

The Pale Orange Dot: The Habitability and Spectrum of Hazy Earths



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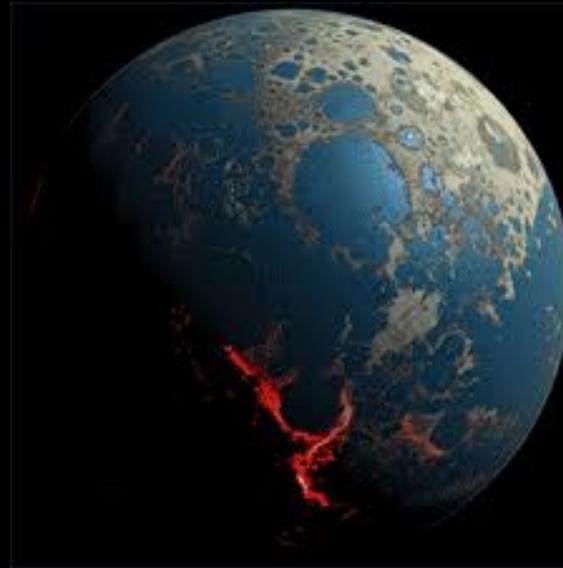
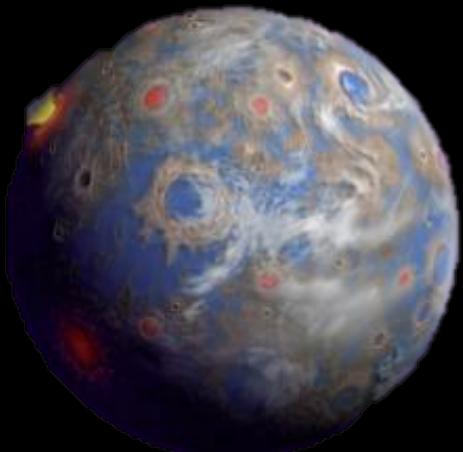


W

what color is an Earthlike planet?



the different faces of Earth through time

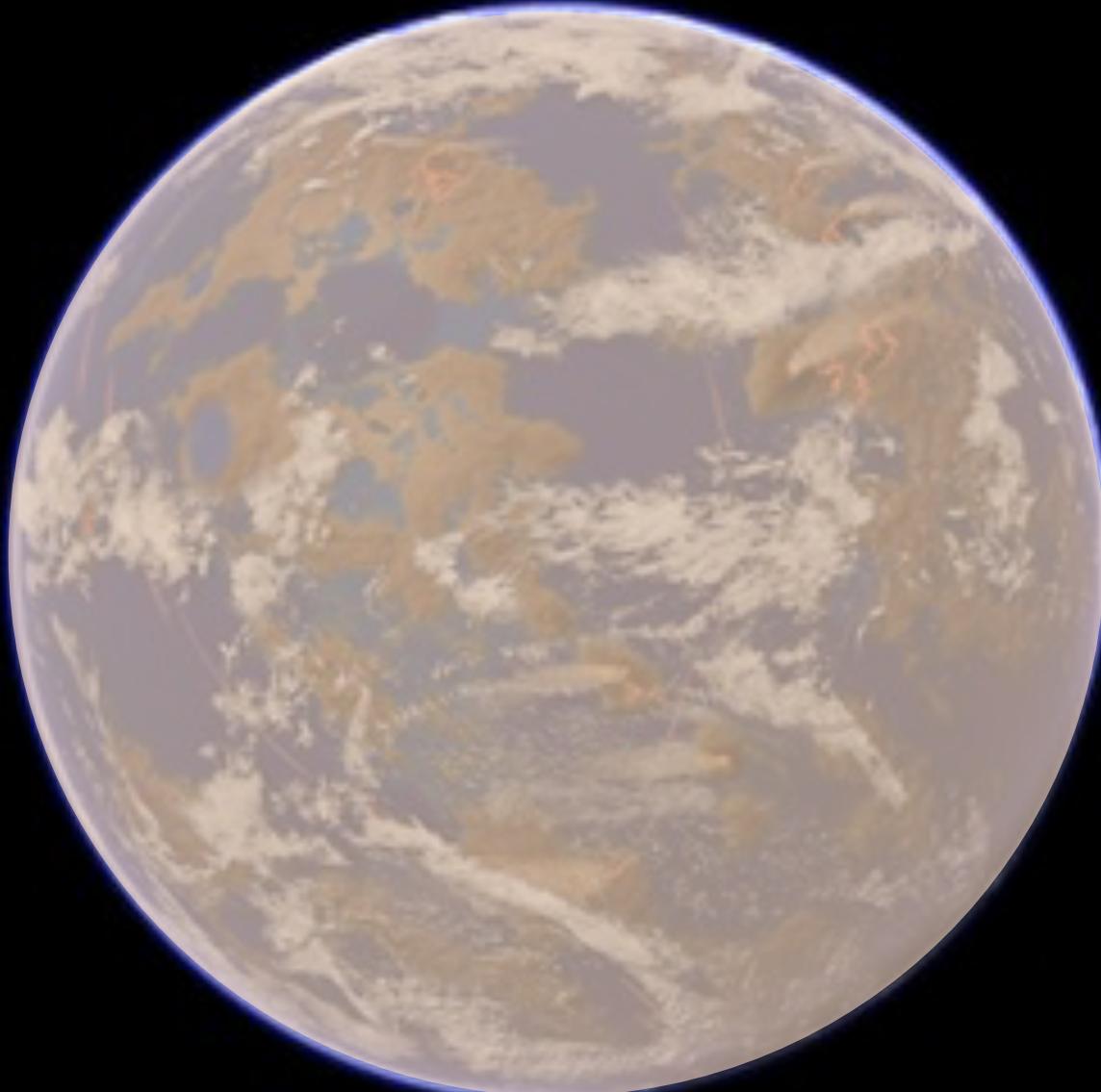


A Different World: Archean Earth



Anoxic atmosphere → more methane (CH_4)

Hazy Archean Earth



Anoxic atmosphere → more methane (CH_4)

If $\text{CH}_4/\text{CO}_2 > 0.1\text{-}0.2 \rightarrow$ haze

Hazy Archean Earth

Pavlov et al 2001a

Pavlov et al 2001b

Trainer et al 2004

Trainer et al 2006

Haqq-Misra et al 2008

Domagal-Goldman et al 2008

Zerkle et al 2008

Kurzweil et al 2013

Izon et al 2015

Anoxic atmosphere → more methane (CH_4)

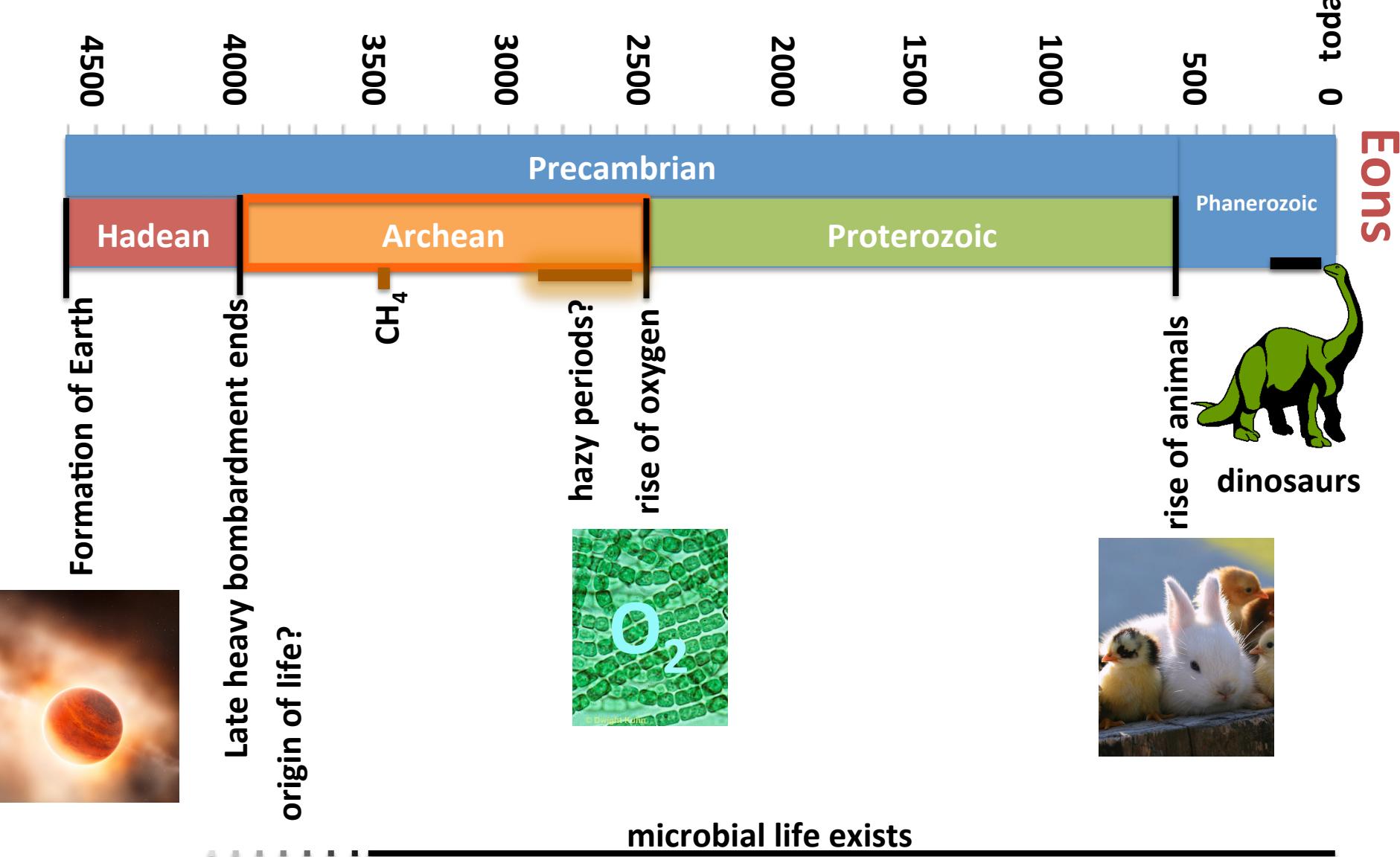
If $\text{CH}_4/\text{CO}_2 > 0.1\text{-}0.2 \rightarrow$ haze

**photochemical smog ≈
organic haze**

A photograph showing a dense urban landscape under a thick layer of orange-tinted smog. The city skyline is visible in the background, with several skyscrapers standing out against the hazy sky. In the foreground, there's a mix of buildings and what appears to be a river or waterfront area with some boats. The overall atmosphere is one of air pollution and poor visibility.

Titan

millions of years ago

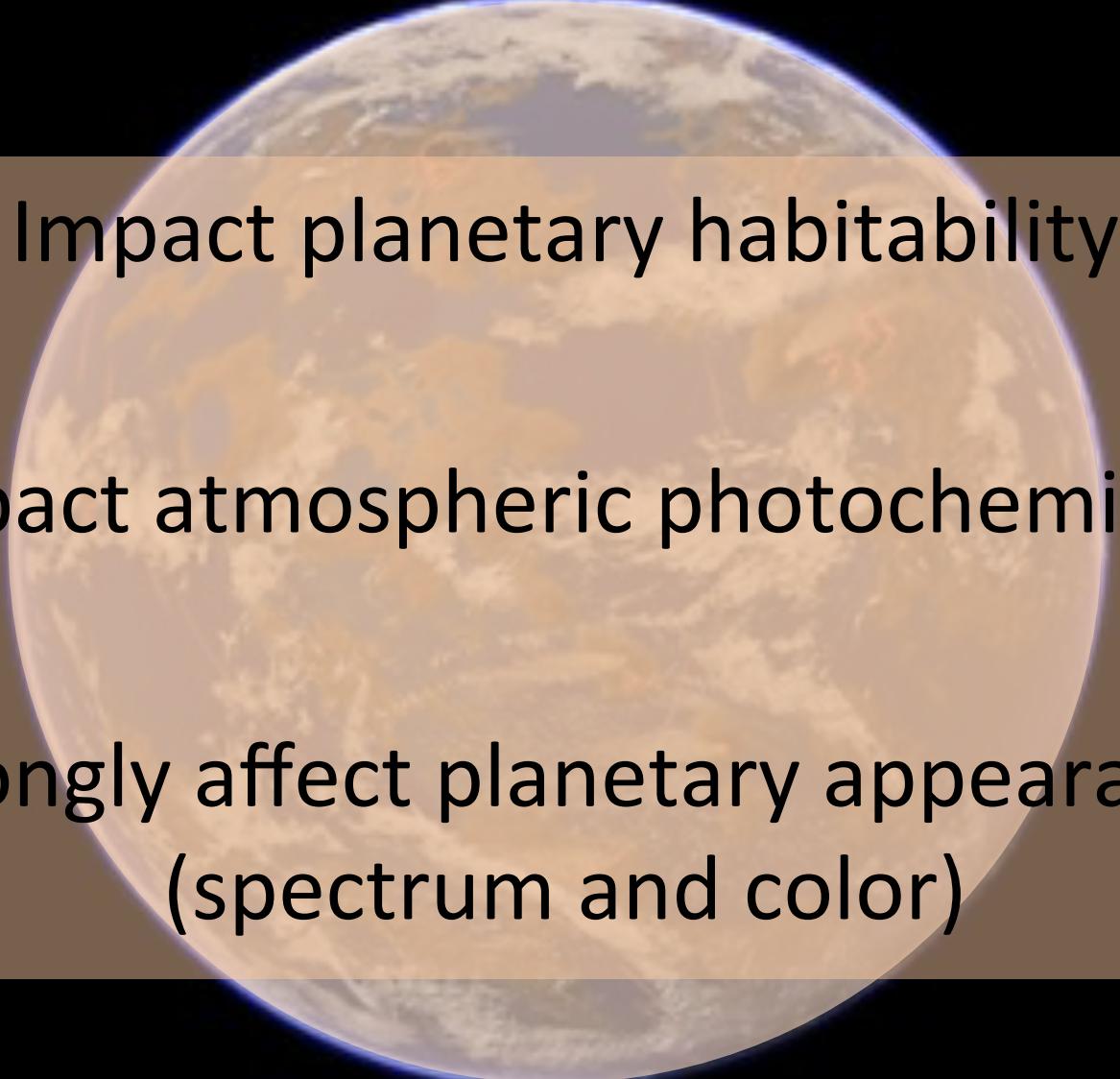


Are hazy earths common?



Anoxic, methane-rich
earths may be common

how hazes affect planets

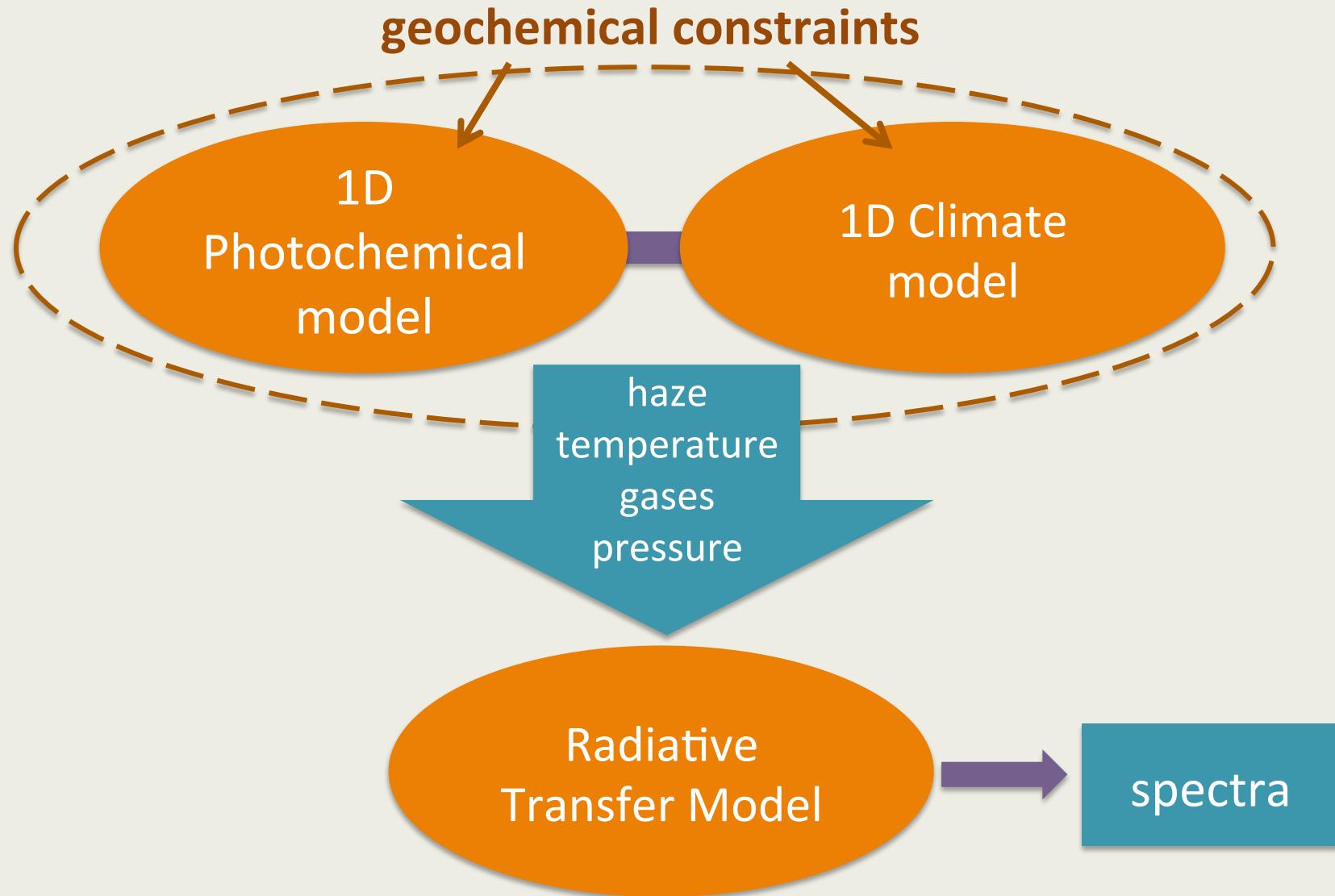


Impact planetary habitability

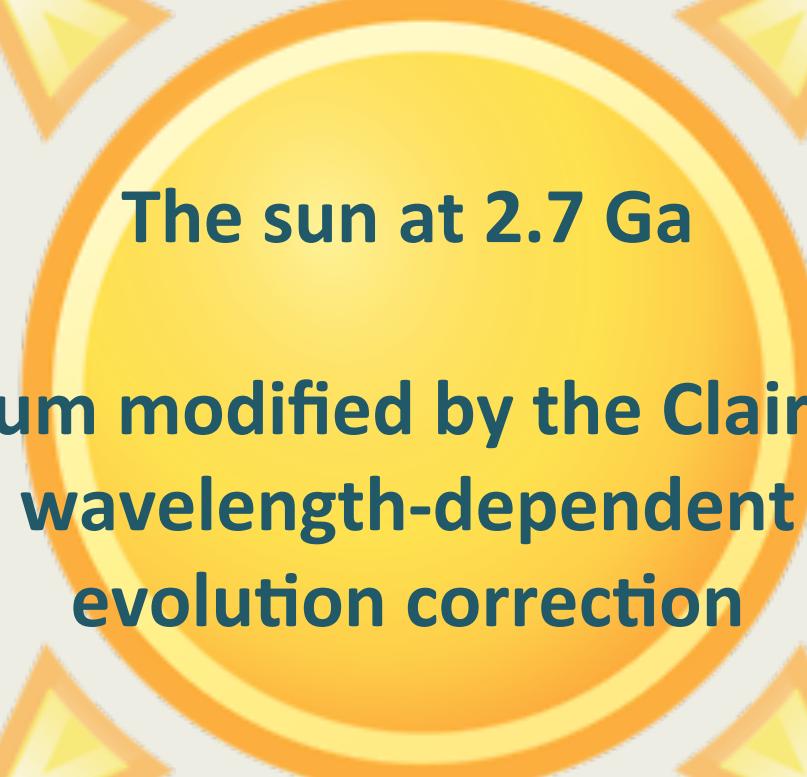
Impact atmospheric photochemistry

Strongly affect planetary appearance
(spectrum and color)

simulating Archean Earth conditions



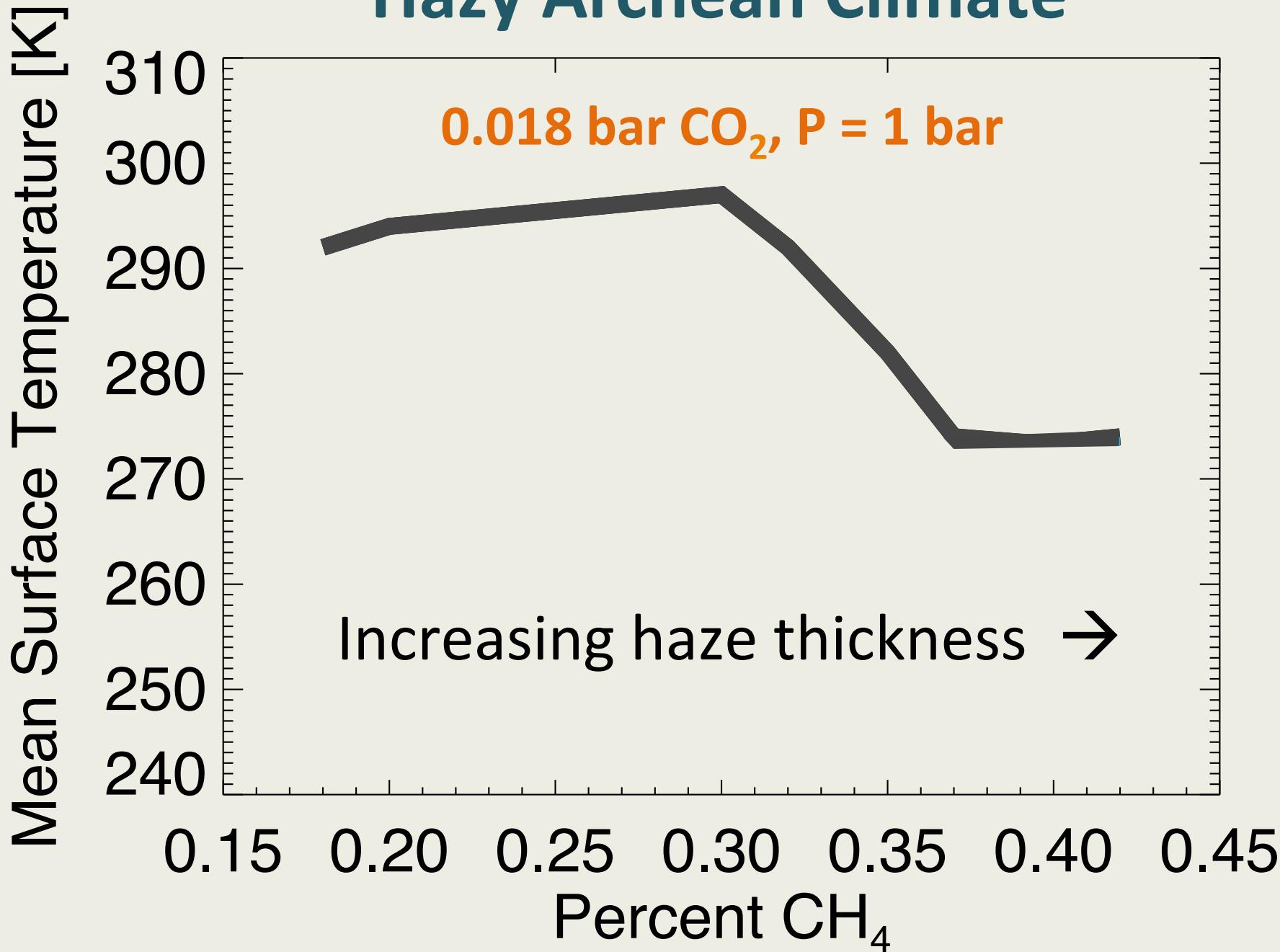
our model's star



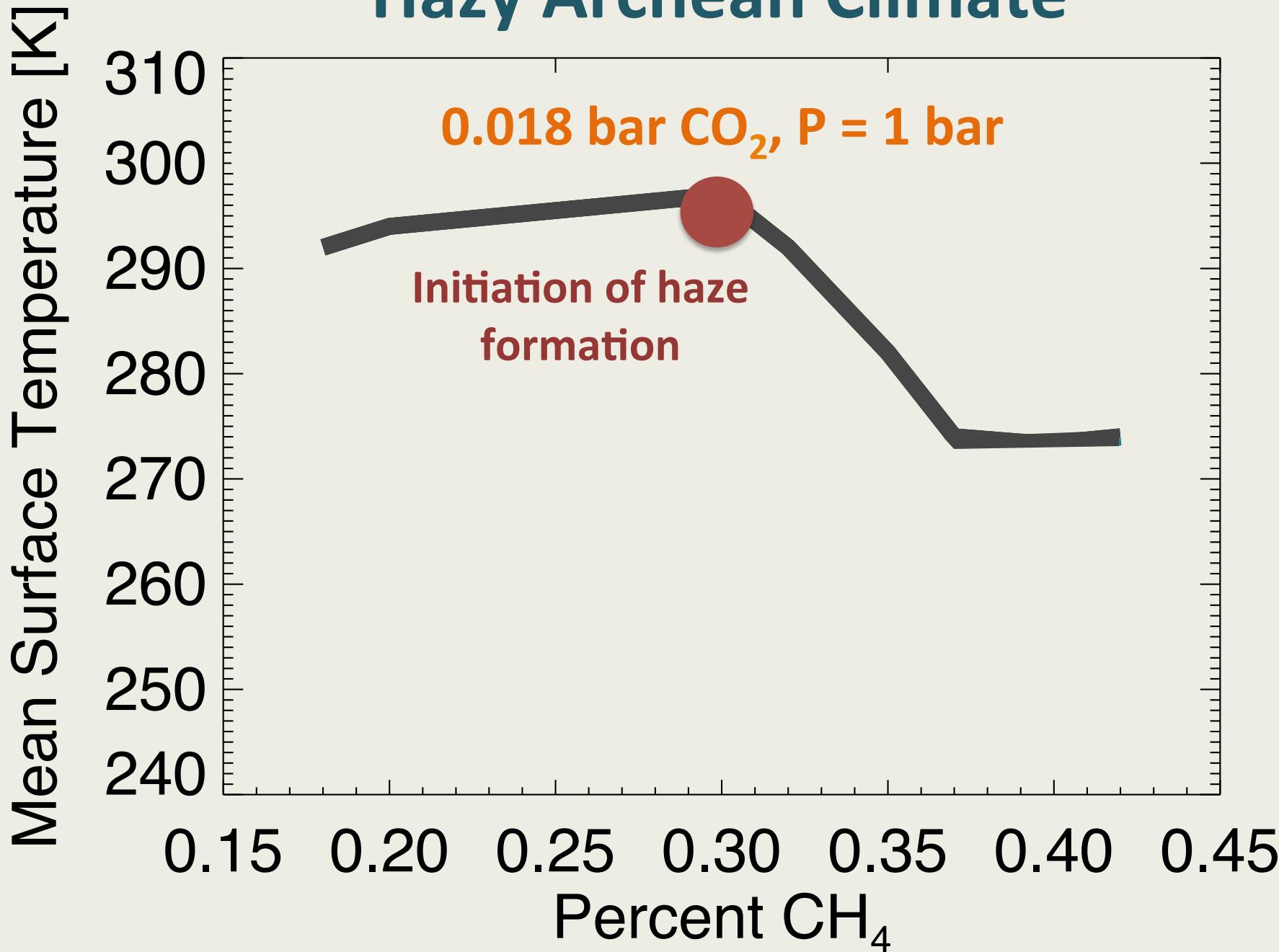
The sun at 2.7 Ga

Spectrum modified by the Claire et al.
2012 wavelength-dependent solar
evolution correction

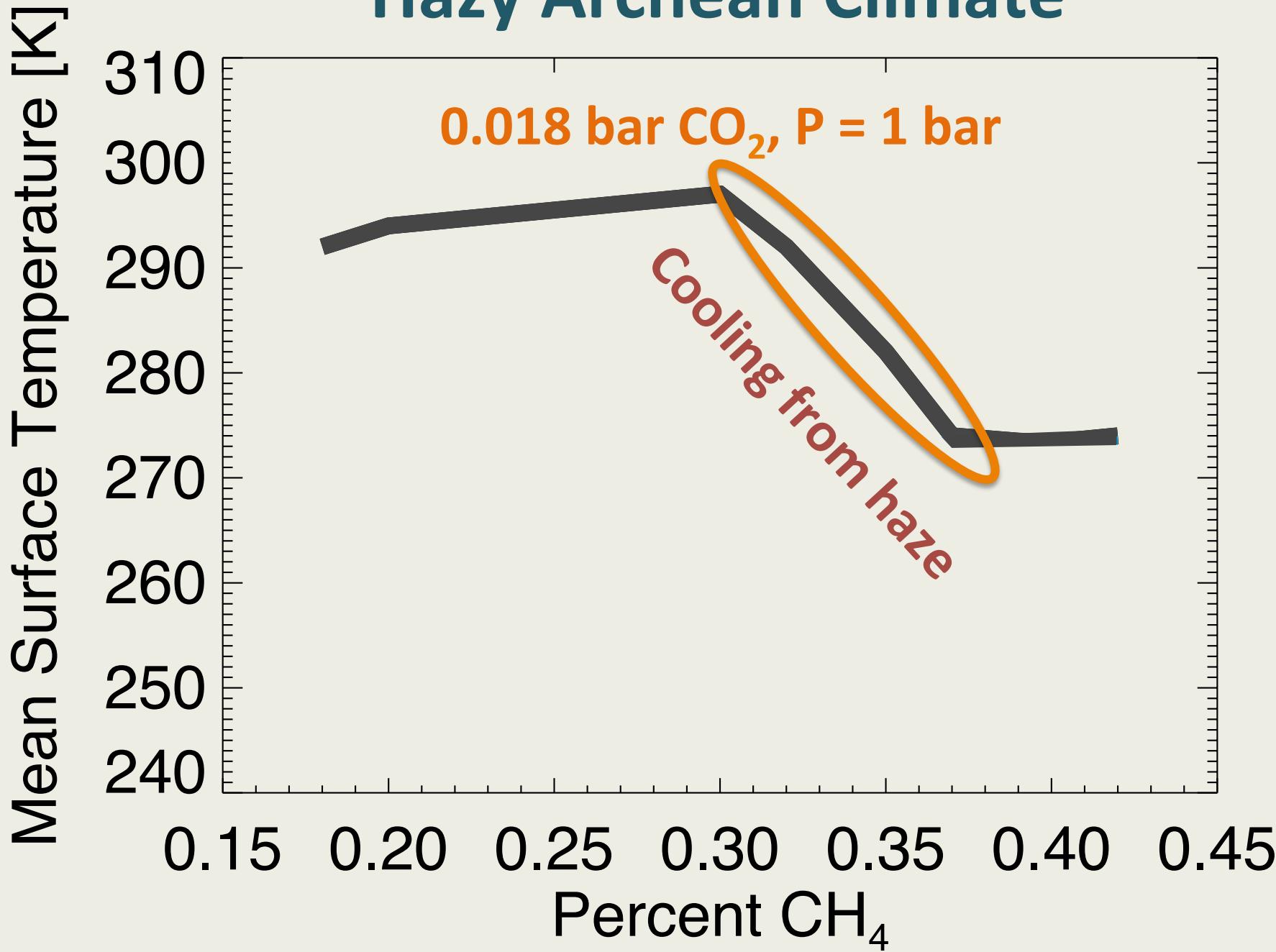
Hazy Archean Climate



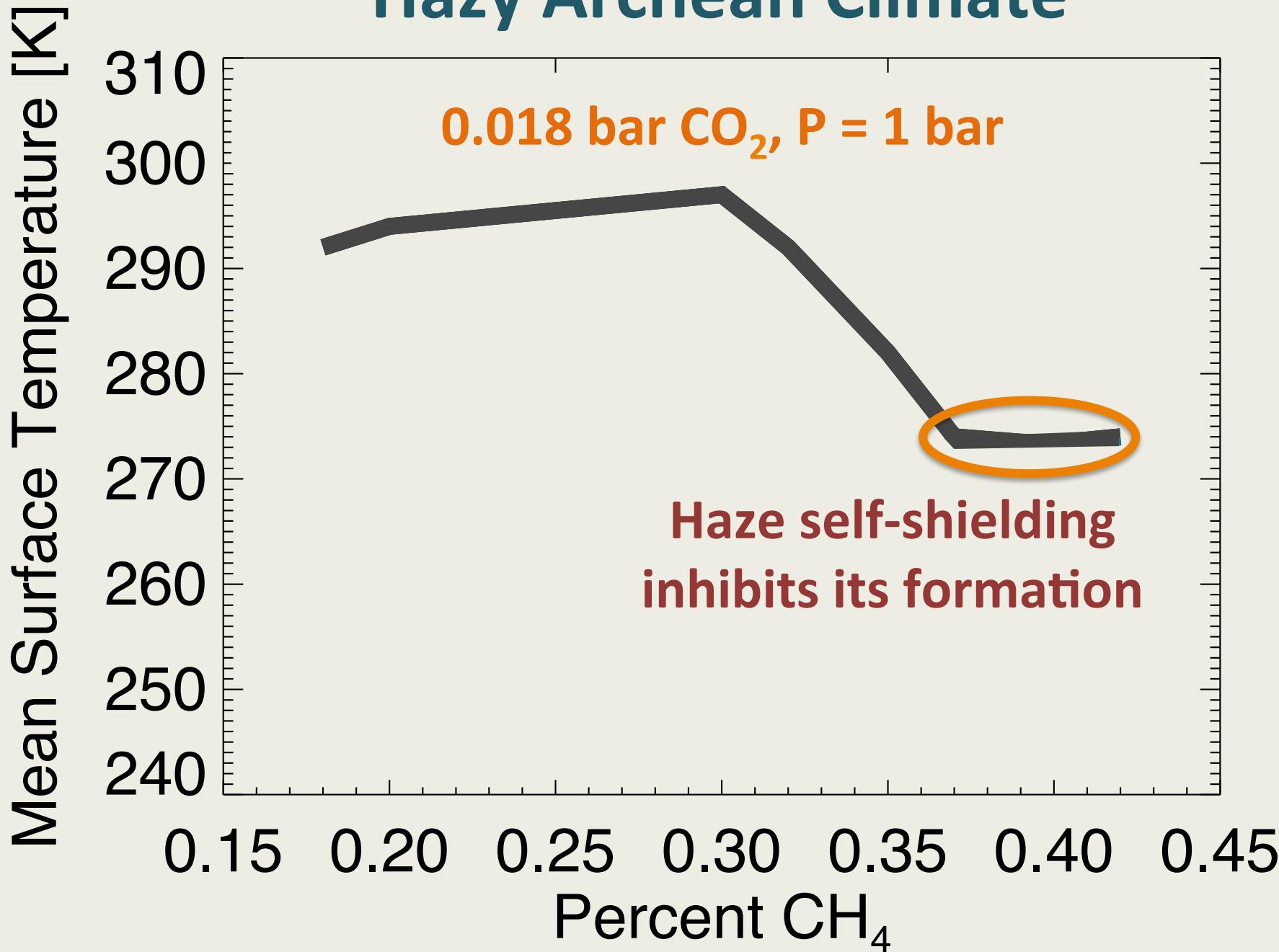
Hazy Archean Climate



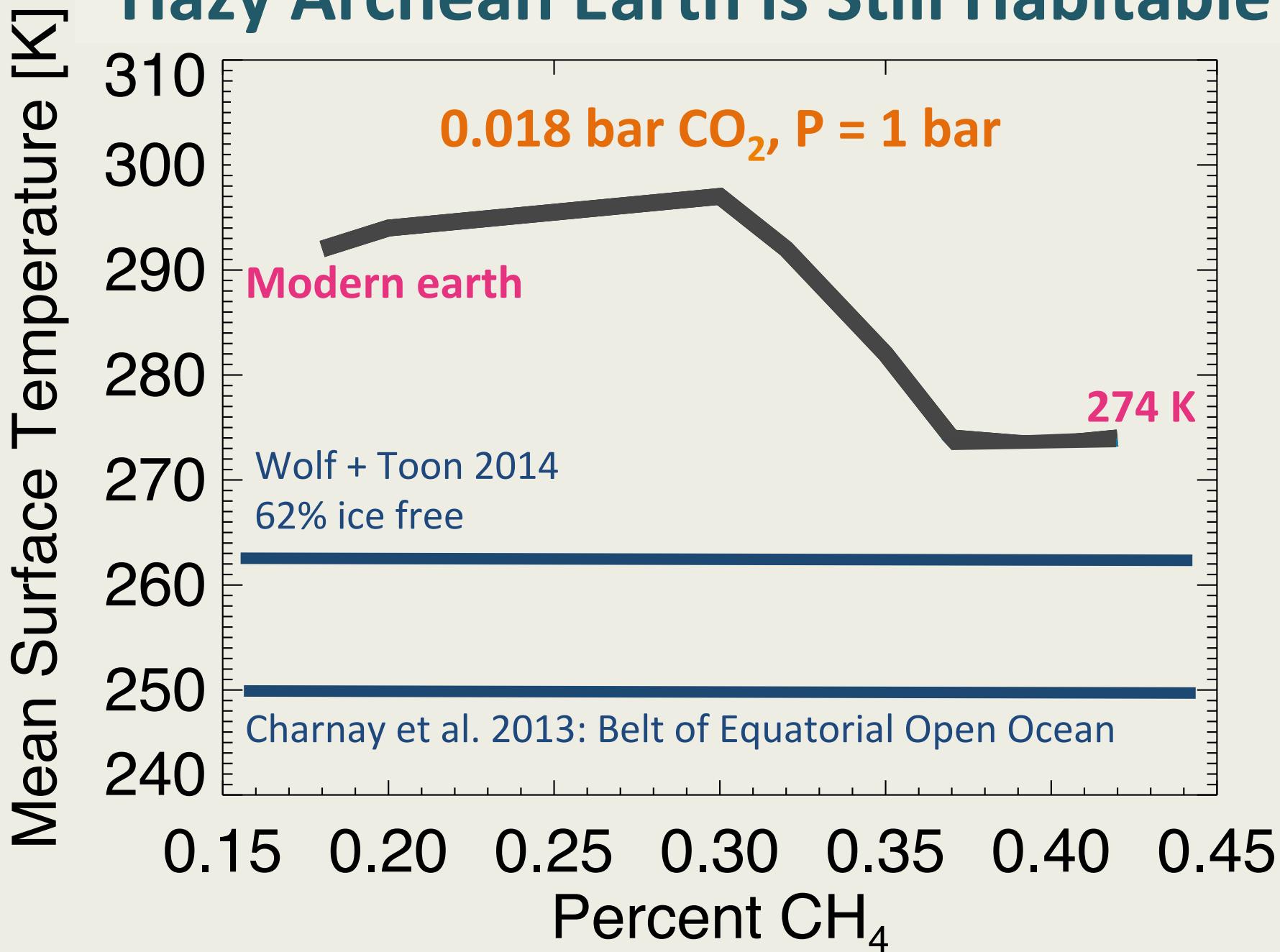
Hazy Archean Climate



Hazy Archean Climate



Hazy Archean Earth is Still Habitable



Hazy Archean Climate

ture [K]

310
300

0.018 bar CO₂, P = 1 bar

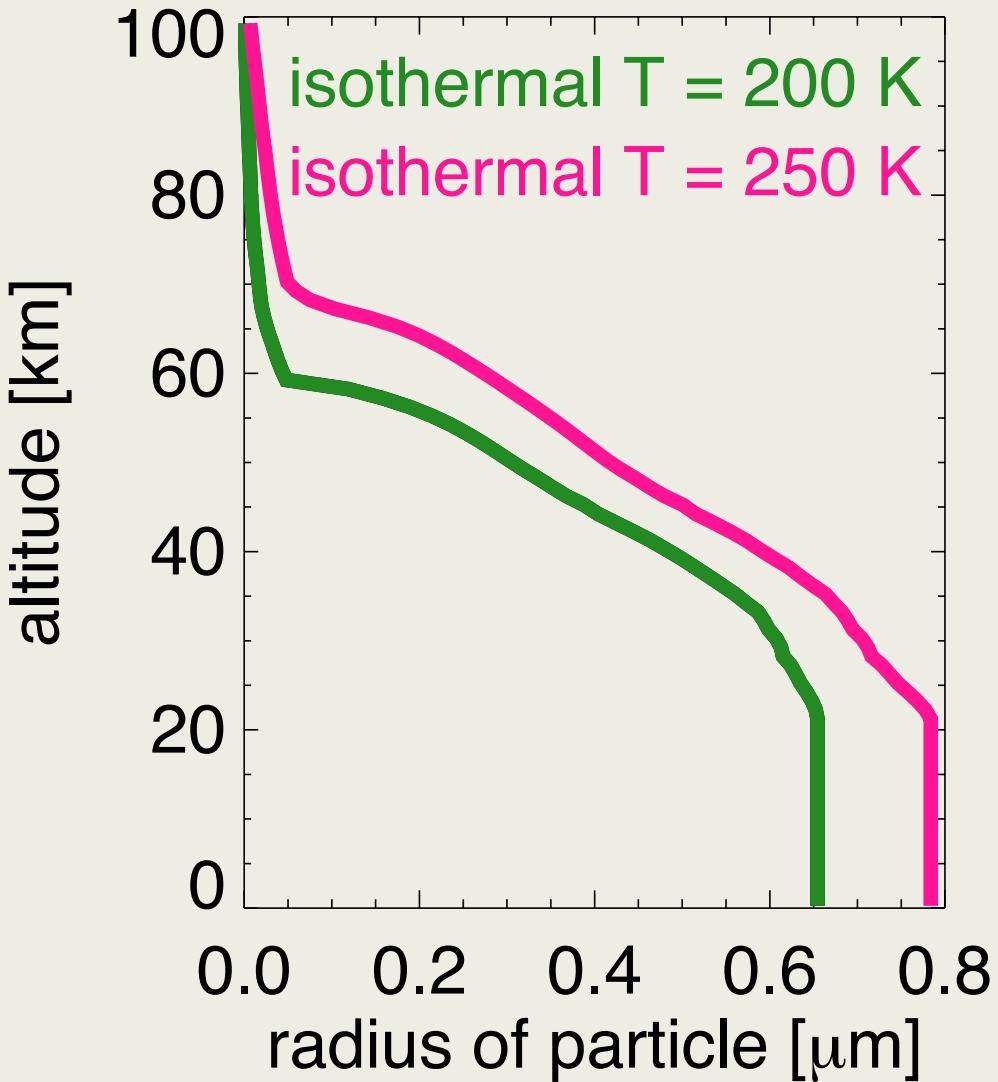
Haze cools the planet but hazy planets can still be habitable.

Mean Surface

260
250
240

0.15 0.20 0.25 0.30 0.35 0.40 0.45
Percent CH₄

hotter atmosphere = larger particles

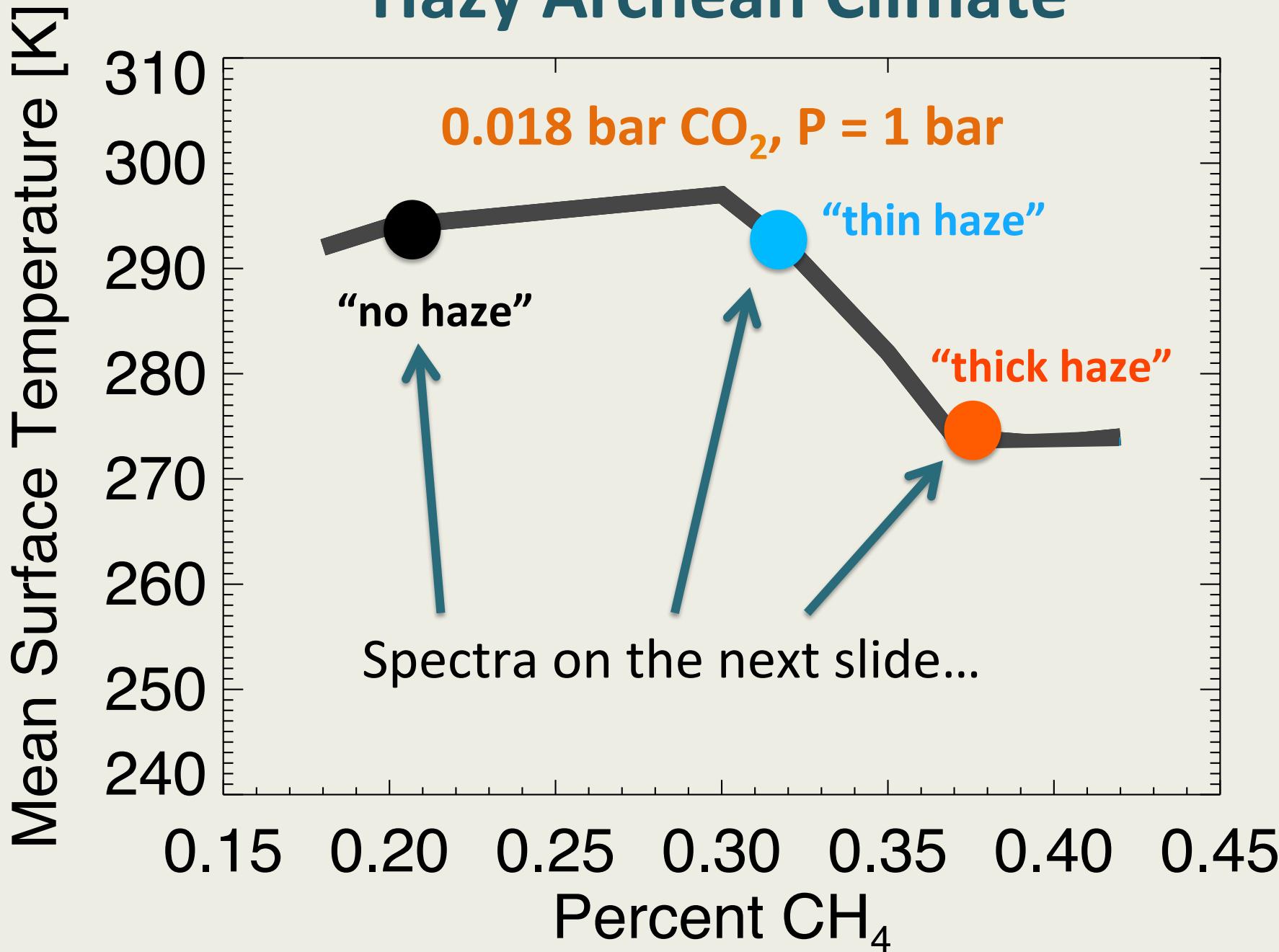


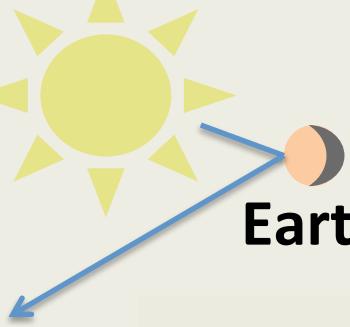
Max radius $\sim 0.6 \mu\text{m}$

Max radius $\sim 0.8 \mu\text{m}$

hotter atmosphere
↓
more rapidly moving
particles
↓
shorter particle
coagulation timescale

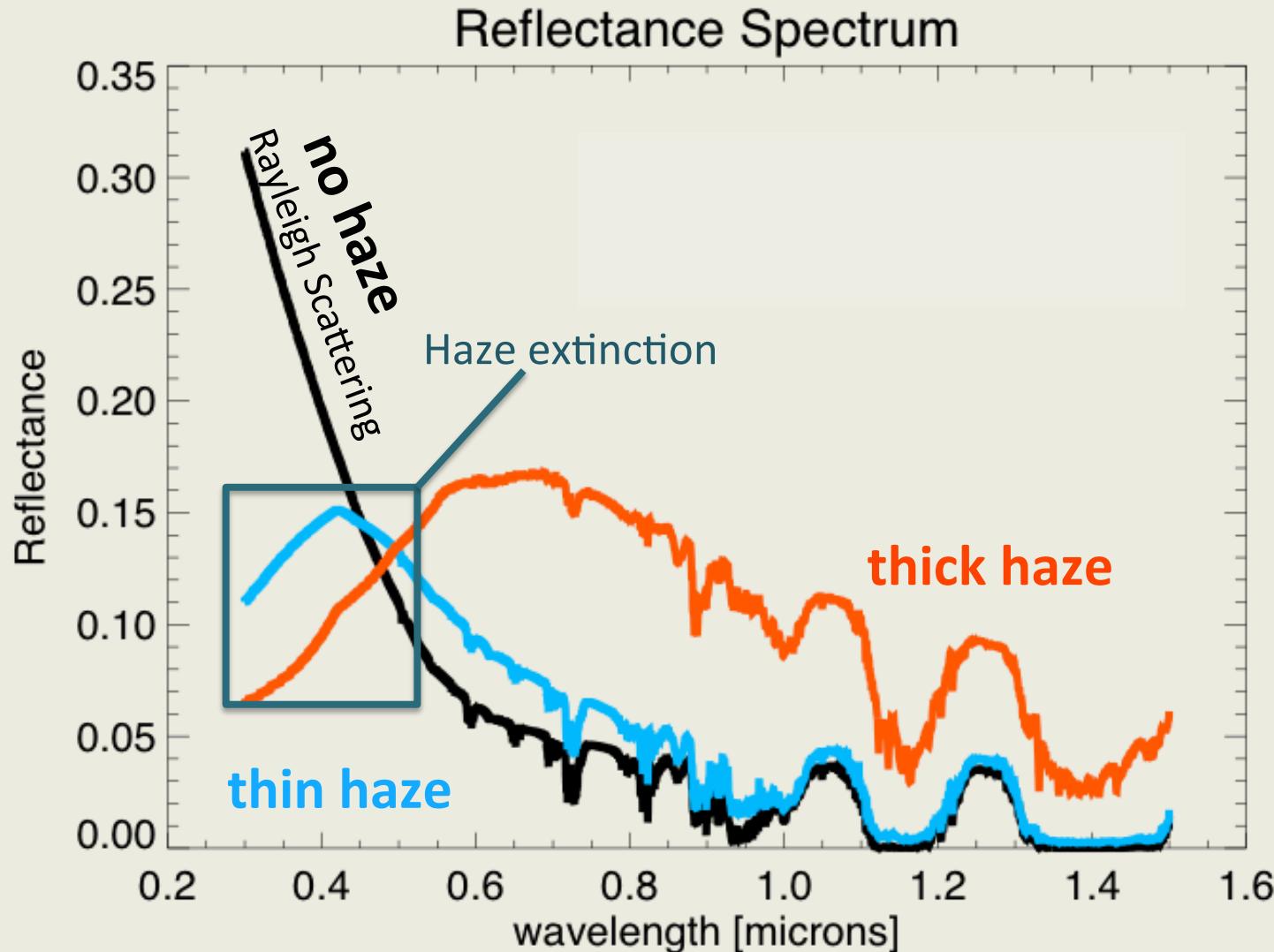
Hazy Archean Climate





reflection spectra

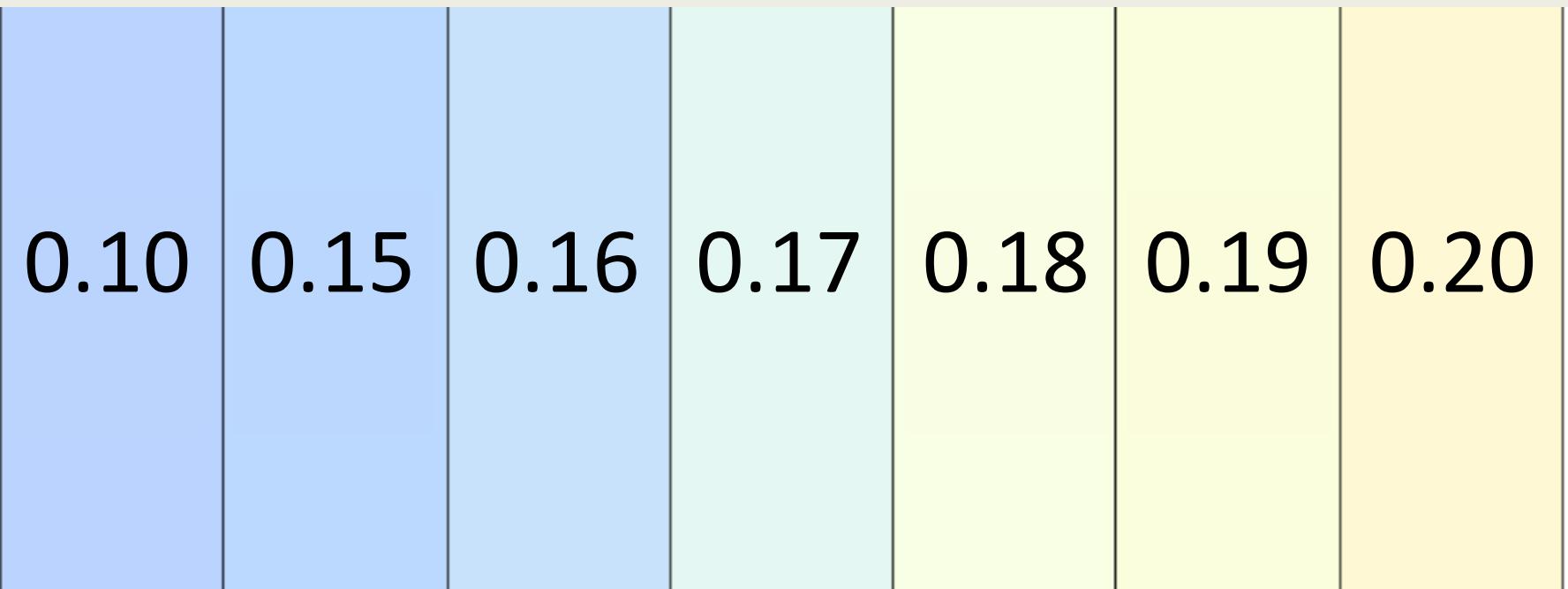
Earth with $p\text{CO}_2 = 0.018 \text{ bar}$, 1 bar total pressure

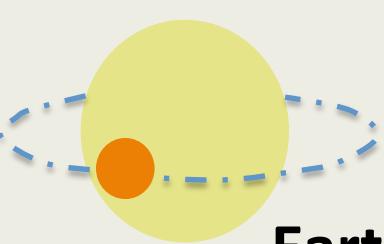


the pale orange dot to the eye

$\text{CH}_4/\text{CO}_2 =$

color alone may be a bad
discriminator of earth-like planets

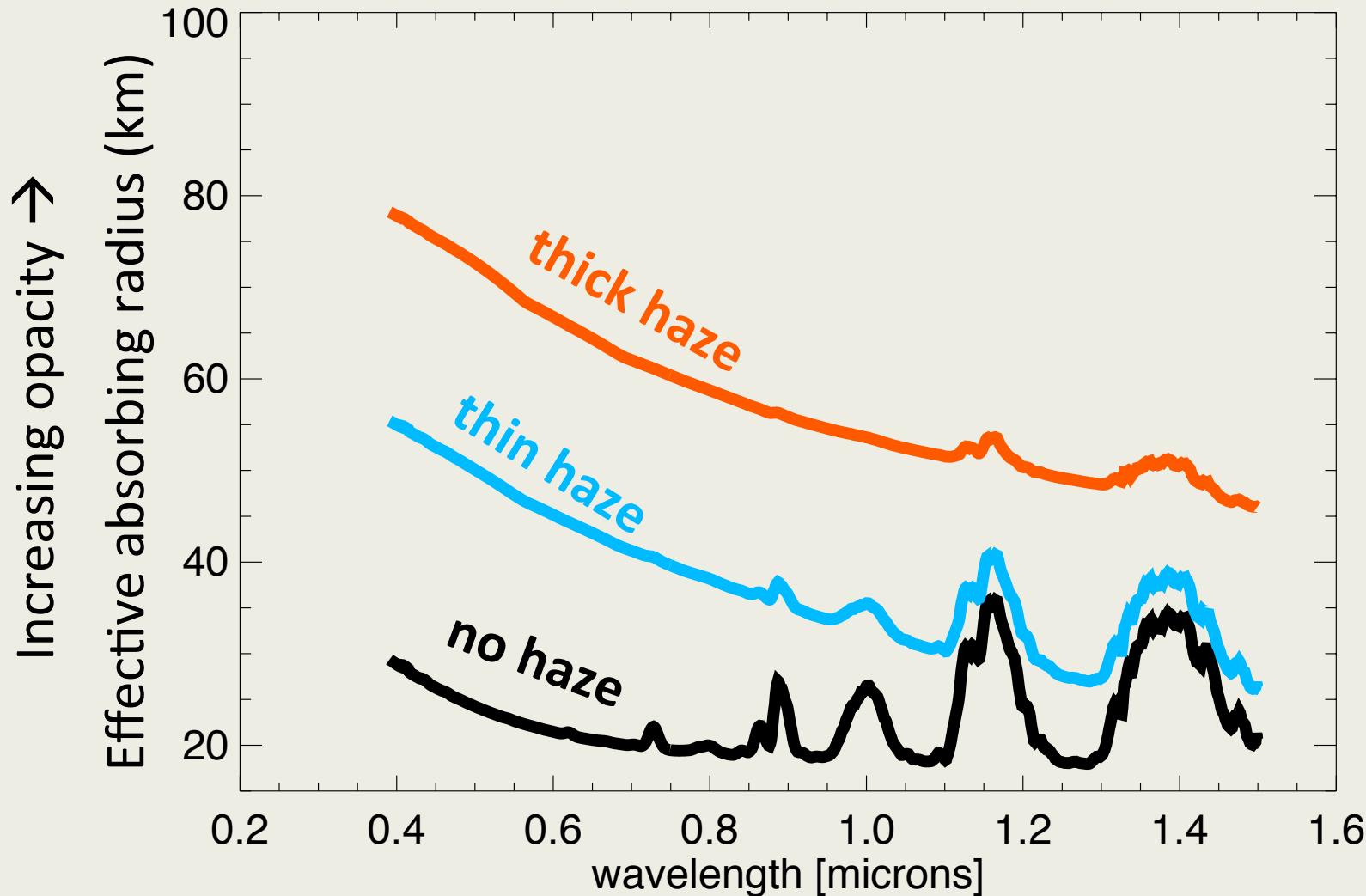


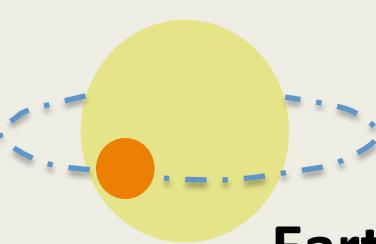


transit transmission

Earth with $p\text{CO}_2 = 0.018 \text{ bar}$, 1 bar total pressure

Transit Transmission

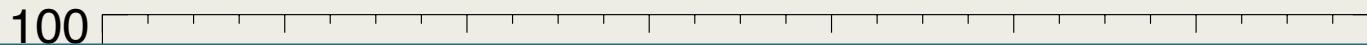




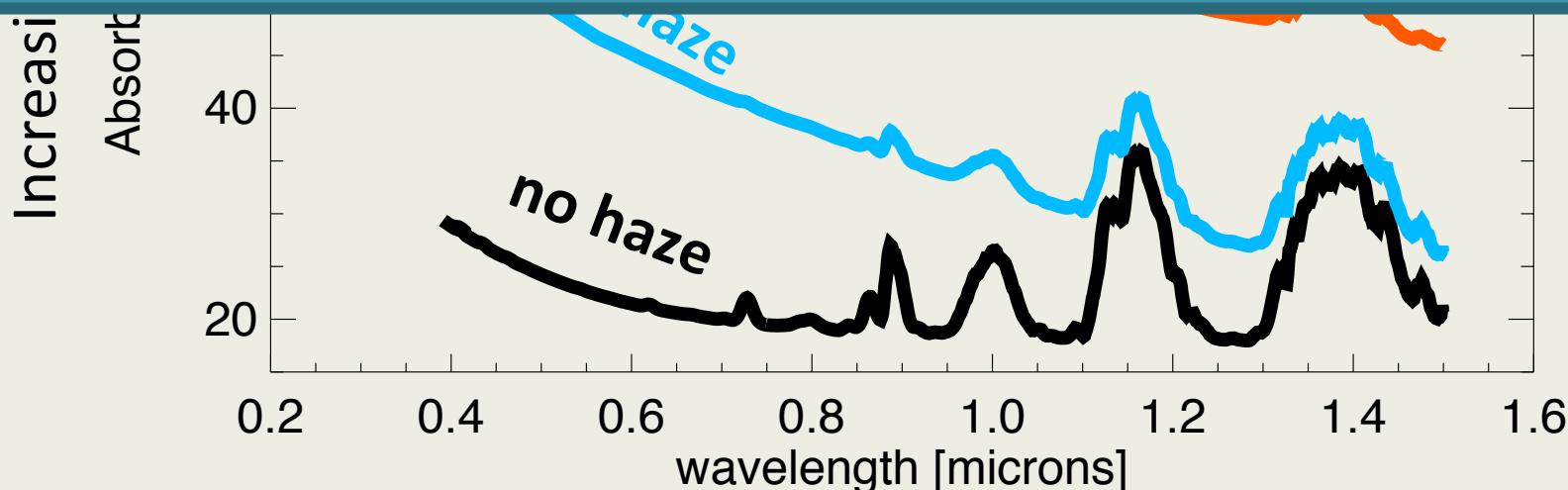
transit transmission

Earth with $p\text{CO}_2 = 0.018 \text{ bar}$, 1 bar total pressure

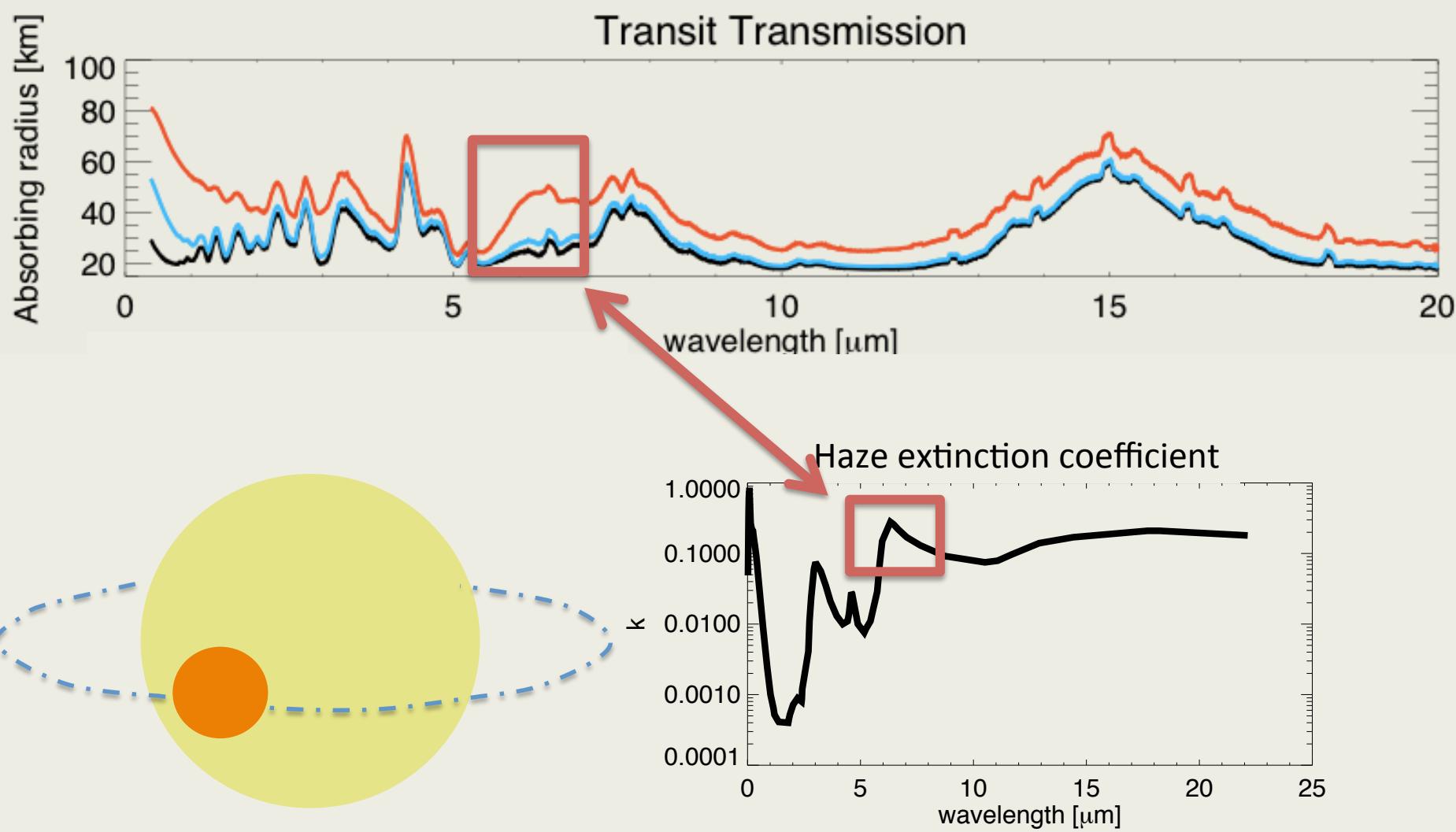
Transit Transmission



Hazes = can't see as deeply into a planet's atmosphere + weaker absorption features



transit transmission



Khare et al 1984 refractive indices

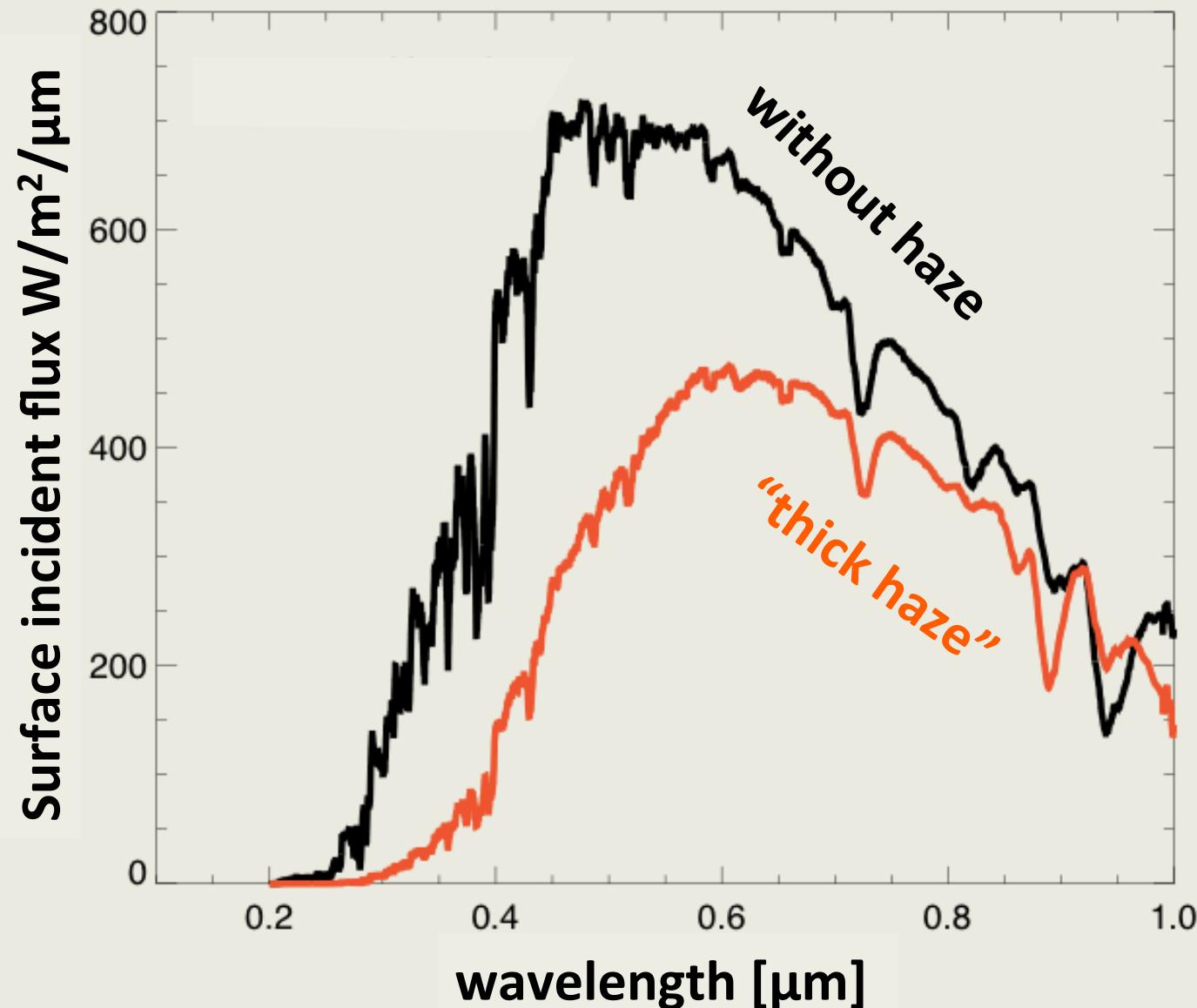
haze as a biosignature?

At Earthlike CO₂ levels, estimated abiotic methane production rates are insufficient to form an organic haze

Biological fluxes (10²-10³ x higher) do produce haze for Earthlike CO₂

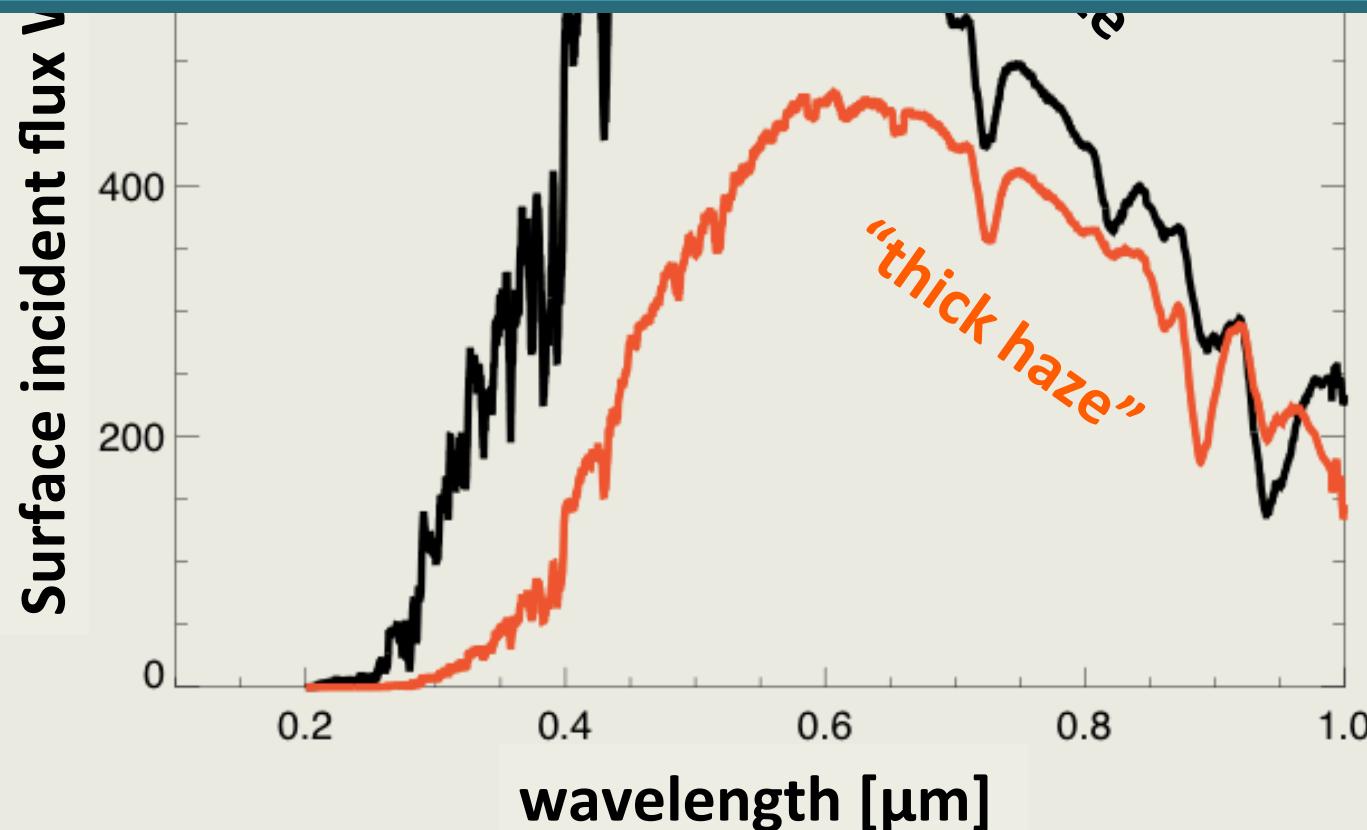
(Kharecha et al 2005, Guzmán-Marmolejo et al 2013)

spectrum at the ground



UVC ($\lambda < 0.28\mu\text{m}$) without haze
 $= 1 \text{ W/m}^2$

UVC with haze = 0.03 W/m^2

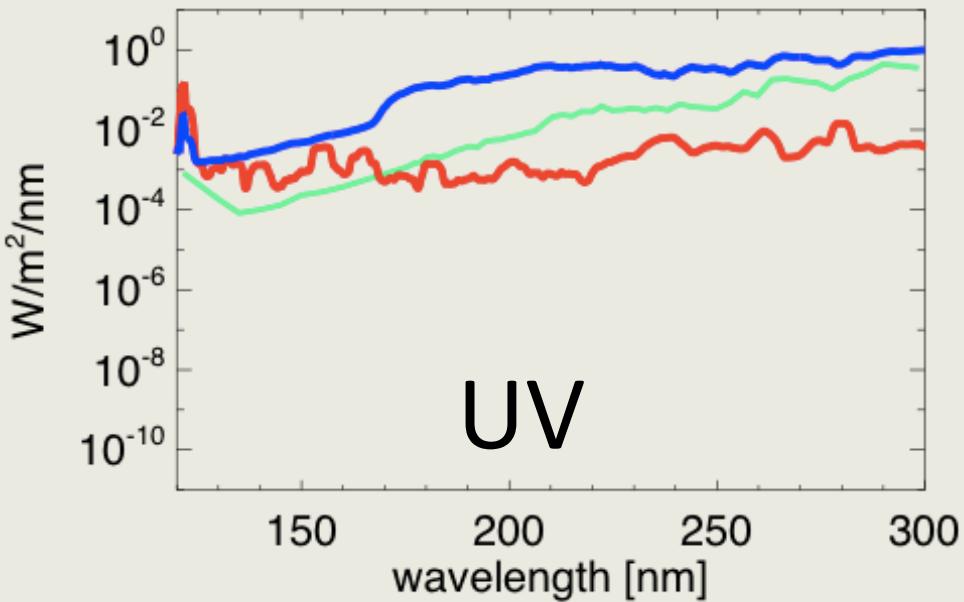
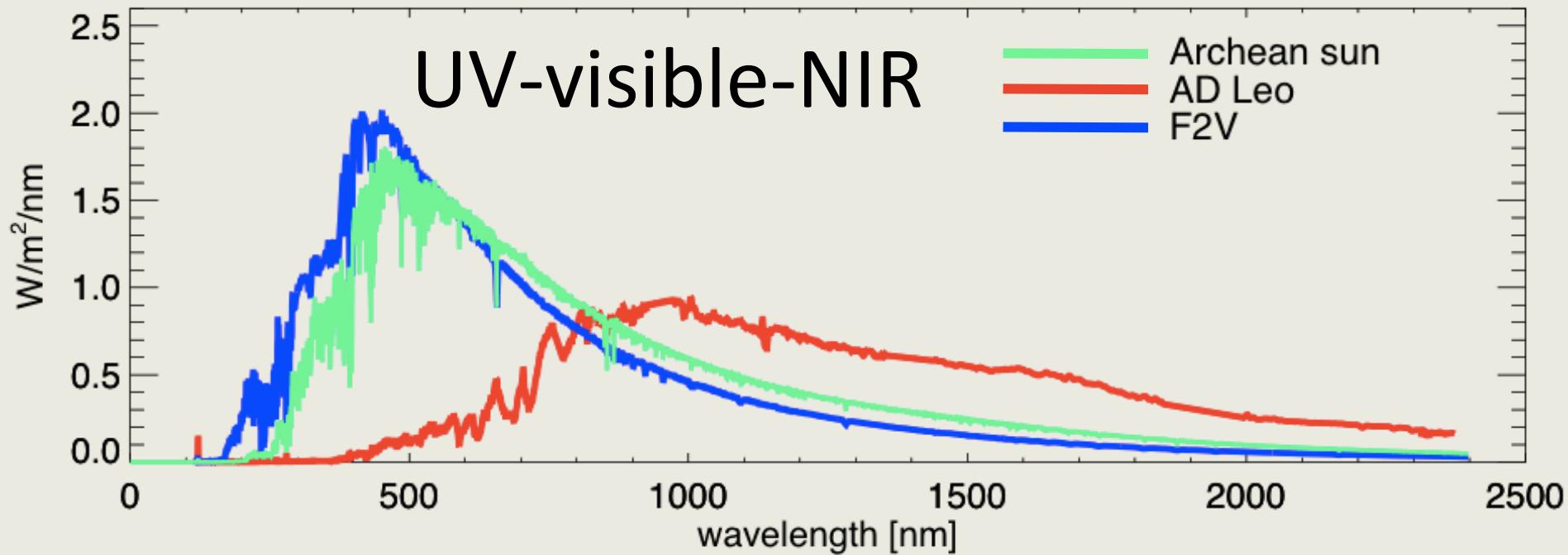




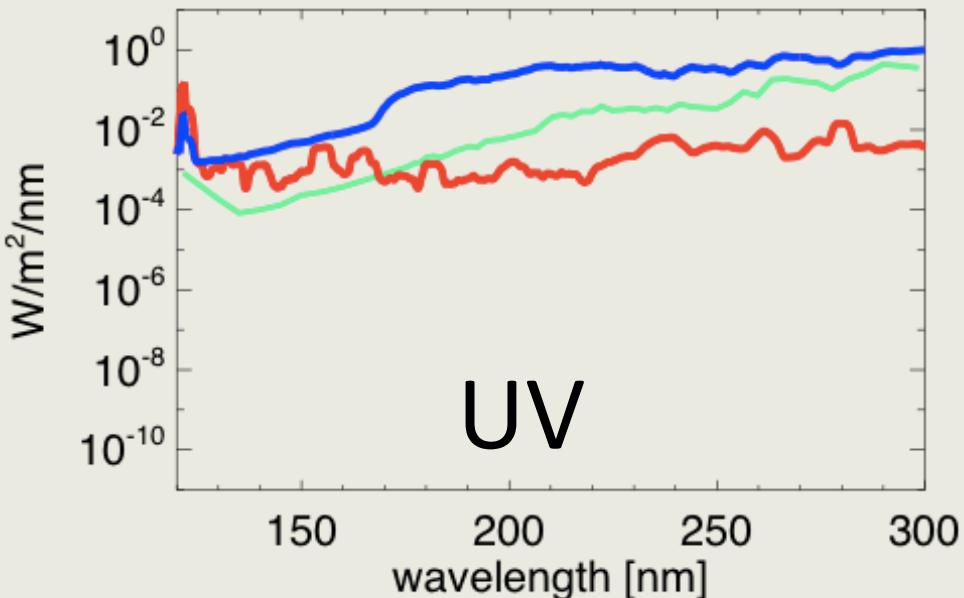
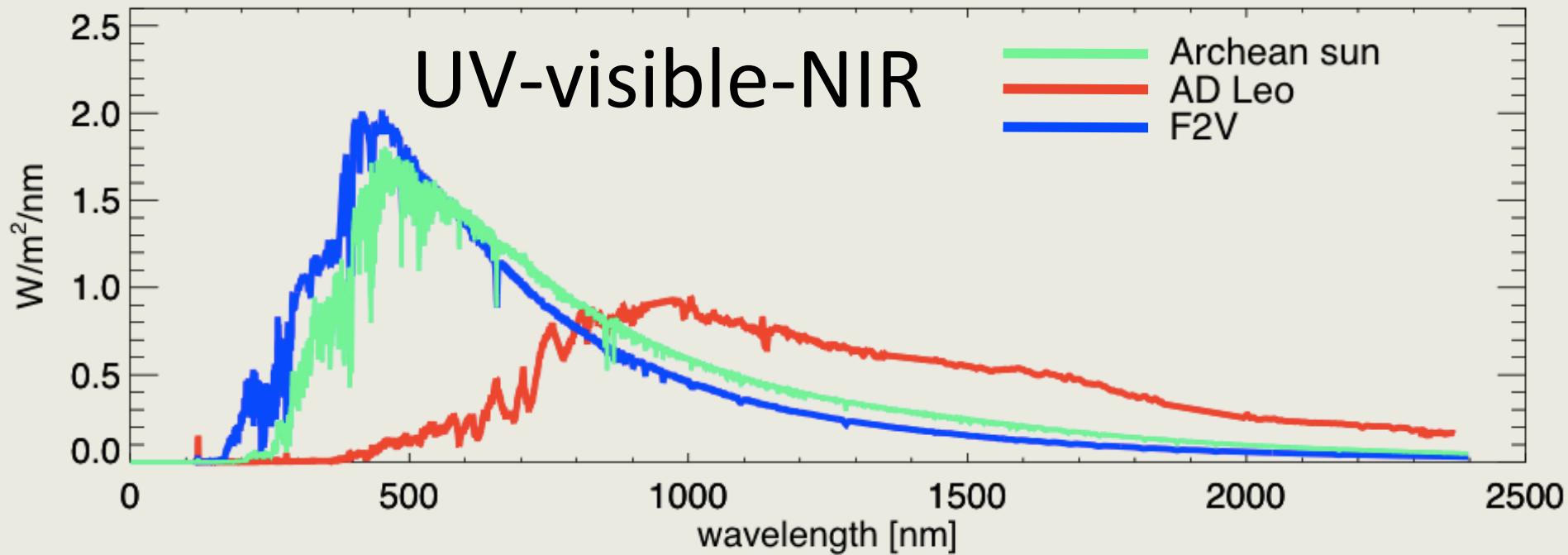
What about hazy planets
around other stars?

UV spectral energy distribution
matters...



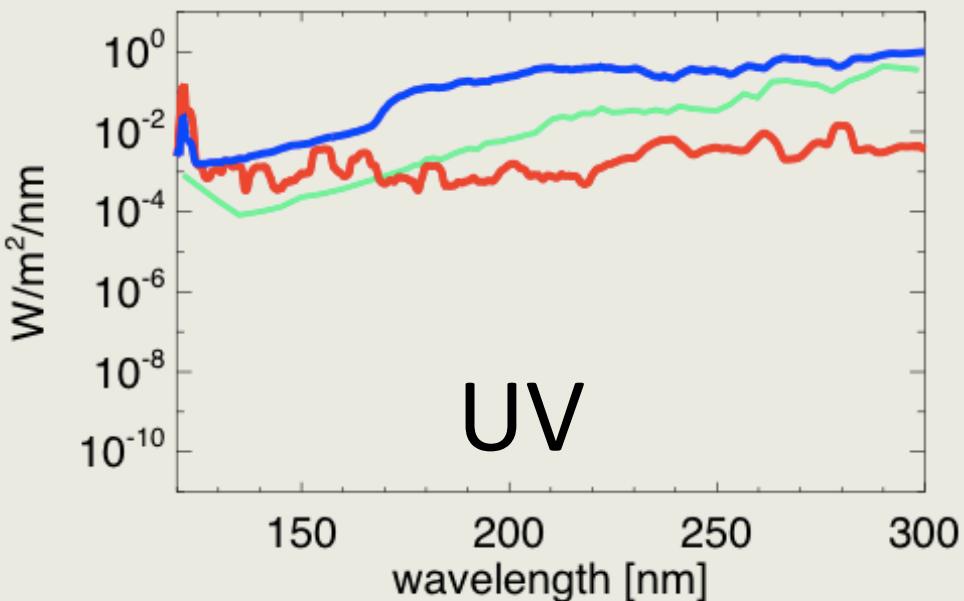
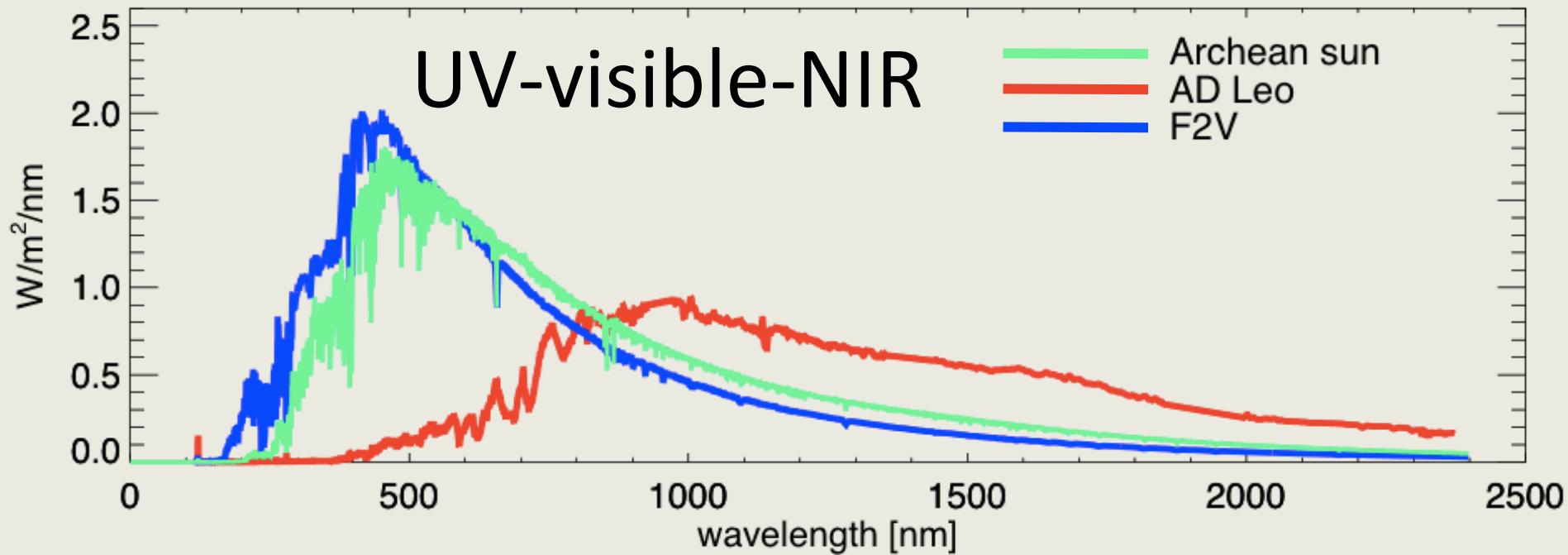


Archean sun
F2V
AD Leo



F2V star: oxygen radicals from H₂O and CO₂ photolysis destroy organic haze precursors

Result: no haze forms

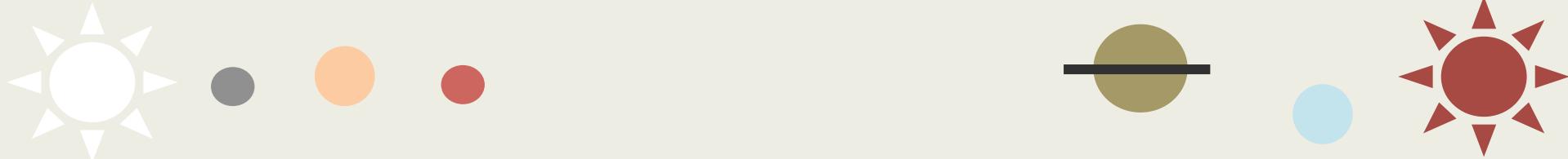


AD Leo: intermediate UV flux. Hazes form, but at higher CH_4/CO_2 ratio (0.7) than the sun ($\text{CH}_4/\text{CO}_2 \sim 0.2$)



take aways

- The Archean haze cools the planet but not necessarily below habitability. Haze may provide an alternative UV shield to ozone
- Organic hazes have strong, detectable spectral features at short and MIR wavelengths
- For earthlike planets, organic haze = biosignature?
- The spectrum of the host star can strongly affect haze production



Thank you!

Danke!