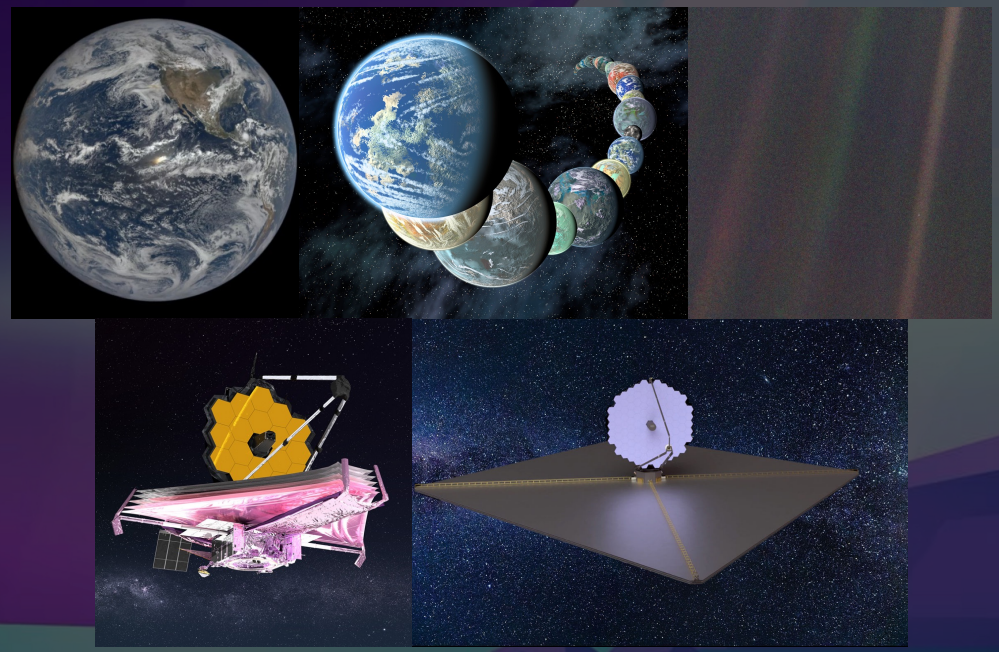
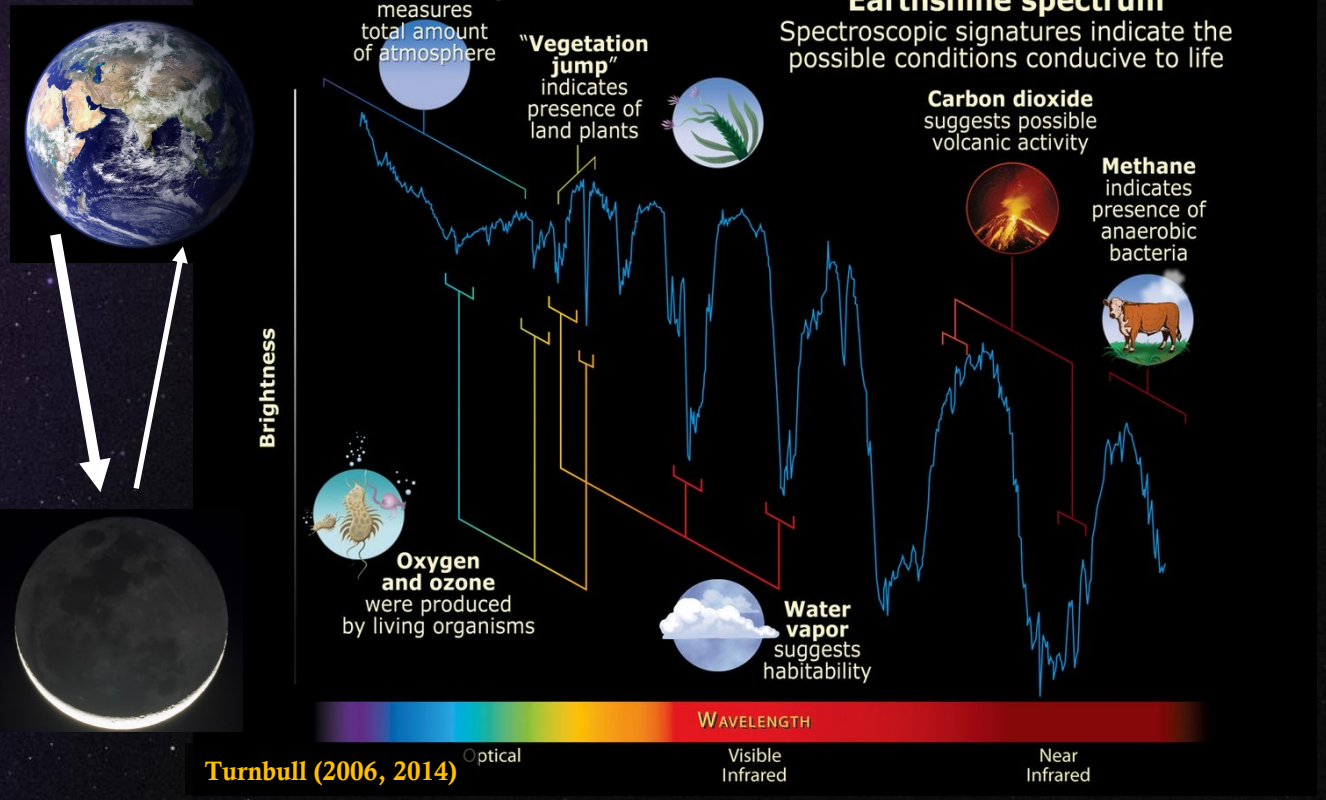
Earth as an Exoplanet: Relevance to ExoEarths

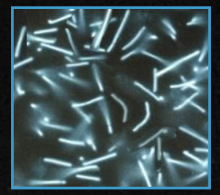


Edward Schwieterman
University of California, Riverside

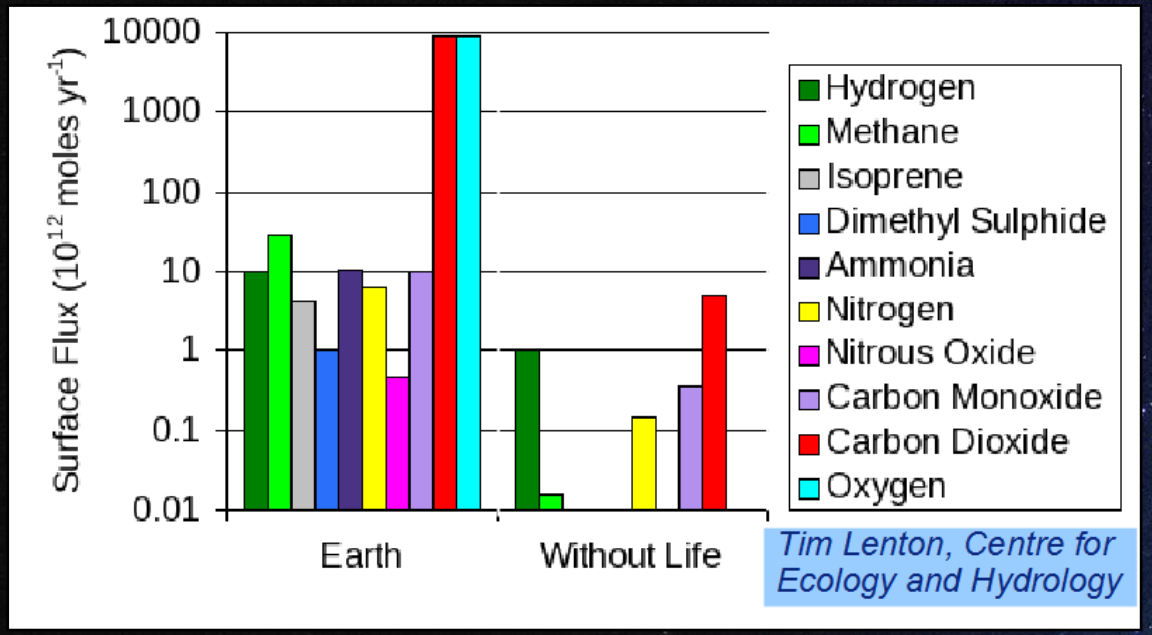
ExoPAG 28
San Antonio, TX
10/1/2023

Earth is a Dynamic, Habitable, Geological Active, Living Planet



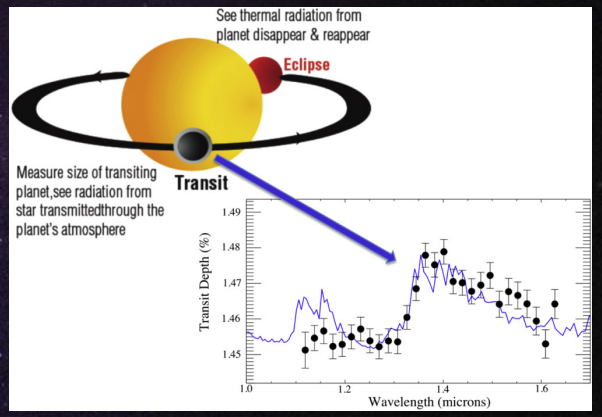


Fluxes of biogenic gases distinguish Earth from an abiotic counterpart

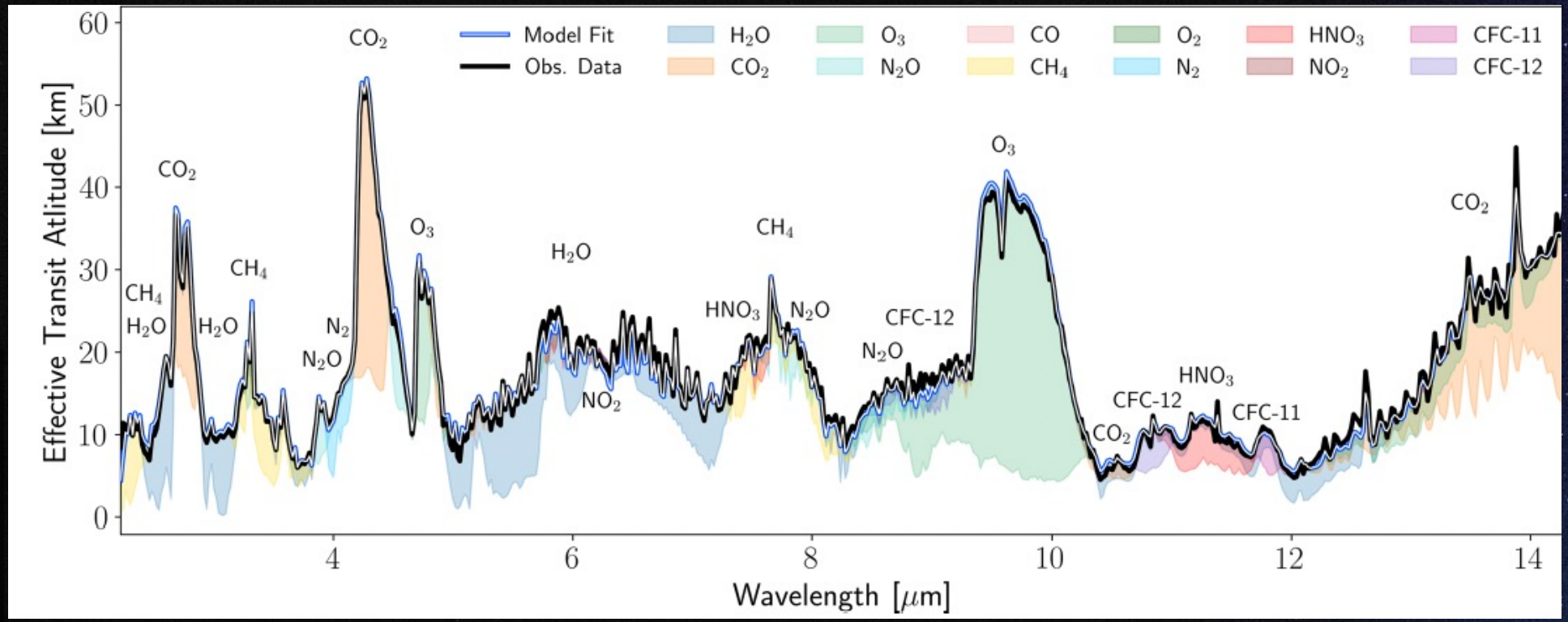


Life processes (e.g., carbon cycle, nitrogen cycle, oxygenic photosynthesis) have a large lever arm on Earth's atmospheric composition on geologically short timescales. These processes impact the remote spectrum.

Earth's Transmitted Light Spectrum & Its Features



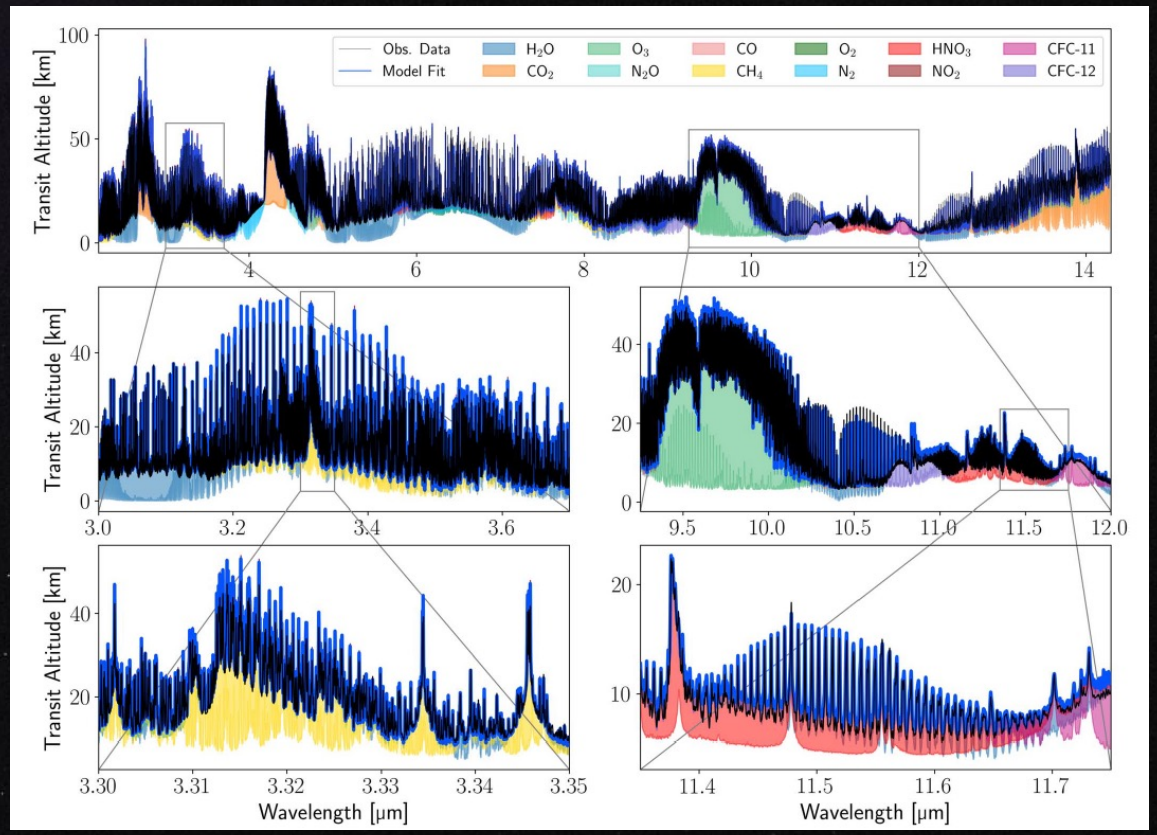
Top: illustration from Deming+2018; **Right:** model retrieval from Lustig-Yaeger+2023 using reconstructed Earth transmission spectrum from Macdonald & Cowan 2019, derived from SCISAT ACE-FTS data

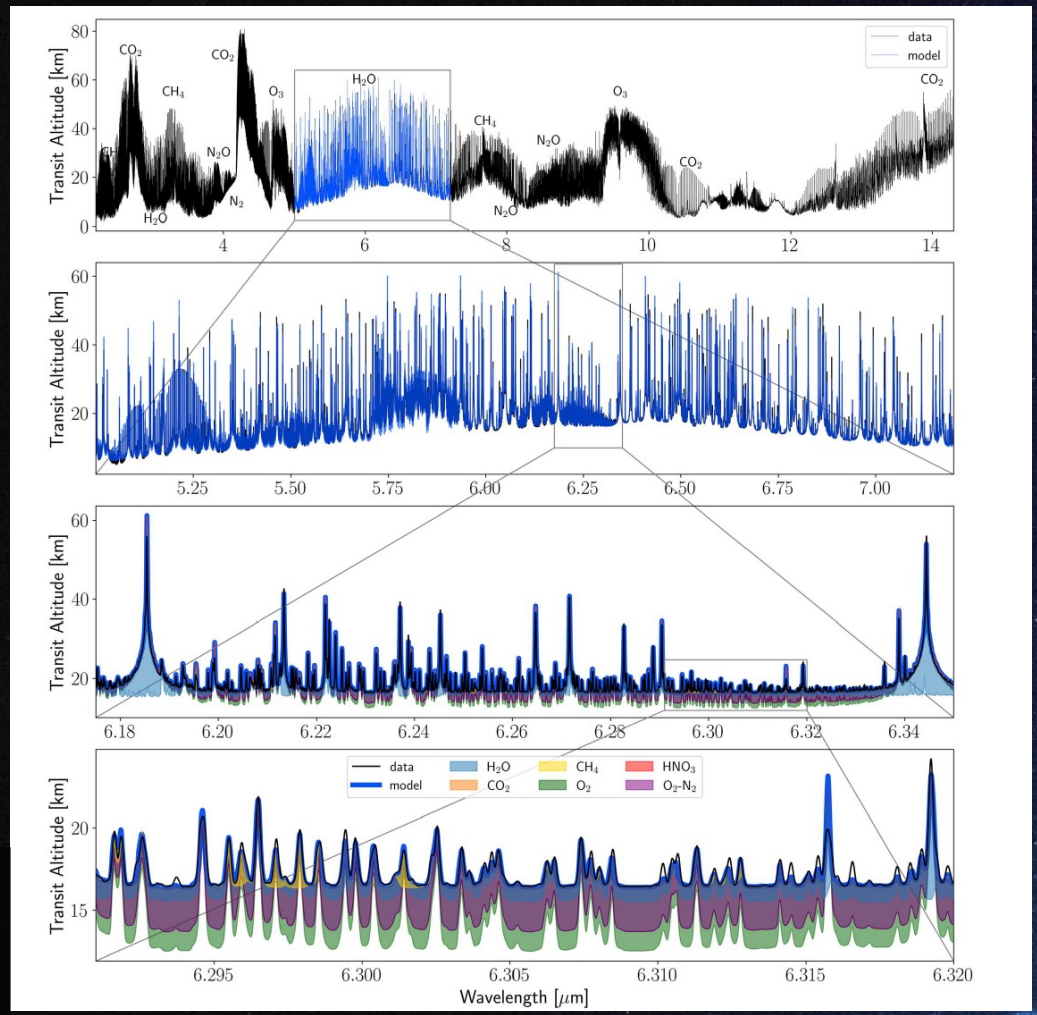


Spectrum contains gaseous habitability markers CO_2 (2.7, 4.3, 15 μm), H_2O (6 μm), and N_2 (4.2 μm); biosignatures CH_4 (3.3, 7.7 μm), O_3 (4.7, 9.7 μm) and N_2O (4, 7.7, 8.5 μm) and technosignatures CFC-11 (CCl_3F; 11.8 μm), CFC-12 (CCl_2F_2), and NO_2 (6.2 μm).

Earth's Transmitted Light Spectrum—High Resolution

Transit Altitude [Km]

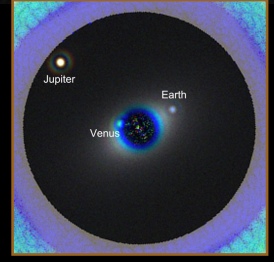




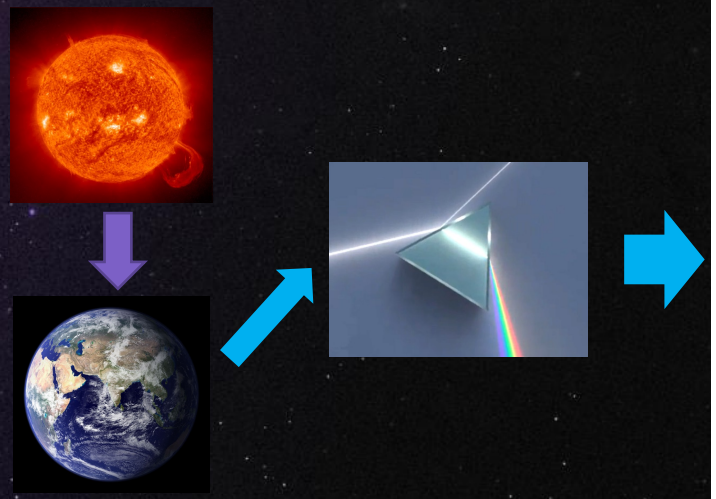
High-res data ($\Delta\nu$ = 0.02 cm^{-1}; R=10^5 at 5 μm) are excellent for teasing out trace gas features and contributions from CIA (O_2-O_2; O_2-N_2)

Macdonald & Cowan (2019, 2023); Lustig-Yaeger+2023

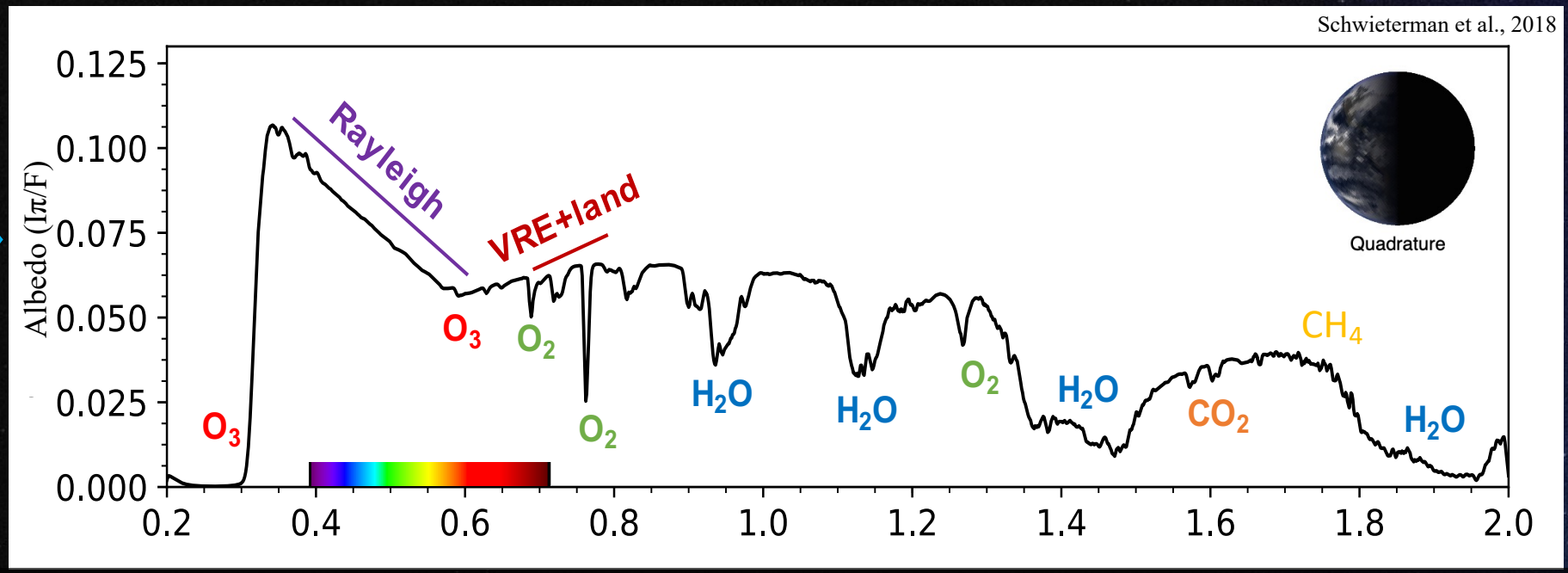
Earth's Reflected Light Spectrum and Its Features



Accessible Wavelength Regions will Depend on Observing Mode and Instrumentation

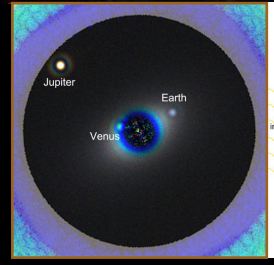


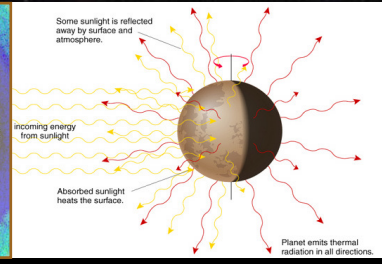
"Reflected light" – the light from the star is reflected (and/or scattered) by the planet to the distant observer.



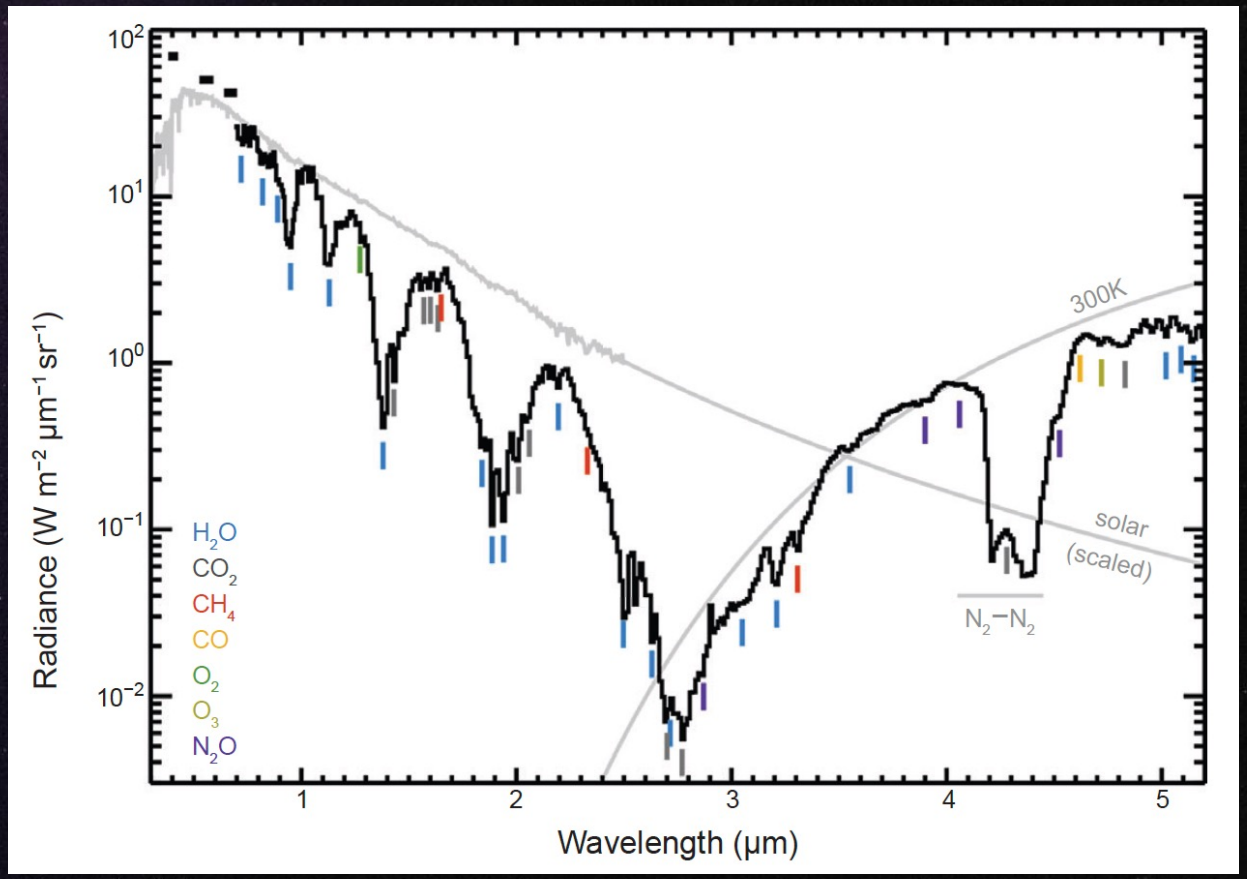
An Earth spectrum at quadrature (half illumination) in ultraviolet (UV), visible (VIS), and near-infrared (NIR) wavelengths shows features from oxygen (O_2), ozone (O_3), water vapor (H_2O), and carbon dioxide (CO_2). Rayleigh scattering from Earth's blue sky is shown (λ^{-4}). A small signature from Earth's vegetation red-edge (VRE) is apparent.

Importance of Wavelength-Range & Observing Mode



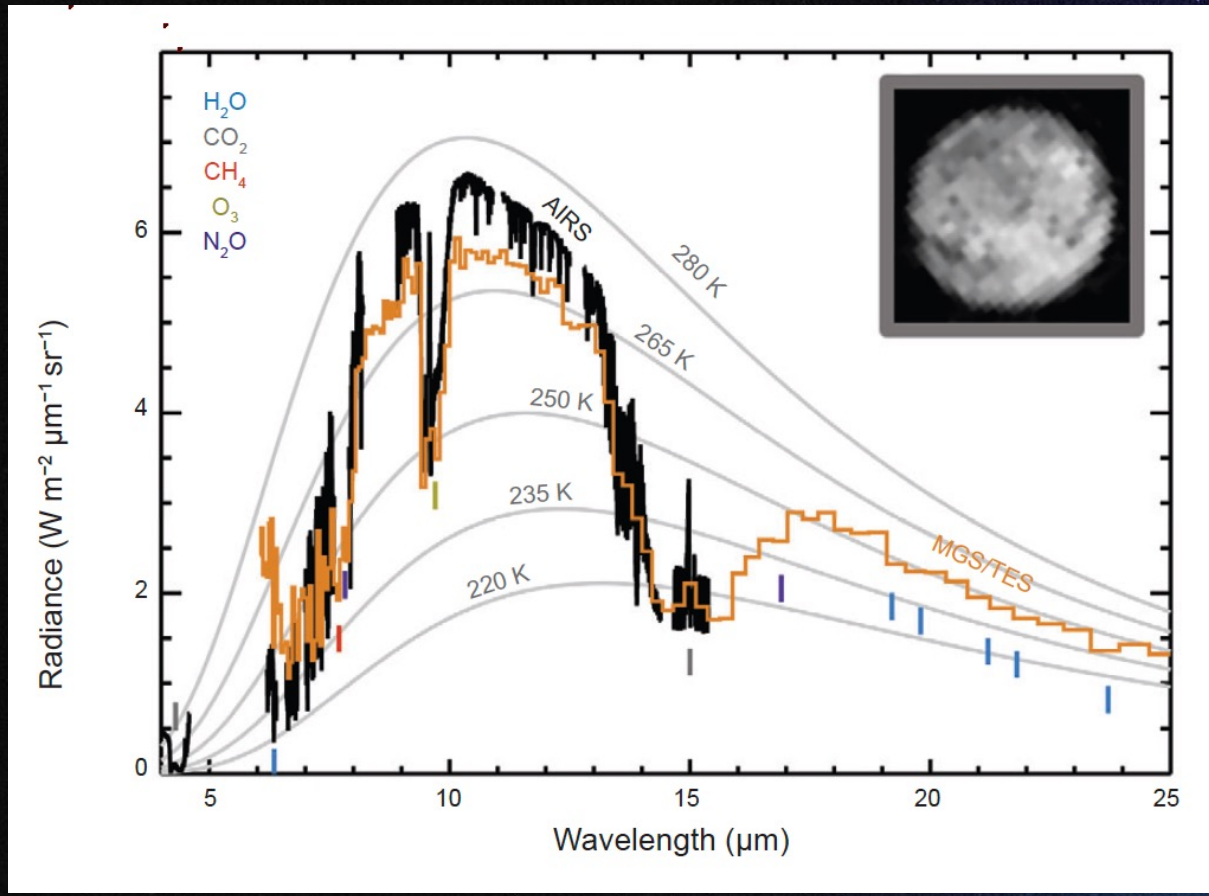


Earth's Reflected and NIR-emitted Light



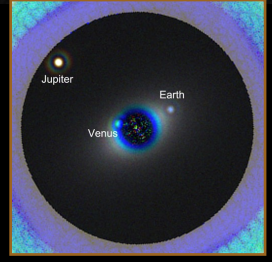
Interesting features where there is little flux…

Earth's Thermal Infrared Spectrum

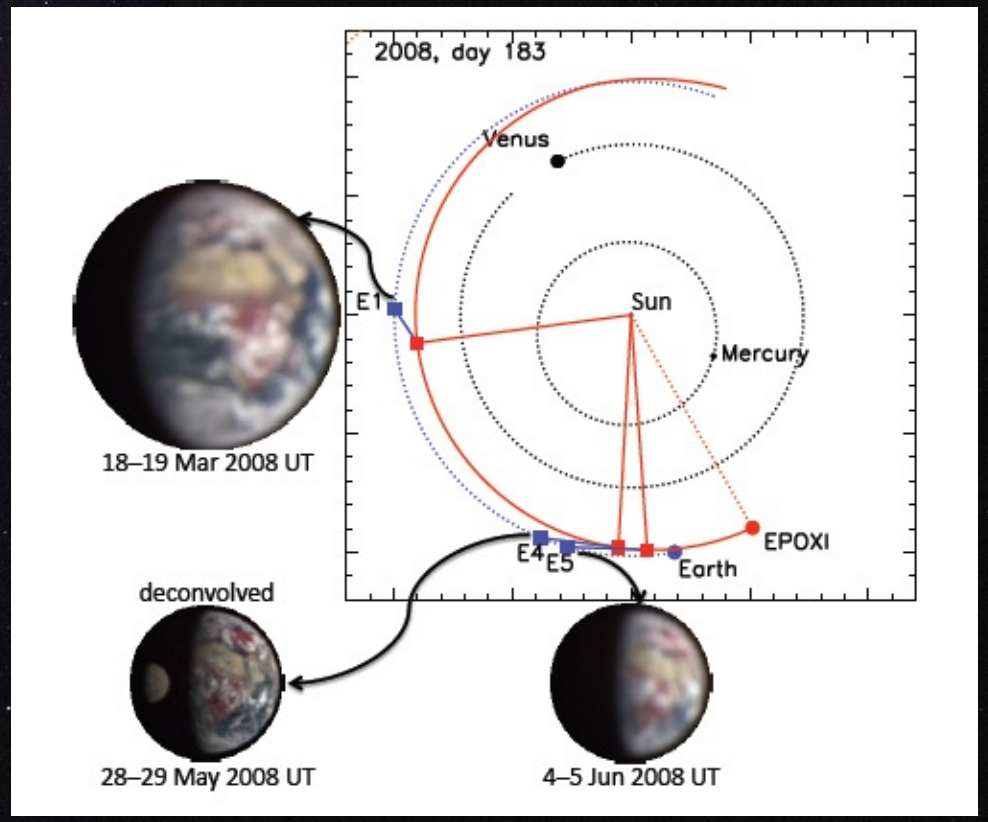


Robinson & Reinhard, *Planetary Astrobiology*

Limited Existing Disk-Averaged, Phase-Dependent Data



EPOXI/Deep Impact (Livengood+ 2011)

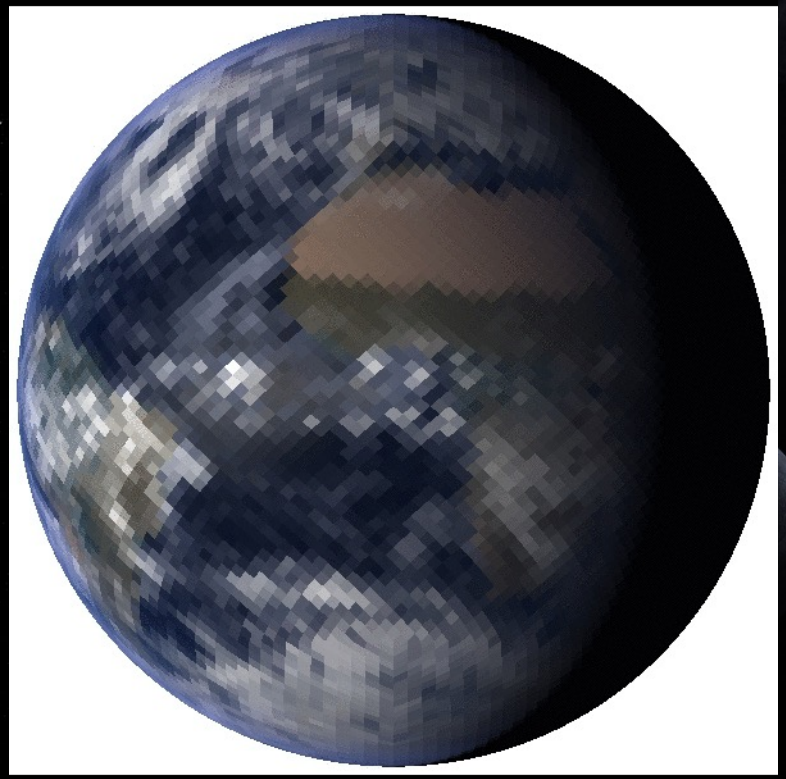


DSCOVR/EPIC (e.g, Carlson+2019)

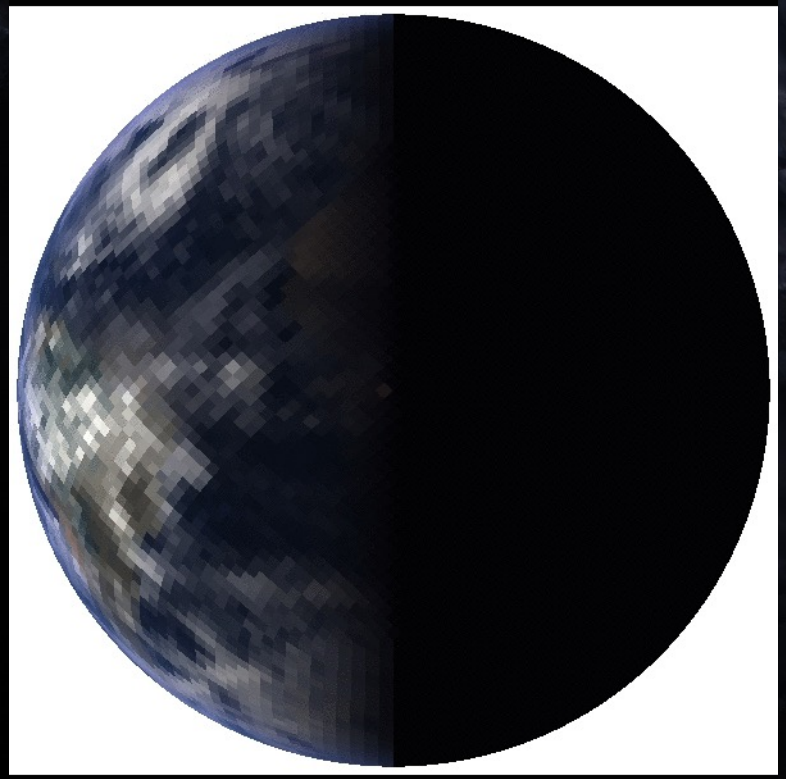
(Validated) Earth Models Can Provide Predictions at Other Phase Angles

Earth Orbital Phase Evolution

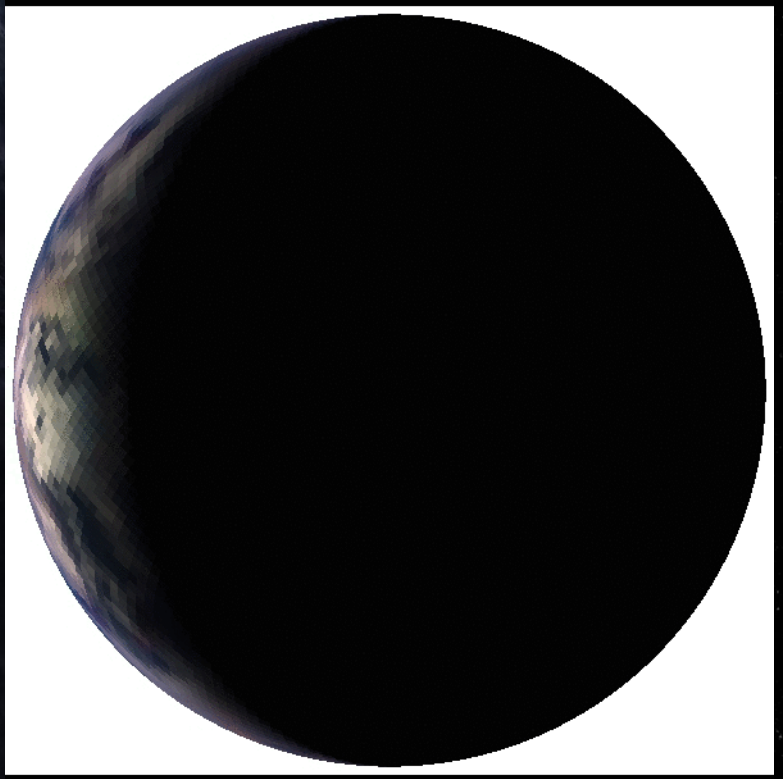
Gibbous (α = 45°)



Quadrature (α = 90°)



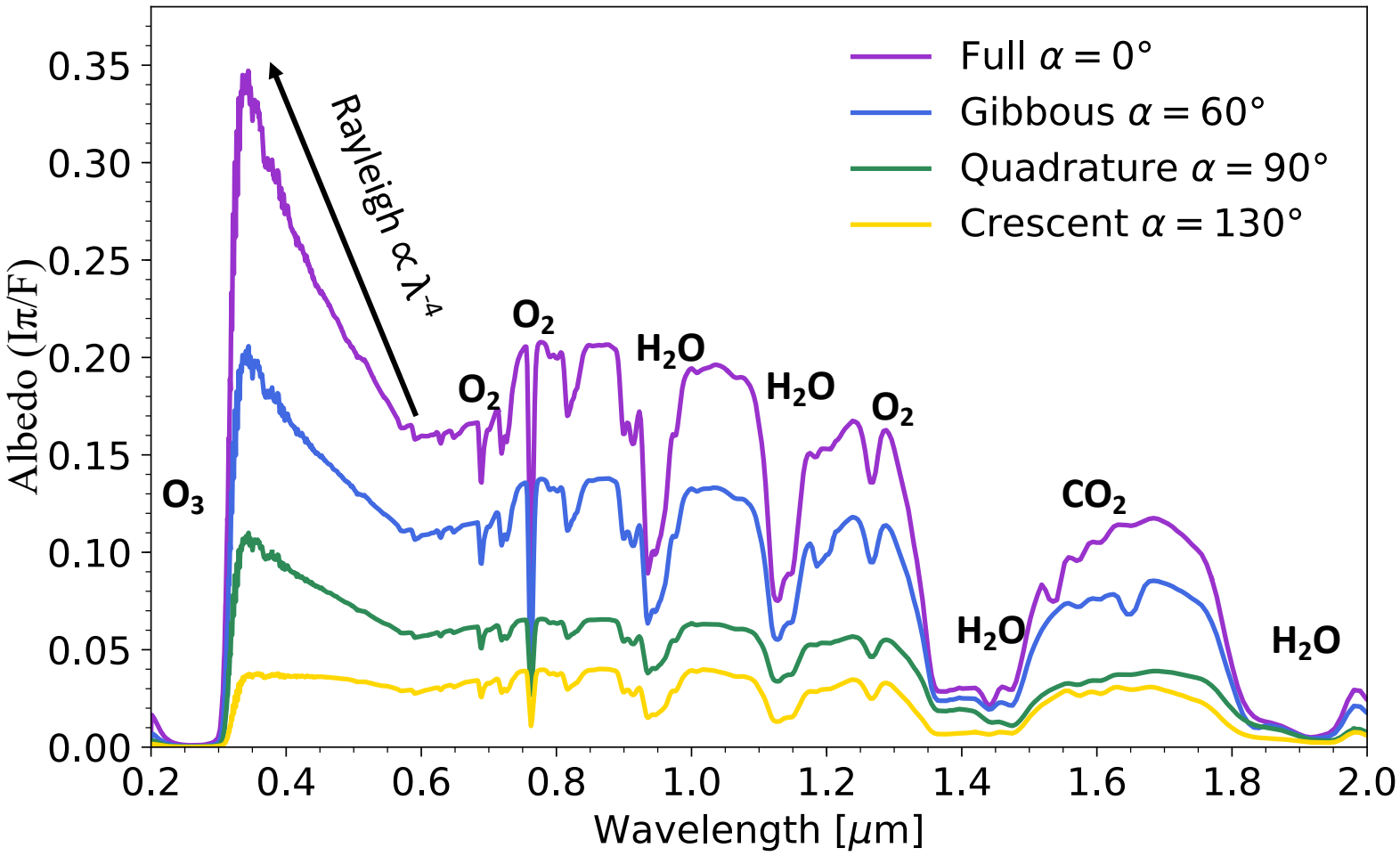
Crescent (α = 135°)

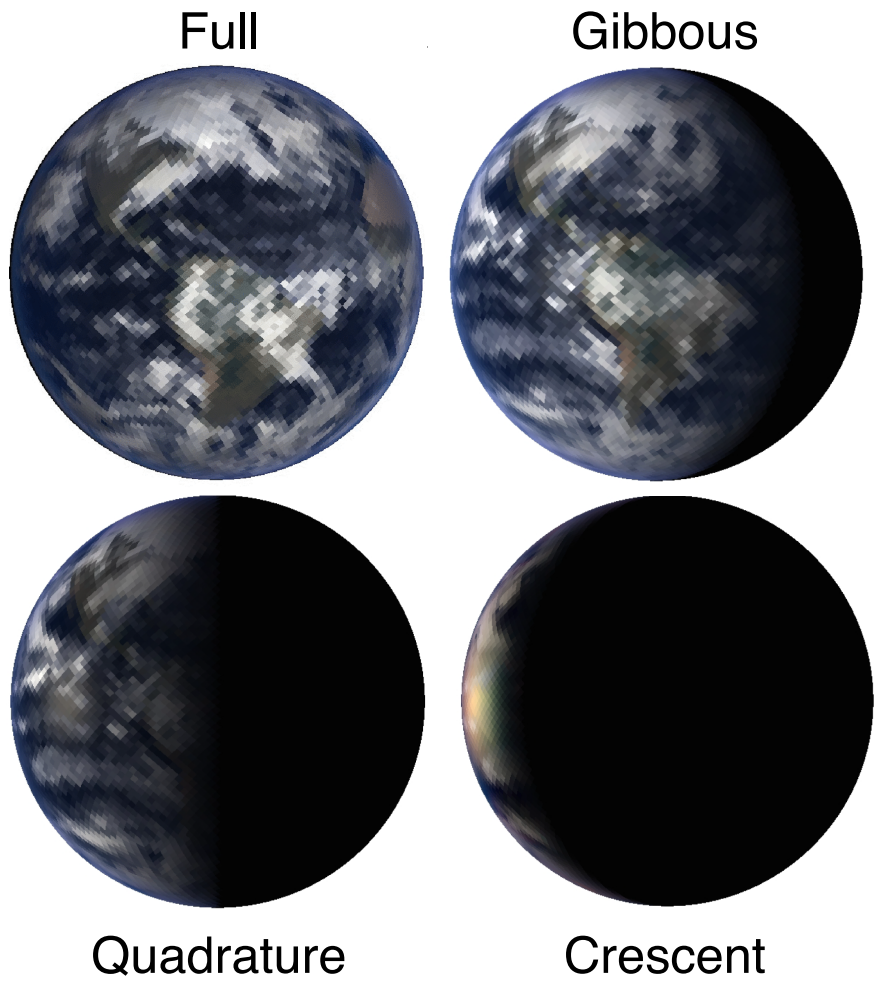


VPL Earth Model (e.g., Robinson+2011, 2014)

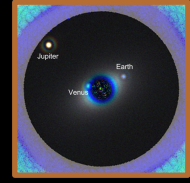
Spectrum as a Function of Phase

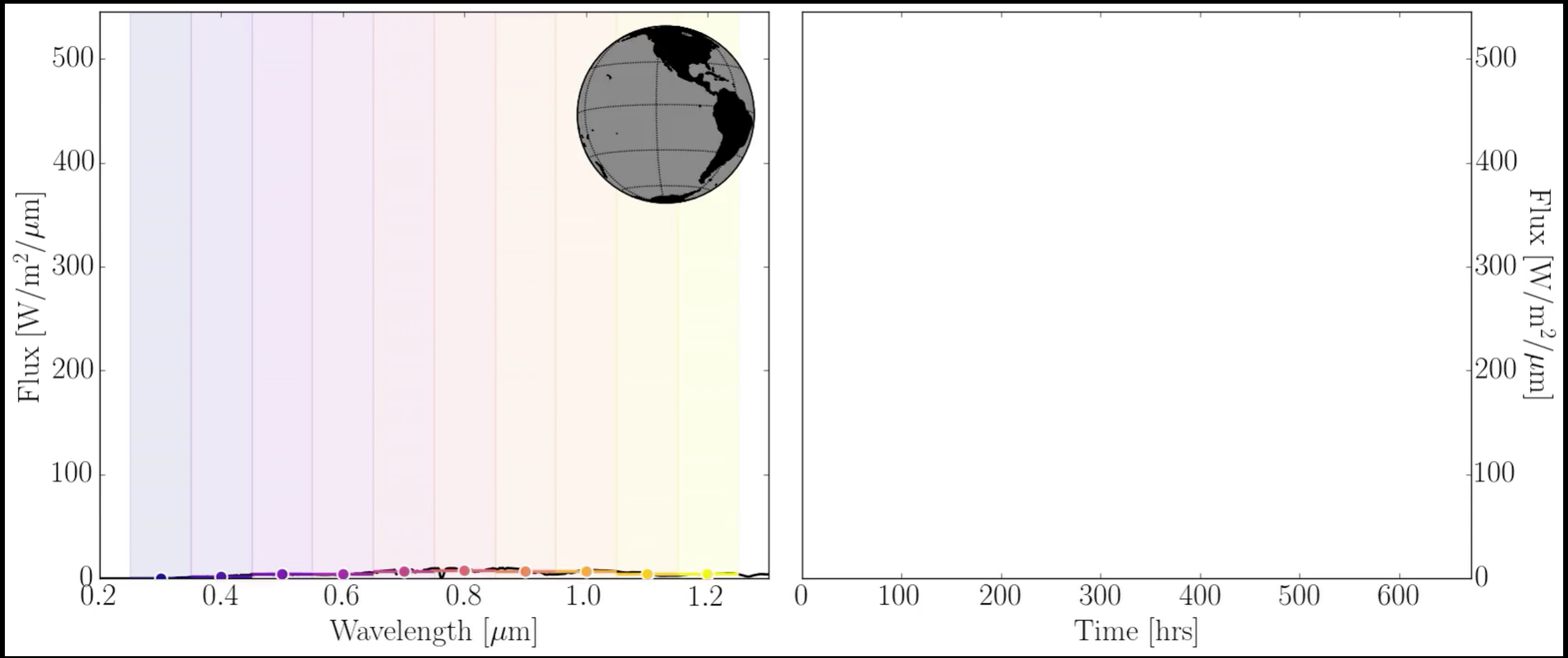
VPL Earth Model





Earth Shows Wavelength-Dependent Phase and Diurnal Variations

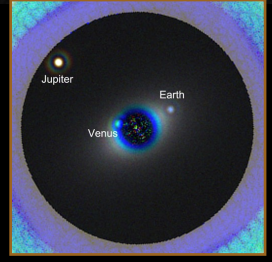


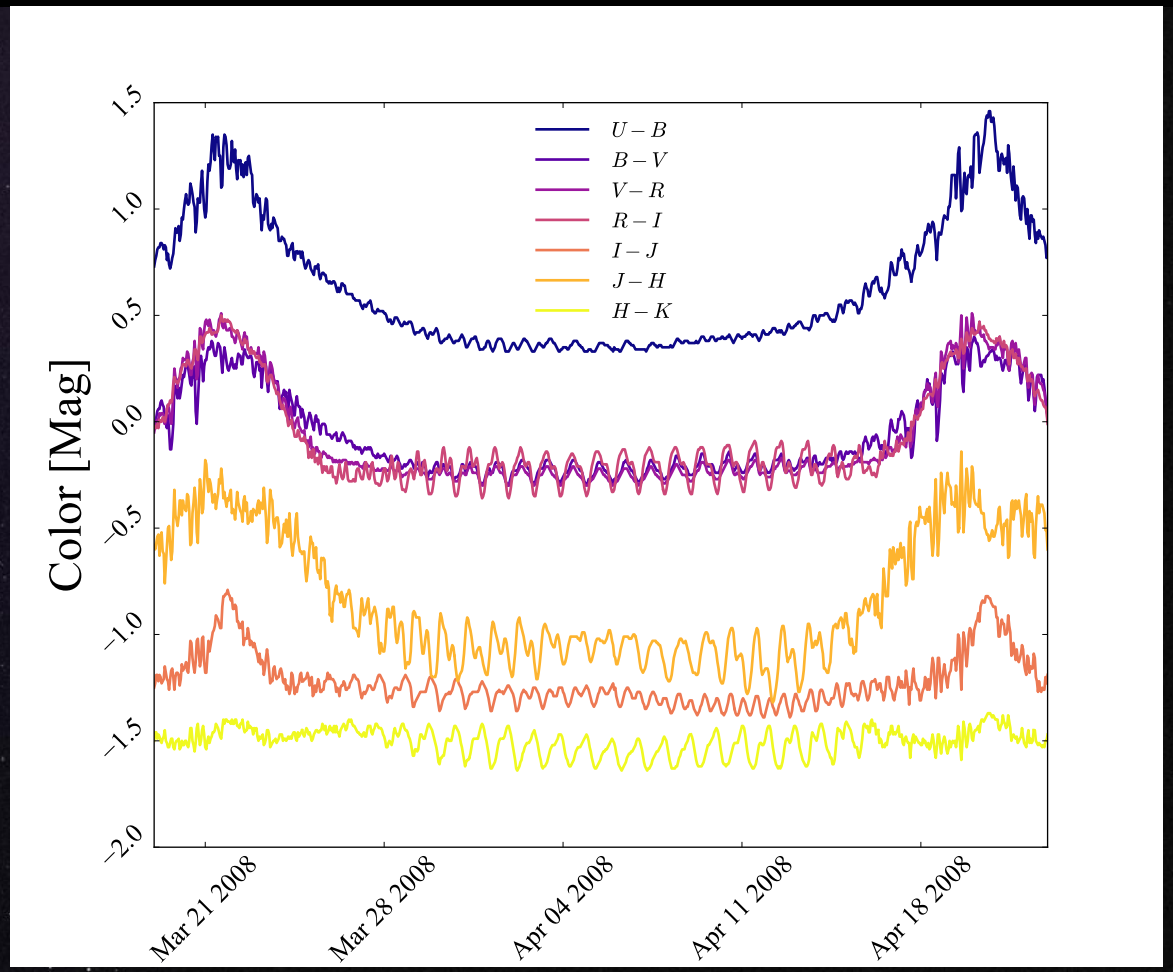


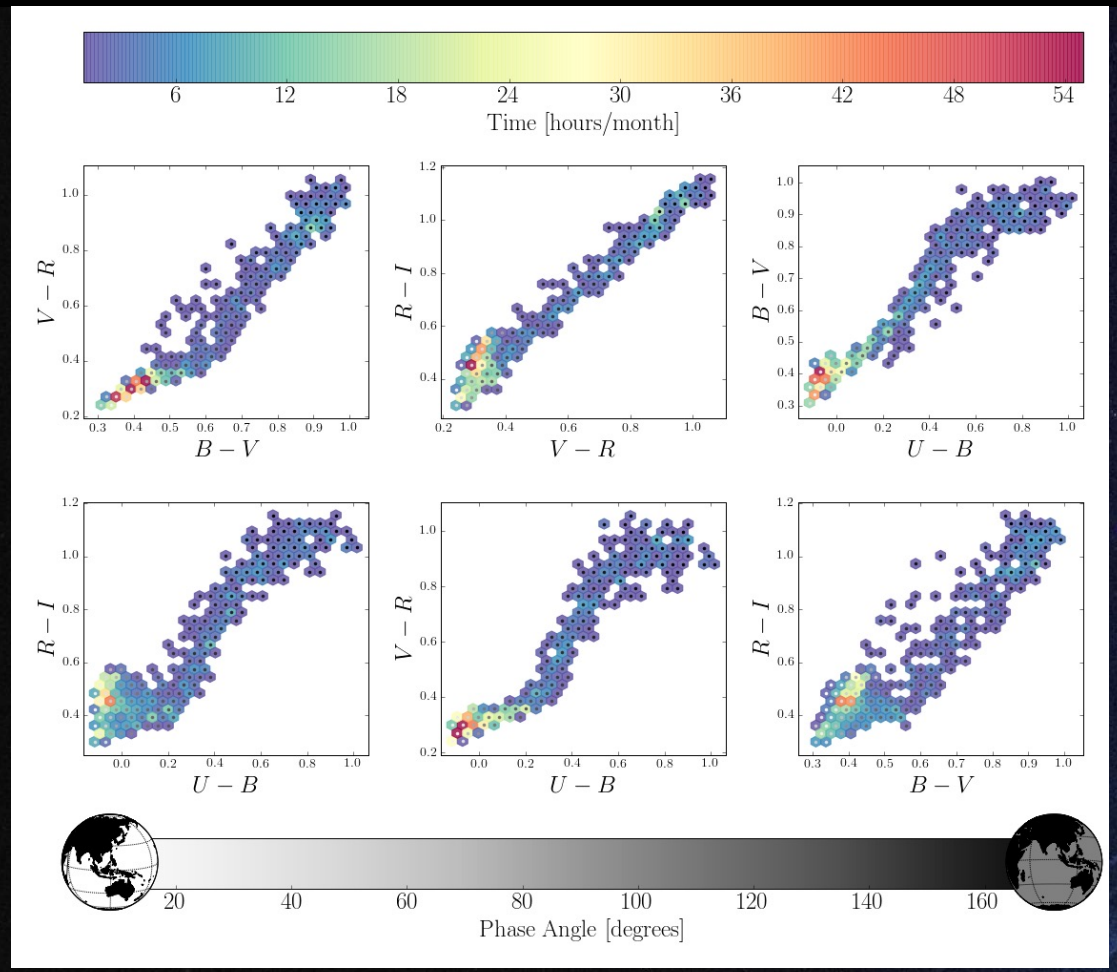
Earth from Moon one month database with 1-hr cadence [Model]

Credit: J. Lustig-Yaeger, E. Schwieterman, & VPL Team

Earth Displays Diverse Colors Over Its Phase Evolution





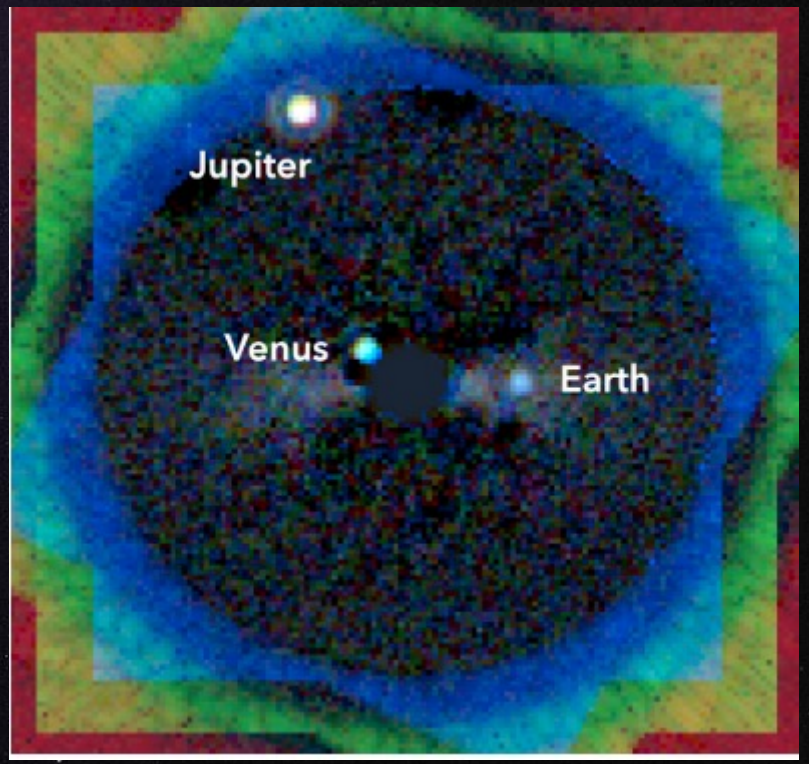


Earth from Moon one month database with 1-hr cadence [Model]

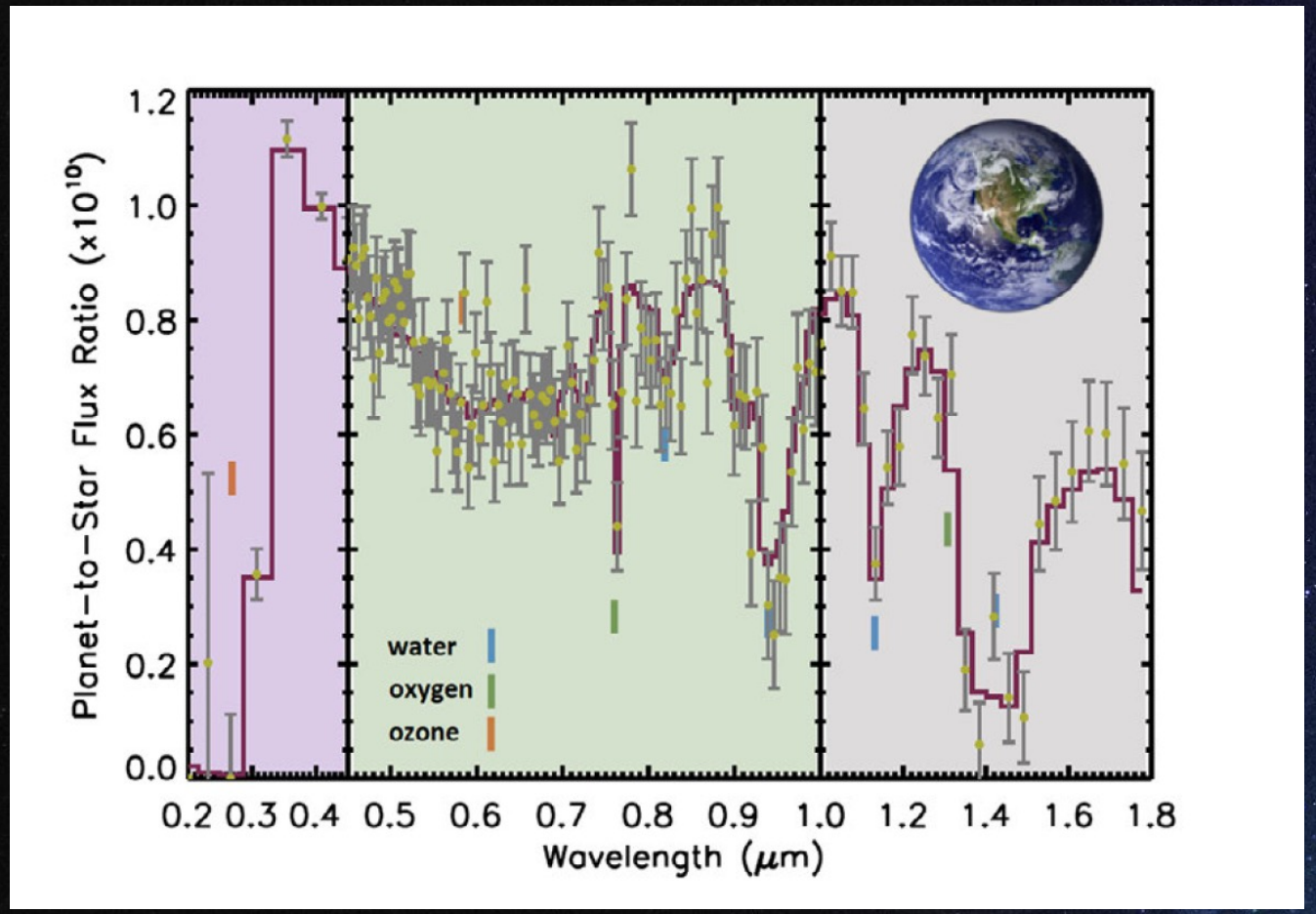
Credit: J. Lustig-Yaeger, E. Schwieterman, & VPL Team

How An ExoEarth Would Be Imaged in Reflected Light (HWO)

Star nulling by coronagraph or starshade (10^{10})

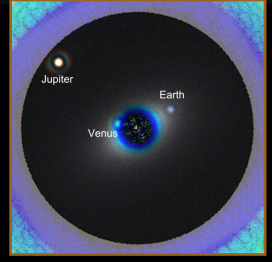


LUVOIR Report; Roberge et al. 2018

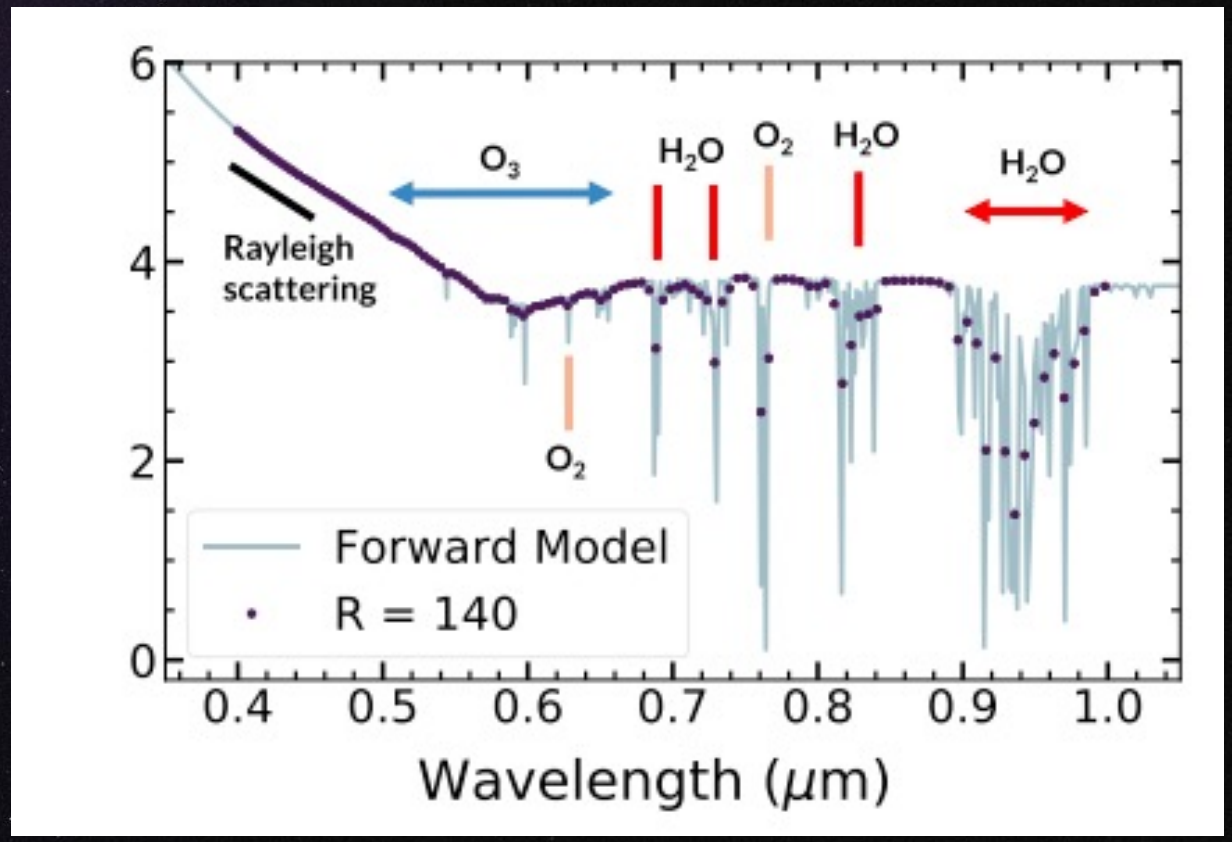


HabEx Report; Robinson et al. 2016

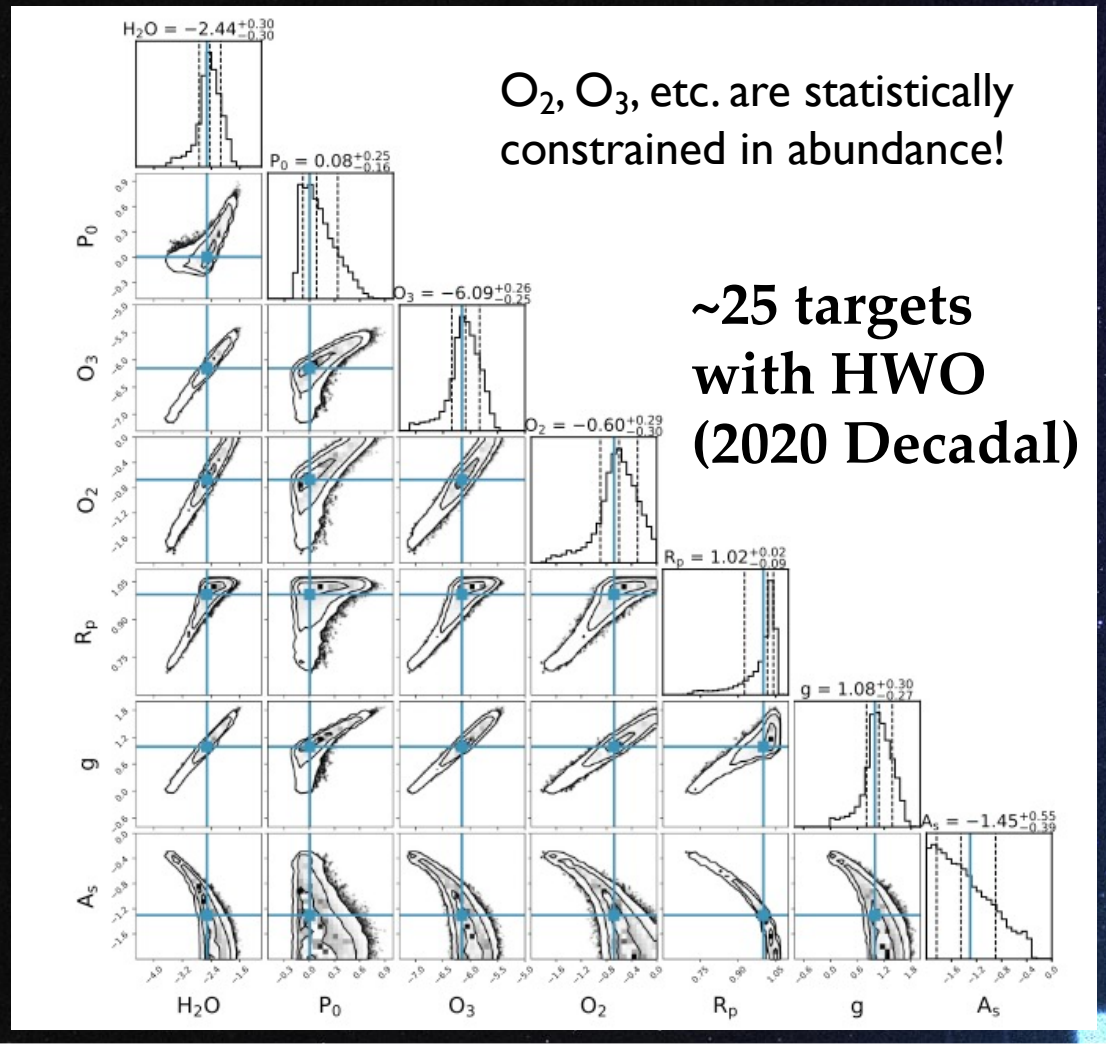
Atmospheric Retrievals Will Help Confirm Signatures



Employing an Inverse Model



Feng et al. 2018, AJ, 155:200

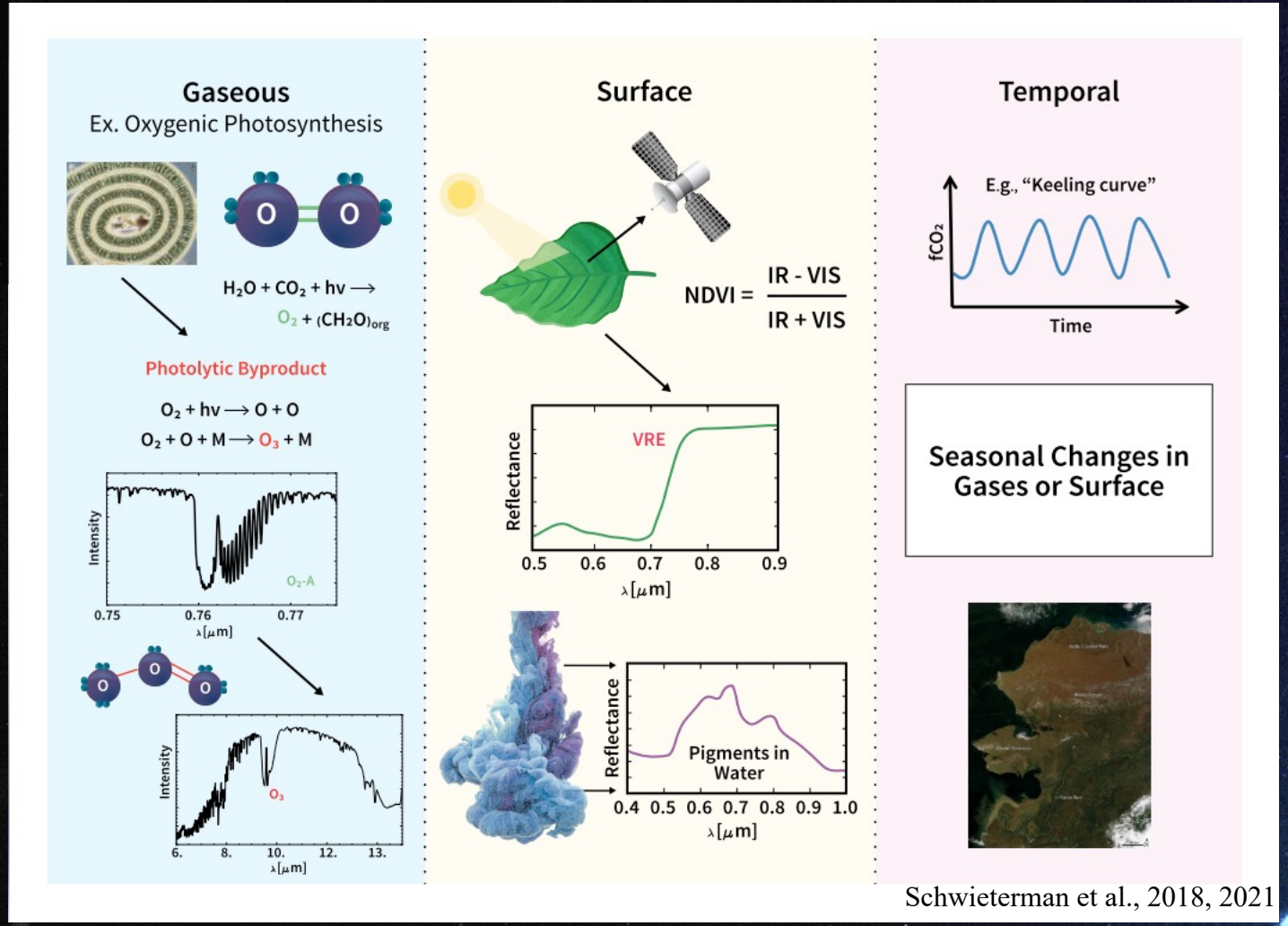


O_2, O_3, etc. are statistically constrained in abundance!

~25 targets with HWO (2020 Decadal)

Extending Earth Biosignatures to Those Possible on ExoEarths

- **Atmospheric Gases:** O_2, O_3, CH_4, N_2O, DMS—$(CH_3)_2S$, DMSe—$(CH_3)_2Se$, C_5H_8, CH_3Cl, CH_3Br, CH_3SH, PH_3, NH_3, etc.
- **Surface Features:** Vegetation Red Edge (VRE), anoxygenic photosynthesis, rhodopsins, other pigments
- **Temporal Changes:** Seasonal Change in Gas (e.g., CO_2, CH_4, O_3 or Pigments)
- **Always Context-Dependent!**



Schwieterman et al., 2018, 2021

Earth Through Time: Biosignature Combinations (Reflected Light)

Anoxic, no haze: $CH_4 + H_2O + \lambda^{-4} + CO_2$

Strongest Anoxic: haze + H_2O + CH_4 + CO_2

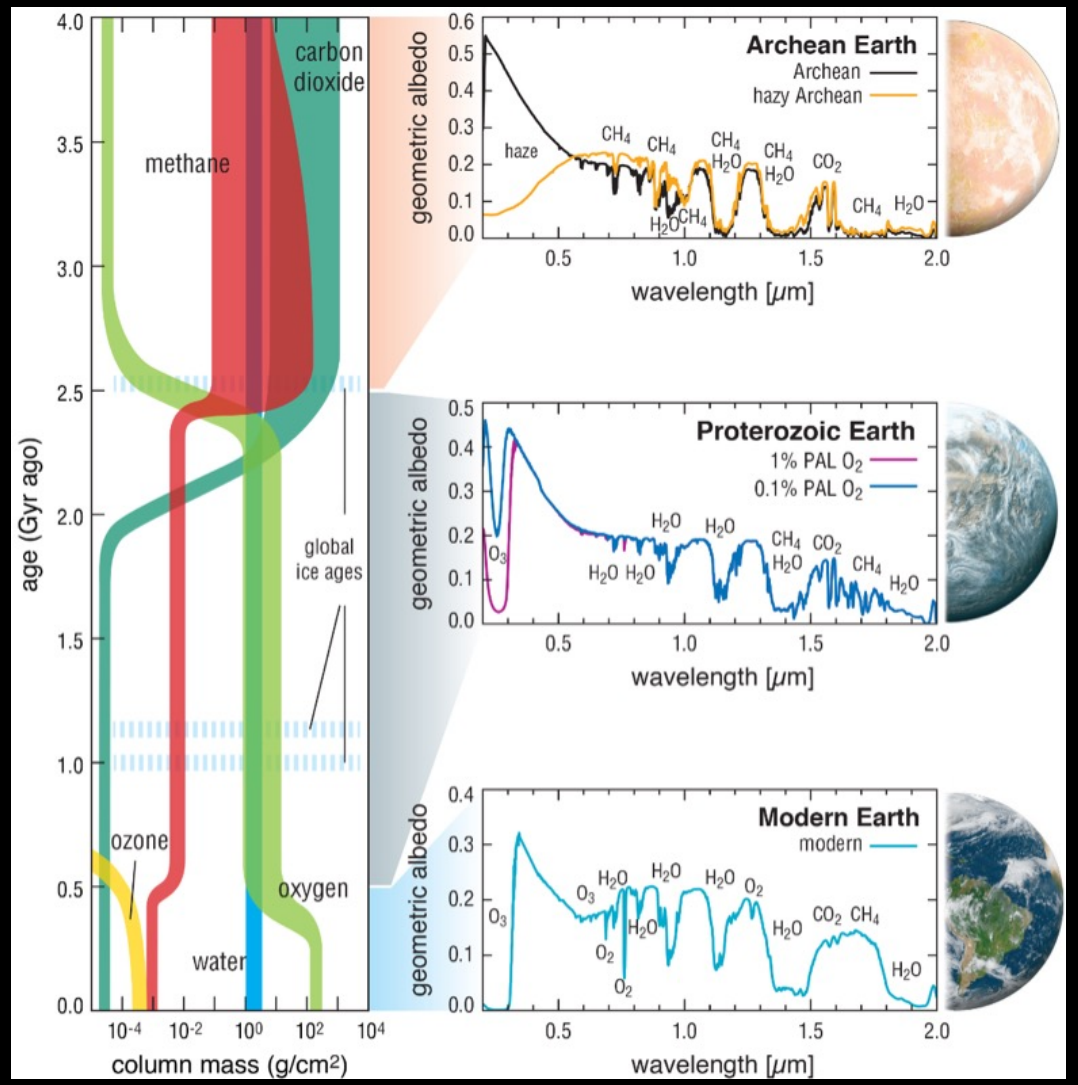
Weakly Oxygenated: O_3 + λ^{-4} + H_2O [+ CH_4]

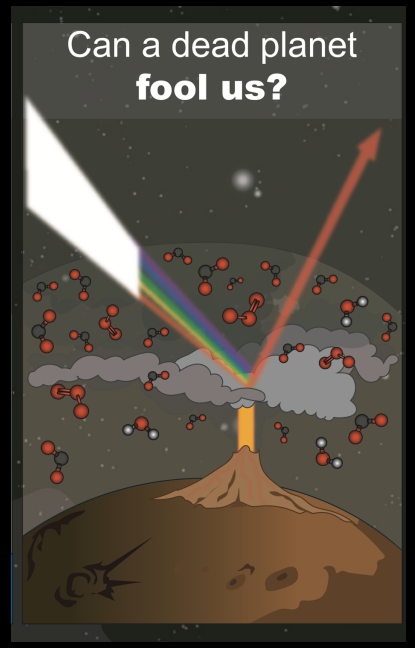
Strong Oxygen-rich: O_3 + λ^{-4} + H_2O + O_2

Strongest Oxygen-rich: O_3 + λ^{-4} + H_2O + O_2 + CH_4

Biosignatures and false positive evaluators are ordered by their relative detectability in atmospheric spectra

LUVOIR Final Report





Context can help rule out "false positives"

Detecting H_2O, CH_4, and/or the Rayleigh slope ($\propto \lambda^{-4}$) can confirm biological nature of O_2/O_3.

Certain features (O_2-O_2 CIA) would confirm a "**false positive**."

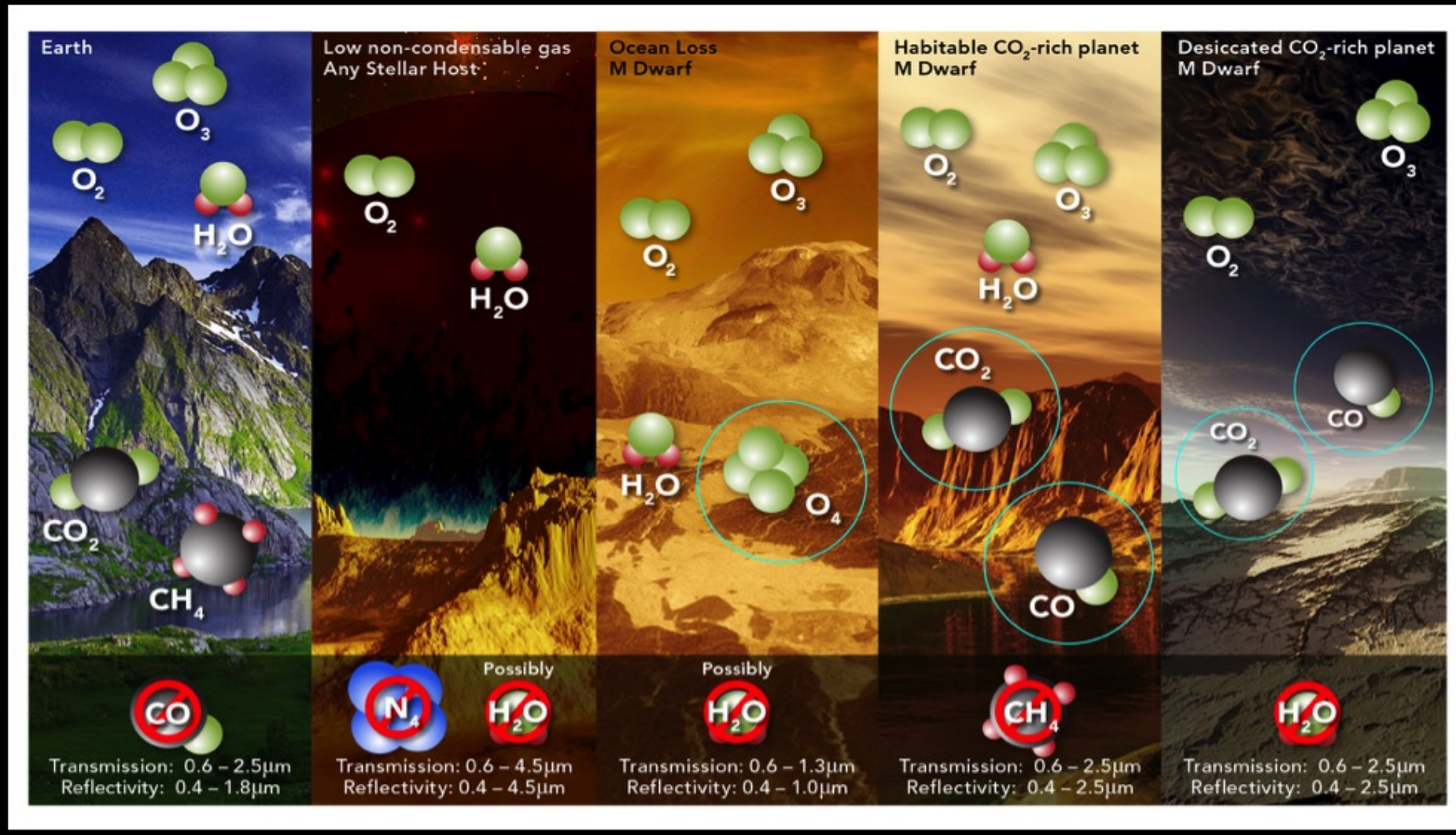


Image Credit R. Hasler e.g., Tian+2015; Domagal-Goldman+14,Hu+2020; Meadows+2017,2018; Schwieterman+2016

Searching for Life via Thermodynamic Disequilibria

A search for life on Earth from the Galileo spacraft

Carl Sagan*, W. Reid Thompson*, Robert Carlson†, Donald Gurnett‡ & Charles Hord§

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

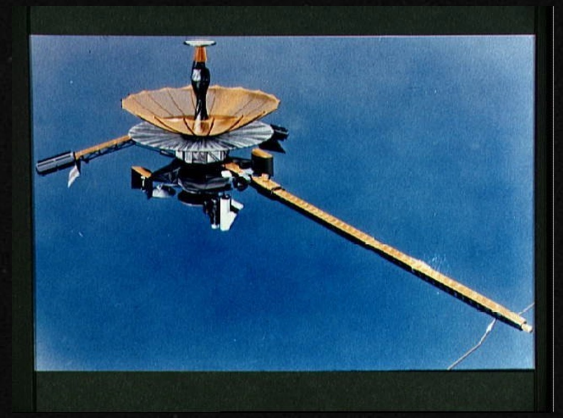
Molecule	Standard abundance (ground-truth Earth)	Galileo value*	Thermodynamic equilibrium value Estimate 1†	Estimate 2‡
N_2	0.78		0.78	
O_2	0.21	0.19 ± 0.05	0.21§	
H_2O	0.03–0.001	0.01–0.001	0.03–0.001	
Ar	9×10^{-3}		9×10^{-3}	
CO_2	3.5×10^{-4}	$5 \pm 2.5 \times 10^{-4}$	3.5×10^{-4}	
CH_4	1.6×10^{-6}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

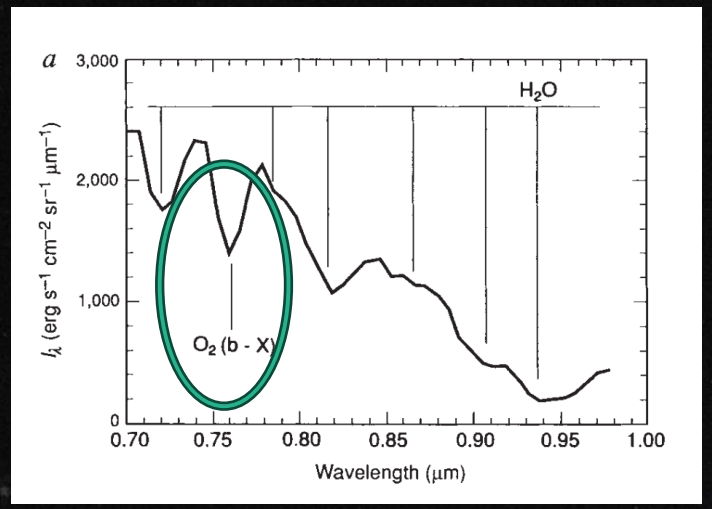
† From ref. 16 (P, 1 bar; T, 280 K).

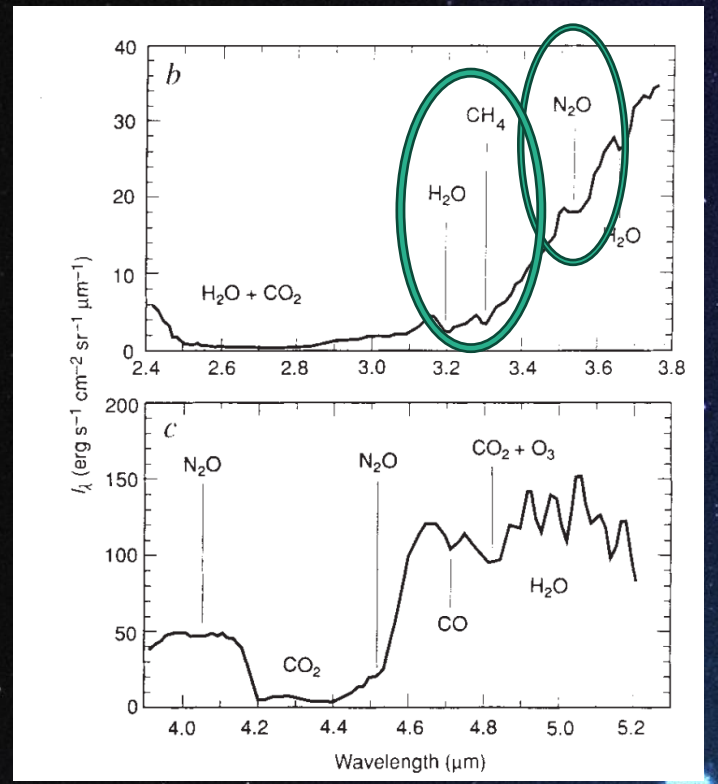
‡ From ref. 17 (P, 1 bar; T, 298 K).

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



Kinetic disequilibrium is most important! CH_4 lifetime ~10 years. N_2O ~140 years.





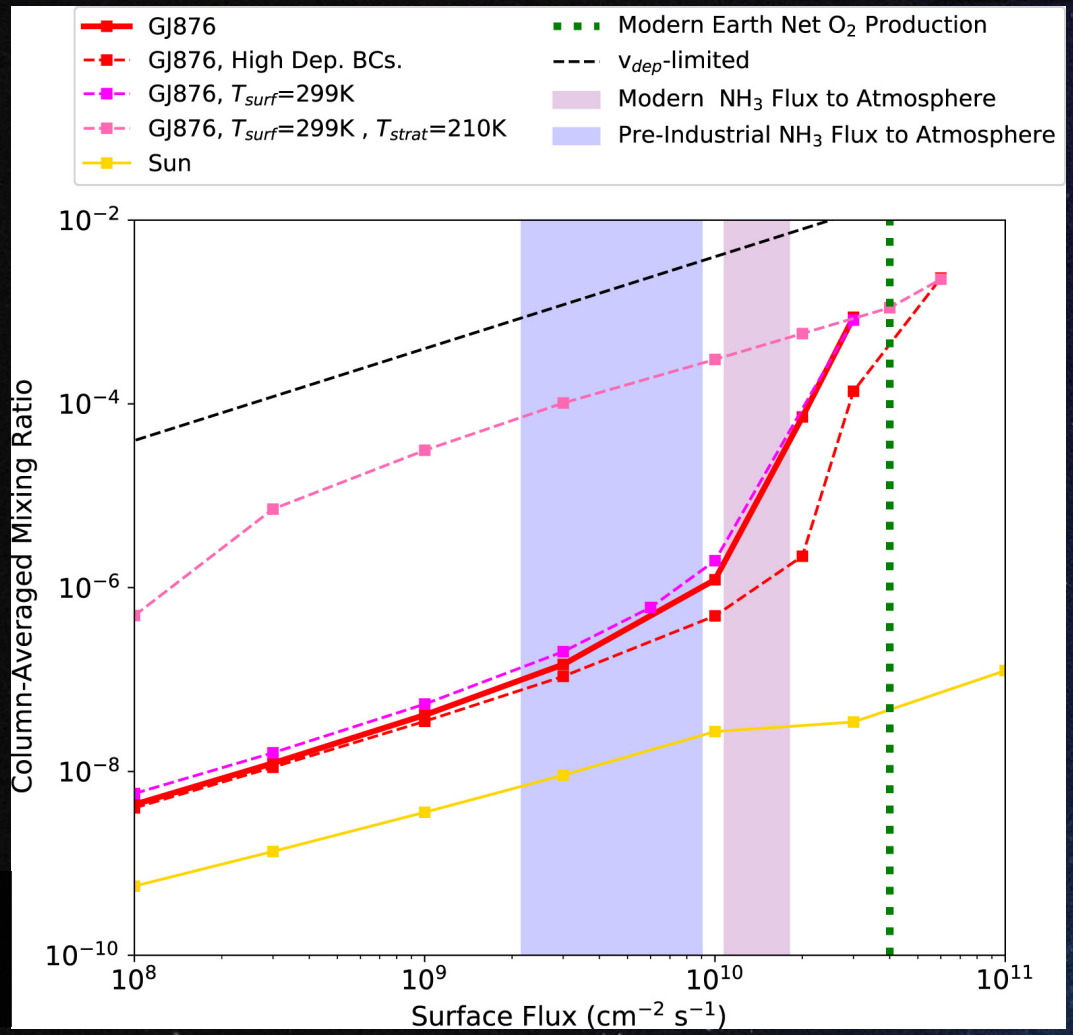
Biogenic Gases on Earth: "Equilibrium" vs. "Non-Equilibrium" Gases

"Photochemical Runaway" (Ranjan+2022, AJ, 930:131)

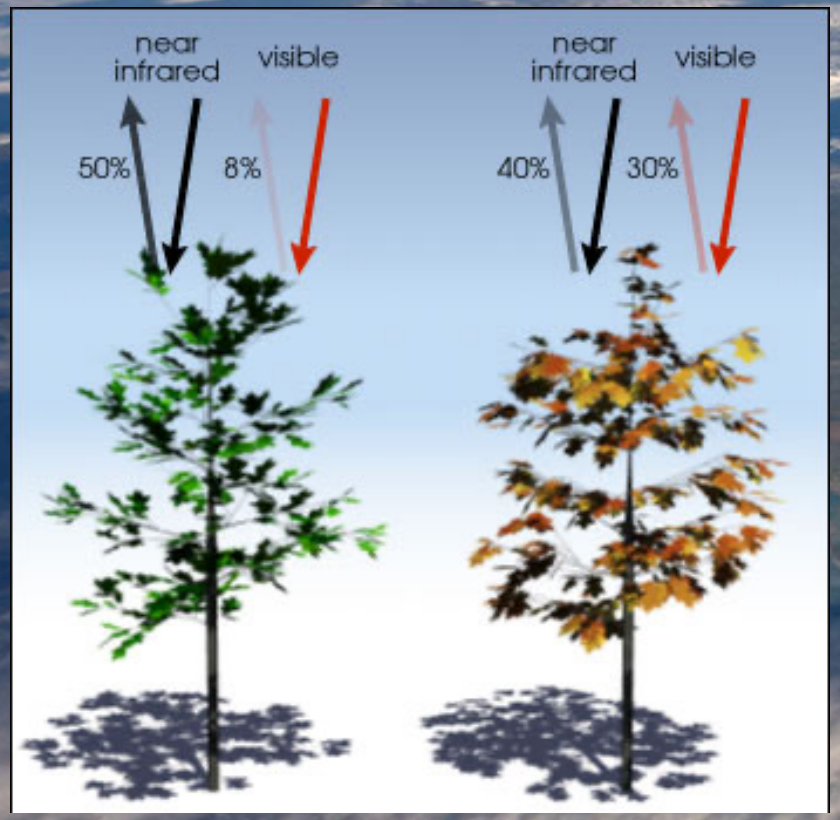
Gases formed at equilibrium in gas giant atmospheres (or via volcanism), but with strong kinetic disequilibrium in N_2-CO_2-[-O_2] or temperate H_2 Atmospheres, e.g., CH_4 (Thompson+2022), NH_3 (Philips+2021, Huang+2022), PH_3 (Sousa-Silva+2020).

Gases not formed via equilibrium (albeit with other abiotic sources), e.g., DMS/DMDS (Domagal-Goldman+2011), isoprene—C_5H_8 (Zhan+2021), halomethanes (Leung+2022; **see poster!**), N_2O (Schwieterman+2022).

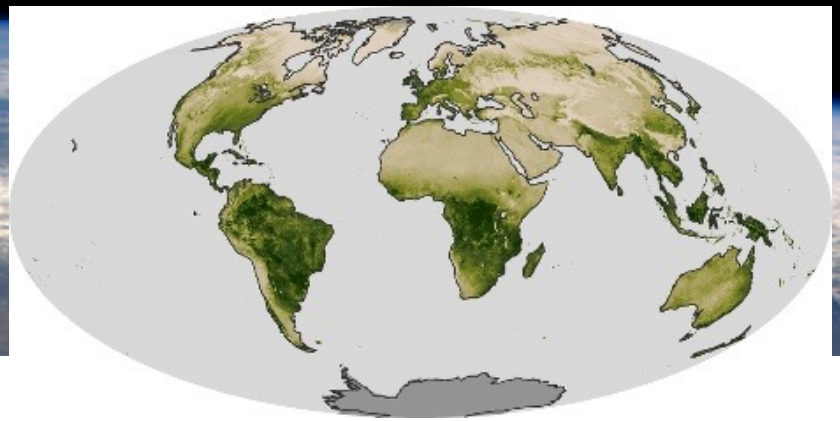
Gas lifetime will be a strong function of flux and host star spectrum—longer lifetimes for later stars.

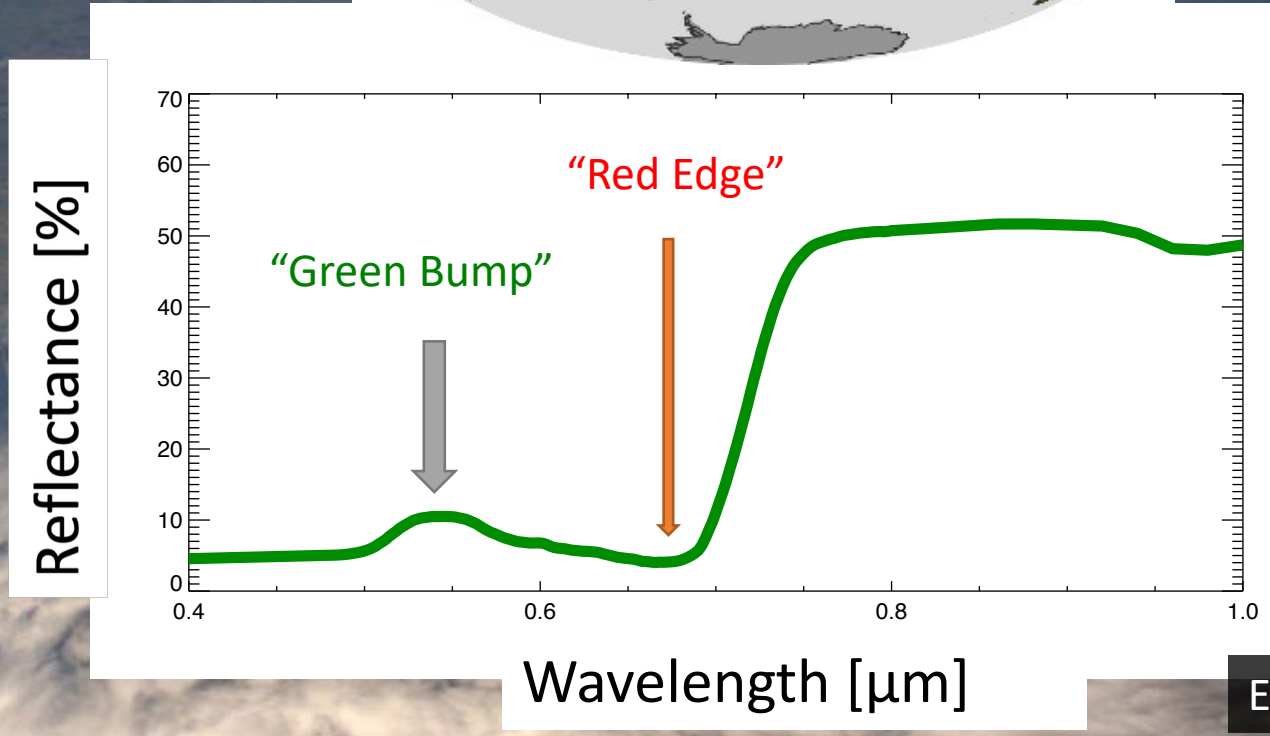


Surface Biosignature: Vegetation "Red Edge"



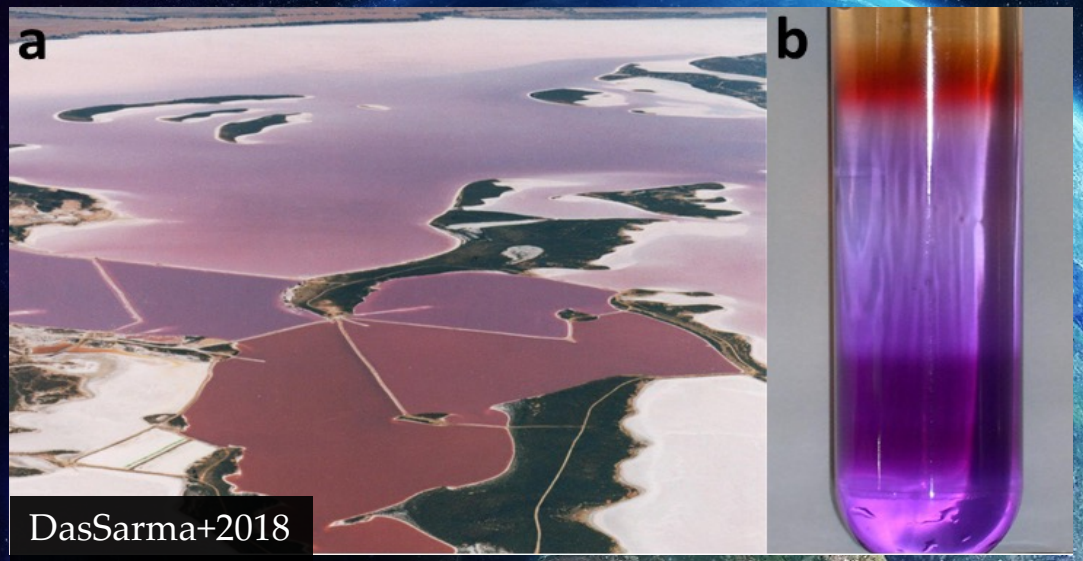
NASA Earth Observatory





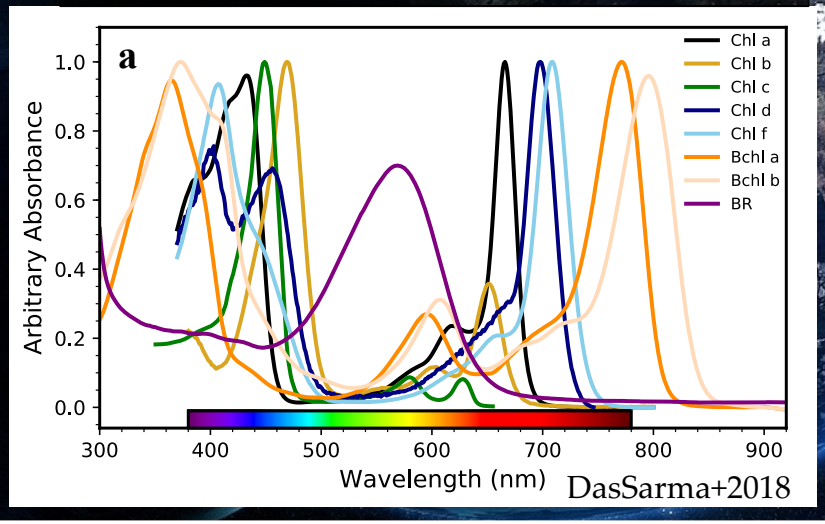
E.g., Seager (2005)

Halophiles: Rhodopsin & Carotenoids



Bacteriochlorophylls and Carotenoids

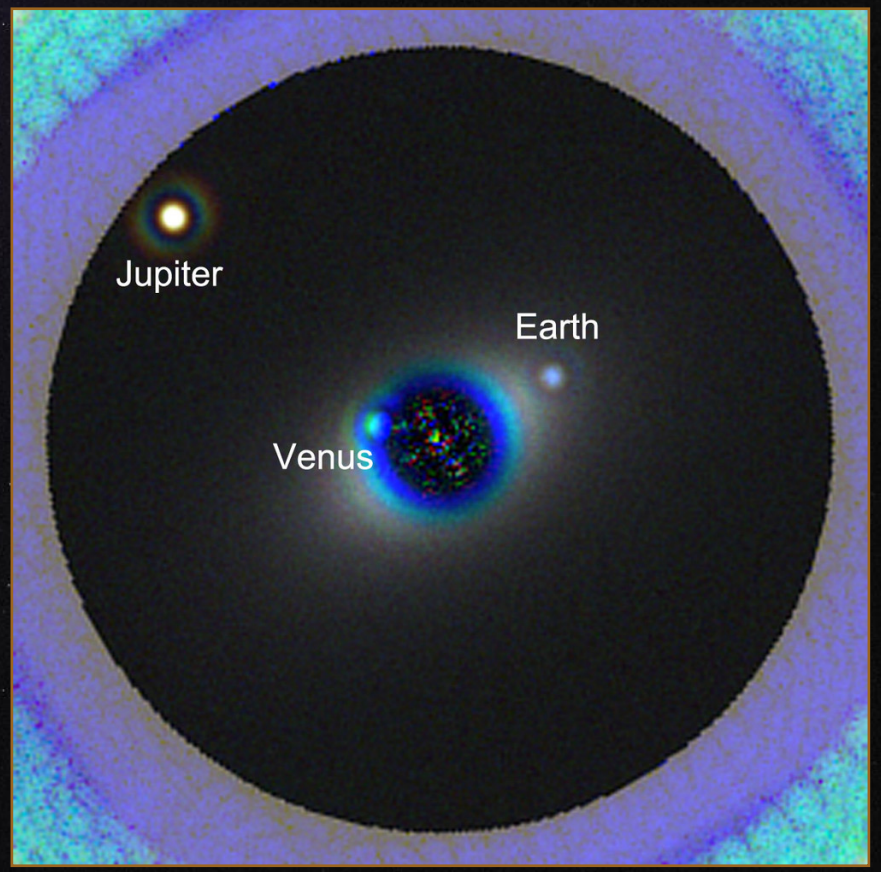
Complementary Absorption



San Francisco Salt Ponds

Questions?

Thank you!



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