Ultraviolet-Driven Atmospheric Degeneracies of an Archean-Analog TRAPPIST-1 e

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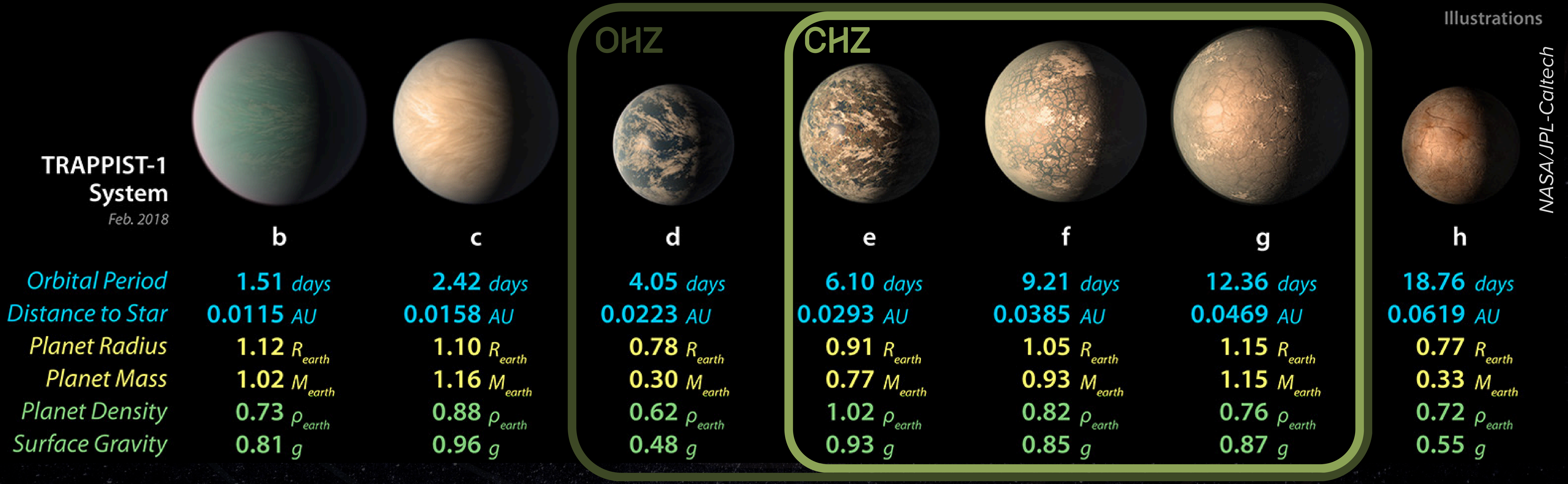
TRAPPIST-1: A TRICKY FLAGSHIP SYSTEM



Ultracool M8V star with 7 rocky planets; 4 within the habitable zone

Observations generally rule out H_2-rich and thick CO_2 atmospheres, but secondary, Earth-like atmospheres are still possible for TRAPPIST-1 e and beyond (Glidden+2025)

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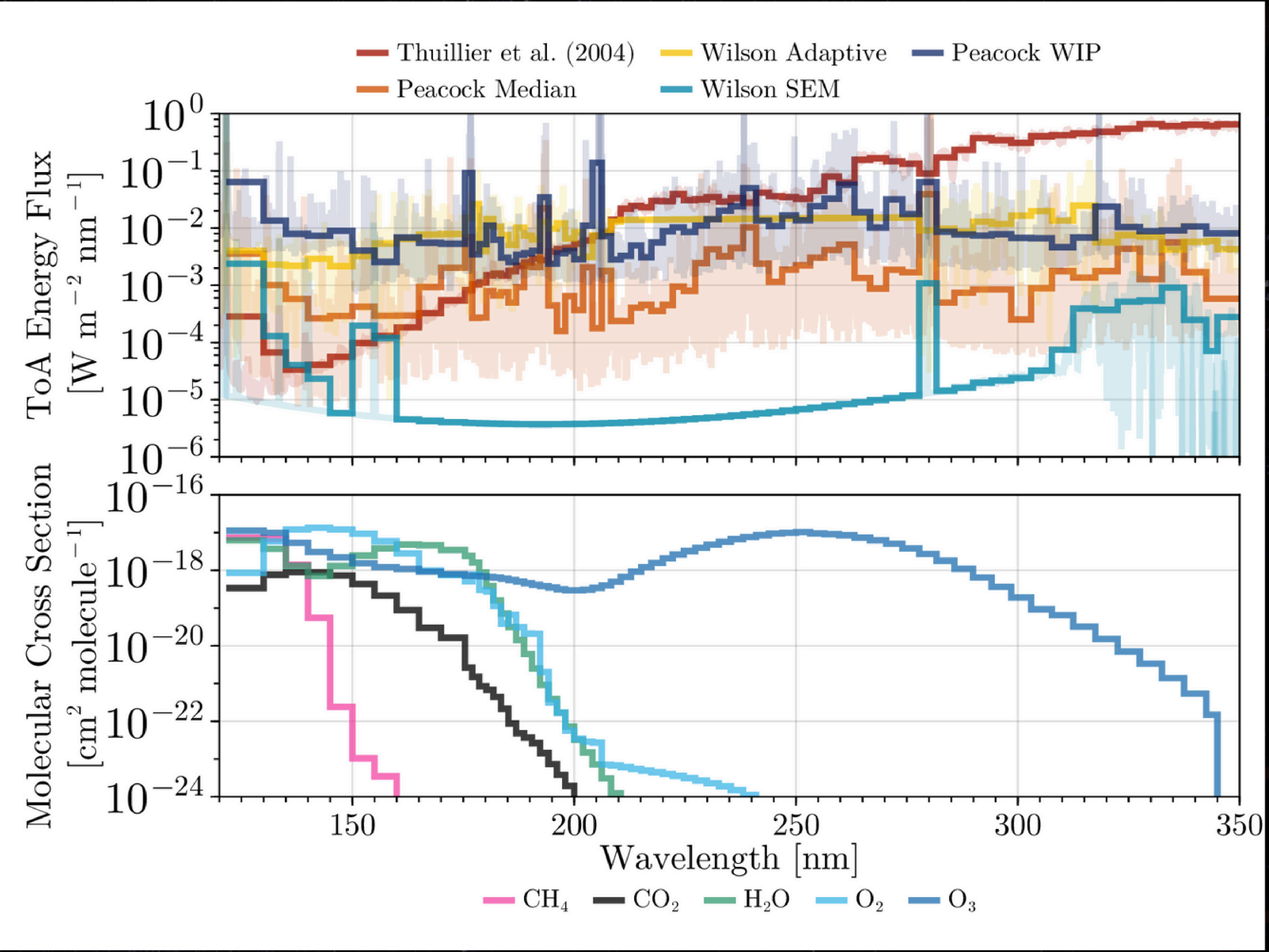
AN UNCERTAIN UV SPECTRUM

- Several TRAPPIST-1 SEDs have been published in the literature
  - Peacock 2019 & work-in-progress update
  - Two by Wilson et al. (2021)

- These SEDs primarily differ in the NUV (175 - 312.5 nm) and FUV (120 - 175 nm)

- Atmospheric photochemistry is sensitive to the UV SED



Sneed et al. (in prep.)

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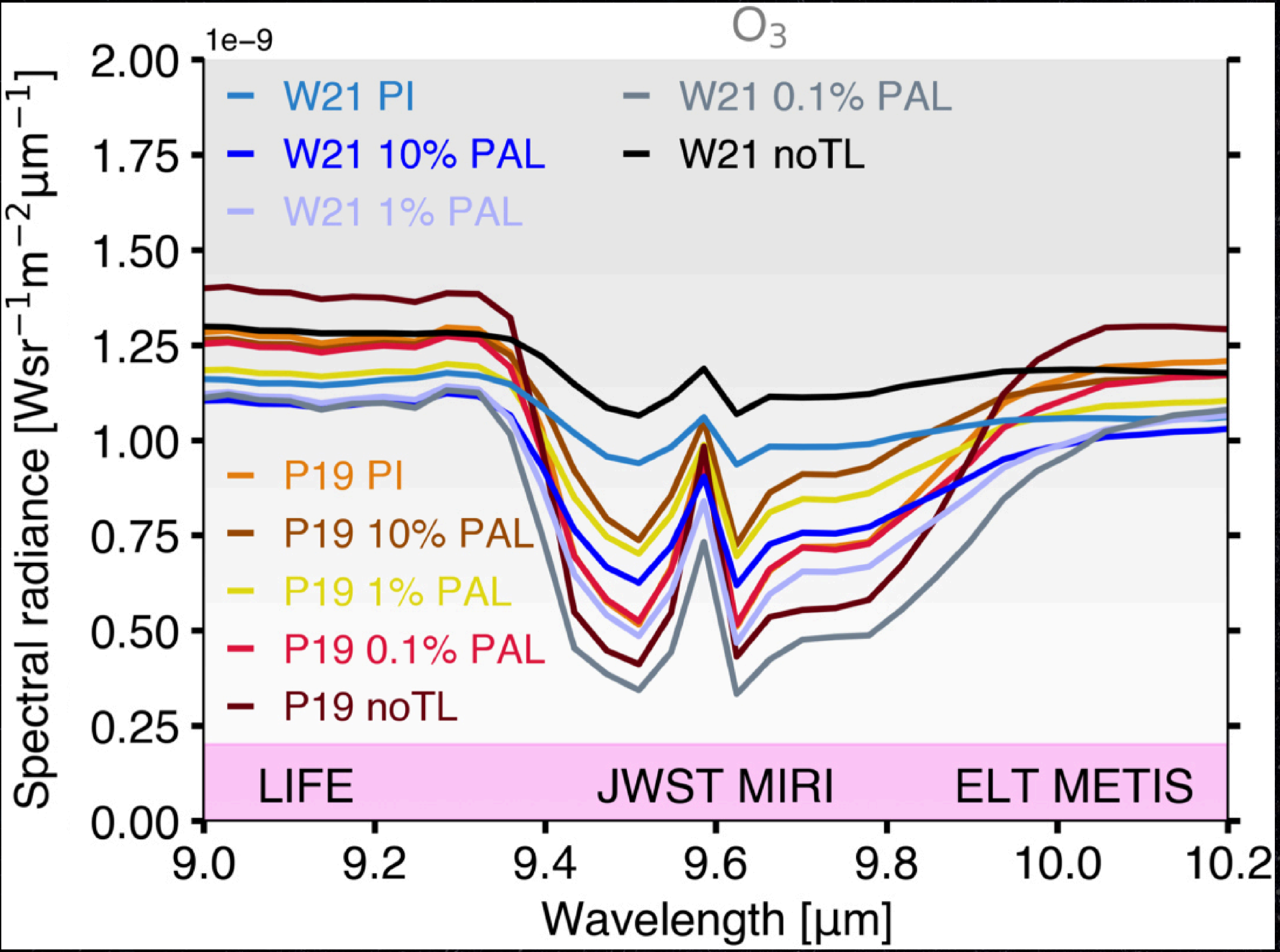
OXYGENATED ATMOSPHERE UNCERTAINTIES

Cooke et al. (2023)



- Cooke et al. (2023) compared the Peacock 2019 SED against the Wilson 2021 SEM SED for a pre-industrial Earth-like TRAPPIST-1 e
  - Used 3D WACCM6 Earth System Model
  - Increased O_3 with Wilson+2021 SEM compared to Peacock+2019
  - Highlights differing predictions for TRAPPIST-1 planetary atmospheres
- **Do these SED uncertainties also influence Archean-analog atmospheric chemistry?**
- **How does this affect potential biosignatures of late M-dwarfs?**

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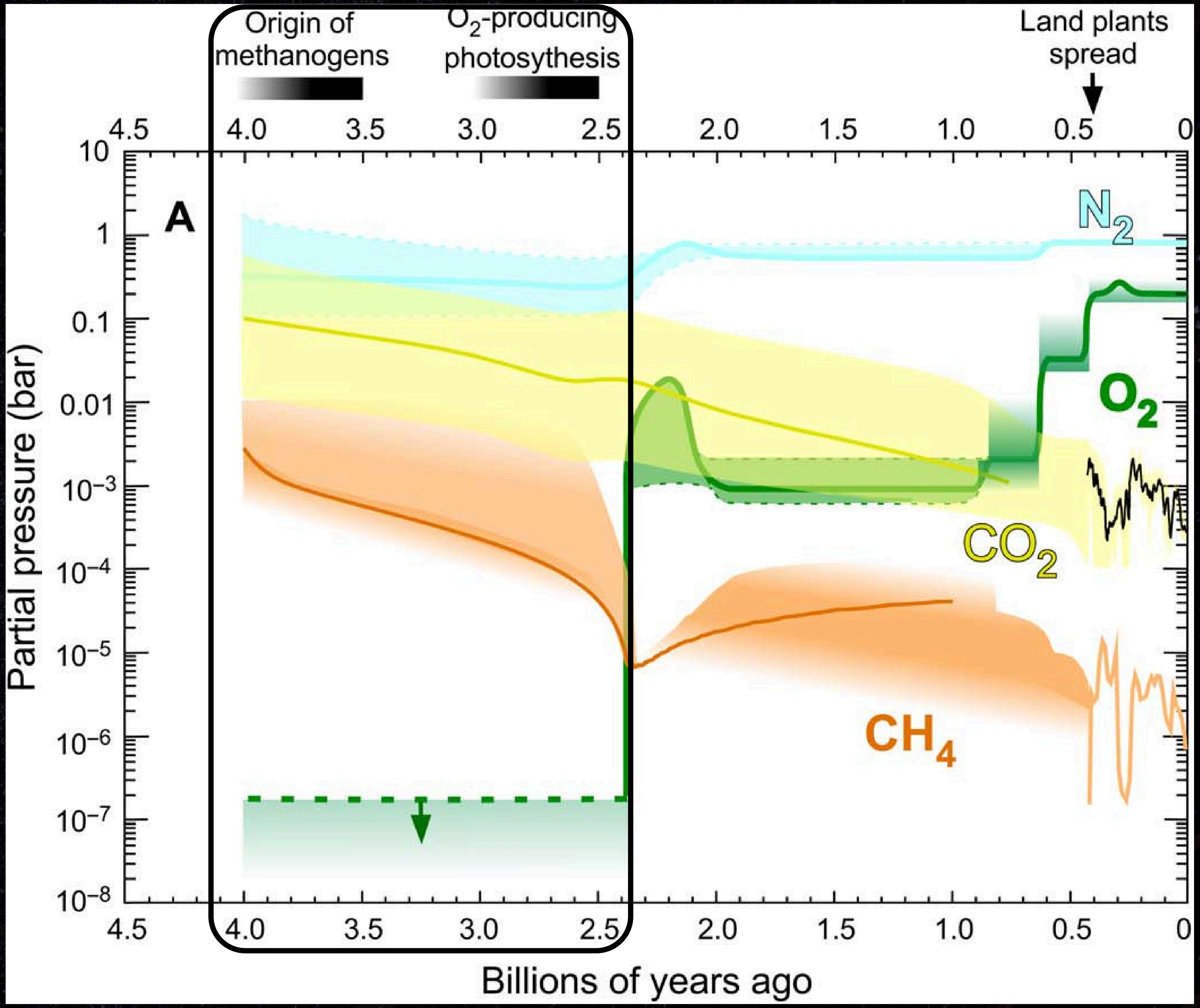
EARTH'S ARCHEAN EON

Peter Sawyer / Smithsonian Institution



Catling & Zahnle (2020)

- 4.0 to 2.5 Billion Years Ago
  - Earliest confirmed evidence for life
- CO_2 & CH_4 can be a bio-indicator
- Archean-like planets may be common around M dwarfs

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MODELING

- We adopted the one-dimensional photochemical model included in **Atmos**
    - solves continuity equations for photolysis, chemistry, and vertical mixing
    - No suitable 3D photochemical model for anoxic atmospheres
- Models include a **1 bar** atmosphere, **10% of which is CO_2**
- Surface temperature of 288.4 K assumed, with a temperature-pressure profile assuming a moist adiabat until an isothermal 180 K stratosphere is reached
- **CH_4 surface fluxes** are changed between 10^9 (representing a geologic flux), 10^{10}, and 10^{11} molecules per square centimeter per second (representing a modern biotic flux)
- Deposition rates of H_2, CO, and O_2 are set based upon whether a biotic (microbial drawdown) or abiotic (geologic drawdown) regime is tested (Kharecha et al. 2005)
- Synthetic transmission spectra are generated using **SMART**

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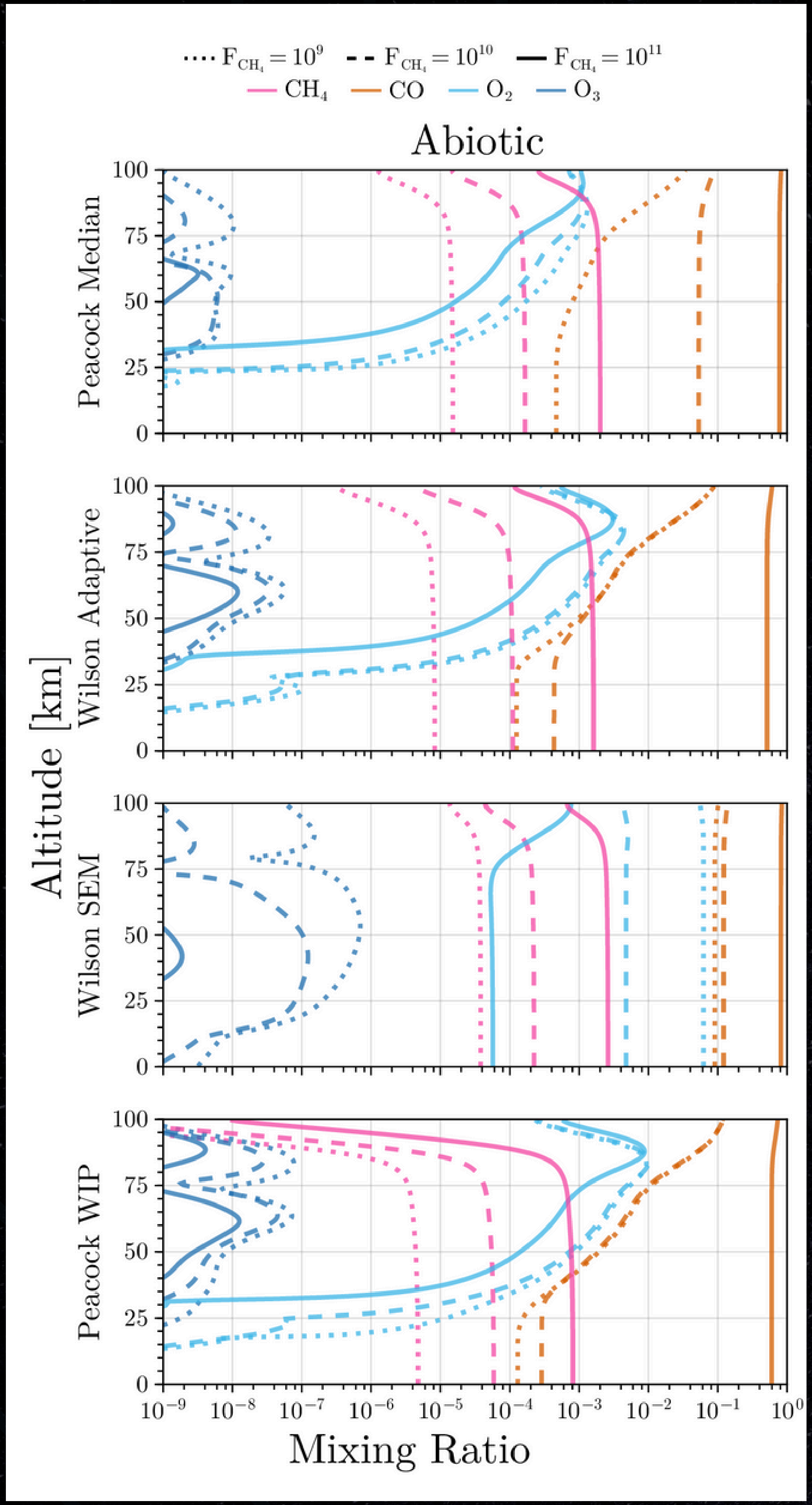

PHOTOCHEMISTRY

- Methane concentrations can vary by several orders of magnitude
  - surface flux
  - spectral energy distribution
- FUV photolysis breaks down CO_2 into CO and O
  - In abiotic regimes, CO drawdown into the surface is slow
  - CO buildup in atmosphere

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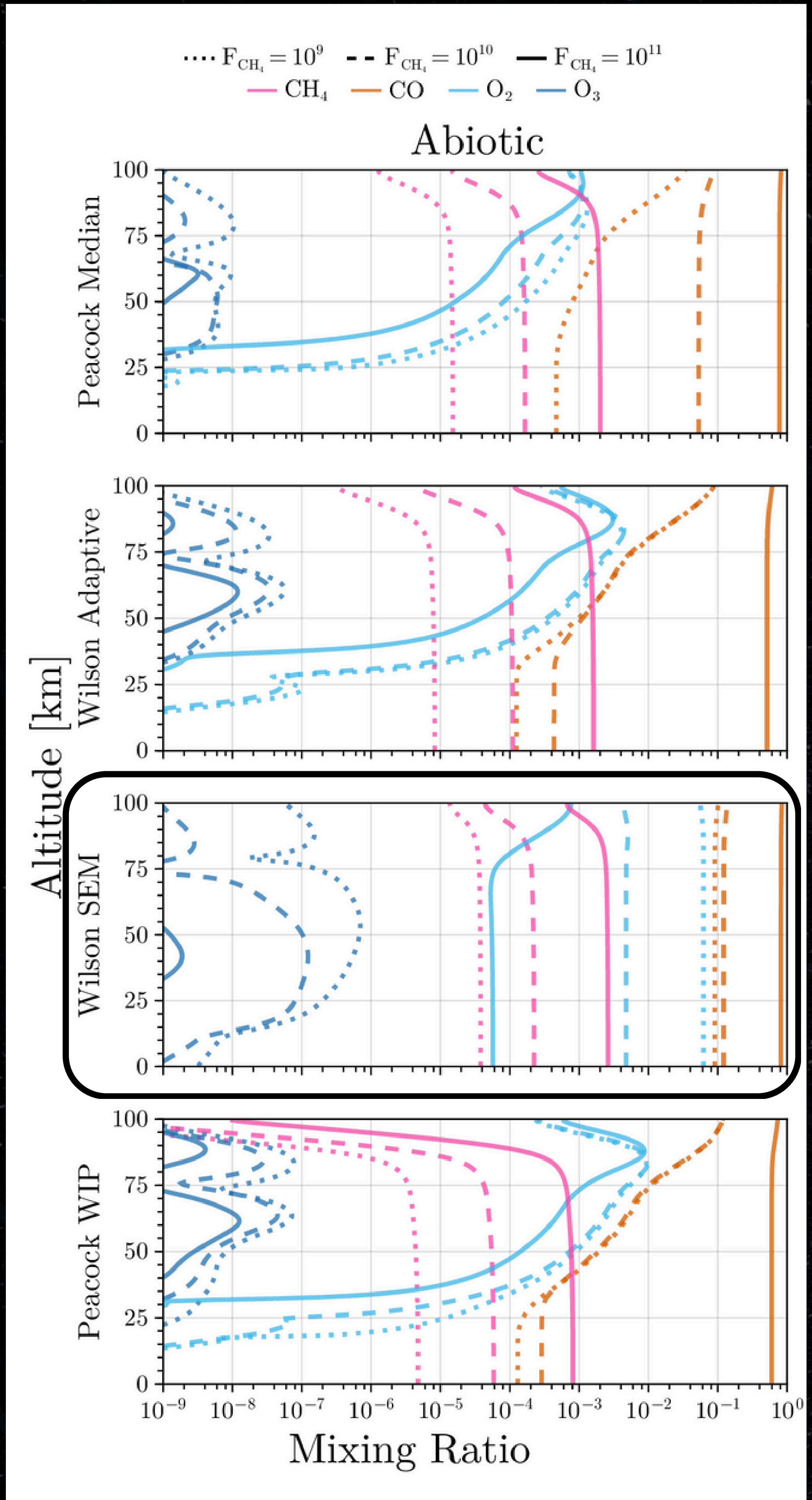

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- In the Wilson SEM case, simultaneous O_2 and CO production is evident
  - False-positive biosignature pair, allowing for simultaneous CH_4 & O_2
  - Formed from extremely high FUV flux

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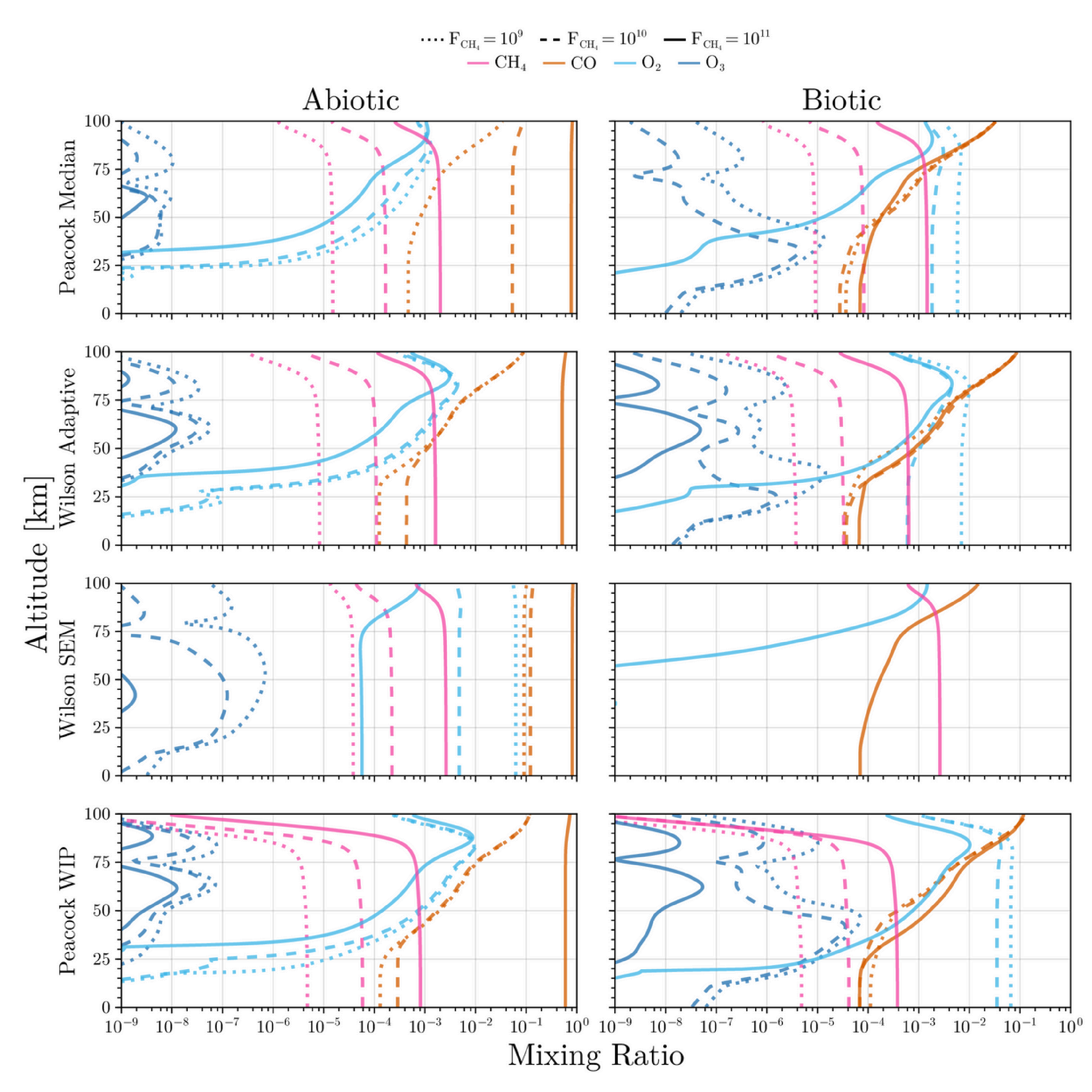

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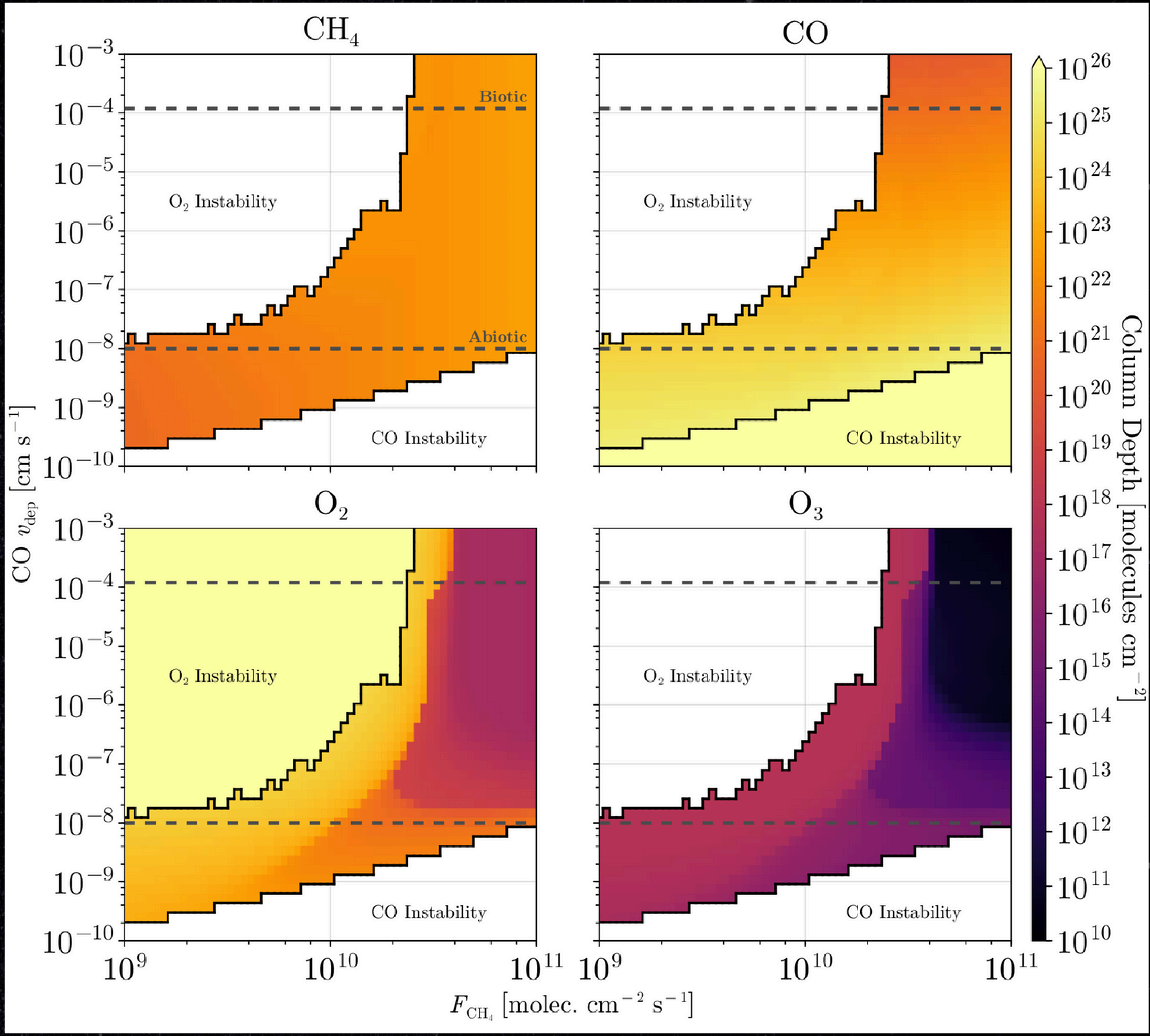
  - False-positive biosignature pair, allowing for simultaneous CH_4 & O_2
  - Formed from extremely high FUV flux
- In biotic regimes, CO drawdown is faster, allowing for O_2 buildup
  - $O + O + M \rightarrow O_2 + M$
  - $O_2 + O + M \rightarrow O_3 + M$
  - Nonphotosynthetic O_2 biosignature!

STABILITY GRIDS

- To explain why only one biotic Wilson SEM run converged, we tested the stability of the model
    - Grid runs of methane flux vs. CO depositional velocity
- Partial pressure of O_2 > total pressure for low CH_4 fluxes and high CO depositional velocities
- Partial pressure of CO > total pressure for high CH_4 fluxes and low CO depositional velocities
- Atmospheres in unstable areas are physically possible, but not modelabled when assuming a fixed P_{surf}



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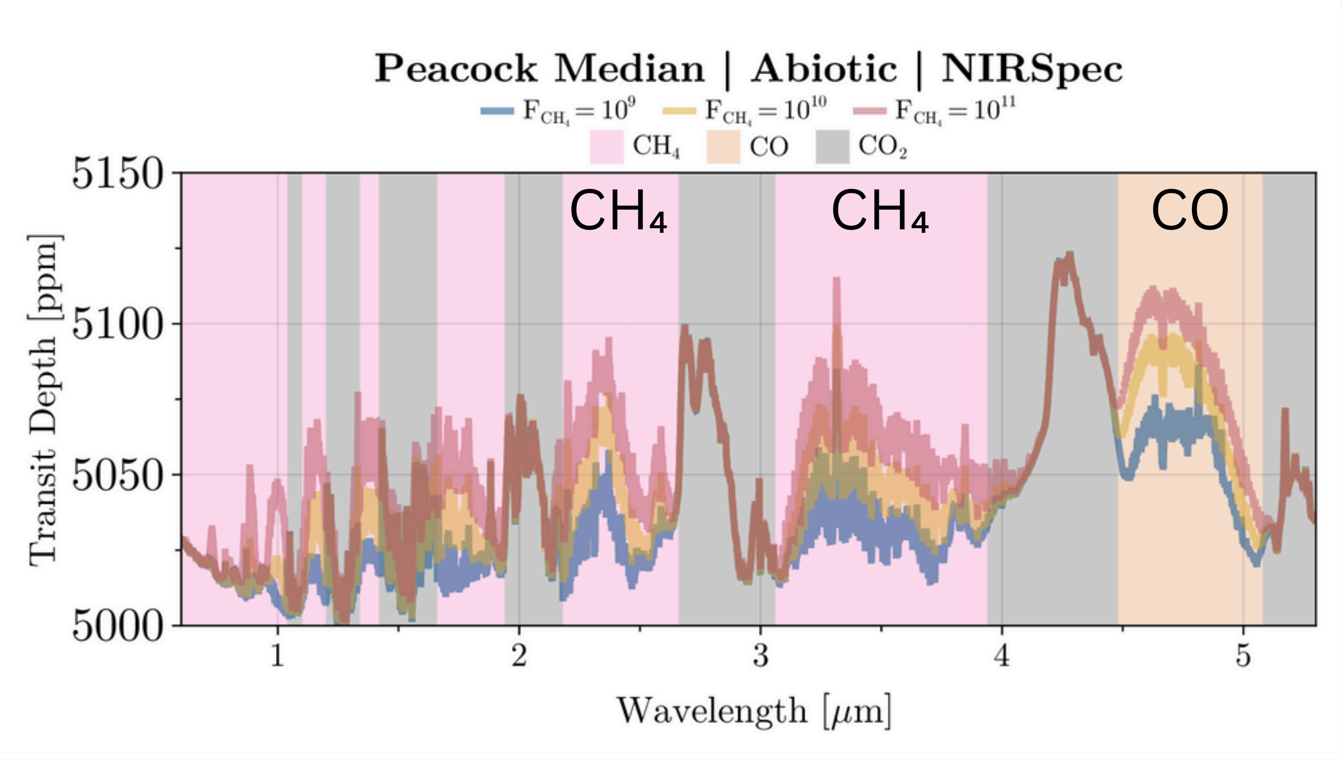
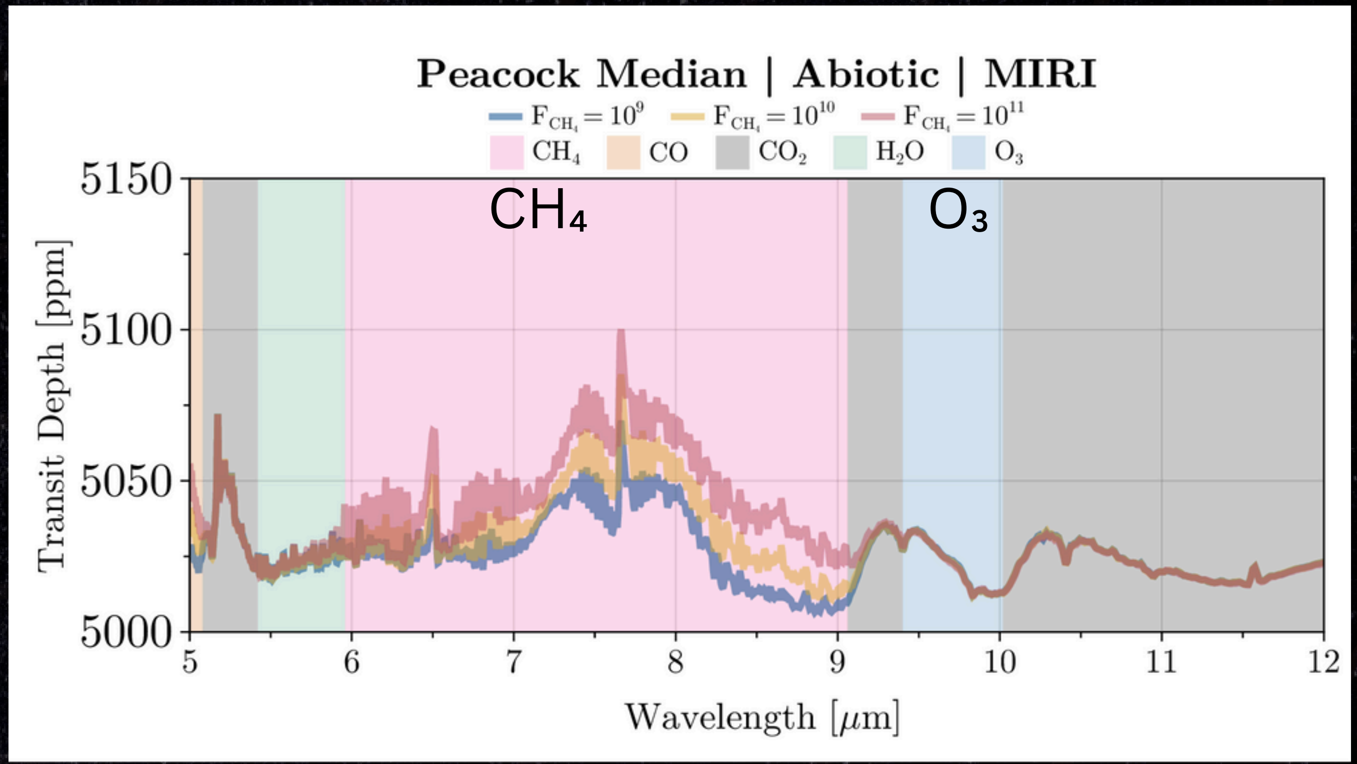
SMART TRANSMISSION SPECTRA - ABIOTIC

Sneed et al. (in prep.)

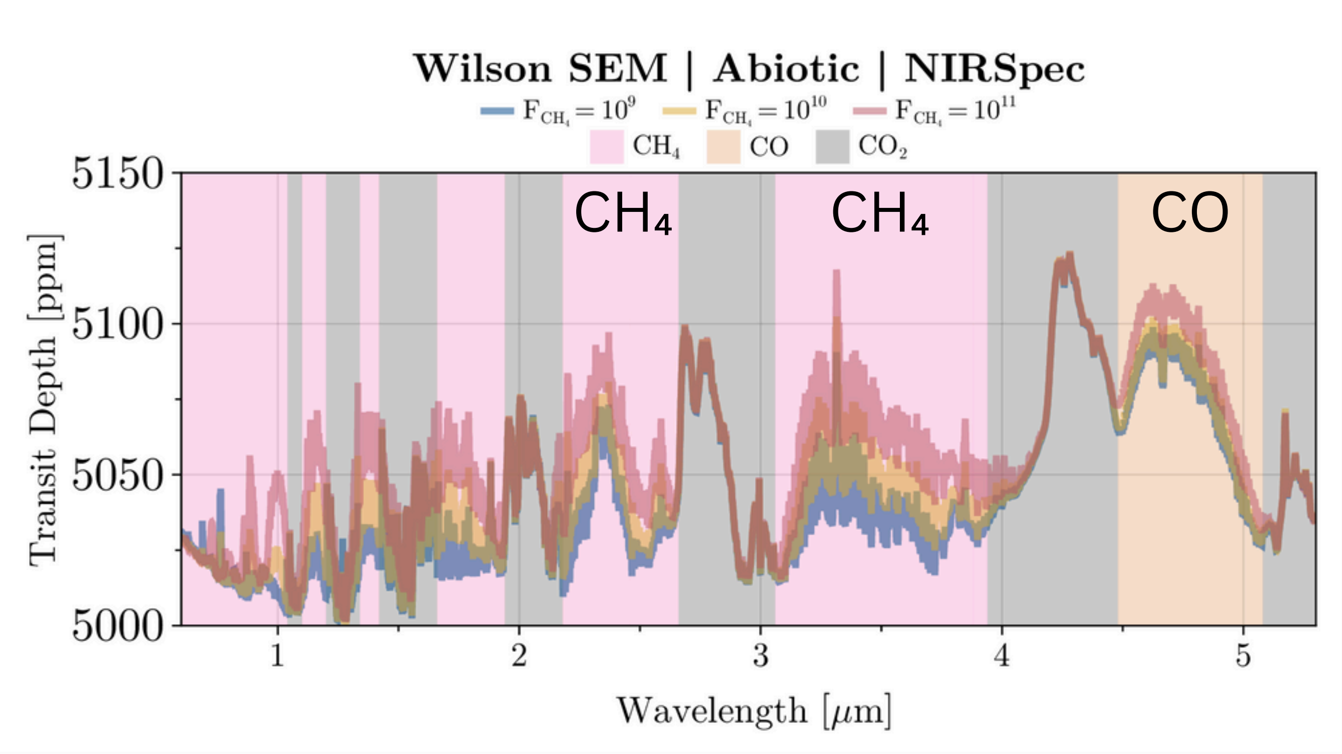
NIRSpec | **MIRI**

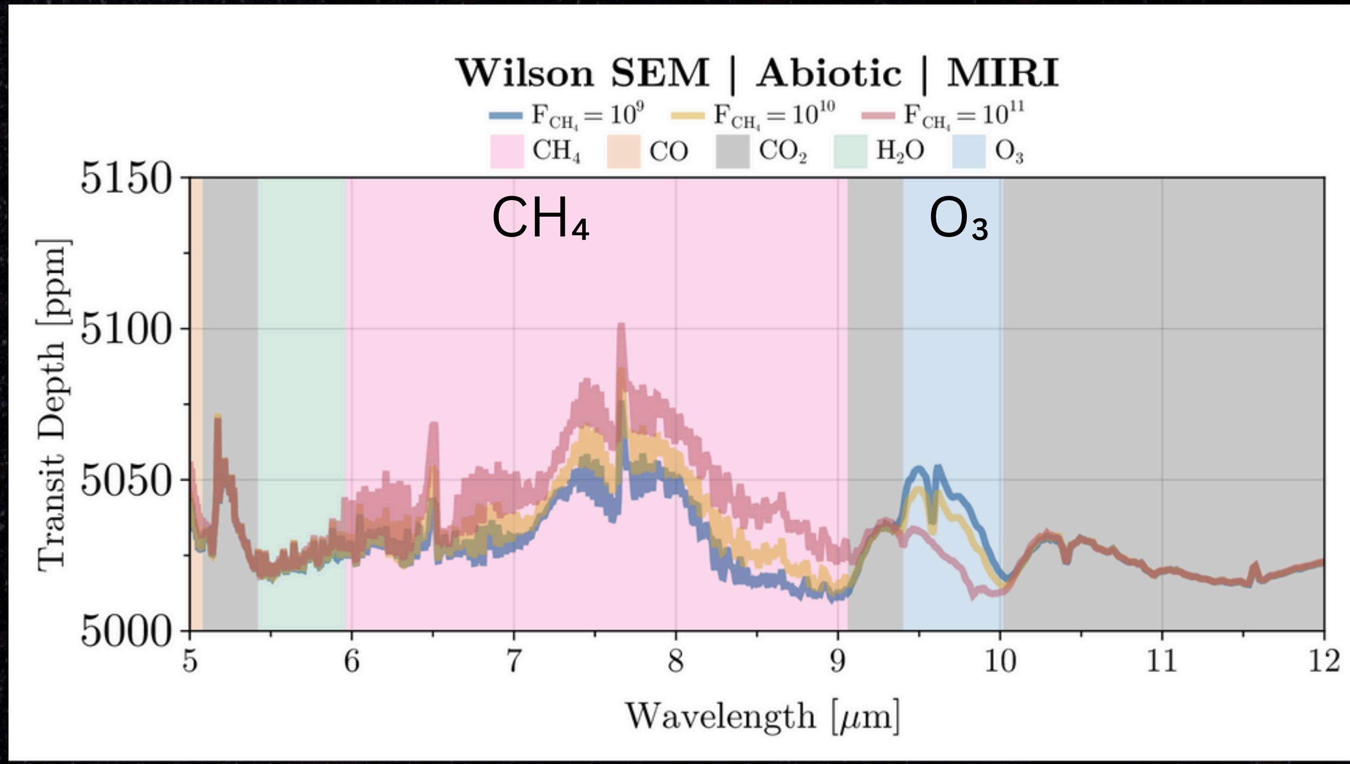
Peacock+2019





Wilson SEM





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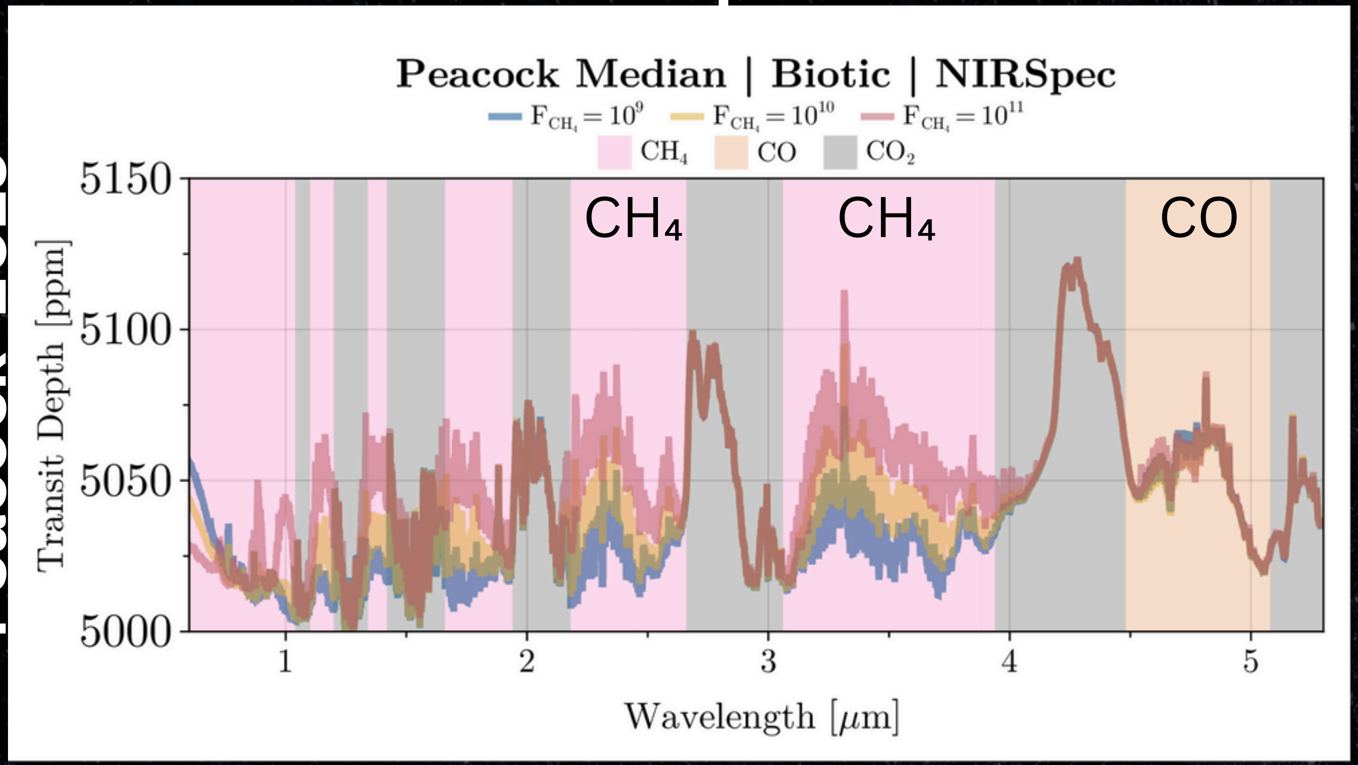
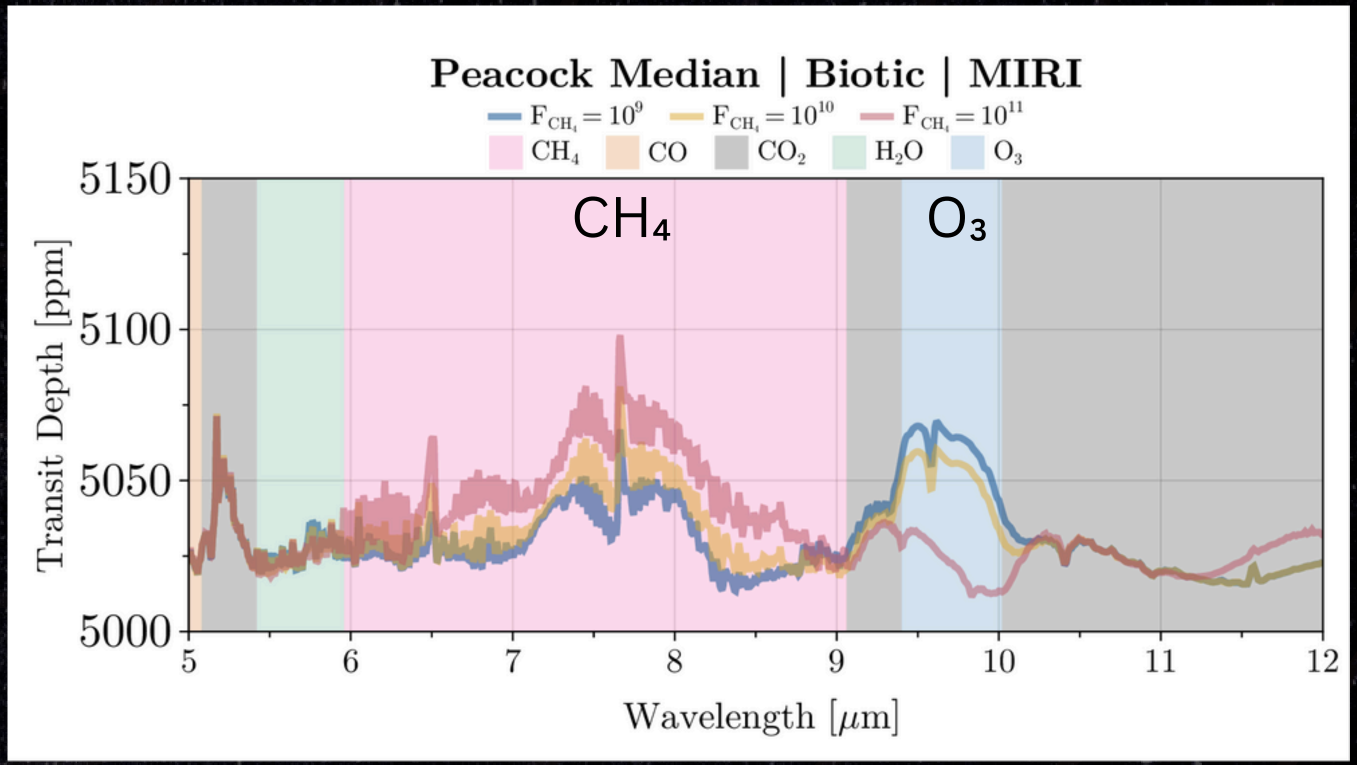
SMART TRANSMISSION SPECTRA - BIOTIC

NIRSpec

MIRI

Peacock+2019





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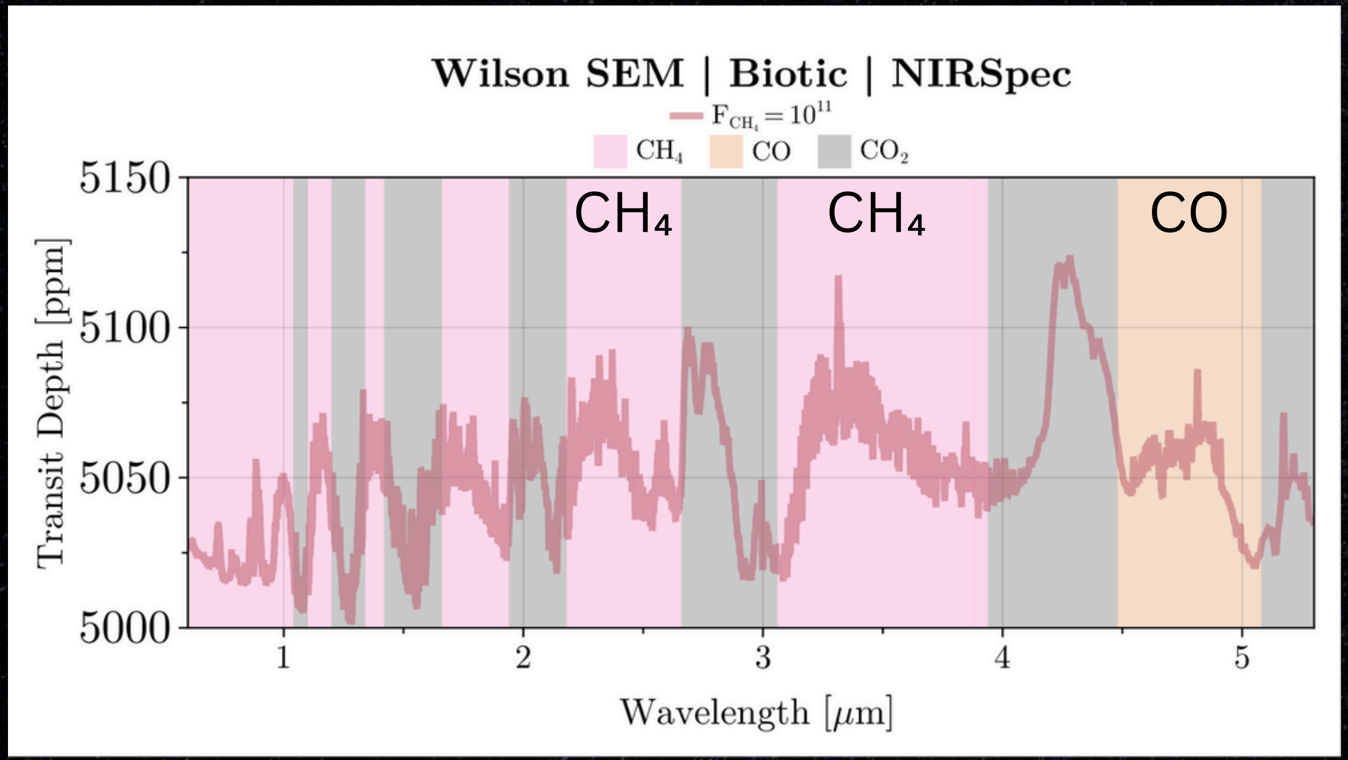

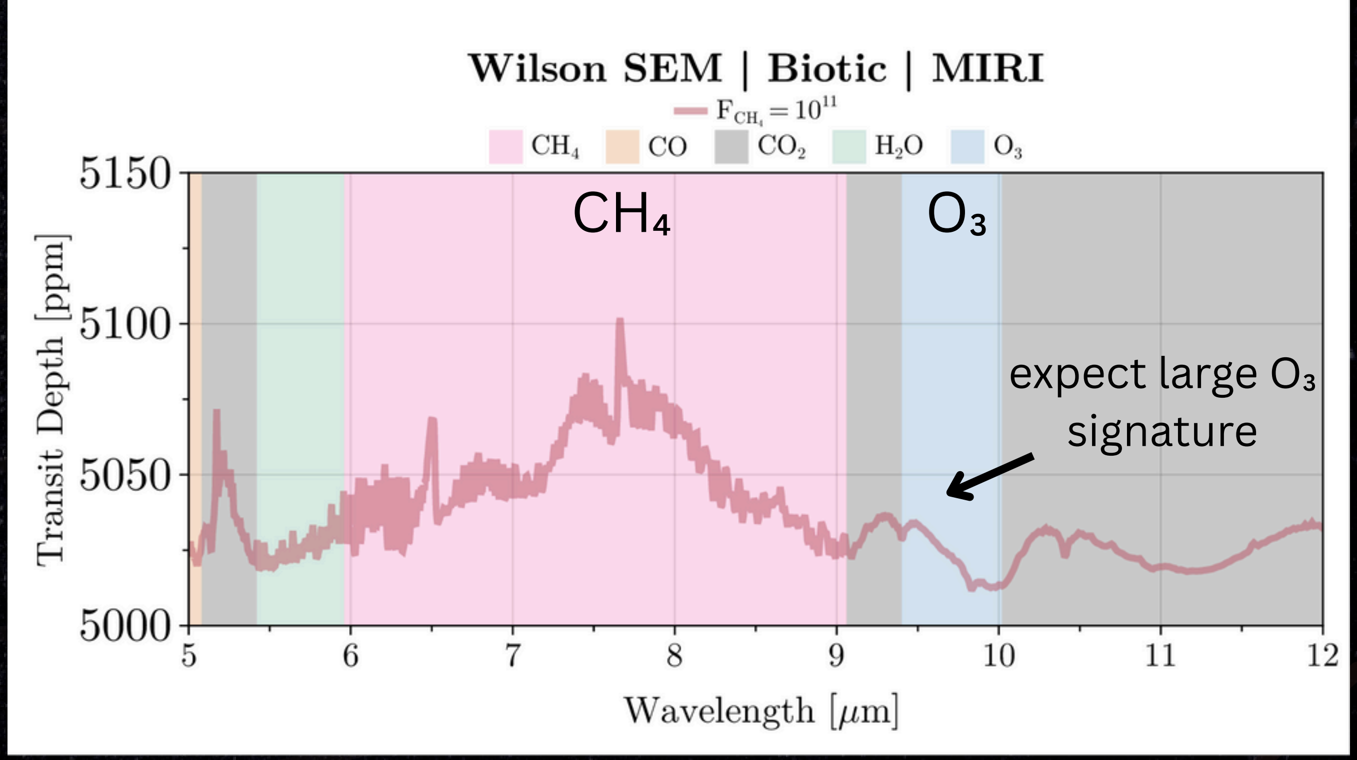

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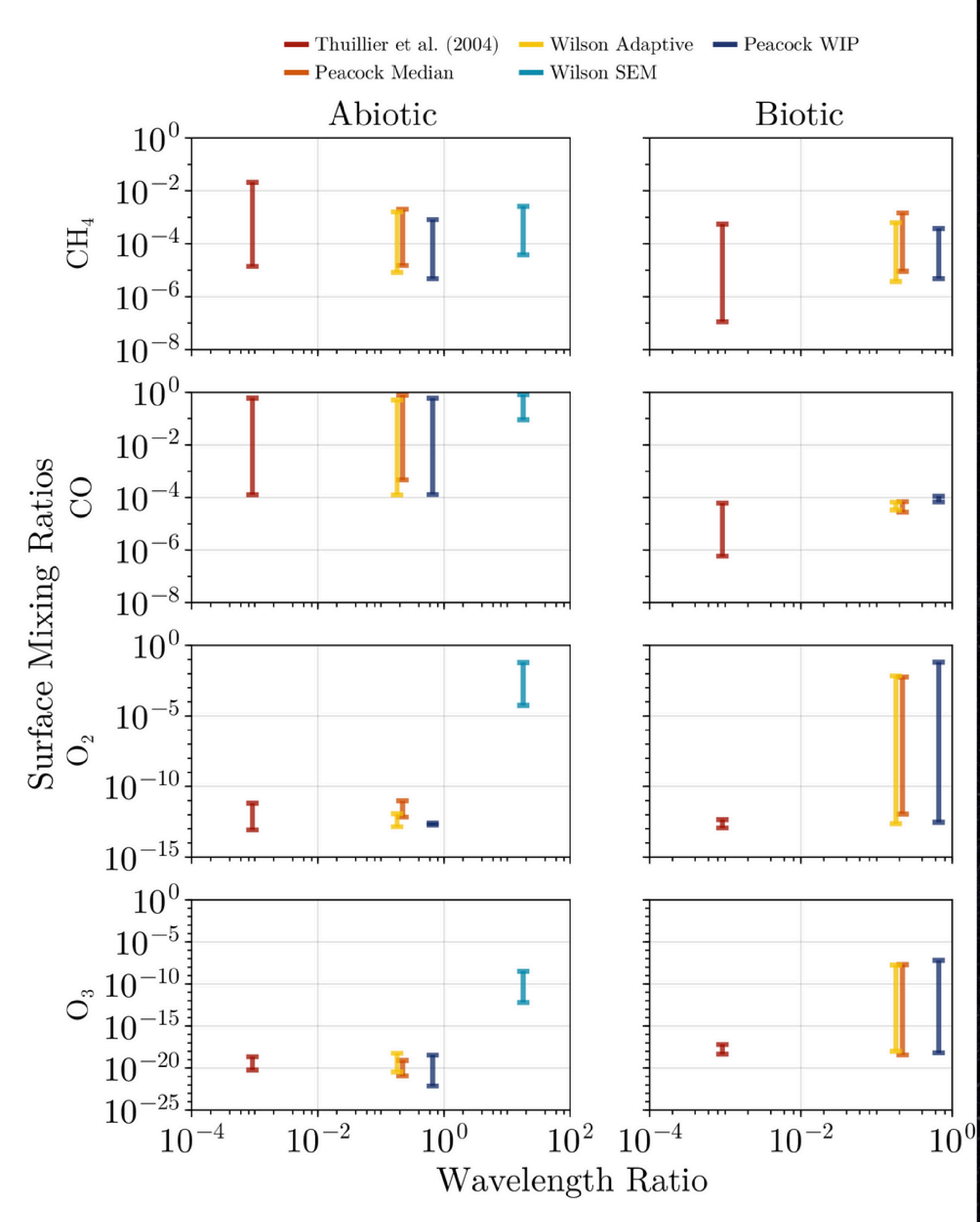

WAVELENGTH RATIO

- We use a modified version of a method developed within Harman et al. (2015) to specify when O_2 runaways occur
- The included SEDs primarily differ in the NUV (175 - 312.5 nm) and FUV (120 - 175 nm)
- The Wilson SEM SED has an FUV/NUV ratio that is much larger than the other included SEDs
- This high FUV/NUV ratio encourages CO_2 photolysis while reducing H_2O photolysis
  - Allows for a simultaneous buildup of both O_2 and CO in the abiotic regime
  - Potential false-positive biosignature, although CO remains as an antibiosignature

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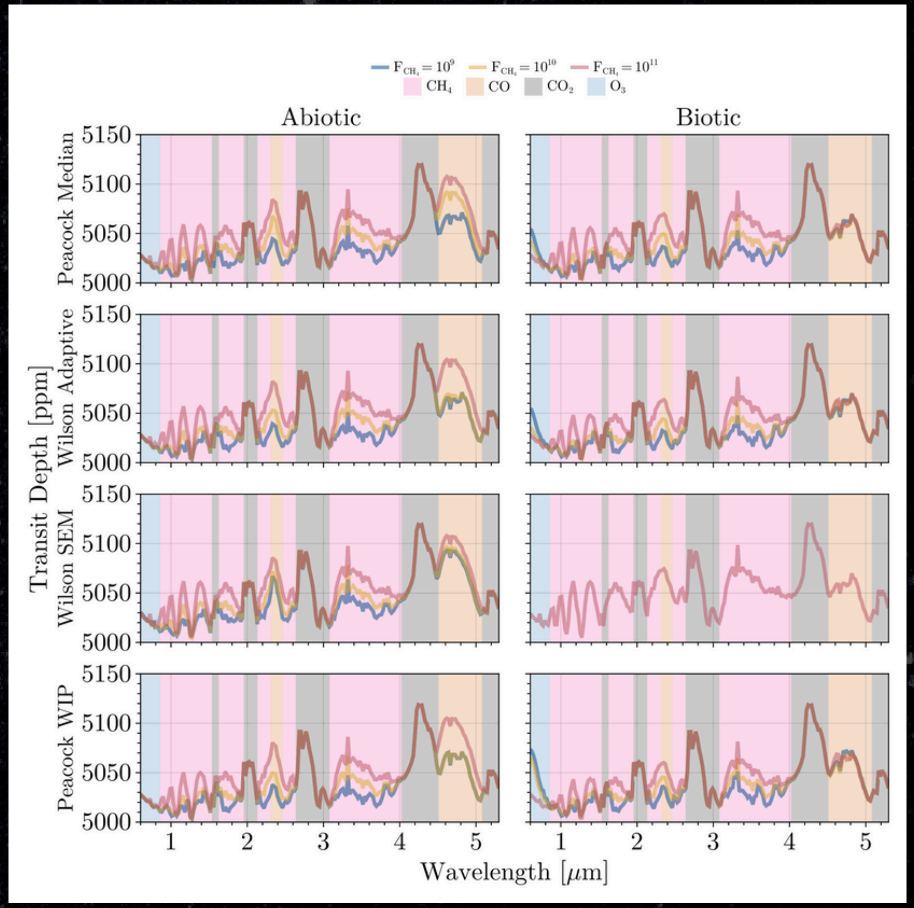
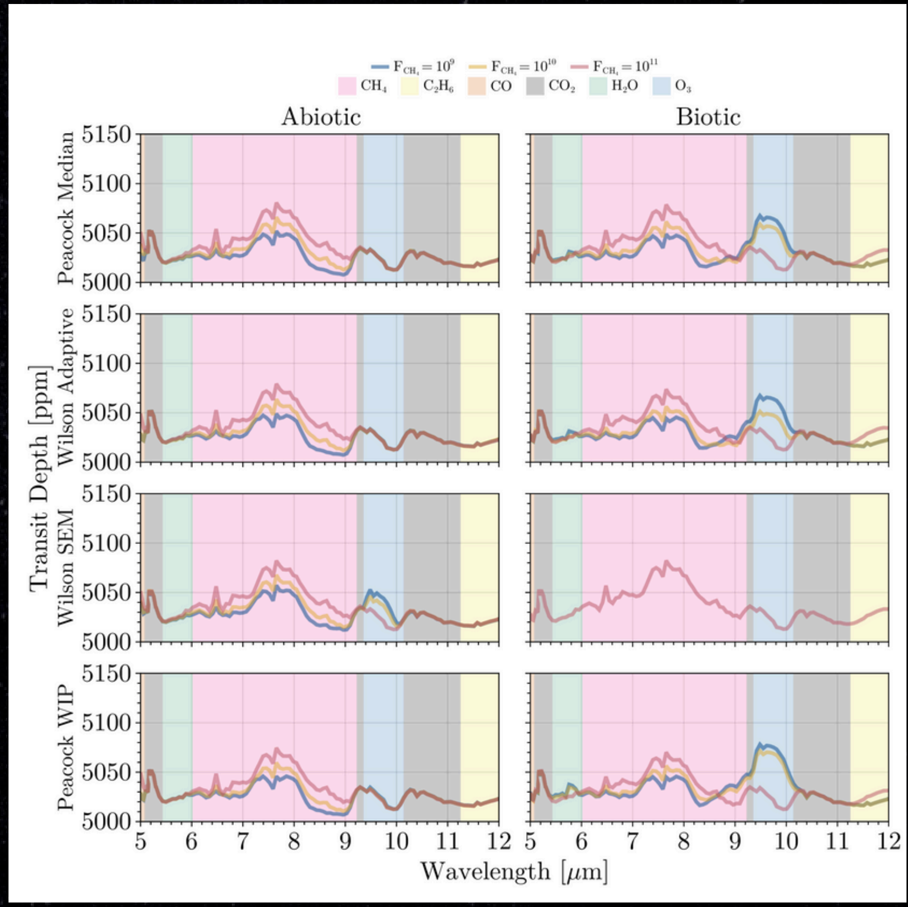
IN SUMMARY

- O_2 and O_3 accumulation is sensitive to the FUV/NUV ratio (Harman+2015)
  - If Wilson SEM can't be ruled out, false-positive CH_4-CO_2-O_3 biosignatures combinations are possible for TRAPPIST-1
  - CO detection is a discriminant (Schwieterman+2016, Ranjan+2020)

- Nonphotosynthetic biotic oxygen accumulation possible for planets orbiting M-dwarfs

- Need a more in-depth understanding of late M-dwarf stars to model planetary atmospheres





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THE CH_4-CO_2 BIOSIGNATURE PAIR

- Both CH_4 and CO_2 are produced both abiotically and biotically
  - CH_4 has a short lifetime, and is quickly destroyed through photolysis and by reaction with OH radicals, which are both related to the star
  - To detect both gases, large amounts of CH_4 must be released into the atmosphere continuously (either through widespread volcanism, or through life)

- We are finding more terrestrial planets in the that receive less insolation than the modern Earth, similar to the early Earth
  - These planets need more greenhouse warming to maintain habitability

- Increased concentrations of CO_2 can shield CH_4 from UV radiation
  - This extends the atmospheric lifetime of CH_4, allowing it to build up

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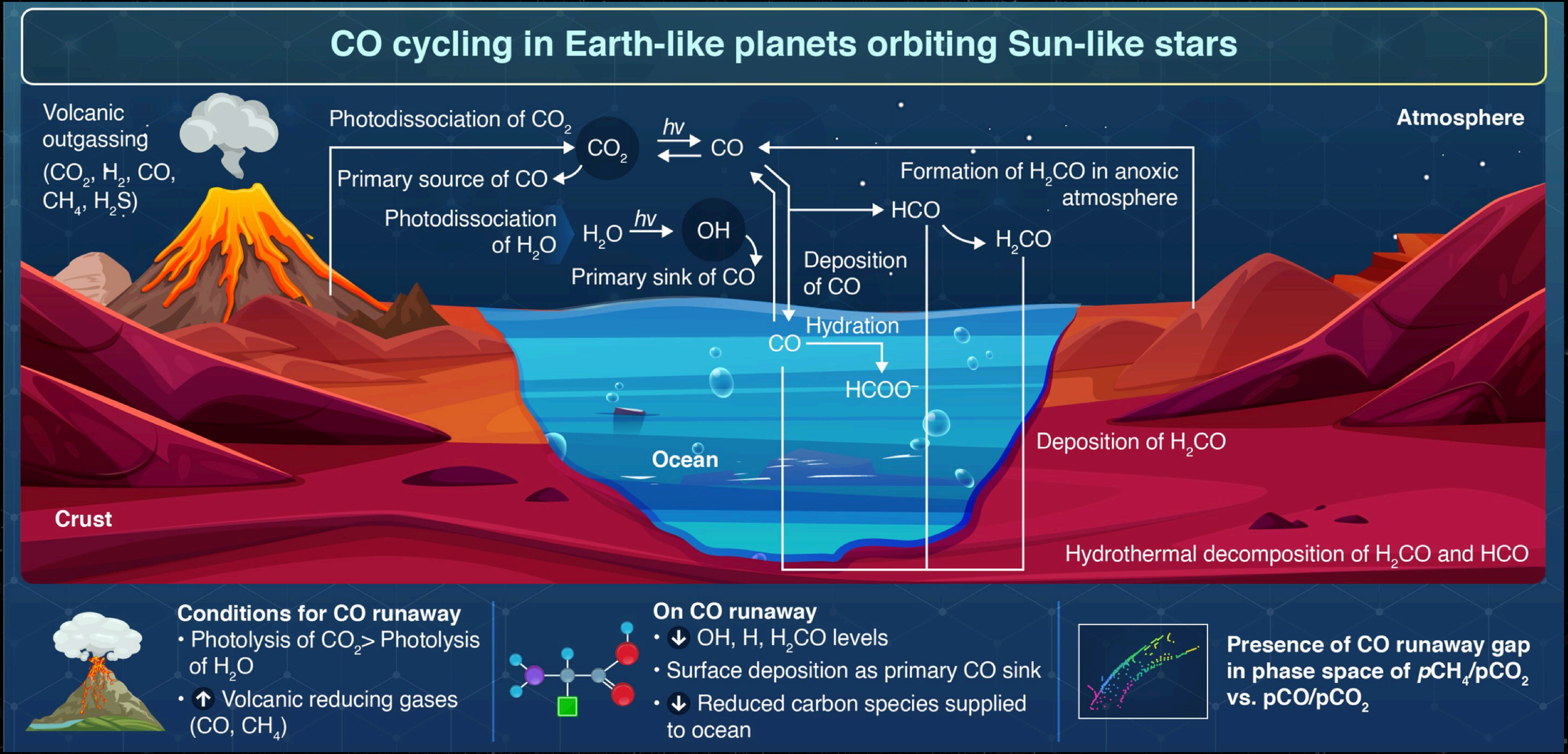
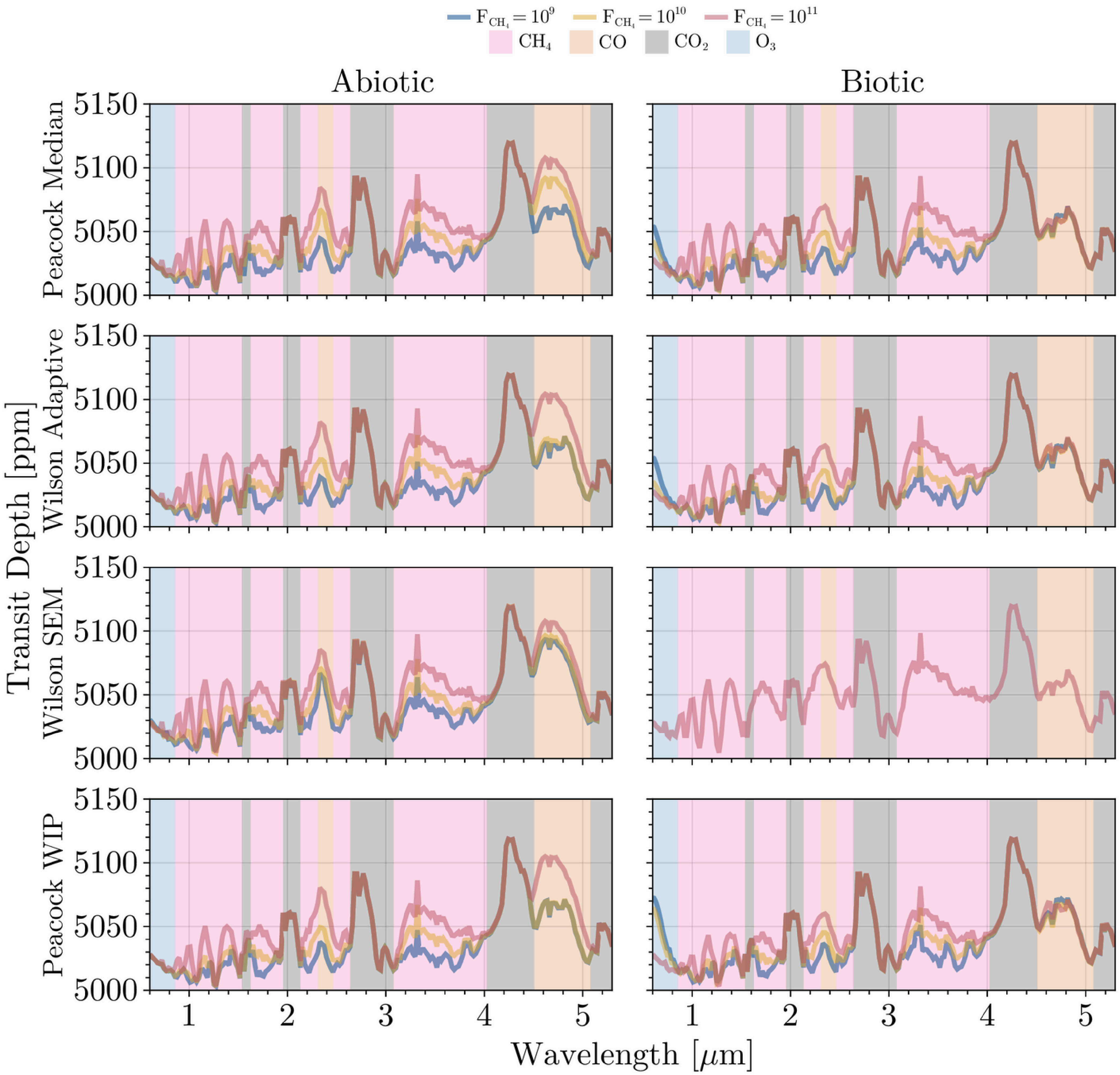
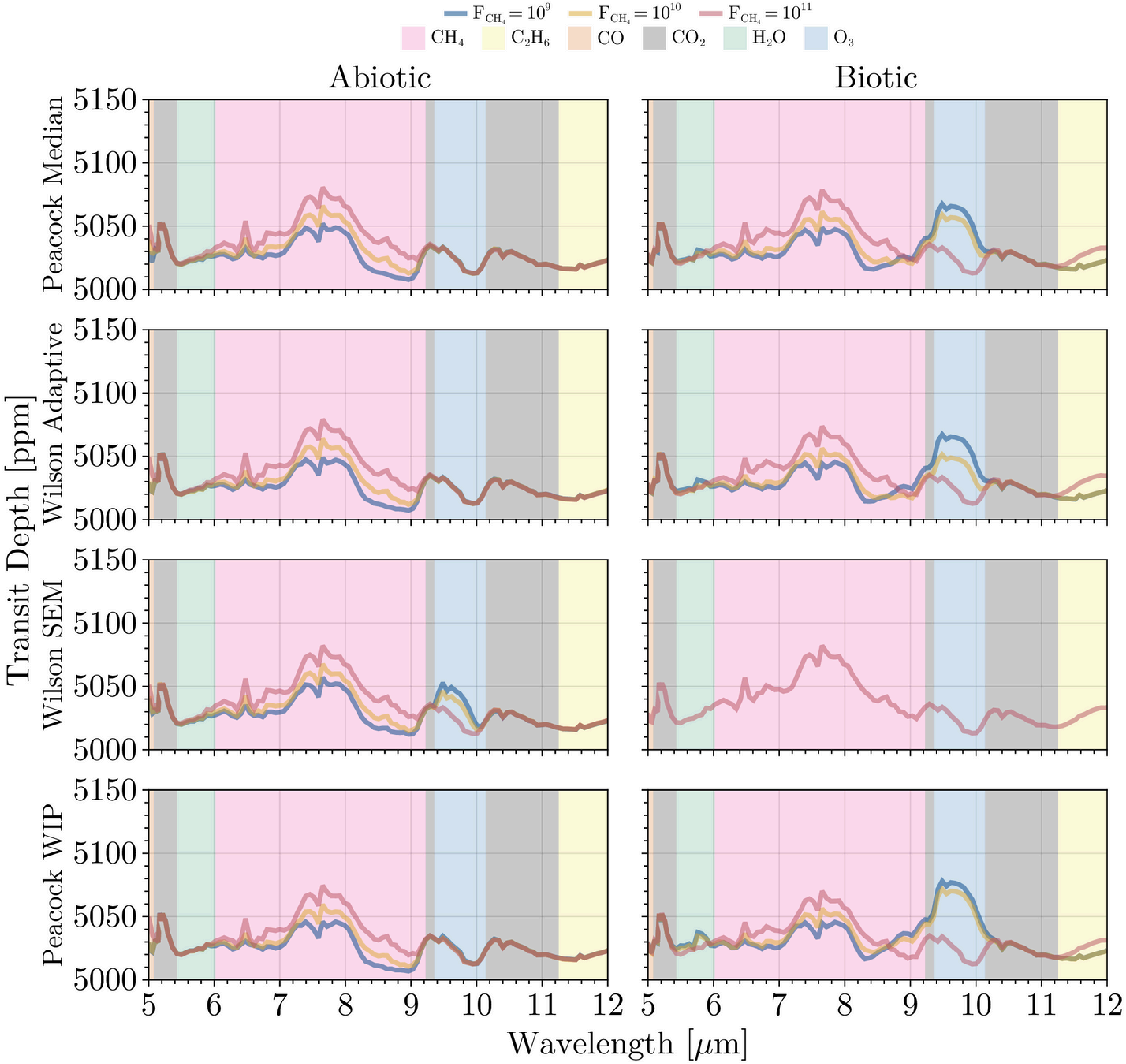
Watanabe and Ozaki (2024)




$F_{CH_4} = 10^9$
$F_{CH_4} = 10^{10}$
$F_{CH_4} = 10^{11}$
CH_4
CO
CO_2
O_3
Abiotic
Biotic
Peacock Median
Wilson Adaptive
Wilson SEM
Peacock WIP
Transit Depth [ppm]
Wavelength [μm]
5150
5100
5050
5000
1
2
3
4
5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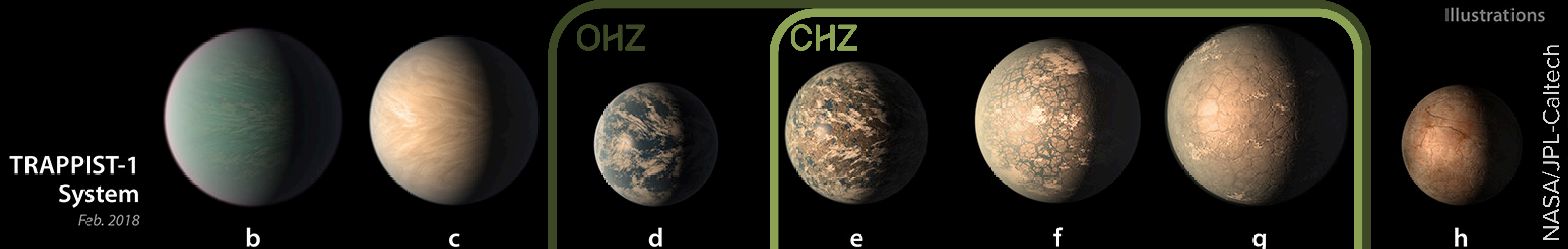
Transit Depth [ppm]
5000 5050 5100 5150
5 6 7 8 9 10 11 12
Wavelength [μm]

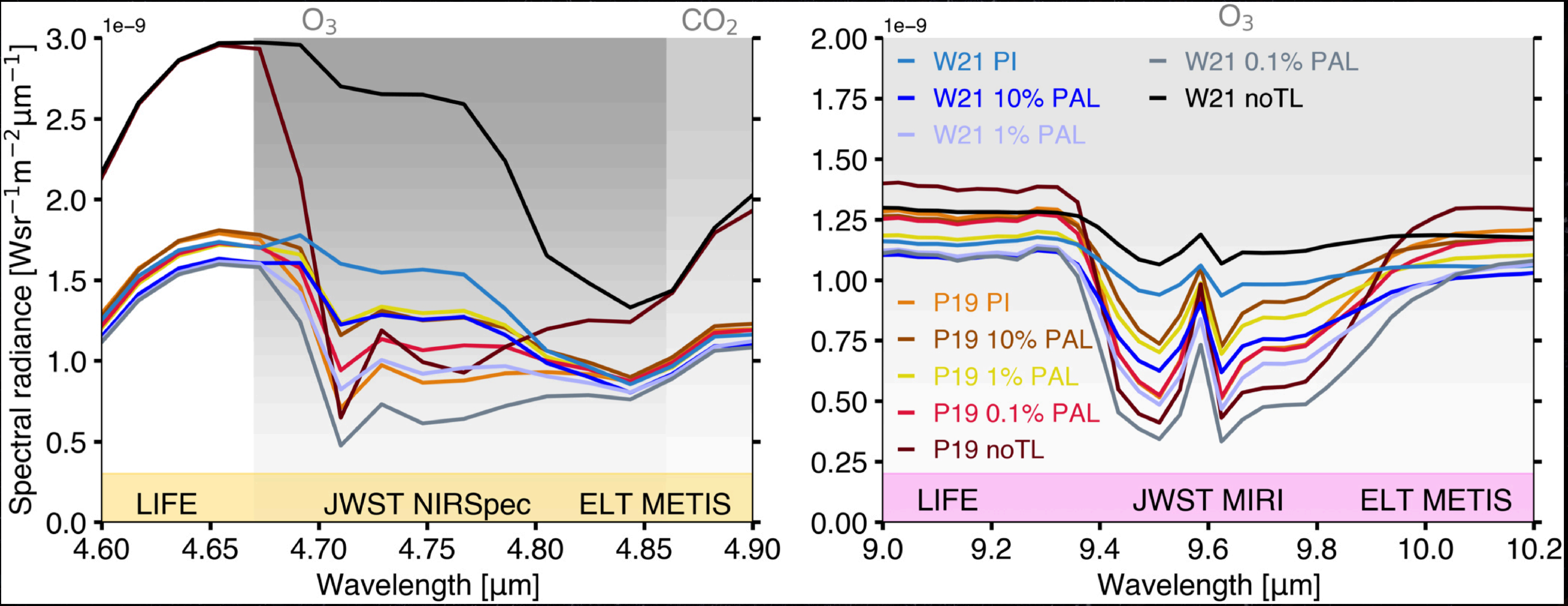
THE TRAPPIST-1 SYSTEM



	b	c	d	e	f	g	h
Orbital Period	1.51 days	2.42 days	4.05 days	6.10 days	9.21 days	12.36 days	18.76 days
Distance to Star	0.0115 AU	0.0158 AU	0.0223 AU	0.0293 AU	0.0385 AU	0.0469 AU	0.0619 AU
Planet Radius	1.12 R_{earth}	1.10 R_{earth}	0.78 R_{earth}	0.91 R_{earth}	1.05 R_{earth}	1.15 R_{earth}	0.77 R_{earth}
Planet Mass	1.02 M_{earth}	1.16 M_{earth}	0.30 M_{earth}	0.77 M_{earth}	0.93 M_{earth}	1.15 M_{earth}	0.33 M_{earth}
Planet Density	0.73 ρ_{earth}	0.88 ρ_{earth}	0.62 ρ_{earth}	1.02 ρ_{earth}	0.82 ρ_{earth}	0.76 ρ_{earth}	0.72 ρ_{earth}
Surface Gravity	0.81 g	0.96 g	0.48 g	0.93 g	0.85 g	0.87 g	0.55 g

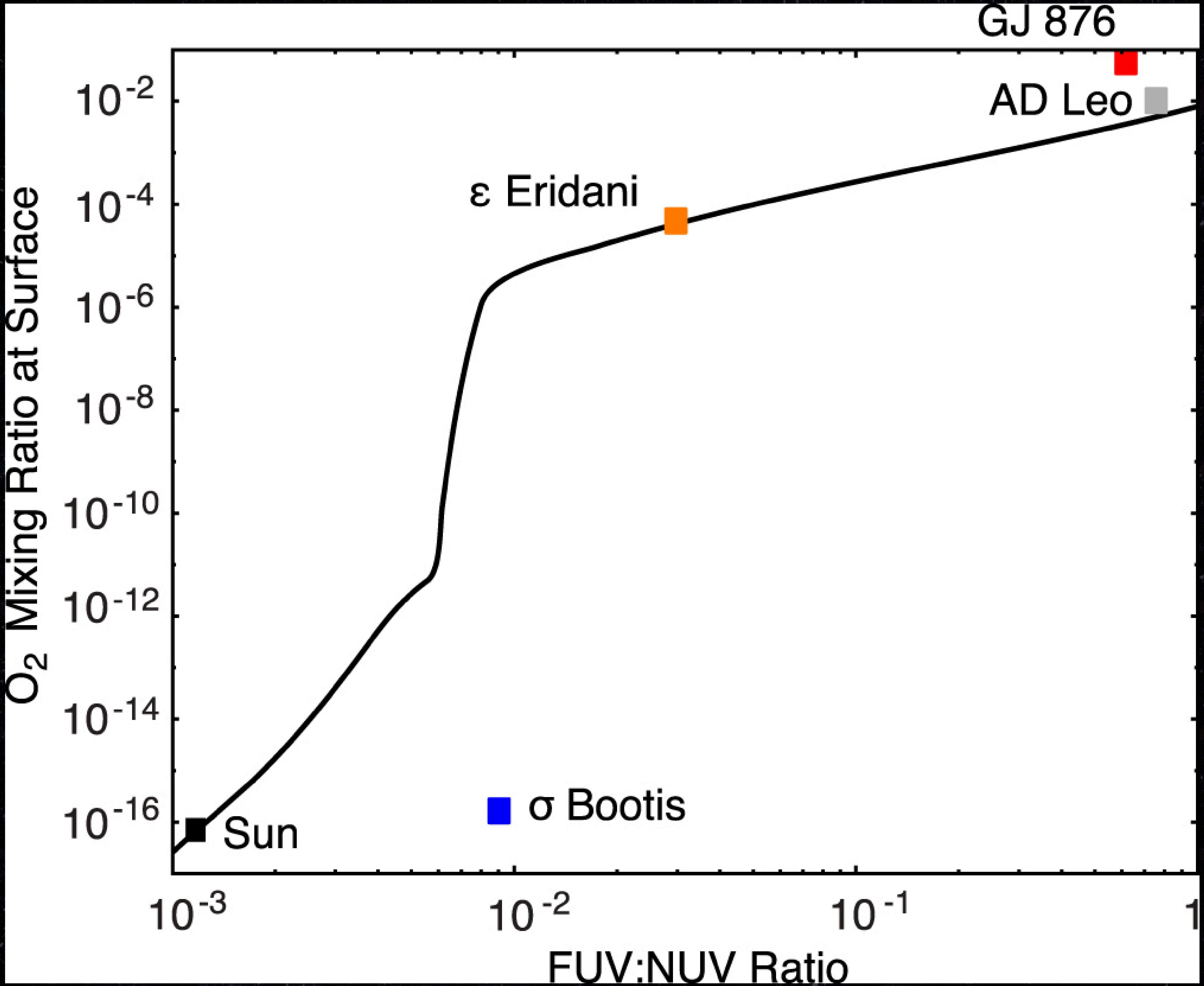
- TRAPPIST-1 is a red-dwarf M8V star that is 40.8 light-years away
  - It is a small ($R_s = 0.1\ \mathrm{R}_\odot$), cool ($T_s = 2566\ \mathrm{K}$), and dim ($L_s = 5.4 \cdot 10^{-4}\ \mathrm{L}_\odot$) star
  - M-dwarves also produce stellar flares, although TRAPPIST-1 is old
- Seven terrestrial planets, four of which could be potentially habitable

DEGENERATE OZONE CONCENTRATIONS



Cooke et al. (2023)

- Cooke et al. (2023) compared the Peacock et al. (2019) spectra against Wilson et al. (2021) SEM for **pre-industrial** Earth-like TRAPPIST-1 e scenarios
  - Uses three-dimensional WACCM6 Earth System Model
  - Increased O_3 concentrations, up to a factor of 26 difference



Harman et al. (2015)

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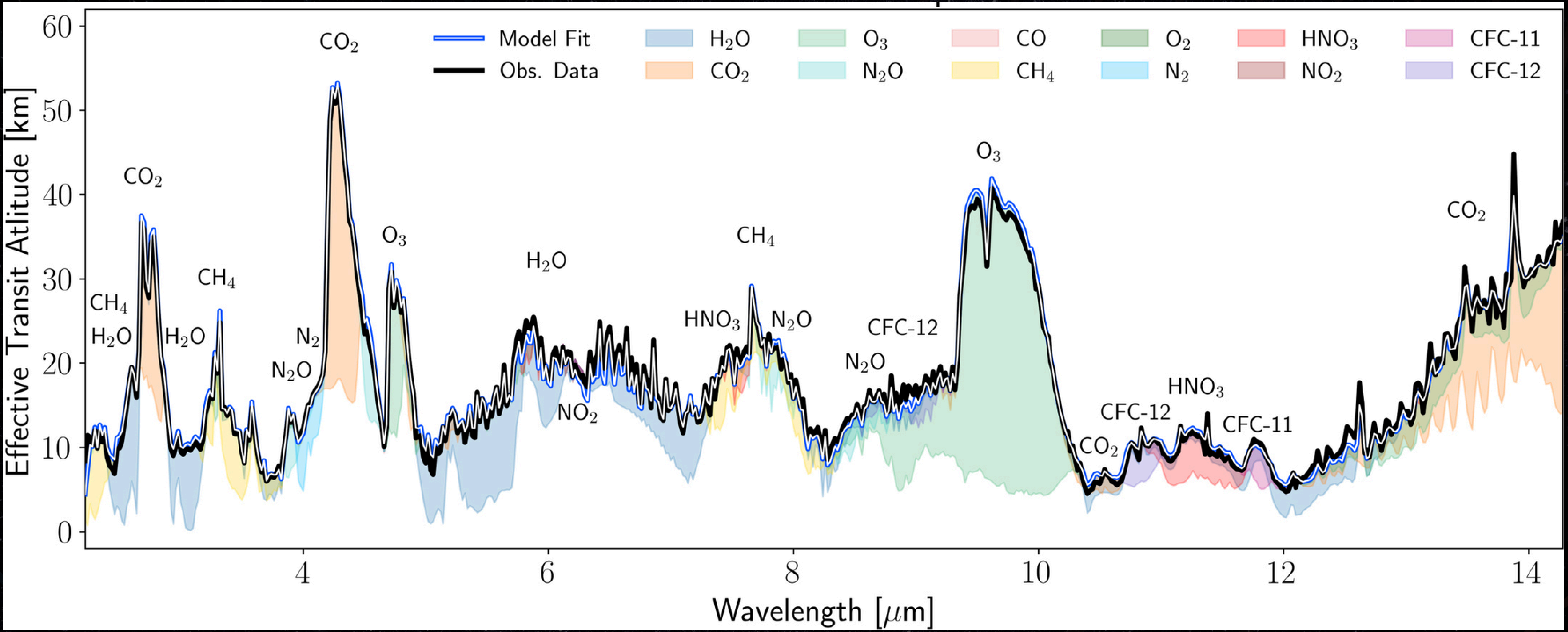
TRANSMISSION SPECTRUM OF MODERN EARTH



Lustig-Yaeger at al. (2023)

78% N_2 | 21% O_2 | 1% Ar | 420 ppm CO_2 | 2 ppm CH_4 | 0.3 ppm N_2O | 220 ppt CFC-11 | 480 ppt CFC-12

- In the modern era, our strongest atmospheric biosignature is O_3
  - Trichlorofluoromethane and Dichlorodifluoromethane also present