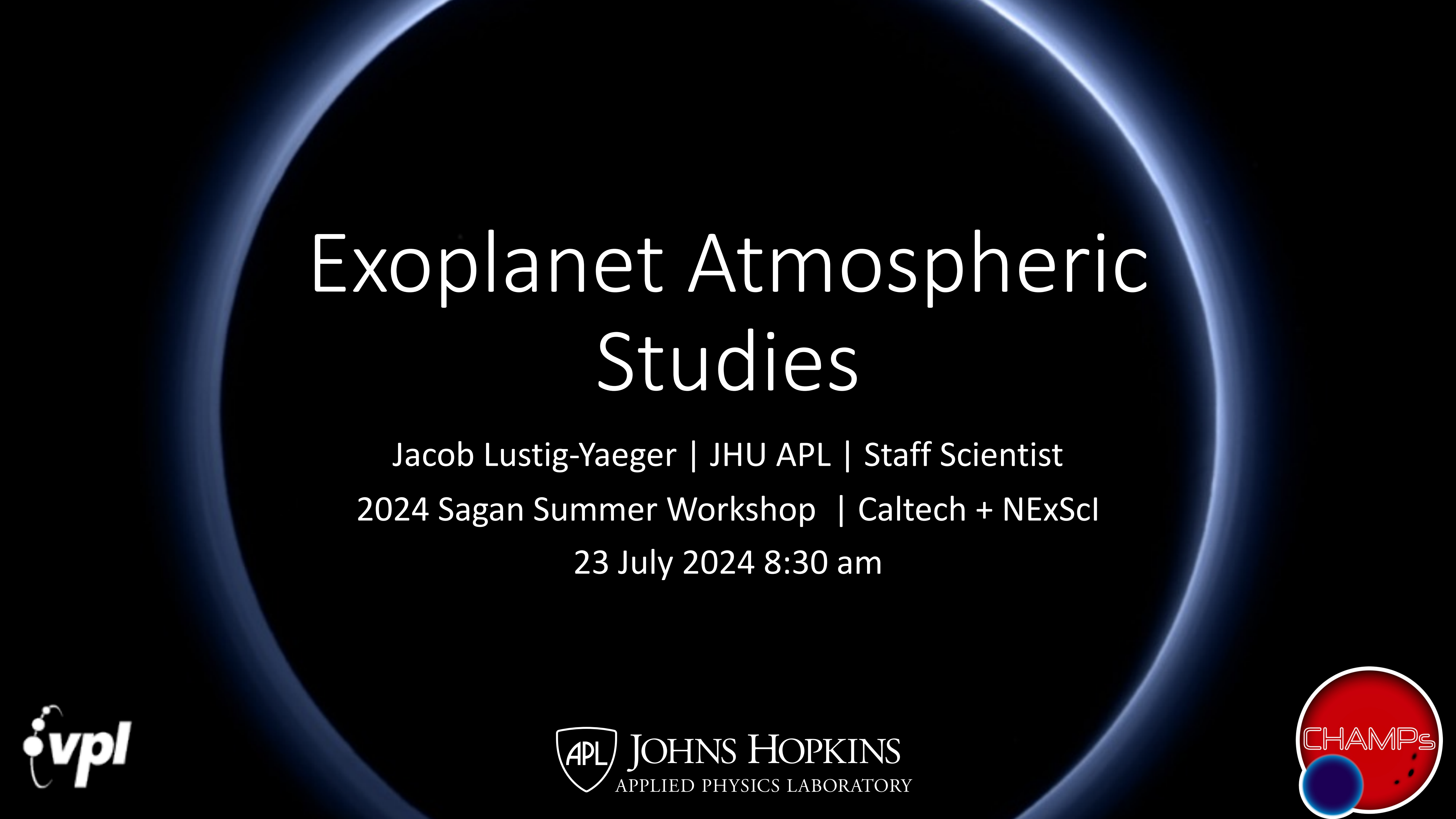


Exoplanet Atmospheric Studies

Jacob Lustig-Yaeger | JHU APL | Staff Scientist

2024 Sagan Summer Workshop | Caltech + NExScI

23 July 2024 8:30 am

vpl

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

CHAMPs

Atmospheres are the interface between a planet and the rest of the universe

A layer of gravitationally bound gas

It filters starlight incident on the planet and moderates the light that leaves it

A dance of physics and chemistry that drives dynamics and climate

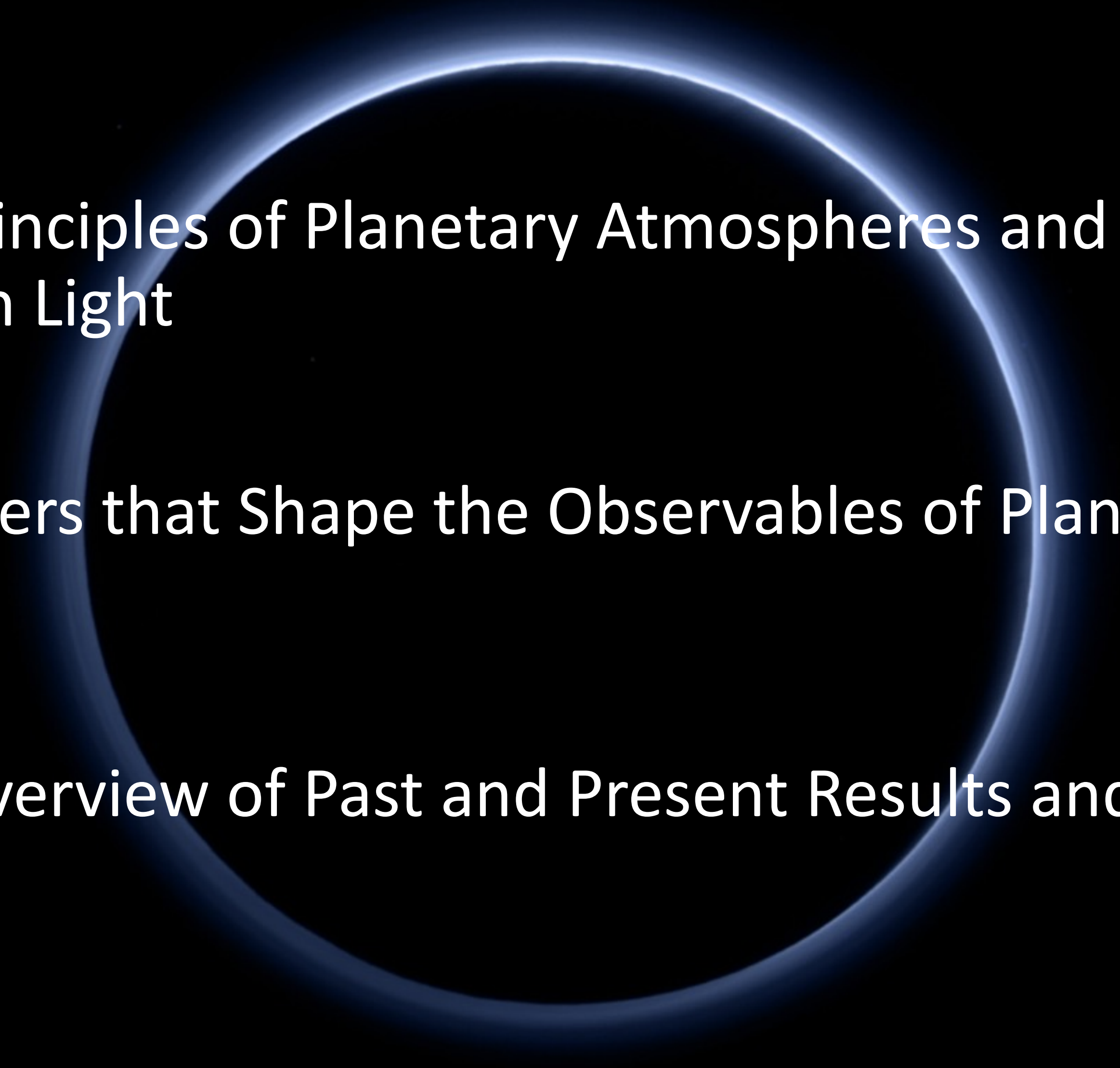
Remotely observable and amenable to distant study by us

Shaped by the formation of the planet and its evolutionary history

Can contain gaseous byproducts of life processes and spectroscopically broadcast evidence of a global biosphere

NASA/JHUAPL/SwRI

Exoplanet Atmospheric Studies



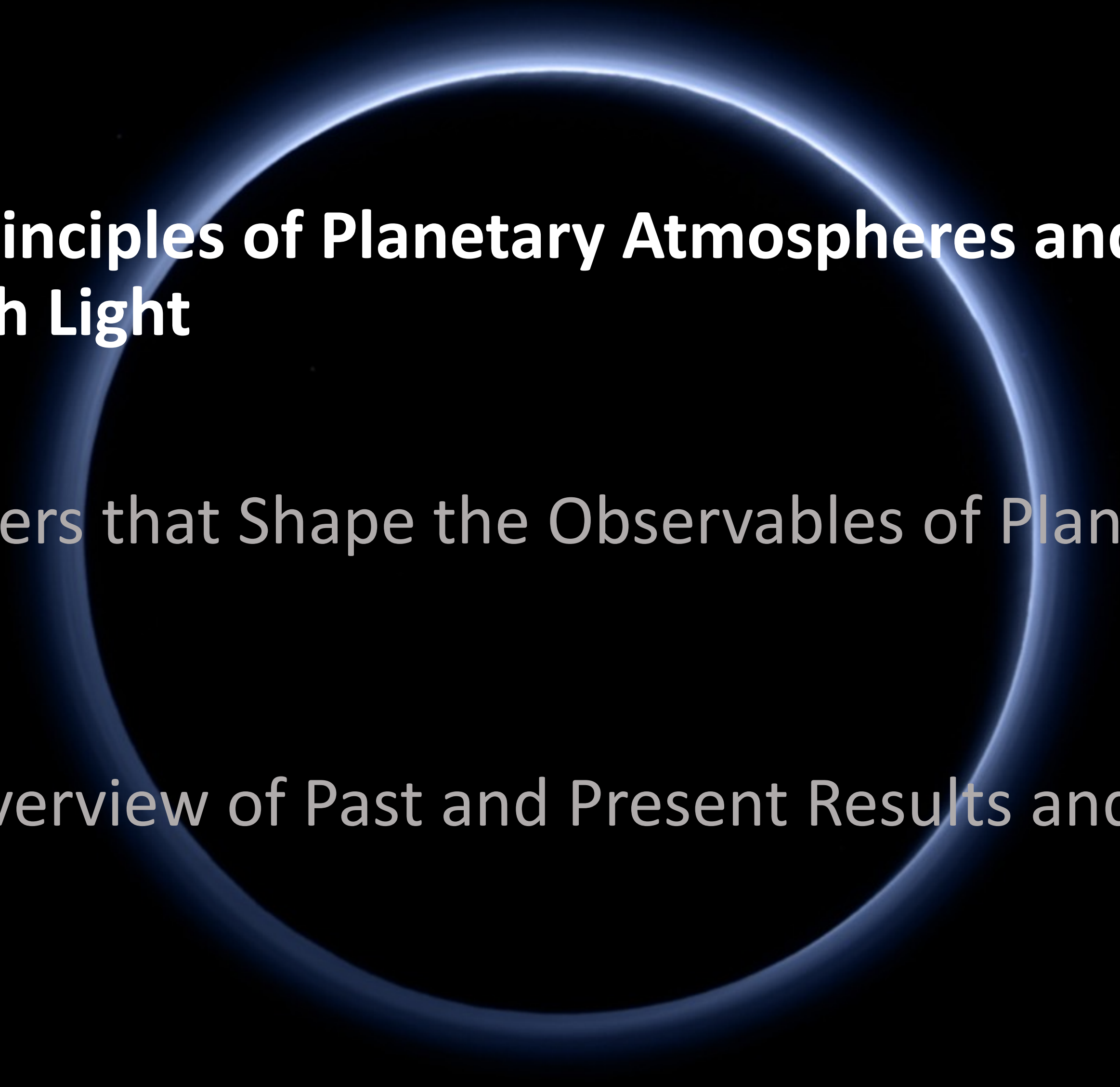
Part 1 – Basic Principles of Planetary Atmospheres and their Interactions with Light

Part 2 – Key Levers that Shape the Observables of Planetary Atmospheres

Part 3 – Brief Overview of Past and Present Results and Future Goals

NASA/JHUAPL/SwRI

Exoplanet Atmospheric Studies



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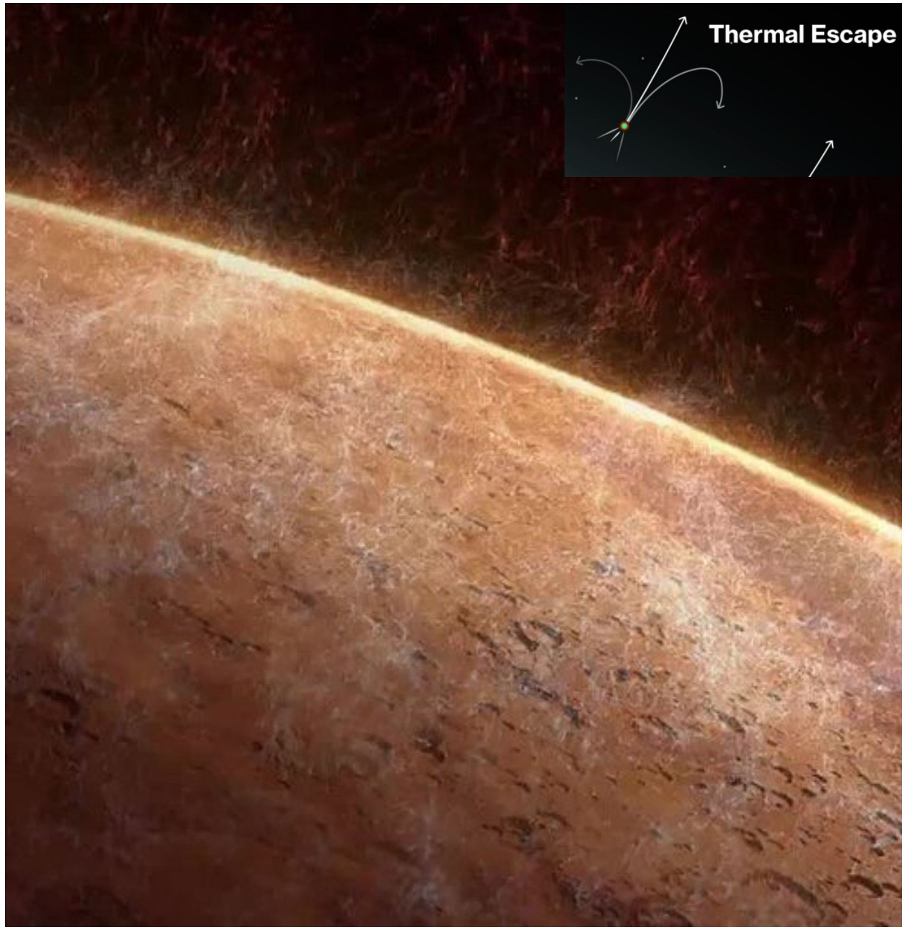
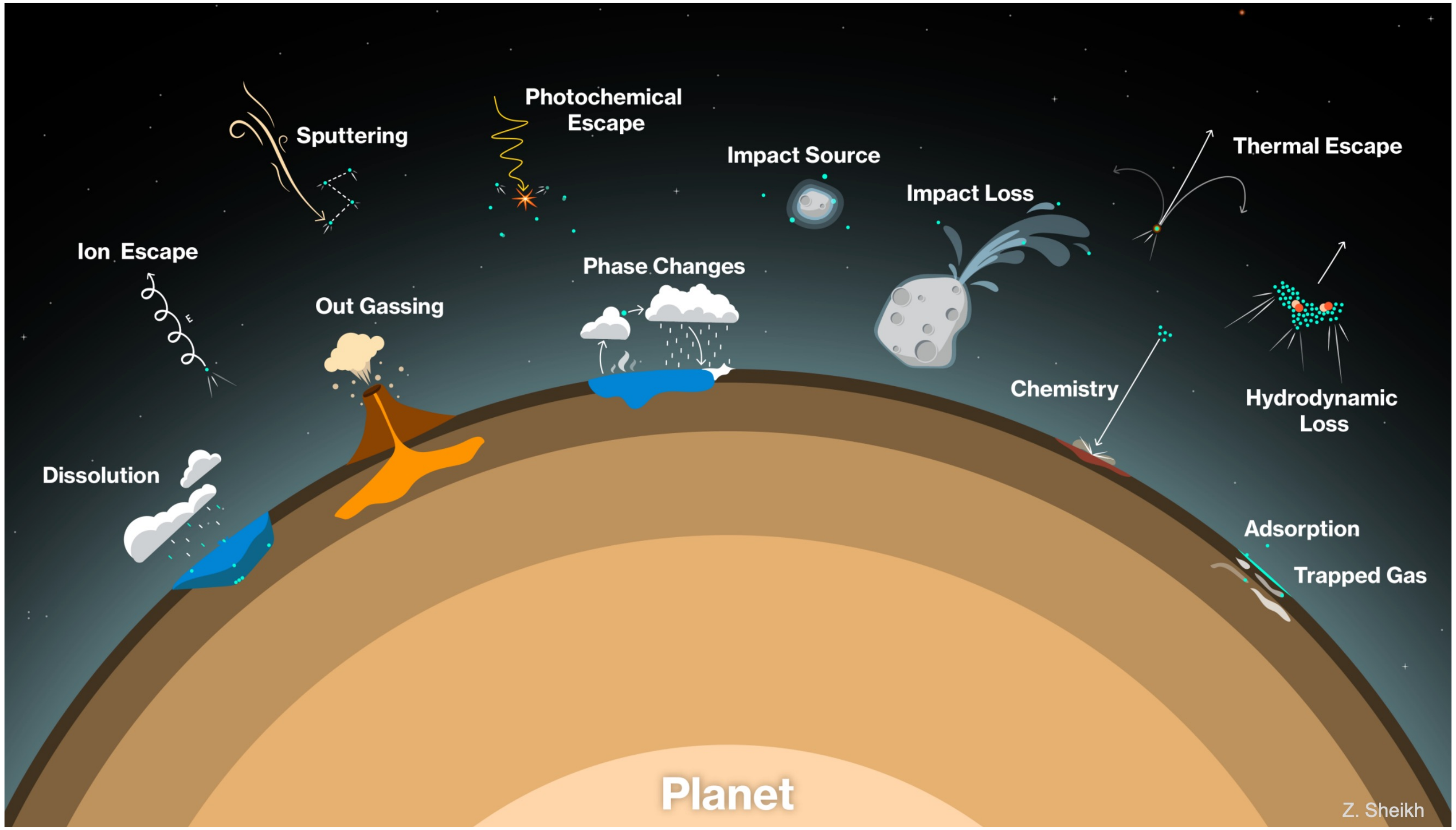
Stability against Atmospheric Escape

$$\overbrace{\sqrt{\frac{2GM_p}{R_p}}}^{\substack{\text{Escape Velocity}\\ \text{from the planet}}} > \underset{\substack{\uparrow\\ \text{Typical “rule of thumb” to}\\ \text{achieve stability}}}{6}\,\overbrace{\sqrt{\frac{2k_BT}{m}}}^{\substack{\text{Thermal Velocity}\\ \text{of the gas}}}$$



Many Atmospheric Source and Loss Processes



Credit: David Brain
LASP / University of Colorado

Hydrostatic Equilibrium

A gradient in gas pressure balanced against gravity

Hydrostatic Equilibrium:

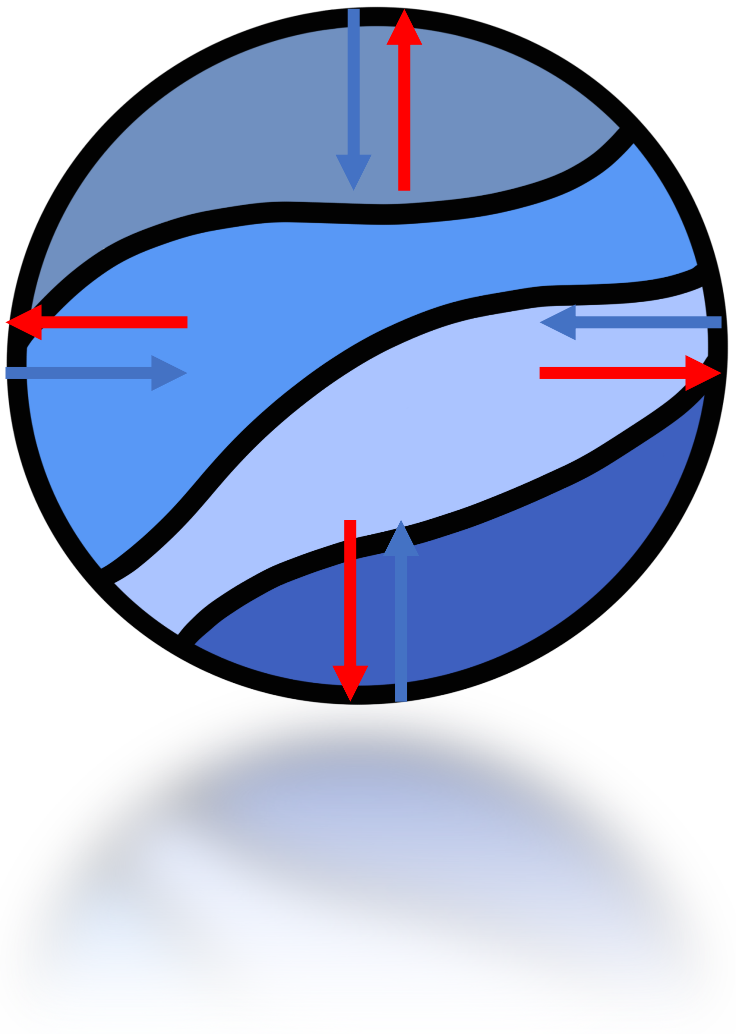
$$\frac{dP}{dz} = -\rho g$$

+ Ideal Gas Law ($P = \rho RT$), gives:

$$P = P_s e^{-z/H}$$

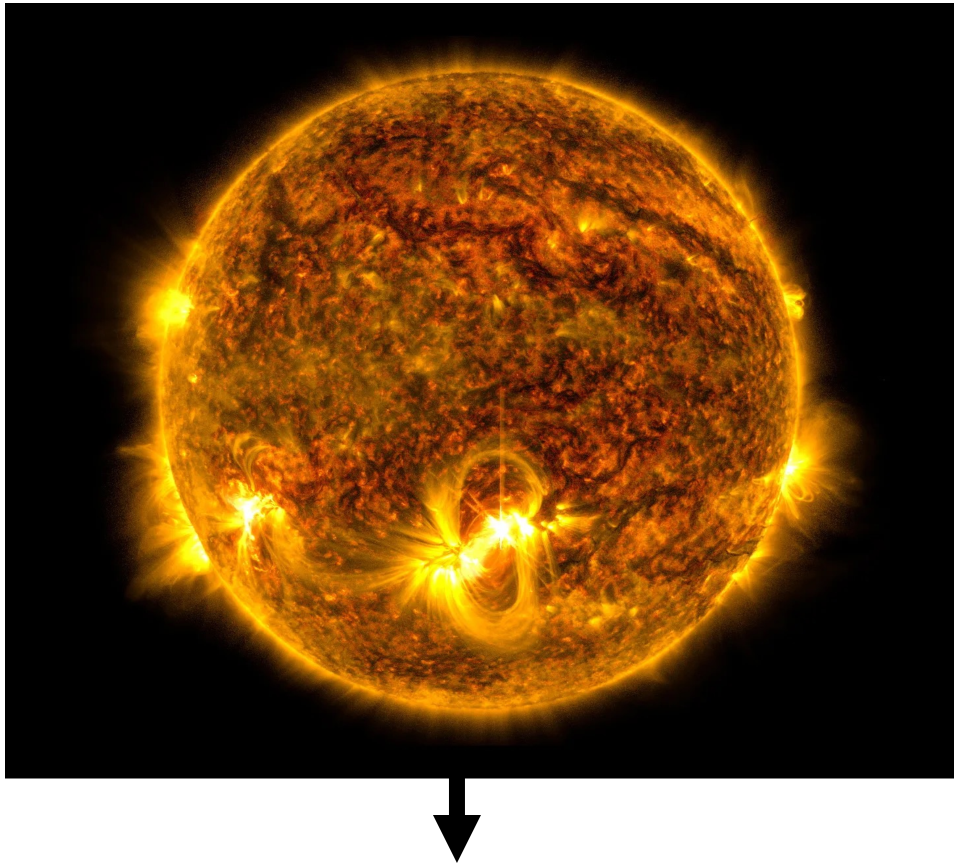
Where the (Pressure) Scale Height:

$$H = \frac{k_B T}{\mu_m m_H g}$$

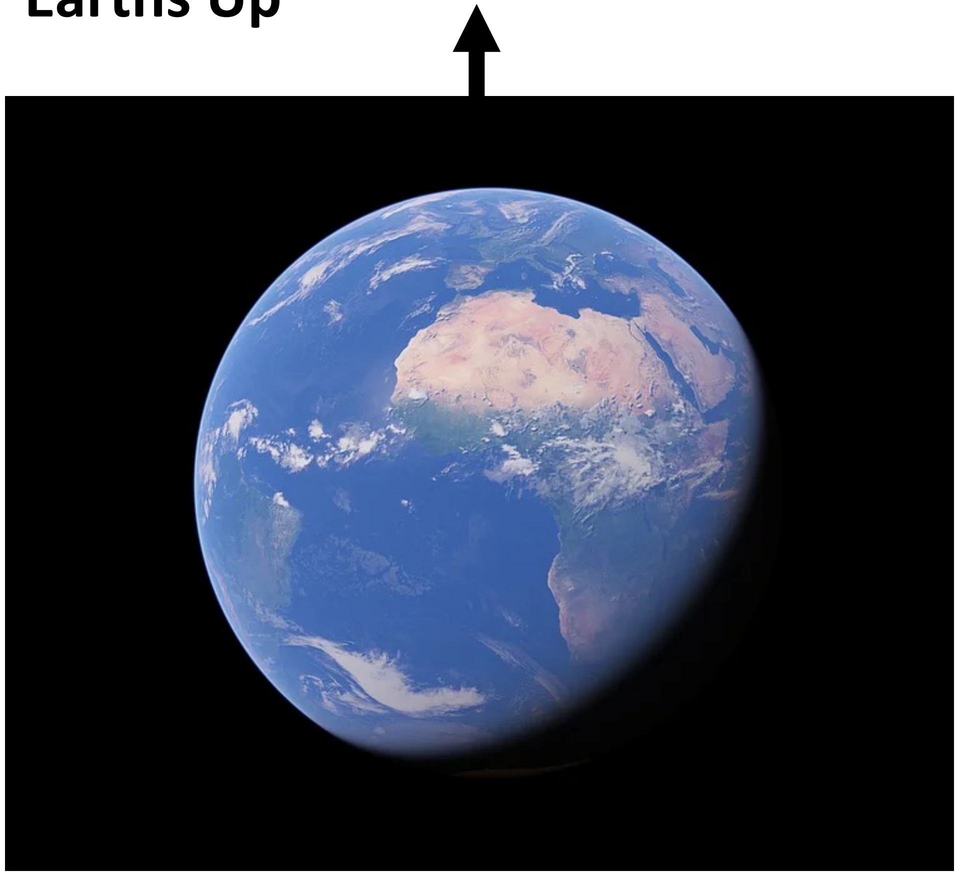


Two Different Atmospheric Modeling Approaches

Stars Down



Earths Up



Two Different Atmospheric Modeling Approaches

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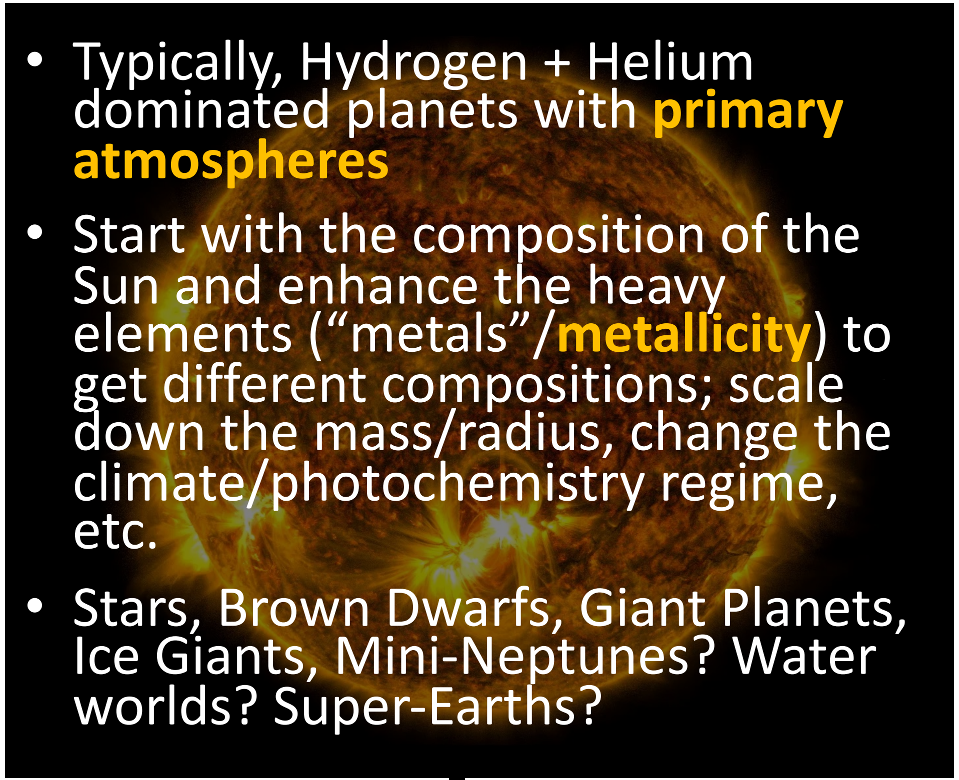
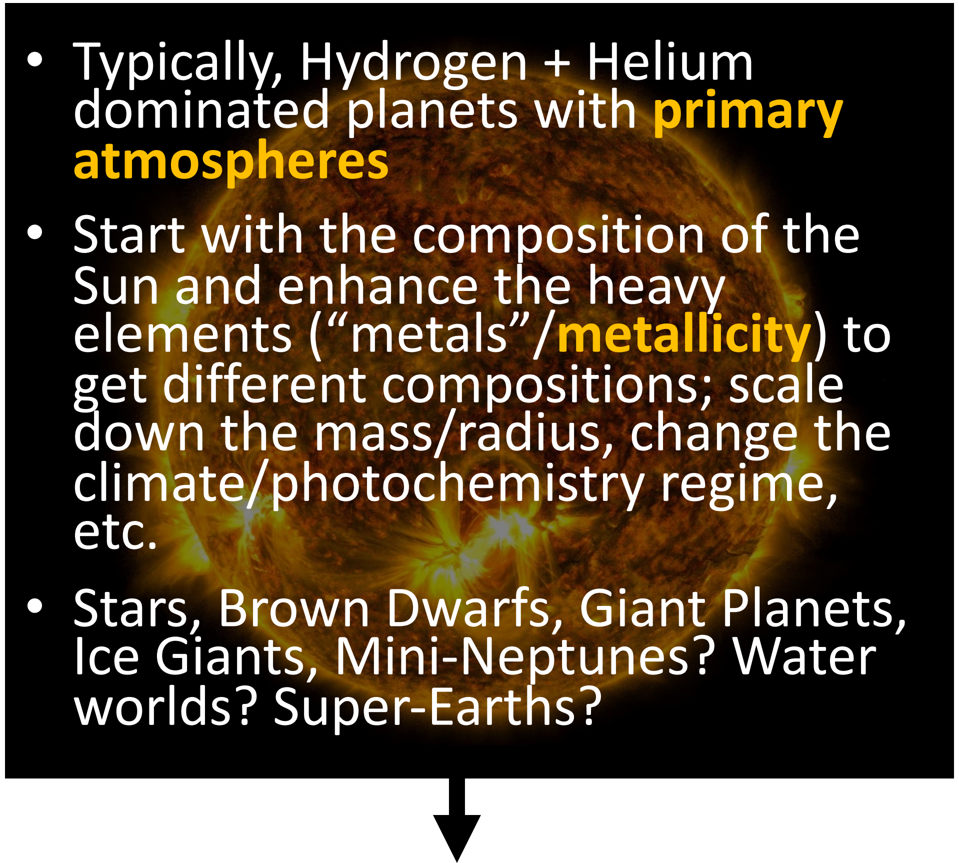


- Typically, Hydrogen + Helium dominated planets with **primary atmospheres**
- Start with the composition of the Sun and enhance the heavy elements (“metals”/**metallicity**) to get different compositions; scale down the mass/radius, change the climate/photochemistry regime, etc.
- Stars, Brown Dwarfs, Giant Planets, Ice Giants, Mini-Neptunes? Water worlds? Super-Earths?

Earths Up

Two Different Atmospheric Modeling Approaches

Stars Down



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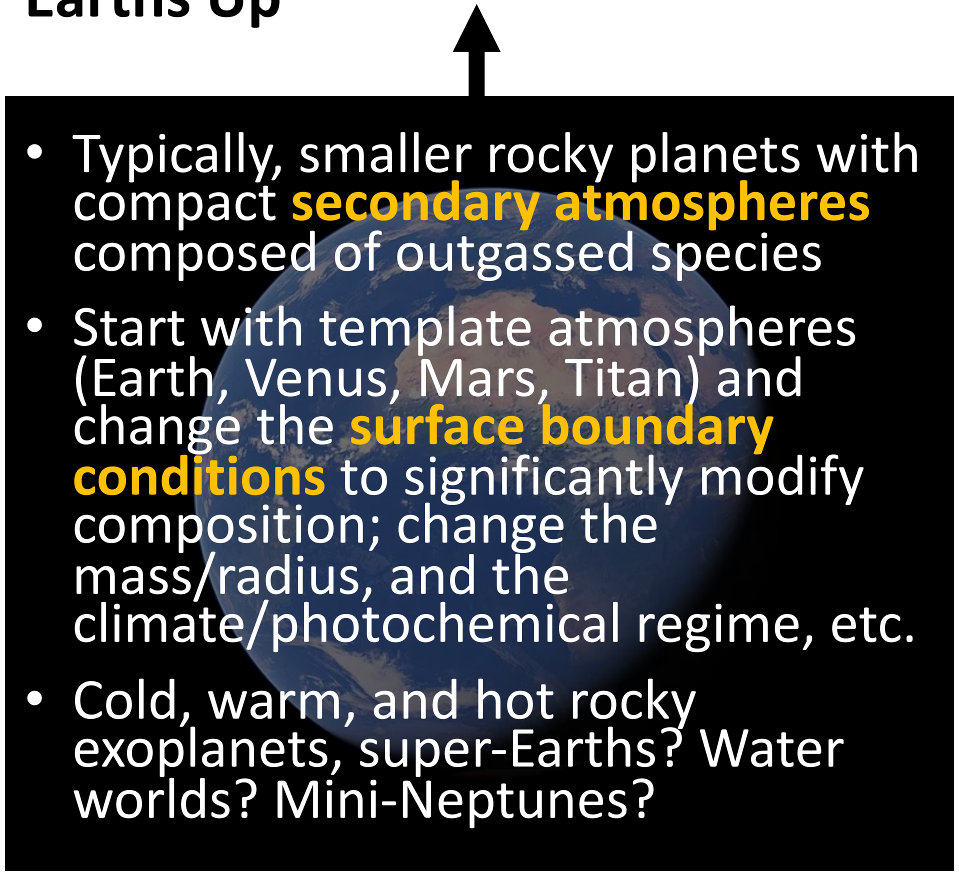
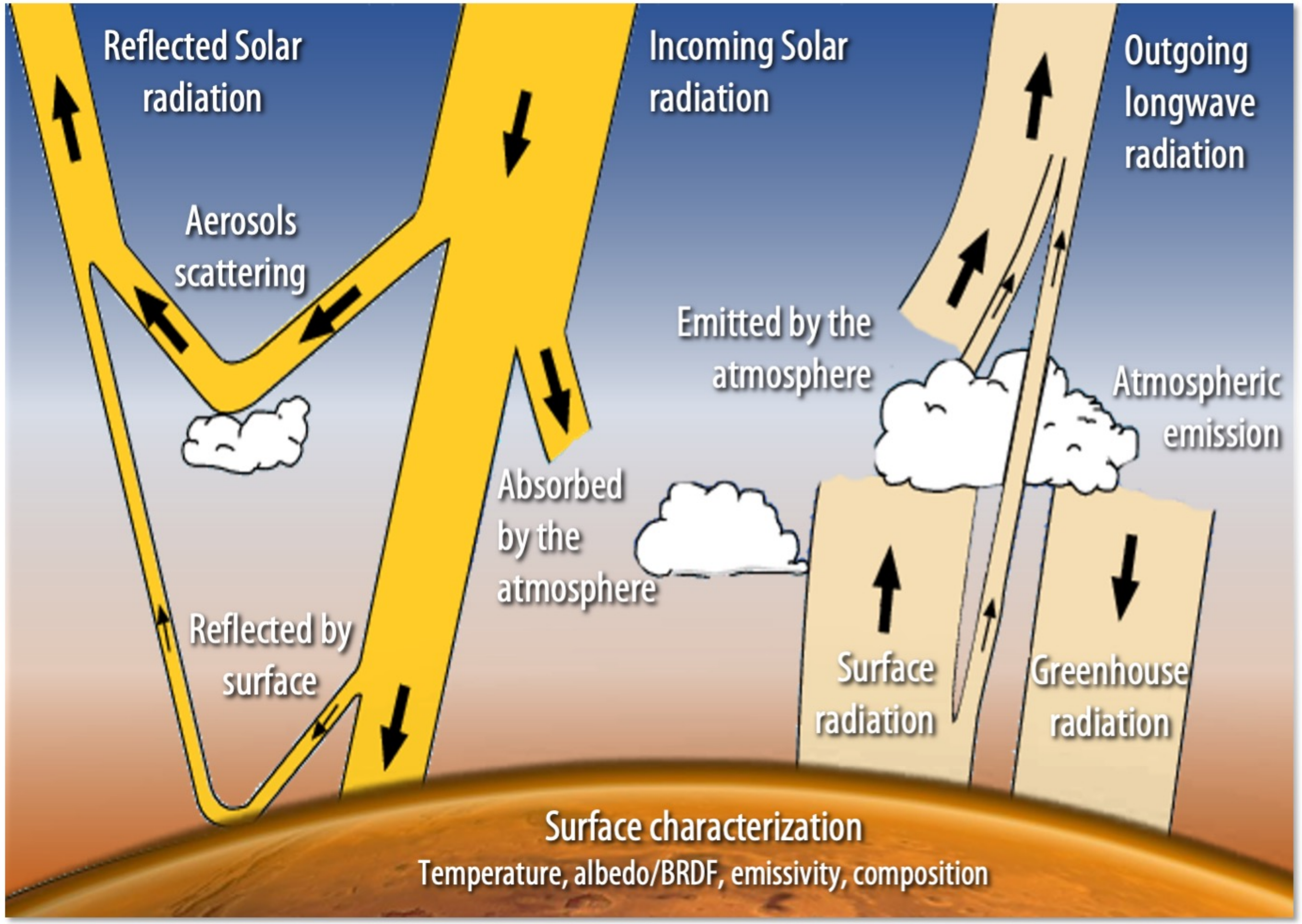


- Typically, smaller rocky planets with compact **secondary atmospheres** composed of outgassed species
- Start with template atmospheres (Earth, Venus, Mars, Titan) and change the **surface boundary conditions** to significantly modify composition; change the mass/radius, and the climate/photochemical regime, etc.
- Cold, warm, and hot rocky exoplanets, super-Earths? Water worlds? Mini-Neptunes?

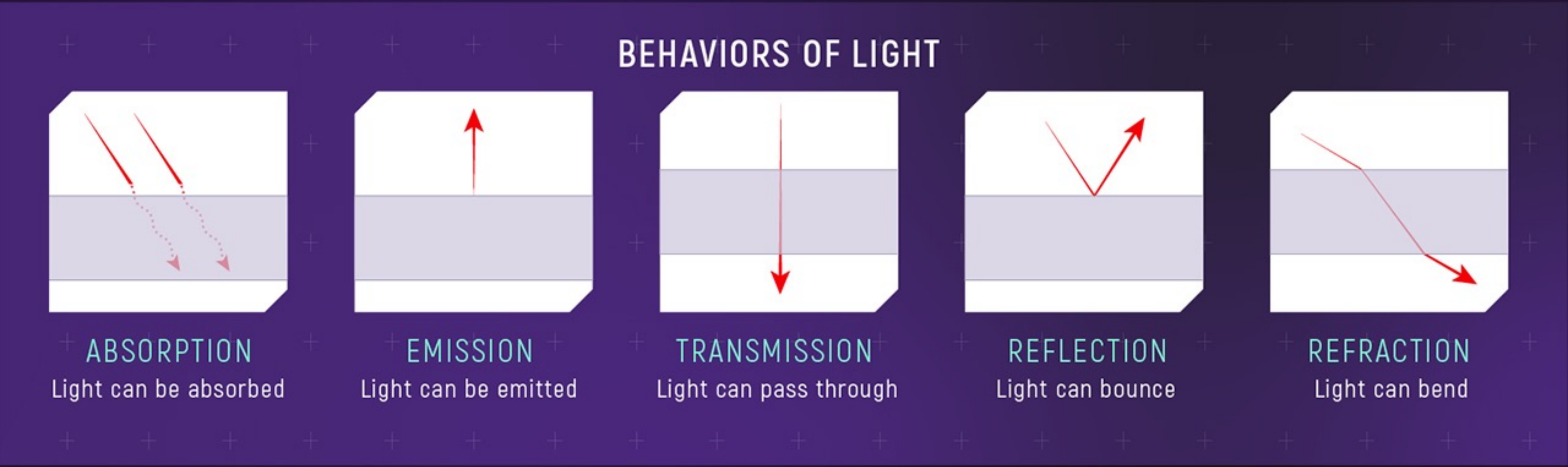
Radiative Transfer in Planetary Atmospheres

- Describes interactions between light and matter and is critical to atmospheric climate and observables.
- *How does light enter and exit the atmosphere?*
- *How and where does starlight heat the atmosphere?*
- *How does scattered incident light and emerging thermal emission escape the atmosphere and become observable?*



See e.g., Heng & Marley (2018)

Villanueva et al. (2018); Planetary Spectrum Generator: https://psg.gsfc.nasa.gov/



BEHAVIORS OF LIGHT

ABSORPTION
Light can be absorbed

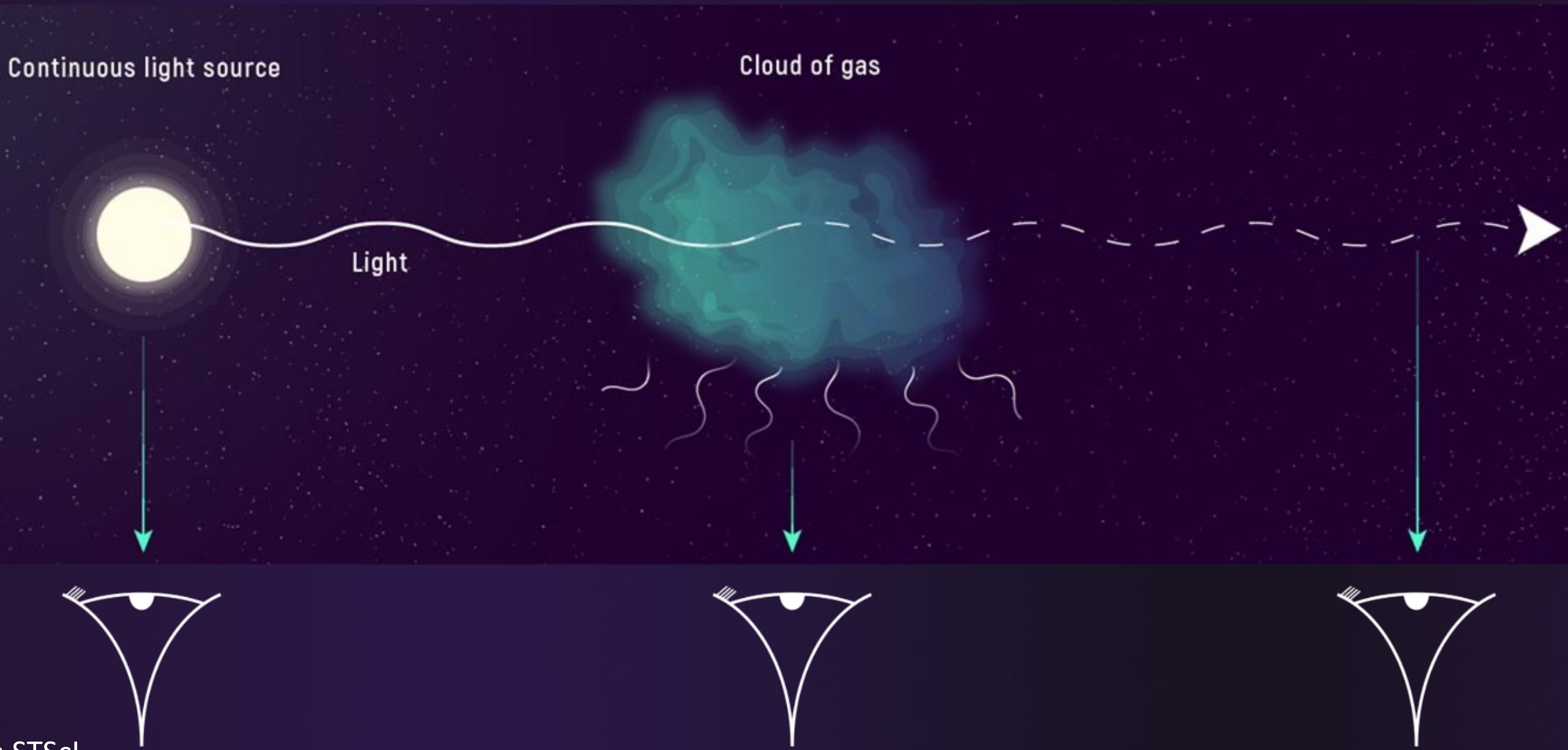
EMISSION
Light can be emitted

TRANSMISSION
Light can pass through

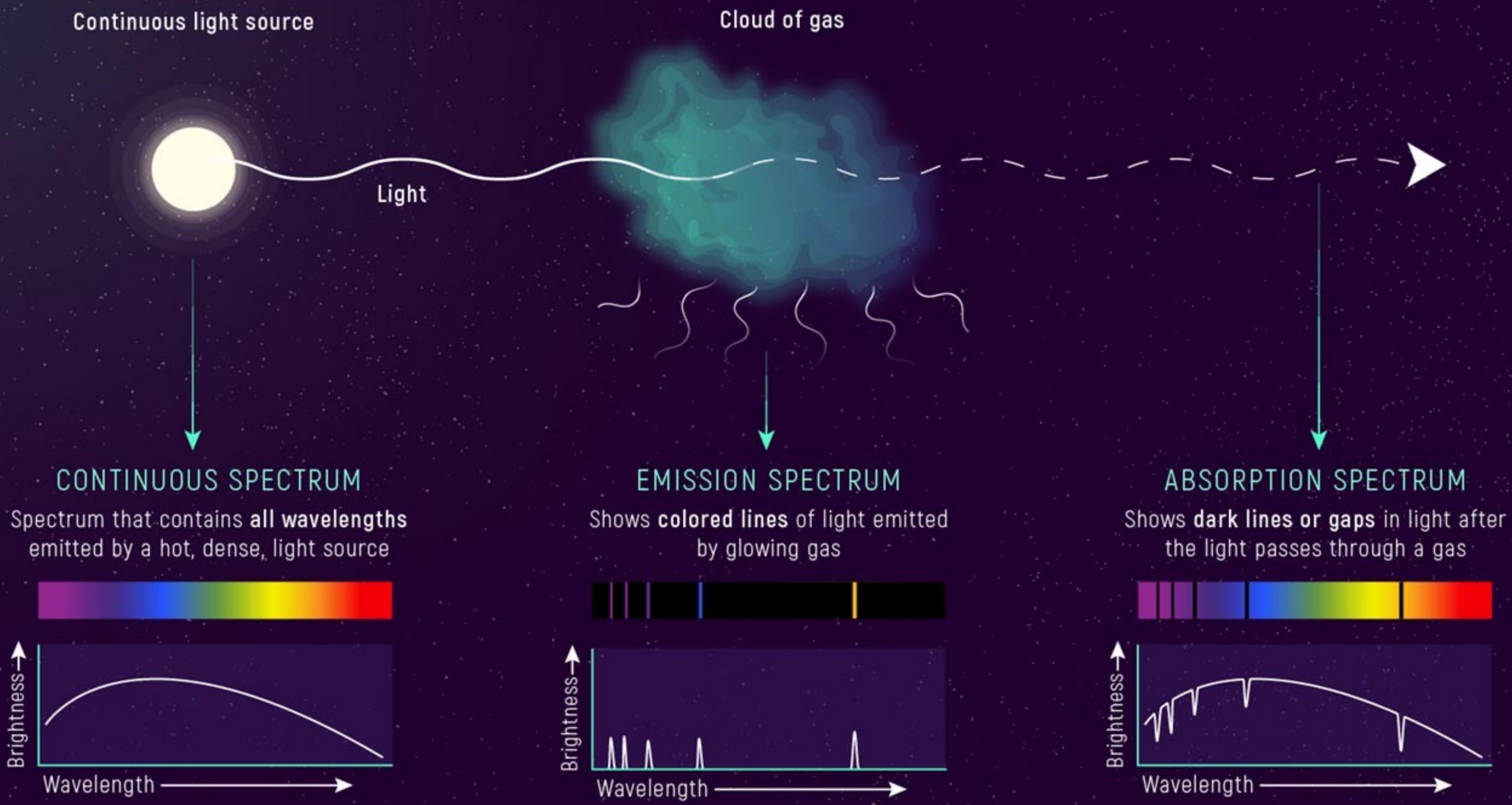
REFLECTION
Light can bounce

REFRACTION
Light can bend

Credit: STScI



Credit: STScI



CONTINUOUS SPECTRUM

Spectrum that contains **all wavelengths** emitted by a hot, dense, light source

EMISSION SPECTRUM

Shows **colored lines** of light emitted by glowing gas

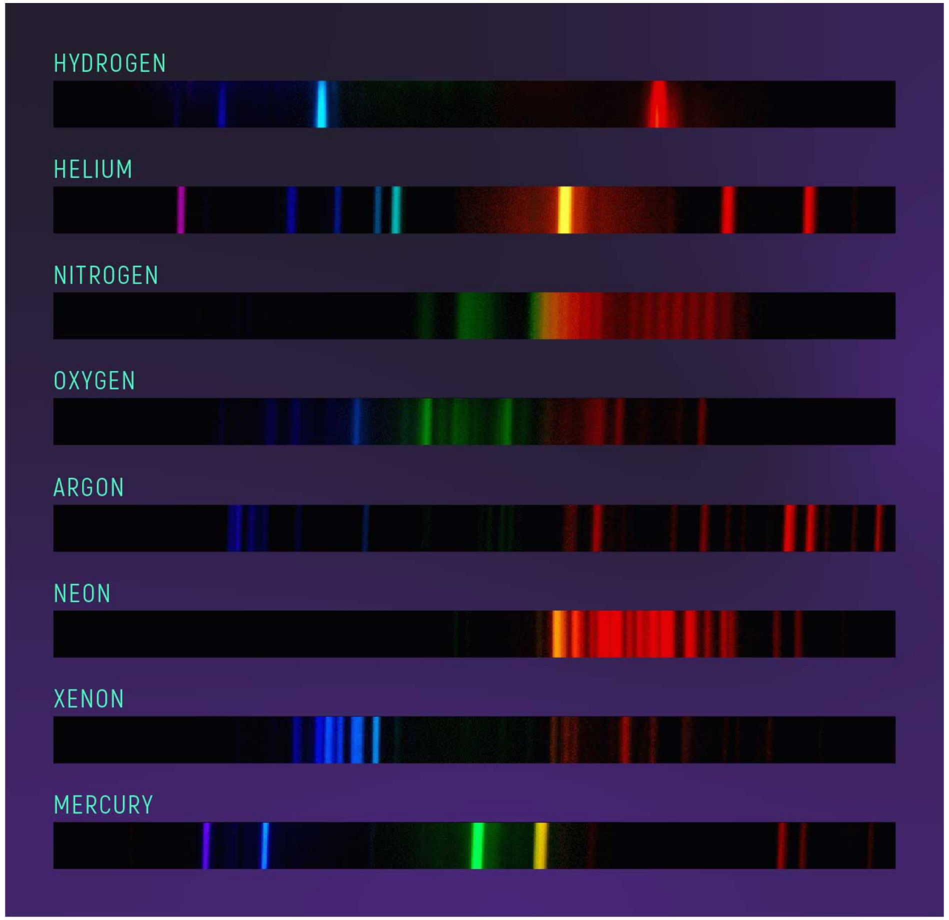
ABSORPTION SPECTRUM

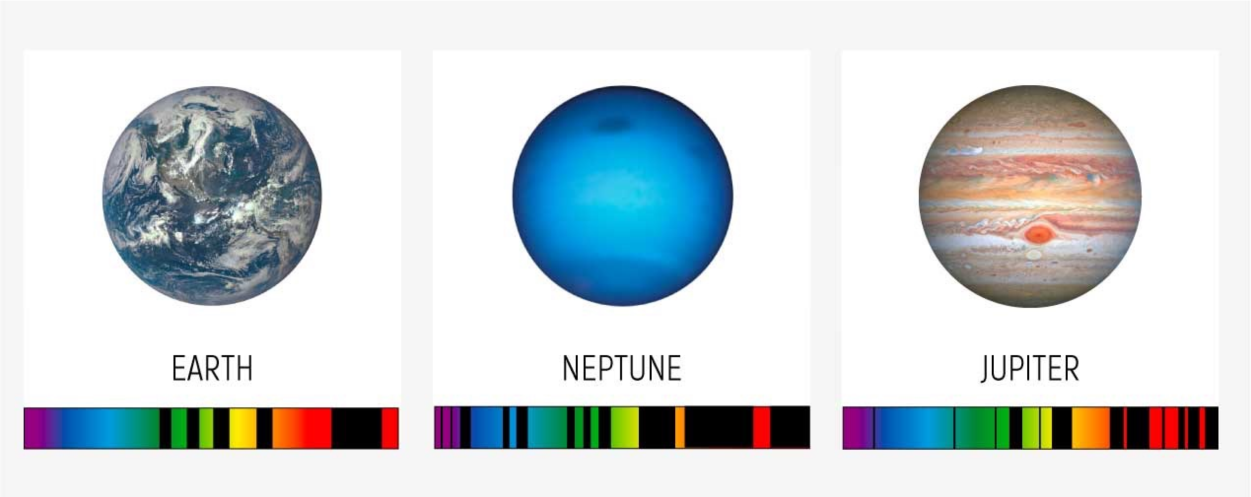
Shows **dark lines or gaps** in light after the light passes through a gas

Credit: STScI

Each Atom and Molecule have a Unique* Spectral Fingerprint

*should you have the spectral resolution to distinguish them

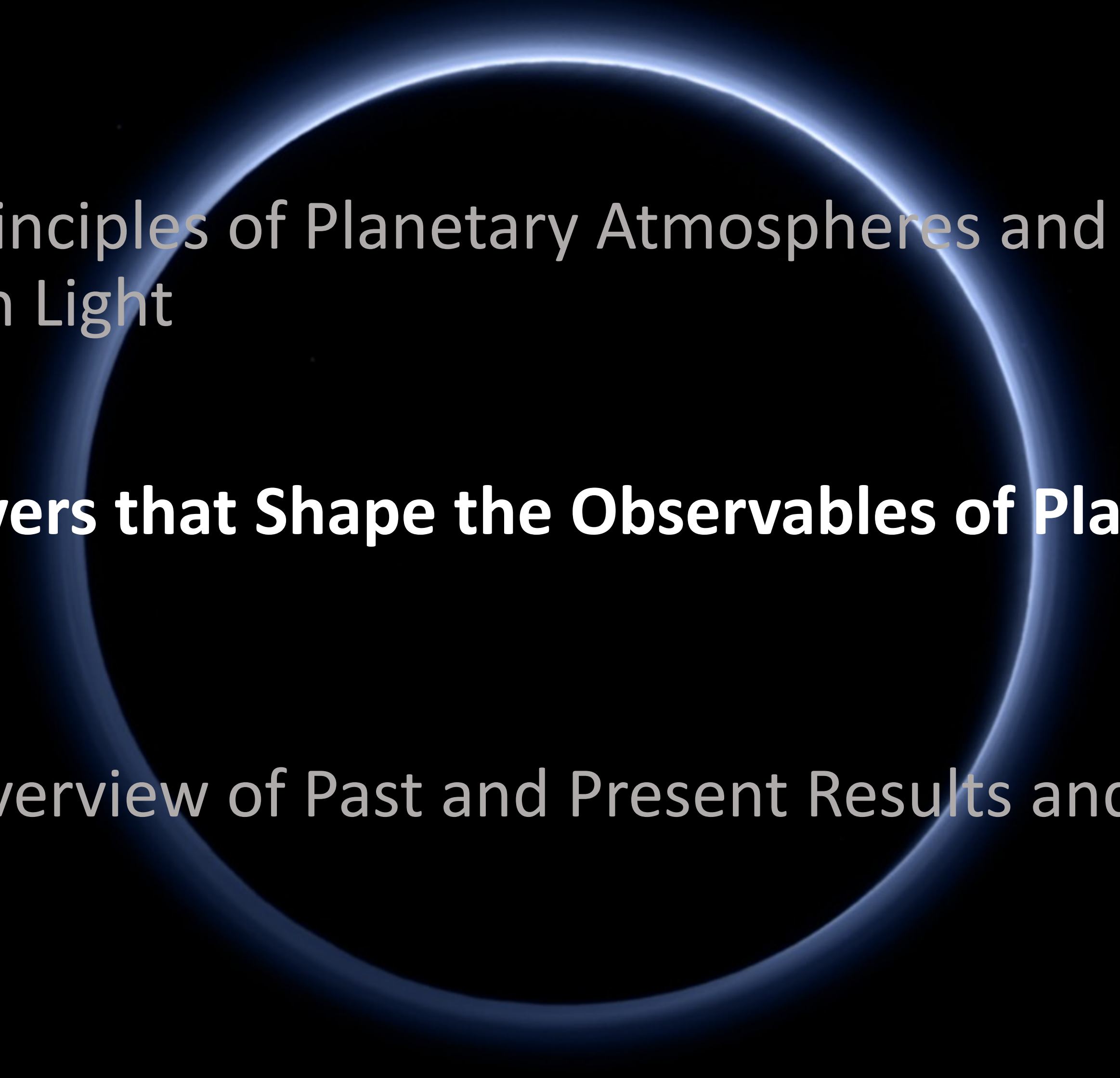




Fundamental laboratory measurements provide the Rosetta Stone needed to decipher combinations of gases in planetary spectra

Credit: STScI

Exoplanet Atmospheric Studies



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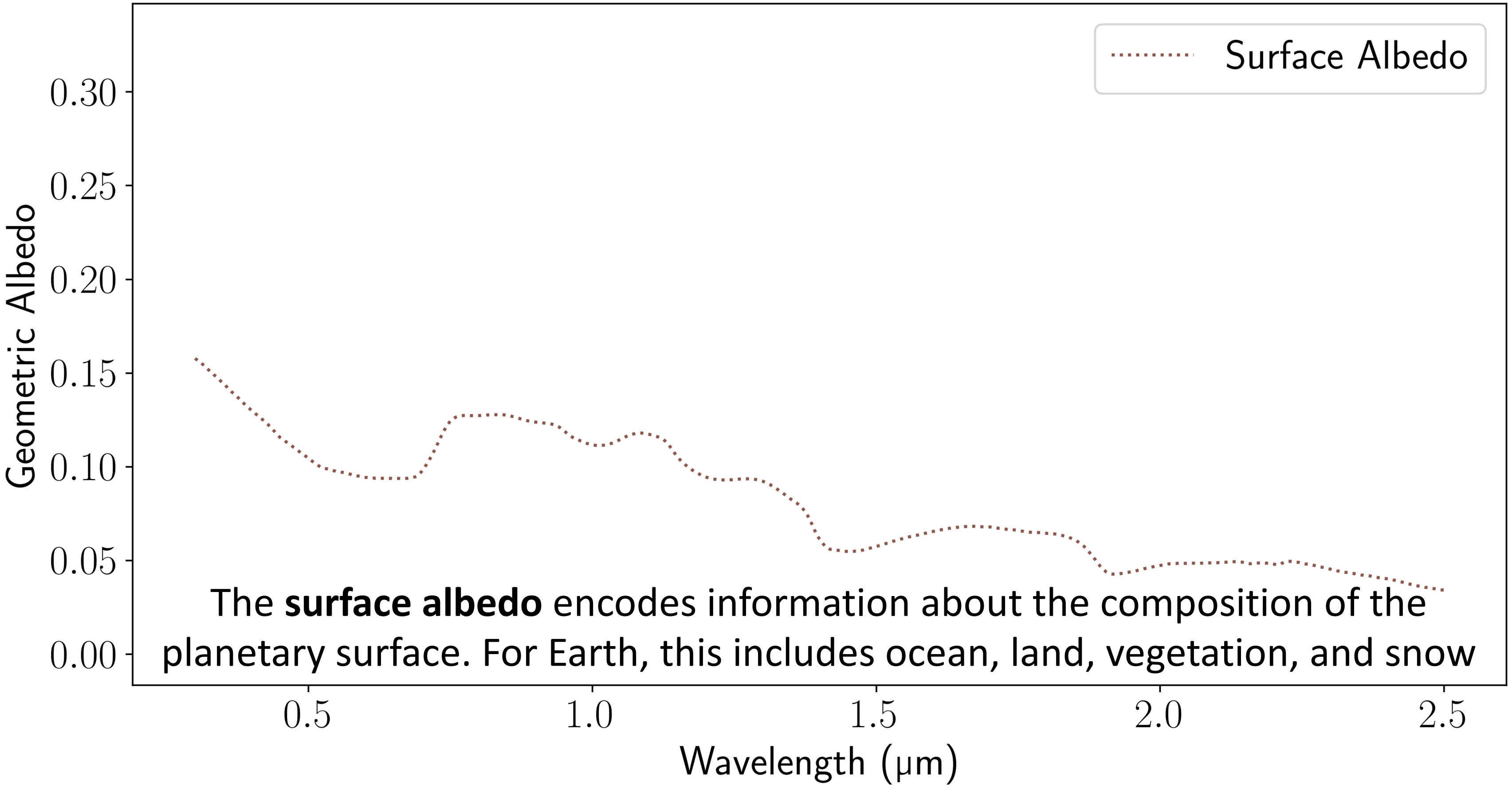
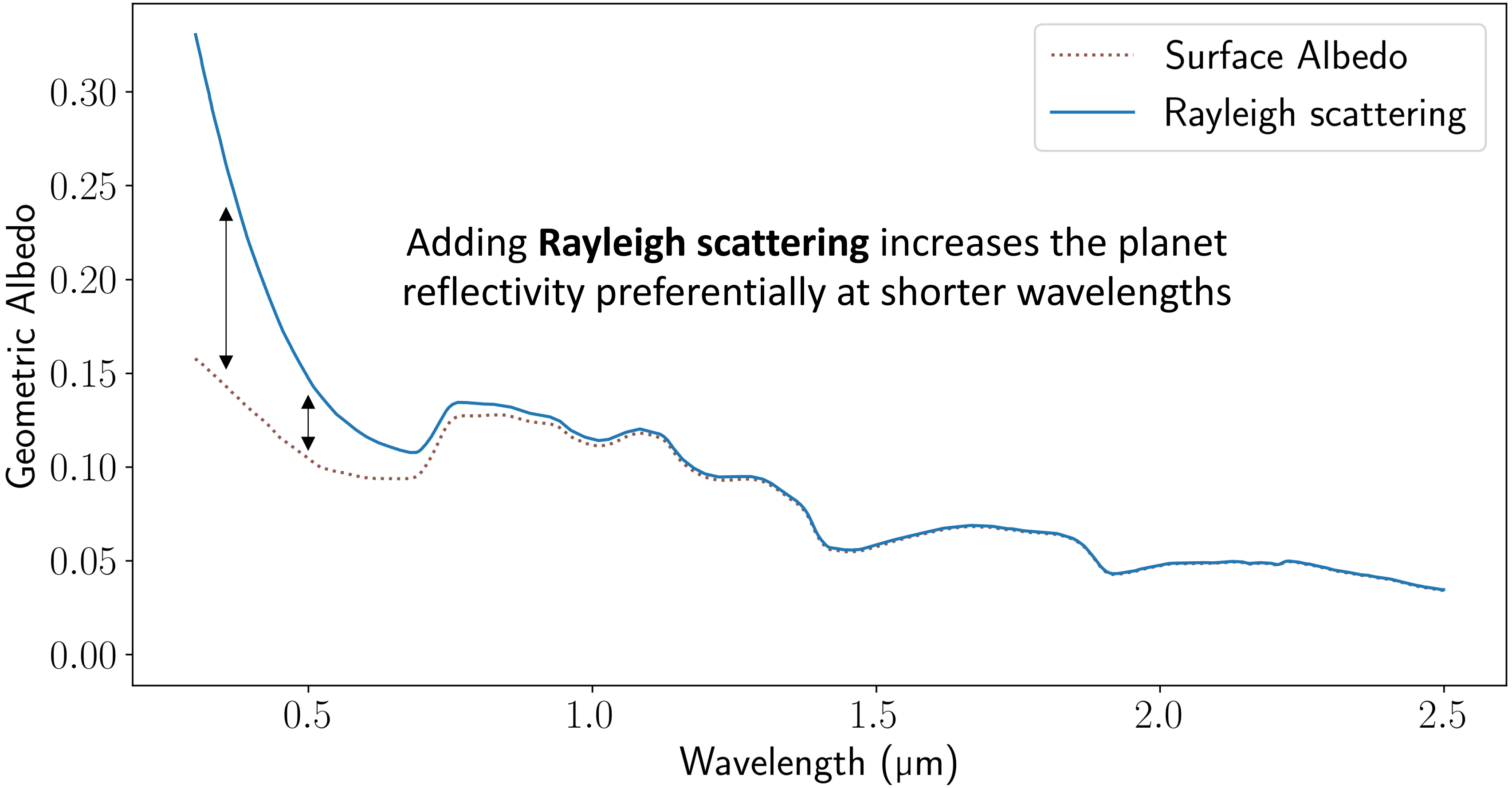
Deconstructing Earth’s Reflectance Spectrum



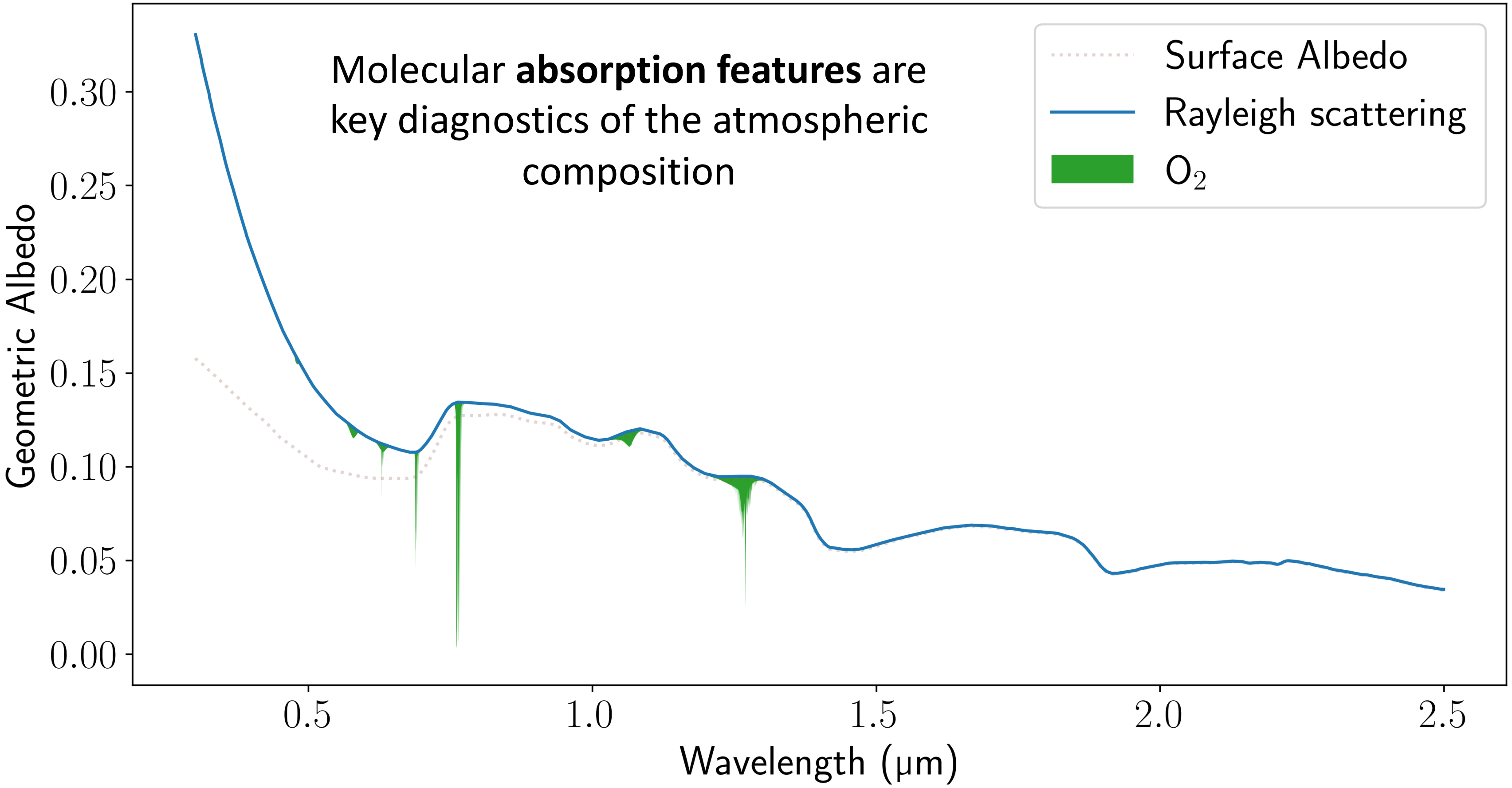
The **surface albedo** encodes information about the composition of the planetary surface. For Earth, this includes ocean, land, vegetation, and snow

Deconstructing Earth’s Reflectance Spectrum



Adding **Rayleigh scattering** increases the planet reflectivity preferentially at shorter wavelengths

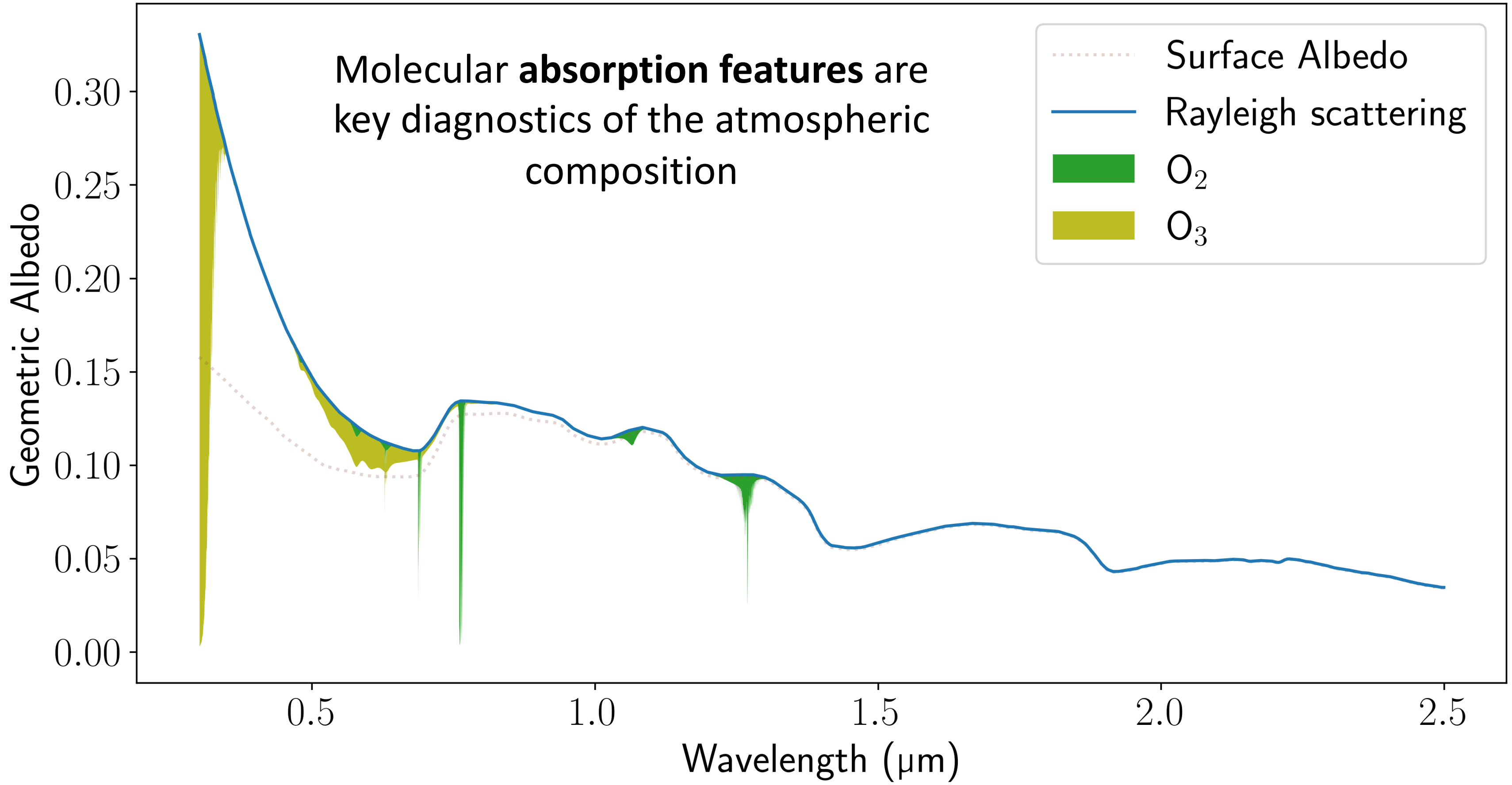
Deconstructing Earth’s Reflectance Spectrum



Molecular **absorption features** are key diagnostics of the atmospheric composition

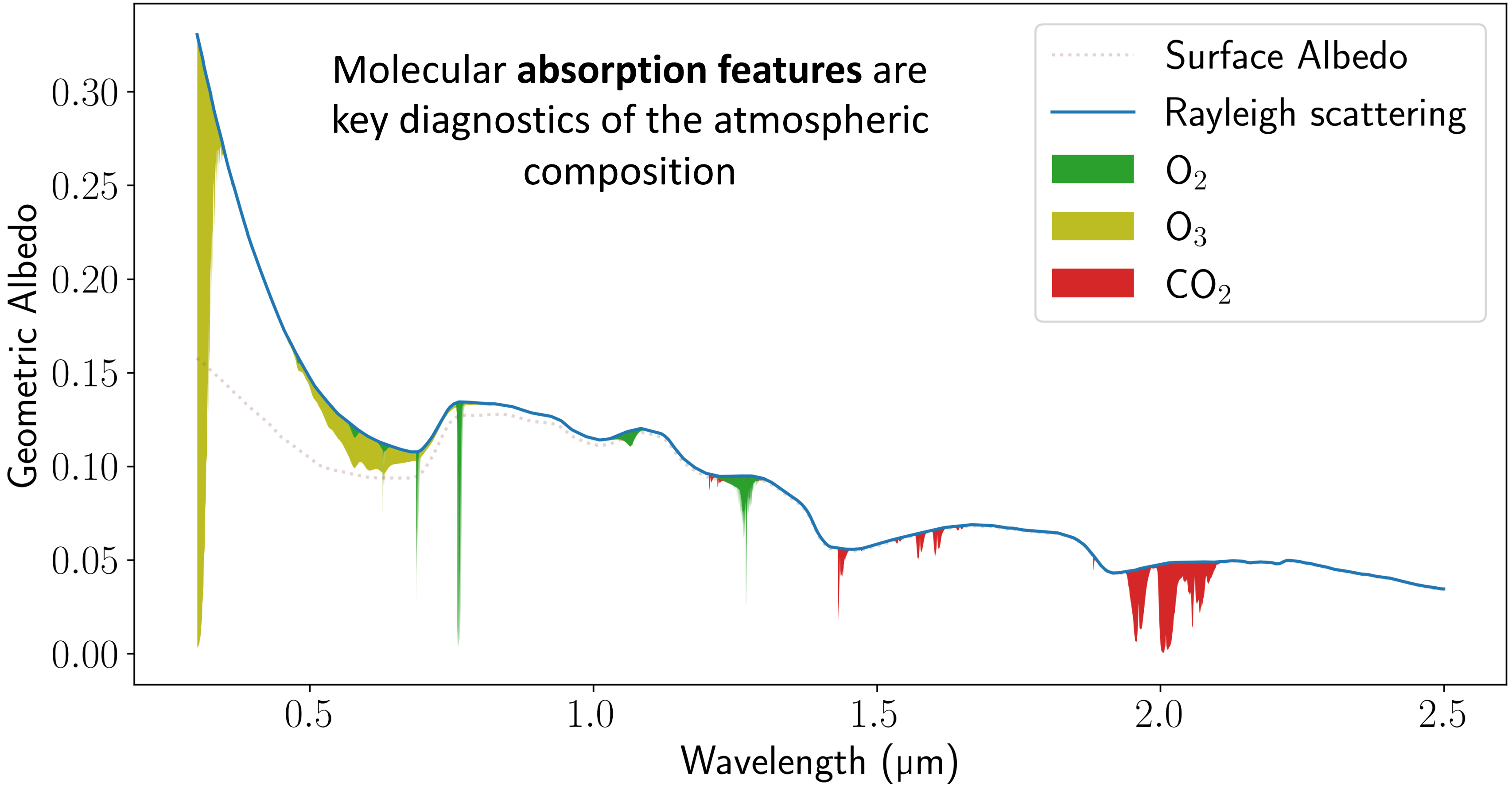
O_2 is a biosignature produced by oxygenic photosynthesis

Deconstructing Earth's Reflectance Spectrum



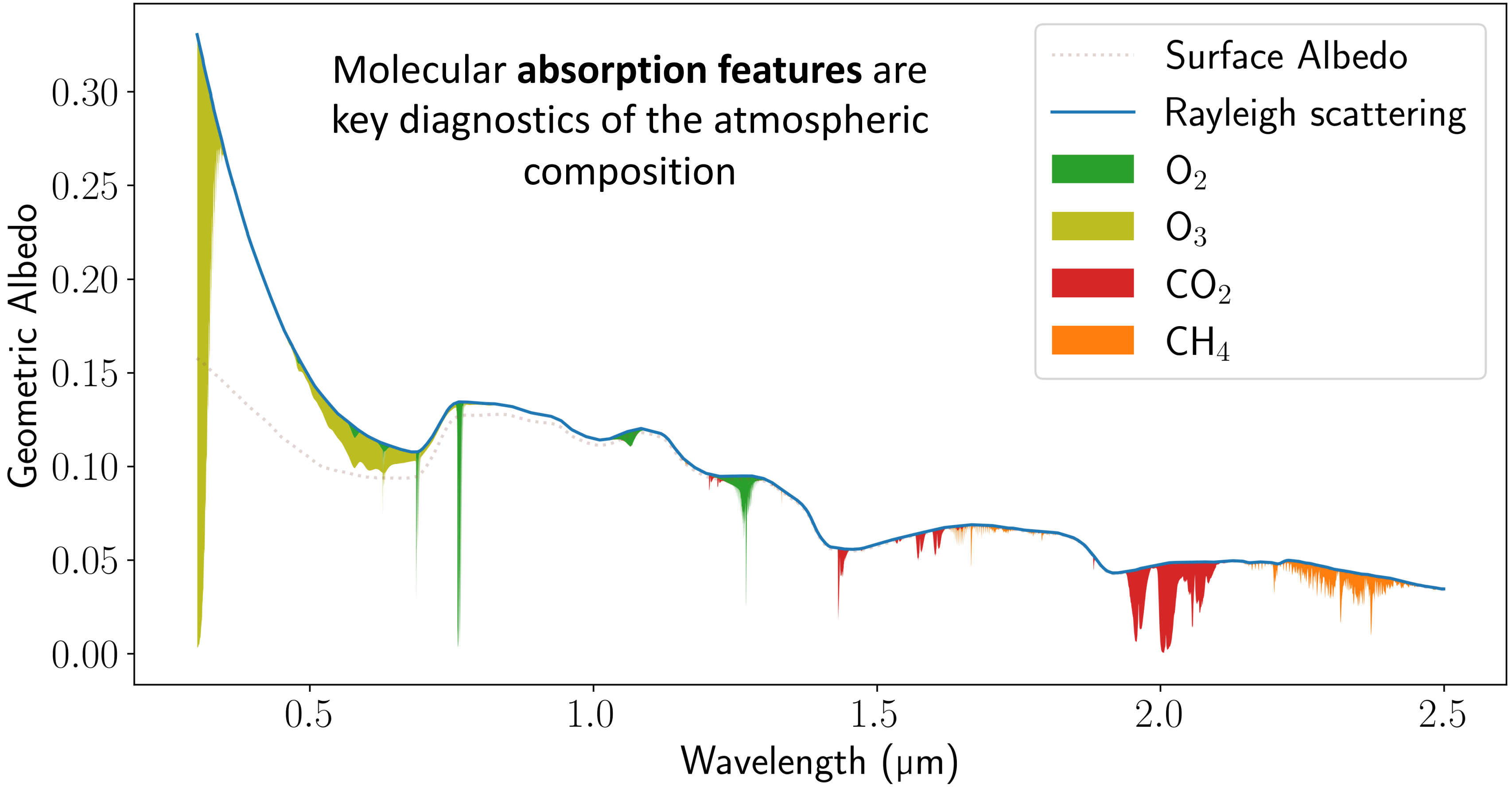
O_3 is a biosignature produced by the photochemical destruction of O_2

Deconstructing Earth’s Reflectance Spectrum



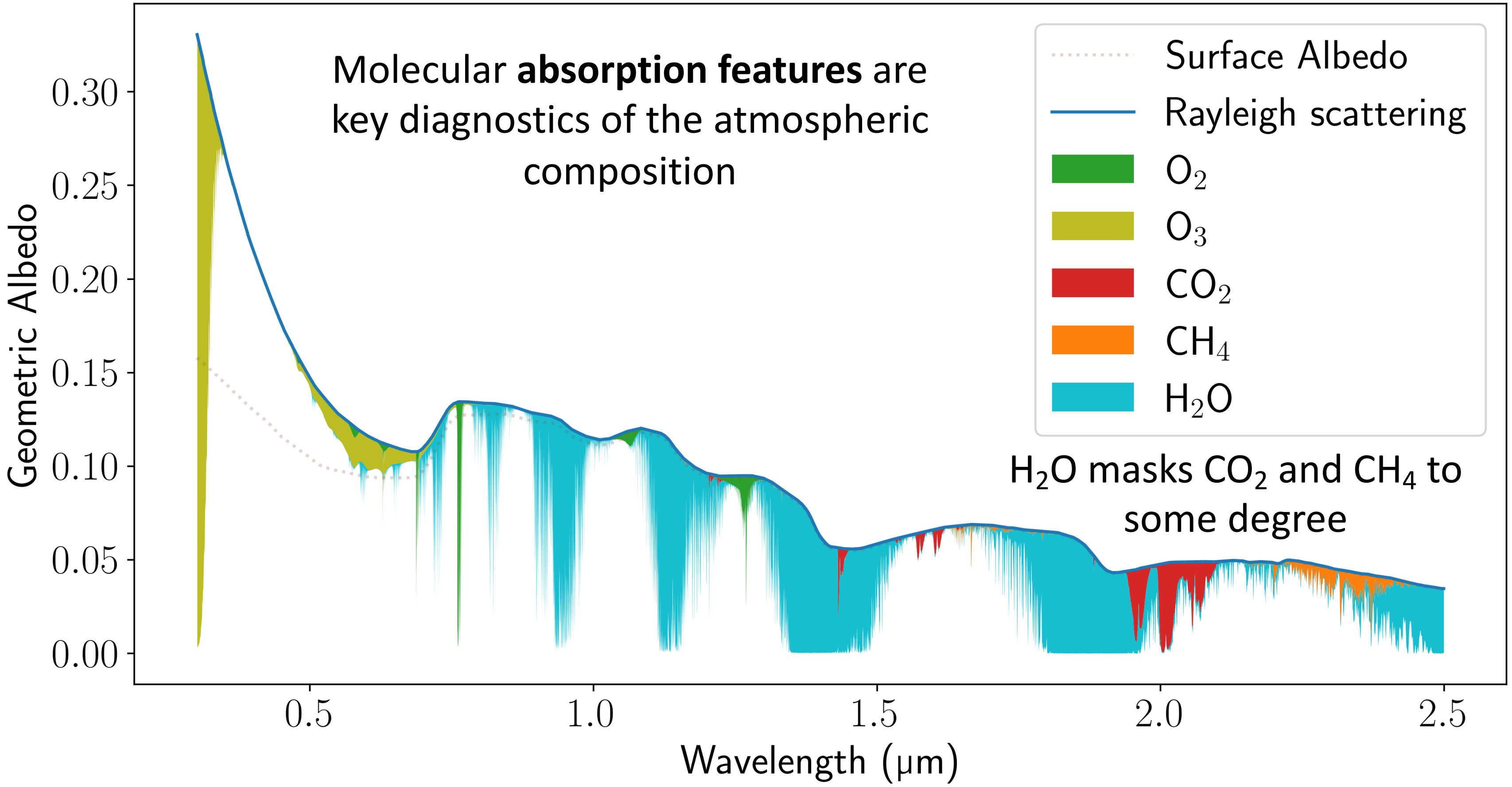
CO_2 is a key clue about the habitability and geological context of the planet

Deconstructing Earth’s Reflectance Spectrum



CH_4 is a biosignature produced by methanogenesis by microbes

Deconstructing Earth’s Reflectance Spectrum

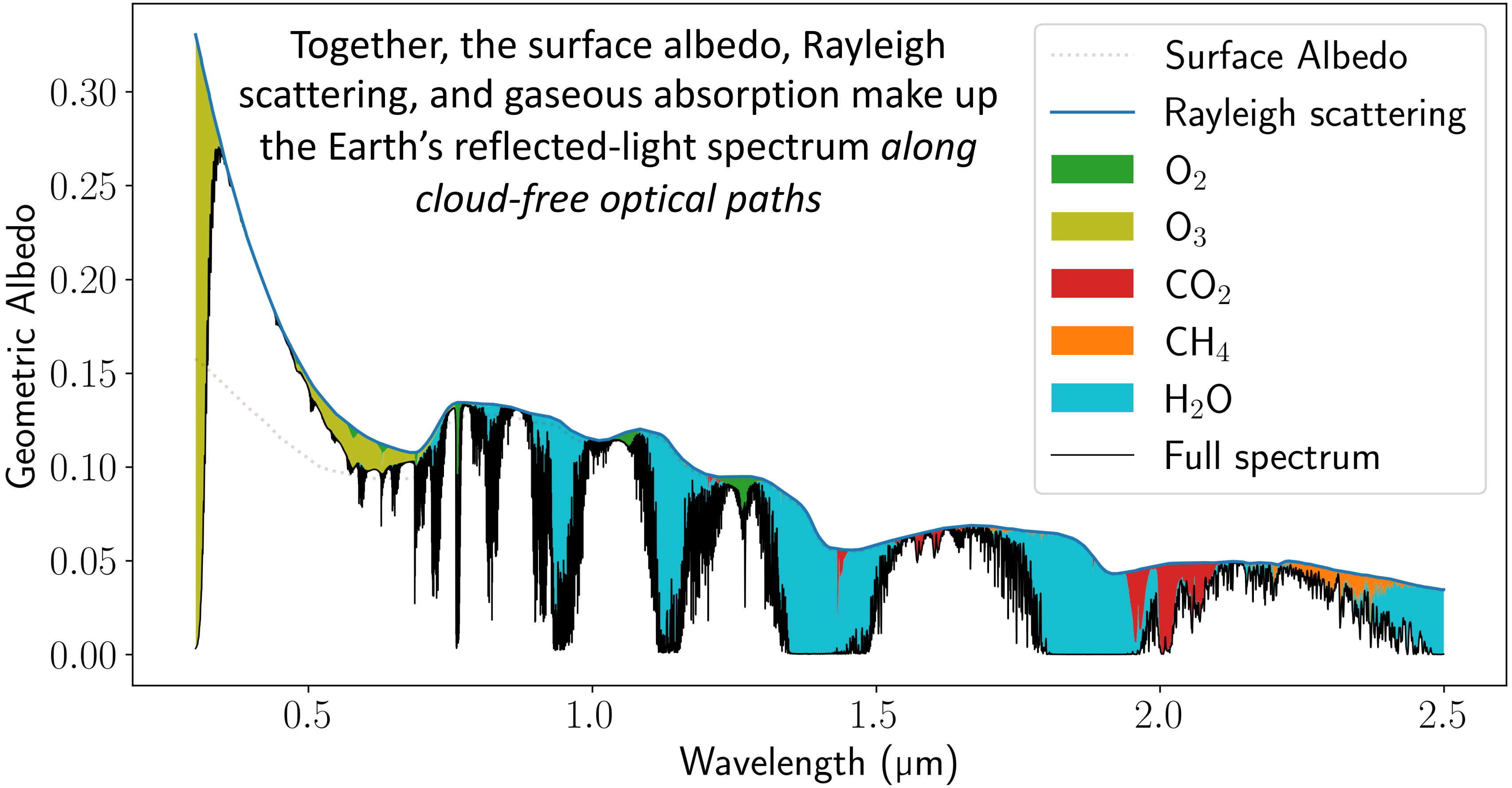


Molecular **absorption features** are key diagnostics of the atmospheric composition

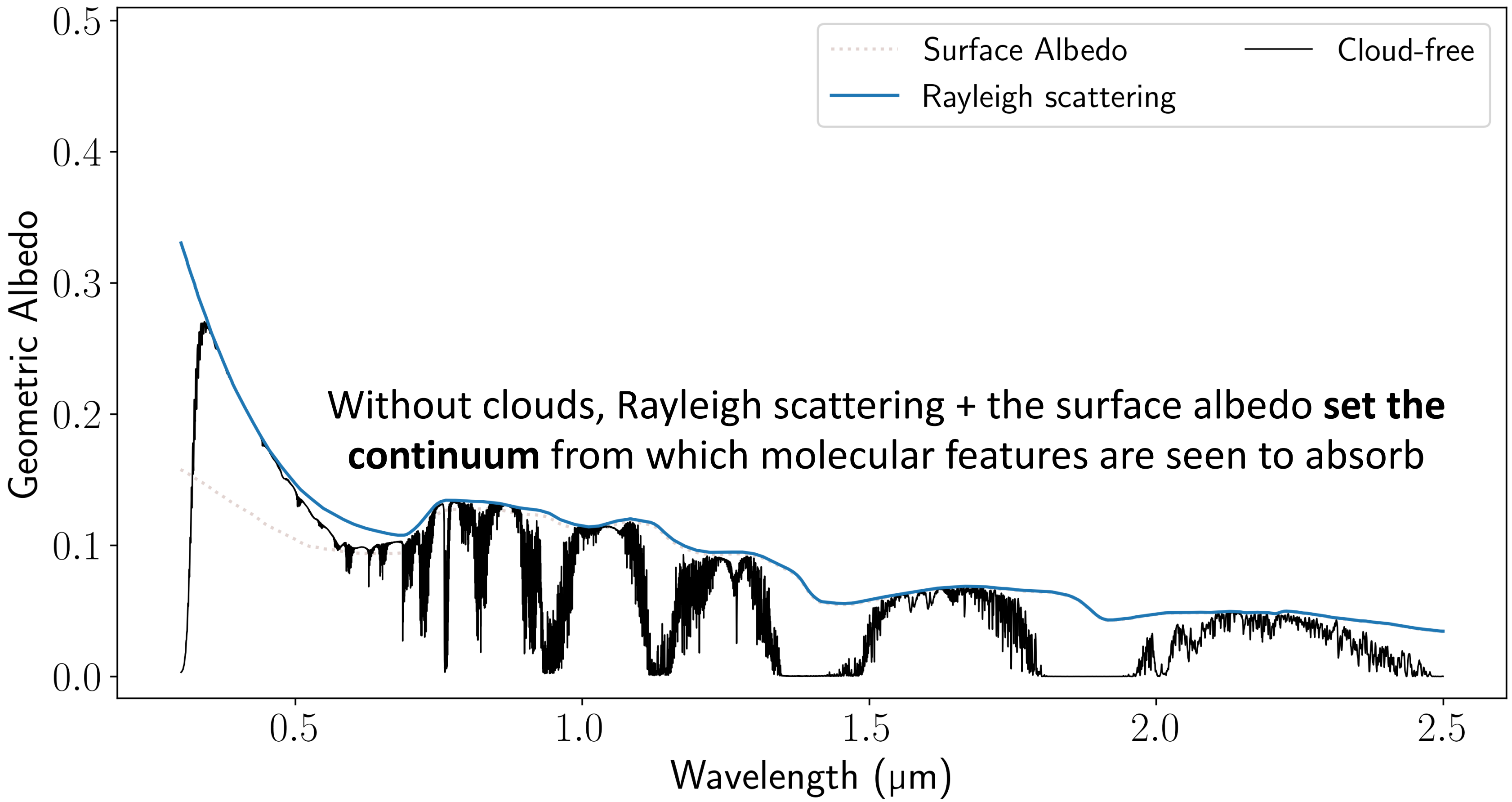
H_2O masks CO_2 and CH_4 to some degree

H_2O is a key habitability indicator, particularly when concentrated in the lower atmosphere

Deconstructing Earth’s Reflectance Spectrum

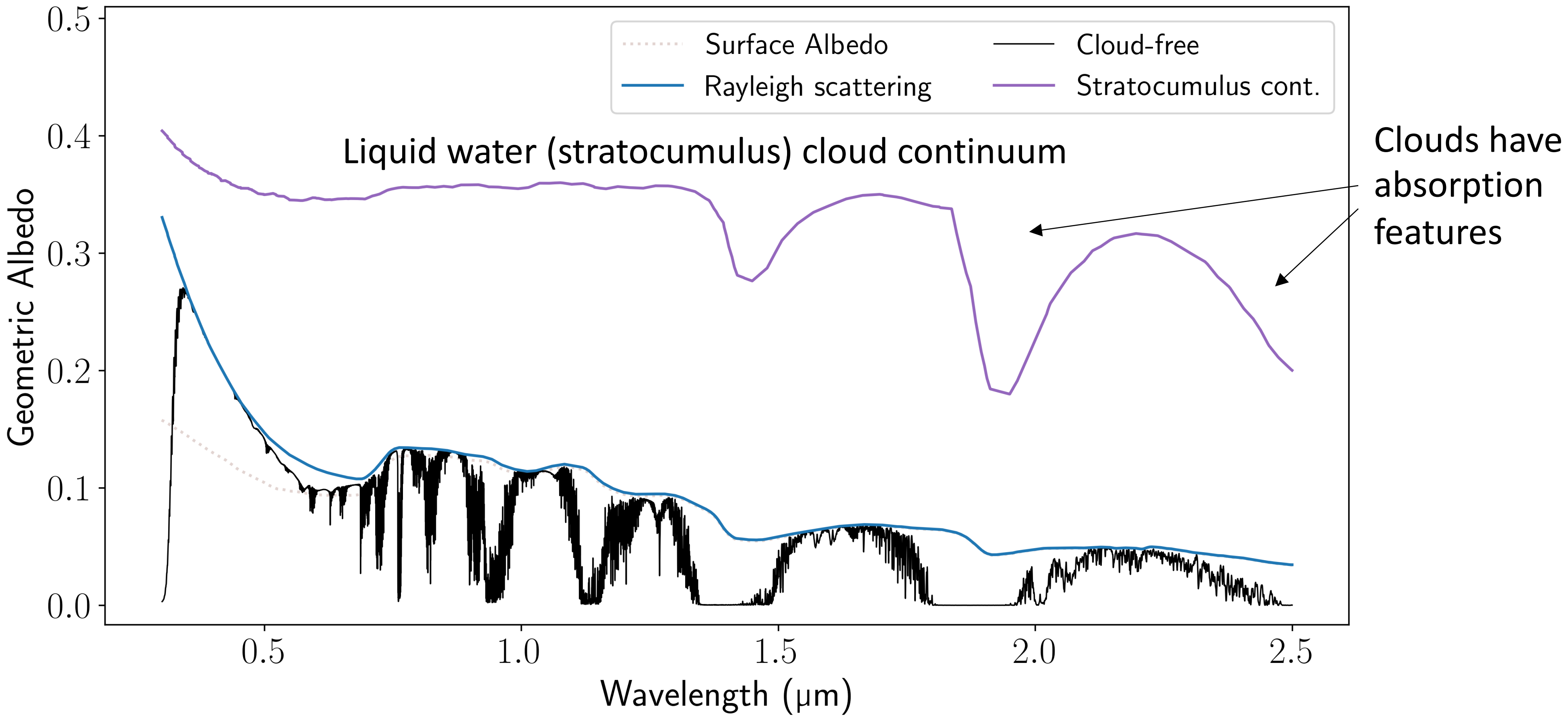


Deconstructing Earth’s Reflectance Spectrum



Without clouds, Rayleigh scattering + the surface albedo **set the continuum** from which molecular features are seen to absorb

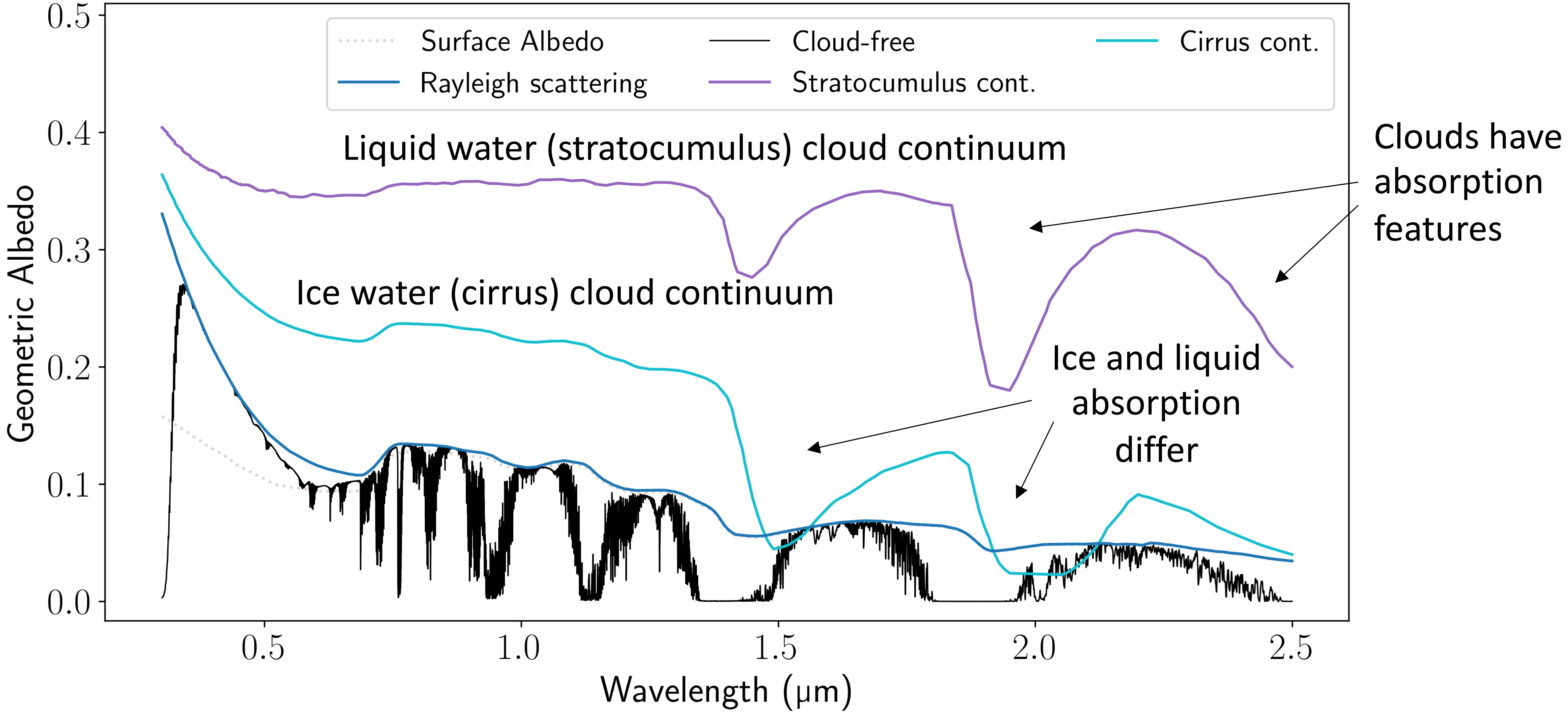
Deconstructing Earth’s Reflectance Spectrum



Clouds have absorption features

Deconstructing Earth's Reflectance Spectrum

Clouds **partially masks** the Rayleigh scattering and surface albedo, and **combine with them to set the continuum**



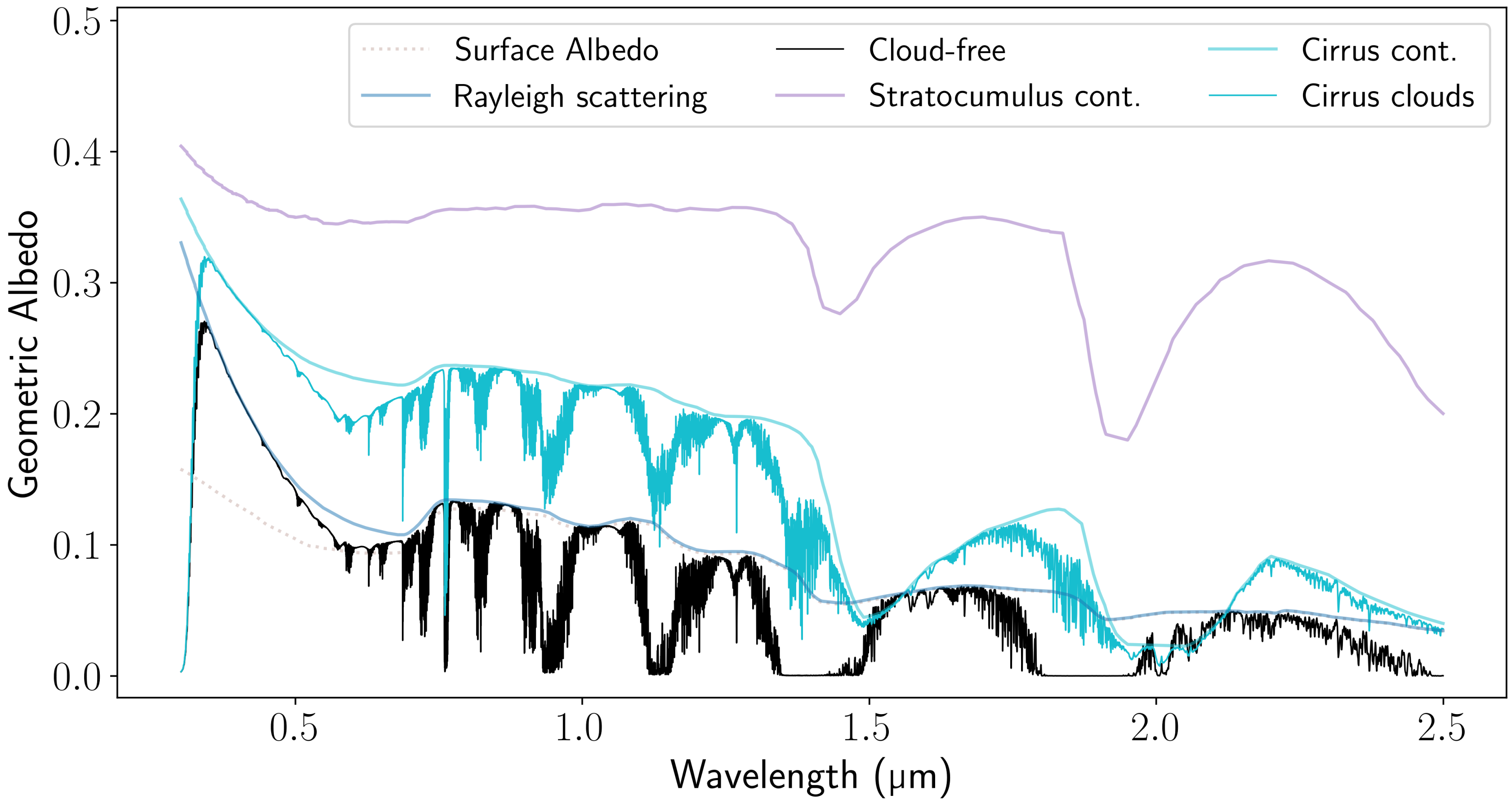
Liquid water (stratocumulus) cloud continuum

Ice water (cirrus) cloud continuum

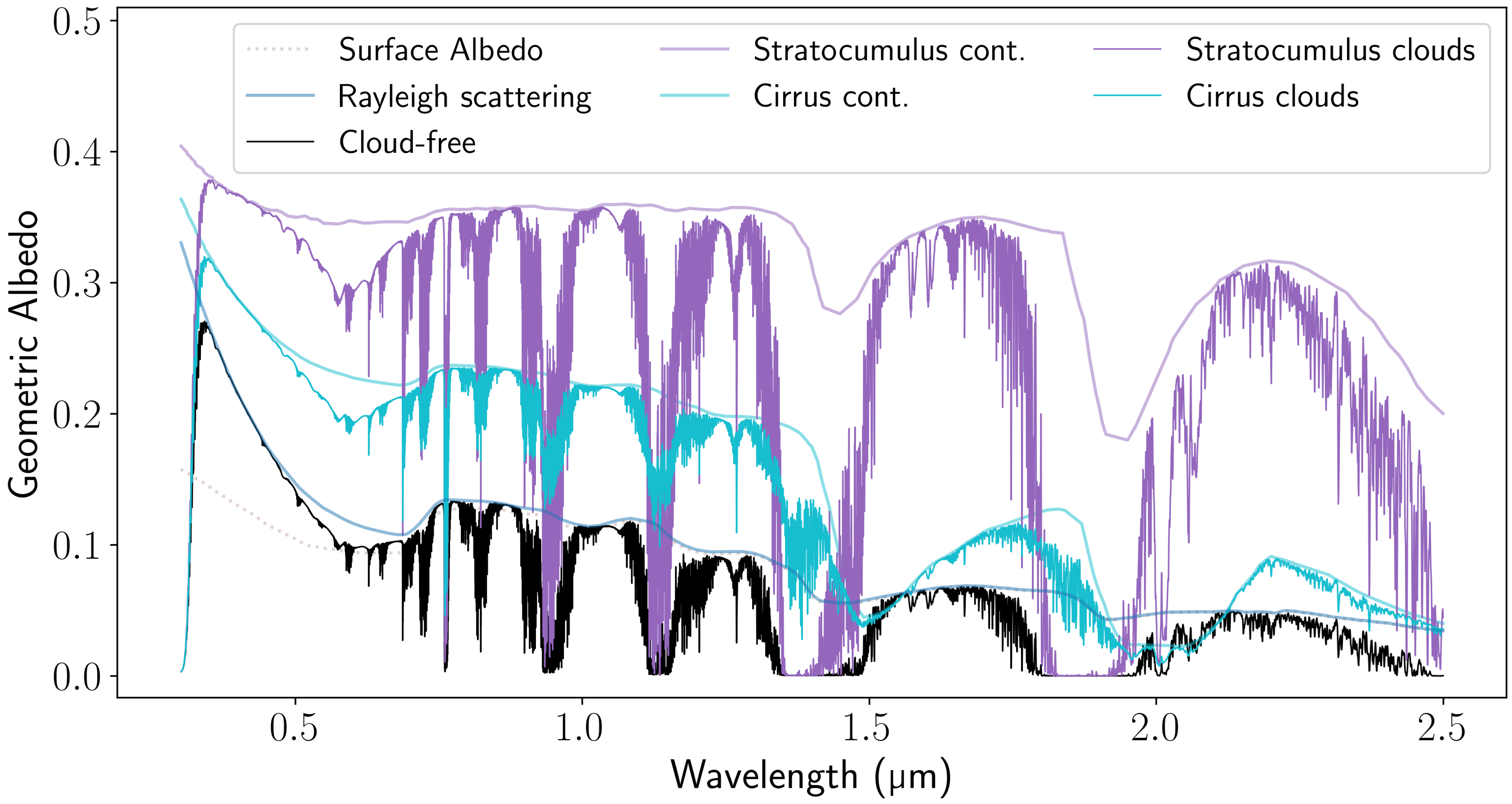
Clouds have absorption features

Ice and liquid absorption differ

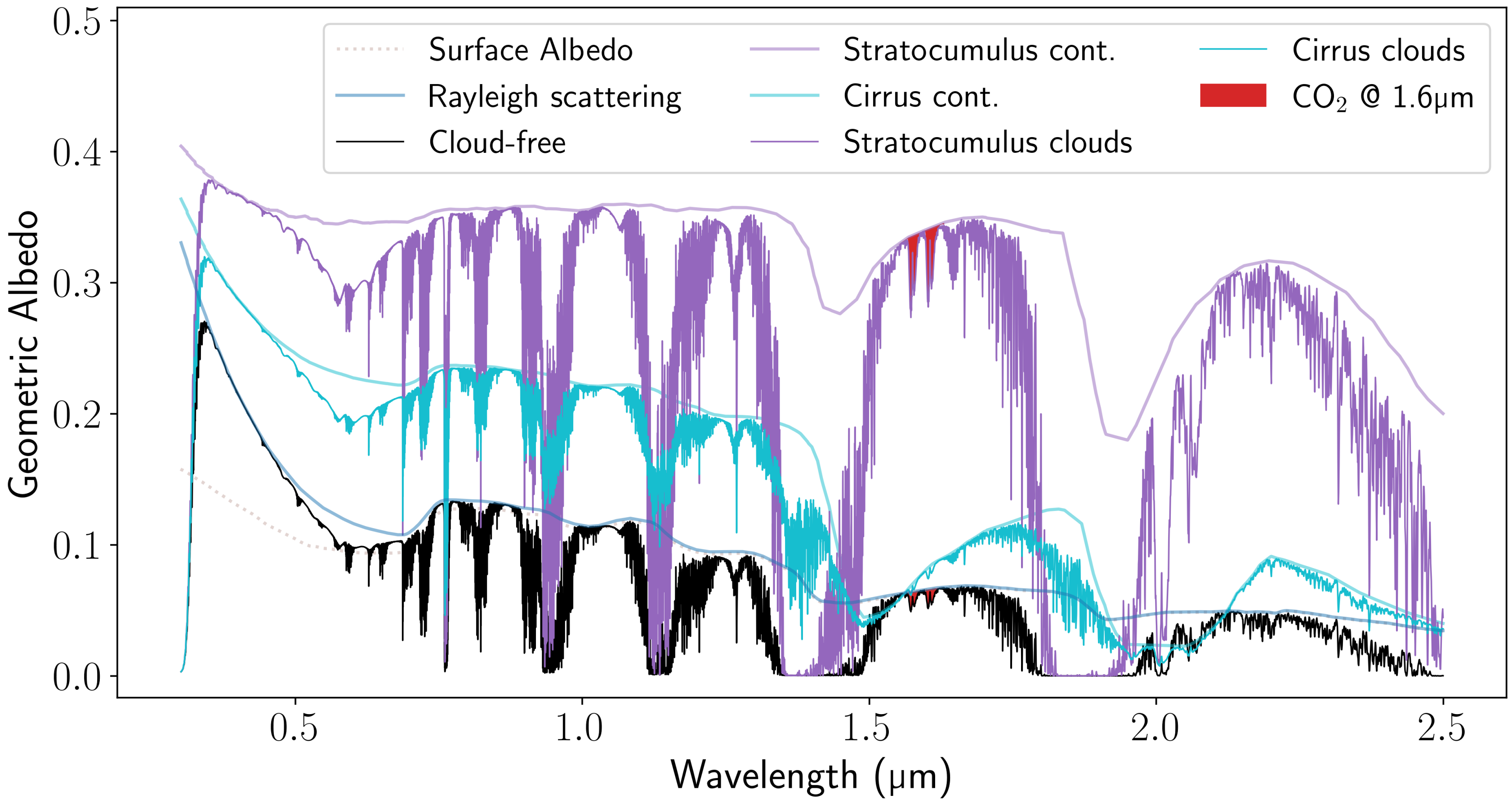
Deconstructing Earth's Reflectance Spectrum



Deconstructing Earth's Reflectance Spectrum



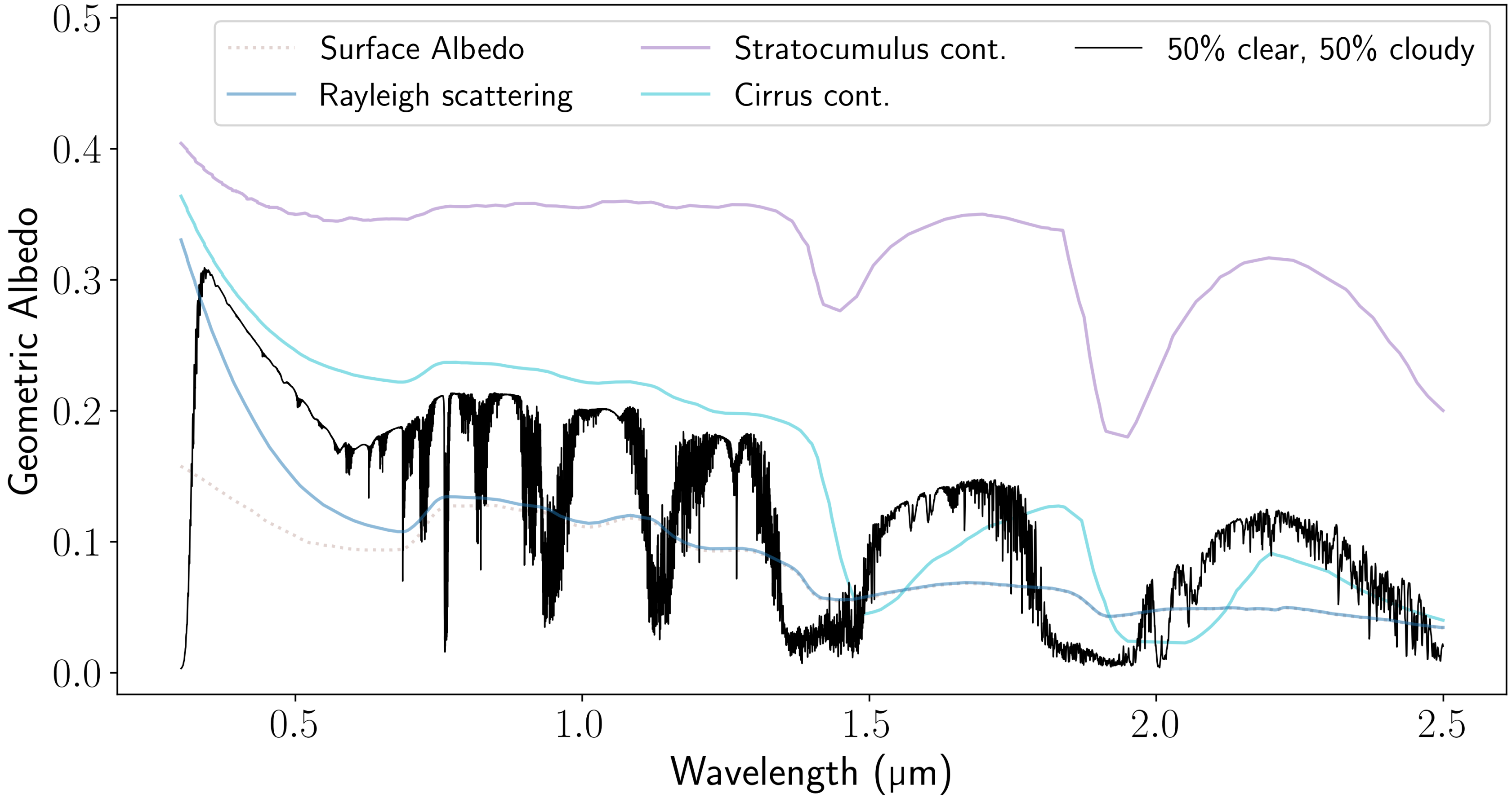
Deconstructing Earth’s Reflectance Spectrum



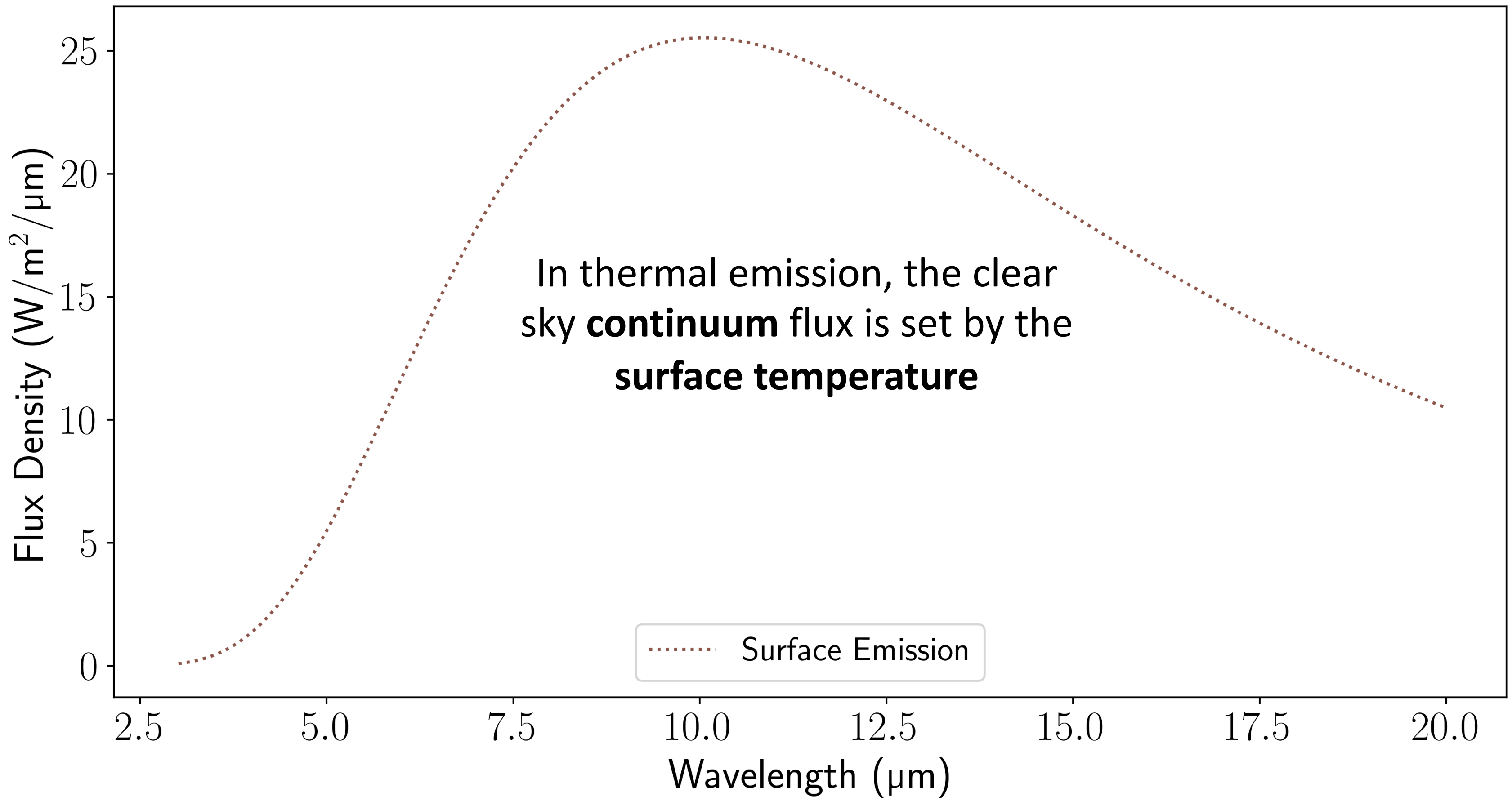
Clouds can dramatically **increase or decrease** the size of absorption features

Deconstructing Earth's Reflectance Spectrum

On average, Earth has about 50% cloud coverage, so the disk-integrated spectrum that we observe from afar is a weighted mean of the clear and cloudy spectra

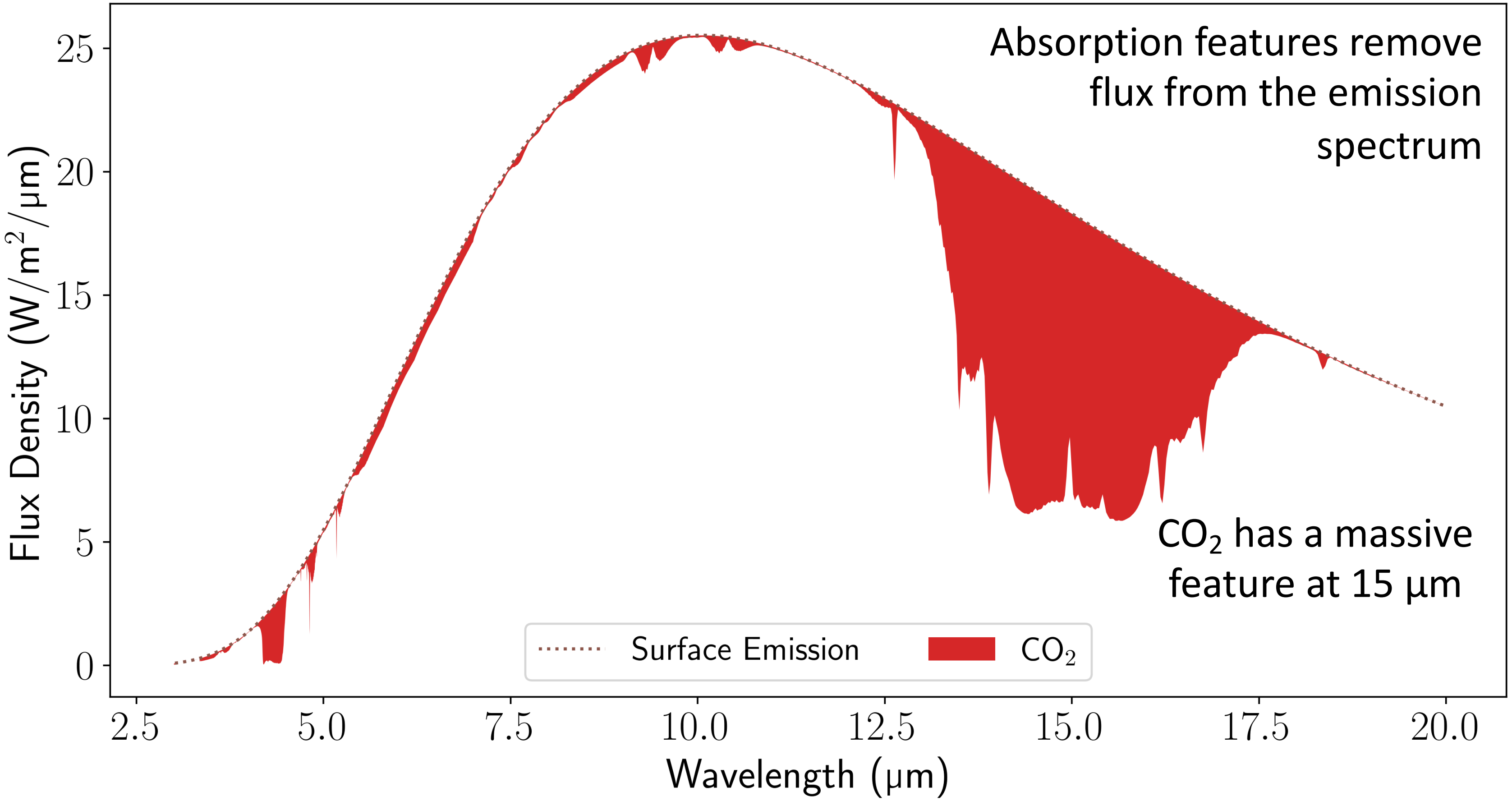


Deconstructing Earth’s Thermal Emission Spectrum



In thermal emission, the clear sky **continuum** flux is set by the **surface temperature**

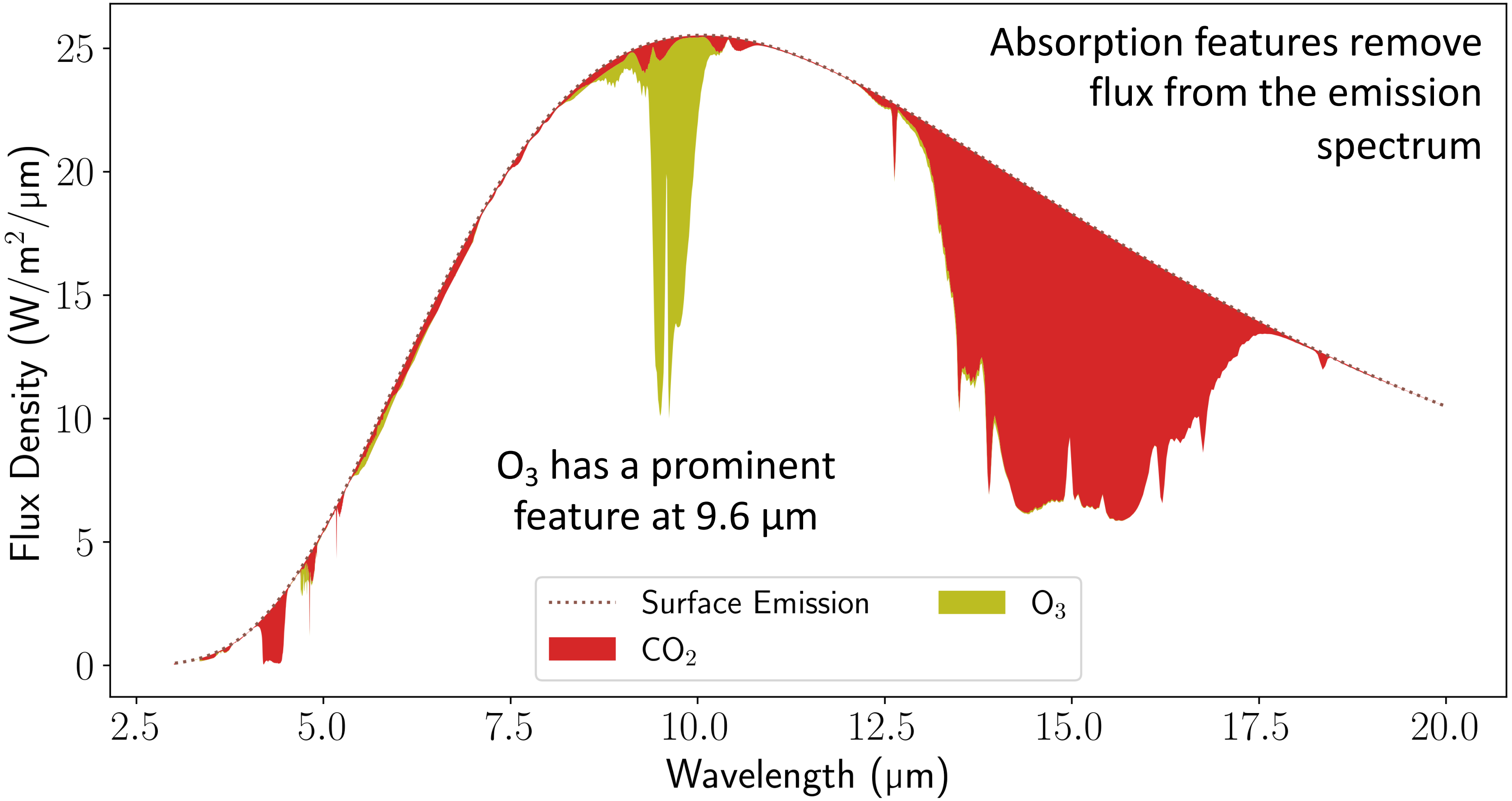
Deconstructing Earth's Thermal Emission Spectrum



Absorption features remove flux from the emission spectrum

CO_2 has a massive feature at 15 μm

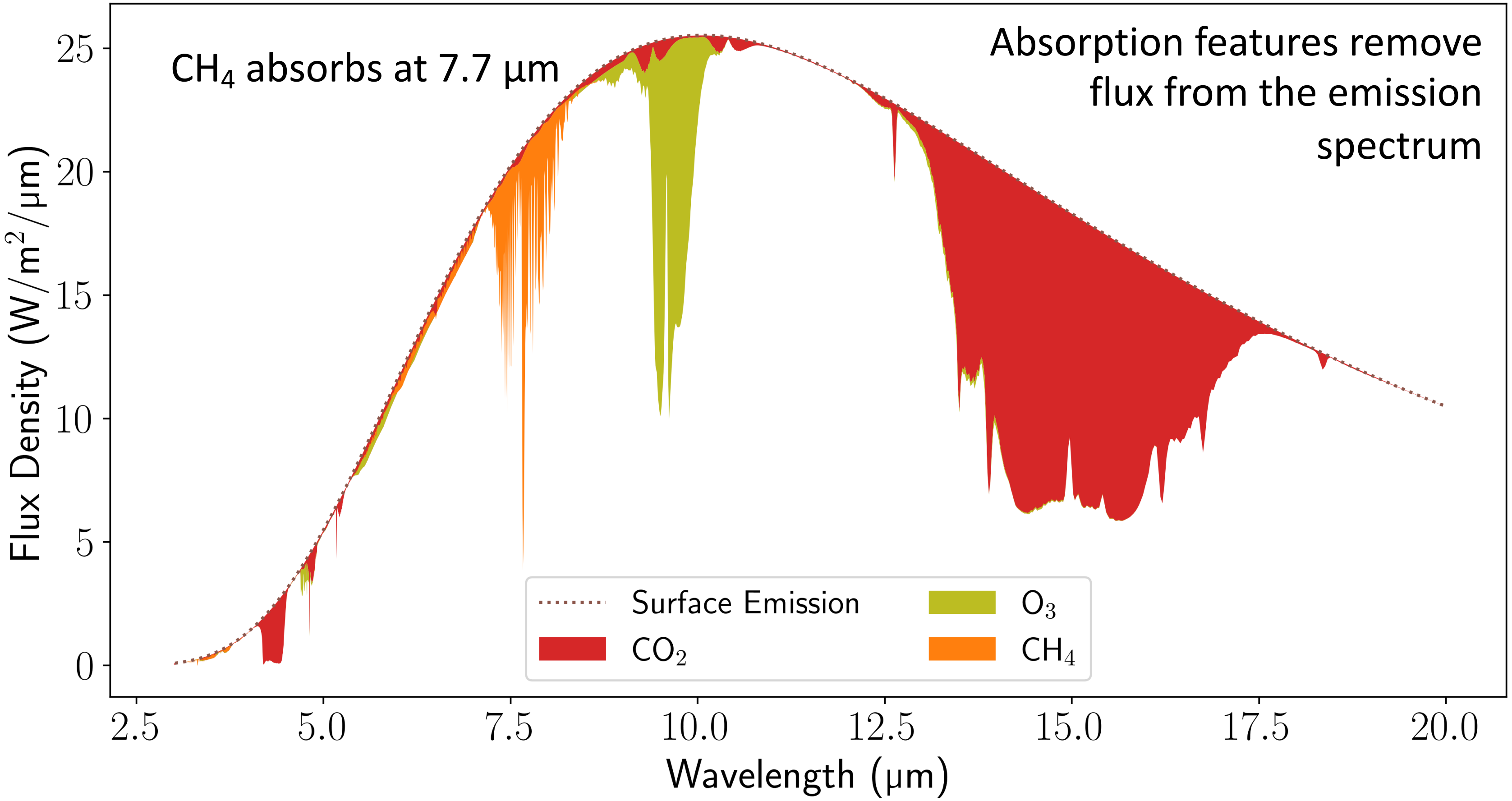
Deconstructing Earth’s Thermal Emission Spectrum



Absorption features remove flux from the emission spectrum

O_3 has a prominent feature at 9.6 μm

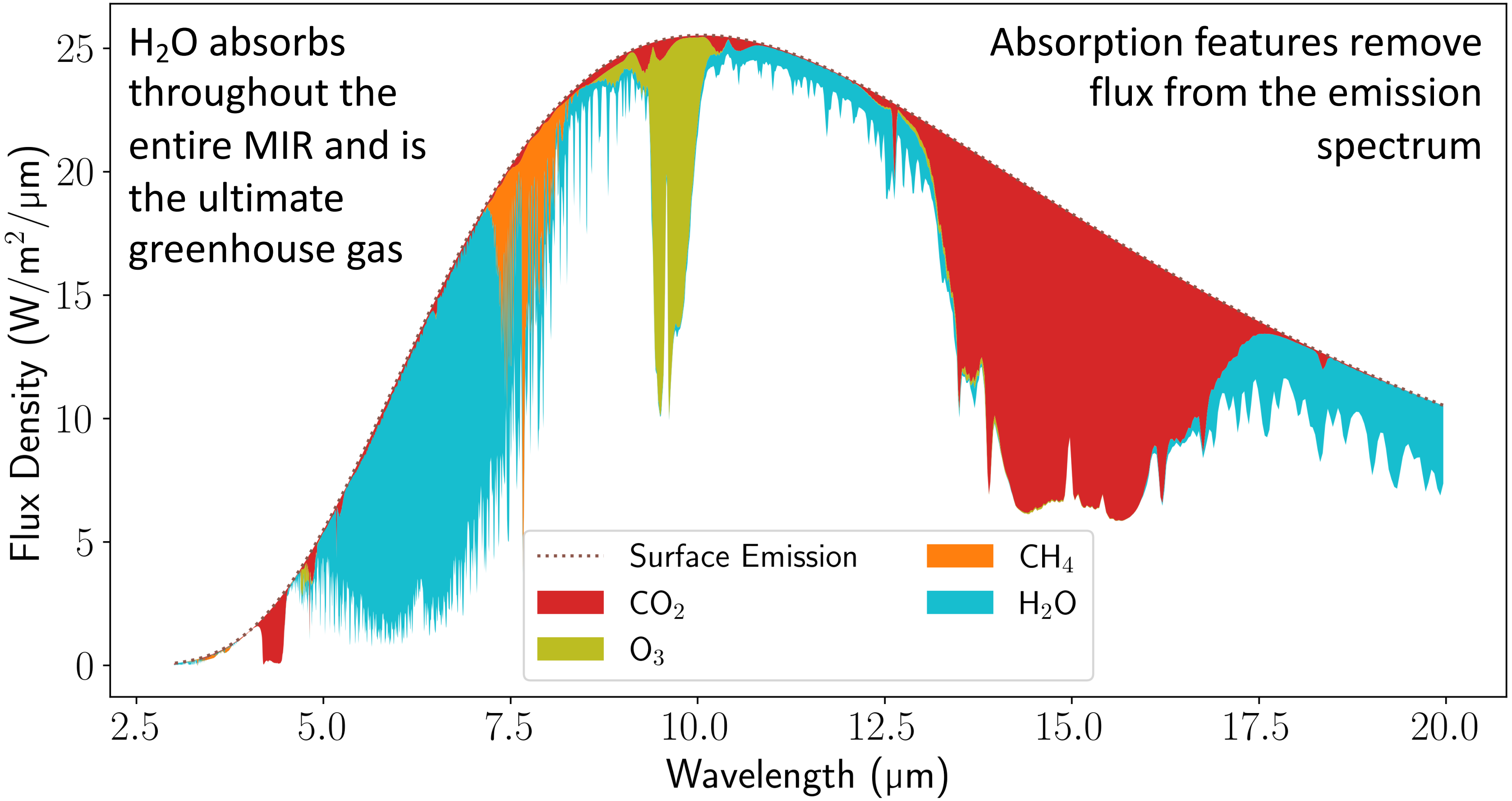
Deconstructing Earth’s Thermal Emission Spectrum



CH_4 absorbs at 7.7 µm

Absorption features remove flux from the emission spectrum

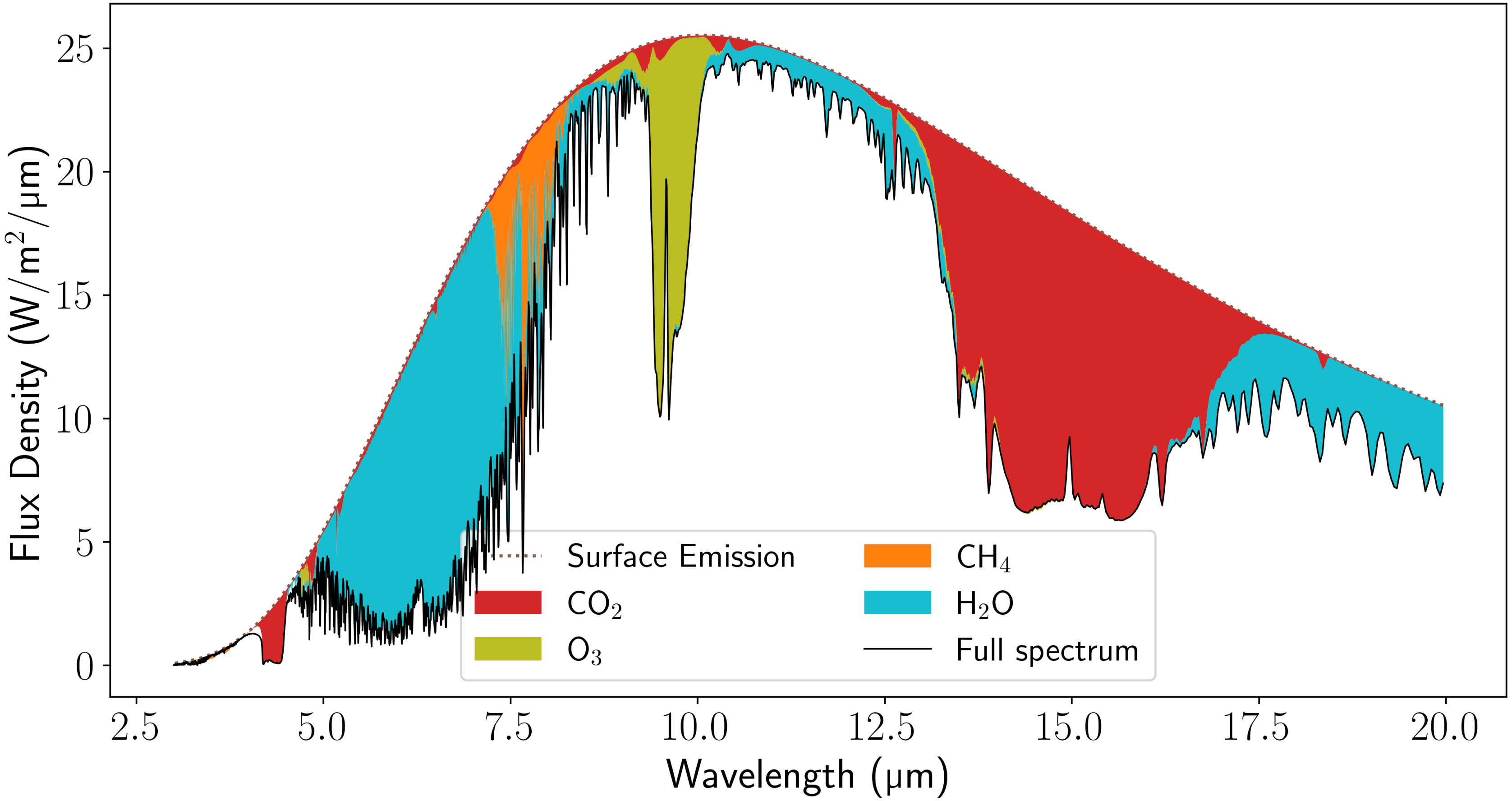
Deconstructing Earth’s Thermal Emission Spectrum



H_2O absorbs throughout the entire MIR and is the ultimate greenhouse gas

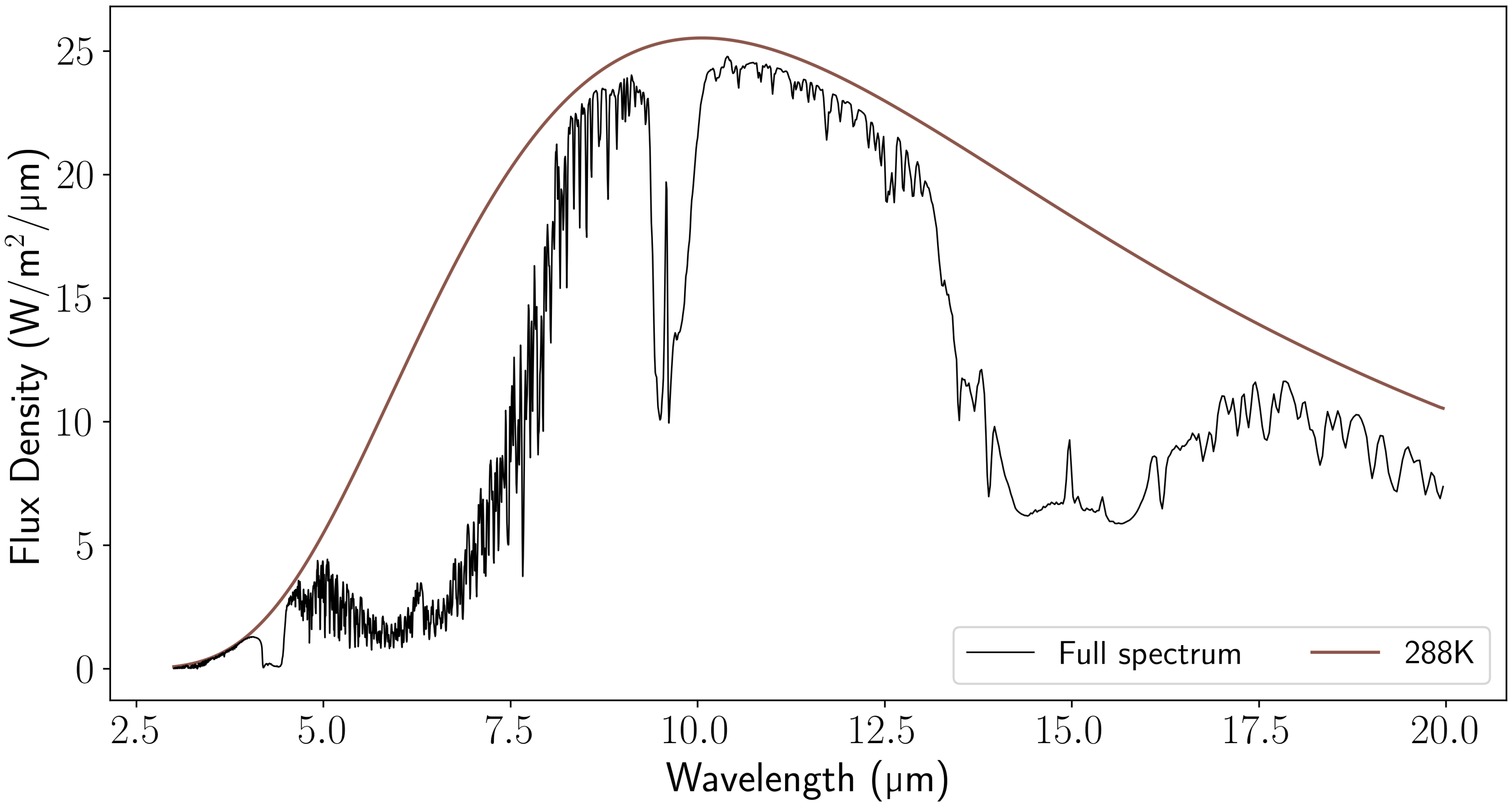
Absorption features remove flux from the emission spectrum

Deconstructing Earth’s Thermal Emission Spectrum



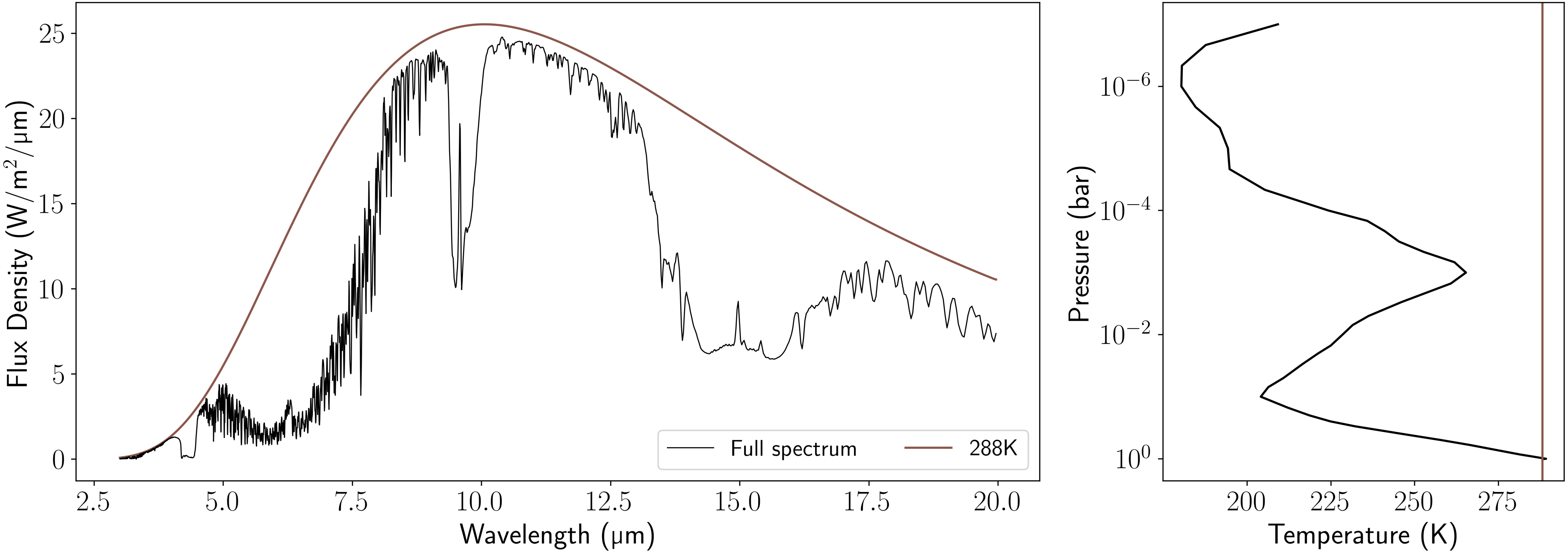
Together, the surface thermal emission and molecular absorption make up the Earth’s emission spectrum *along cloud-free optical paths*

Deconstructing Earth’s Thermal Emission Spectrum



Deconstructing Earth’s Thermal Emission Spectrum

The Pressure-Temperature (PT) profile can help understand why the emission spectrum looks as it does



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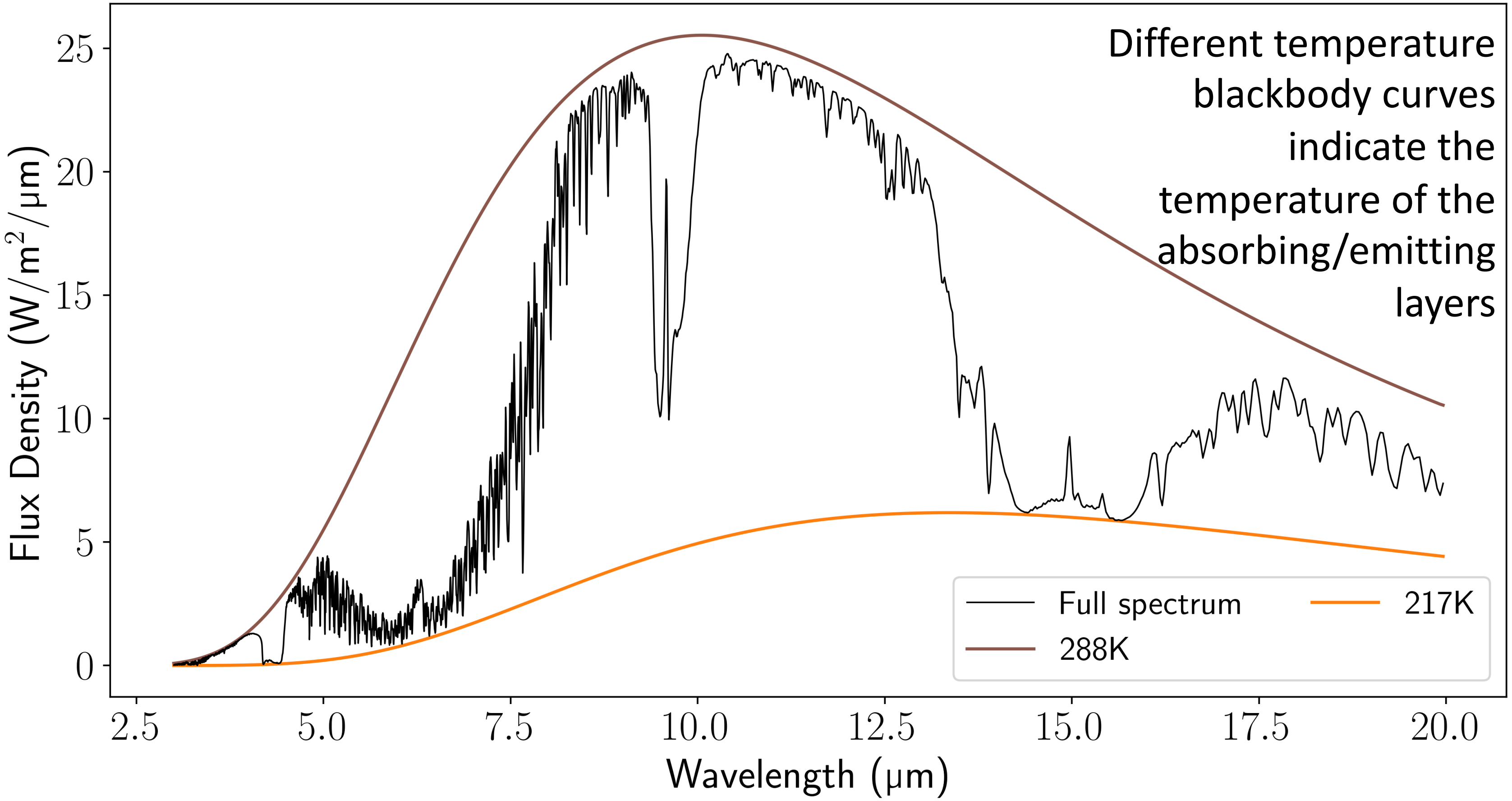
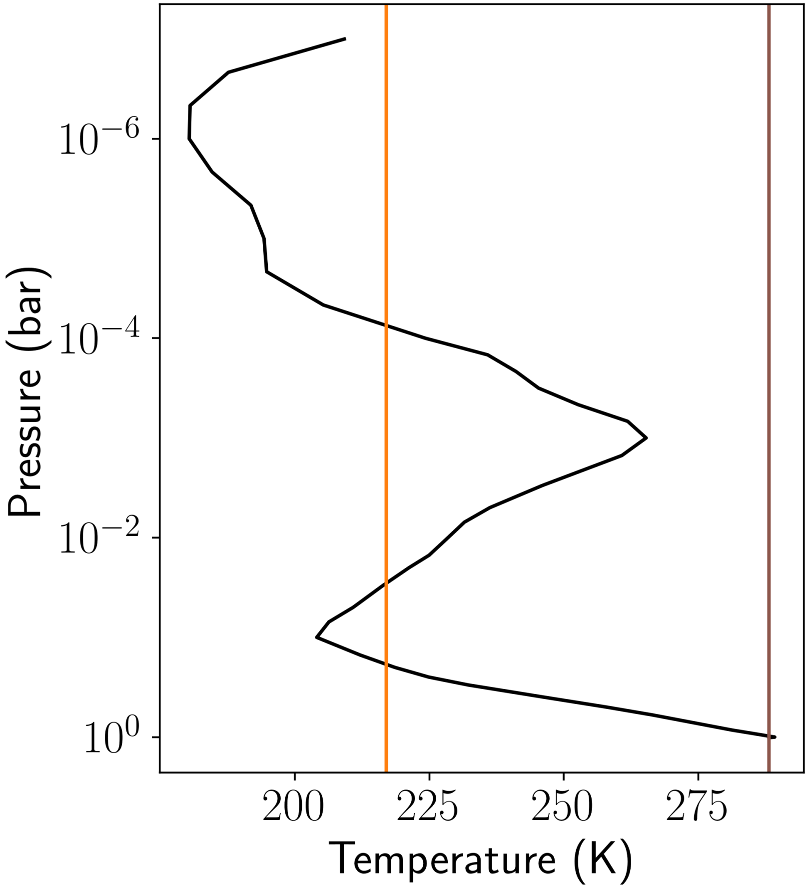
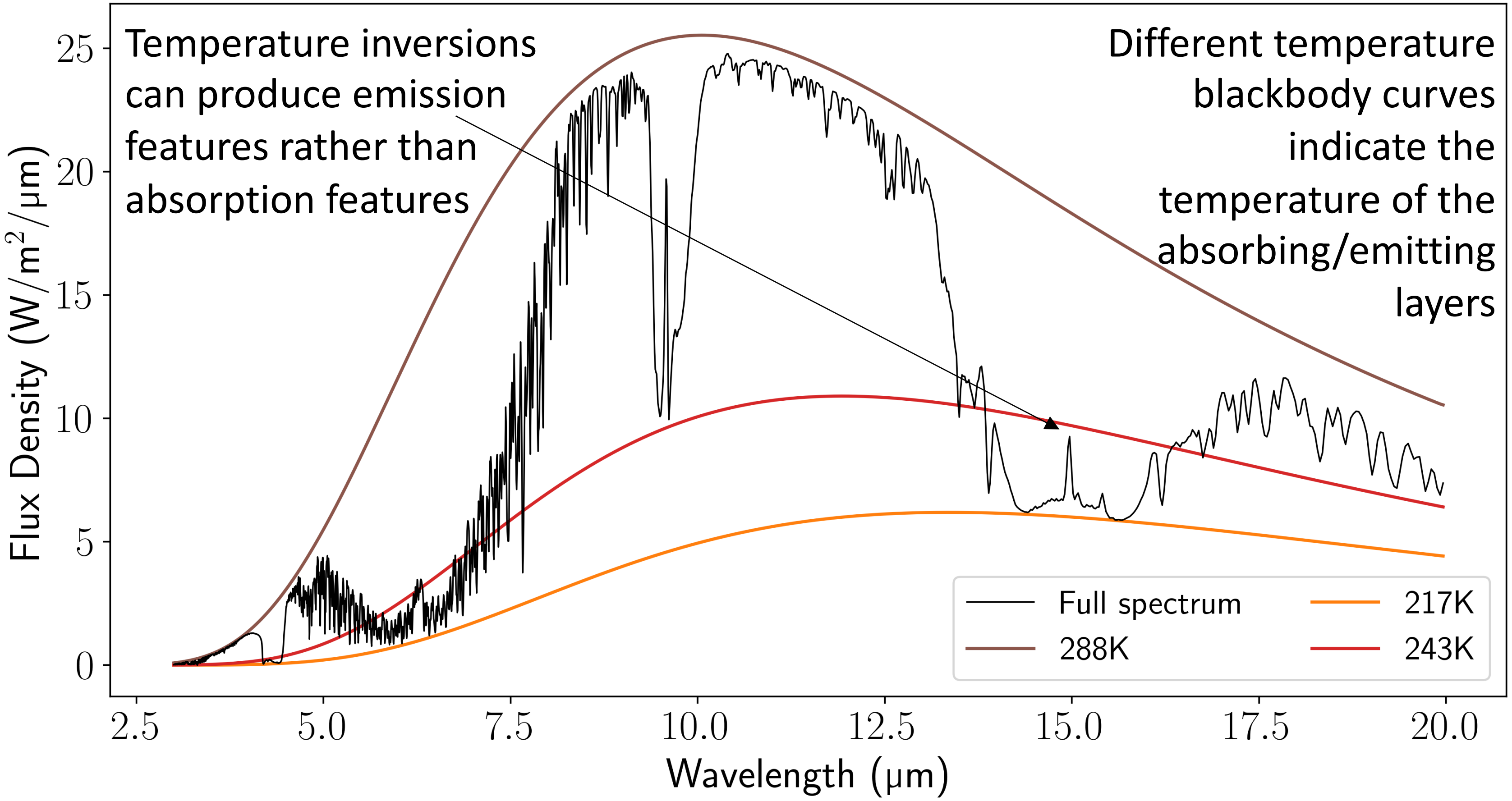




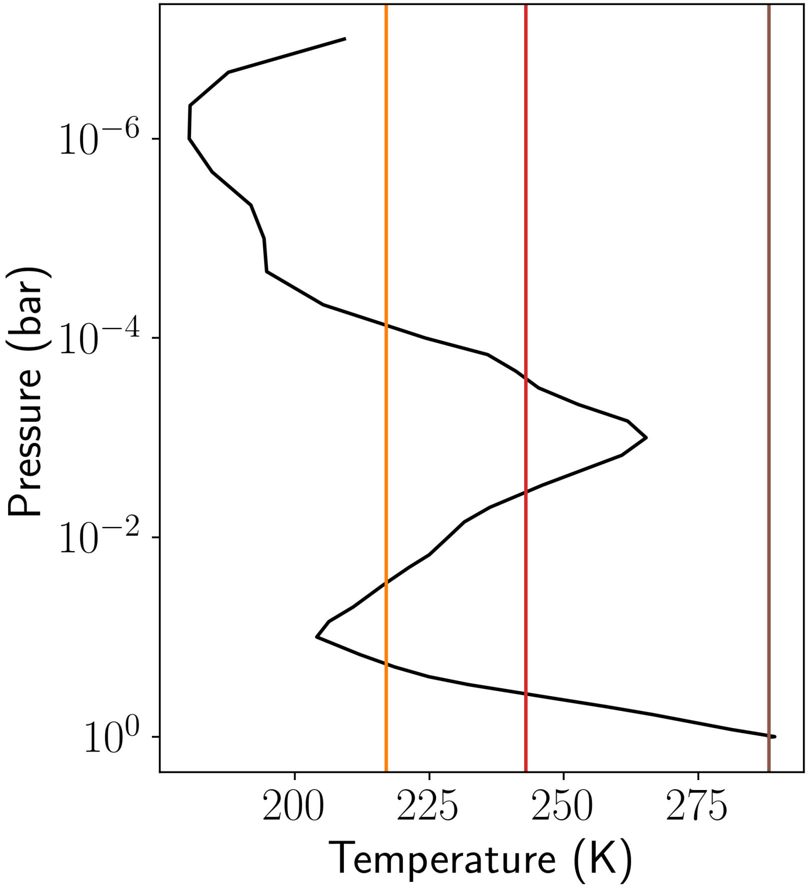
The bottoms of the deep absorption bands have low flux because they come from absorption in cooler atmospheric layers above the surface

Deconstructing Earth’s Thermal Emission Spectrum

The Pressure-Temperature (PT) profile can help understand why the emission spectrum looks as it does


Temperature inversions can produce emission features rather than absorption features

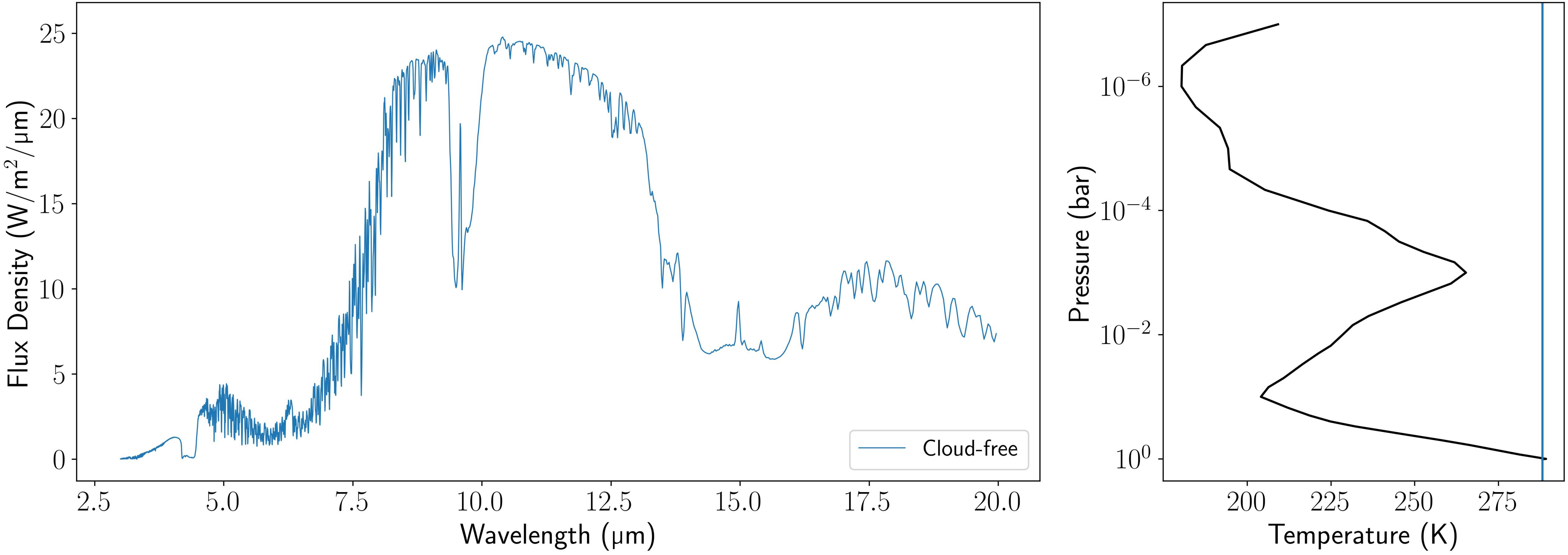
Different temperature blackbody curves indicate the temperature of the absorbing/emitting layers



The bottoms of the deep absorption bands have low flux because they come from absorption in cooler atmospheric layers above the surface

Deconstructing Earth’s Thermal Emission Spectrum

Cloud opacity can decrease emission to space and set the continuum at lower temperatures



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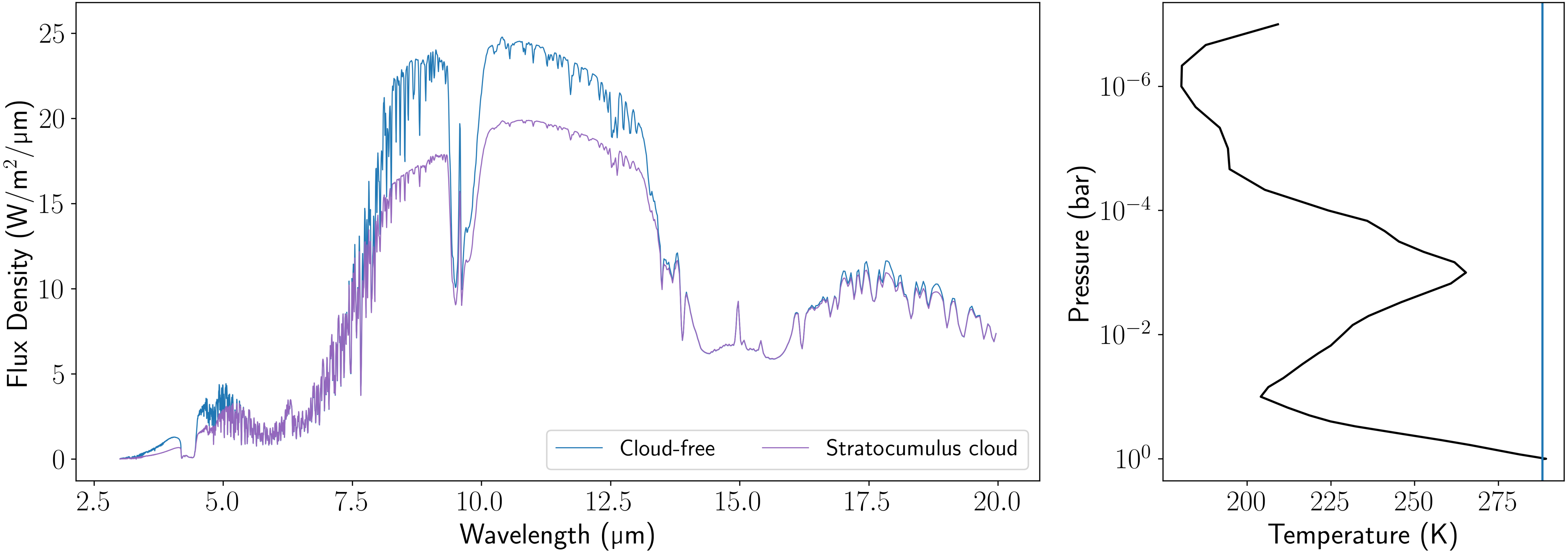

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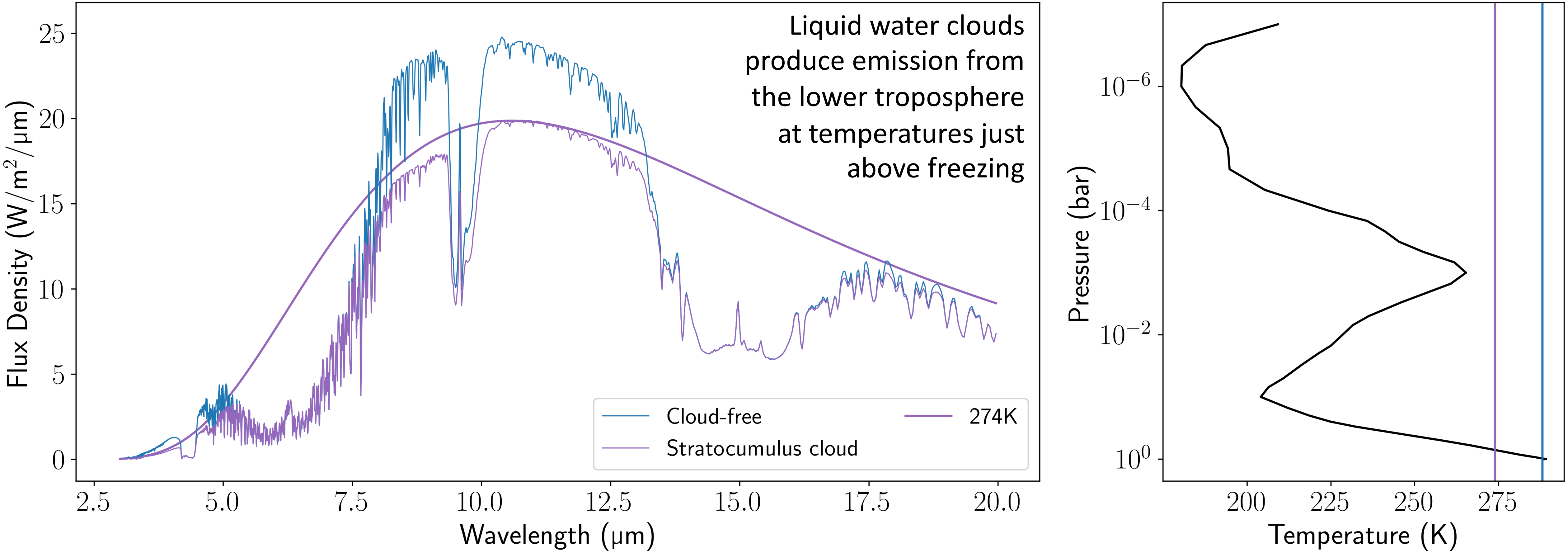
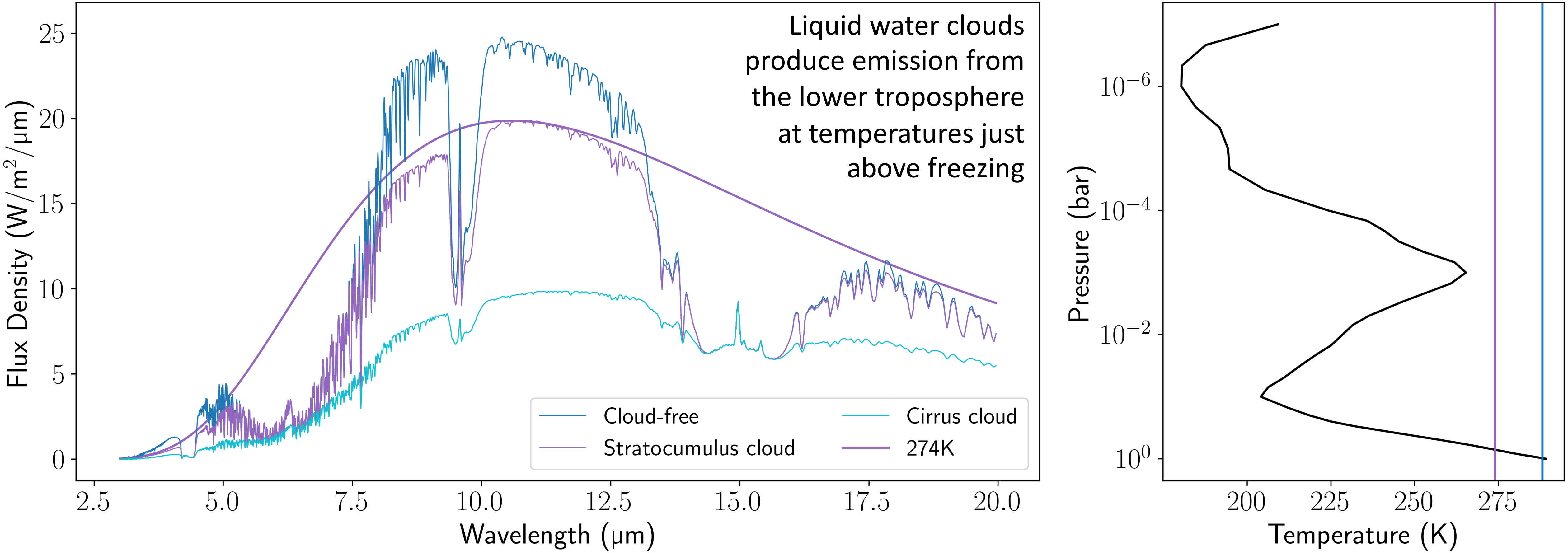


Liquid water clouds produce emission from the lower troposphere at temperatures just above freezing

Deconstructing Earth’s Thermal Emission Spectrum

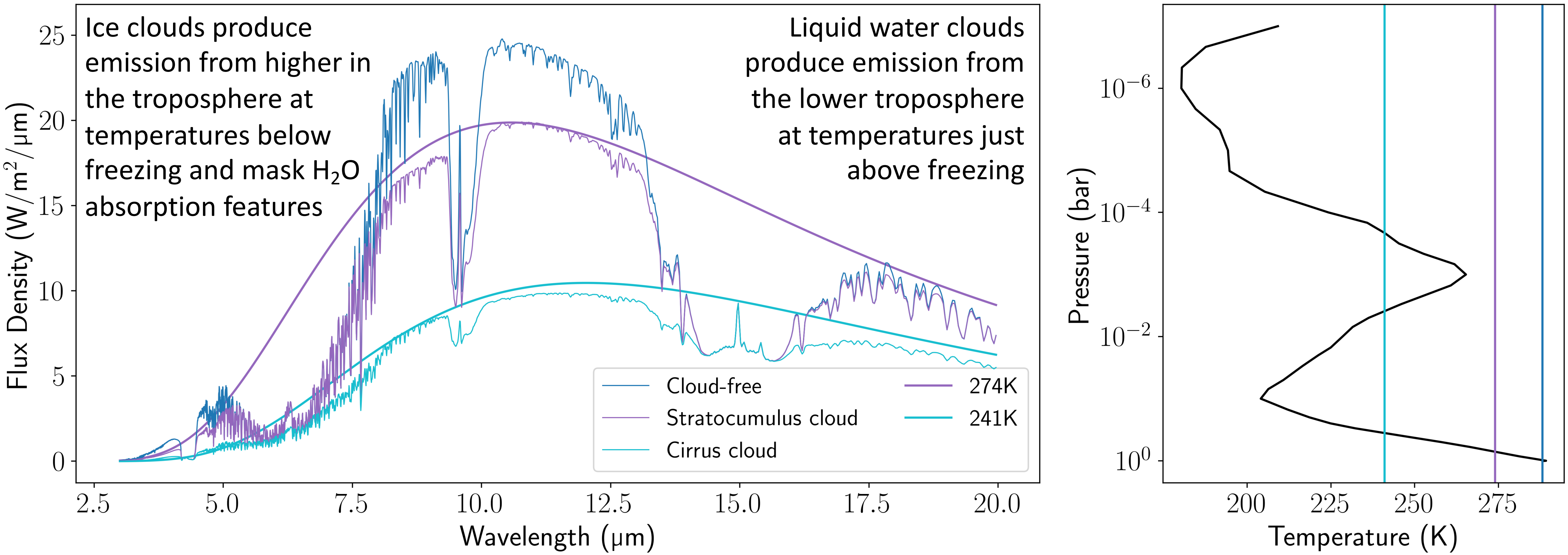
Cloud opacity can decrease emission to space and set the continuum at lower temperatures



Liquid water clouds produce emission from the lower troposphere at temperatures just above freezing

Deconstructing Earth’s Thermal Emission Spectrum

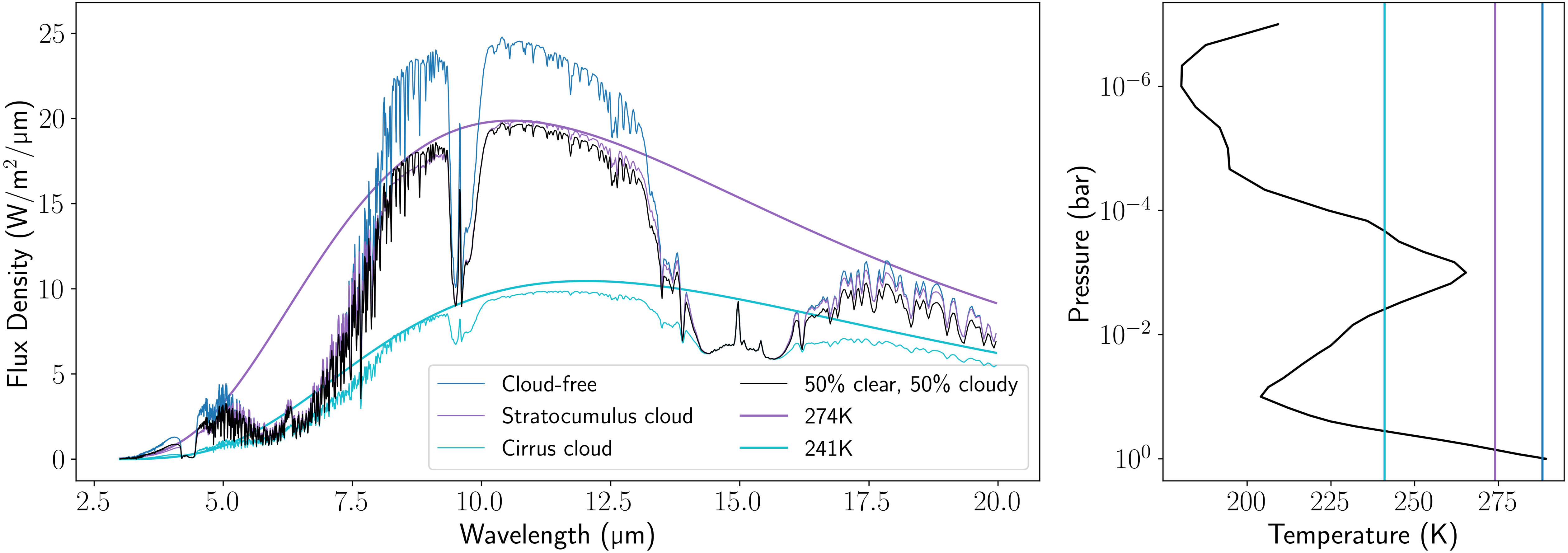
Cloud opacity can decrease emission to space and set the continuum at lower temperatures


Ice clouds produce emission from higher in the troposphere at temperatures below freezing and mask H_2O absorption features

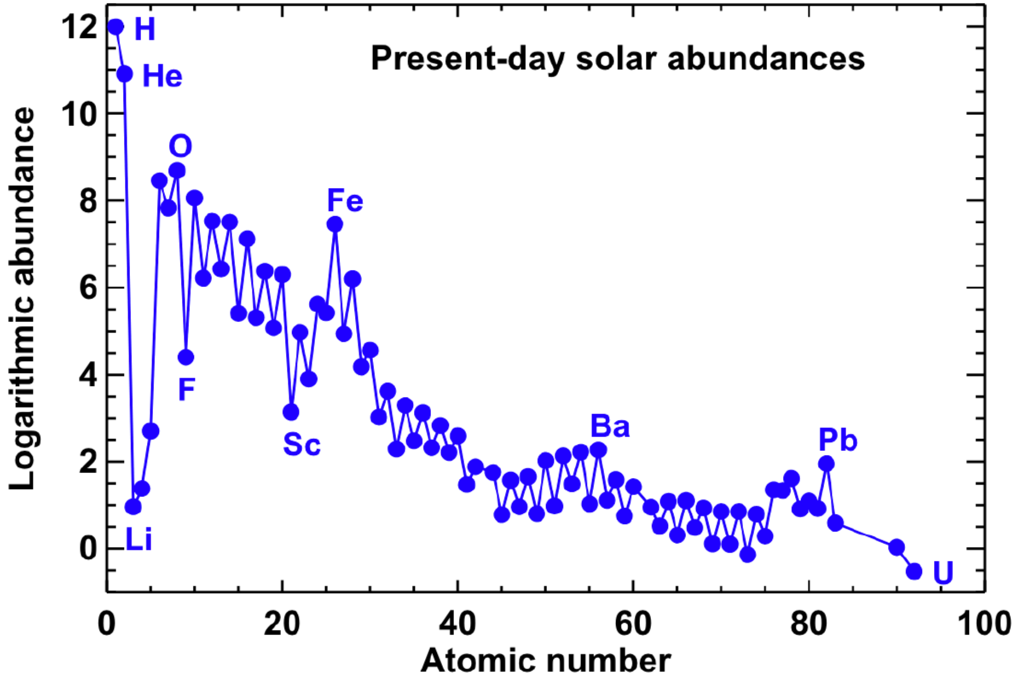
Liquid water clouds produce emission from the lower troposphere at temperatures just above freezing

Deconstructing Earth’s Thermal Emission Spectrum

Like reflected light, the disk-integrated emission spectrum that we observe from afar is a weighted mean of the clear and cloudy spectra and may change over time as cloud fractions vary



Metallicity to Describe Atmospheric Composition

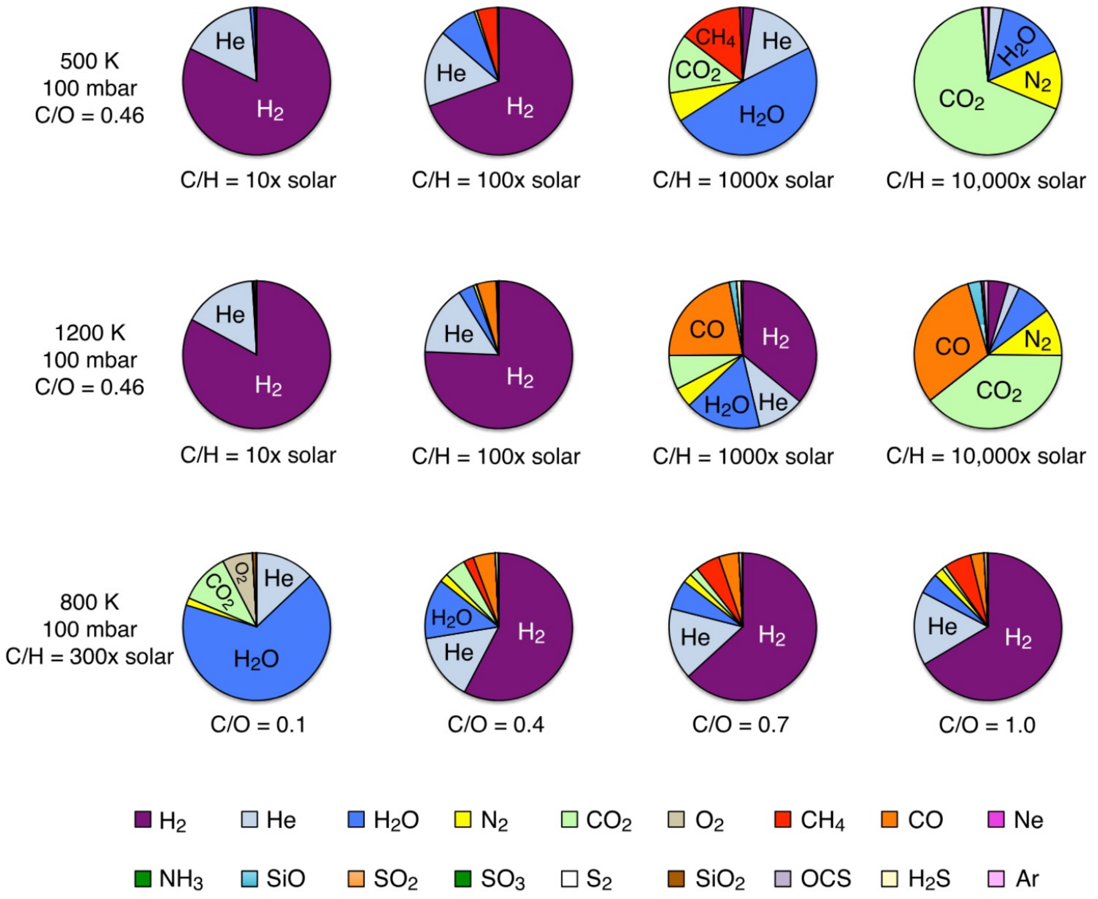


- Metallicity is the factor by which "metals" are enhanced above their solar abundances:

$$\left[\frac{\mathrm{X}}{\mathrm{H}}\right] = \log_{10}\left(\frac{(N_{\mathrm{X}}/N_{\mathrm{H}})}{(N_{\mathrm{X}}/N_{\mathrm{H}})_{\odot}}\right)$$

Asplund et al. (2021); Rauscher (upcoming review chapter)

Metallicity to Describe Atmospheric Composition



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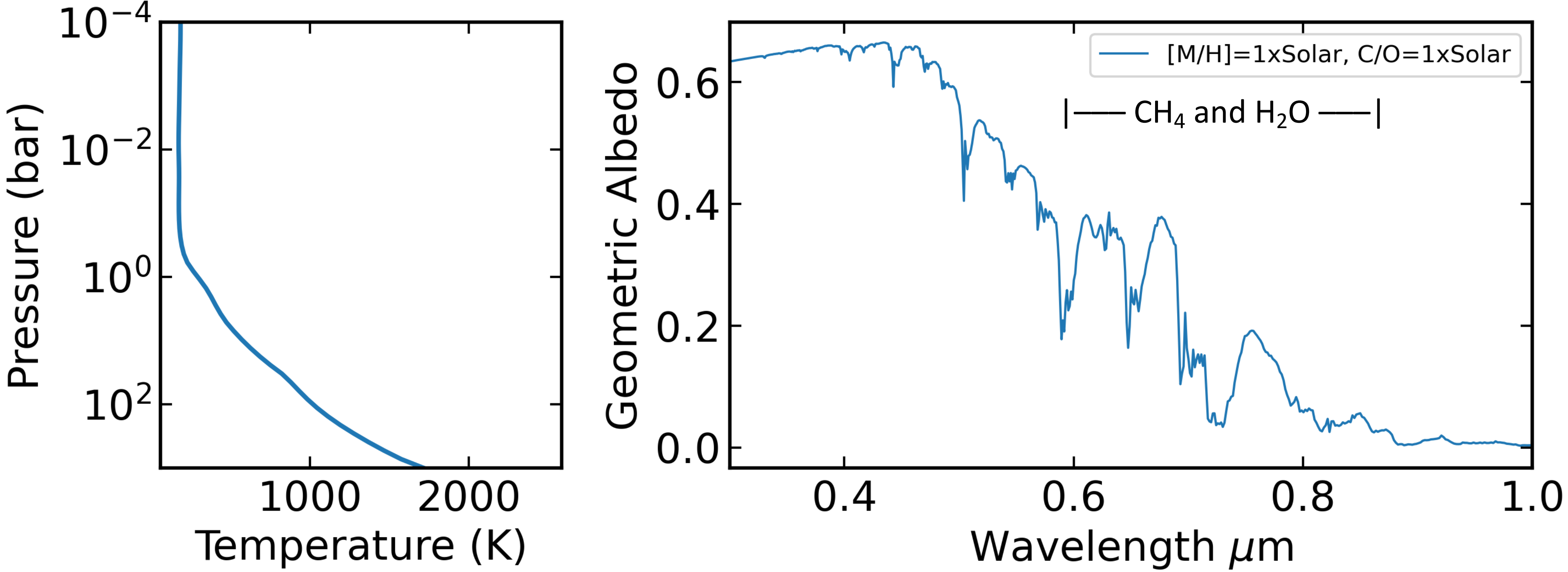
$$\left[\frac{\mathrm{X}}{\mathrm{H}}\right] = \log_{10}\left(\frac{(N_{\mathrm{X}}/N_{\mathrm{H}})}{(N_{\mathrm{X}}/N_{\mathrm{H}})_{\odot}}\right)$$

- Temperature, metallicity, and C/O ratio can dramatically change the expected equilibrium composition of exoplanets (e.g. Moses et al. 2013)

Moses et al. (2013); Rauscher (upcoming review chapter)

Impact of Metallicity on Spectra

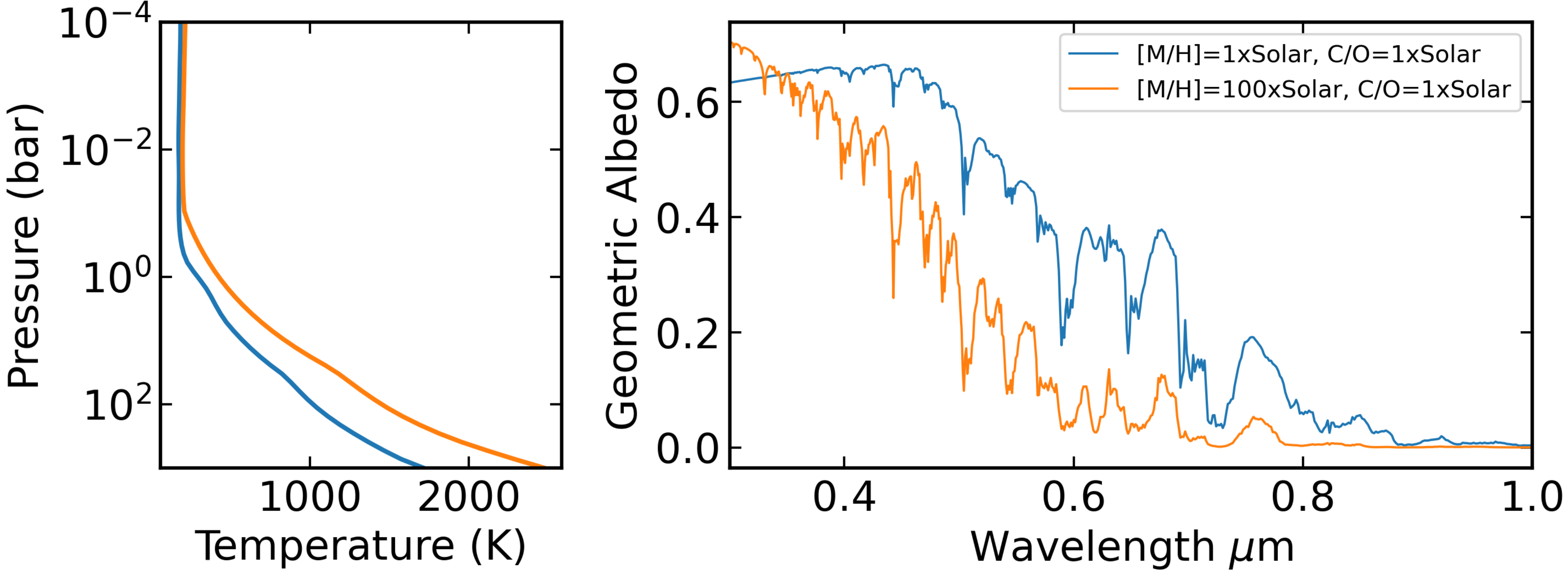
A hypothetical cloud-free Jupiter at 1.2 AU (T_{eq}=200K) around a Sun-like star in reflected light



Figures by Laura Mayorga

Impact of Metallicity on Spectra

A hypothetical cloud-free Jupiter at 1.2 AU (T_{eq}=200K) around a Sun-like star in reflected light

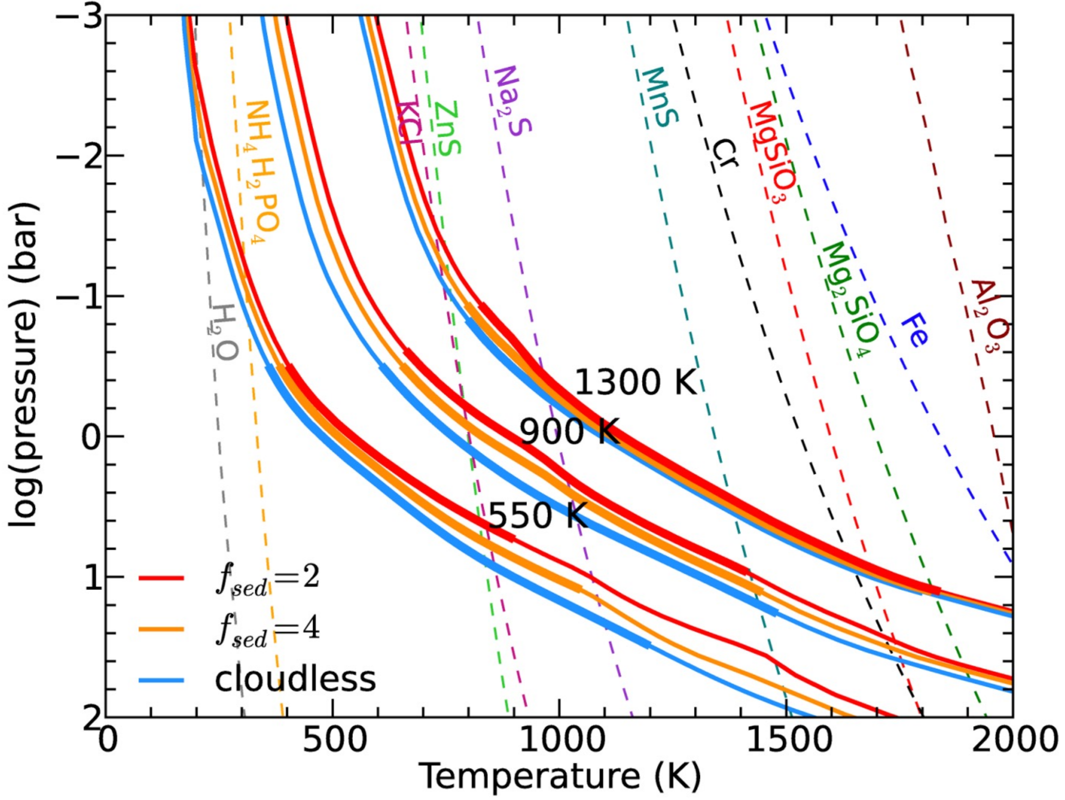


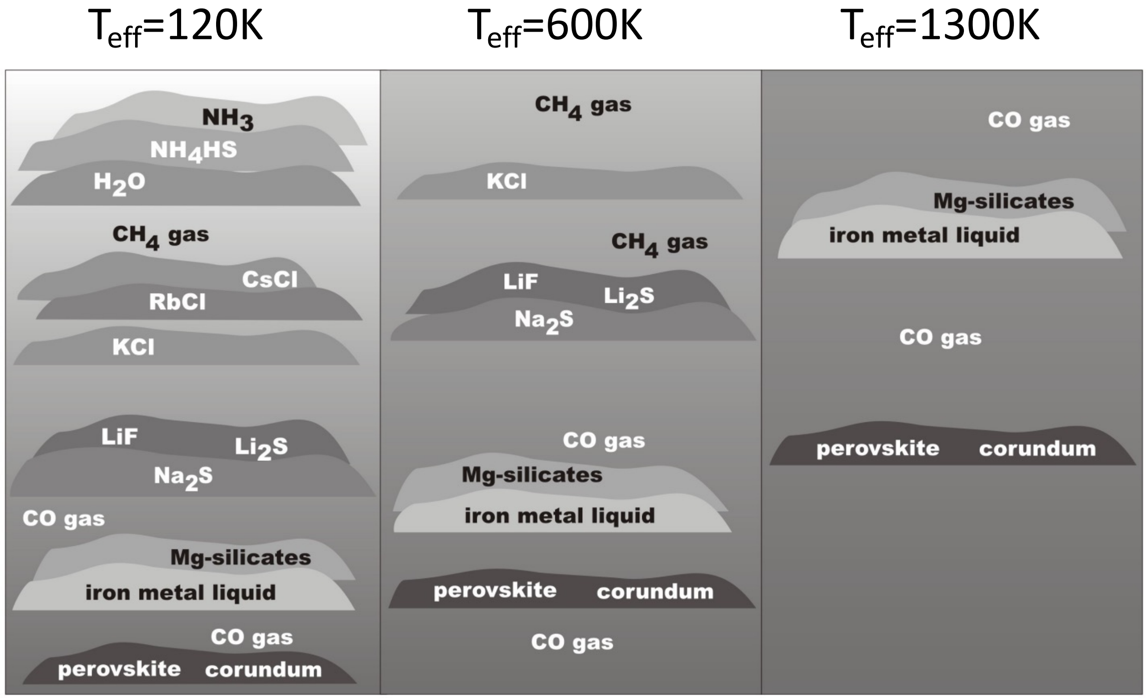
Figures by Laura Mayorga

Cloudy with a chance of more clouds

Clear skies are the exception, not the rule

Clouds form where the PT profile crosses the condensation curve for a given species





At lower temperatures the more refractory clouds form at greater depth, with more volatile clouds above

Marley et al. (2013)
Comparative Climatology of Terrestrial Planets

Morley et al. (2012); Lodders et al. (2004)

Reflected Phase Curves

Reflected-light phase curves measure the disk-integrated planet brightness as a function of phase.

Solar system planetary observations demonstrate radical departures from simple Lambertian scattering, and strong wavelength dependent variability (e.g., Mayorga et al. 2016, 2021; Robinson et al. 2010).

Optical phase curves probe aerosol, Rayleigh, and/or surface scattering properties.

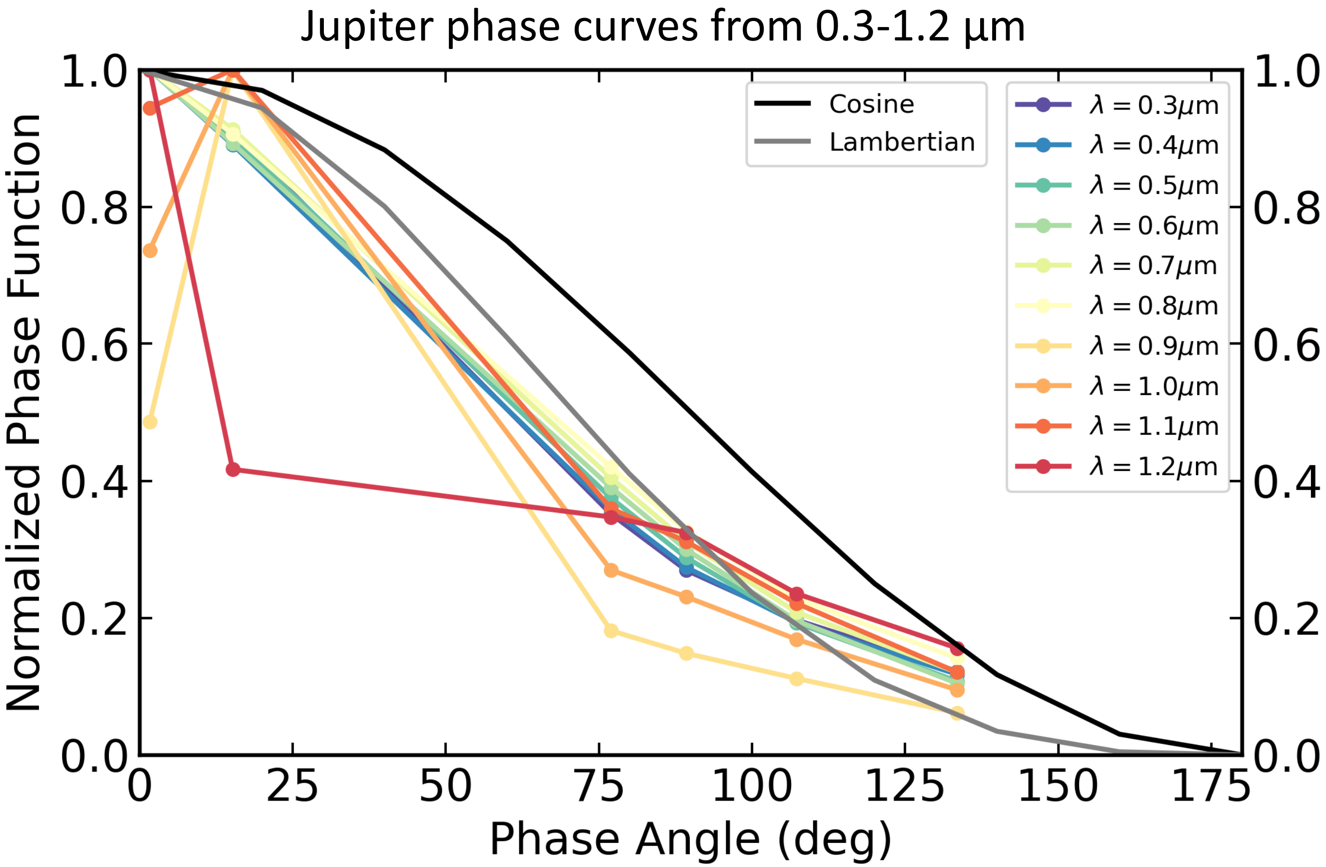
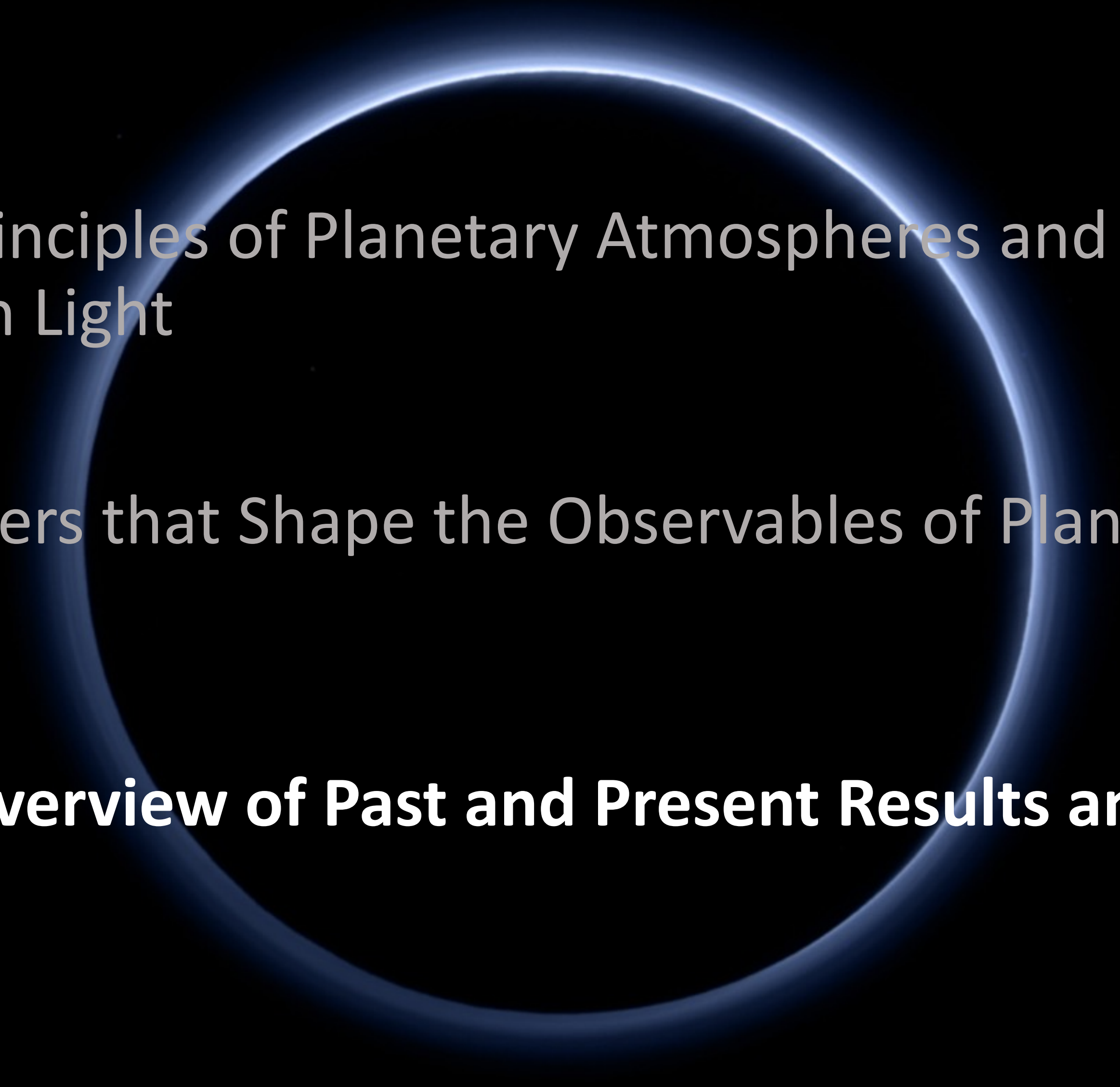


Figure by Laura Mayorga
Data from Coulter, Barnes, & Fortney (2022)

Exoplanet Atmospheric Studies



Part 1 – Basic Principles of Planetary Atmospheres and their Interactions with Light

Part 2 – Key Levers that Shape the Observables of Planetary Atmospheres

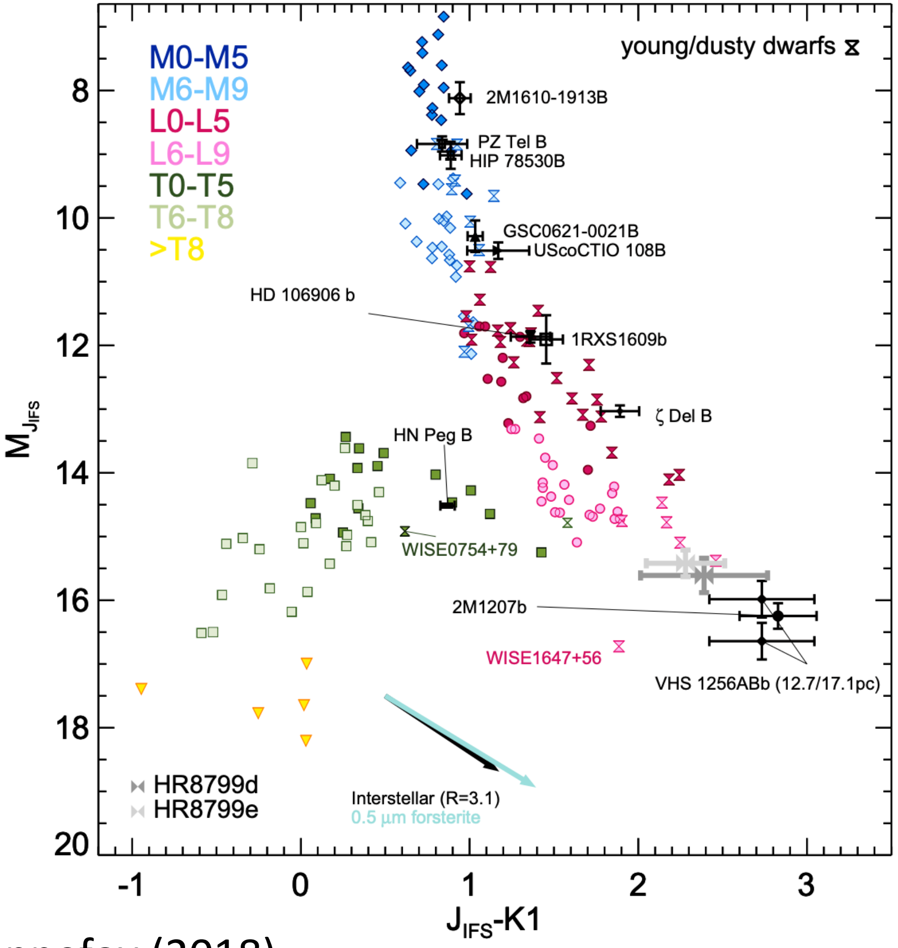
Part 3 – Brief Overview of Past and Present Results and Future Goals

NASA/JHUAPL/SwRI

Past Findings

GPI/SPHERE atmospheric results

Initial Photometry (circa 2010)



Biller & Bonnefoy (2018)

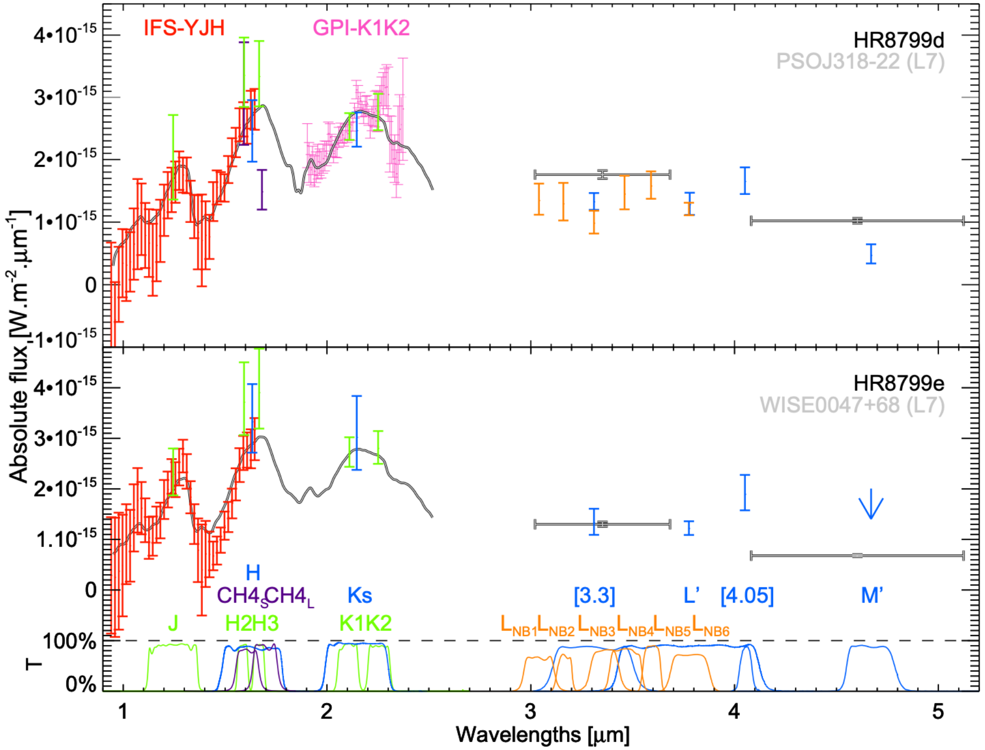
- Early photometry was able to distinguish brown dwarfs from young planets with similar effective temperatures.
- Exoplanets and brown dwarfs begin as M-type objects and then cool over time, moving red-wards to the L spectral type, then transition to the comparatively blue T spectral type (due to strong methane absorption that removes flux predominantly in the K band).
- Young planetary mass objects retain red colors and L spectral types down to much lower T_{eff} than BDs, due to lower surface gravity, atmospheric structure, and/or patchy clouds that inhibit CH_4 absorption.

Past Findings

GPI/SPHERE atmospheric results

- Initial near-IR spectra confirmed that the red colors exhibited by young planets relate to their low surface gravities

High Contrast Spectroscopy (circa 2013-2016)

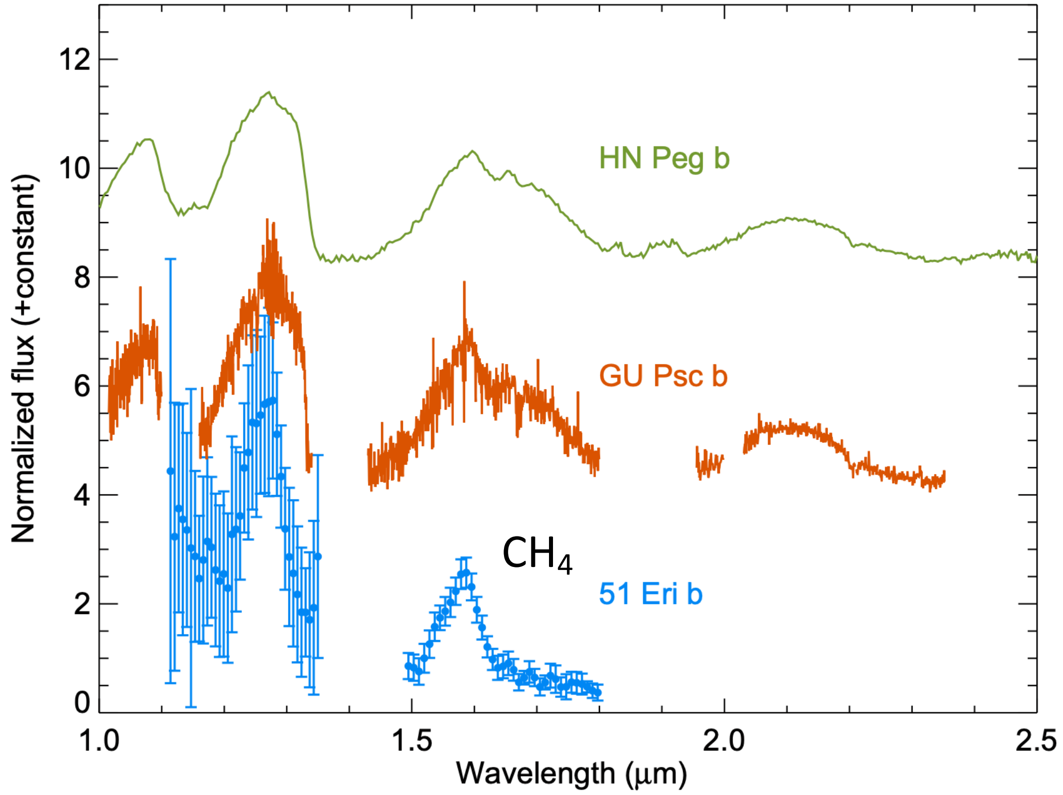


Biller & Bonnefoy (2018)

Past Findings

GPI/SPHERE atmospheric results

- Initial near-IR spectra confirmed that the red colors exhibited by young planets relate to their low surface gravities
- 51 Eri b is the first exoplanet with clear CH_4 absorption (GPI; Macintosh et al. 2015), suggesting that the L/T transition occurs at considerably lower T_{eff} for low surface gravity planets than high g BDs



Biller & Bonnefoy (2018)

For more, see Jean-Baptiste Ruffio’s Talk on “High and Mid-dispersion Spectroscopy (R > 1000)” on Wednesday

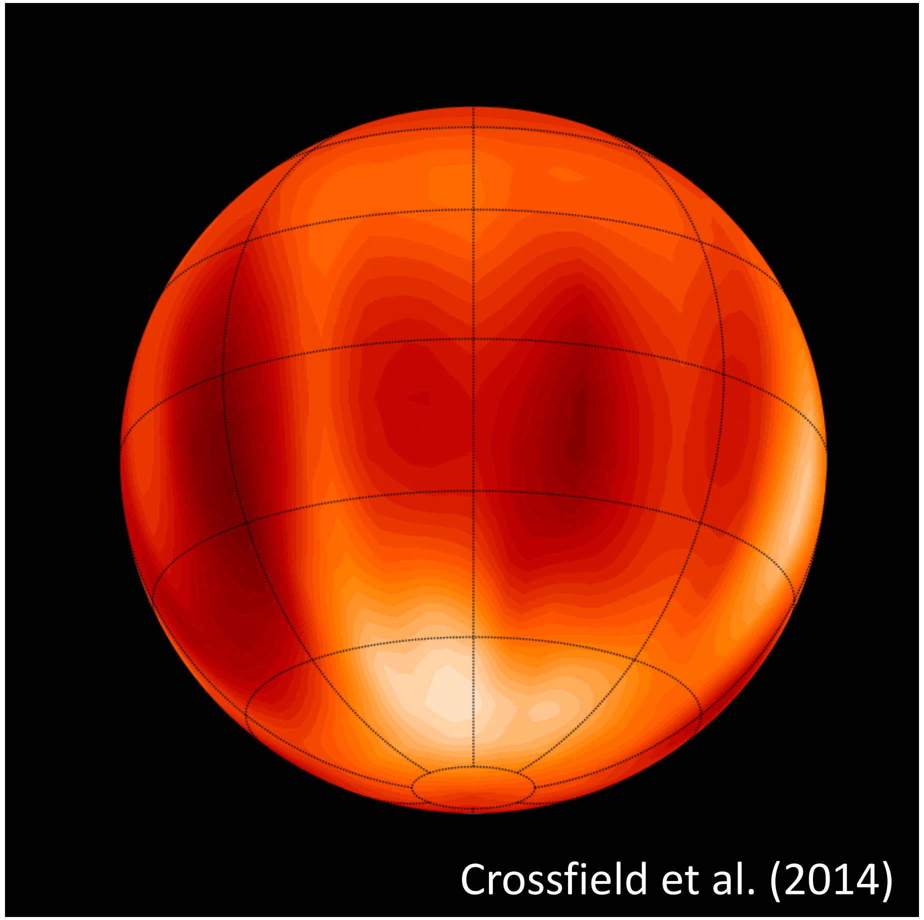
Past Findings

VLT/CRIRES Planet Rotational Mapping

Rotationally modulated variability occurs when:

1. Rotation periods are short
2. Surface/photosphere inhomogeneities are present (e.g. clouds or thermo-chemical instabilities)

High-resolution spectrographs on extremely large telescopes will enable similar mapping of directly imaged exoplanet companions.



Crossfield et al. (2014)

Doppler map of the early T variable brown dwarf Luhman 16B

Biller & Bonnefoy (2018)

For more, see Kim Ward-Duong's Talk on "Space vs. Ground: JWST Case Studies" on Thursday

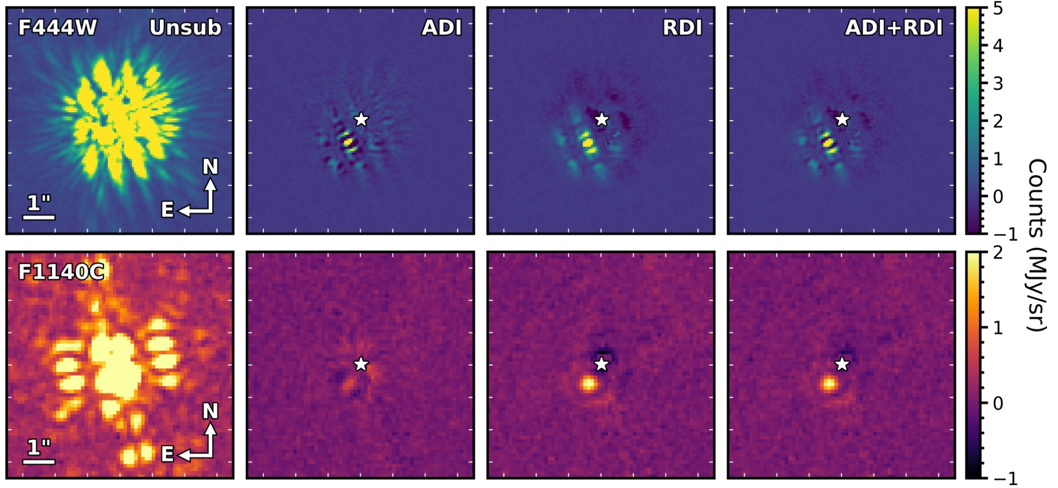
Recent Findings

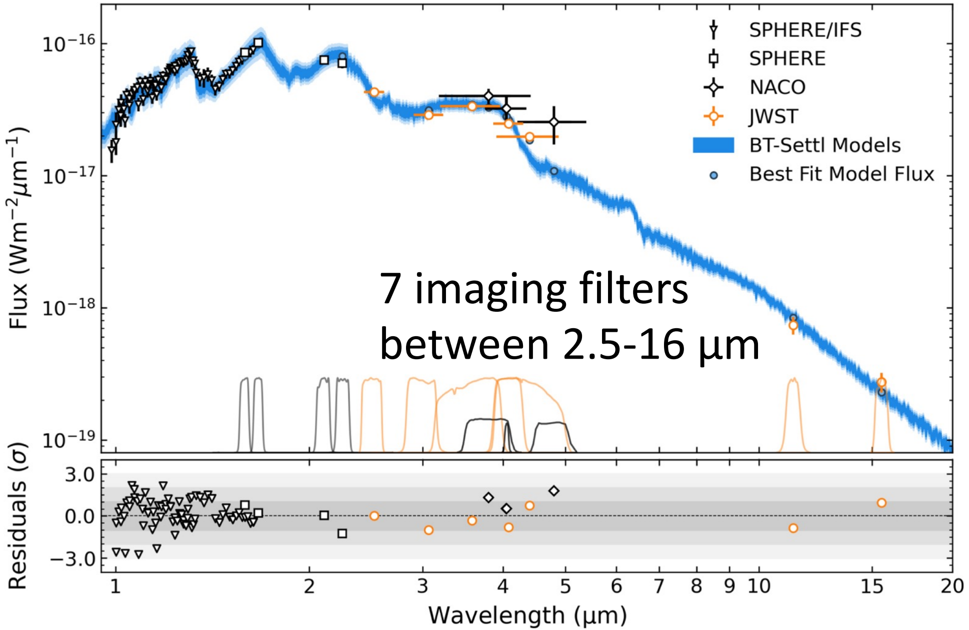
JWST coronagraph initial results on atmospheres: HIP 65426b

- JWST enabled the first-ever direct detection of an exoplanet beyond 5 μm (Carter et al. 2023)
- With ~10x enhancement in performance over predictions, JWST contrast limits provide sensitivity to sub-Jupiter companions with masses as low as $0.3 M_{\mathrm{Jup}}$ beyond separations of ∼100 au (Carter et al. 2023).
- The precision of the 3-5 µm data may be sufficient to provide constraints on the relative abundances of CH_4 and CO, which can probe disequilibrium chemistry (Zahnle & Marley 2014; Miles et al. 2020).

NIRCam: 4.4 µm

MIRI: 11.3 µm





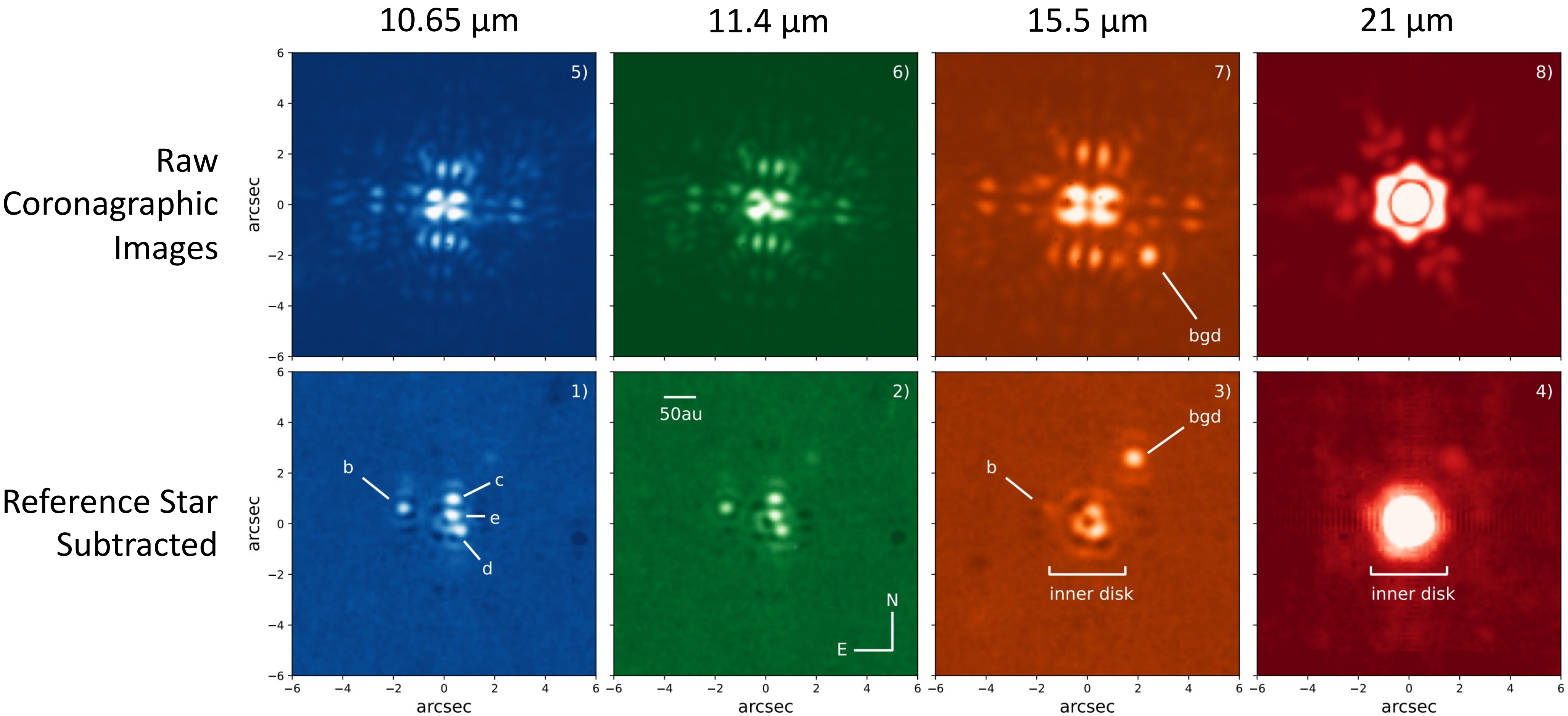
7 imaging filters between 2.5-16 µm

Carter et al. (2023)

For more, see Kim Ward-Duong's Talk on "Space vs. Ground: JWST Case Studies" on Thursday, and John Debes talk on Disk Science next!

Recent Findings

JWST coronagraph initial results on atmospheres: HR 8799

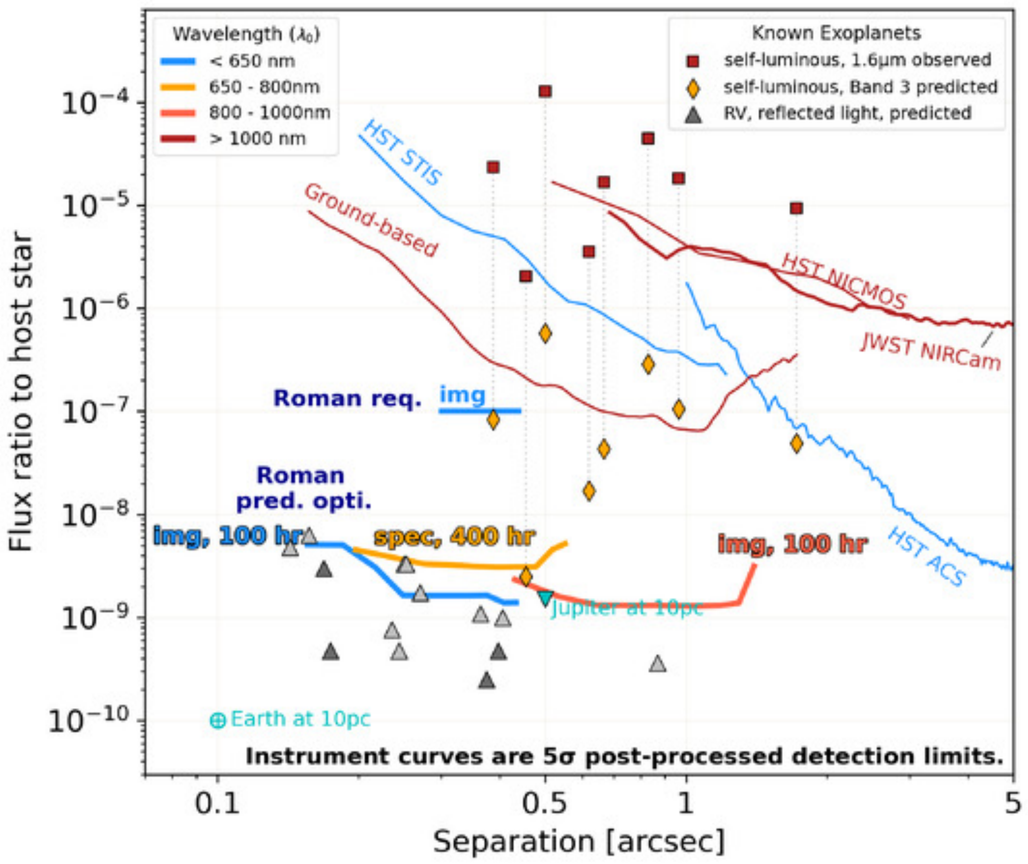


Boccaletti et al. (2024)

For more, see Bertrand Mennesson’s Talk on “Roman Coronagraph” on Friday

Future Goals

Roman-CGI Technology Demonstration



Bailey et al. (2023)

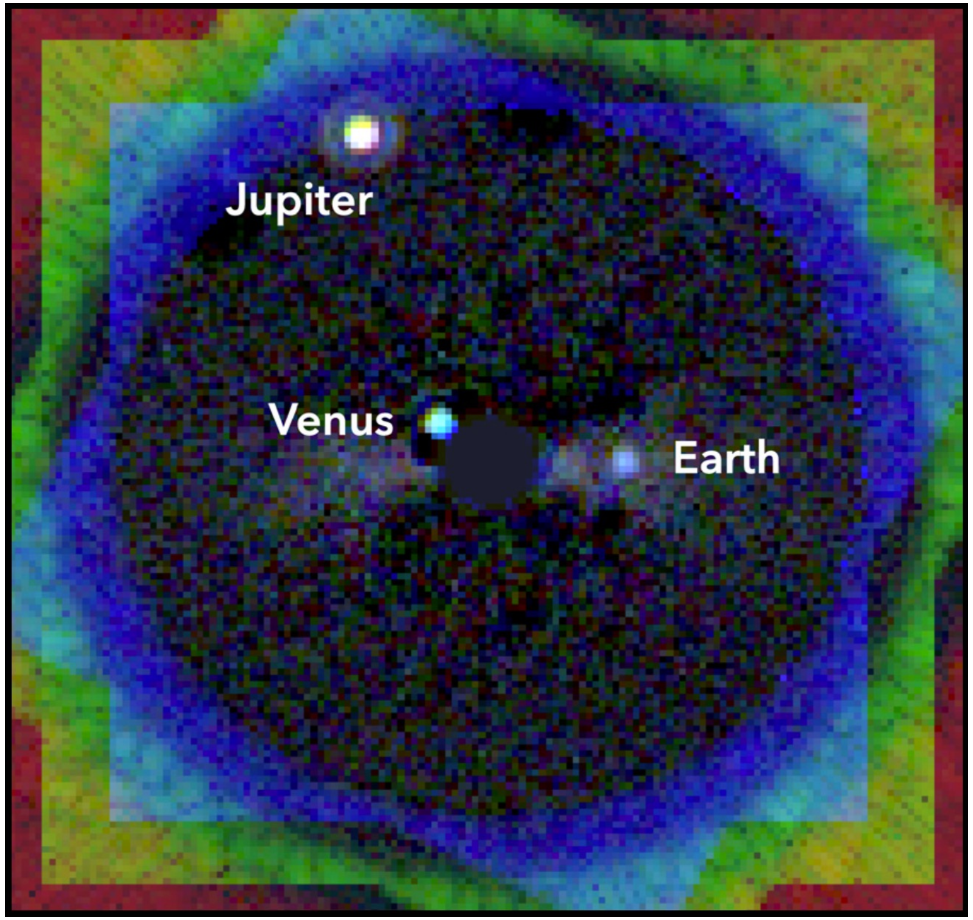
- The *Nancy Grace Roman Space Telescope* will fly with a coronagraph capable of the first reflected light measurements of gas giants
- Predicted visible-light flux ratio detection limit of 10^{-8} or better (Bailey et al. 2023).
- While Roman’s success will be determined by the instrument performance, atmospheric characterization of reflected-light gas giants may be possible and could enable constraints on gas abundances and cloud scattering (Currie et al. 2023; Lupu et al. 2016).

For more, see talks by Chris
Stark and Courtney Dressing

Future Goals

NASA's Habitable Worlds Observatory and the Search for Life

- Goal: Reflected light spectroscopy of Earth-like planets orbiting sun-like stars to perform a robust search for life beyond the solar system.



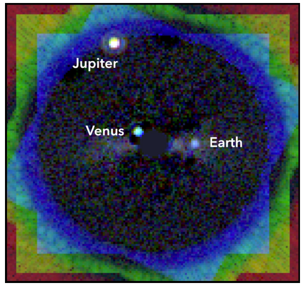
LUVOIR Final Report (2019)

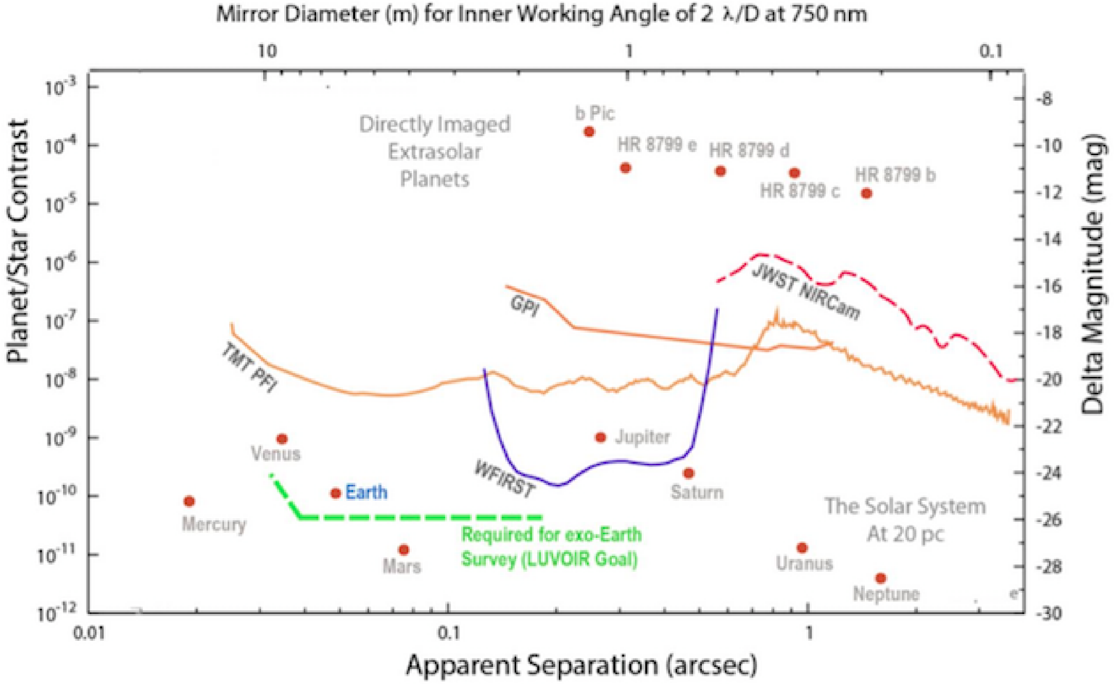
For more, see talks by Chris
Stark and Courtney Dressing

Future Goals

NASA’s Habitable Worlds Observatory and the Search for Life

- Goal: Reflected light spectroscopy of Earth-like planets orbiting sun-like stars to perform a robust search for life beyond the solar system.
- Challenge: High contrast direct imaging at 10^{-10} planet-star contrasts and tight inner working angle.





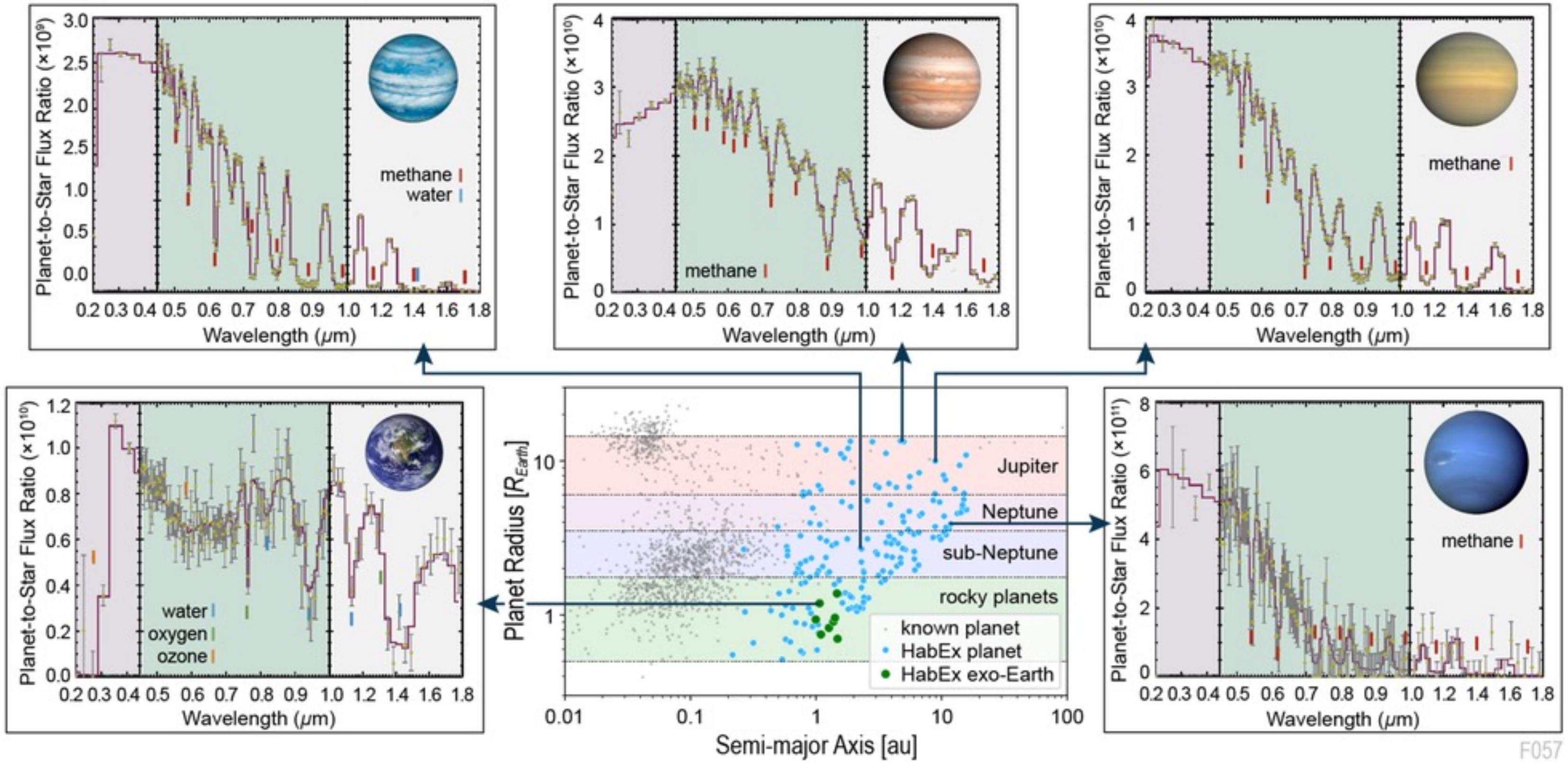
LUVOIR Final Report (2019) Biller & Bonnefoy (2018)

For more, see talks by Chris Stark and Courtney Dressing

Future Goals

NASA’s Habitable Worlds Observatory and the Search for Life

The ability to study Earth-like exoplanet atmospheres means that most types of exoplanets can also be studied, and in many cases, are easier.



HabEx Final Report (2019)

For more, see talks by Chris
Stark and Courtney Dressing

Future Goals

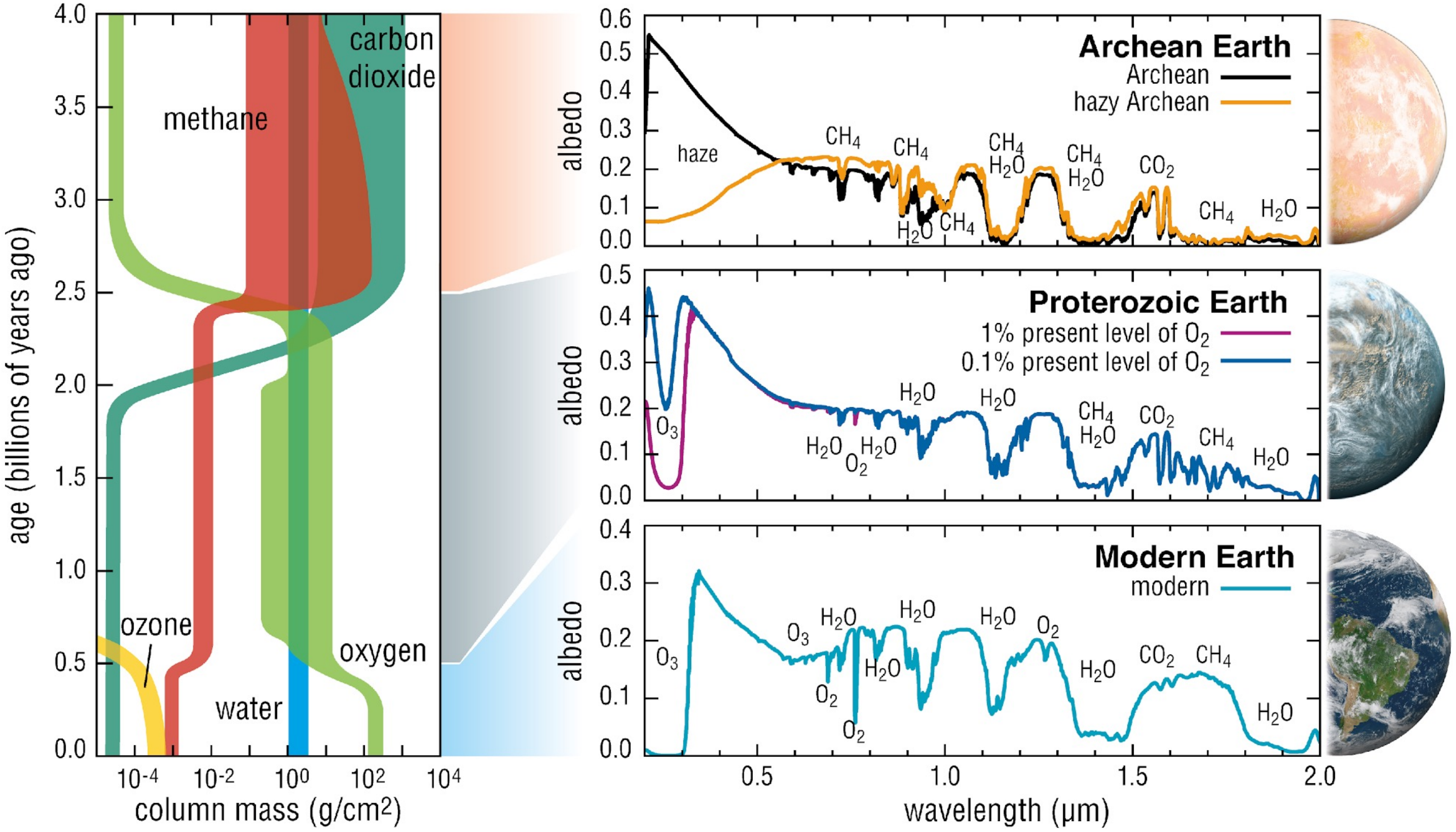
NASA’s Habitable Worlds Observatory and the Search for Life

The LUVOIR & HabEx final reports (2019)
Arney, Domagal-Goldman, Griswold

For more, see talks by Chris
Stark and Courtney Dressing

Future Goals

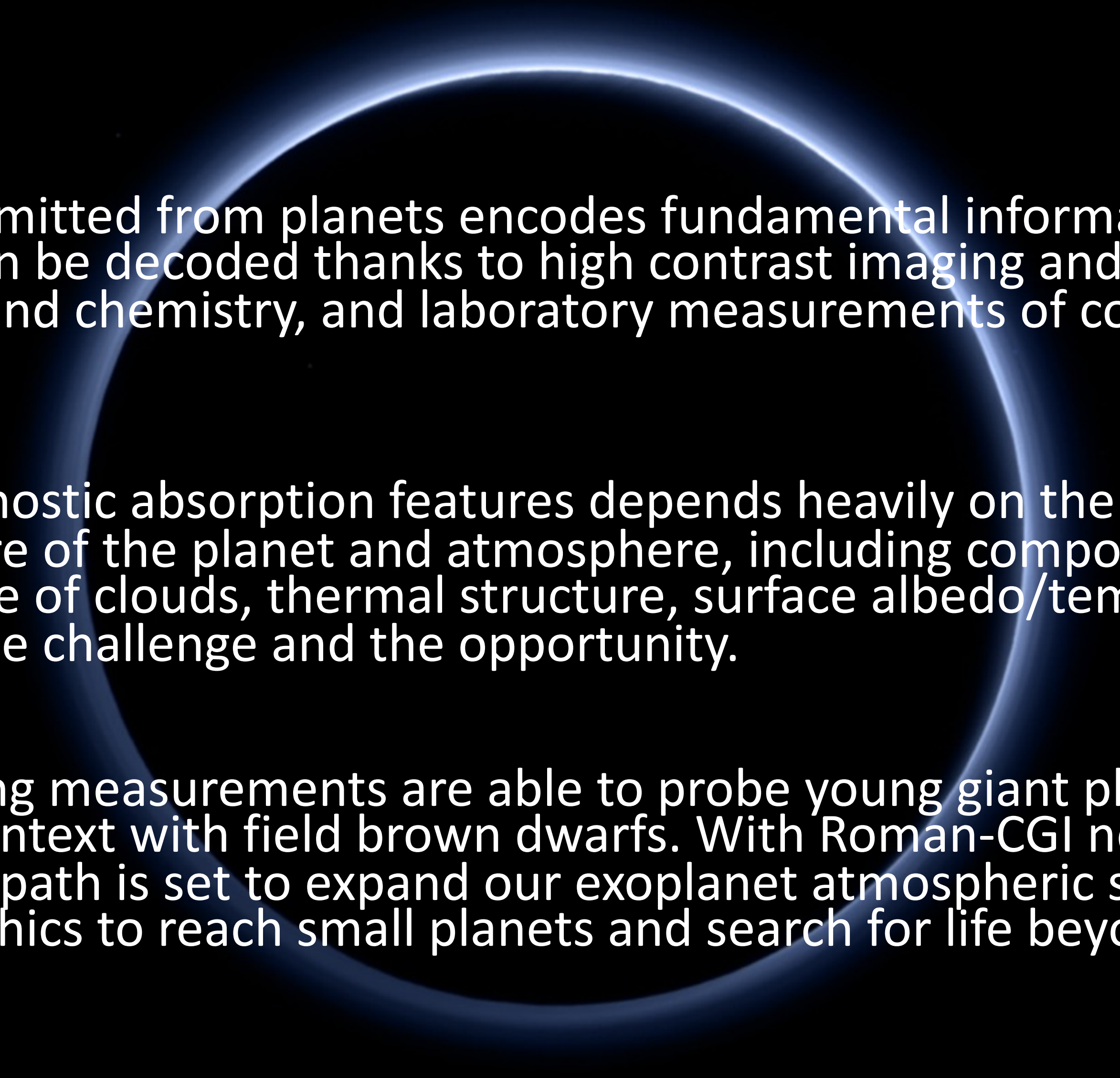
NASA's Habitable Worlds Observatory and the Search for Life



- Earth is more than one planet
- Geologic evidence of Earth's atmospheric composition through time provides multiple archetypal planets, sets of biosignatures, and dominant metabolisms to search for with HWO

The LUVOIR & HabEx final reports (2019)
Arney, Domagal-Goldman, Griswold

In Summary



Light reflected and emitted from planets encodes fundamental information about their atmospheres that can be decoded thanks to high contrast imaging and spectroscopy, the universality physics and chemistry, and laboratory measurements of common and uncommon gases.

The strength of diagnostic absorption features depends heavily on the observing technique, and nature of the planet and atmosphere, including composition/metallicity, presence and altitude of clouds, thermal structure, surface albedo/temperature, and more! Therein lies the challenge and the opportunity.

Current direct imaging measurements are able to probe young giant planet atmospheres and place them in context with field brown dwarfs. With Roman-CGI next and plans for HWO underway, the path is set to expand our exoplanet atmospheric studies across the exoplanet demographics to reach small planets and search for life beyond the solar system.

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Driving Exoplanet Atmosphere Questions that we can all work together to answer

- *What are the properties of individual planets, and which processes lead to planetary diversity?*
- *How Does a Planet's Interior Structure and Composition Connect to Its Surface and Atmosphere?*
- *What Fundamental Planetary Parameters and Processes Determine the Complexity of Planetary Atmospheres?*
- *How Does a Planet's Interaction with Its Host Star and Planetary System Influence Its Atmospheric Properties?*
- *How Do Giant Planets Fit Within a Continuum of Our Understanding of All Substellar Objects?*

- *How do habitable environments arise and evolve within the context of their planetary systems?*
- *What Are the Key Observable Characteristics of Habitable Planets?*
- *How can signs of habitable life be identified and interpreted in the context of their planetary environments?*
- *What Biosignatures Should We Look For?*
- *How Will We Interpret the Biosignatures That We See?*
- *Do Any Nearby Planets Exhibit Biosignatures?*
- *Are we alone?*

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From the Astro2020 Decadal Report