

The Effect of CO₂ Ice Cloud Condensation on the Habitable Zone

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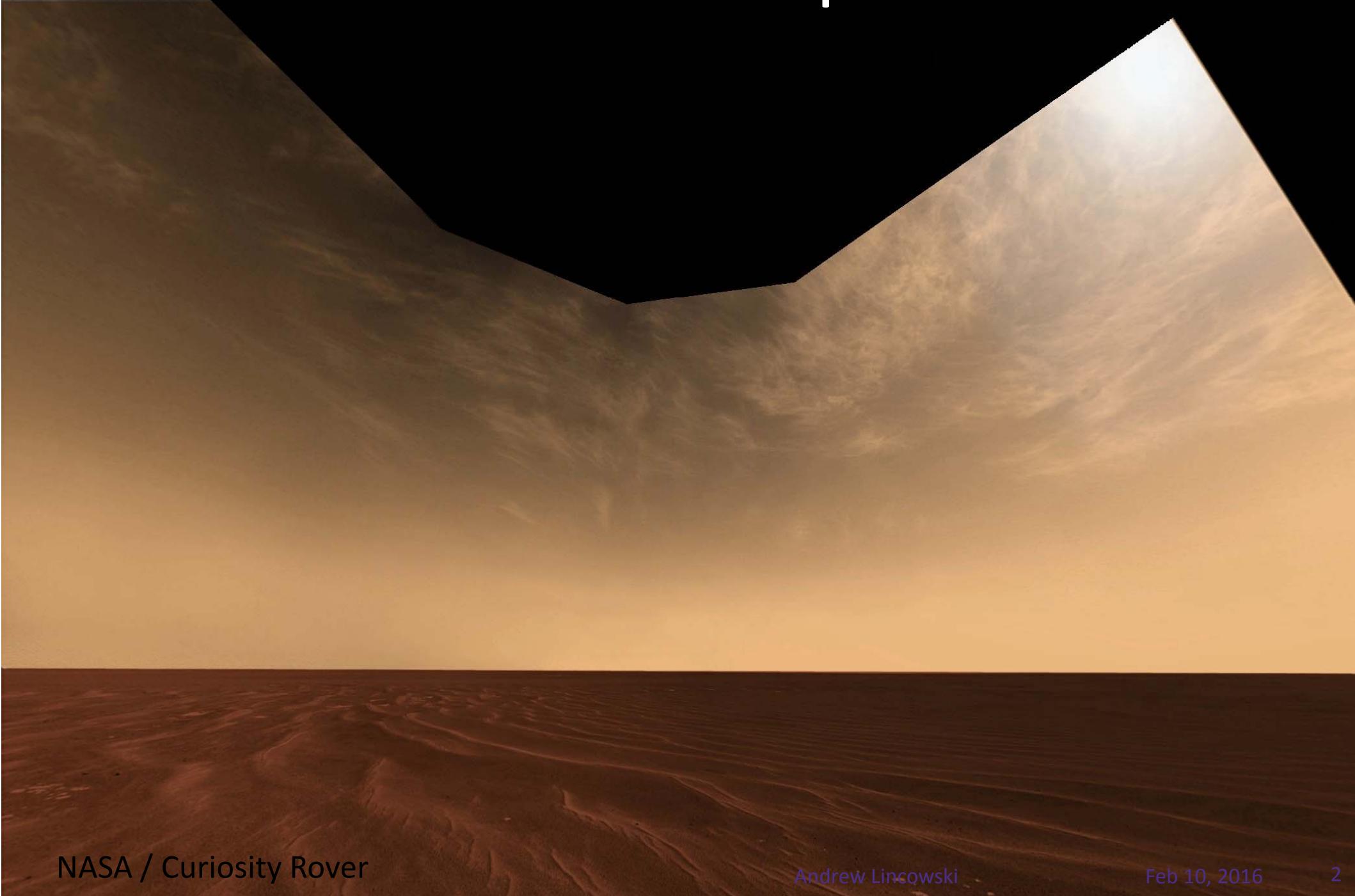
David Crisp, NASA-JPL/CalTech

February 10, 2016

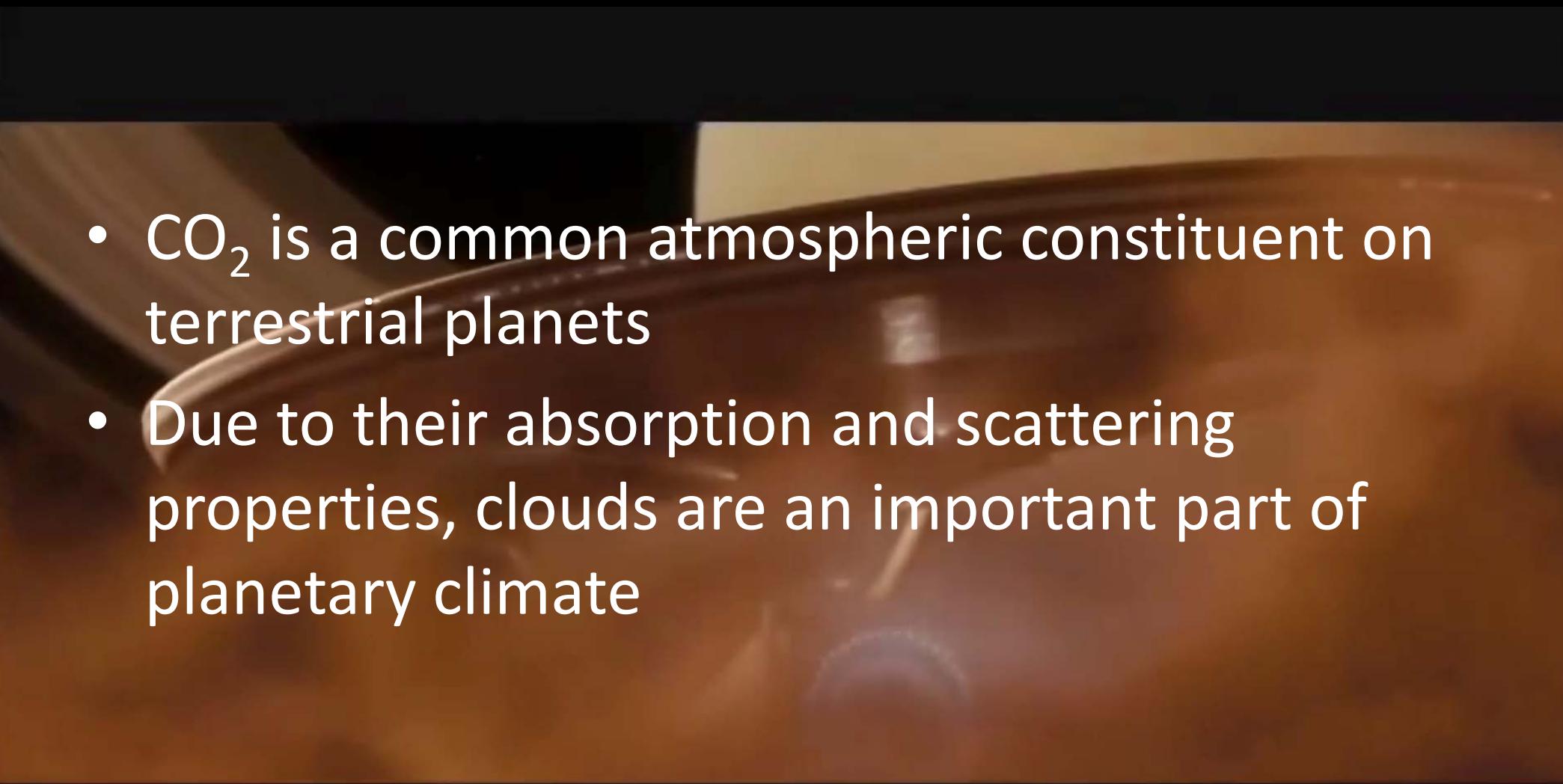
Astrophysics of Planetary Habitability

Vienna, Austria

Clouds are ubiquitous



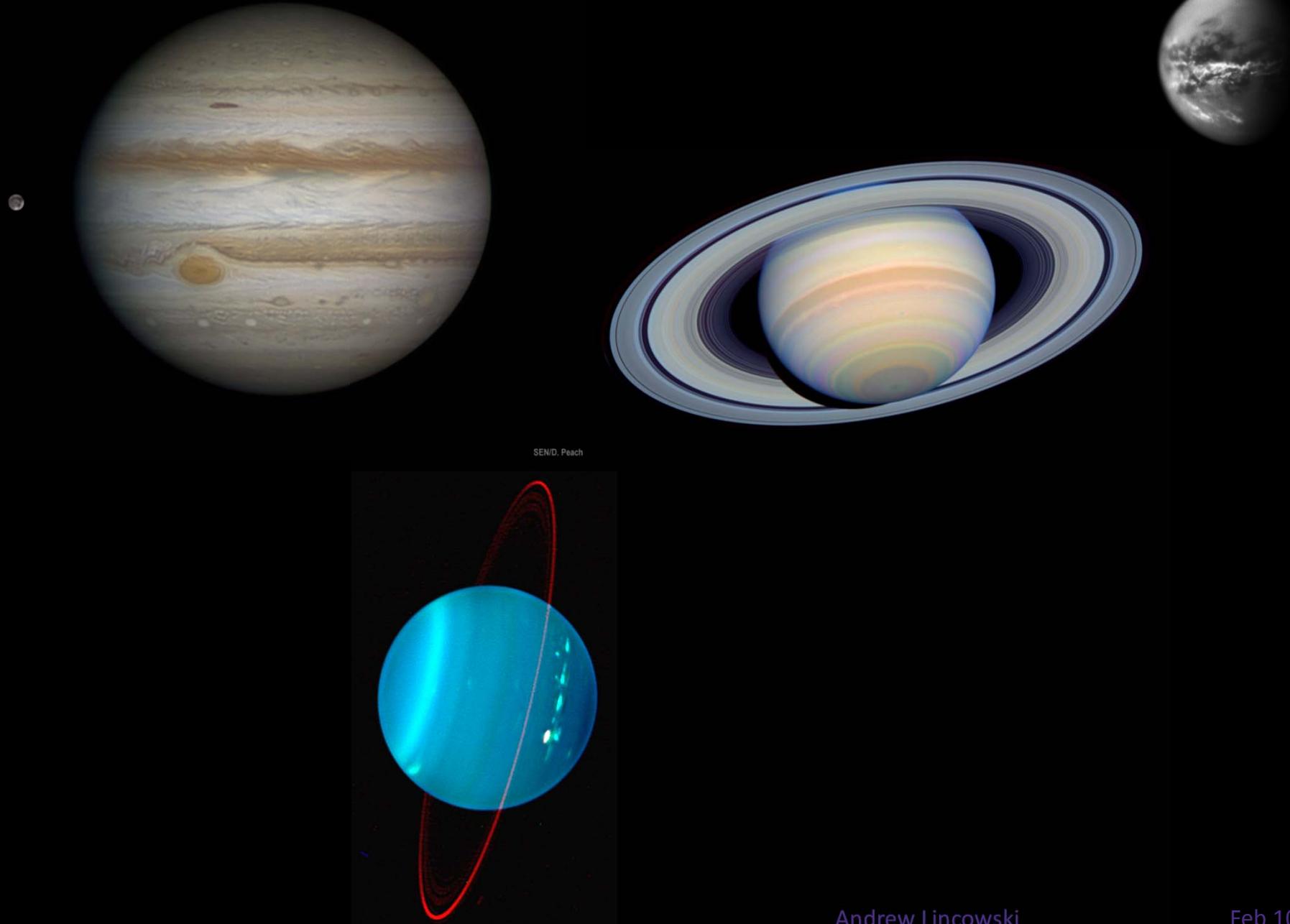
Clouds are ubiquitous



- CO₂ is a common atmospheric constituent on terrestrial planets
- Due to their absorption and scattering properties, clouds are an important part of planetary climate

Clouds are ubiquitous

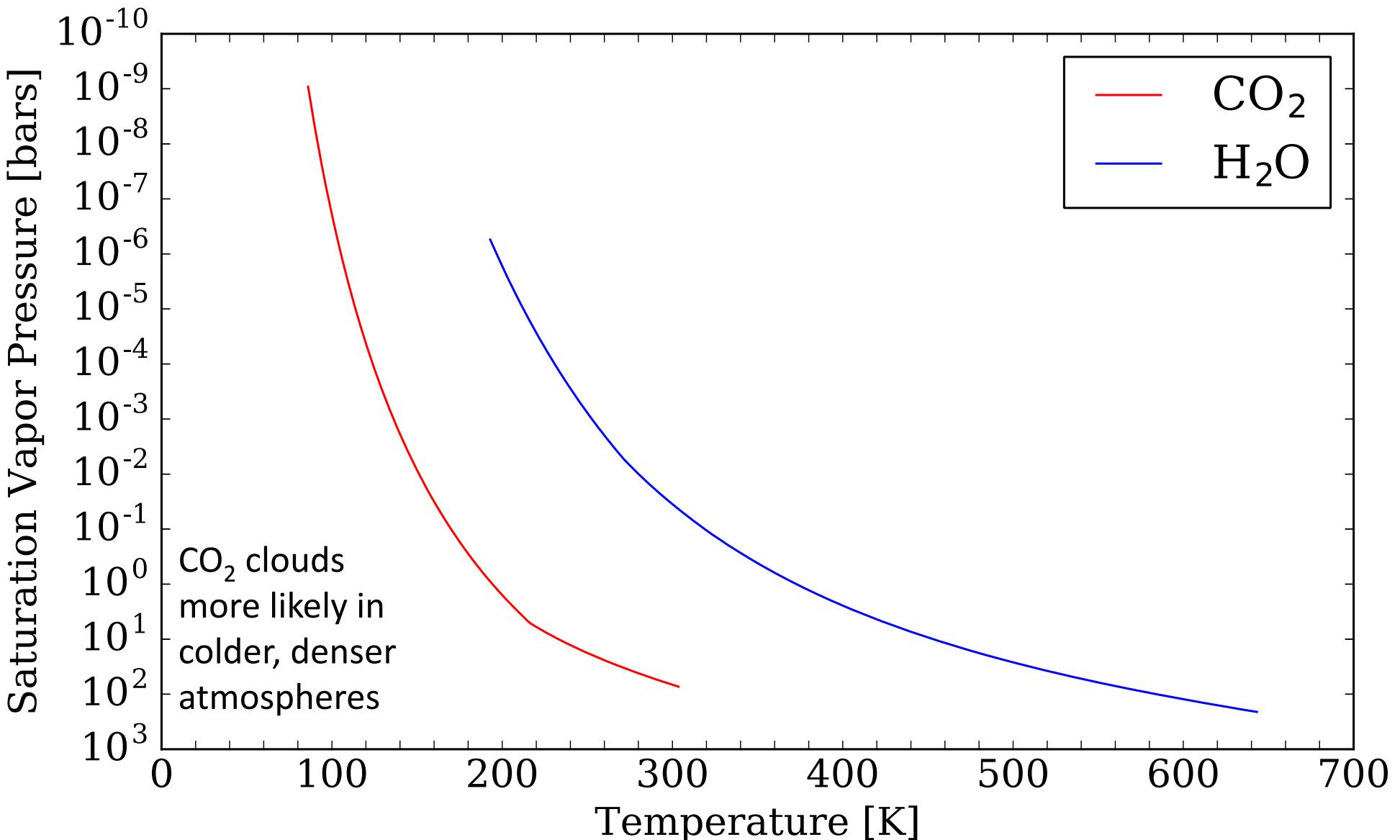
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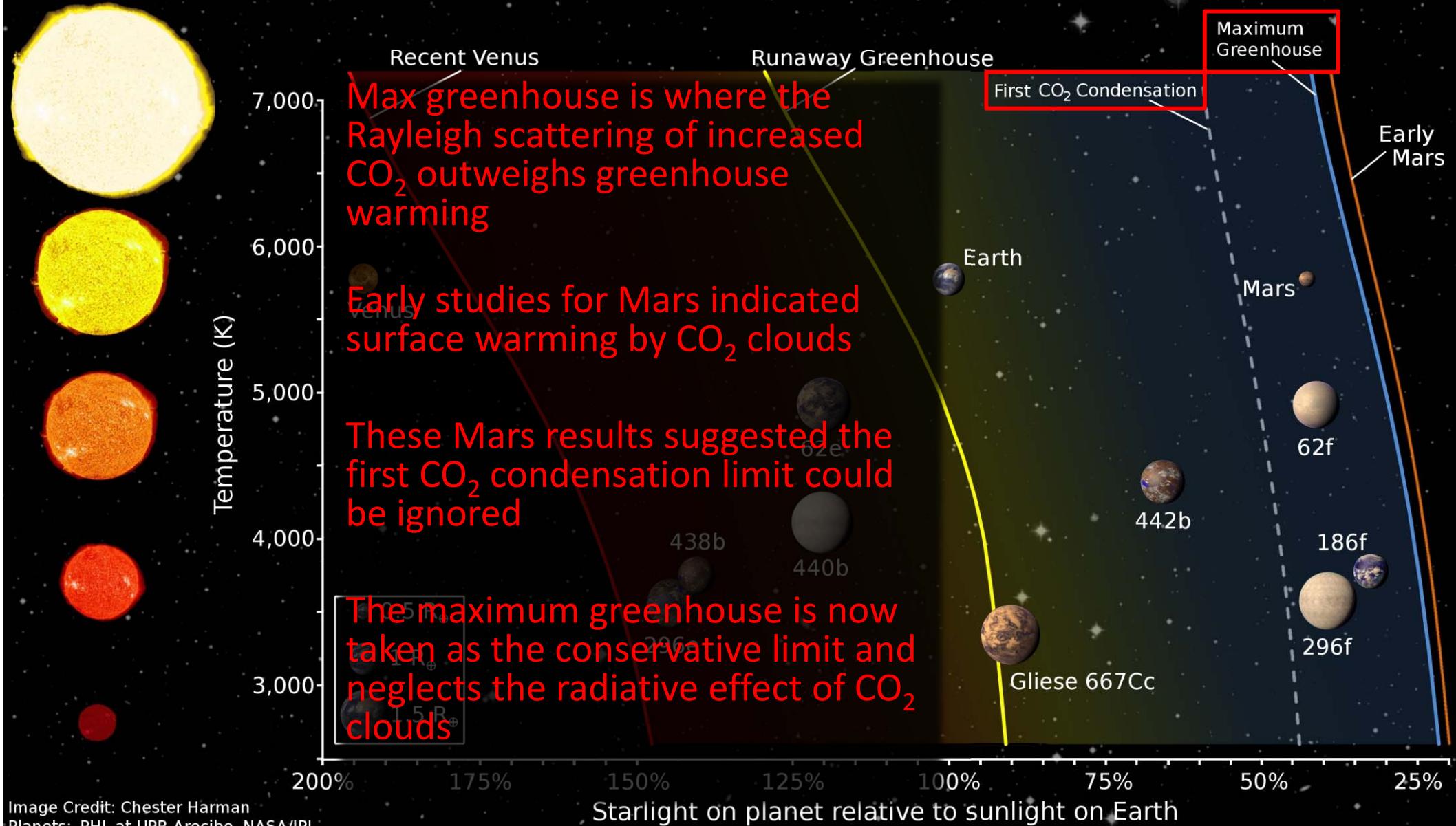
Clouds are ubiquitous

- CO₂ is a common atmospheric constituent on terrestrial planets
- Whether made of CO₂ or something else, clouds are an important part of planetary atmospheres

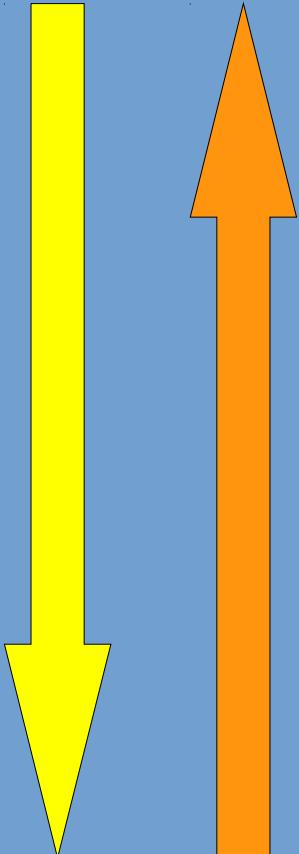
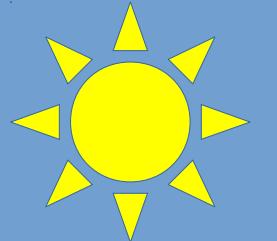
CO_2 condensation curve



Defining the Outer Habitable Zone (OHZ) Limit

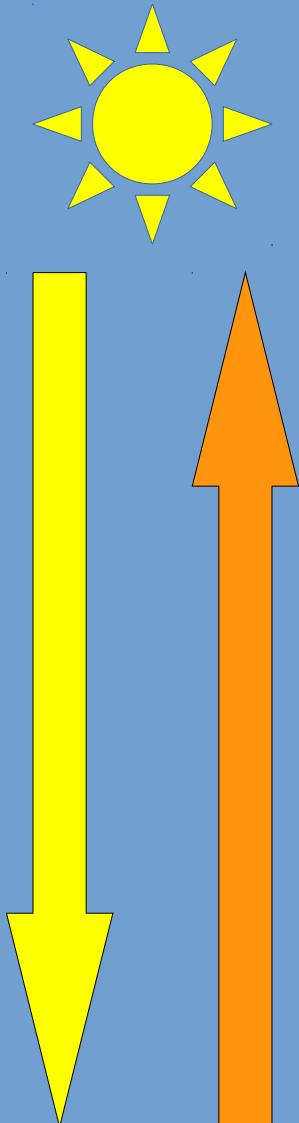


clear sky

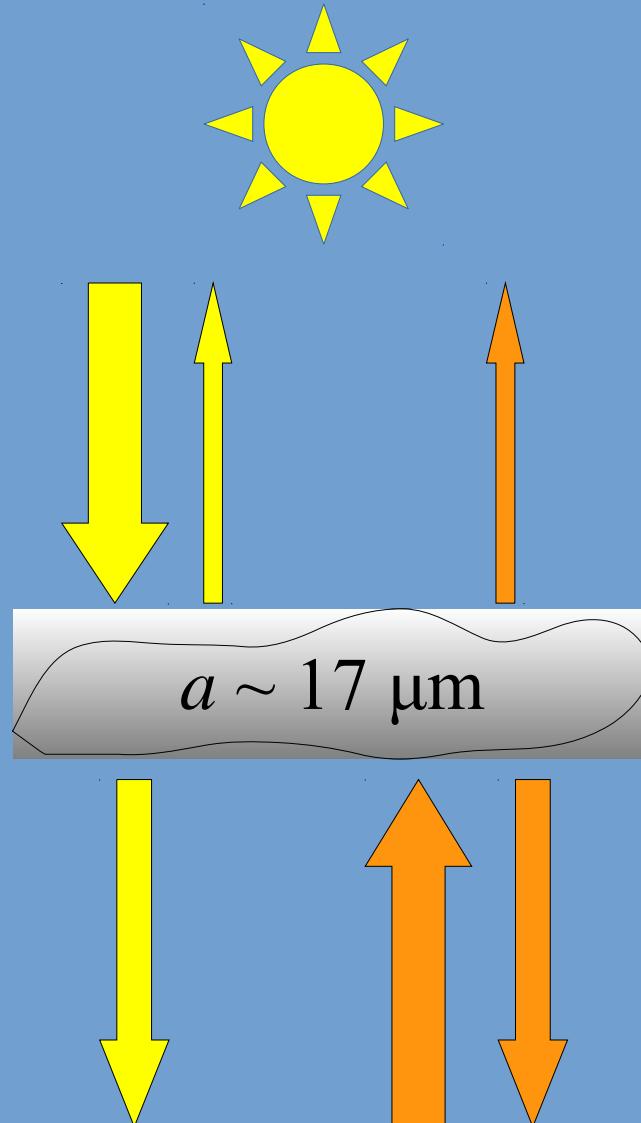


Why would a CO₂ cloud be warming?

clear sky

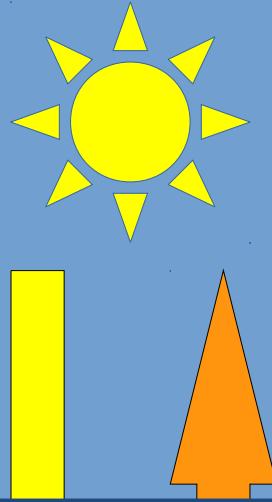


warming

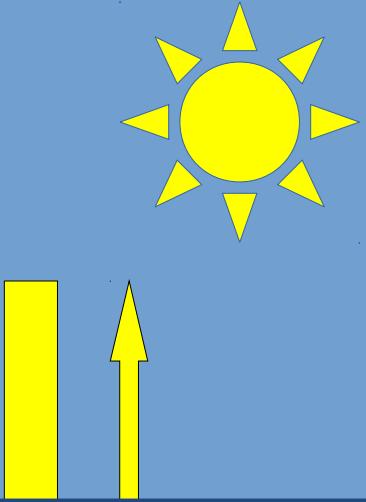


melting snow

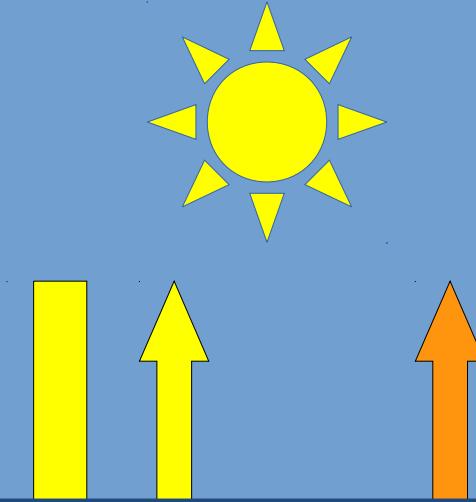
clear sky



warming



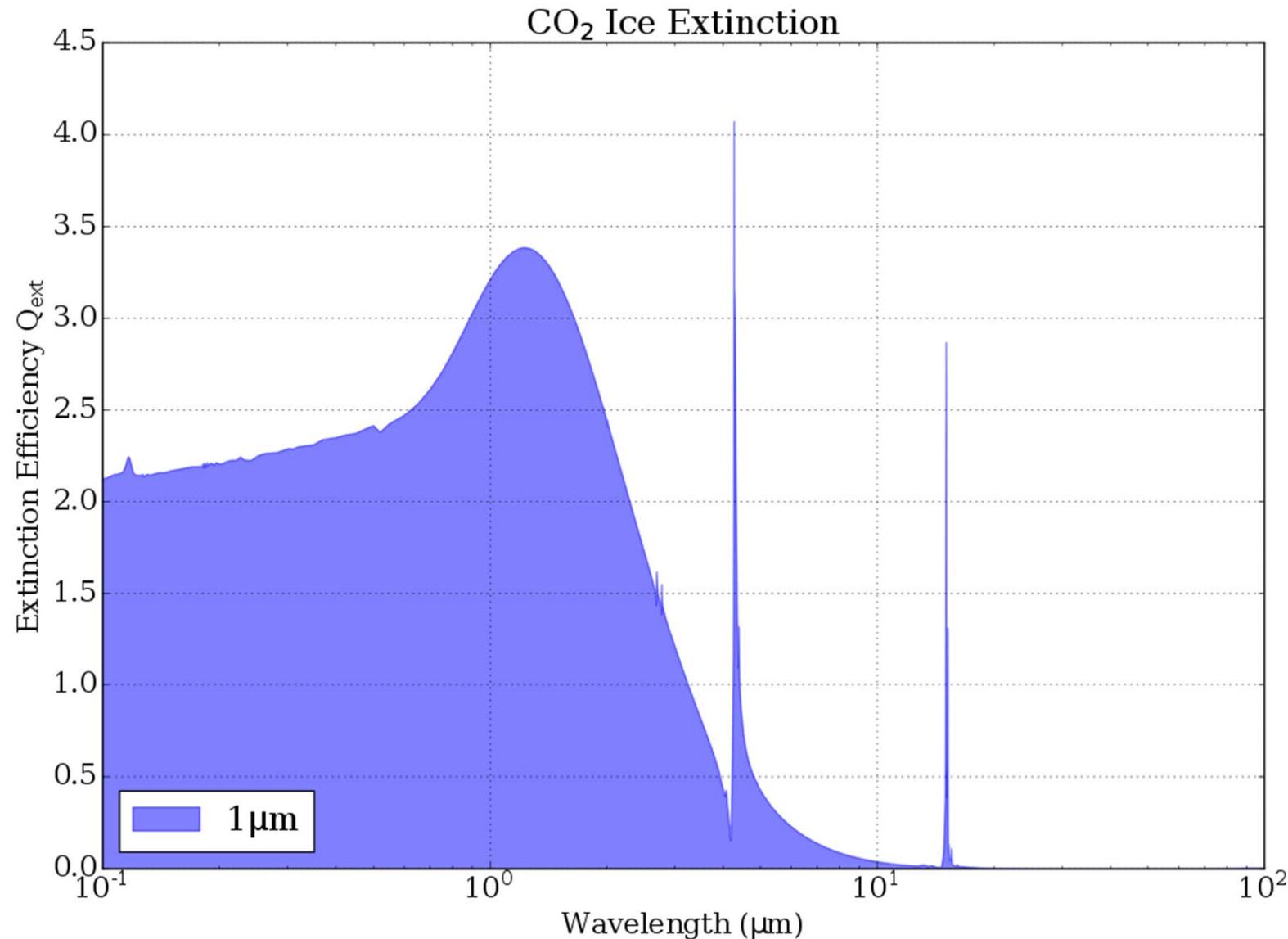
cooling



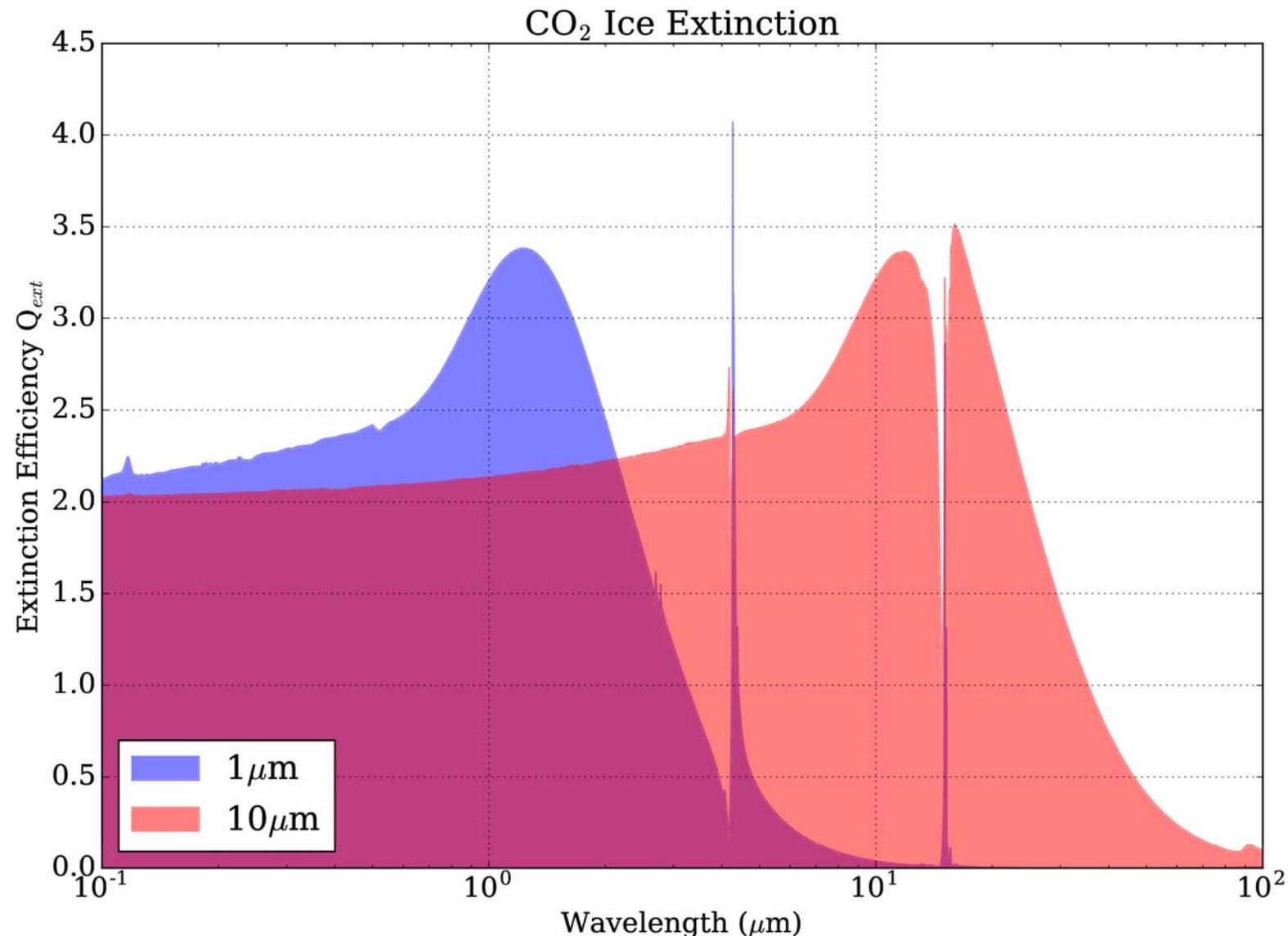
Whether a cloud warms or cools
depends on its wavelength-dependent
scattering properties

melting snow

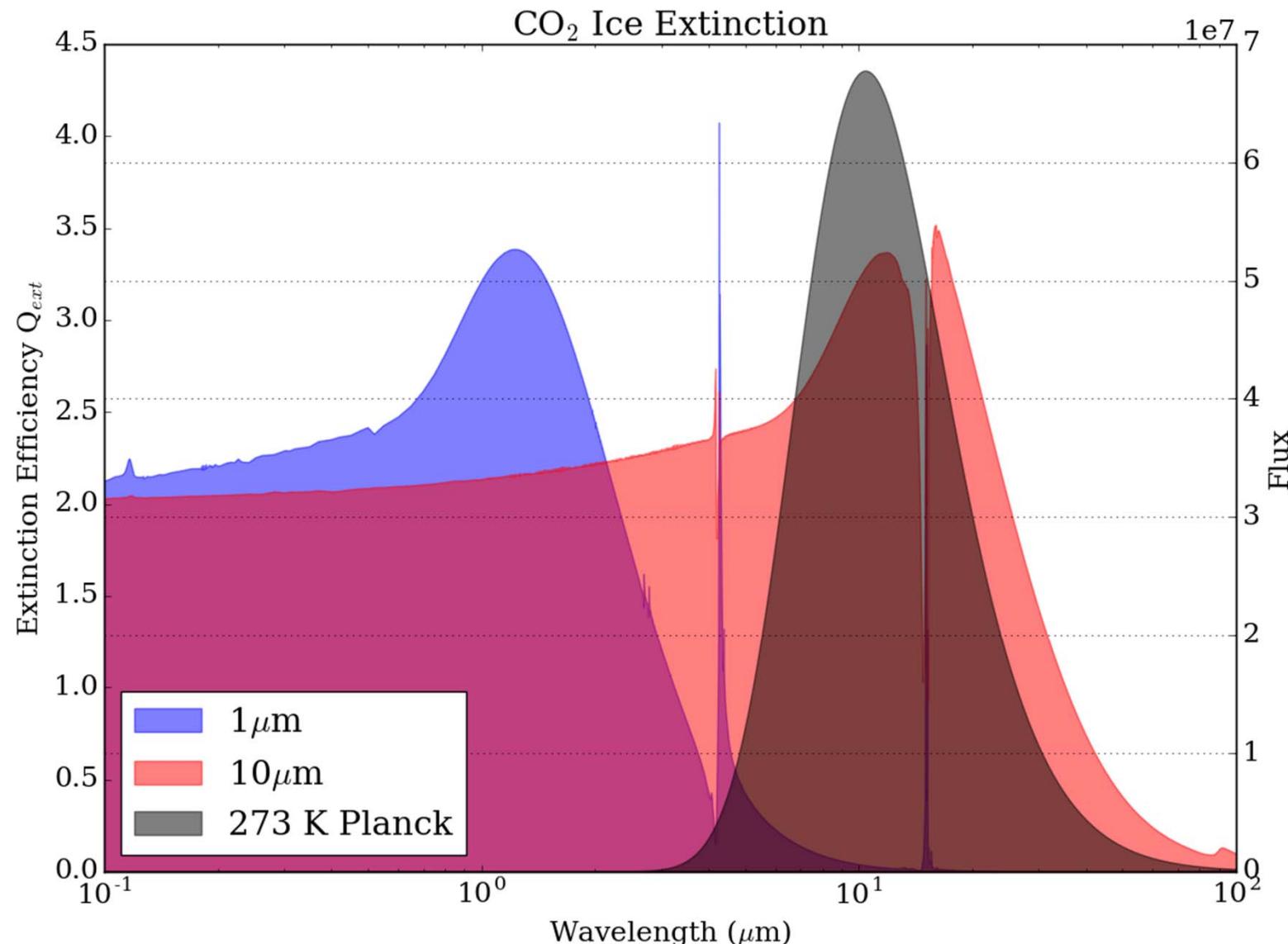
Scattering properties depend on the interplay between wavelength and particle size



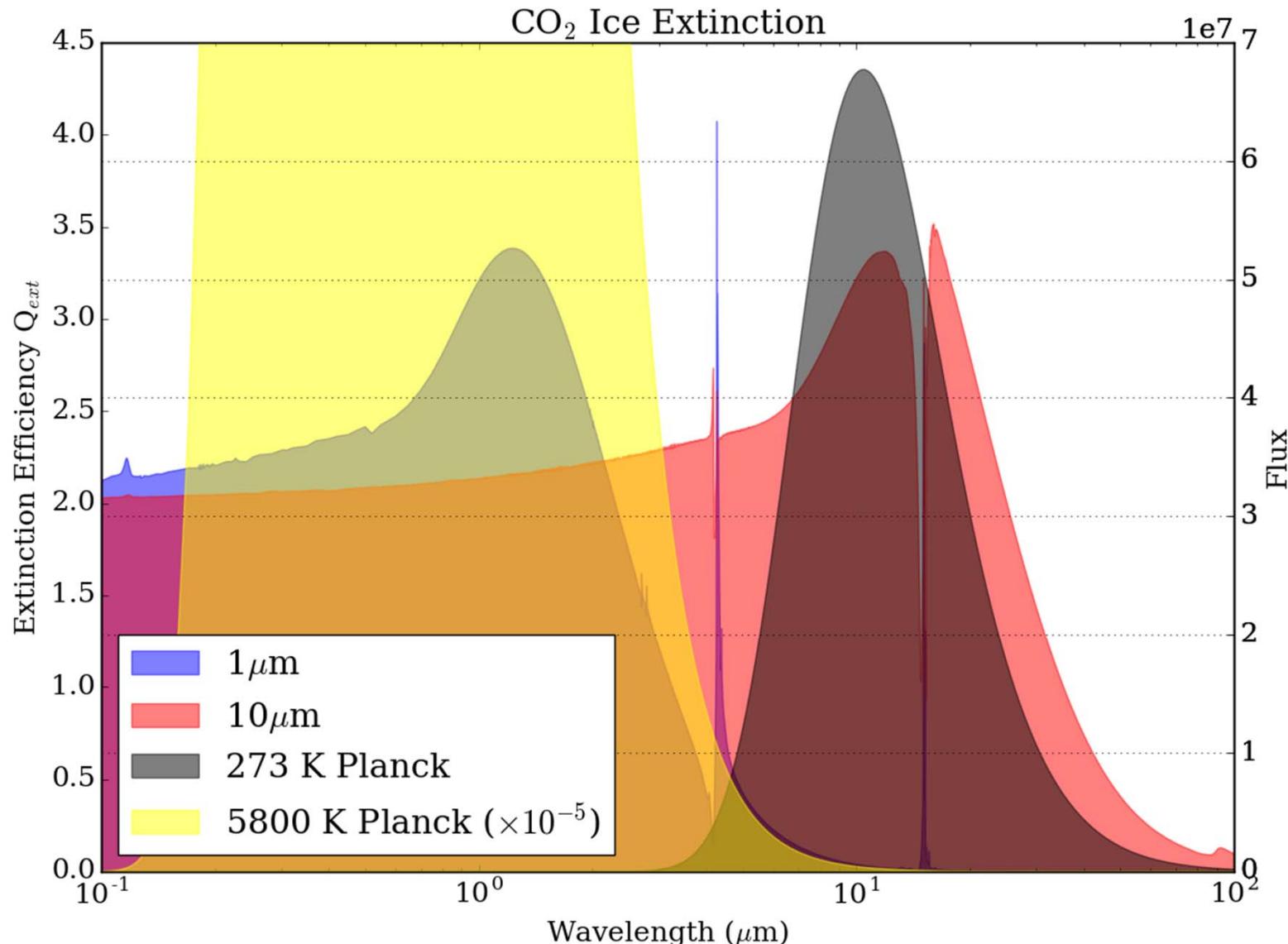
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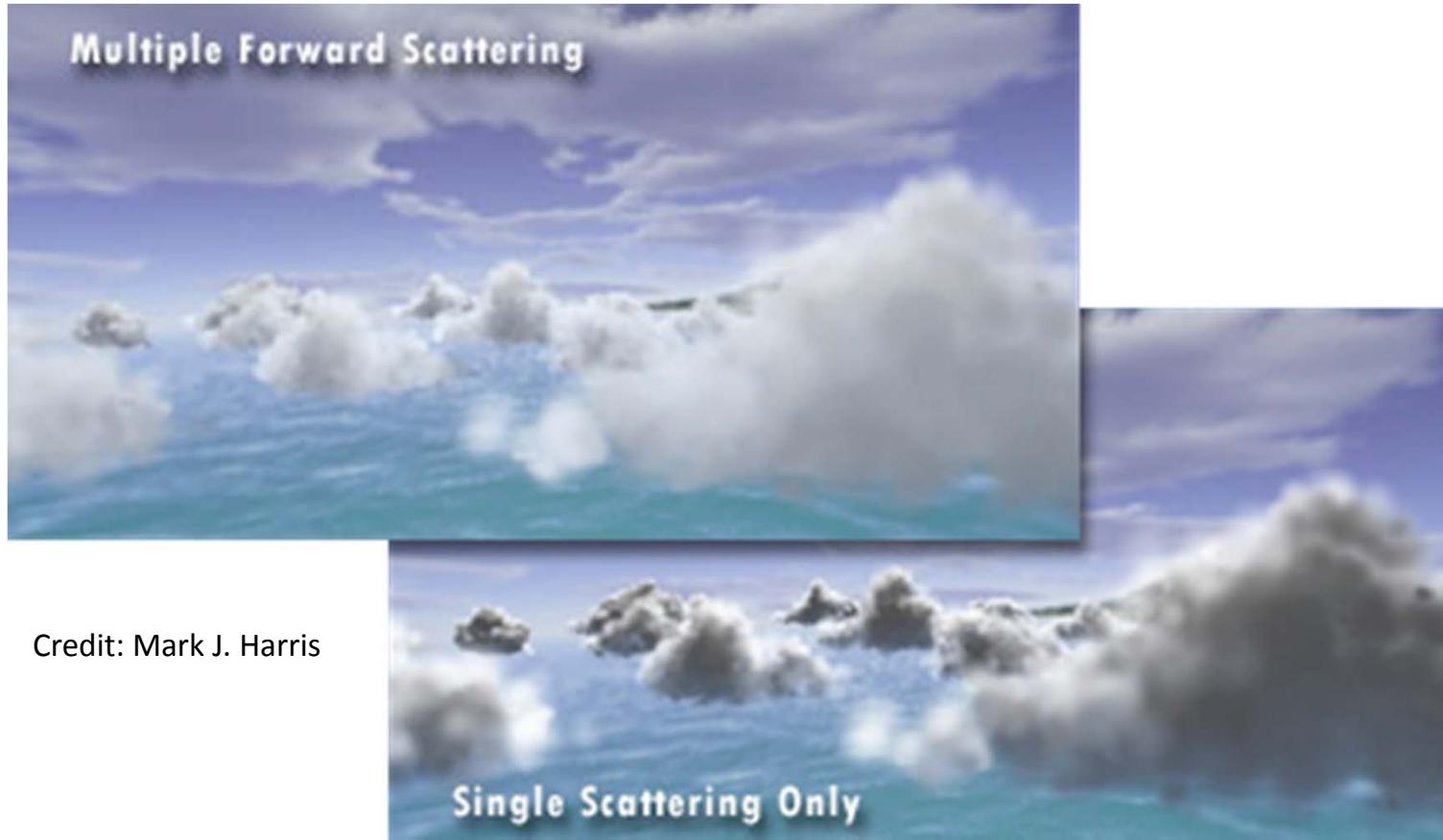
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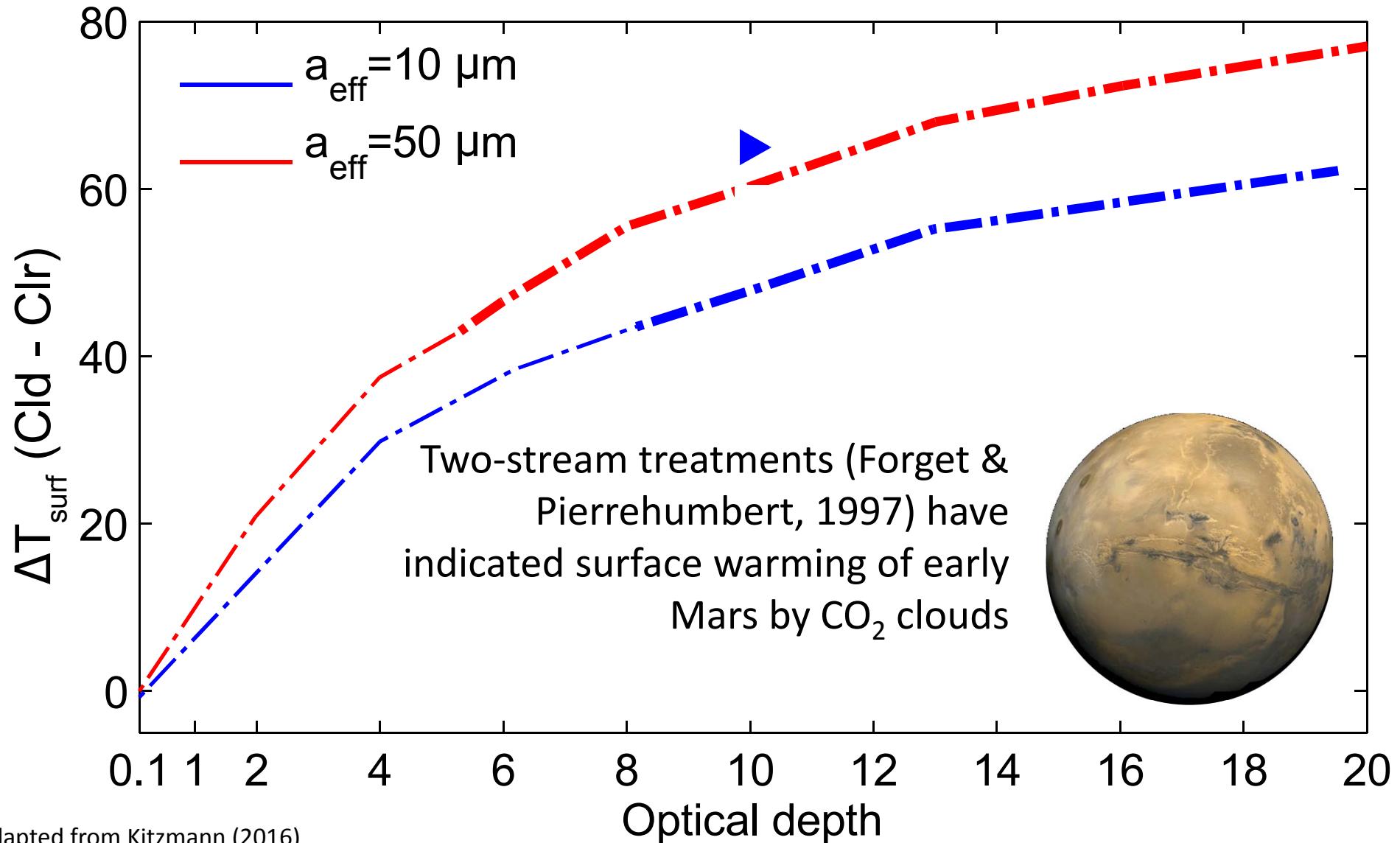


Current standard for OHZ cannot compute cloud scattering



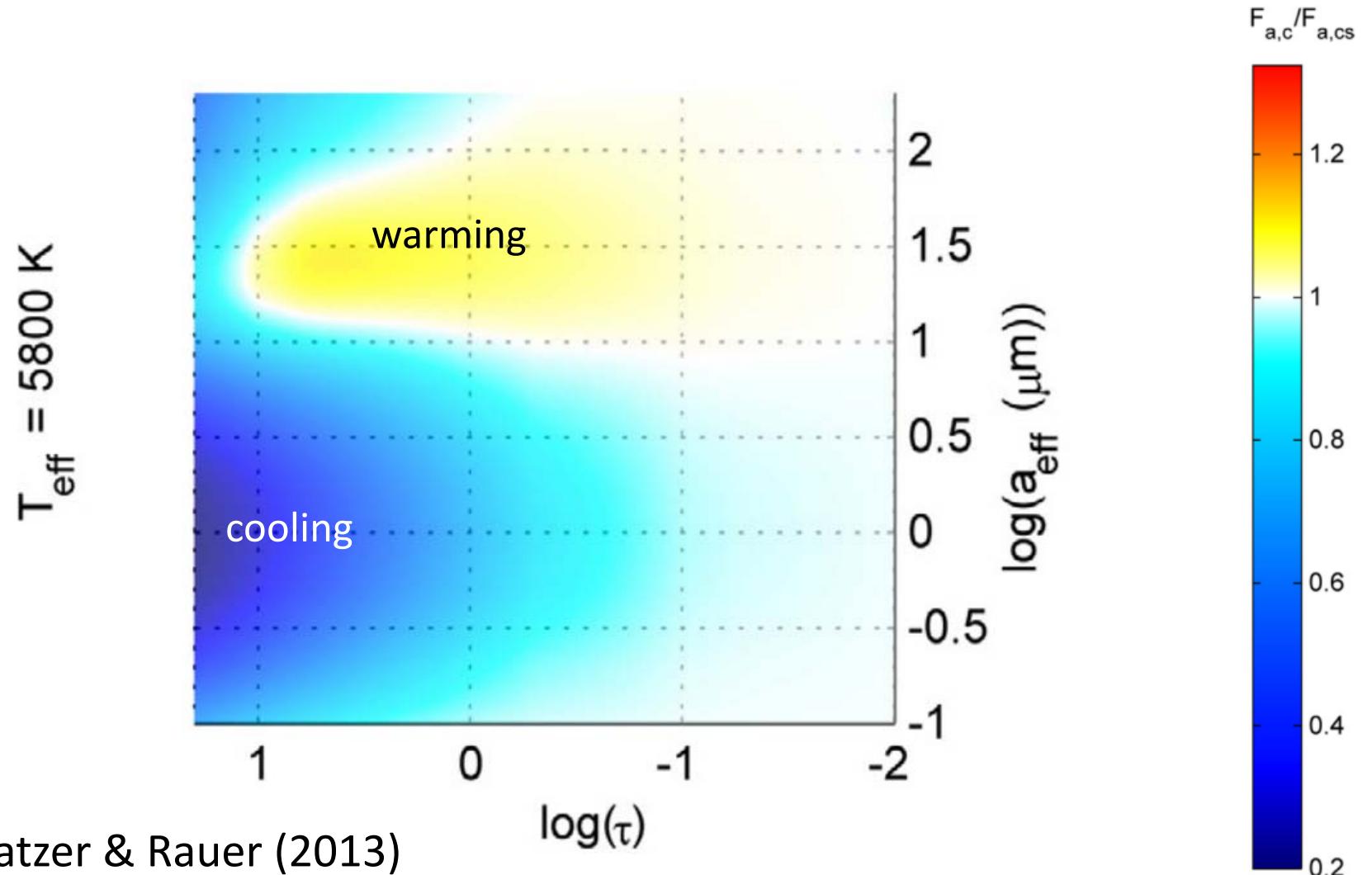
Two-stream models over-estimate cloud absorption and under-estimate scattering

Modeling CO₂ Clouds and Climate



Adapted from Kitzmann (2016)

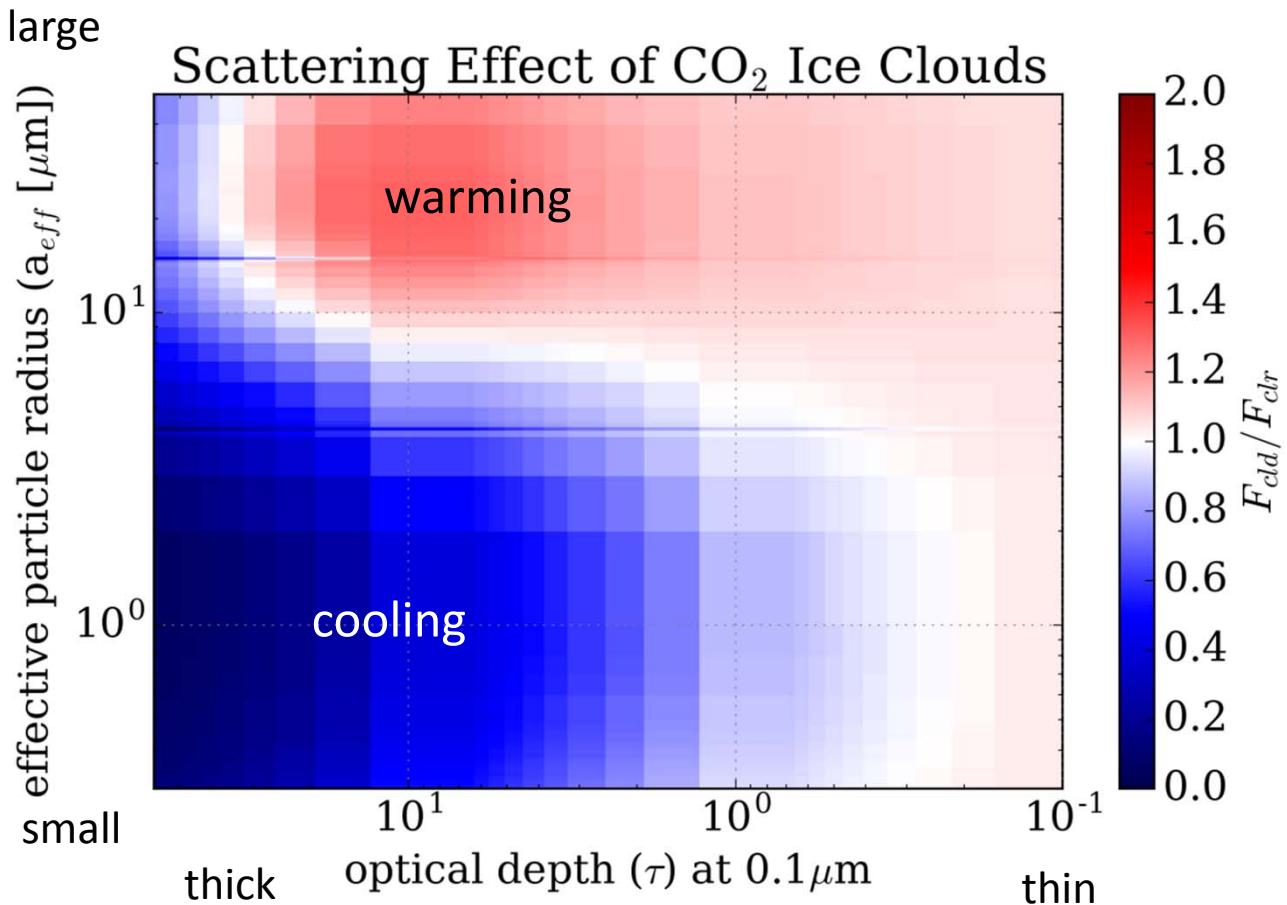
Multi-stream radiative transfer shows clouds may be warming or cooling



Colors represent the ratio of flux trapped in the lower atmosphere compared to a clear sky

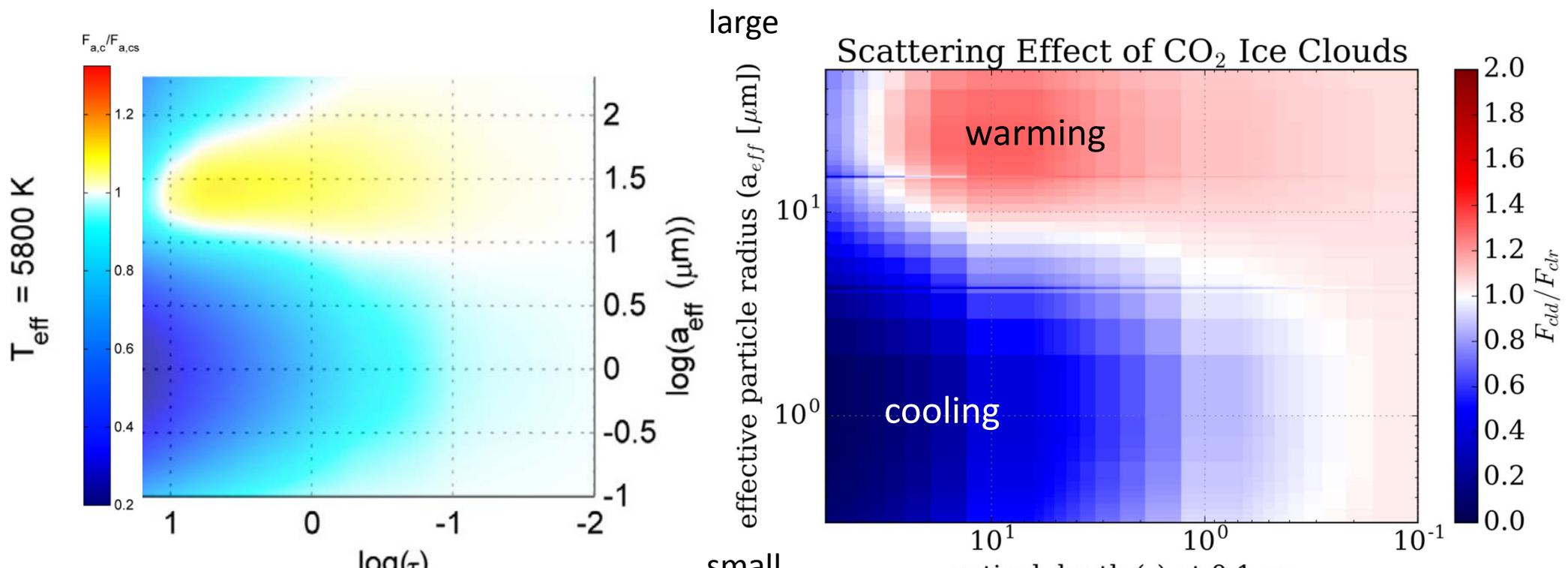
CO₂ ice cloud effects in a model atmosphere

- SMART (Meadows & Crisp, 1996)
- Line-by-line
- Multi-stream
- Multiple scattering
- Terrestrial validations
- Vertically-resolved atmospheric layers (P,T,flux)
- Cloud in region of CO₂ condensation
- 2500+ runs in parameter space



Colors represent the ratio of flux trapped in the lower atmosphere compared to a clear sky

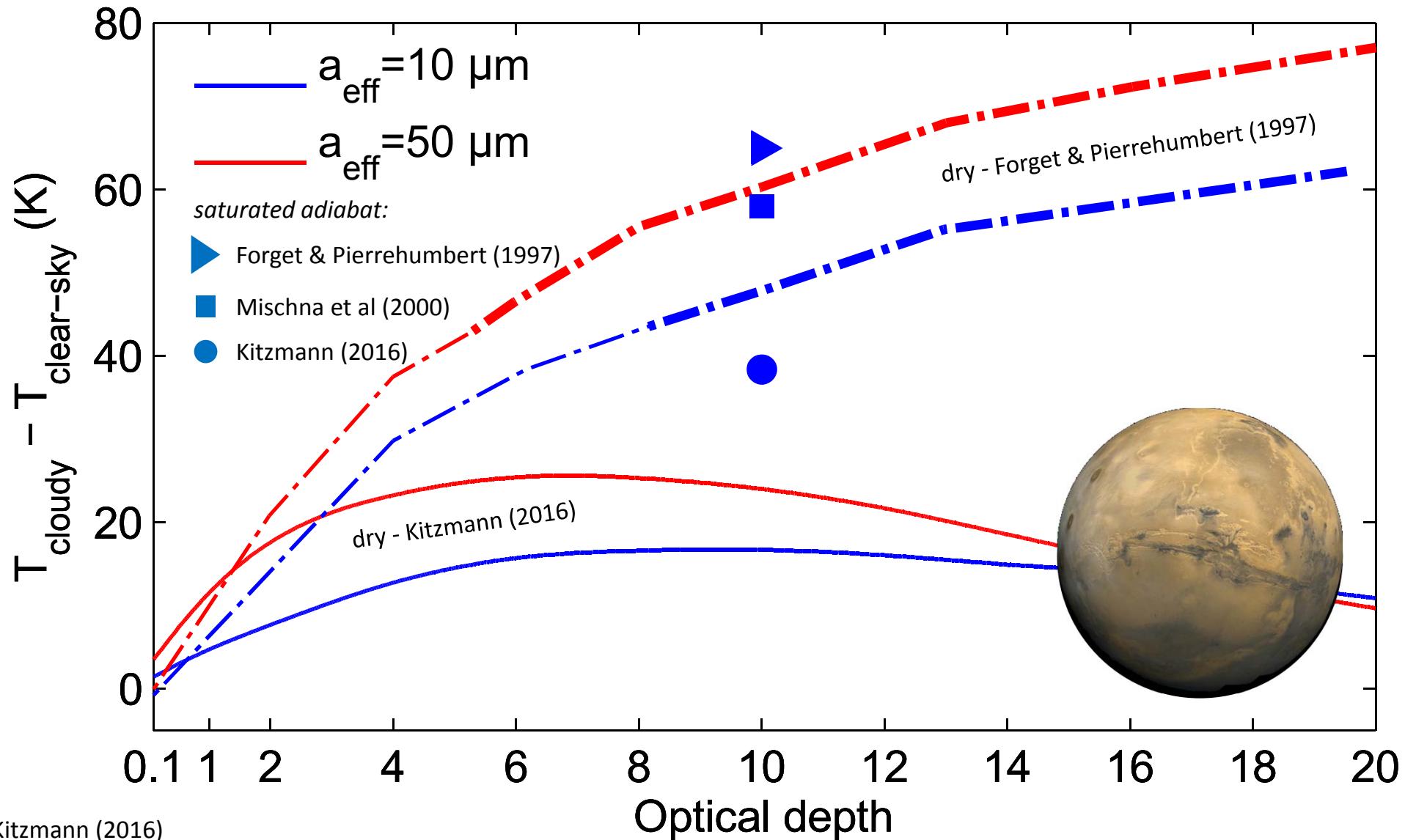
Kitzmann et al (2013) vs SMART



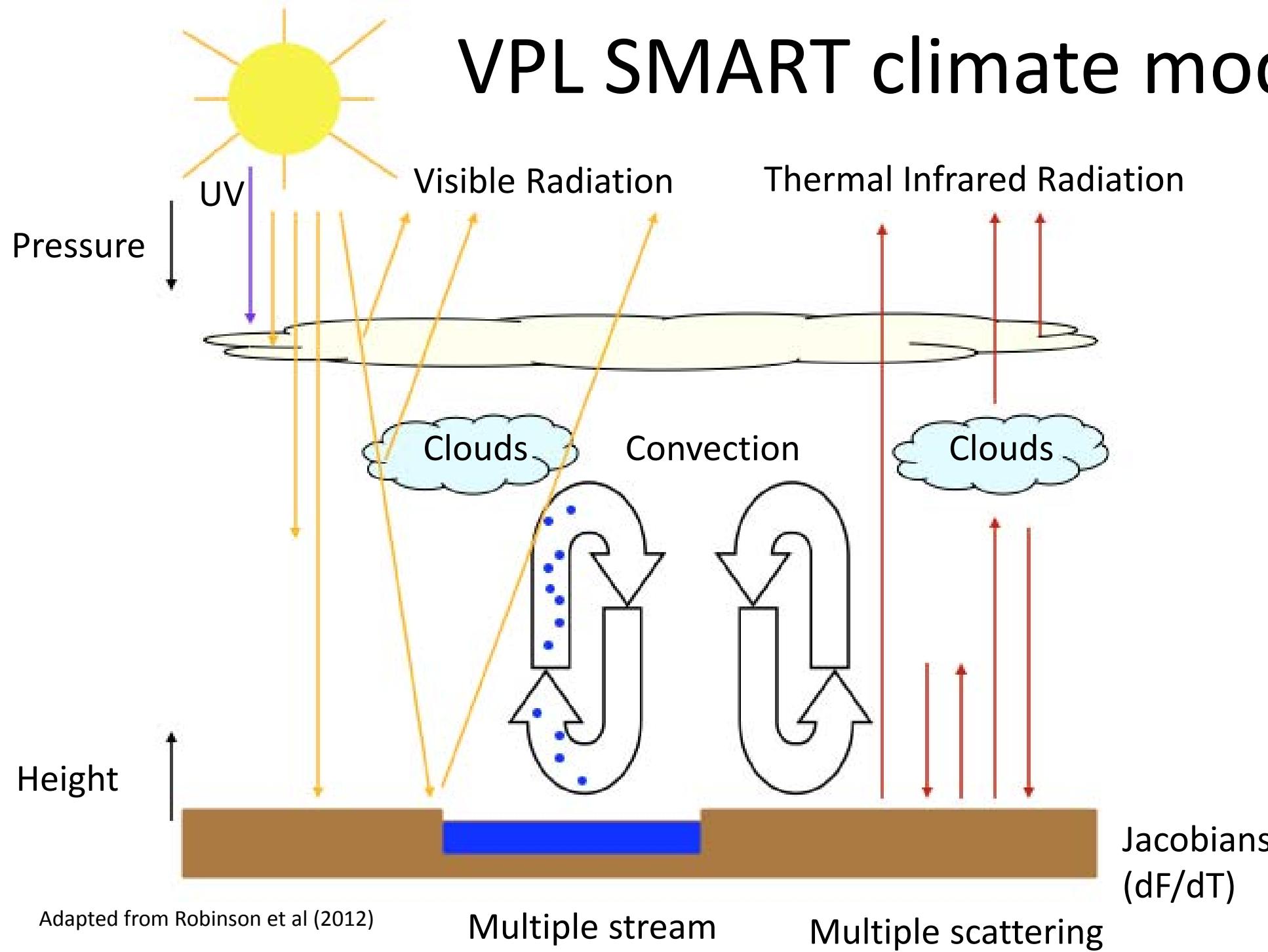
Kitzmann, Patzer & Rauer (2013)

We have verified Kitzmann et al's results

Better treatment of scattering reduces surface warming



VPL SMART climate model

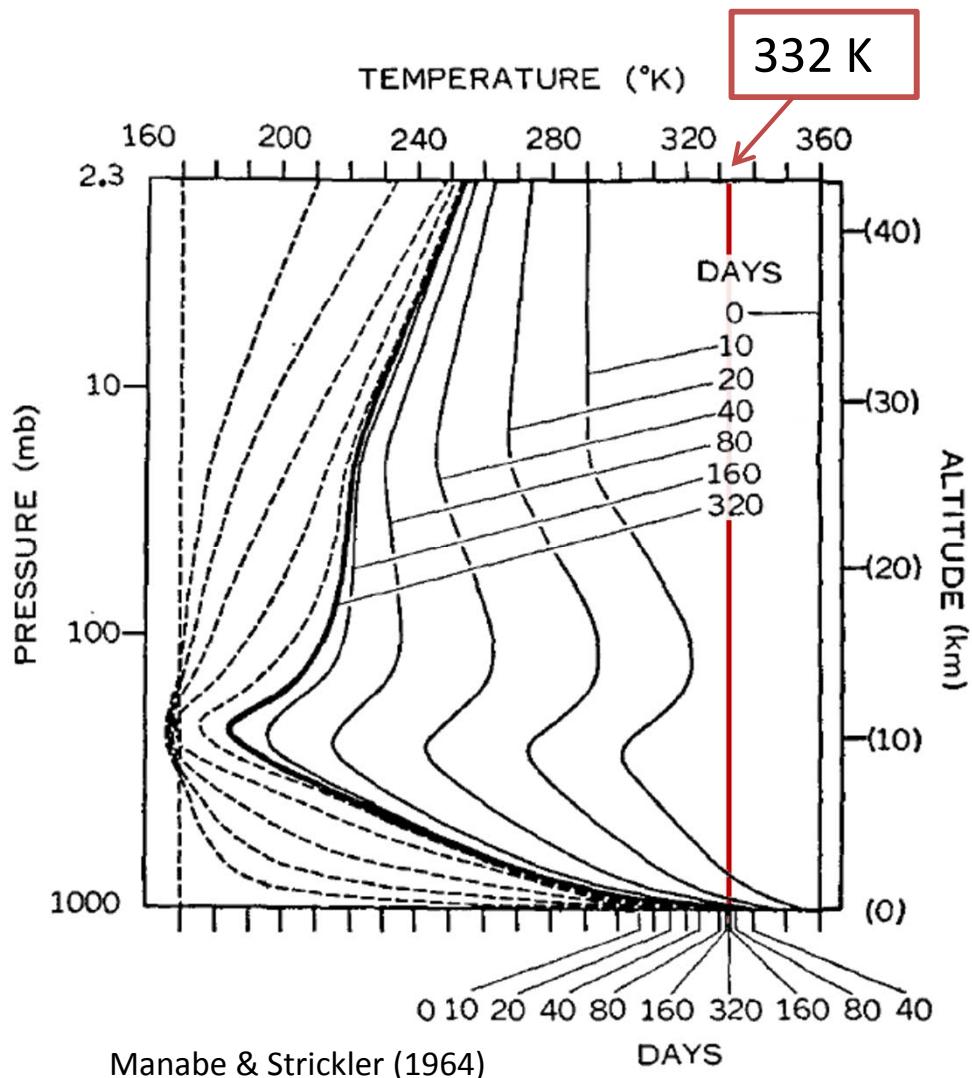


Adapted from Robinson et al (2012)

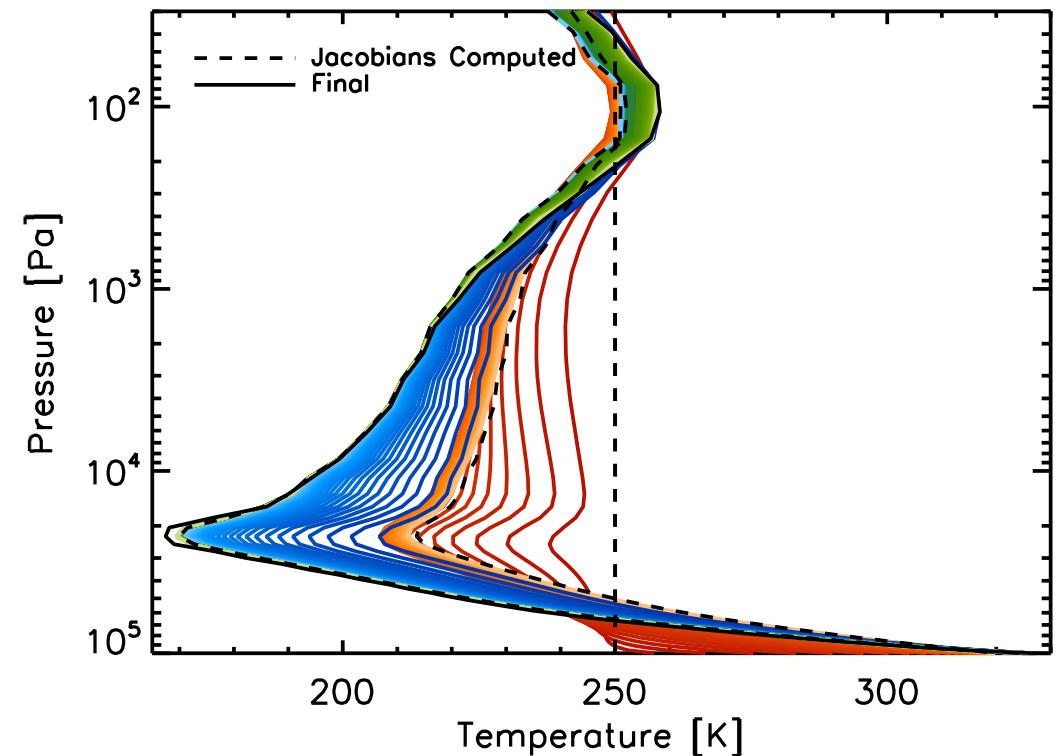
Multiple stream

Multiple scattering

SMART + Climate is validated for radiative-equilibrium Earth



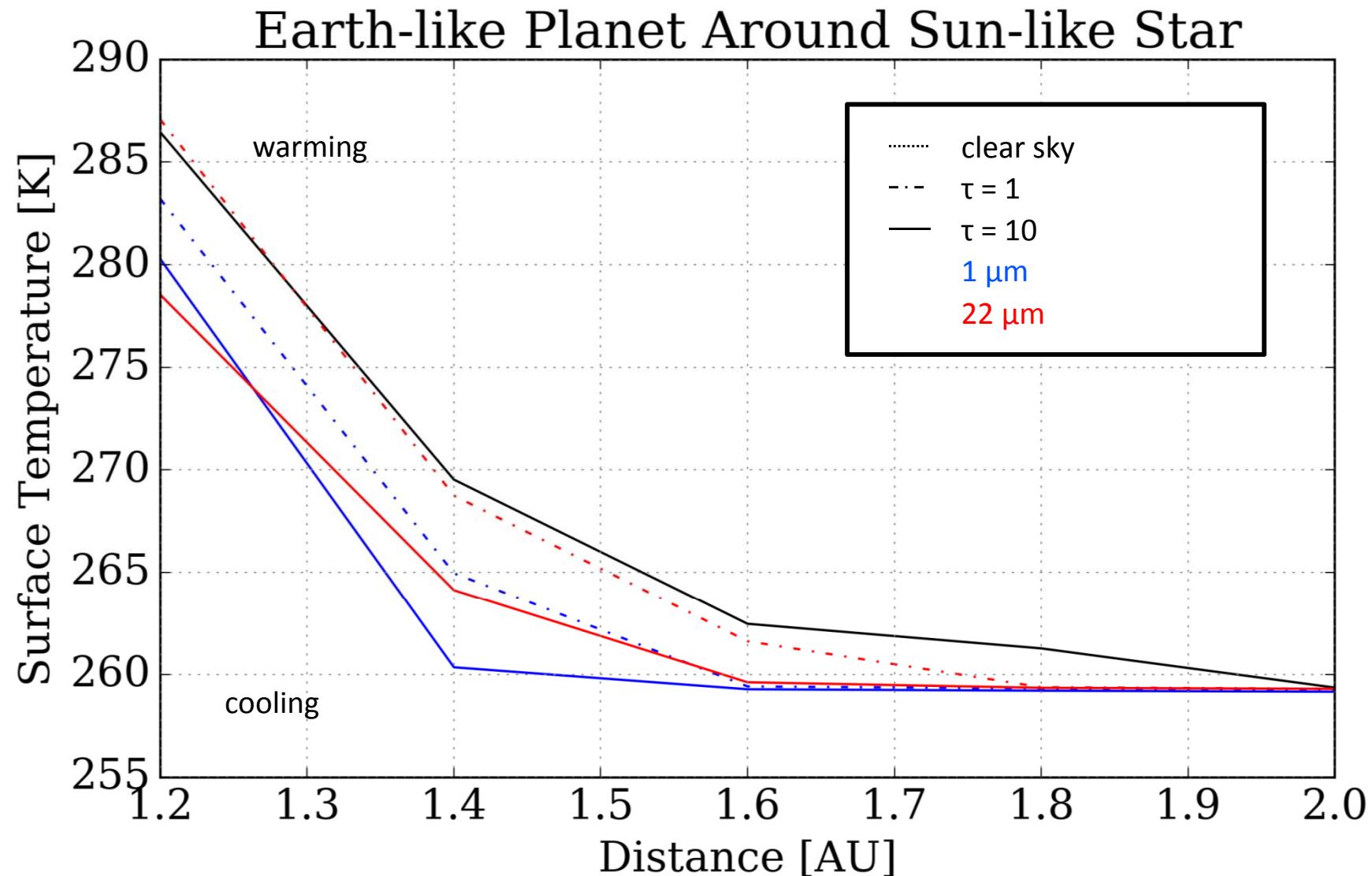
Manabe & Strickler (1964)



Credit: T. Robinson

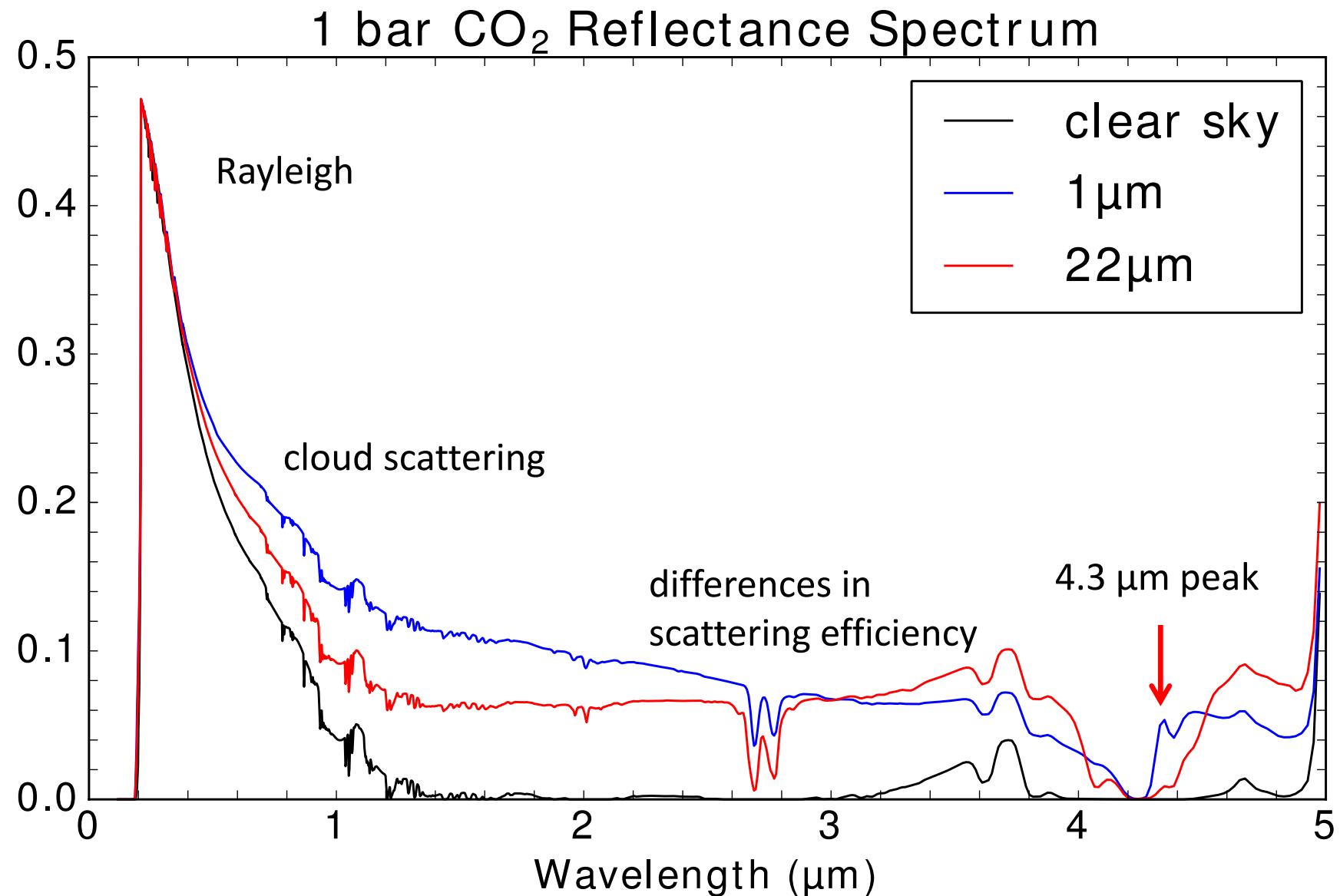
...for clear-sky mid-summer latitudes

Preliminary results



Surface temperatures stabilized but the upper atmosphere is still cooling, indicating the surface temperatures may drop further

Reflectance spectra indicate cloud scattering



Conclusions

- We have developed a new, sophisticated model for calculation of the OHZ limit
- OHZ limit may depend on planet and stellar properties (nature of CO₂ clouds and stellar SED interaction with CO₂ ice)
- When the full radiative effect of CO₂ clouds is included, the current OHZ limit may be too optimistic

Thank You

Acknowledgements:

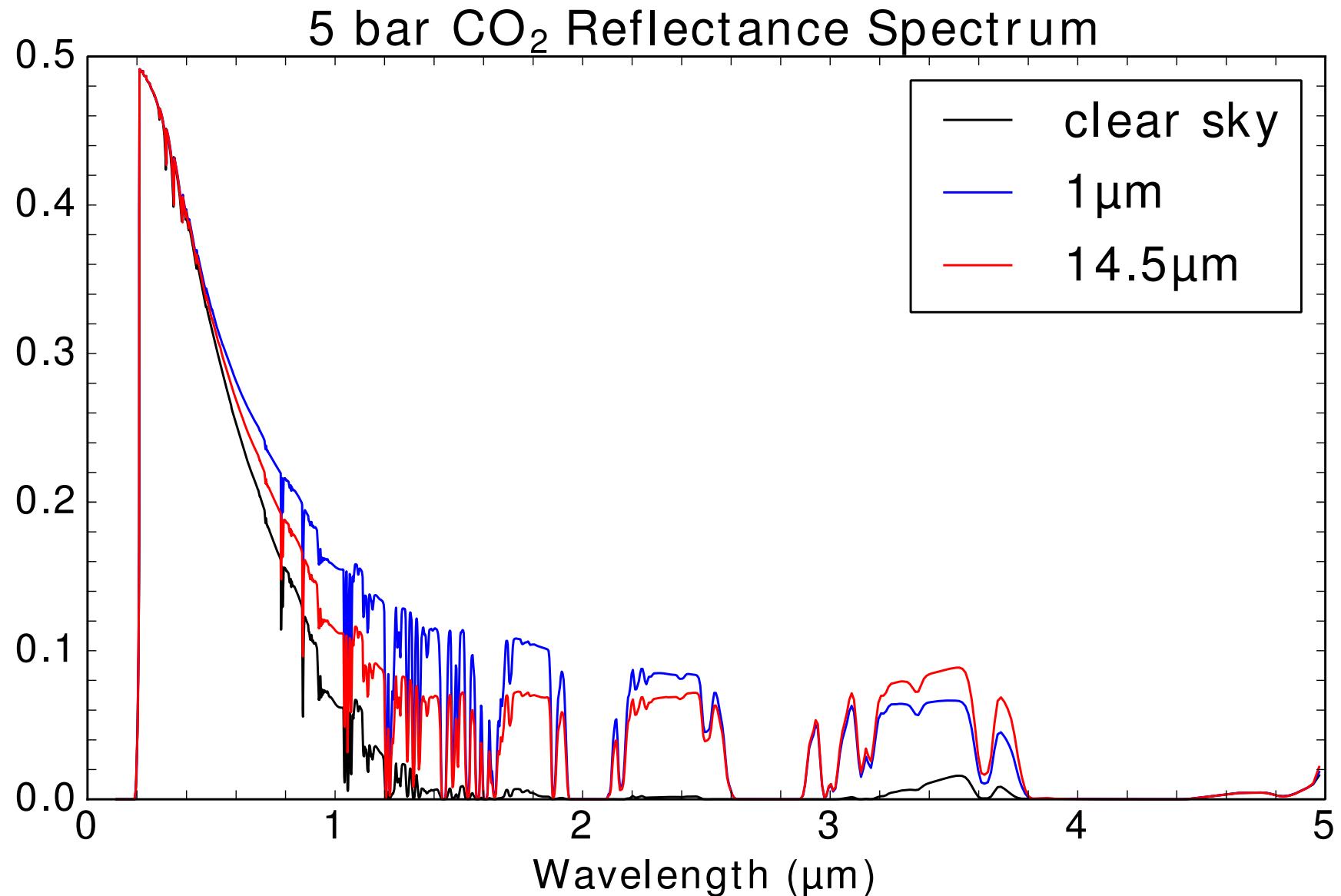
Vikki Meadows, advisor

Ty Robinson, climate model

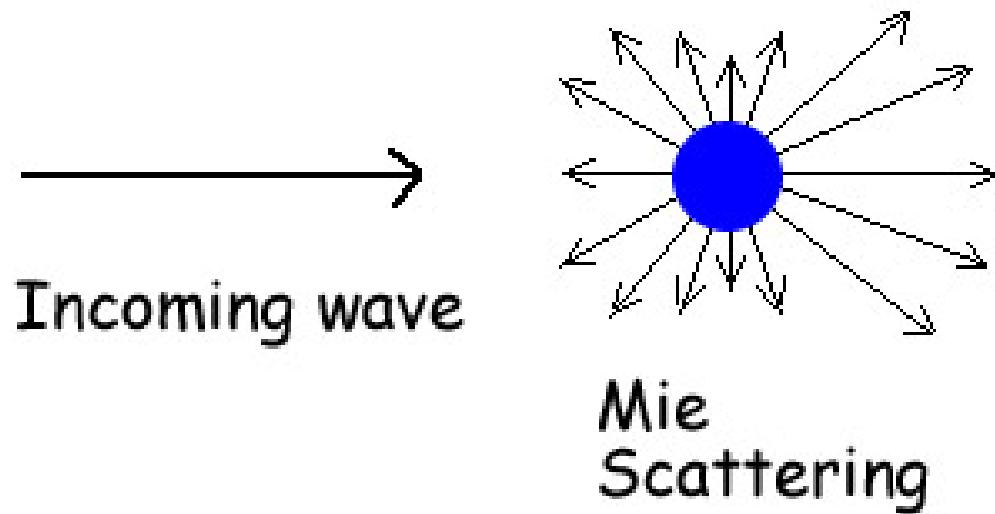
David Crisp, SMART

Astrophysics of Planetary Habitability
scientific organizing committee

Reflectance spectra indicate cloud scattering



Light scattering is angle-dependent



Two-stream models are named for the two angles used to calculate radiative transfer (including scattering), one angle for incoming radiation and one angle for outgoing radiation

Atmosphere Profile

