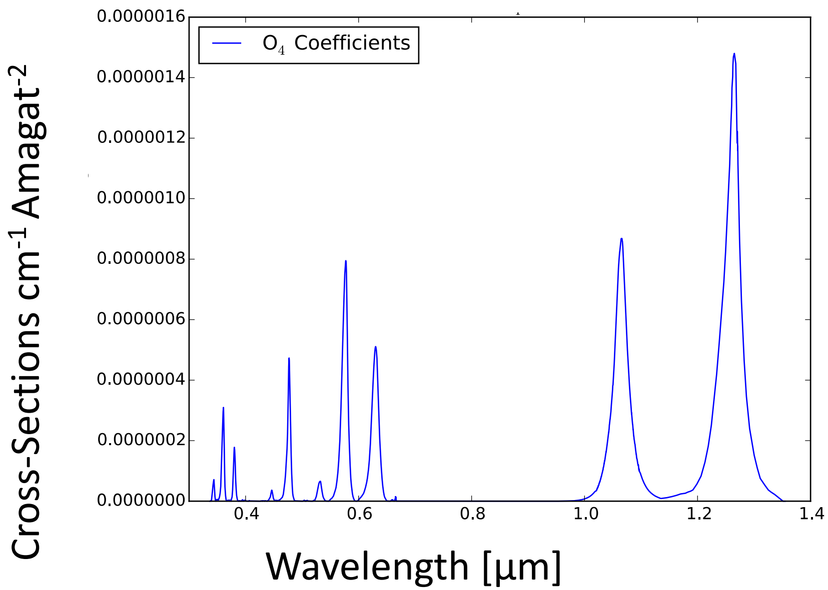


Ty Robinson

The O_4 Molecule in Earth's Disk-Averaged Spectra



O_4 Dimers in the VIS/NIR



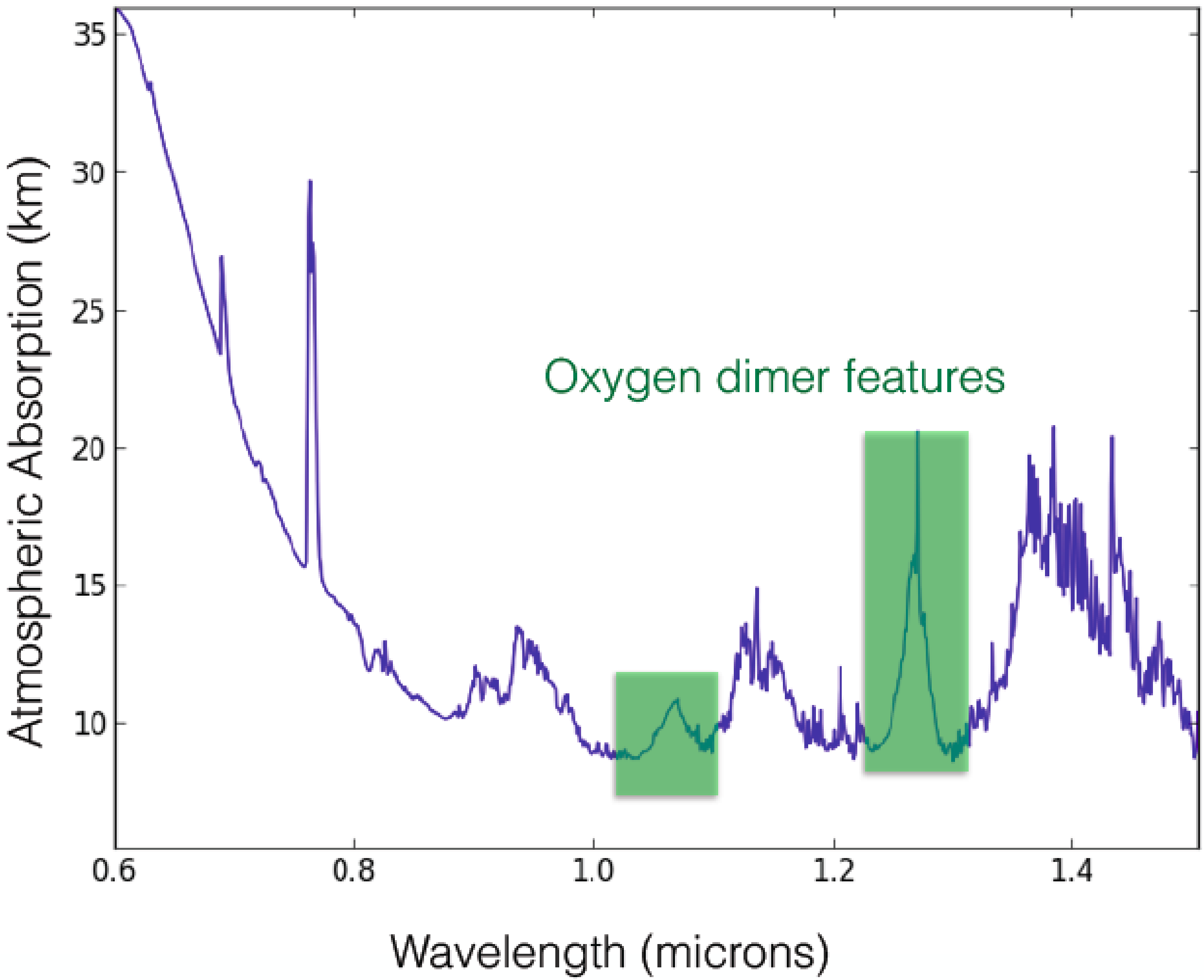
Dimer molecules are bound or quasi-bound states between two molecules (e.g. O_2-O_2 or O_4).

Monomer (O_2) abs ~ density
Dimer (O_4) abs ~ density^2

O_4 absorption is present in Earth's atmosphere (Tinetti et al., 2006; Palle et al, 2009), and would be much stronger in more massive atmospheres

Dimer bands for O_2 exist through the visible and NIR

O_4 in Transit Transmission



Dimer absorption is more sensitive to pressure than the monomers (e.g.O_2), so dimers could be used as pressure gauges.

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

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

Misra et al., 2014

FINDING EXTRATERRESTRIAL LIFE USING GROUND-BASED HIGH-DISPERSION SPECTROSCOPY

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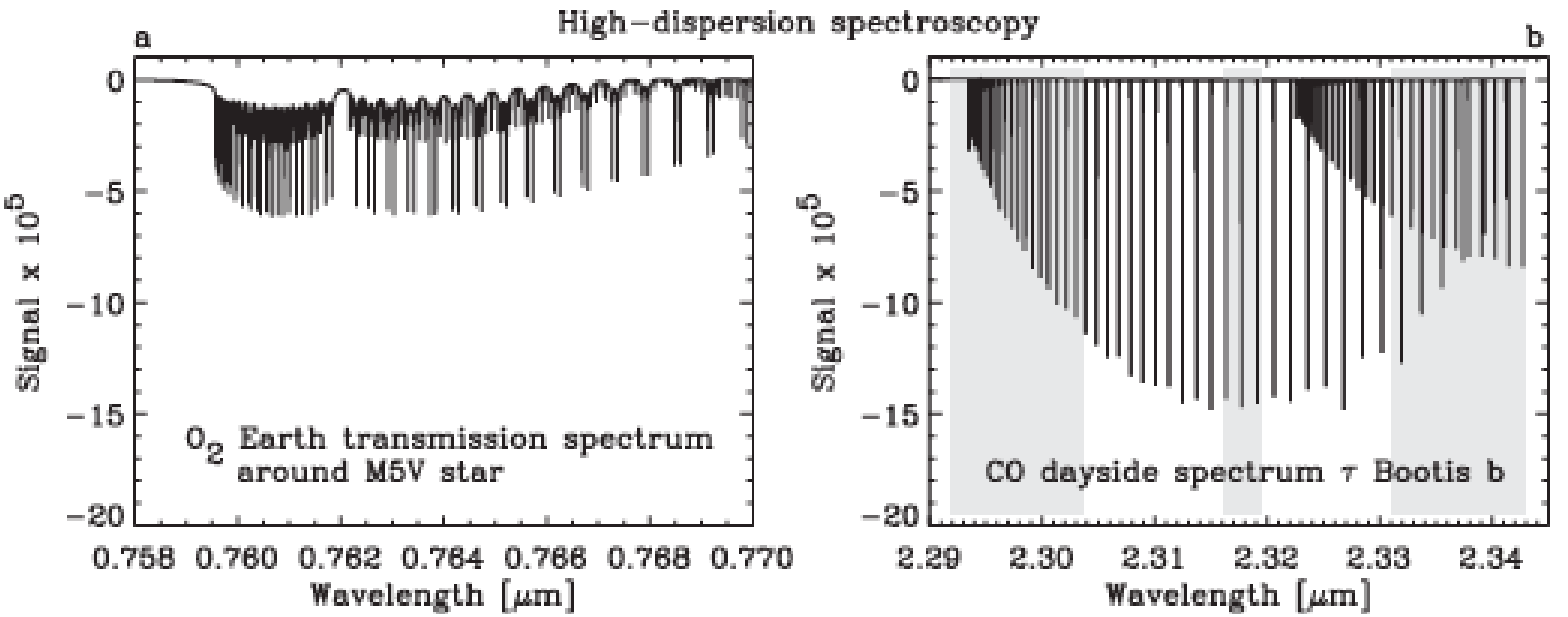
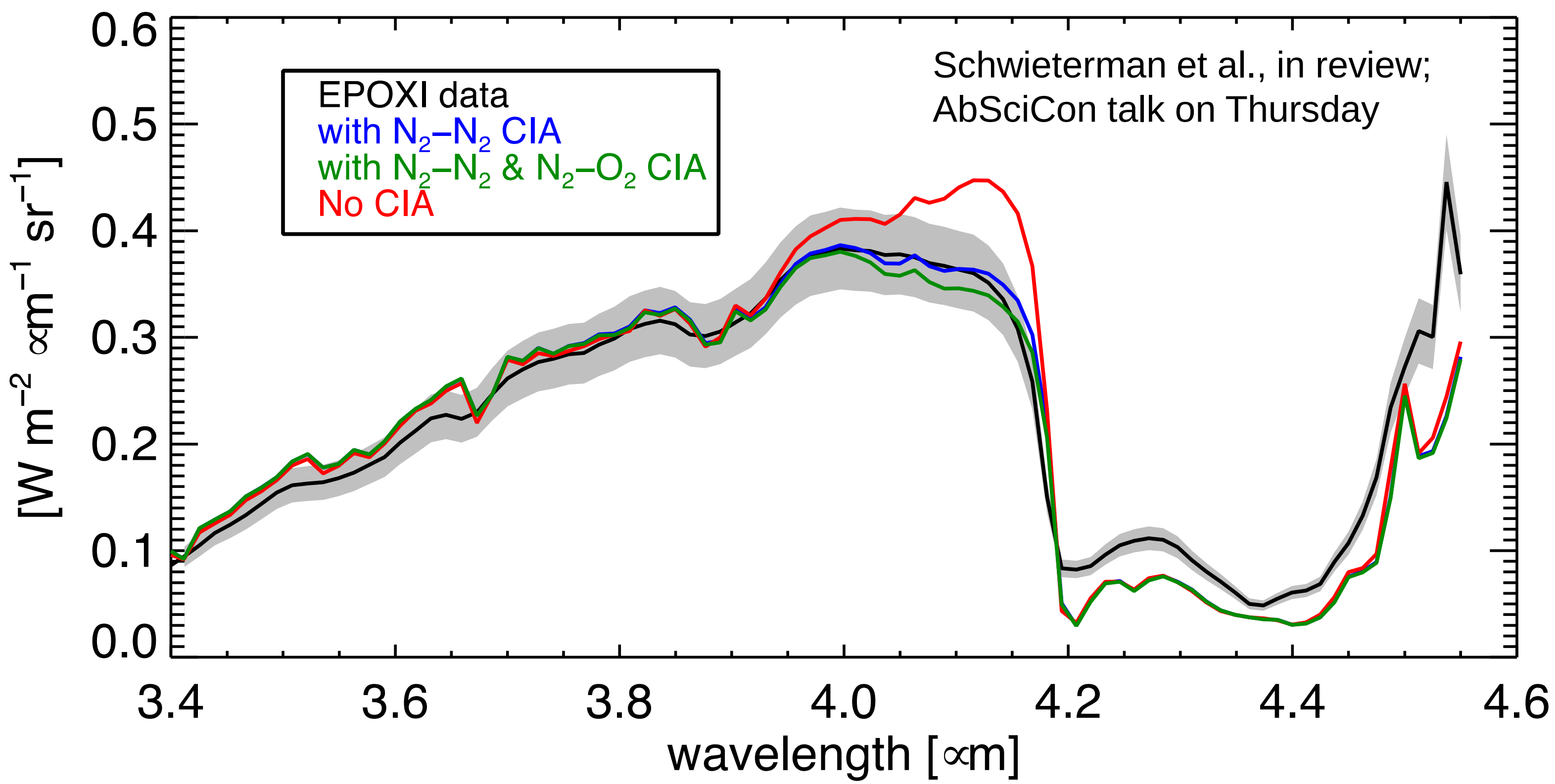


ure 2. Left panel shows the simulated O_2 transmission signal for an Earth-twin transiting an M5 dwarf star. The wavelength range is centered on the oxyge 6 μm *A* band. The transit signal of the bulk of the planet is removed. The right panel shows the model spectrum that best fitted the CO detection in the daysid ctrum of the non-transiting hot Jupiter τ Boötis b (Brogi et al. 2012). The white areas are those wavelength ranges covered by the observations with the Very Larg escope. It shows that the predicted O_2 transmission signal from an Earth-twin in the habitable zone of an M5 red dwarf star is only a factor of three lower than th signal detected by Brogi et al. (2012).

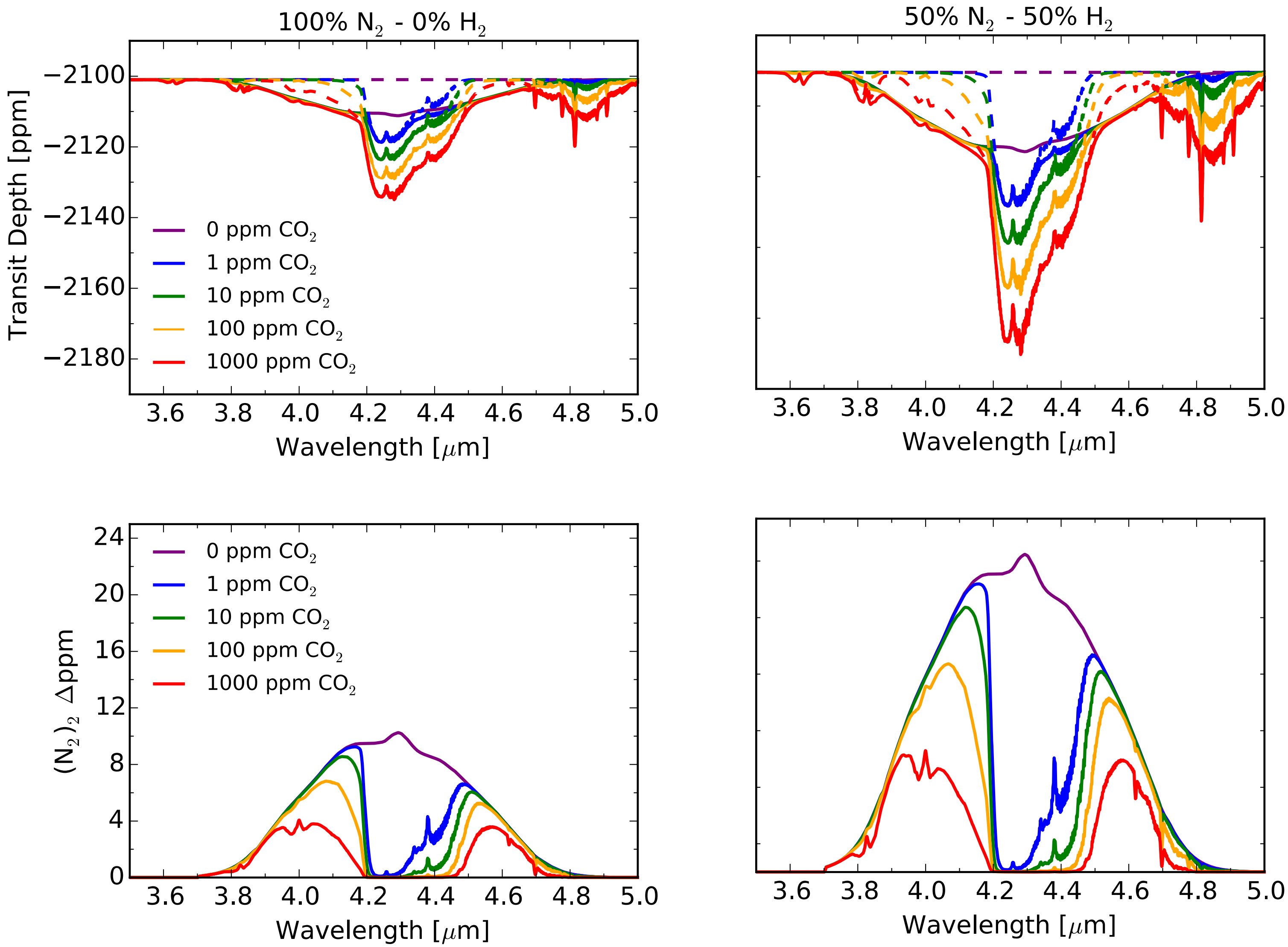
Searching for O_2 using high-resolution spectroscopy may be possible with ELTs

$(N_2)_2$ in Earth's Direct-Imaging Disk-Averaged Spec



- The N_2-N_2 dimer has been detected in EPOXI spectra of the Earth, but its detection in both direct imaging and transit transmission will likely be challenging.
- However, it could be used to determine a lower limit for surface P and help corroborate O_2 as a biosignature.

The $(N_2)_2$ Molecule in Transit Transmission



Schwieterman et al., in review; AbSciCon talk on Thursday!

For an N_2 only atmosphere, the spectral transmission signal from $(N_2)_2$ has a peak amplitude near 10 ppm, (~3ppm for Earth-like levels of CO_2). Increases to 20ppm for N_2/H_2 atmospheres.

False Positives for O_2 and O_3 Exterior to the HZ

The Runaway Greenhouse Classic:

- O_2 buildup due to H_2O photolysis during runaway greenhouse (Ingersoll1969; Kasting 1988; Schindler and Kasting)
- O_3 buildup not possible until the odd H from H_2O photolysis is removed (Schindler and Kasting, 2000; Leconte et al. 2013).

Mars-like Object:

- Available sinks for O_2 would be small, as the planet is too small for volcanism and too cold for surface liquid water
- O_2 produced from H_2O or CO_2 photolysis accumulates on a cold, dry planet (Schindler & Kasting, 2000)

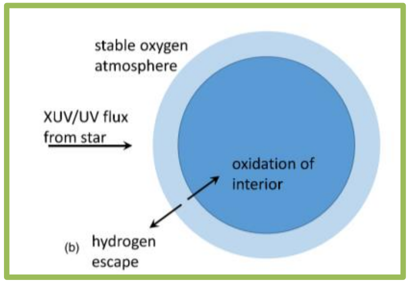
- Mars' atmosphere contains 0.1% O_2 by volume – might be more if Mars more massive and resistant to O_2 loss (McElroy, 1972).

Identifying these cases:

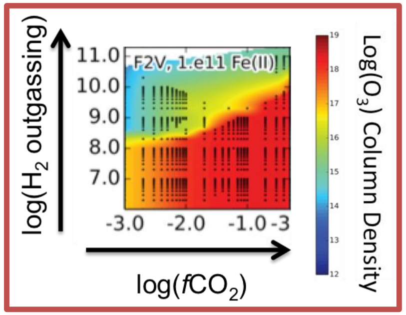
- Position at the edge of or exterior to the habitable zone.
- Strong Lack of H_2O vapor in the spectrum for Runaway O_3 and Mars-like $_{O2}$
- Very strong H_2O in the spectrum for Runaway O_2, until H_2O lost to space.

False Positives For Habitable Zone Planets

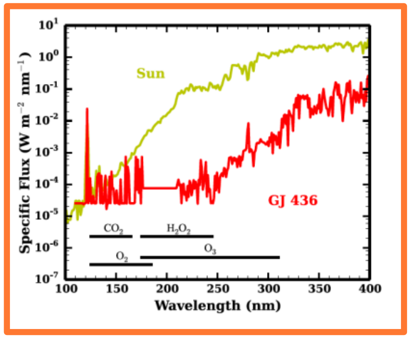
1. H Escape from Thin N-Depleted Atmospheres (Wordsworth & Pierrehumbert 2014)



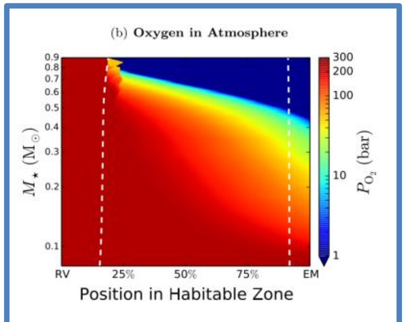
2. Photochemical Production of O_2/O_3 (Domagal-Goldman, Segura, Claire, Robinson, Meadows 2014)



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

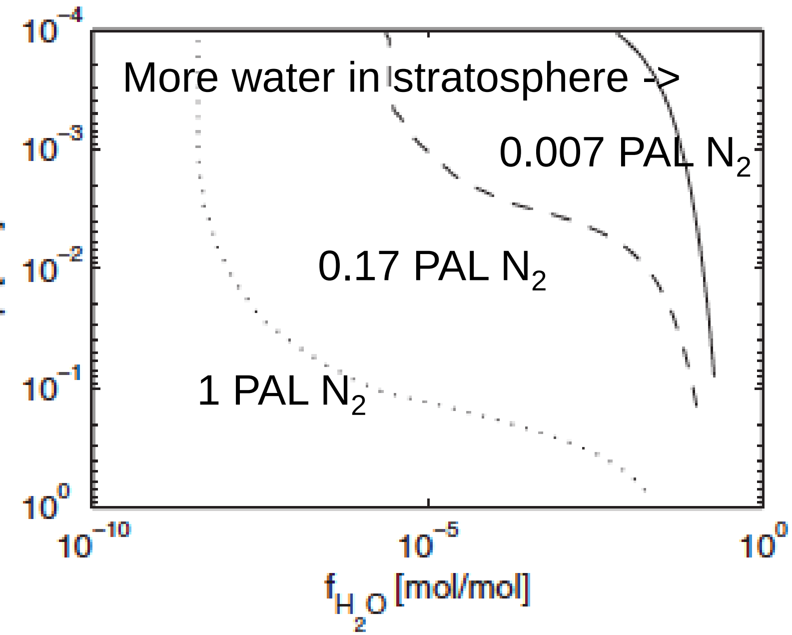


4. CO_2 Photolysis in Dessicated Atmospheres (Gao, Hu, Robinson, Li, Yung, 2015)



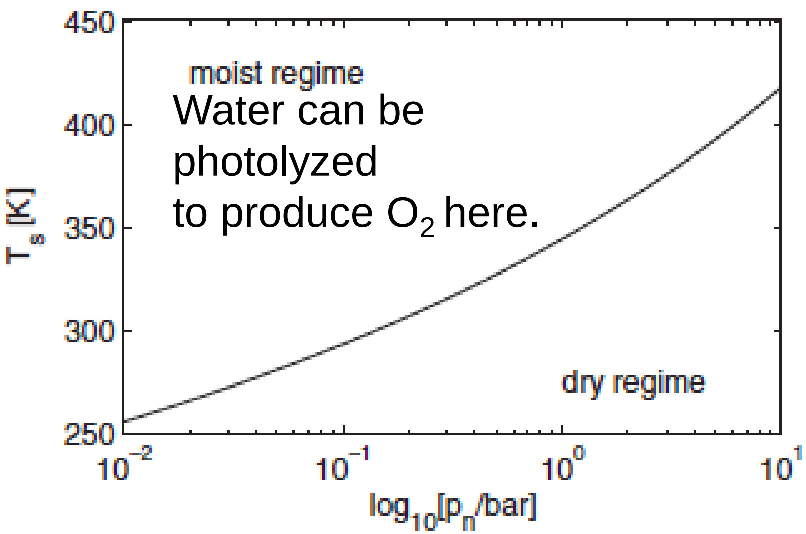
H Escape in N Depleted Atmospheres

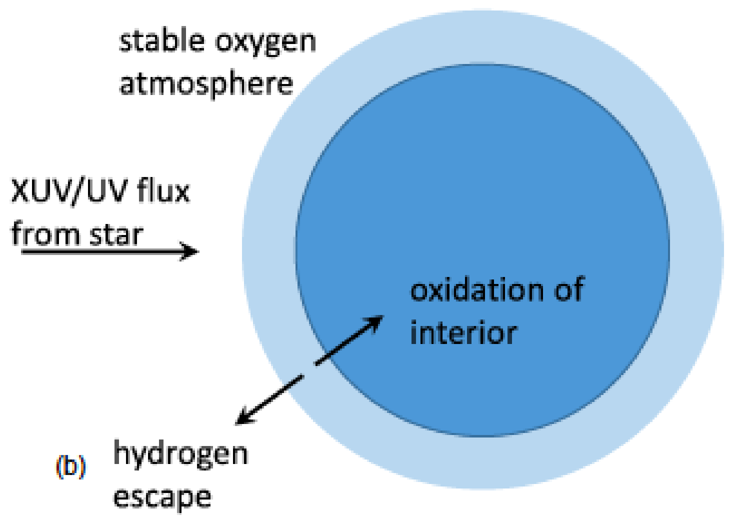
O_2-dominated atmospheres form abiotically *around stars of any spectral type*
(Wordsworth and Pierrehumbert 2014)



The cold trap mechanism that protects H_2O on Earth from photolysis is ineffective when the temperature is high or when the atmospheric inventory of non-condensing gases (e.g., N_2, Ar) is low (< 0.01 PAL N_2).

A self-regulating mechanism (surface oxidation balanced by H escape and increasing O_2 serving as a non-condensing gas) ***gives 0.15 bars O_2*** for an otherwise Earth-like atmosphere.

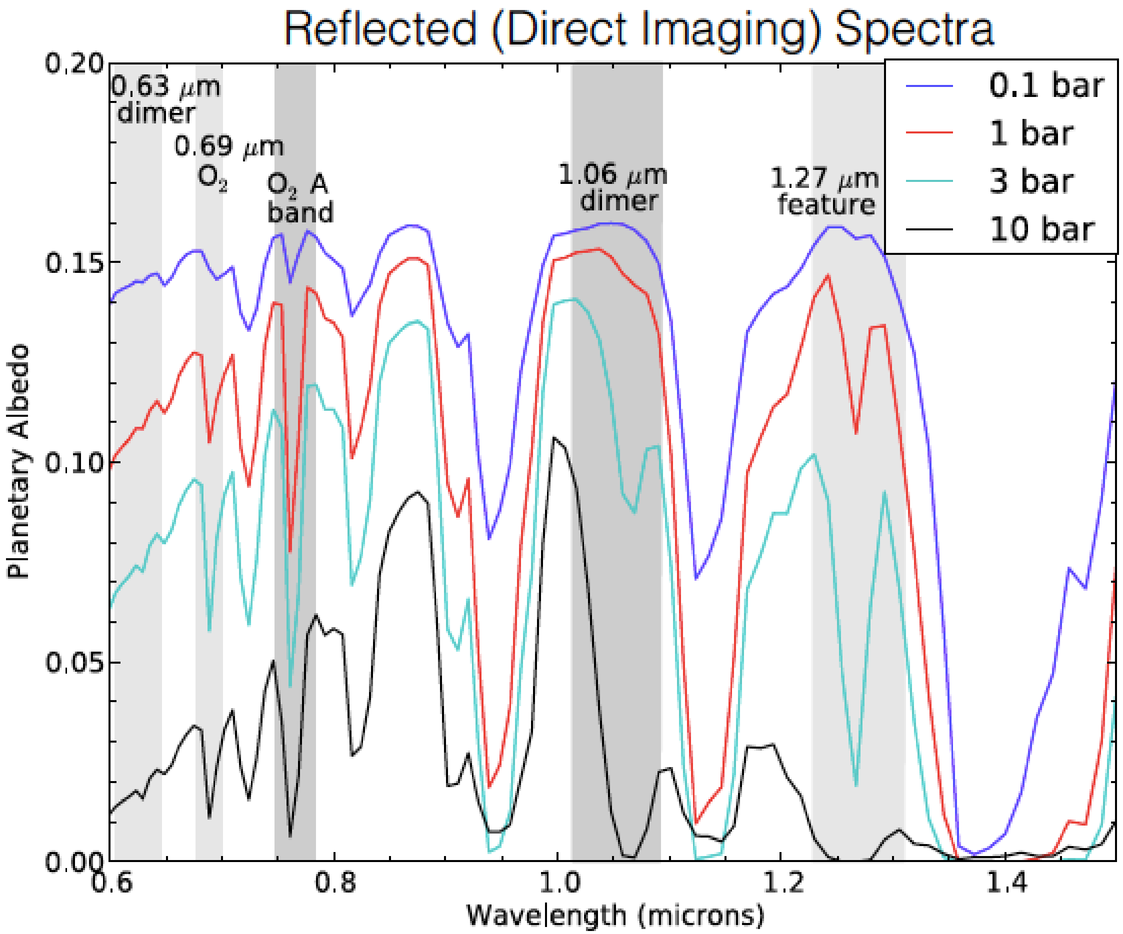


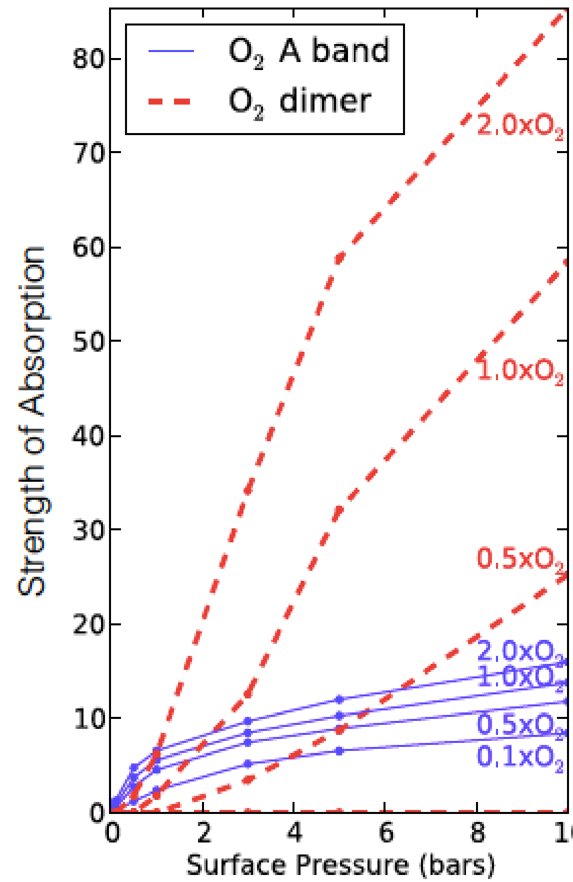


Recognizing H Escape in N Depleted Atmospheres

- Need to set limits on non-condensable gas abundance and understand N_2/O_2 abundance.
- N_2 possibly detected via N_2-N_2 (4.0-4.2μm).
  - Not impossible, but definitely challenging!
  - Easier in atmospheres with high H fraction.
- O_2-O_2 collisional pairs may also provide limits on the the partial pressure of the O_2 component.
  - However, equilibrium value is close to 0.2 bars O_2!

Dimer Molecules as Pressure Indicators

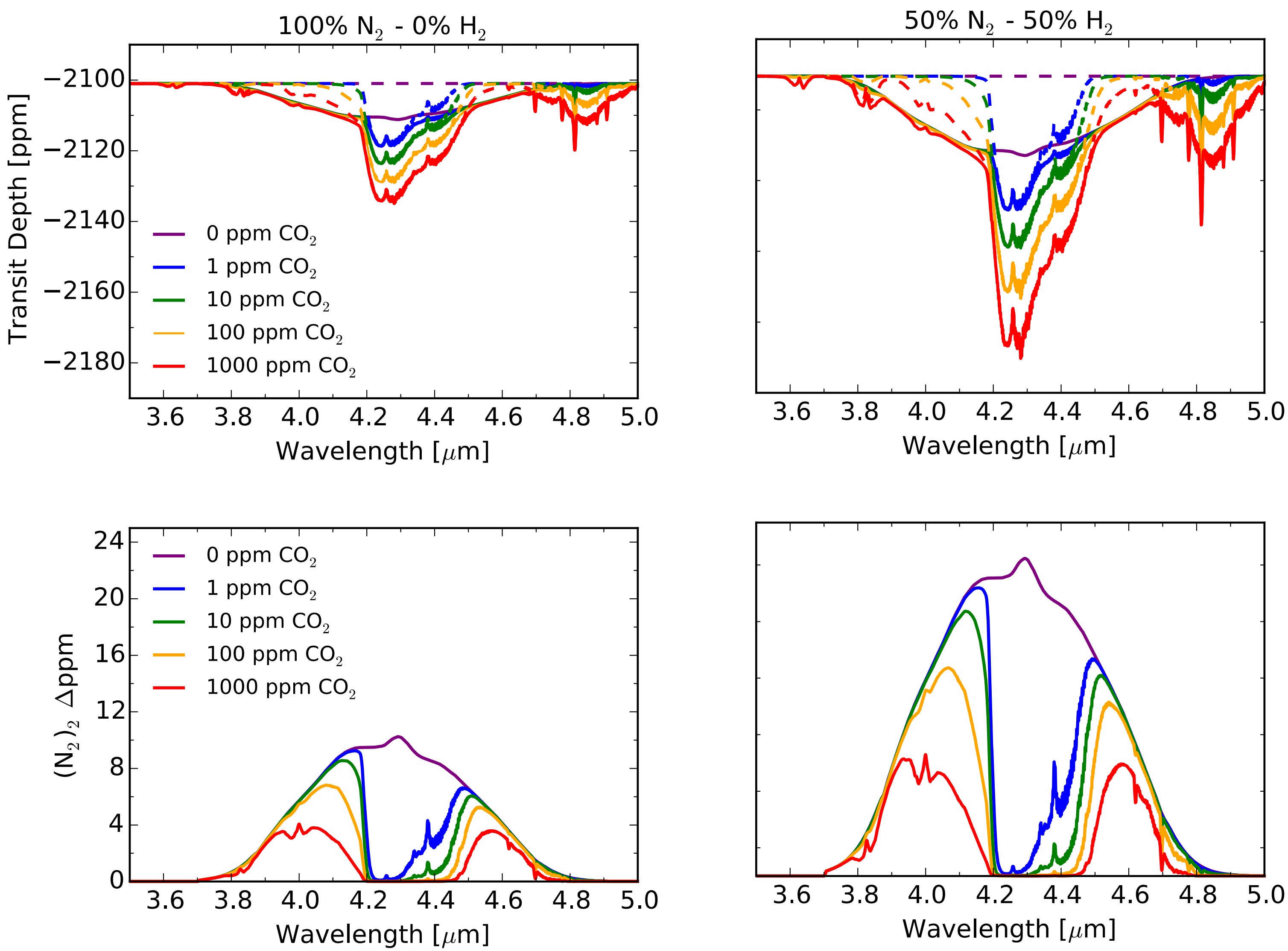




Misra, Meadows,Claire,Crisp (2014).

For transit transmission, JWST may be able to detect the 1.06 and 1.27μm (5.2-sigma) dimer features for a (cloud-free) Earth analog orbiting an M5V star at 5pc, if every single transit it observed! The oxygen A band would likely not be detectable (1.1-sigma), even in the cloud-free case.

The $(N_2)_2$ Molecule in Transit Transmission



Schwieterman et al., in review; AbSciCon talk on Thursday!

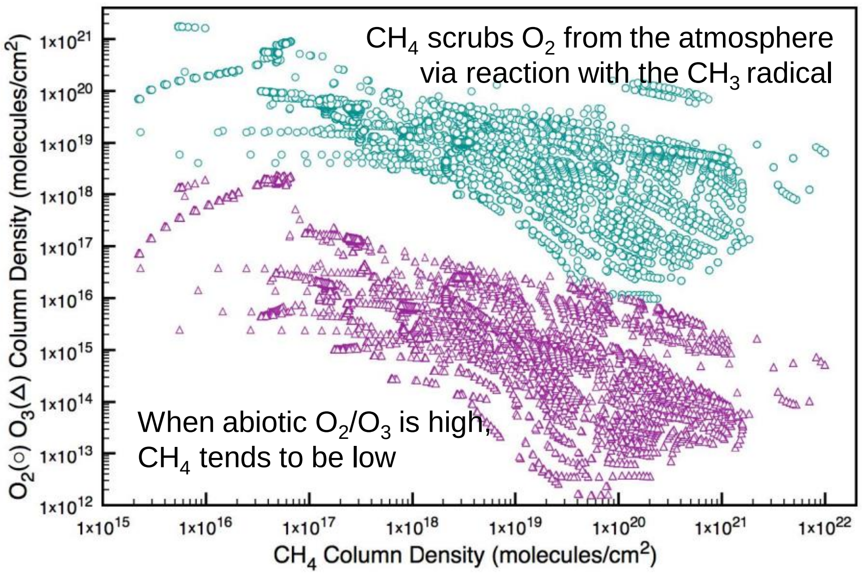
For an N_2 only atmosphere, the spectral transmission signal from $(N_2)_2$ has a peak amplitude near 10 ppm, (~3ppm for Earth-like levels of CO_2). Increases to 20ppm for N_2/H_2 atmospheres.

Generation of Abiotic O_2/O_3 on Planets with Oceans

Host star UV flux and planetary redox state may produce detectable levels of O_2 and/or O_3 abiotically.

- FUV radiation photolyzes CO_2 and O_2 and produces O_3,
- MUV radiation destroys O_3
- If FUV exceeds MUV (as it can do for F and M dwarfs), O3 can be abiotically produced.

Detectable O_3 and CH_4 may be possible around M dwarfs: Build up of O_3 from photolysis of CO_2, for planets with high incident FUVs (Domagal-Goldman et al., 2014).

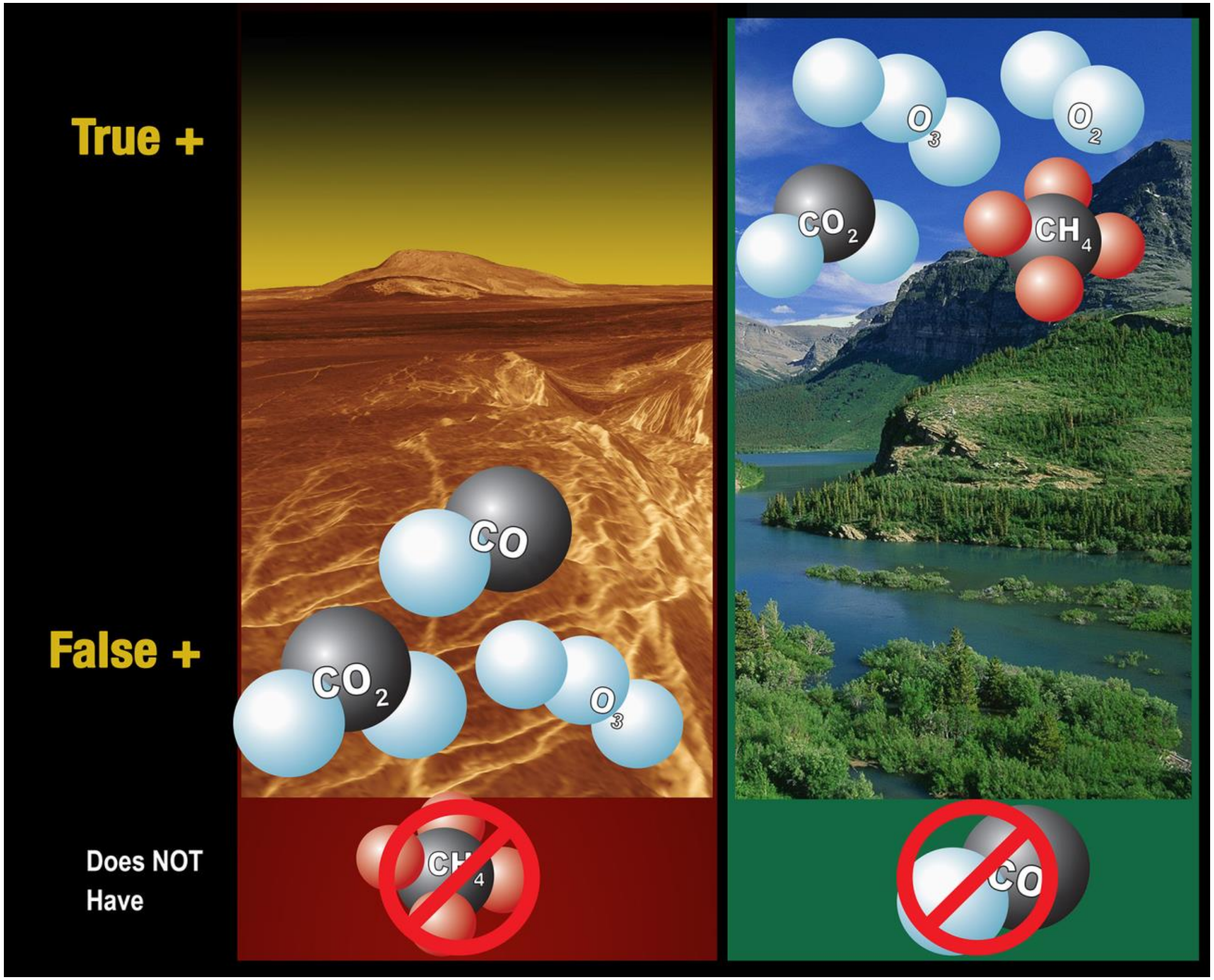


Domagal-Goldman, Segura, Claire, Robinson, Meadows, 2014

High O_2 around M dwarfs: Build-up of O_2 in CO_2-rich atmospheres for M star planets, due to elevated XUV/NUV ratios (Harman et al., 2015)

These processes are highly sensitive to boundary conditions including sinks for CO (aqueous chemistry), which is still poorly understood (Lyons – UCR NAI Team).

Distinguishing False Positives for Abiotic O_2/O_3

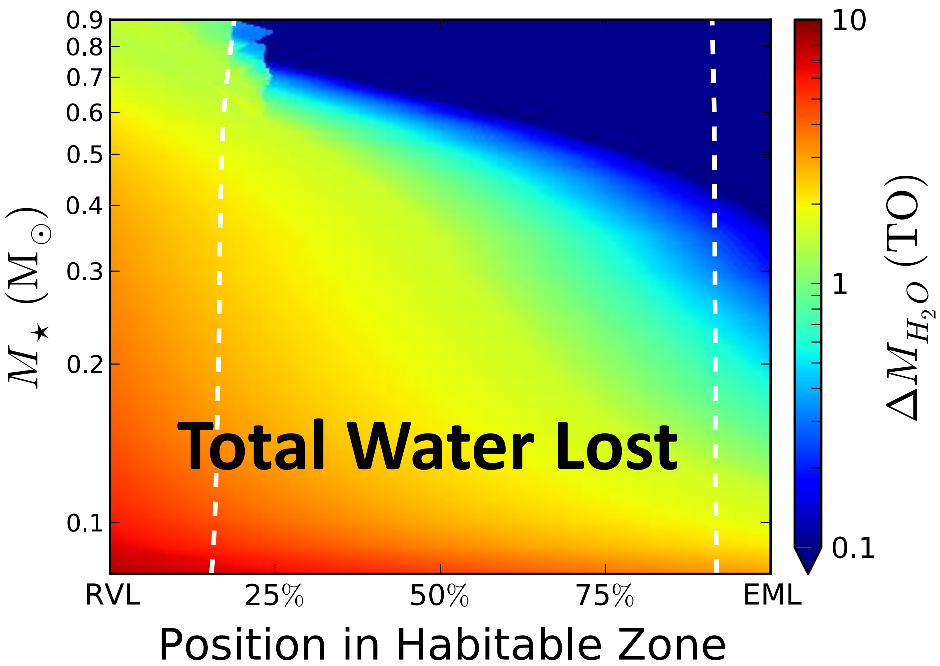


Detecting and quantifying other gases such as O_2, CO and CH_4 could help assess the planetary redox state and discriminate between biological and abiological sources.

Planetary atmospheres with O_2 from photolysis are more likely to show a lack of methane or the presence of CO

Domagal-Goldman et al., 2014

The Super-luminous Phase and Abiotic O_2 Production

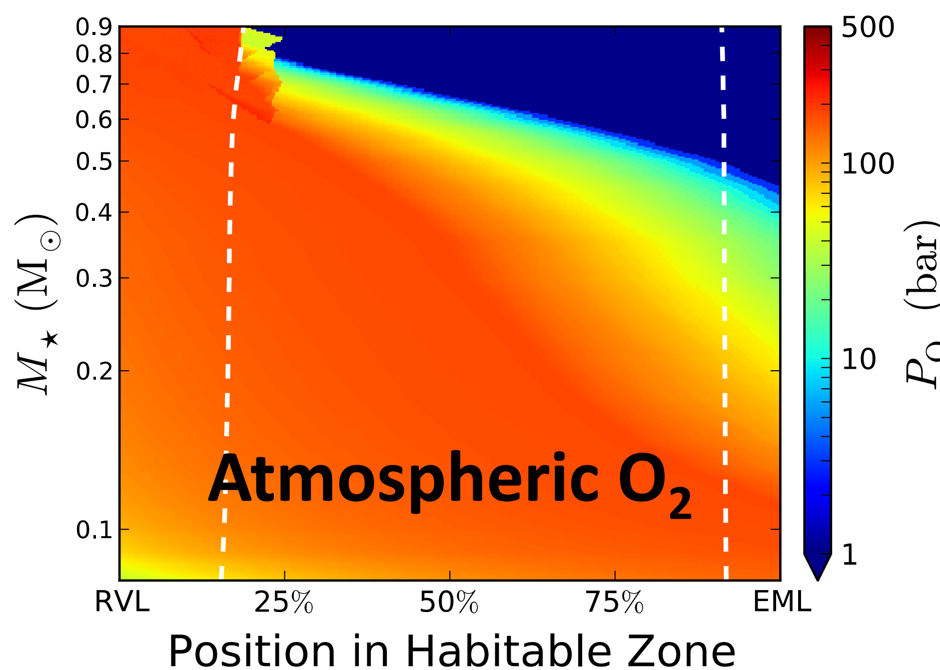


Terrestrial planets can lose several Earth oceans of water via hydrodynamic escape during the PMS "super-luminosu" phase of M dwarfs.

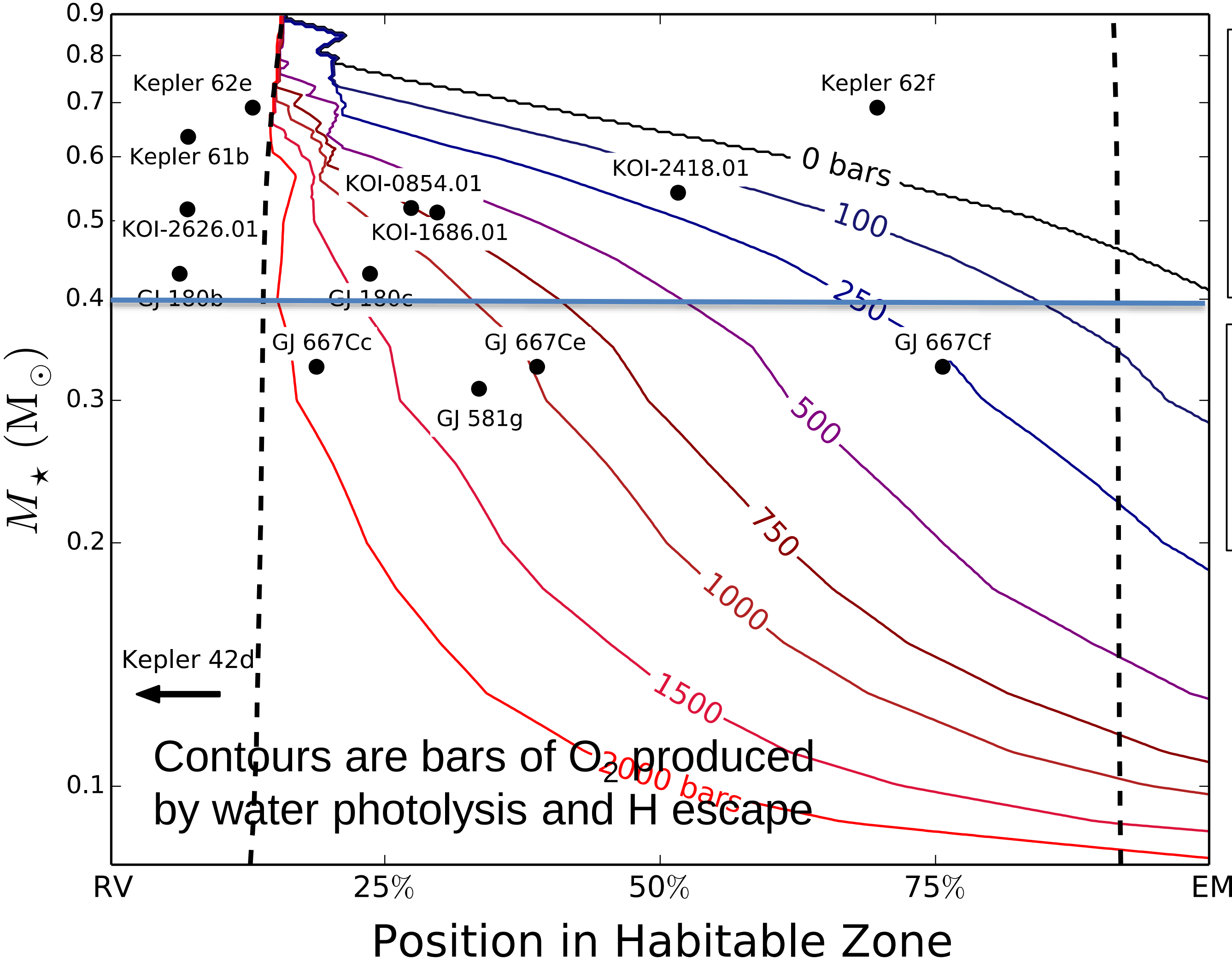
Luger & Barnes (2015)

Depending on the strength of surface sinks, 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



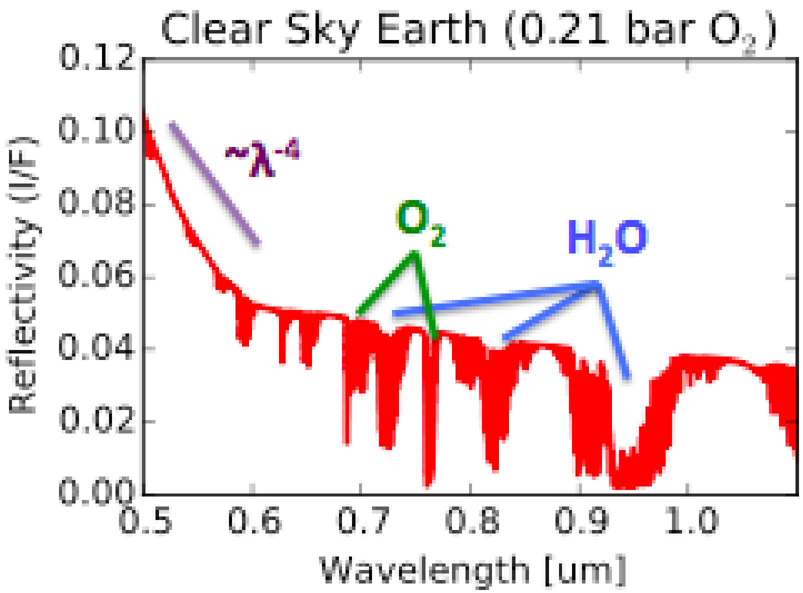
This extra pre-MS luminosity can last for up to a billion years and could dessicate planets formed in the habitable zone of low mass stars within the first 100 Myr

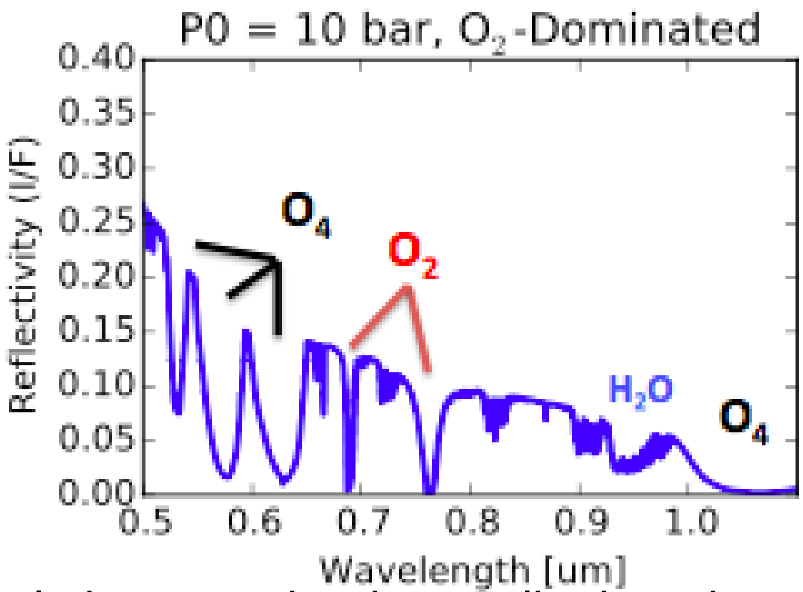
THE PUNCHLINE: Planets orbiting stars above a stellar mass of ~ 0.4 are less likely to experience this phenomenon, especially towards the outer edge of the HZ.

Luger and Barnes, 2015

Recognizing Abiotic O_2 Production from Massive H_2O Loss

- Likely significant for the later type M dwarfs ($M_* > 0.4\ M_\odot$)
- In transit transmission O_4 in the near infrared may be significant.
- In direct imaging, would expect strong bands from the visible wavelength O_4 bands.
- H_2O may be significantly depleted.





Schwieterman et al., in prep; AbSciCon talk Thursday

Generation of Abiotic O_2/O_3 on Planets without Oceans

- **High O_2 and O_3 for dessicated planets orbiting M dwarfs**

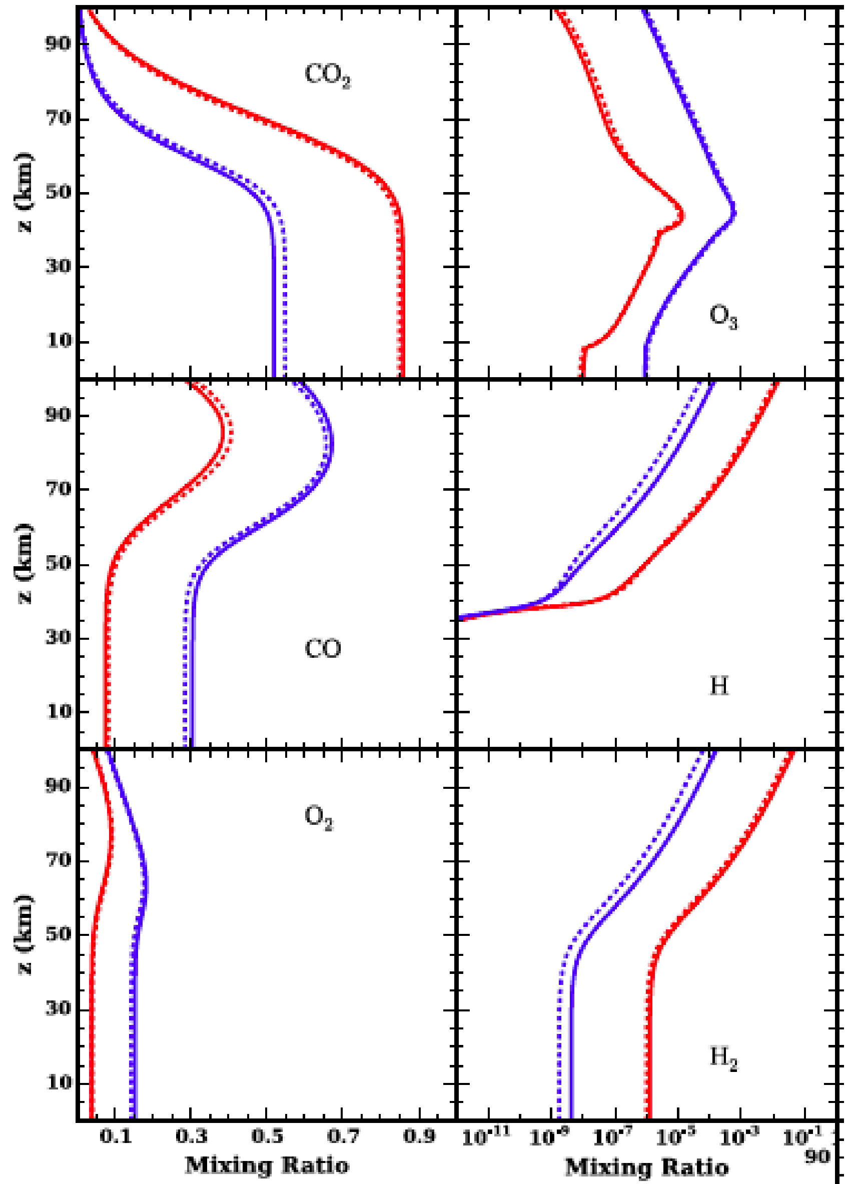
- Around Sun-like stars CO_2 photolysis by FUV

$$CO_2 + h\nu \rightarrow CO + O$$

- is balanced by recombination reactions that depend on water abundance.

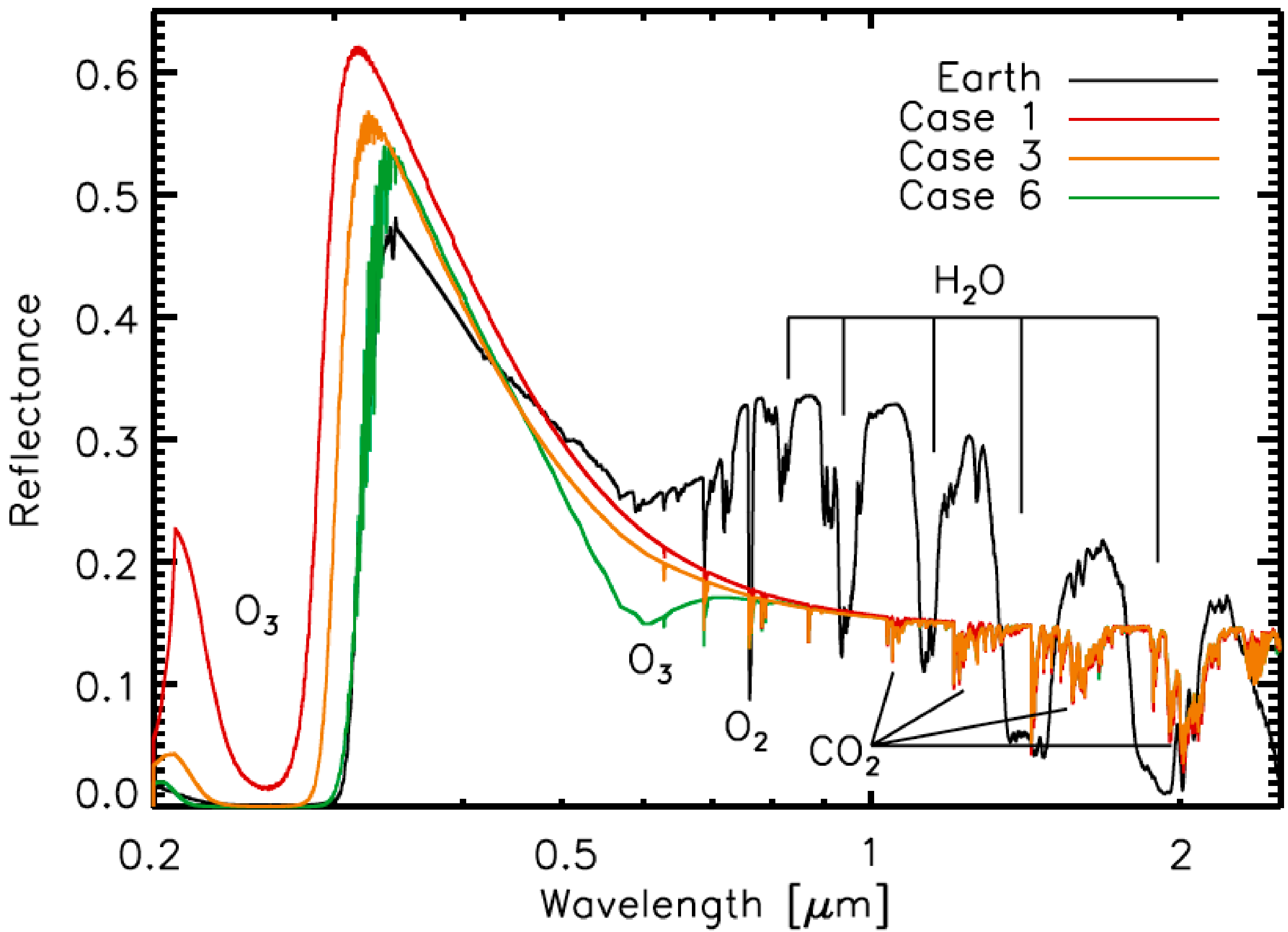
$$H + O_2 + M \rightarrow HO_2 + M$$
$$O + HO_2 \rightarrow OH + O_2$$
$$OH + CO \rightarrow CO_2 + H$$
$$\text{------------------------------}$$
$$CO + O \rightarrow CO_2.$$

- For HZ M dwarf planets dessicated by pre-MS runaway (atmospheric H < 1ppm) there could be a build up of Earth-like quantities (mixing ration 0.15) of O_2 as up to 50% of the atmospheric CO_2 is destroyed.



Gao, Hu, Robinson, Li, Yung (2015)

Recognizing Abiotic O_2/O_3 on Planets without Oceans



Both O_2 and O_3 may be present.
Look for absence of H_2O and presence of CO_2

General Summary

- We now know that abundant oxygen or ozone in an atmosphere could be produced by several abiotic mechanisms, including photolysis and atmospheric escape.

- By better understanding these mechanisms we can choose optimal targets and design better measurements to guard against false positives.

- Understanding the host star’s UV spectrum will improve our understanding of the photochemistry of the planetary atmosphere and help in identifying abiotic and biological sources for atmospheric gases.

Impact for Transit Transmission

- JWST and EELTs – observations of O_2 or even O_4 will be extremely challenging
  - O_2 (0.76um) and visible O_4 (0.4-0.7) obscured by Rayleigh scattering, so NIR O_4 (1.06 & 1.27um) possibly more detectable.
- Detectability of CH_4, CO_2, H_2O and N_2 (4-4.2um) important, not just O_2 or O_4.
- Recommend earlier type M dwarf targets (> 0.4 $M_\odot$) to minimize the possibility of false positives from pre-MS runaway.
- Glint (phase curve) desirable to confirm habitability, and disequilibrium biosignatures - but highly unlikely to be detectable for HZ planets with JWST (Cowan et al., 2015).
- With a big enough telescope, refraction may allow temporal resolution to provide atmospheric altitude resolution. Photochemical O_2 will be concentrated in the upper atmosphere: biological O_2 near the surface.

Impact for Direct Imaging

- Glint should be sought to help confirm habitability, disequilibrium biosignatures, and to identify whether aqueous reactions may affect the atmospheric composition.
  - Relatively “easy” photometric measurement at multiple phases.

- Will likely avoid late M dwarf targets, thereby removing several of the potential false positive mechanisms.

- You can get O_4 “for free” in the visible region (0.4-0.6μm)

- To guard against false positives, need to be able to measure CH_4, CO_2 primarily, and CO and N_2 if possible.

The Virtual Planetary Laboratory

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David Crisp (NASA-JPL/Caltech)
Pan Conrad (NASA-GSFC)
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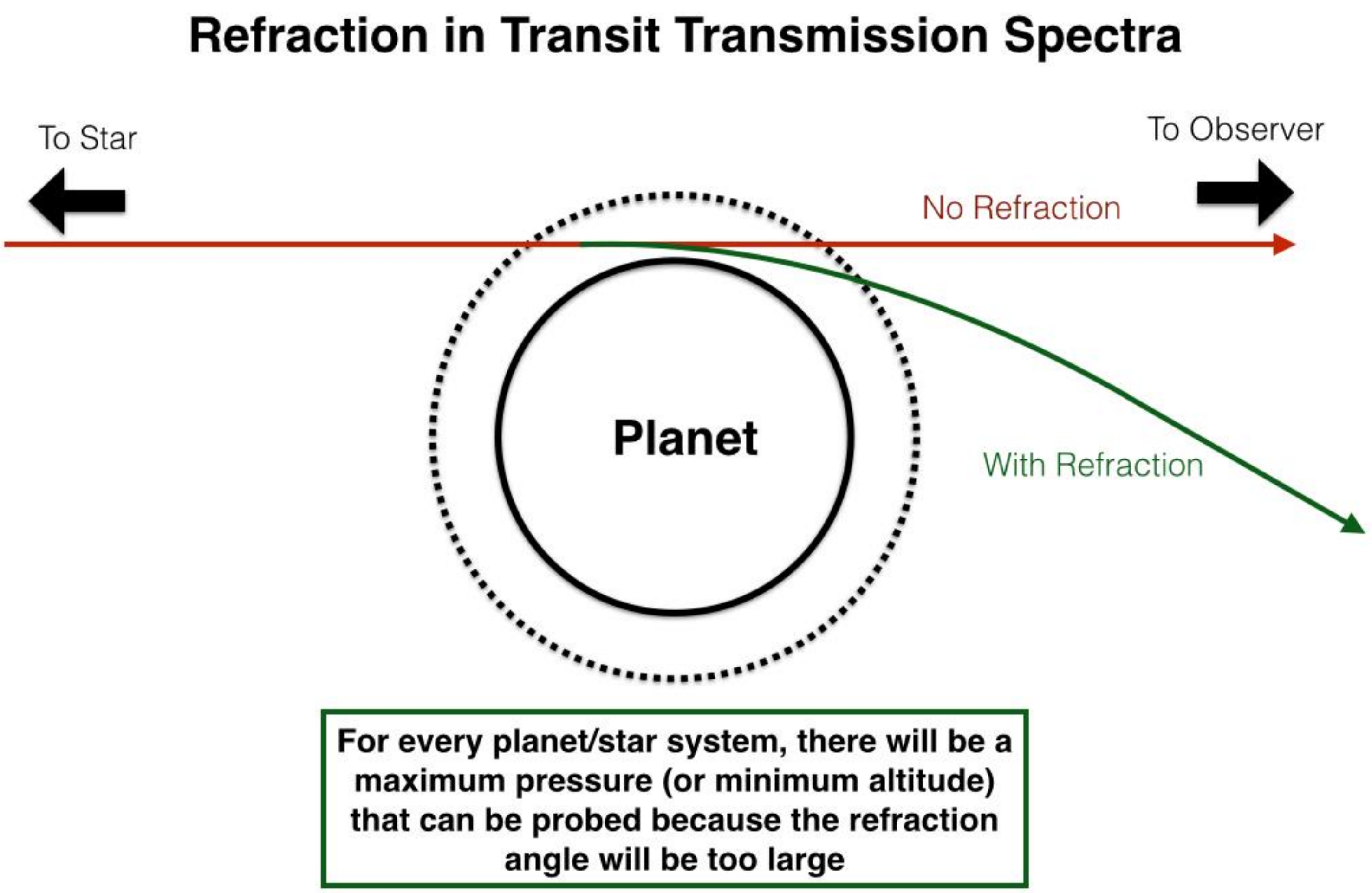
Peter Driscoll (UW)
Peter Gao (Caltech)
Colin Goldblatt (U. Victoria)
Chester (Sonny) Harman (PSU)
Suzanne Hawley (UW)
Tori Hoehler (NASA-Ames)
Jim Kasting (PSU)
Nancy Kiang (NASA-GISS)
Ravi Kopparapu (PSU)
Monika Kress (SJSU)
Rodrigo Luger (UW)
Jacob Lustig-Yaeger (UW)
Victoria Meadows (UW)
Amit Misra (UW)
Niki Parenteau (NASA-Ames)
Ray Pierrehumbert (U. Chicago)
Tom Quinn (UW)
Sean Raymond (Lab. Astrophysique Bordeaux)
Tyler Robinson (NAI-NPP/NASA Ames)
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)

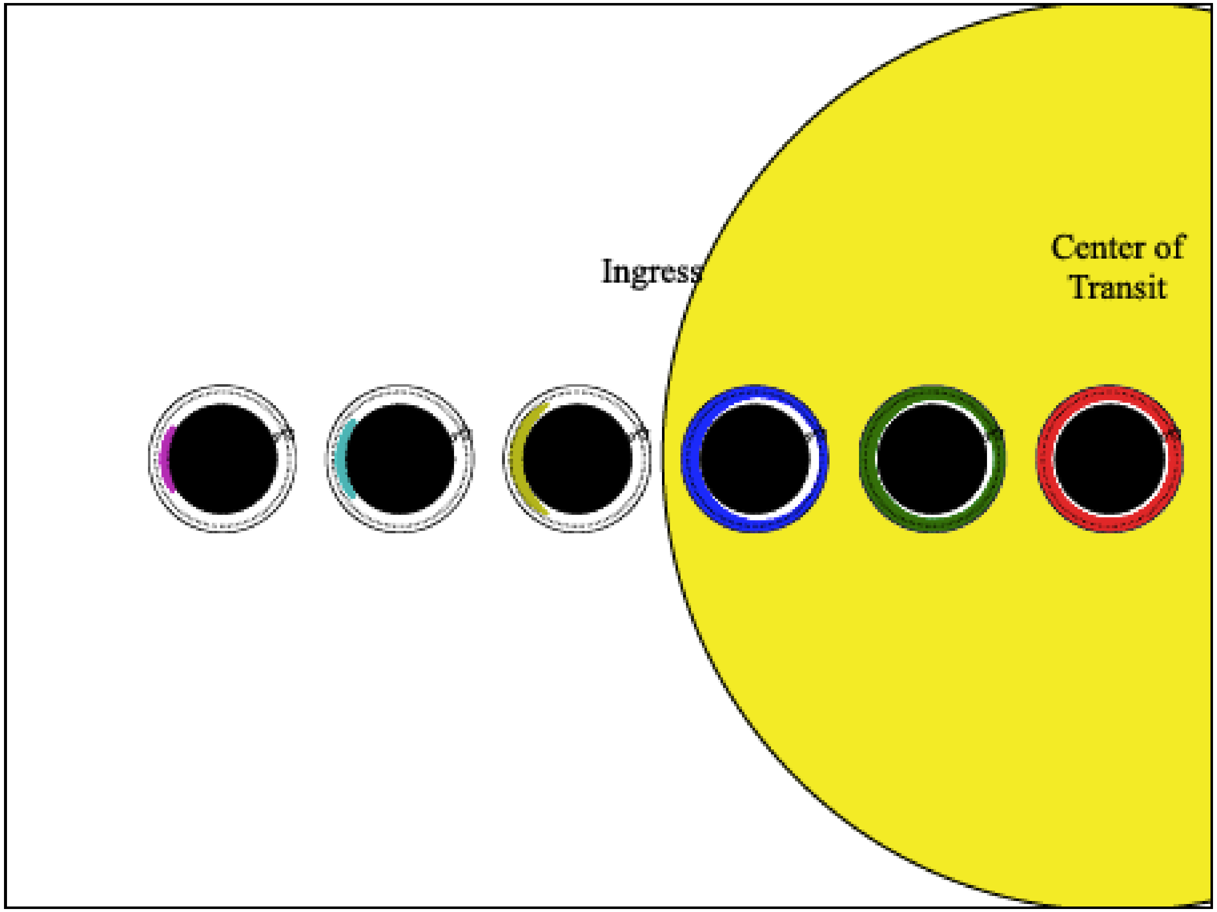
Backup Slides

Refraction Limits Altitudes Probed



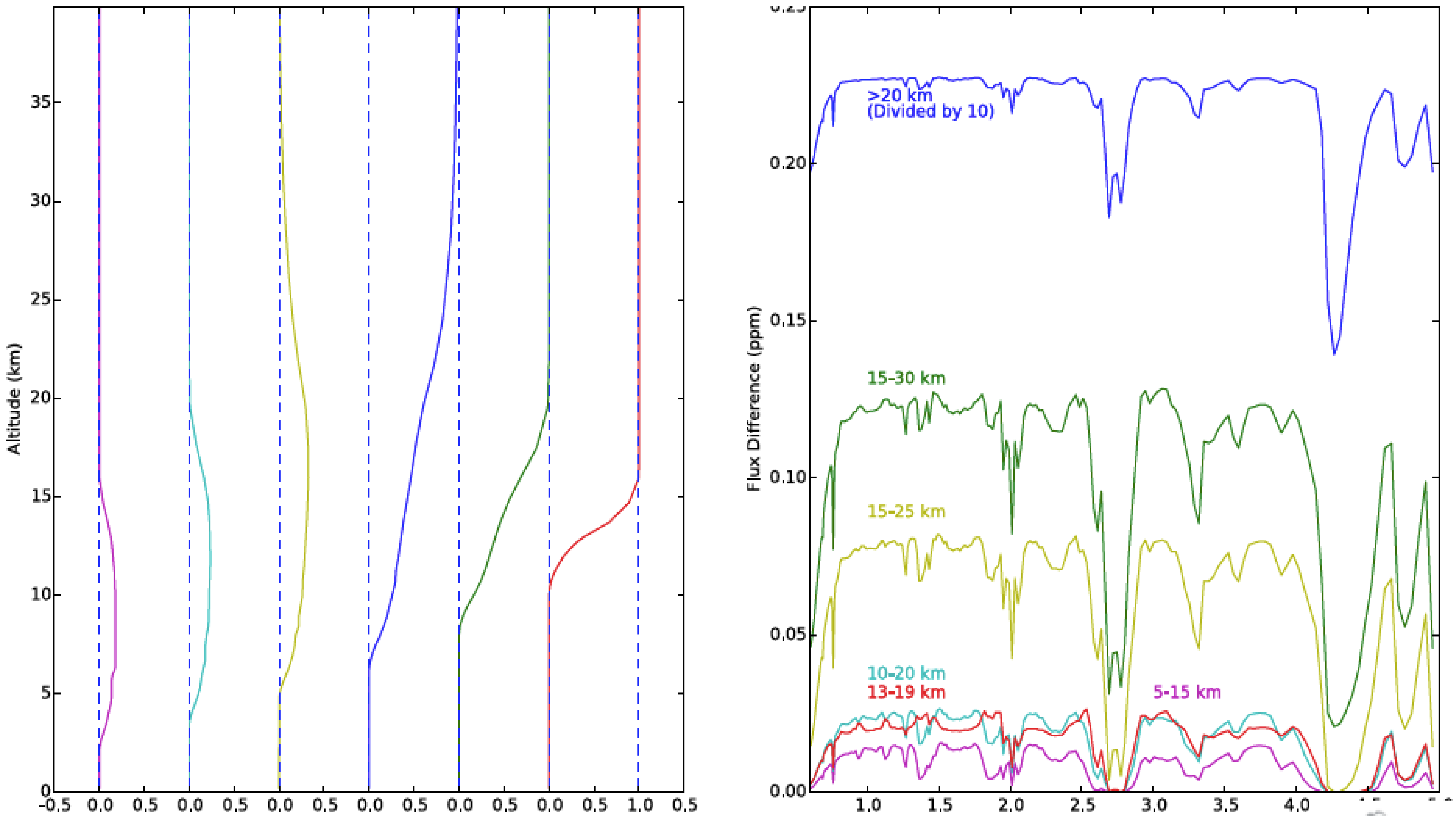
Misra, Meadows and Crisp., 2014b
See also Bertremieux & Kaltenegger, 2014

Refraction as a probe of vertical structure



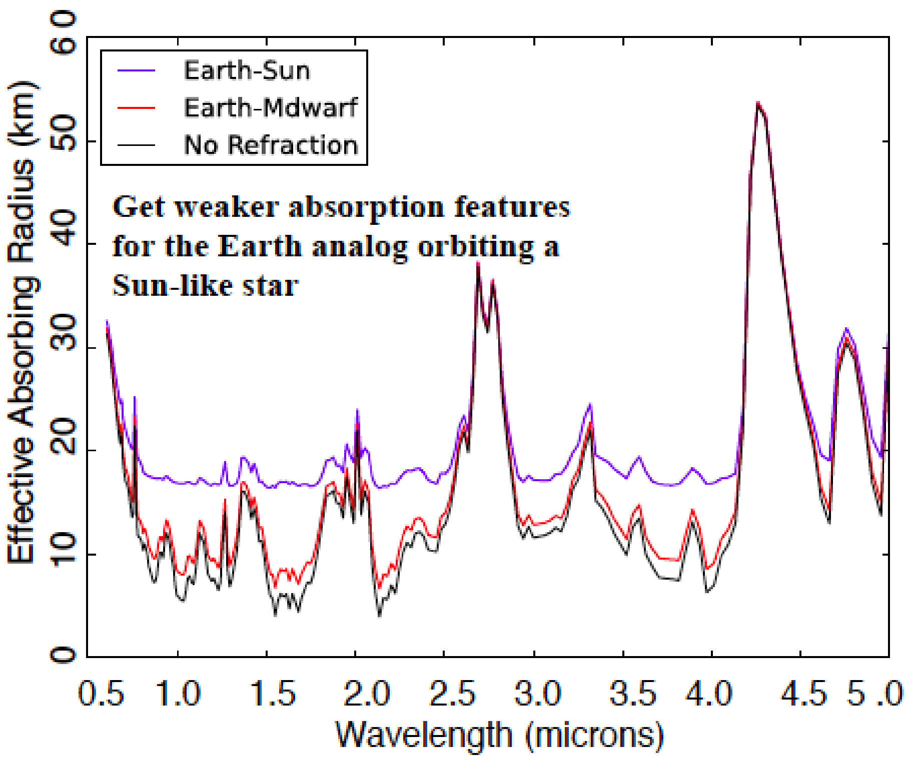
Misra, Meadows and Crisp, 2014.

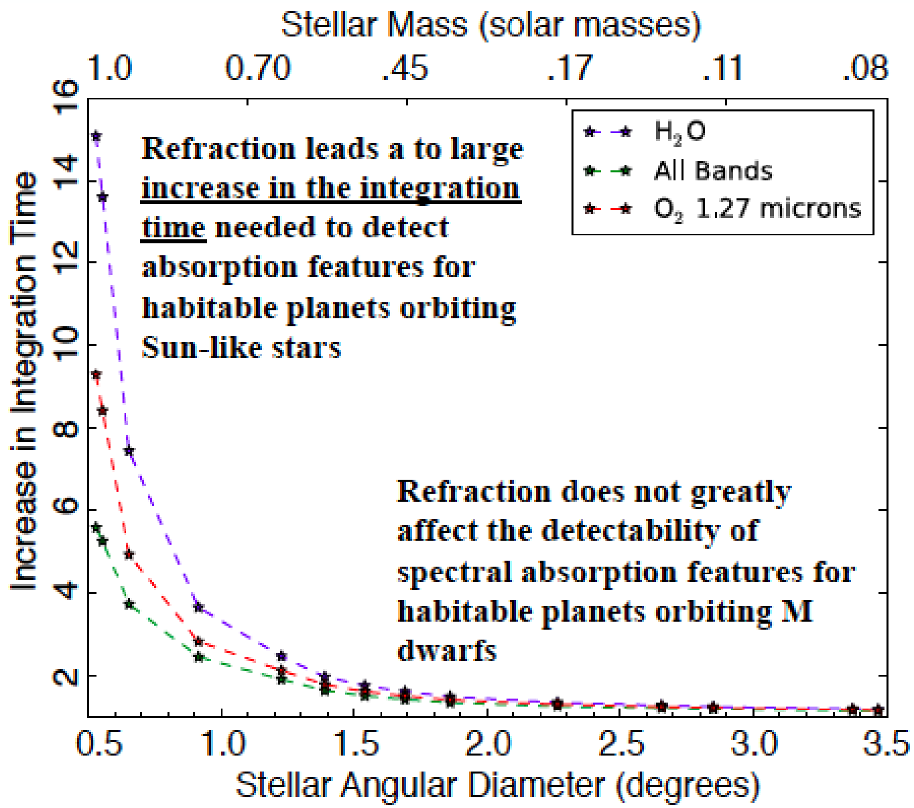
Different atmospheric levels probed give vertical structure



Misra, Meadows and Crisp, 2014.

Refraction Reduces Spectral Features





For planets in the habitable zone of their parent stars refraction does not affect detectability of spectral absorption for M dwarf planets, but does for G dwarf planets.

Misra et al., 2014b