Recipe for a Habitable Planet

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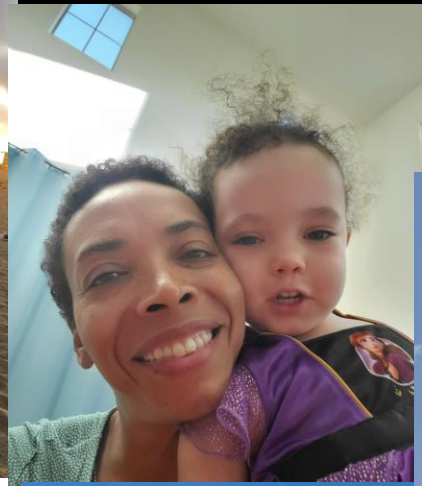
Shields Center for Exoplanet Climate and Interdisciplinary Education (SCECIE)
University of California, Irvine

A moment to pause…

Leading effectively during COVID-19

- **Employees Need Trust and Compassion: Be Present, Even When You're Distant**
- **Employees Need Stability: Prioritize Wellbeing Amid Disruption**
- **Employees Need Hope: Anchor to Your "True North"**

From “3 strategies for leading effectively during COVID-19” (https://www.gallup.com/workplace/306503/strategies-leading-effectively-amid-covid.aspx)



Hobbies:

reading
movies, shows
knitting
mixed media/collage
violin
tea
yoga
good restaurants
spa days
the beach
hiking
smelling flowers
hanging with family

Astrobiology, Vol. 12, No. 1 | Rapid Communications

Suppression of the Water Ice and Snow Albedo Feedback on Planets Orbiting Red Dwarf Stars and the Subsequent Widening of the Habitable Zone

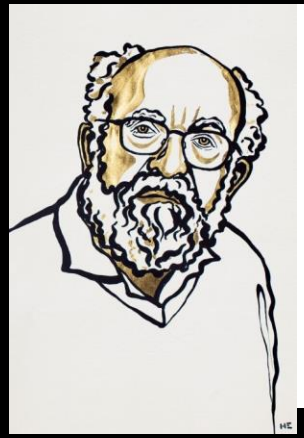
Manoj M. Joshi and Robert M. Haberle

Published Online: 23 Jan 2012 | https://doi.org/10.1089/ast.2011.0668

BINGO

Pre-Major in Astronomy Progr
Increasing Diversity in Ast
Discovering Asteroids w/SOHO
Searching for Star Clusters
A134

WE'RE LIVING
IN A WHOLE NEW UNIVERSE NOW...



Ill. Niklas Elmehed.
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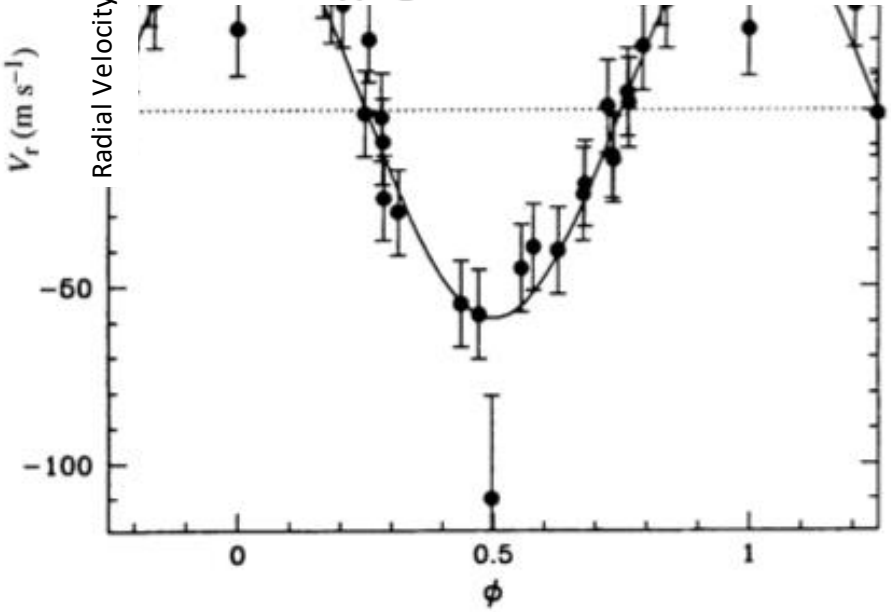
A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.



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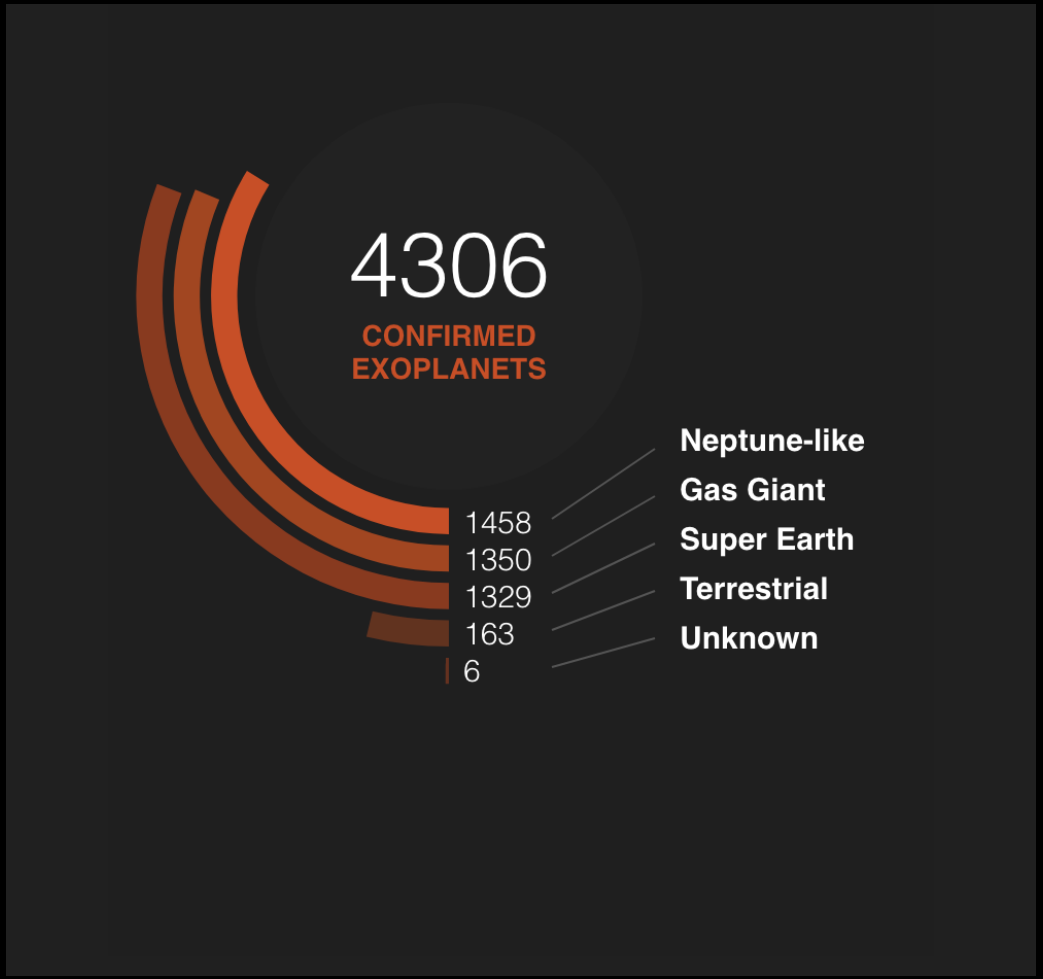
Mayor & Queloz
1995

Nobel Prize in Physics
2019

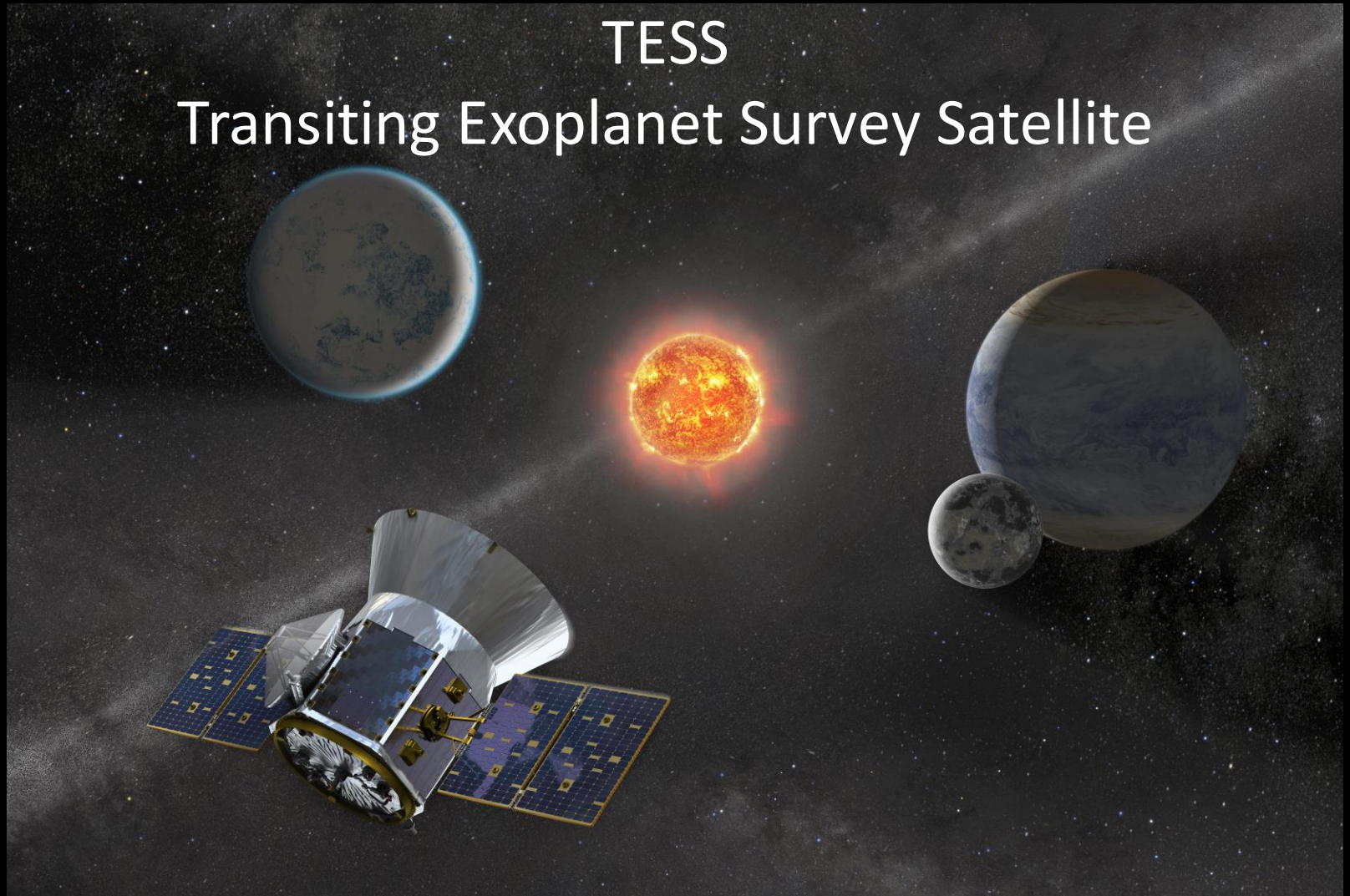


https://exoplanets.nasa.gov/

As of December 2, 2020

NASA's *Kepler* Mission

TESS
Transiting Exoplanet Survey Satellite



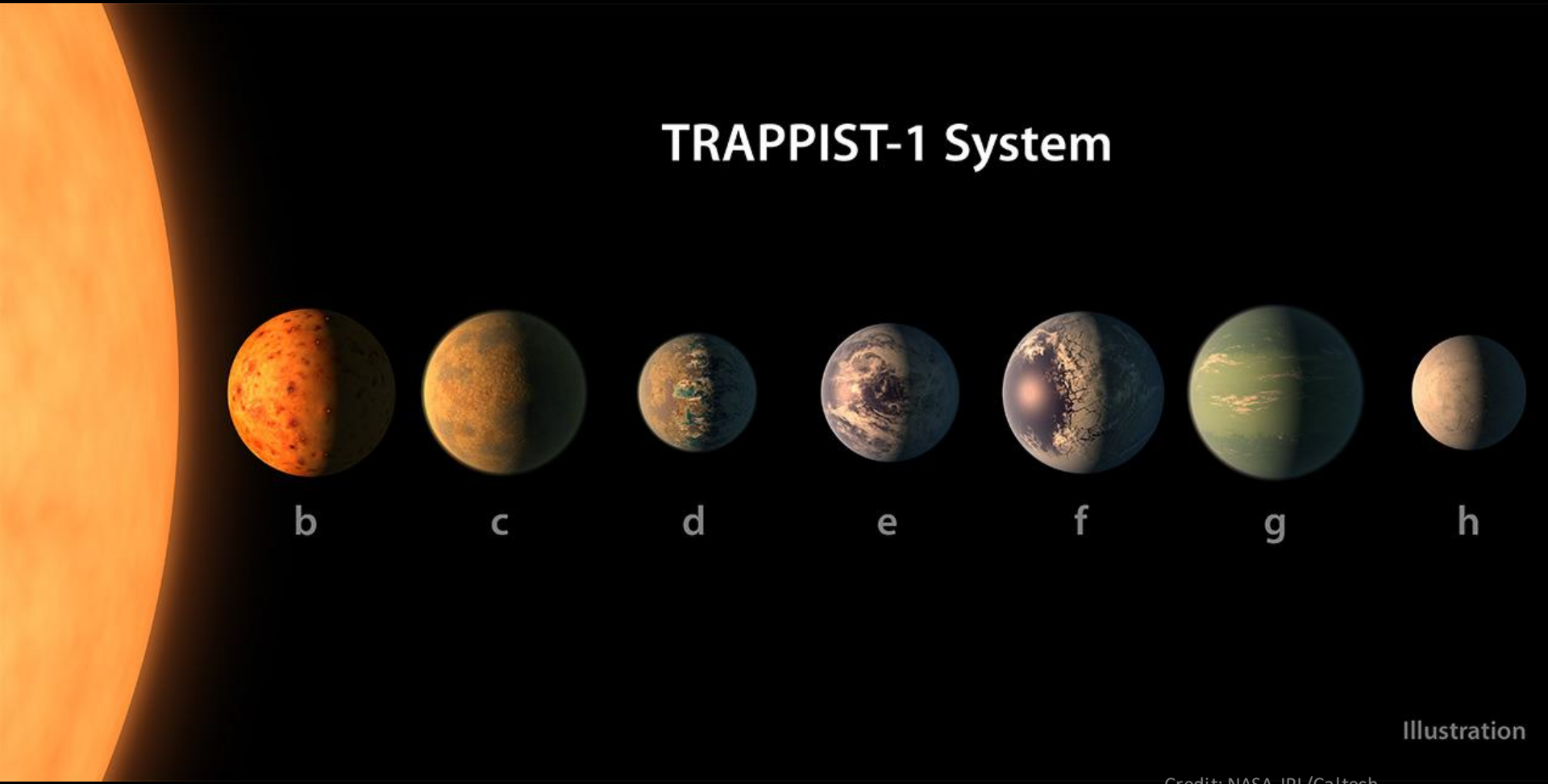

TRAPPIST-1 System
b
c
d
e
f
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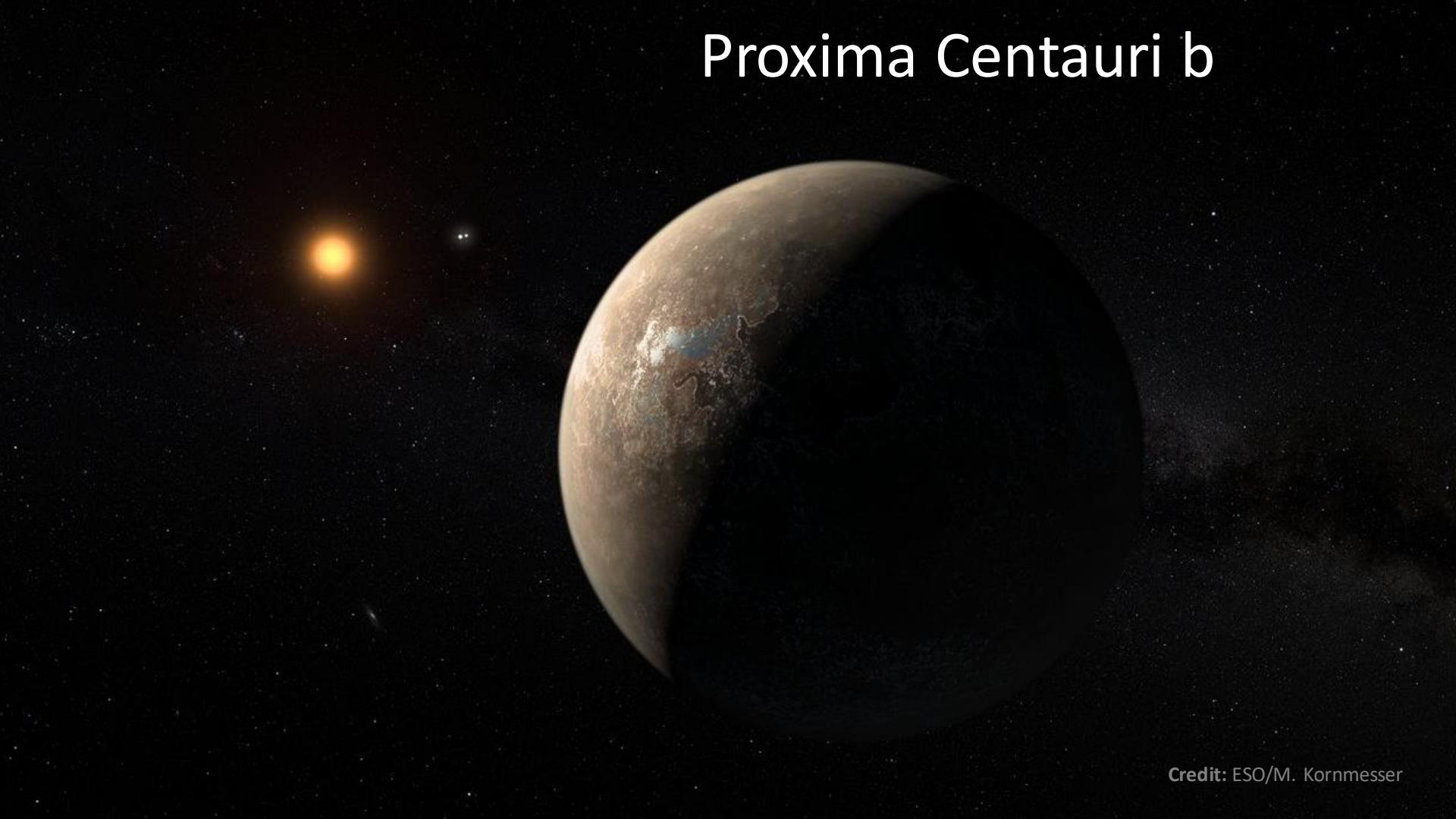
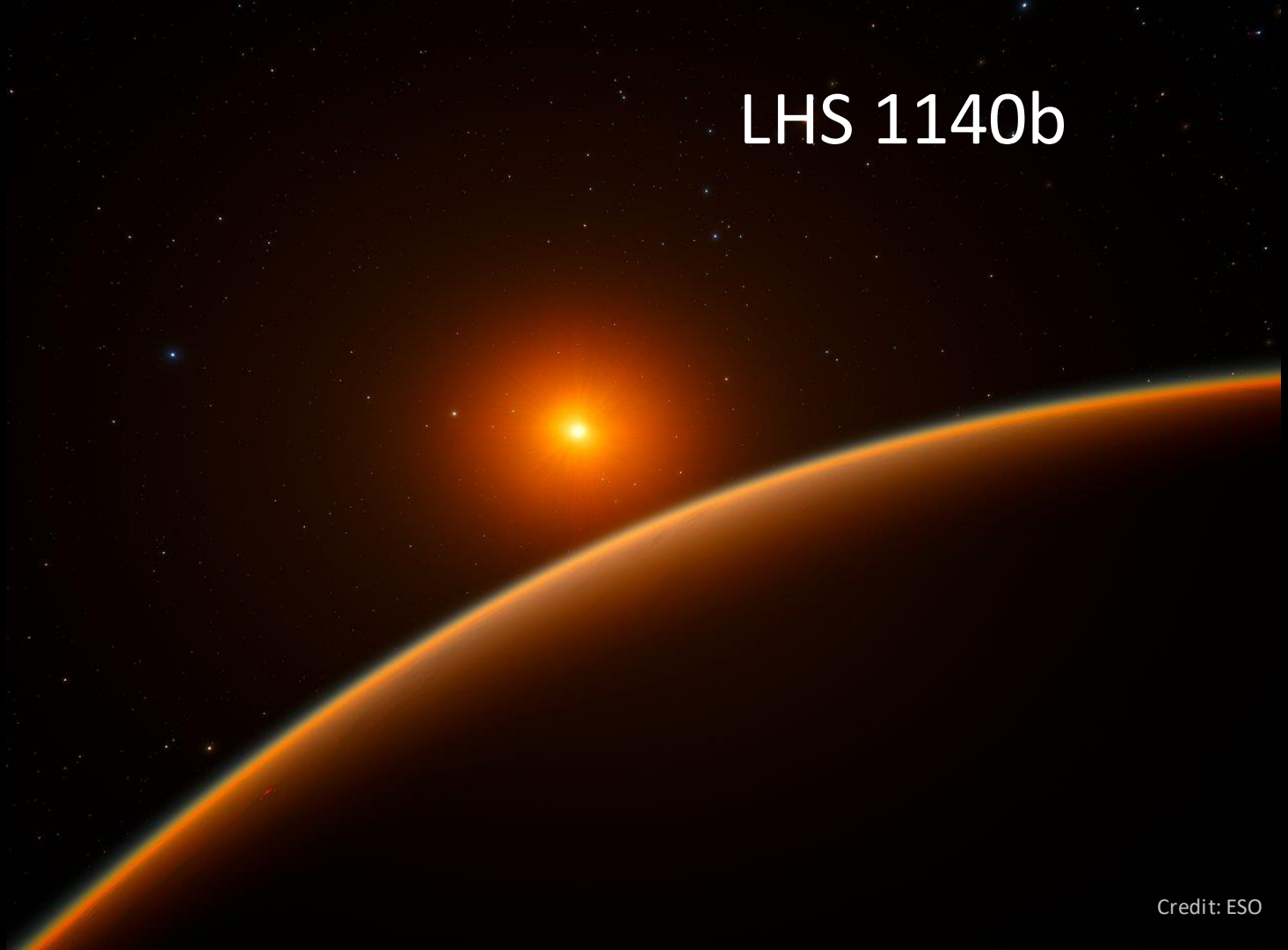
Illustration
Credit: NASA-JPL/Caltech

Proxima Centauri b

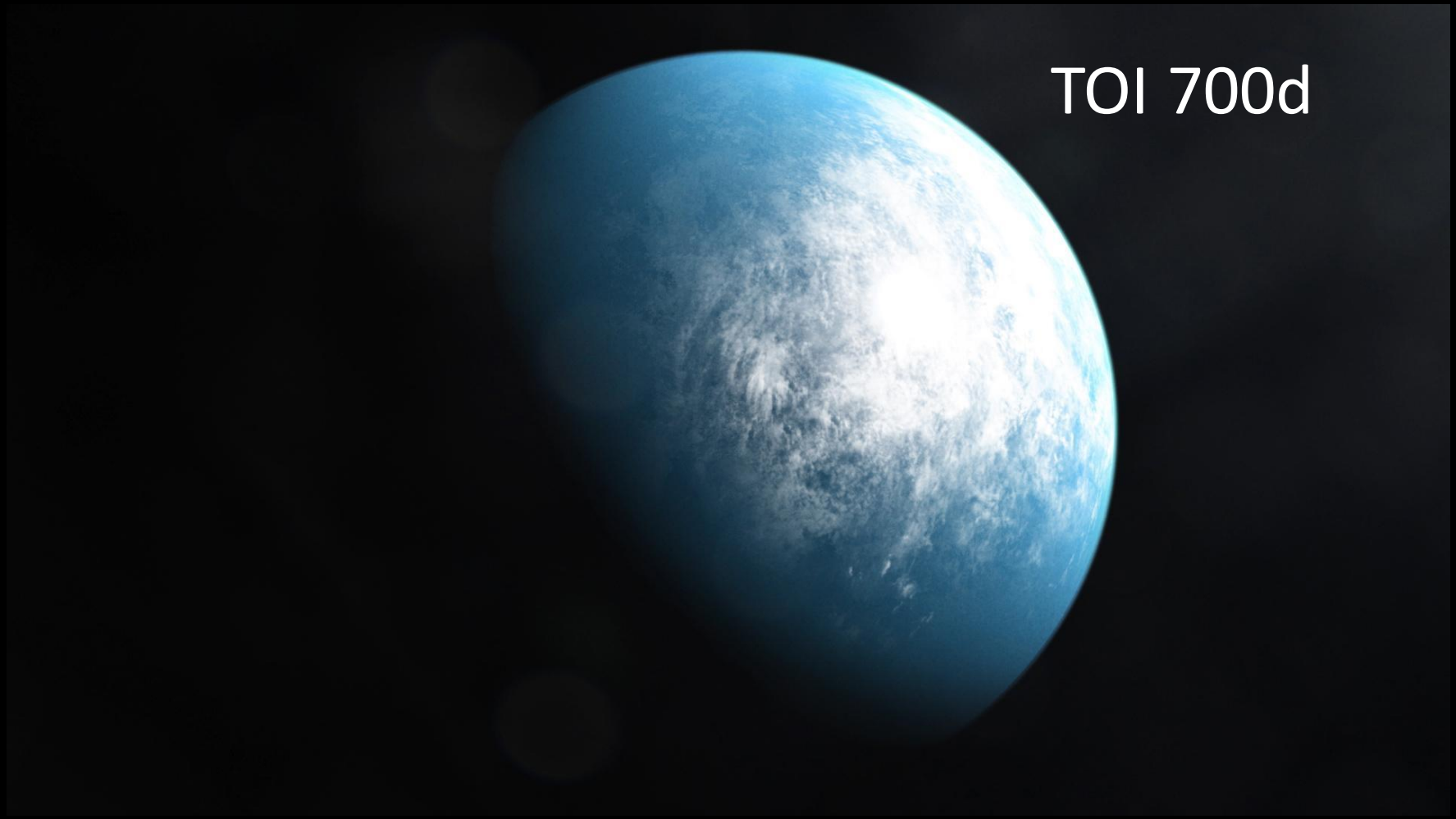


Credit: ESO/M. Kornmesser

LHS 1140b

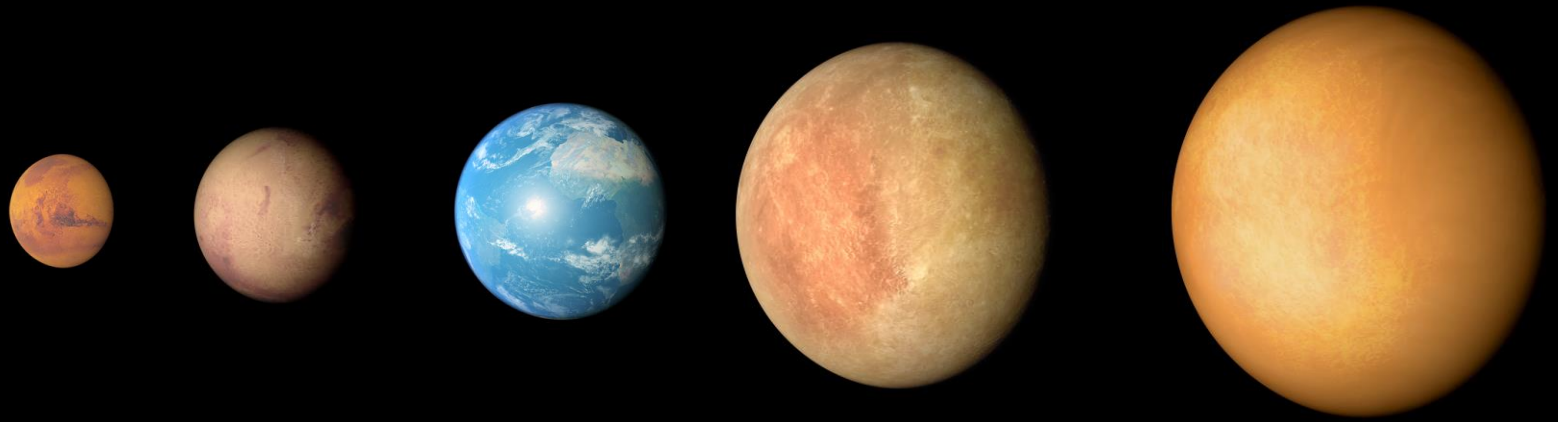


Credit: ESO

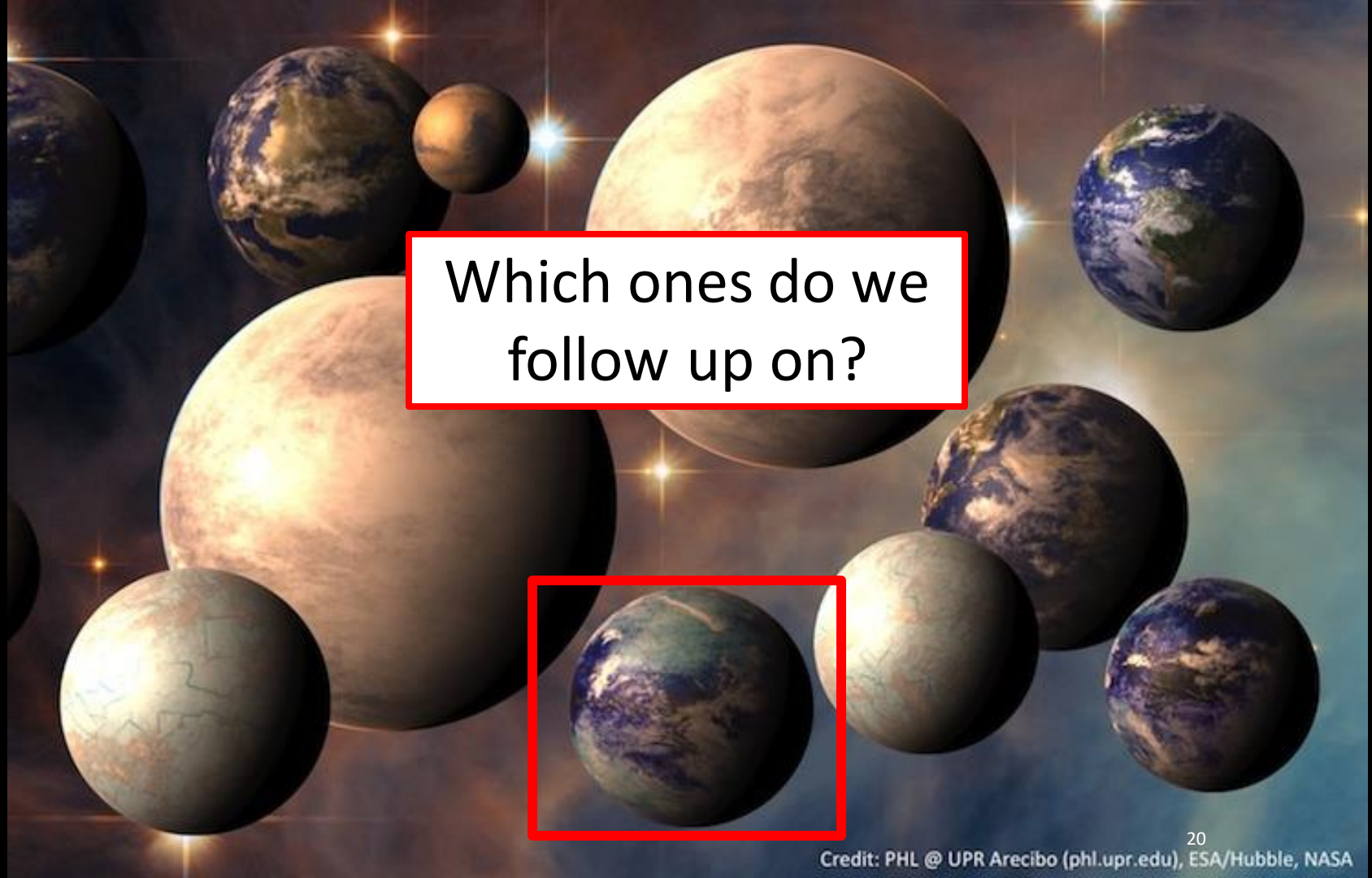


Credit: NASA

TESS planets in the Earth-sized regime

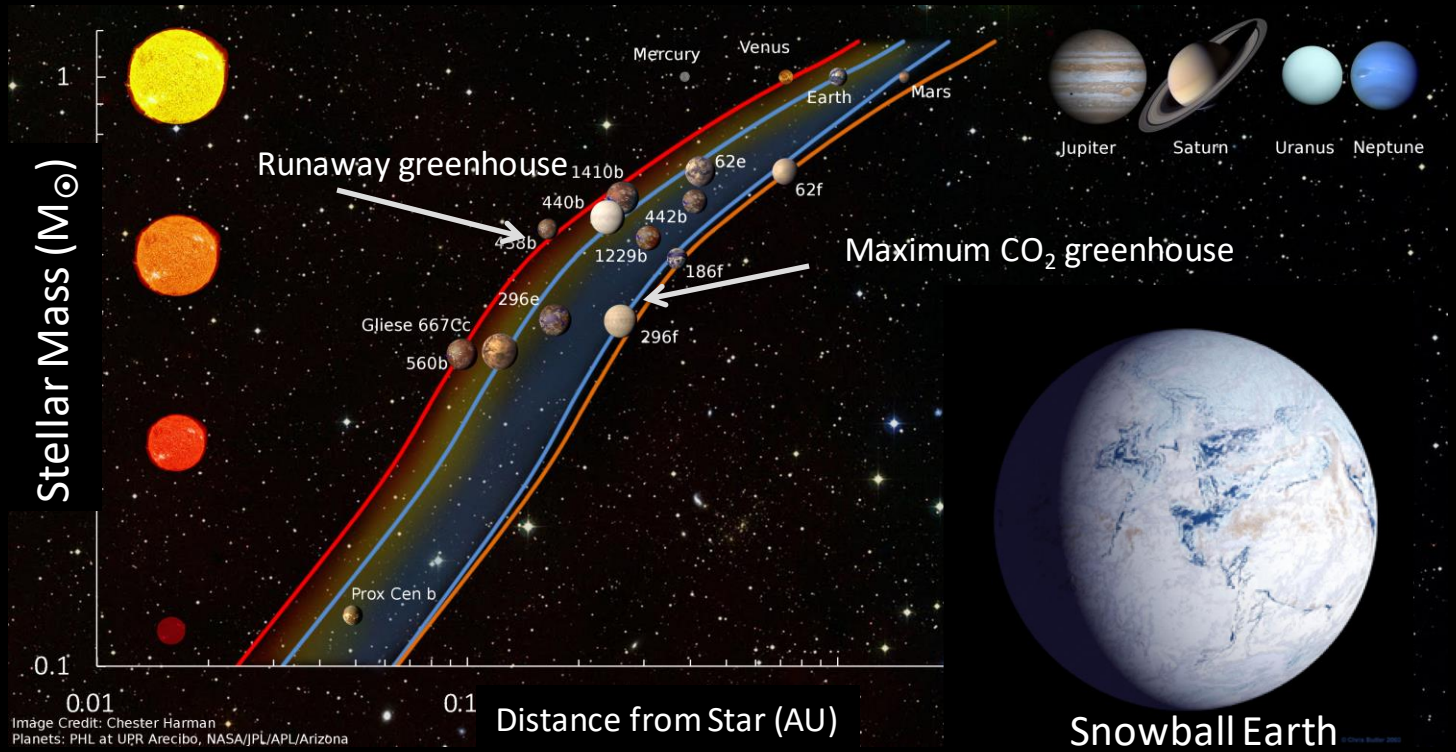


Credit: NASA's Goddard Space Flight Center


Which ones do we follow up on?
Credit: PHL @ UPR Arecibo (phl.upr.edu), ESA/Hubble, NASA

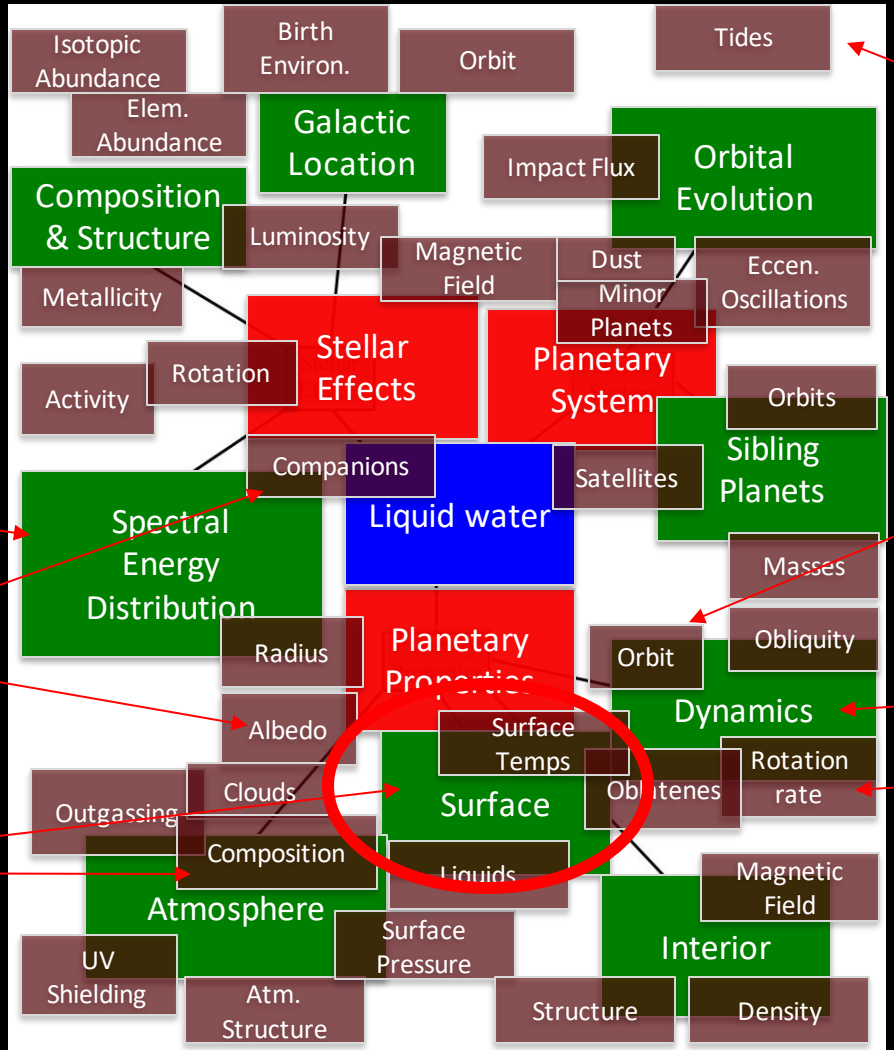
The Habitable Zone

(Kasting et al. 1993, Kopparapu et al. 2013)



Many factors can affect planetary habitability

Liquid water

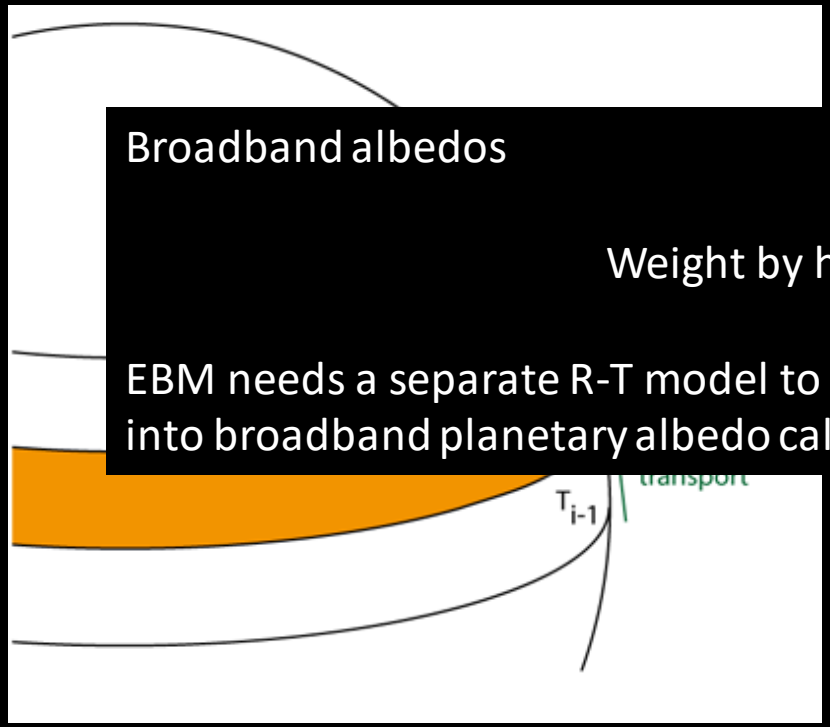


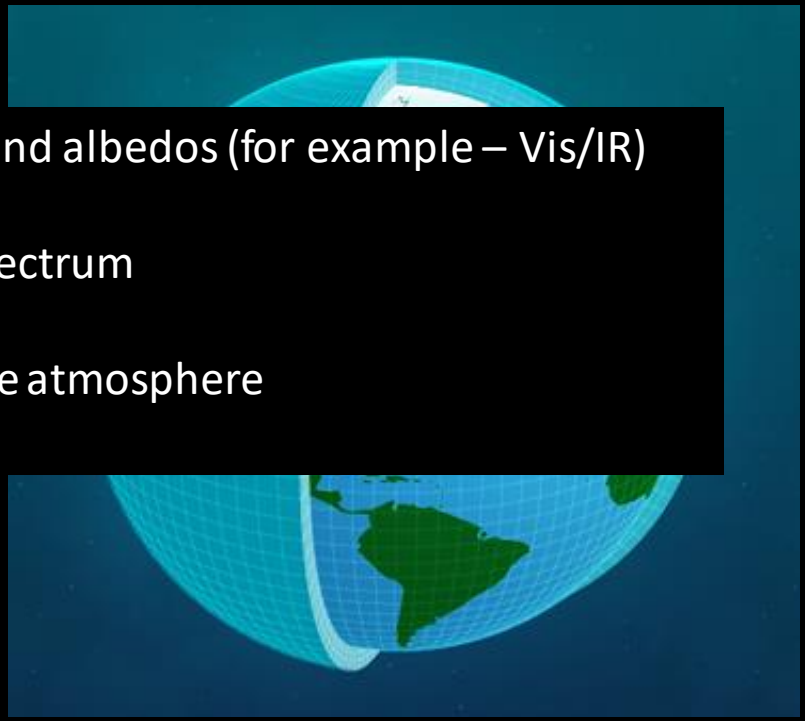
Credit: After Meadows and Barnes 2018

Credit: Anja Buckle

1-D Energy Balance Model (EBM)

Global Climate Model (GCM)





Broadband albedos

Two-band albedos (for example – Vis/IR)

Weight by host star spectrum

EBM needs a separate R-T model to incorporate atmosphere into broadband planetary albedo calculation

Based on McGuffie and Henderson-Sellers (2005)

Koshland Science Museum

Global Climate Model (GCM)
(Ex. CCSM4 (Gent et al. 2011), LMD Generic GCM (Hourdin et a. 2006))

Koshland Science Museum

Conservation of momentum →

$$\frac{d\vec{v}}{dt} = -\frac{1}{\rho}\vec{\nabla}p - \vec{g} + \vec{F}_{fric} - 2\vec{\Omega} \times \vec{v}$$

Mass continuity →

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot (\rho \vec{v})$$

Conservation of energy
(1st law of thermo) →

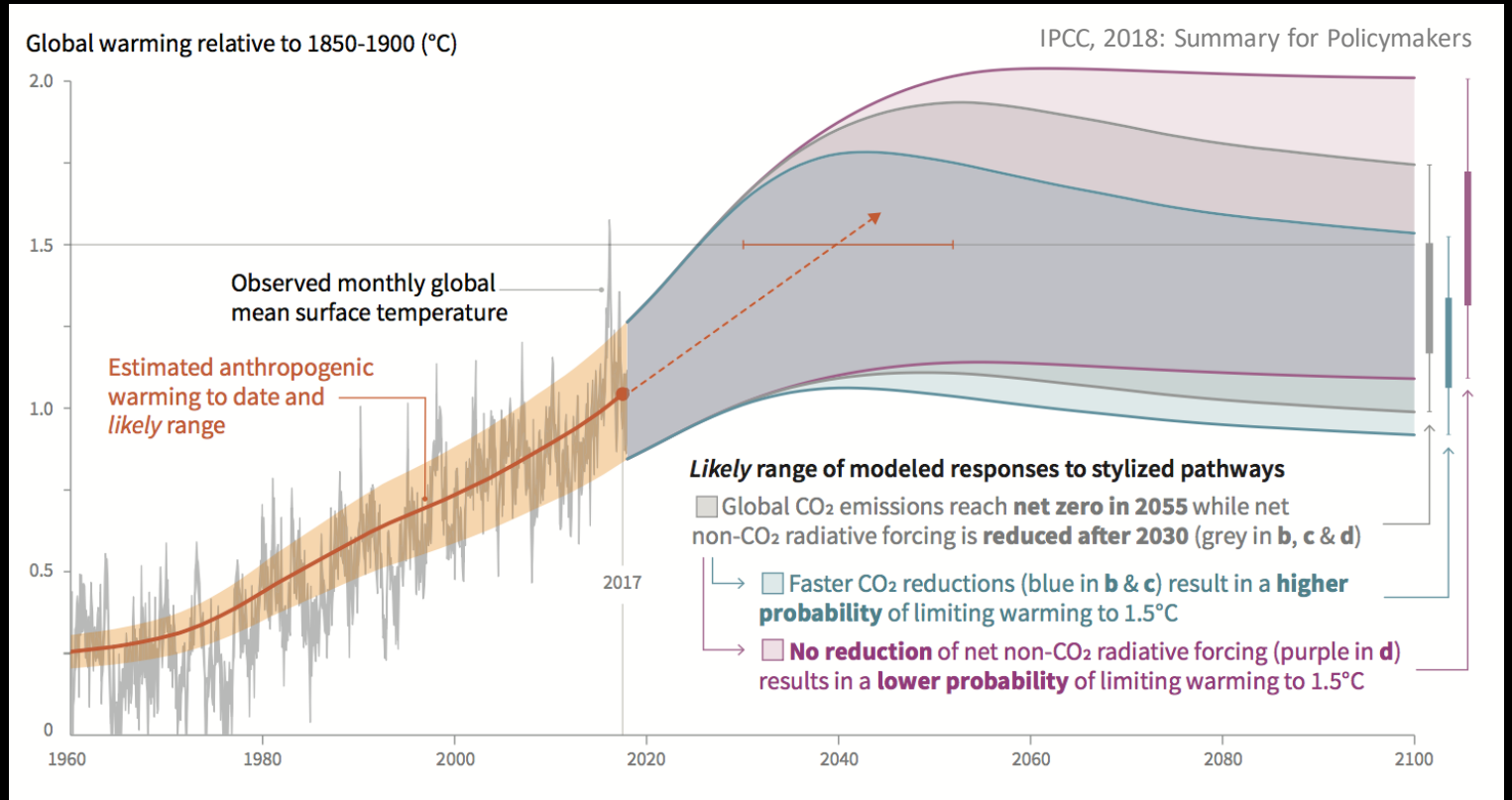
$$Q = C_p \frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt}$$

Equation of state for the atmosphere →

$$p = \rho R T$$

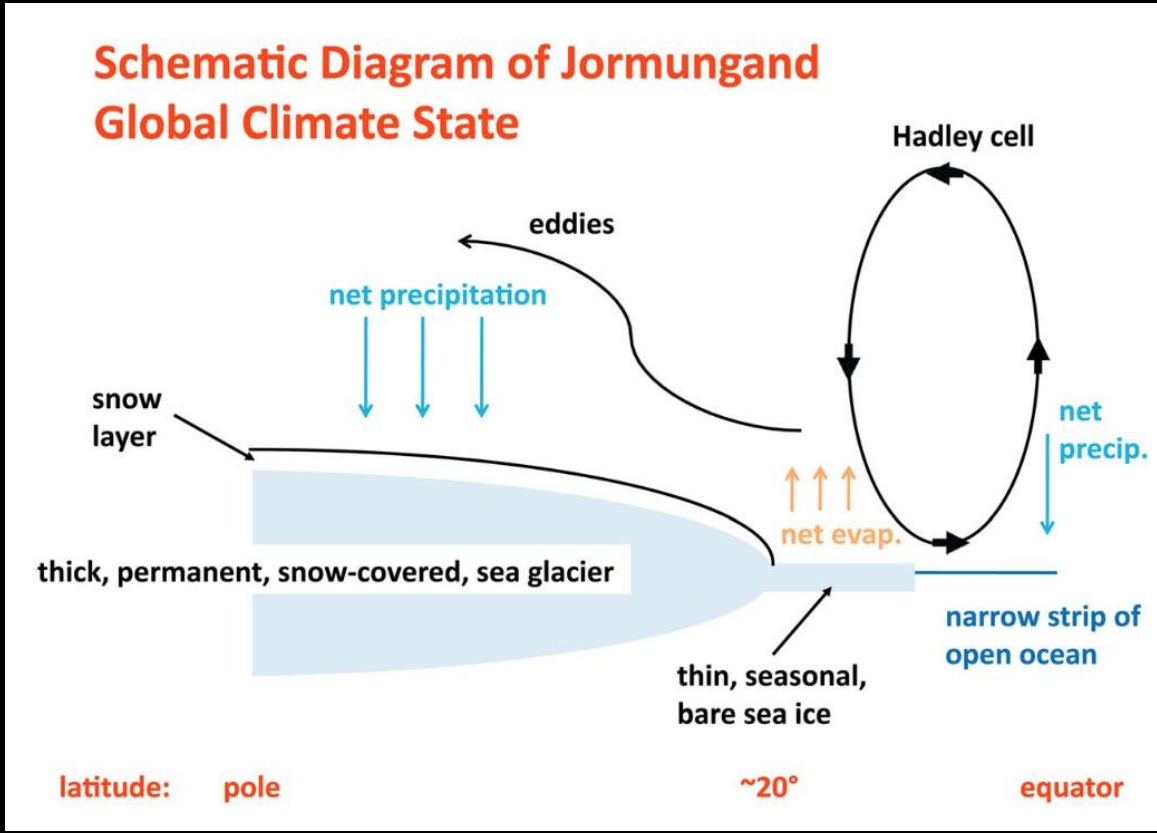
PREDICTING FUTURE CLIMATE ON EARTH

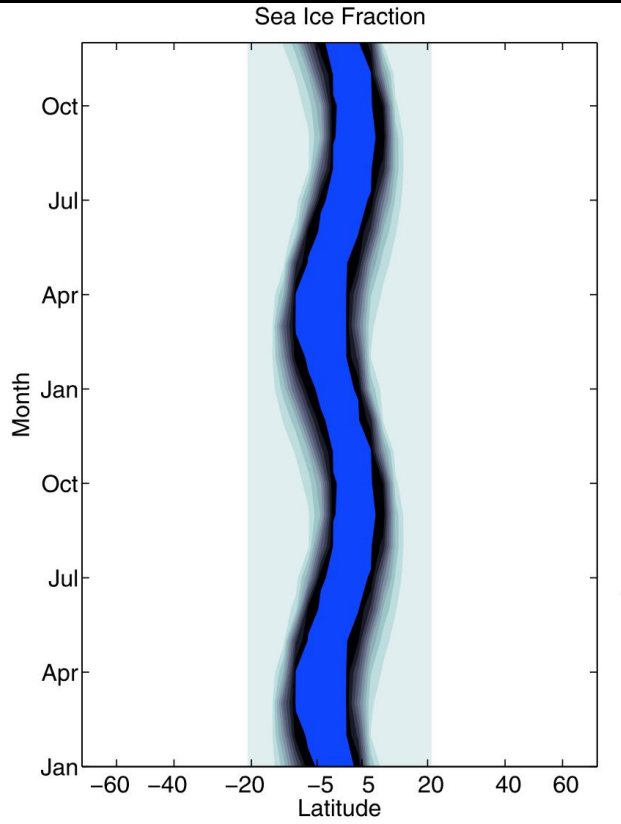
(Smagorinsky et al. 1965, Manabe et al. 1965, Holloway & Manabe 1971, Manabe & Wetherald 1975)



Waterbelt Snowball Earth as refuge for photosynthetic life

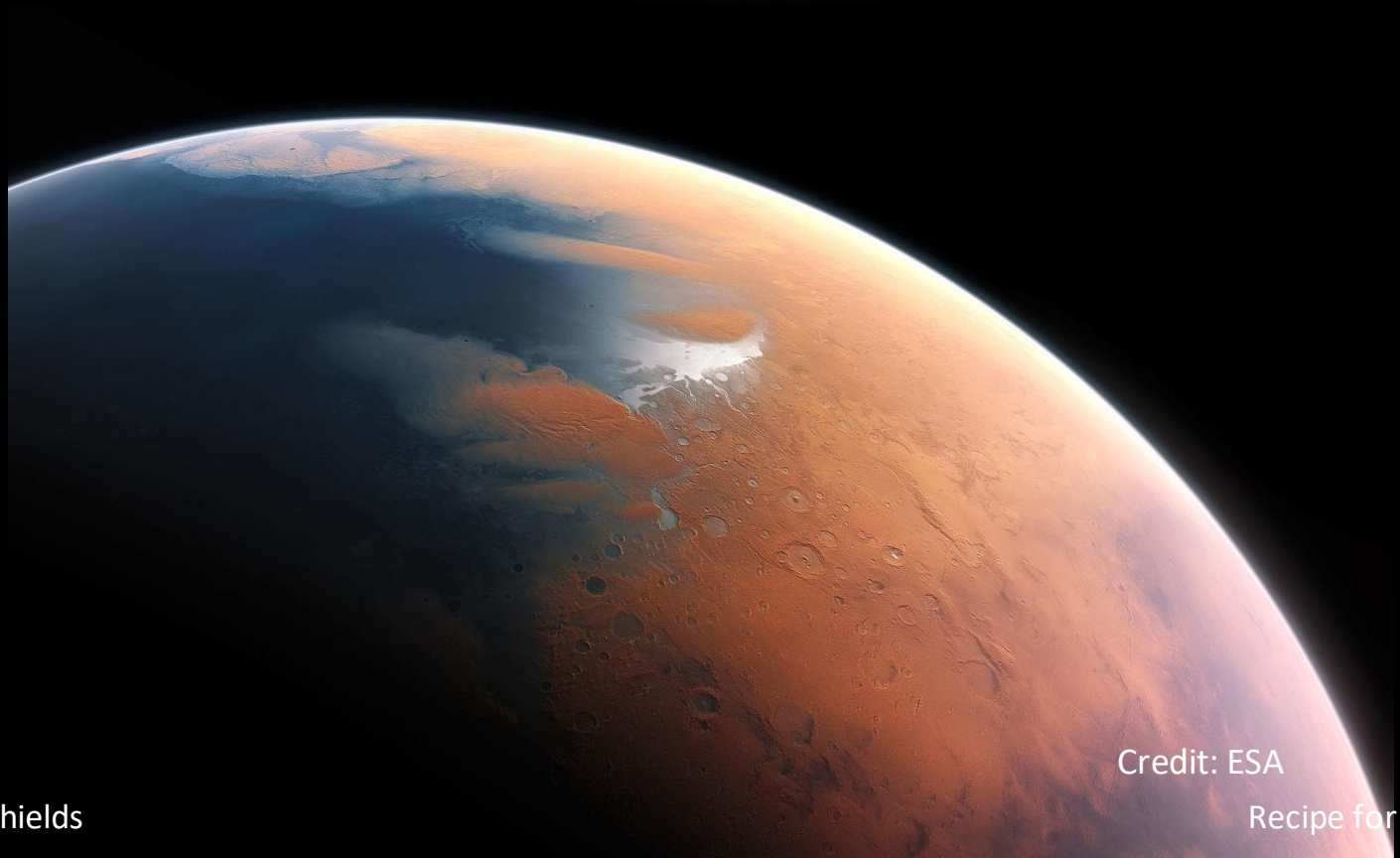
Abbot et al. 2011



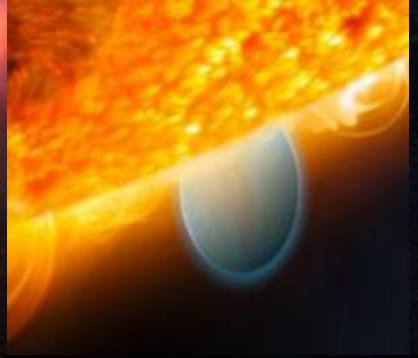


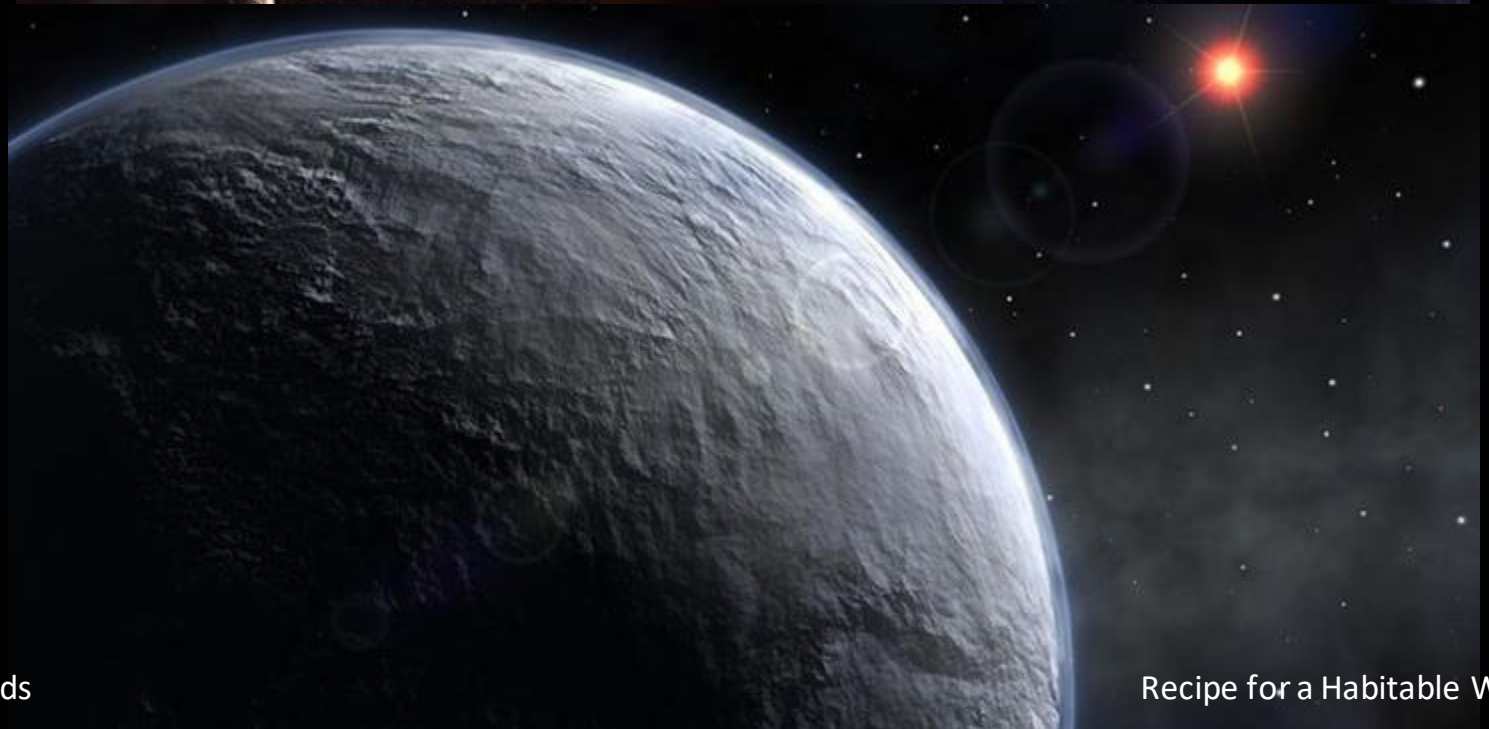
Warming Early Mars

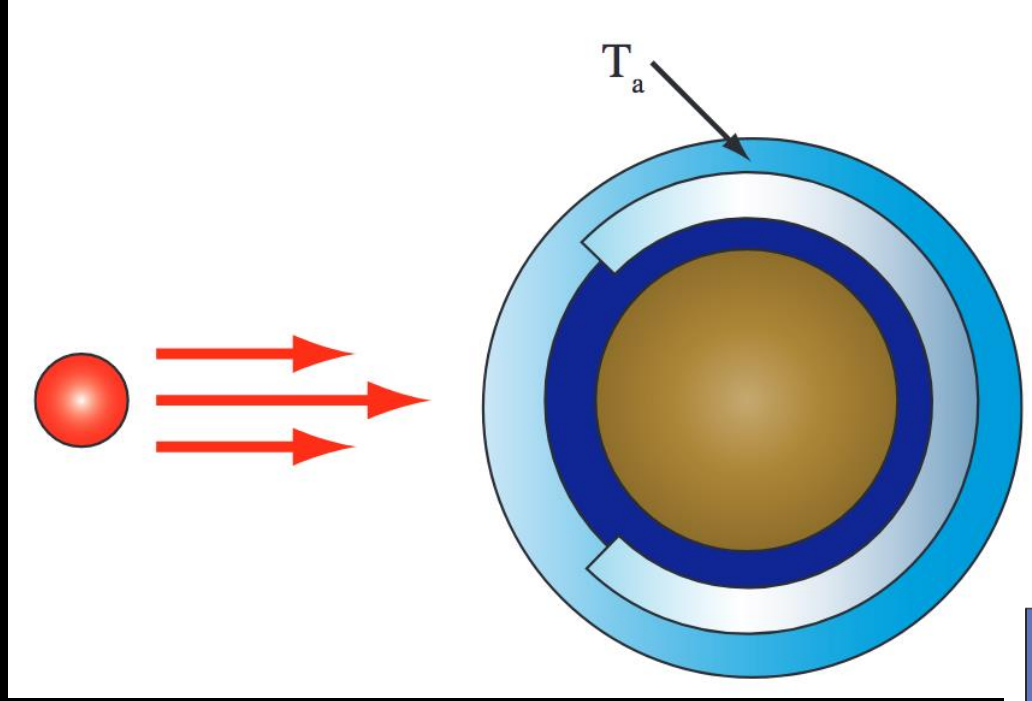
Forget and Pierrehumbert 1997, Colaprete & Toon 2003,
Forget et al. 2013, Kitzmann 2016, Wordsworth et al. 2017



Credit: ESA

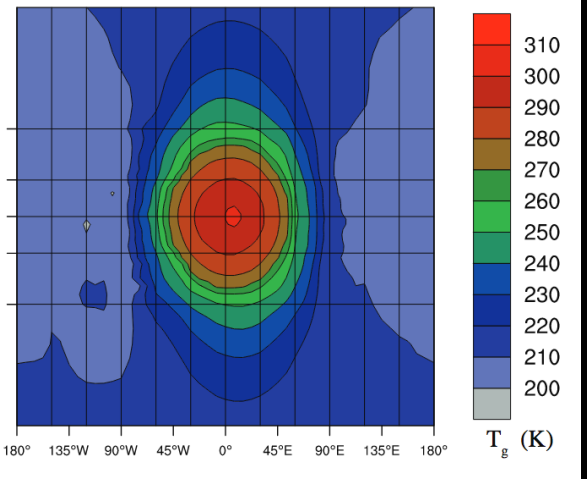




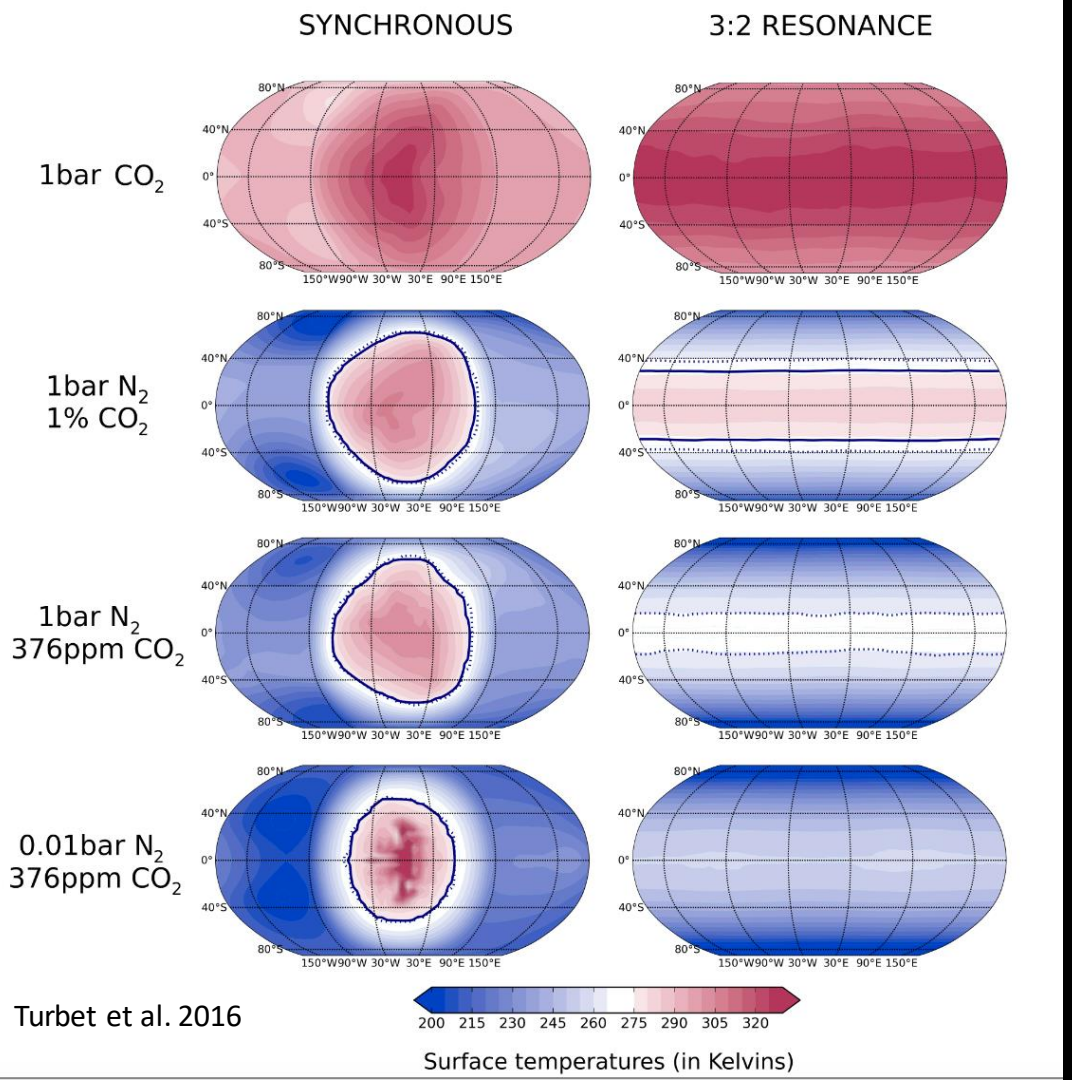


“Eyeball Earth” scenario for Gliese 581 g

Pierrehumbert 2011



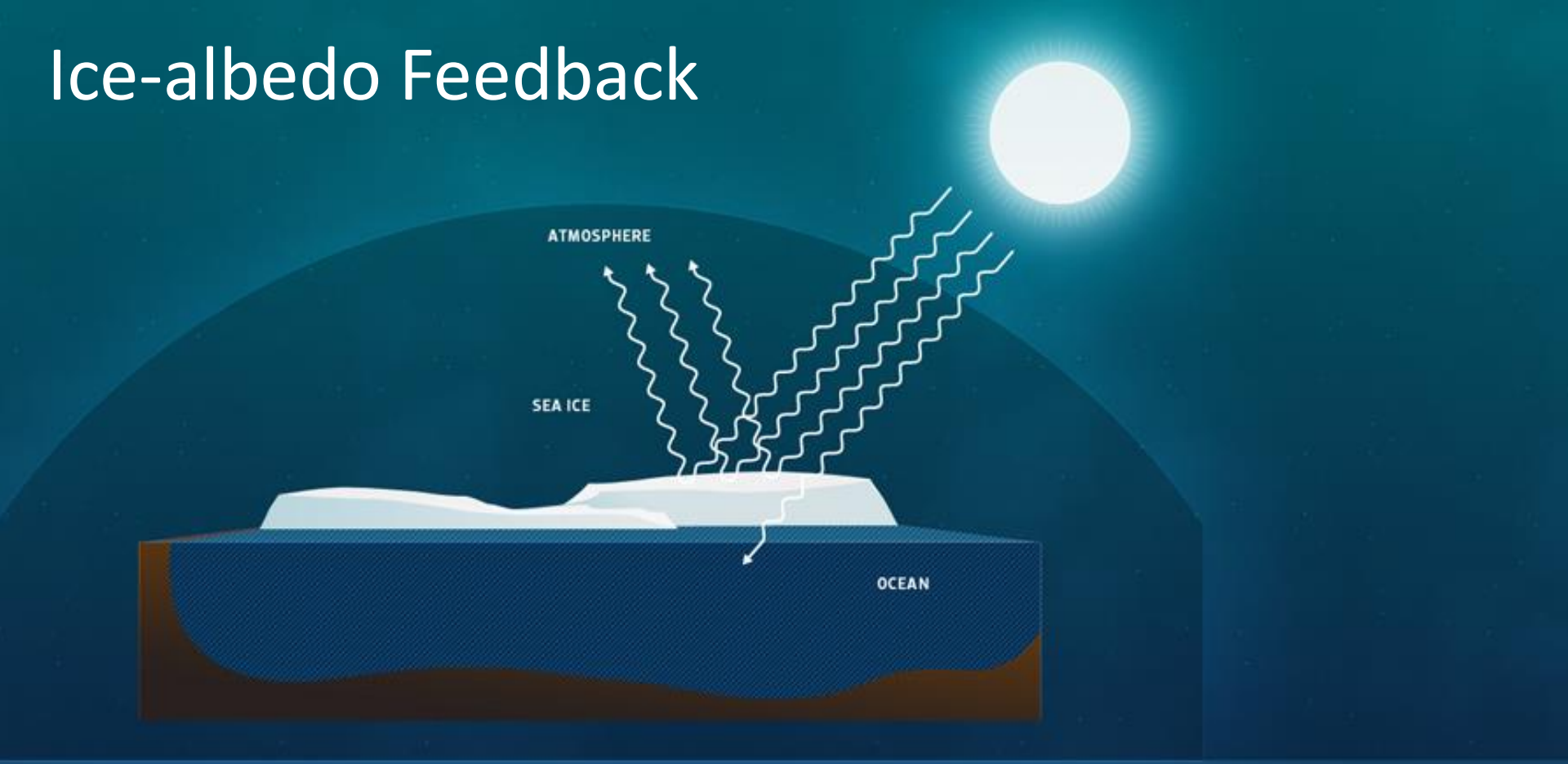
Habitable climates on Proxima Centauri b



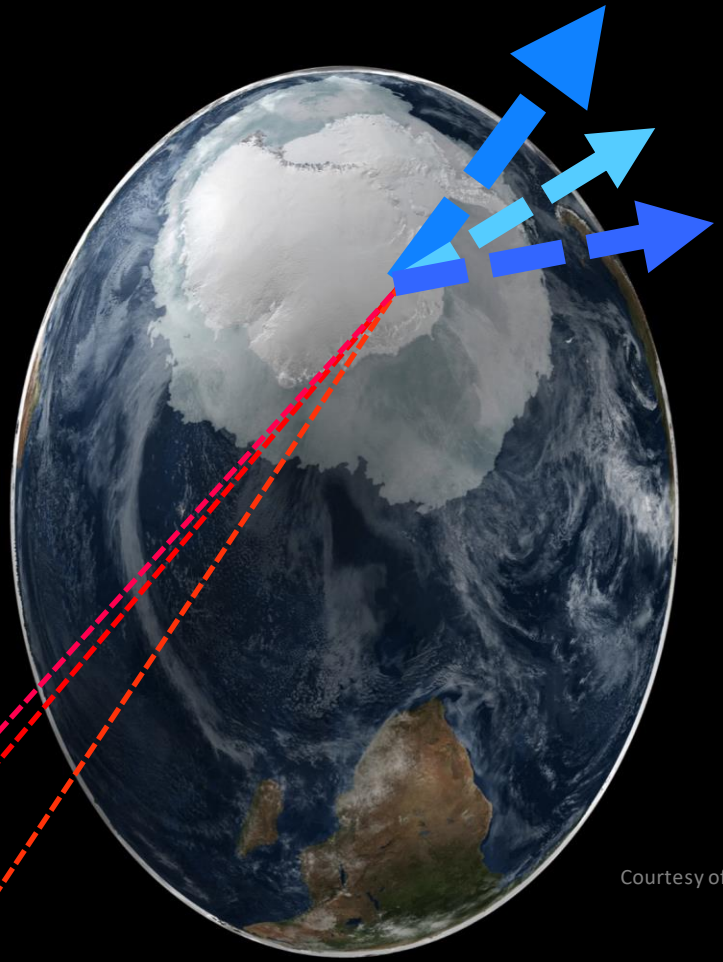
Turbet et al. 2016

Starlight

Ice-albedo Feedback



KOSHLAND
SCIENCE
MUSEUM



Courtesy of NASA

M-dwarf planets

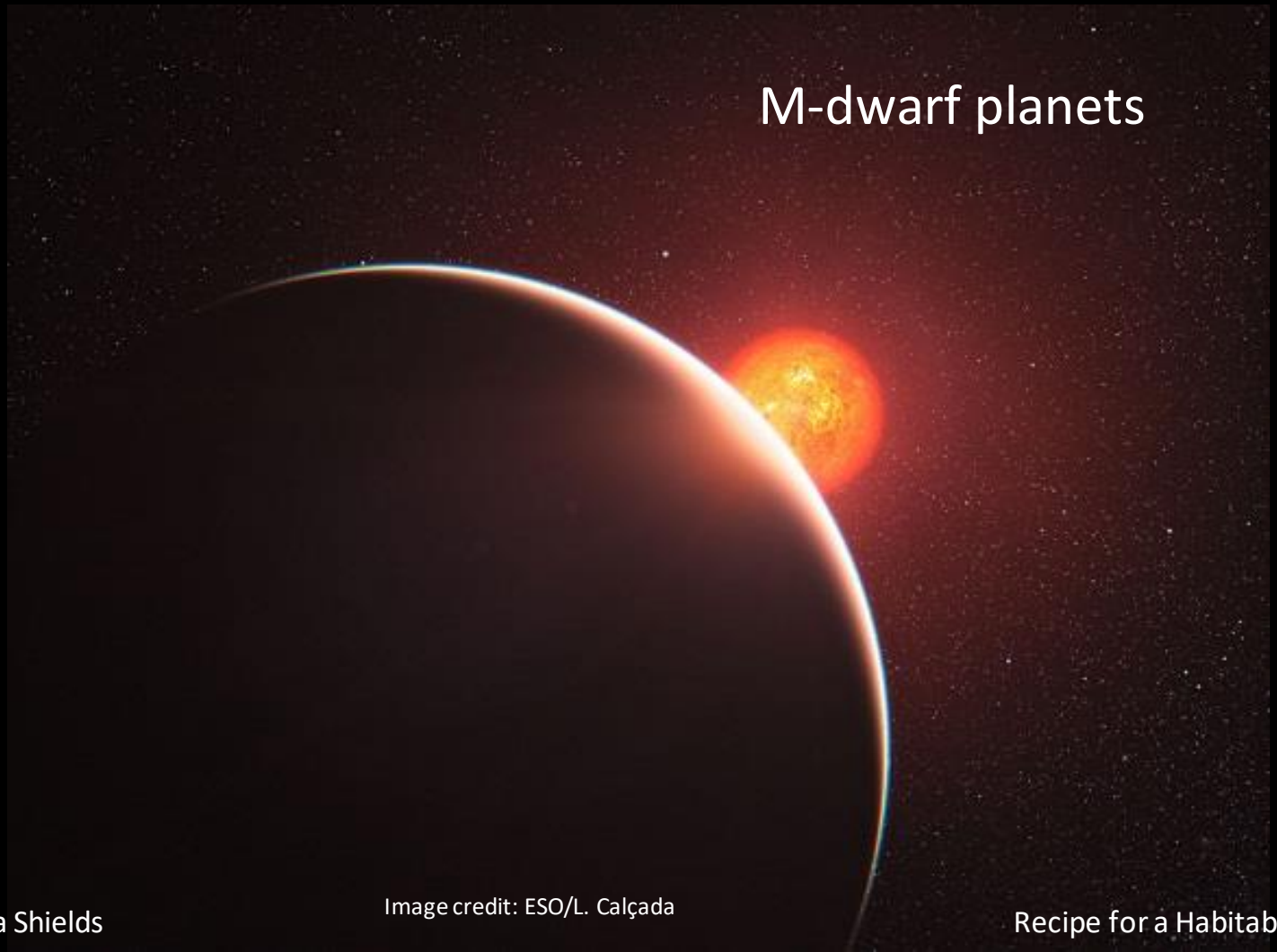
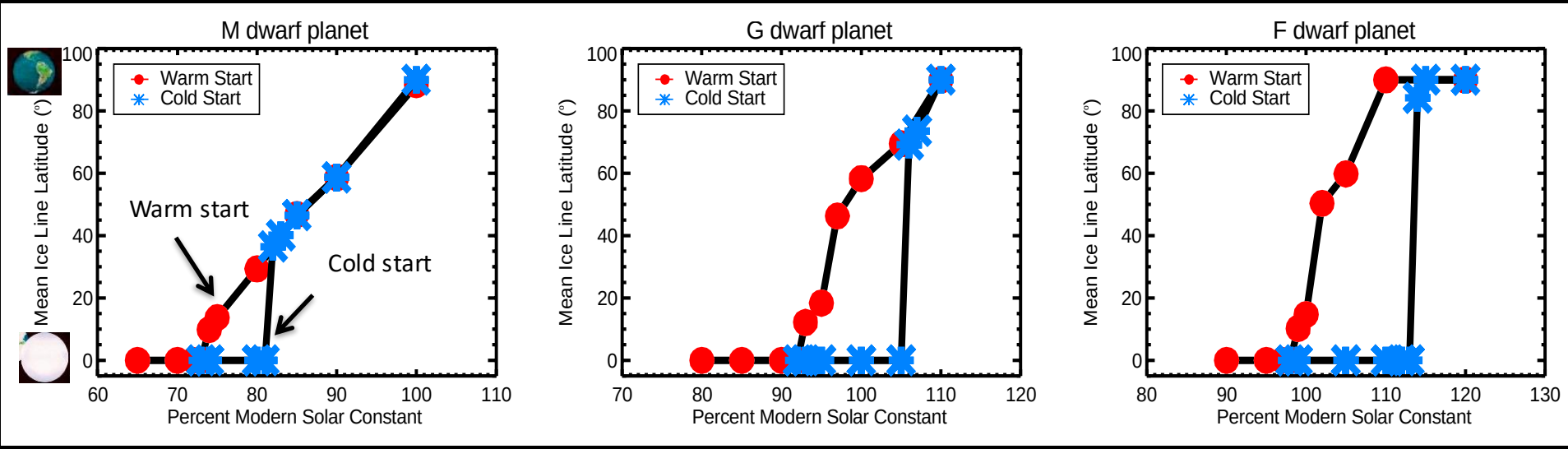


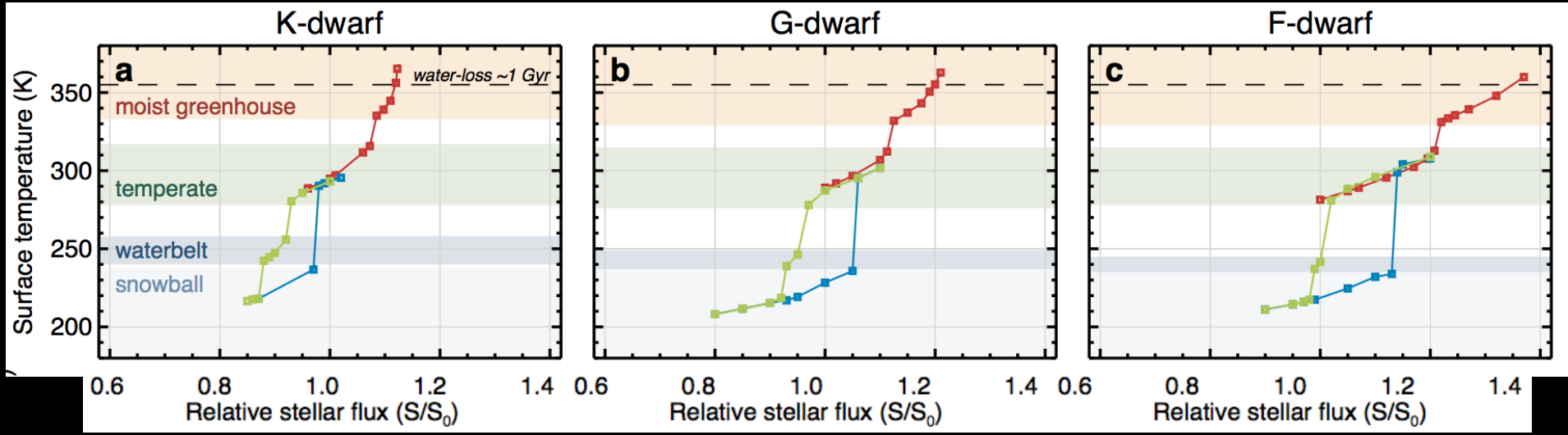
Image credit: ESO/L. Calçada

M-dwarf planets exhibit more stable climates in simulations



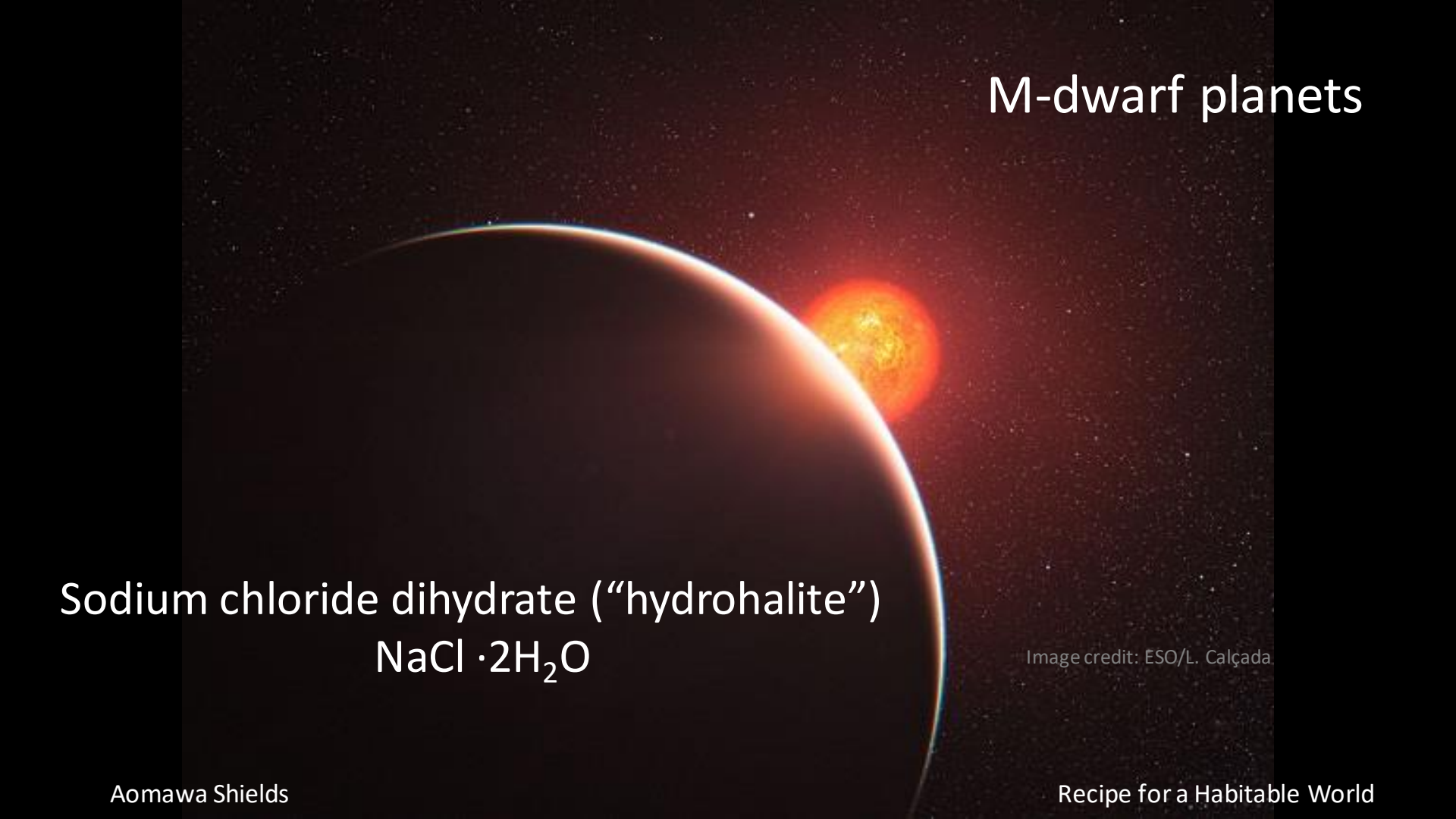
Shields et al. (2013)
Shields et al. (2014)

Effect holds across multiple possible climate regimes



Wolf, Shields+ (2017)

M-dwarf planets

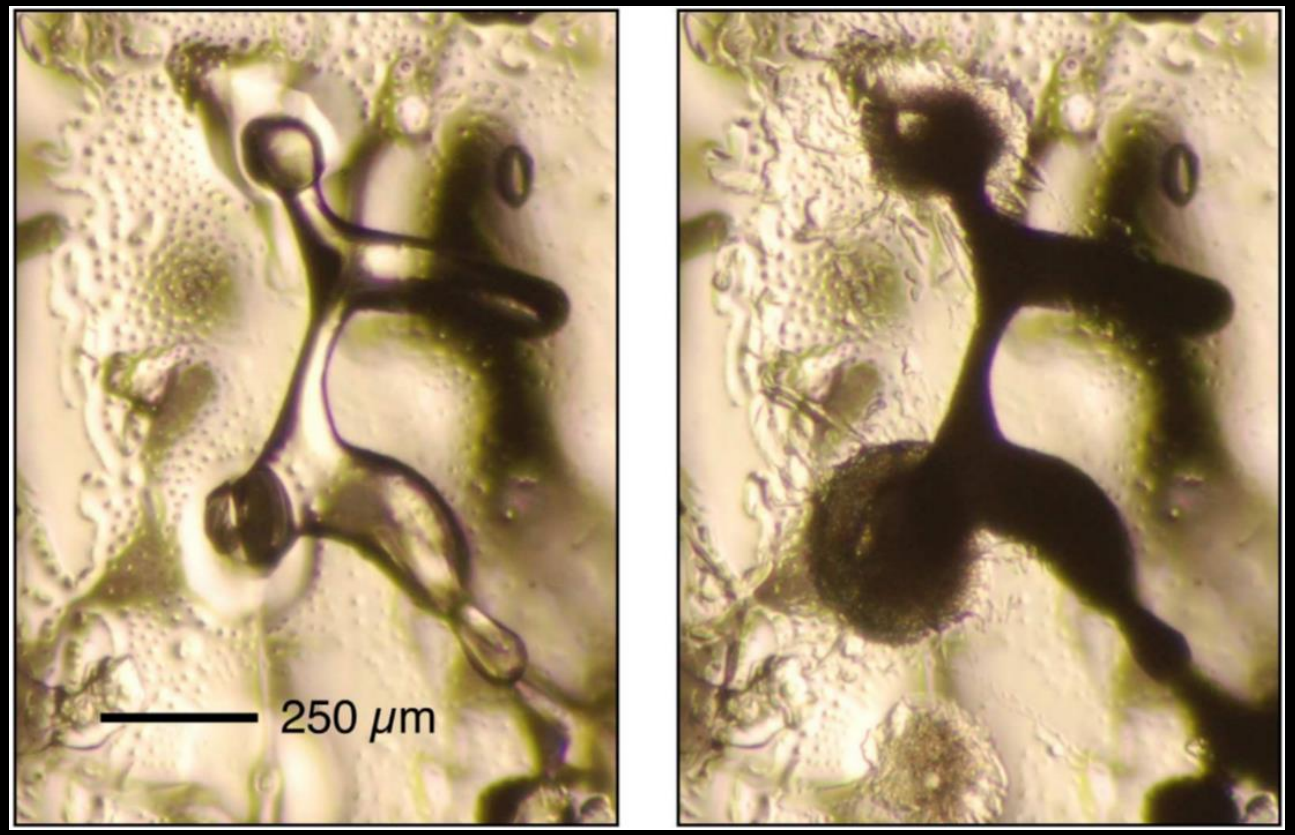


Sodium chloride dihydrate (“hydrohalite”)

$NaCl \cdot 2H_2O$

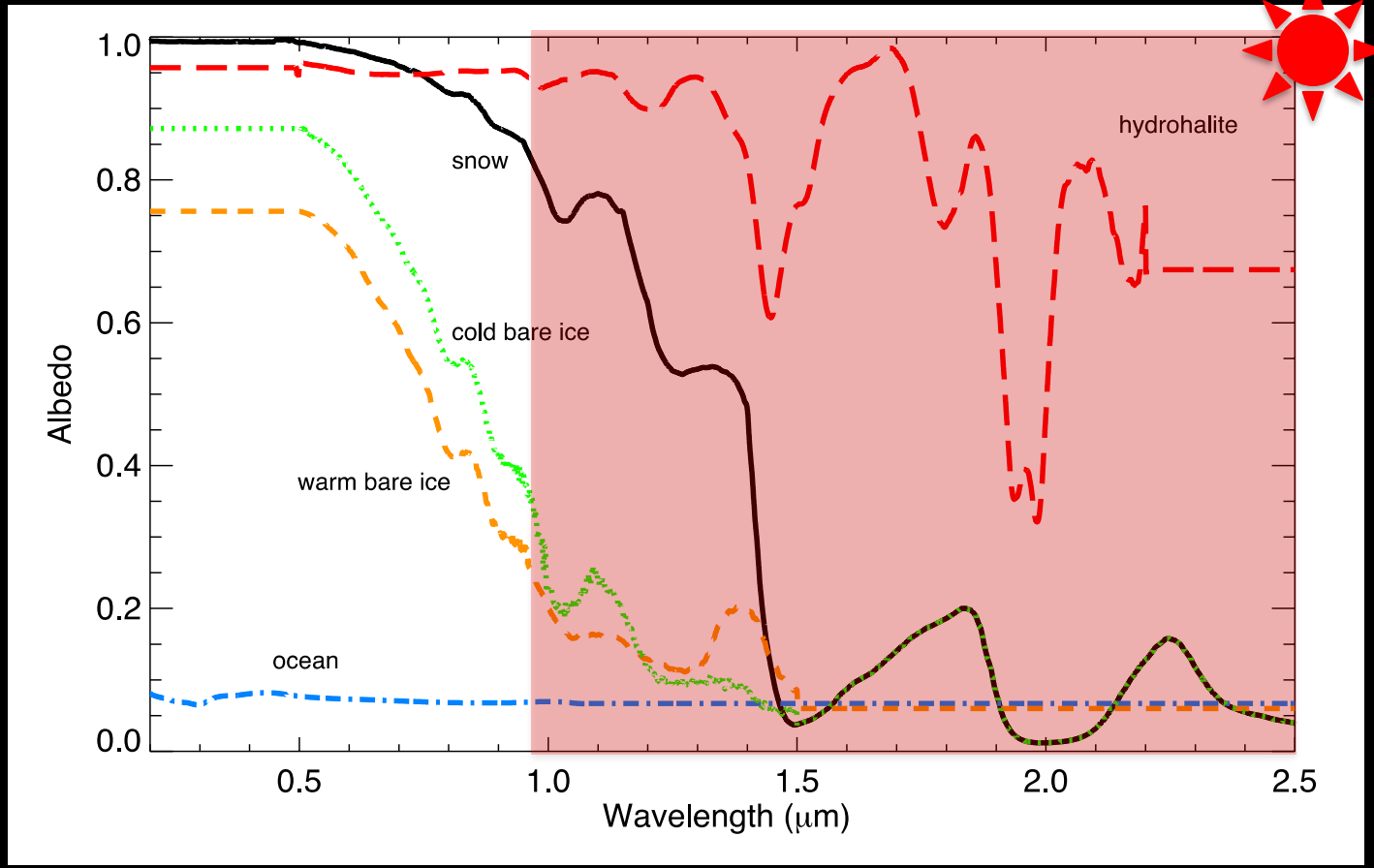
Image credit: ESO/L. Calçada

Hydrohalite precipitation in sea ice
T < -23° C



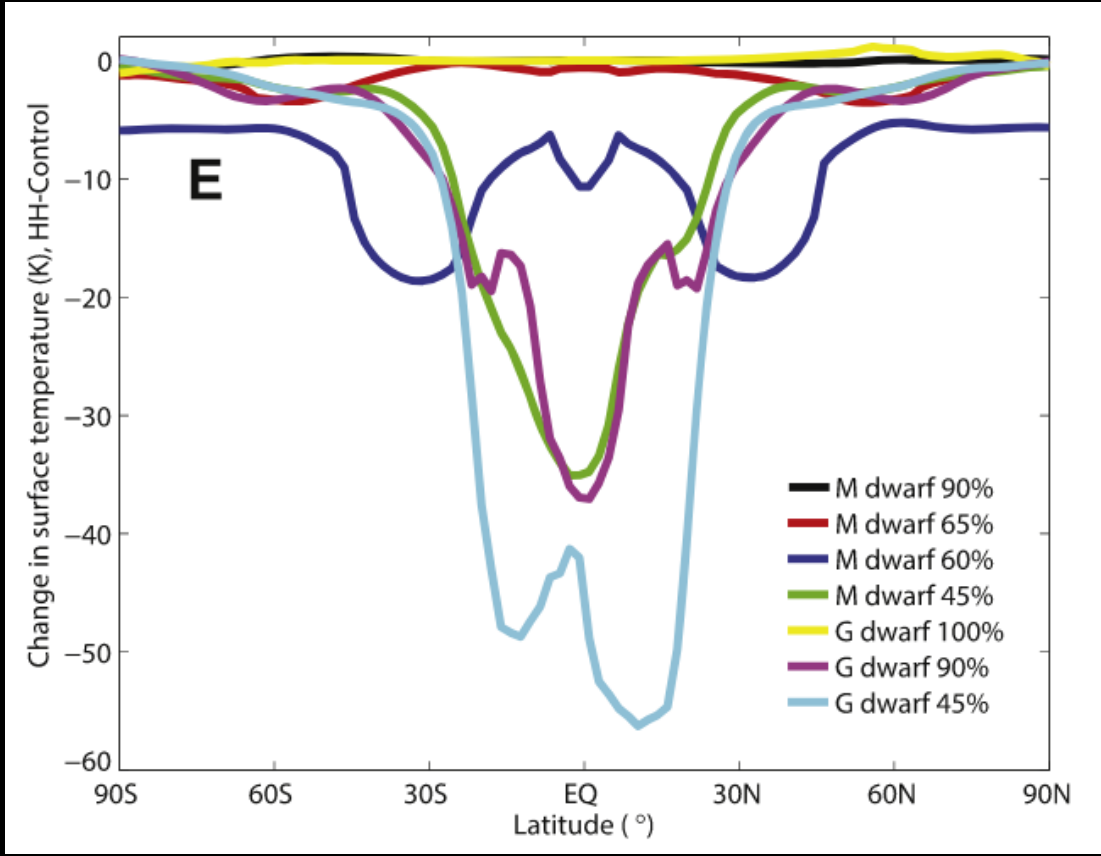
Carns et al. 2015

Hydrohalite is highly reflective in the IR



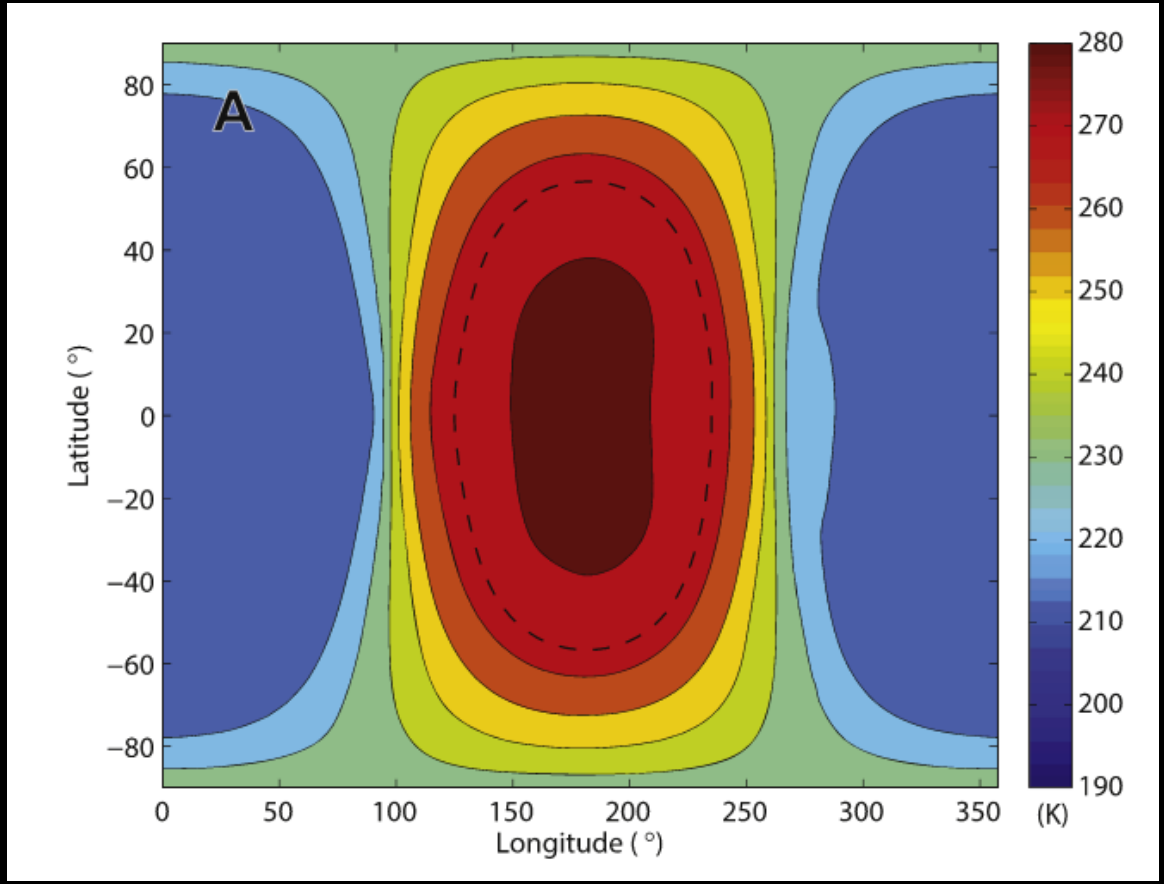
Shields and Carns 2018

Hydrohalite parameterization matters in the HZ, and climate sensitivity increases as instellation is lowered



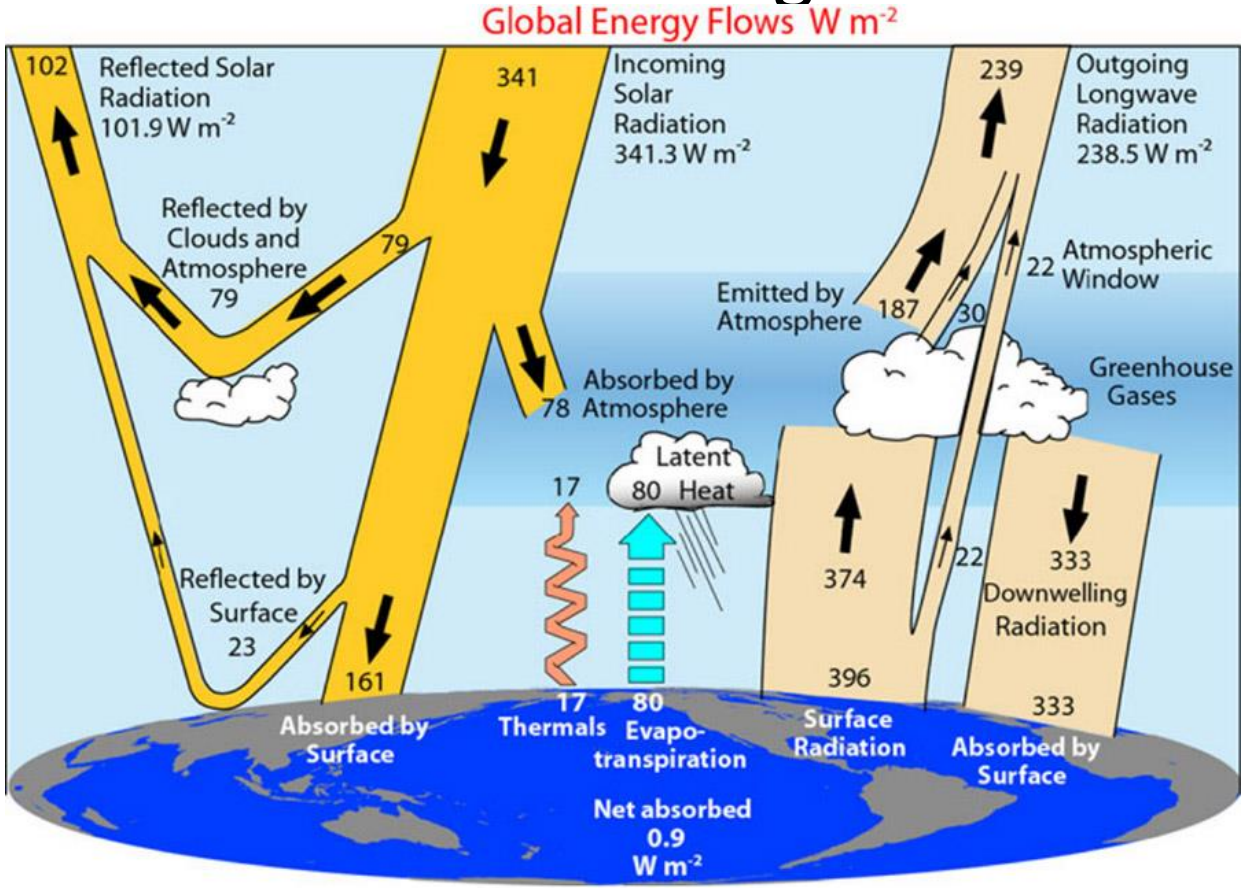
Shields and Carns 2018

Stronger climate sensitivity to hydrohalite parameterization on synchronously-rotating M-dwarf planets

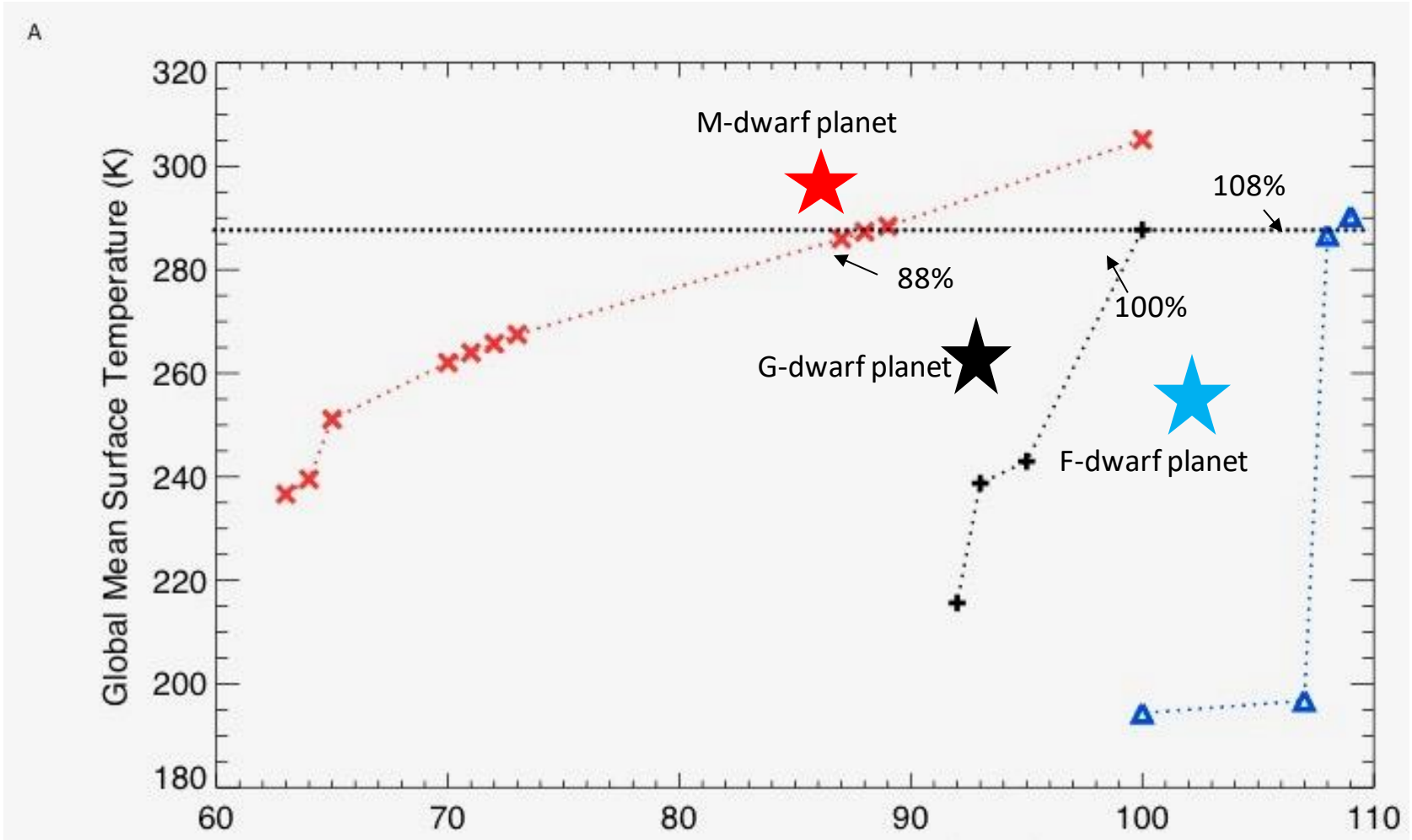


Shields and Carns 2018

Trenberth diagram

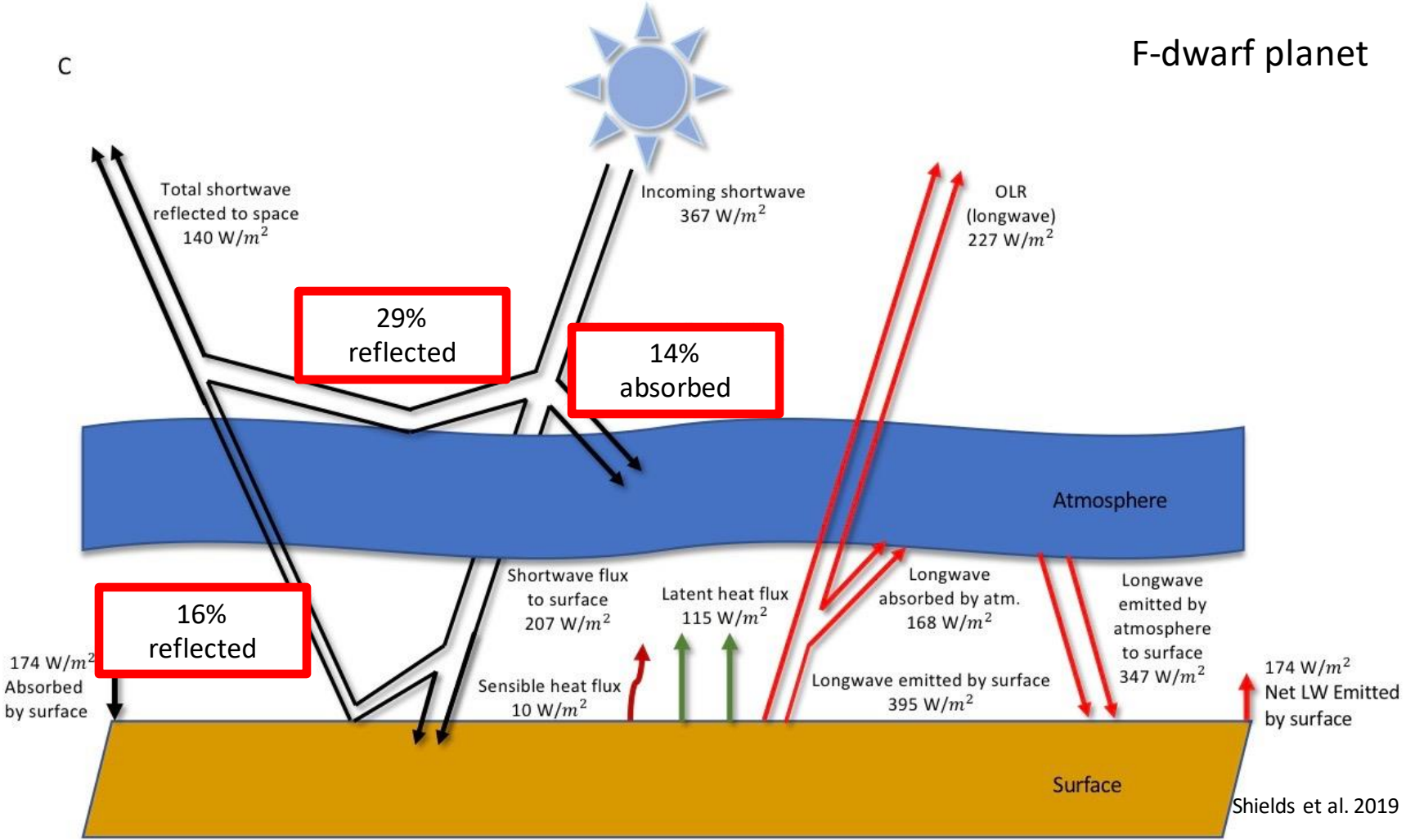


Credit: Kevin Trenberth, John Fasullo and Jeff Kiehl



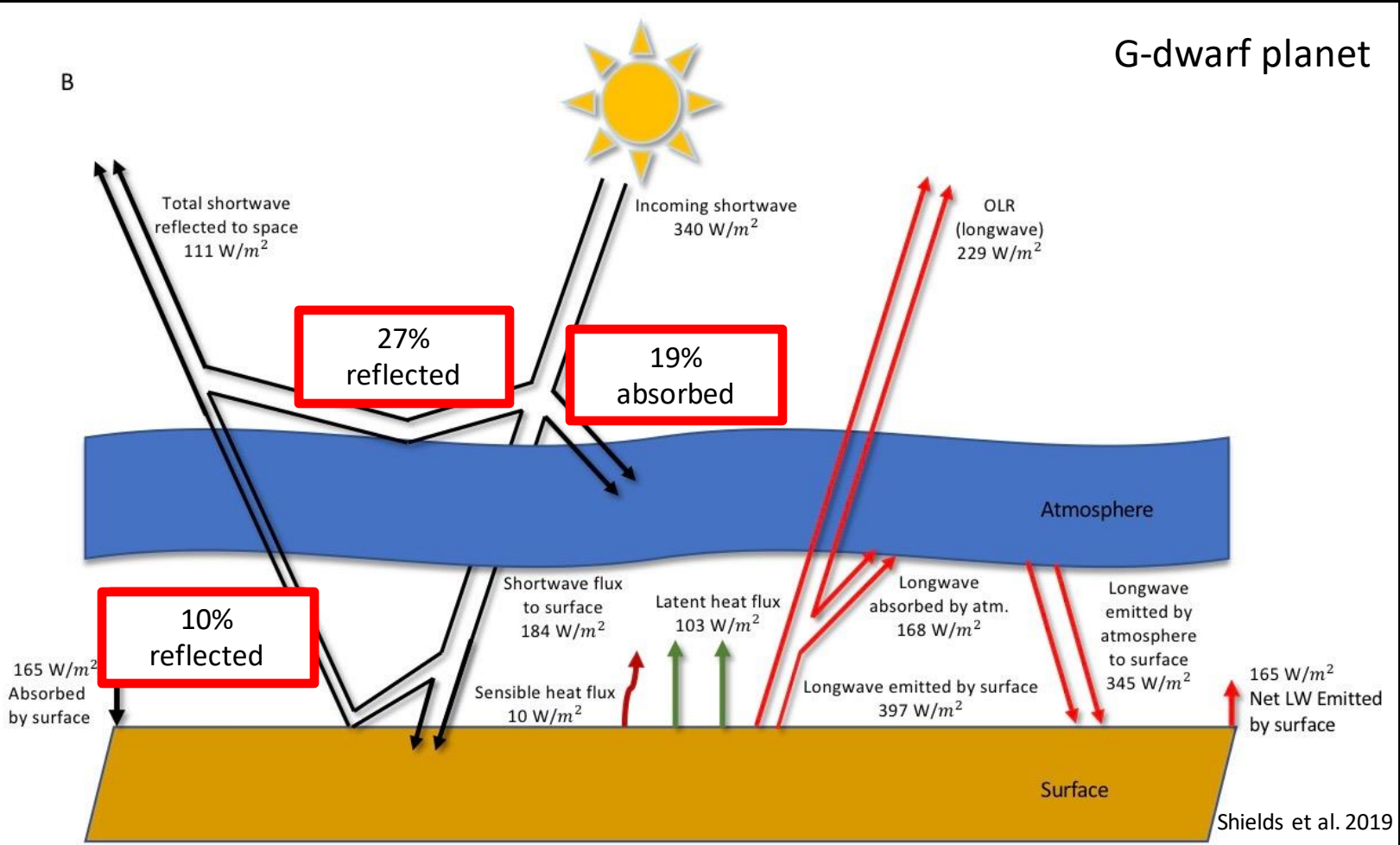
Shields et al. 2019

F-dwarf planet



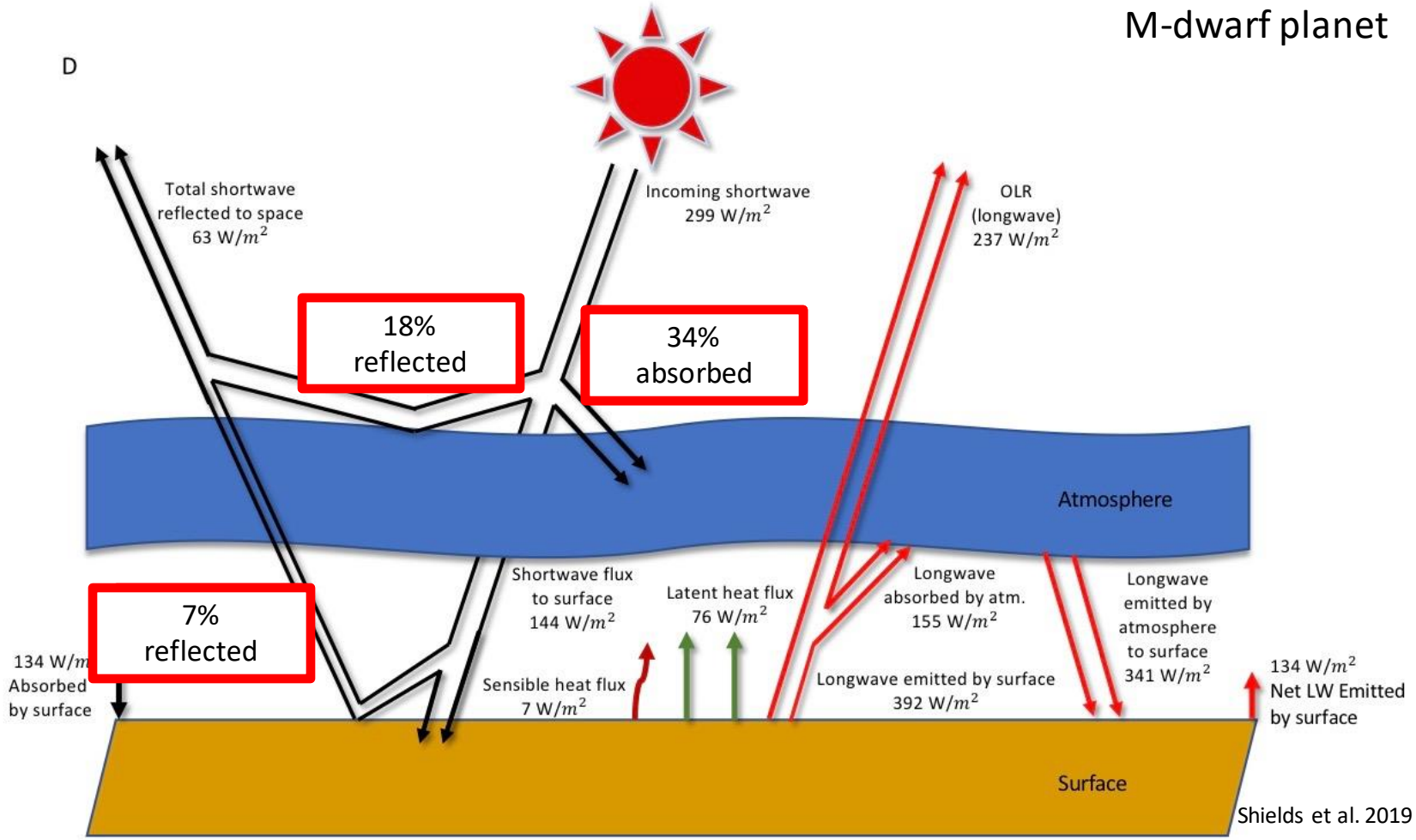
Shields et al. 2019

G-dwarf planet



Shields et al. 2019

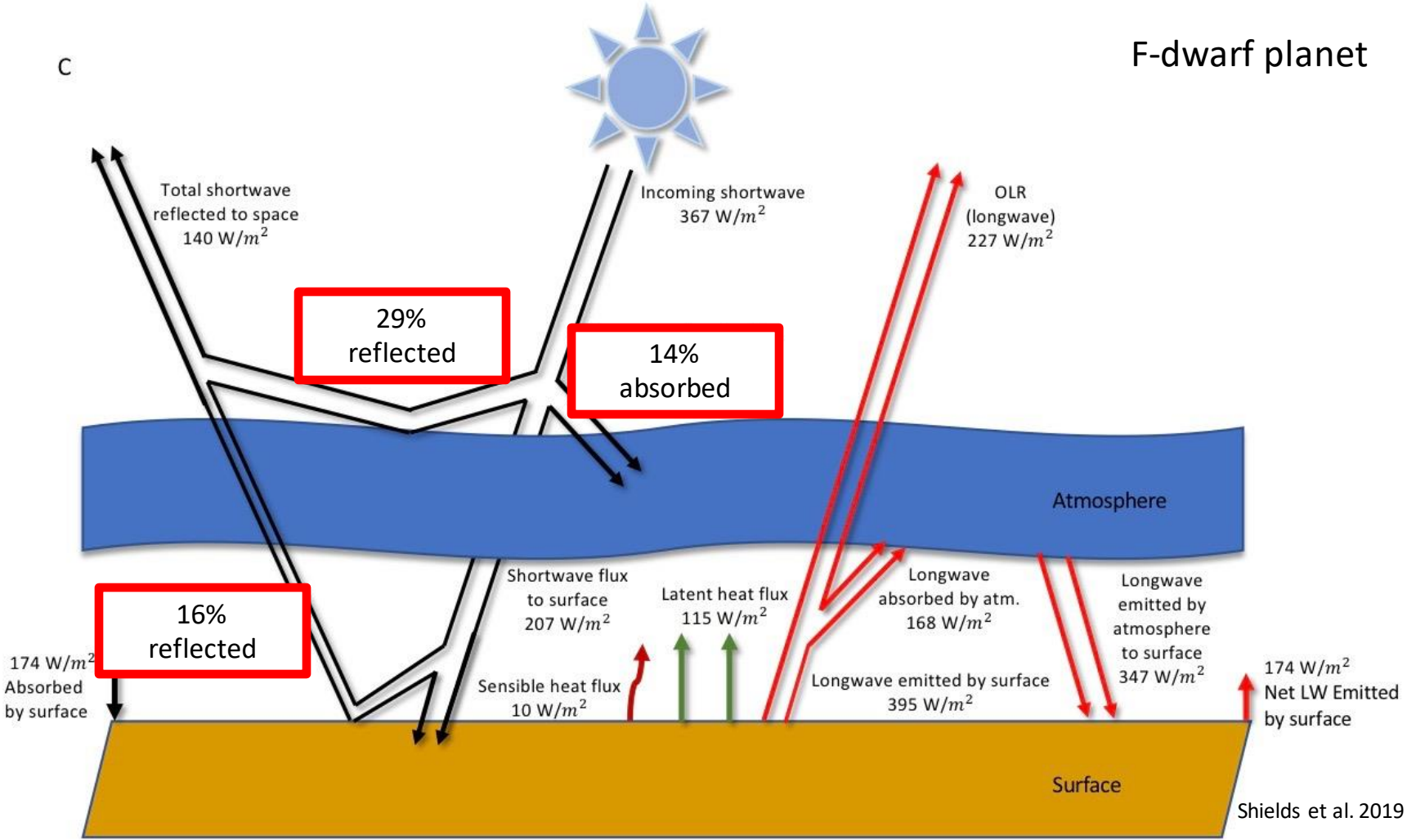
M-dwarf planet



Shields et al. 2019

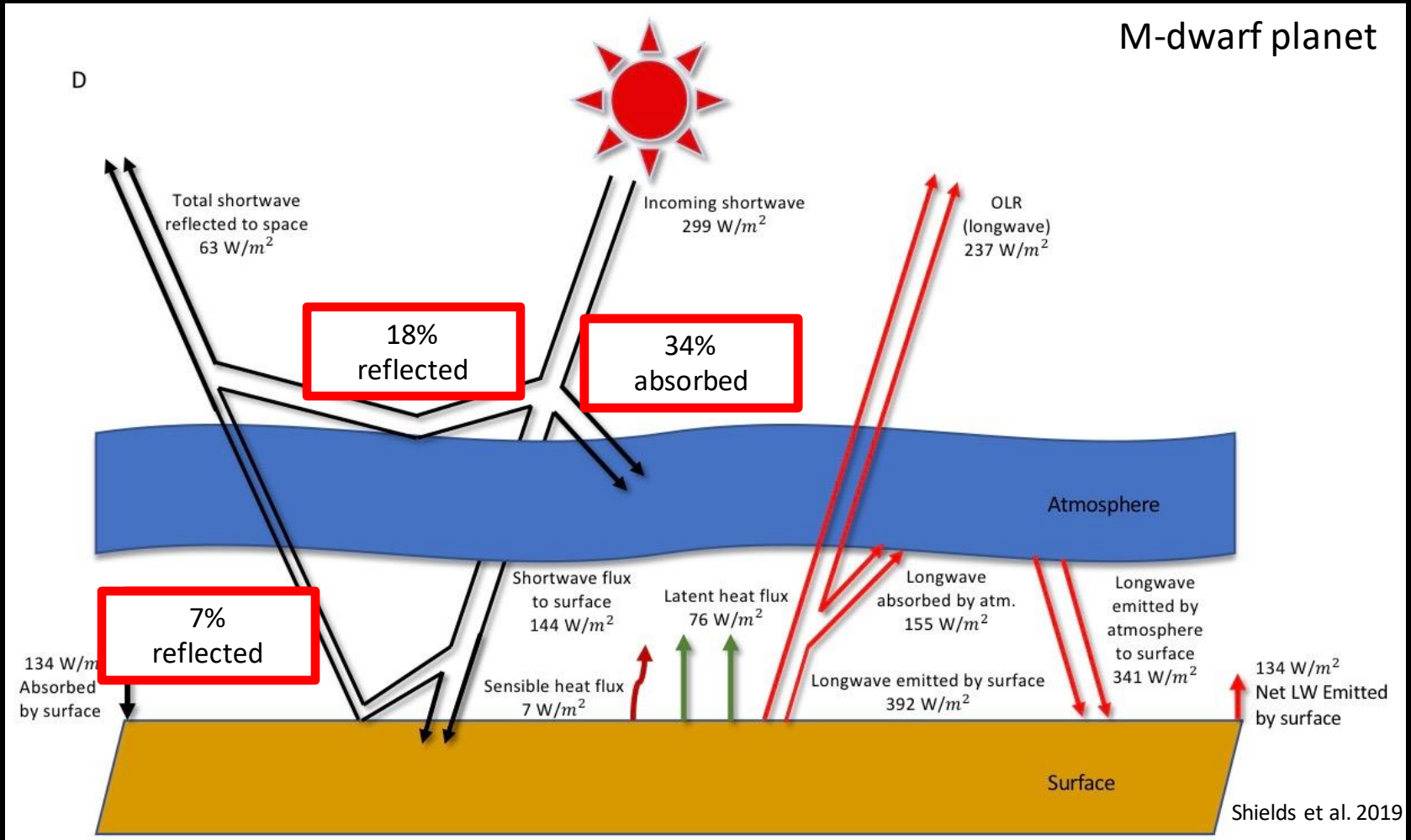
C

F-dwarf planet



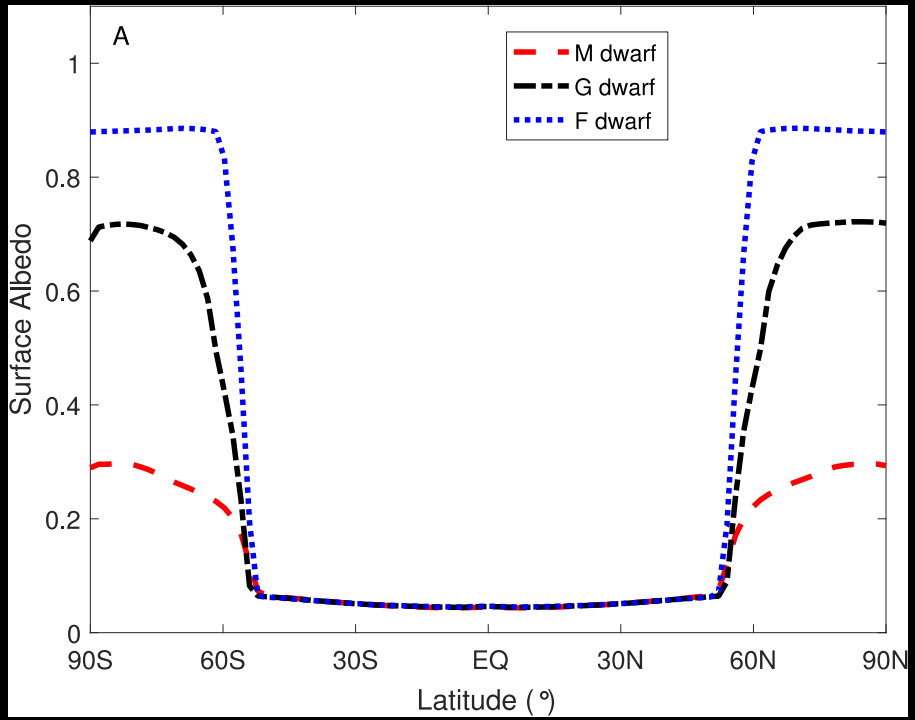
Shields et al. 2019

M-dwarf planet

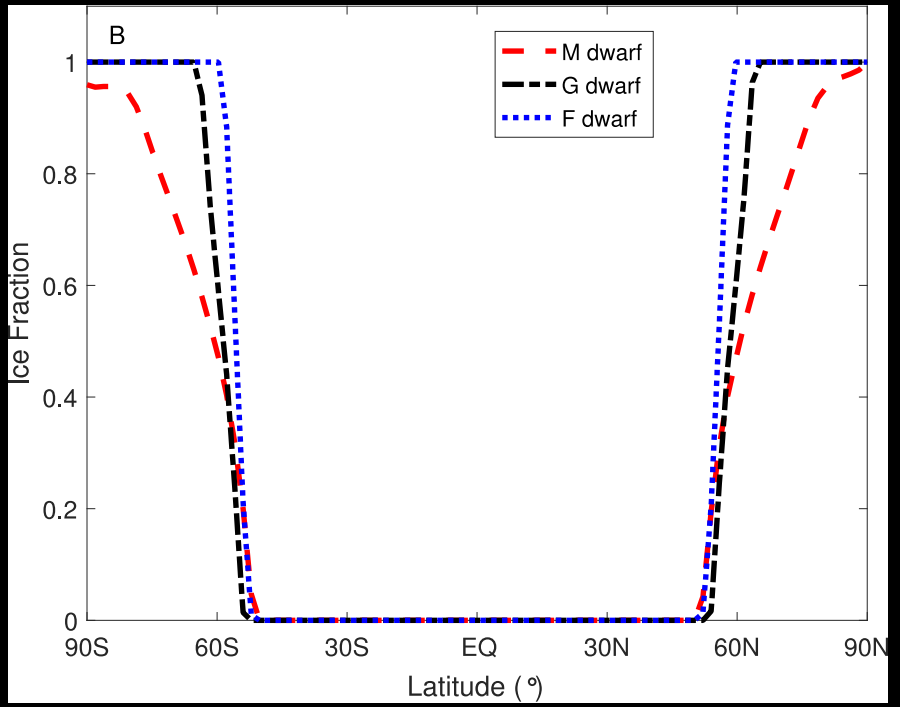


Shields et al. 2019

Surface Albedo

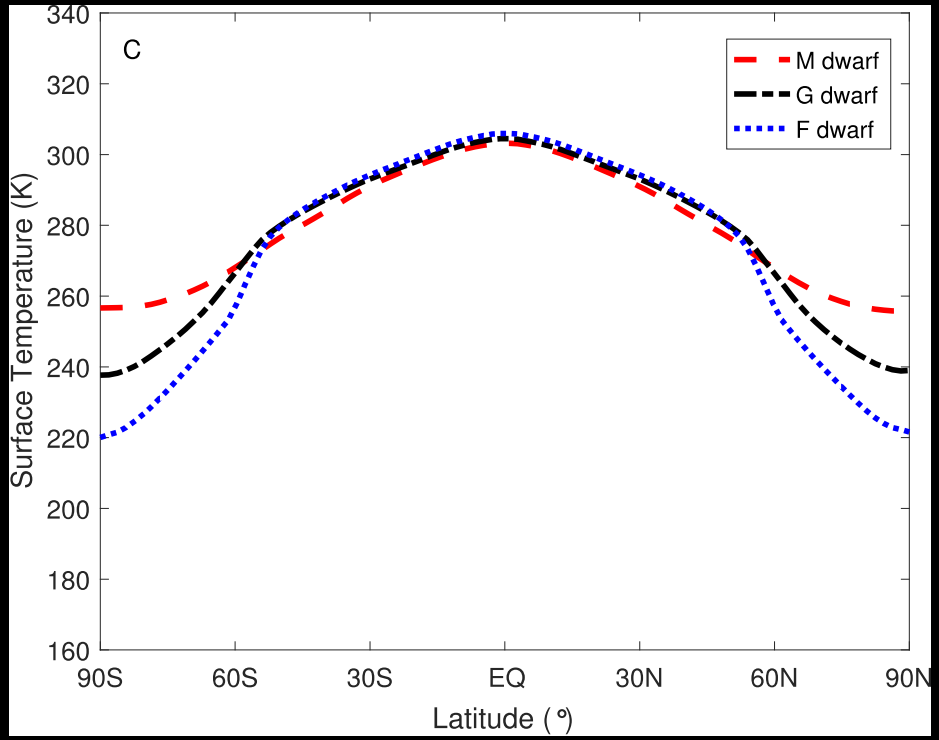


Ice Fraction

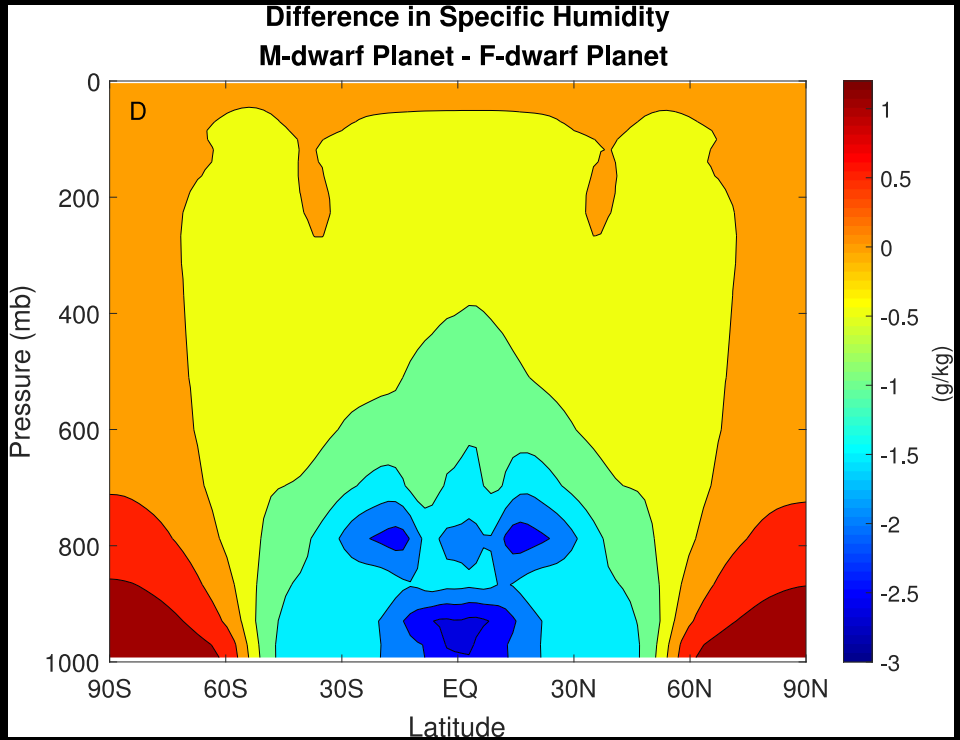


Shields et al. 2019

Surface Temperature

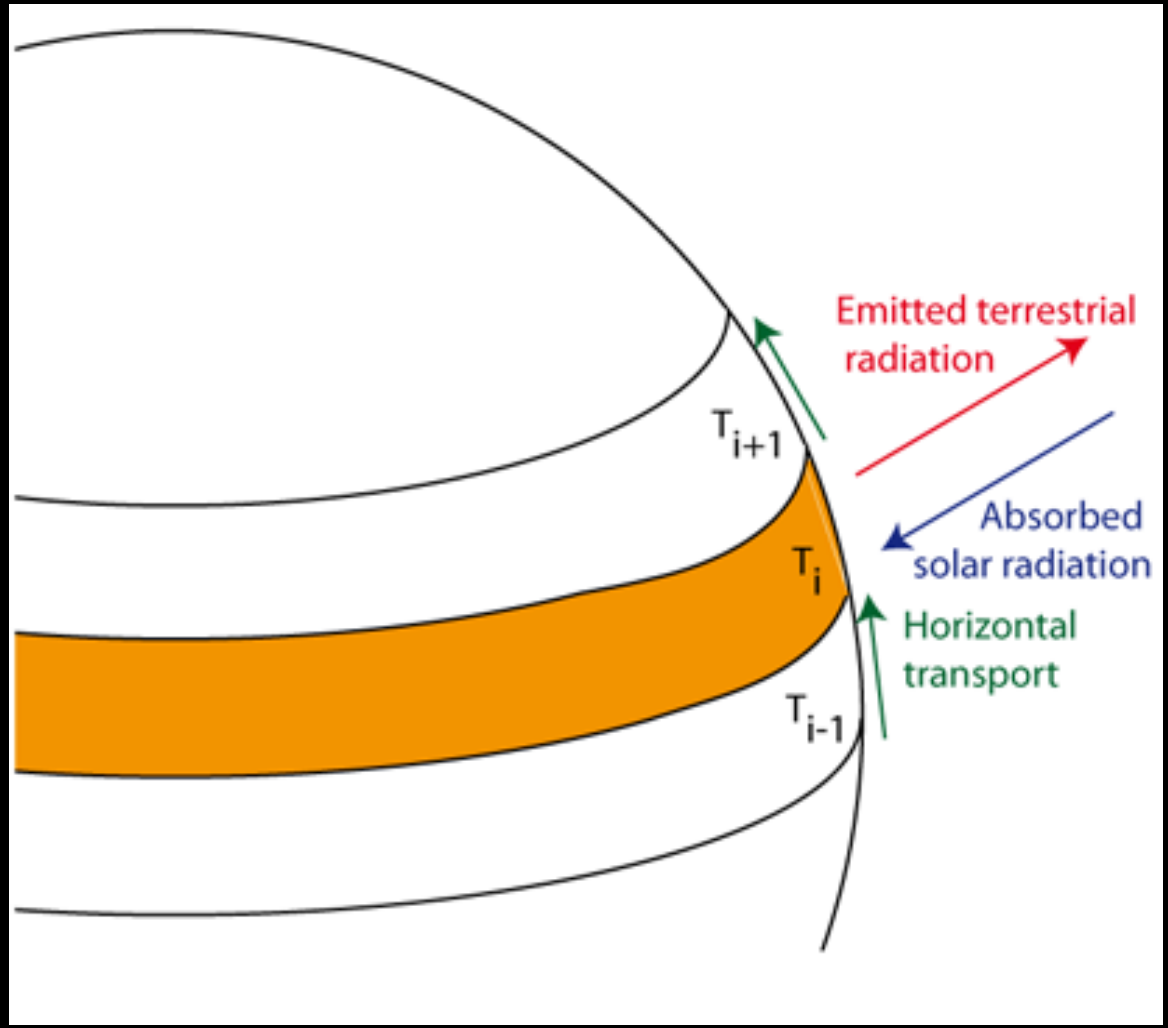


Difference in Specific Humidity



Shields et al. 2019

1-D Energy Balance Model (EBM)



Based on McGuffie and Henderson-Sellers (2005)

EBM

North and Coakley (1979)

$$QS(x,t)(1-\alpha_L) = C_L\frac{dT_L}{dt} - \frac{d}{dx}D(1-x^2)\frac{dT_L}{dx} + \frac{\nu}{f_L(x)}(T_L - T_W) + (A + BT_L)$$

$$QS(x,t)(1-\alpha_W) = C_W\frac{dT_W}{dt} - \frac{d}{dx}D(1-x^2)\frac{dT_W}{dx} + \frac{\nu}{f_W(x)}(T_W - T_L) + (A + BT_W)$$

Planetary response

Heat transport

Ocean and land temperature gradients

Dependence of OLR on Temperature

$$QS(x,t)(1-\alpha_L) = C_L\frac{dT_L}{dt} - \frac{d}{dx}D(1-x^2)\frac{dT_L}{dx} + \frac{\nu}{f_L(x)}(T_L - T_W) + (A + BT_L)$$

$$QS(x,t)(1-\alpha_W) = C_W\frac{dT_W}{dt} - \frac{d}{dx}D(1-x^2)\frac{dT_W}{dx} + \frac{\nu}{f_W(x)}(T_W - T_L) + (A + BT_W)$$

SMART

(Spectral Mapping Atmospheric Radiative Transfer model)

Meadows & Crisp, 1997; Crisp 1997

$$\mu \frac{dI(\tau, \mu, \phi, \nu)}{d\tau} = I(\tau, \mu, \phi, \nu) - S(\tau, \mu, \phi, \nu)$$

$$\begin{aligned} S(\tau, \mu, \phi, \nu) = & \frac{\omega(\tau, \nu)}{4\pi} \int_0^{2\pi} \mathrm{d}\phi' \int_{-1}^{1} \mathrm{d}\mu' P(\tau, \mu, \phi, \mu', \phi', \nu) I(\tau, \mu', \phi', \nu) \\ & + [1 - \omega(\tau, \nu)] B[\nu, T(\tau)] \\ & + \frac{\omega(\tau, \nu)}{4\pi} F_{\odot} P(\tau, \mu, \phi - \mu_{\odot}, \phi_{\odot}, \nu) \exp(-\tau/\mu_{\odot}) \end{aligned}$$

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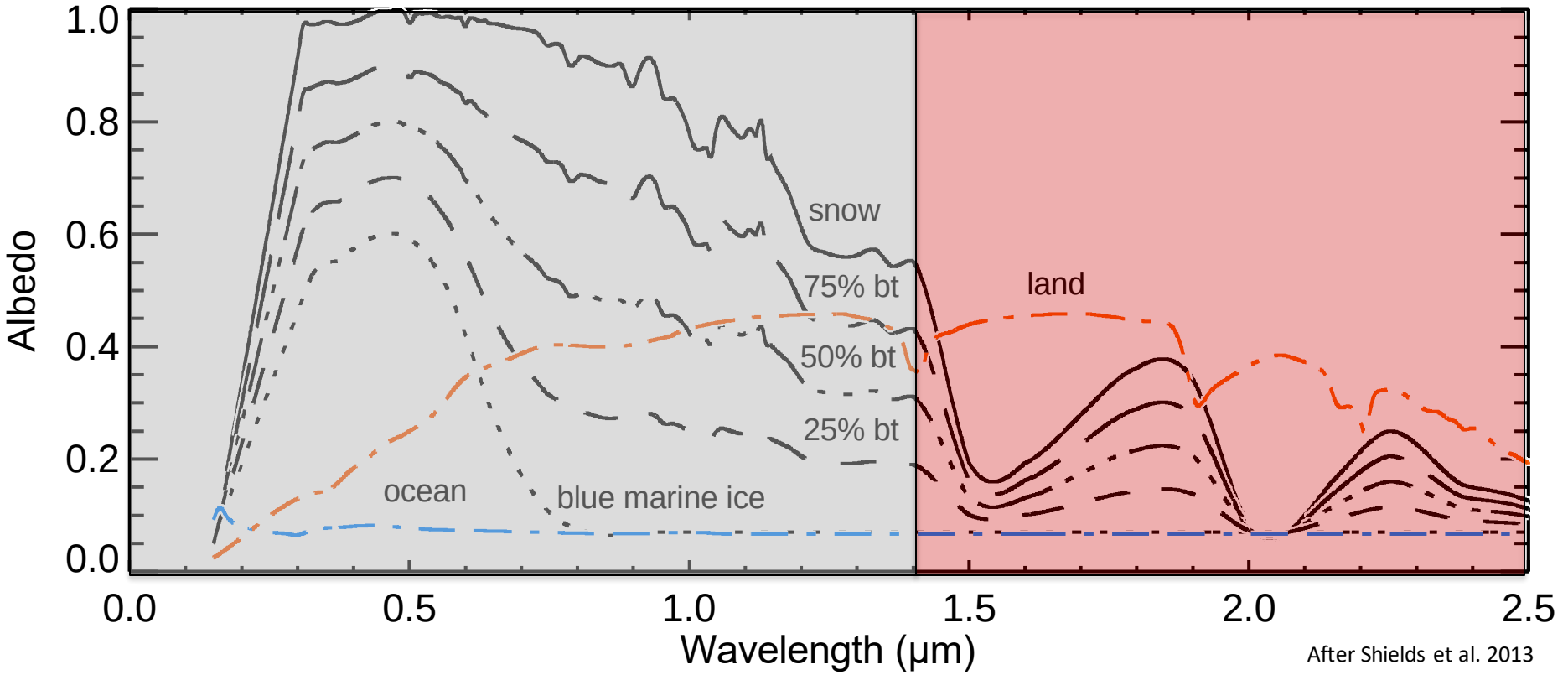
Land planets orbiting M-dwarf stars

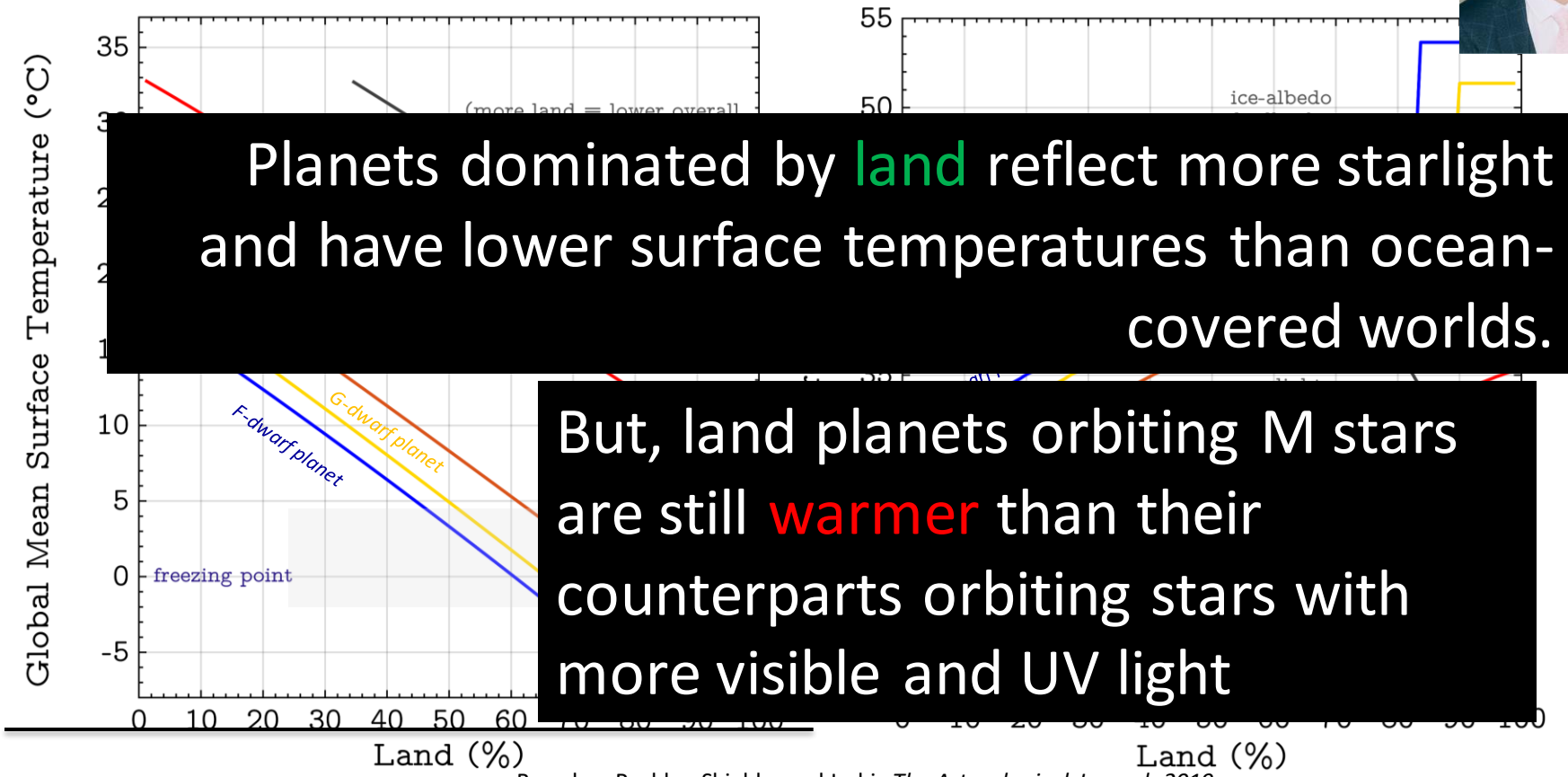


After Shields et al. 2013

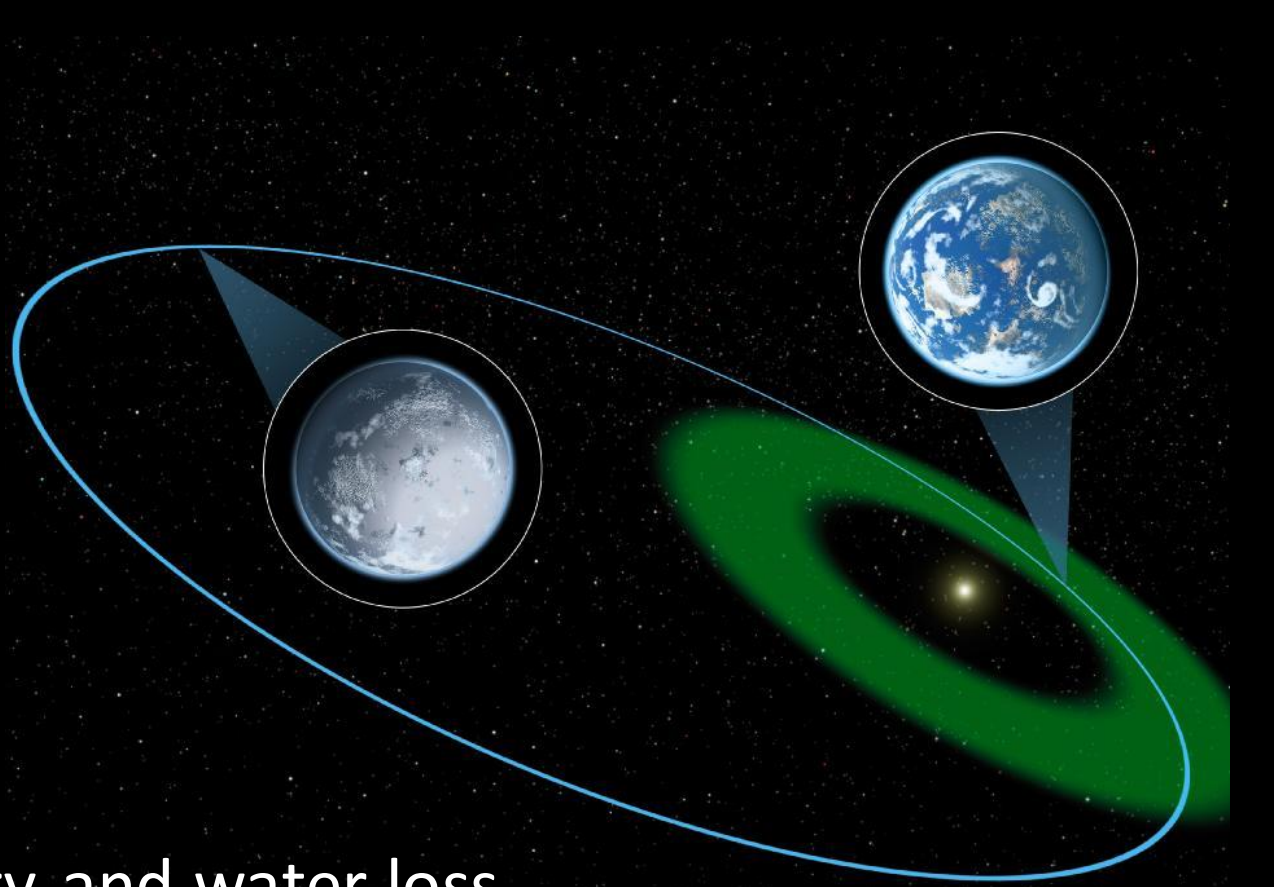
Andrew Rushby

Planets dominated by land reflect more starlight and have lower surface temperatures than ocean-covered worlds.

But, land planets orbiting M stars are still warmer than their counterparts orbiting stars with more visible and UV light



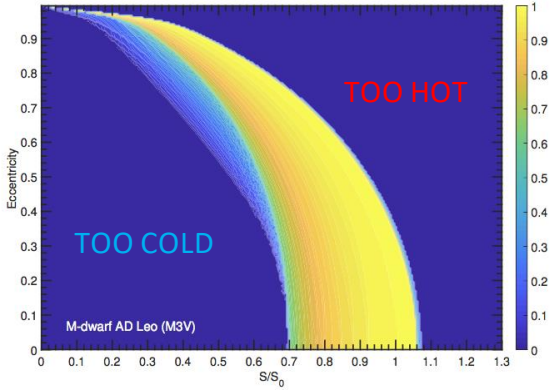
Based on Rushby, Shields, and Joshi, *The Astrophysical Journal, 2019*

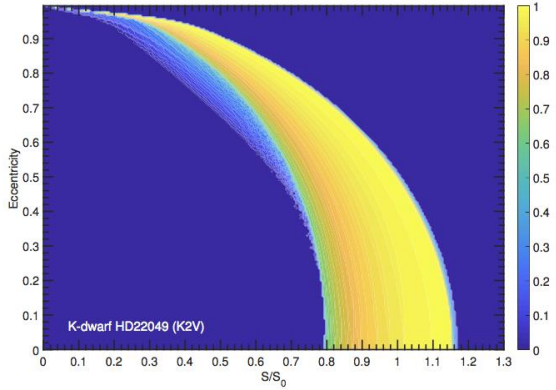


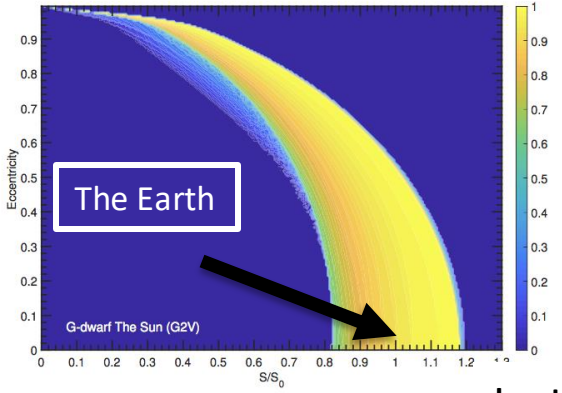
Temporal habitability and water loss on eccentric planets

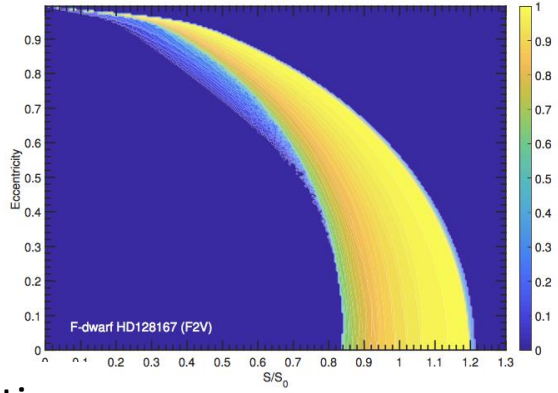
Recipe for a Habitable World

Eccentricity





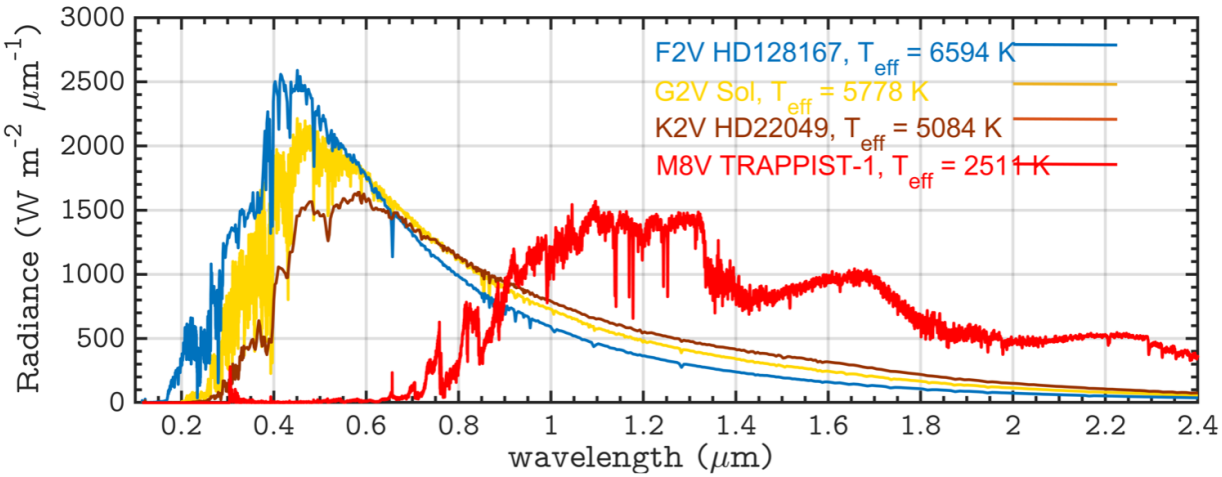


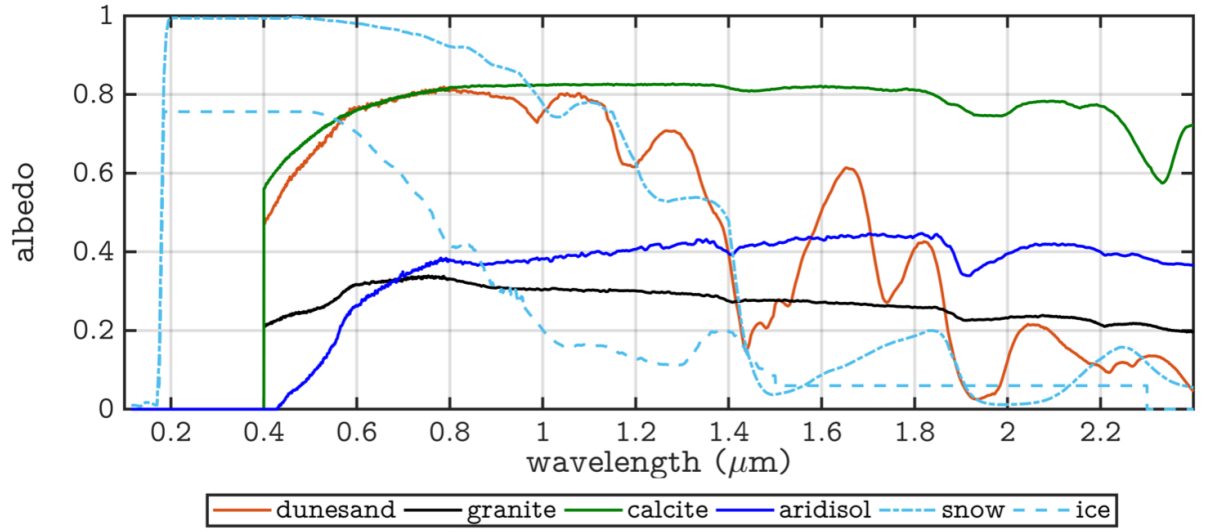


Instellation

Planets orbiting cooler stars are thawed for larger fractions of the year

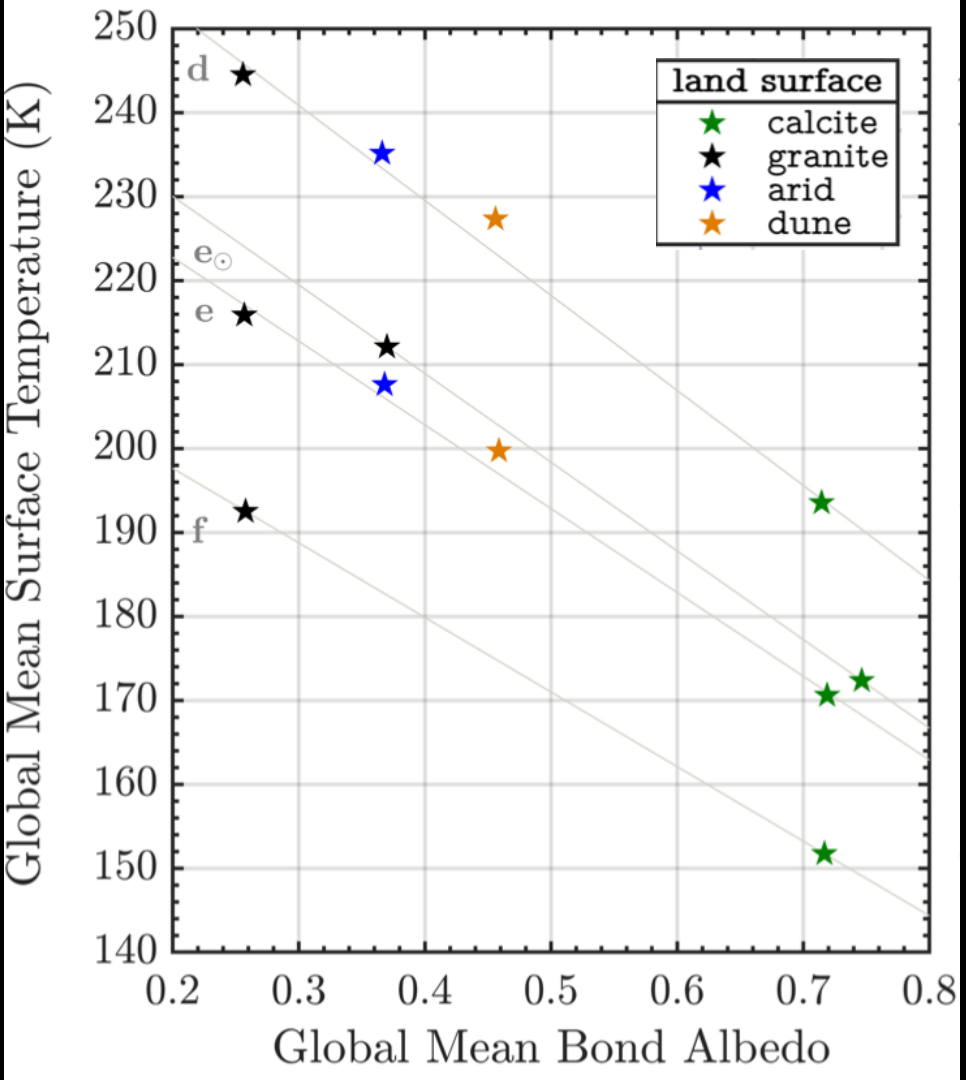
Palubski, Shields, and Deitrick, *The Astrophysical Journal*, 2020





Different land surfaces will have different albedos and resulting effects on the climate of TRAPPIST-1 planets

Rushby, Shields, Wolf, et al. *ApJ,* in review

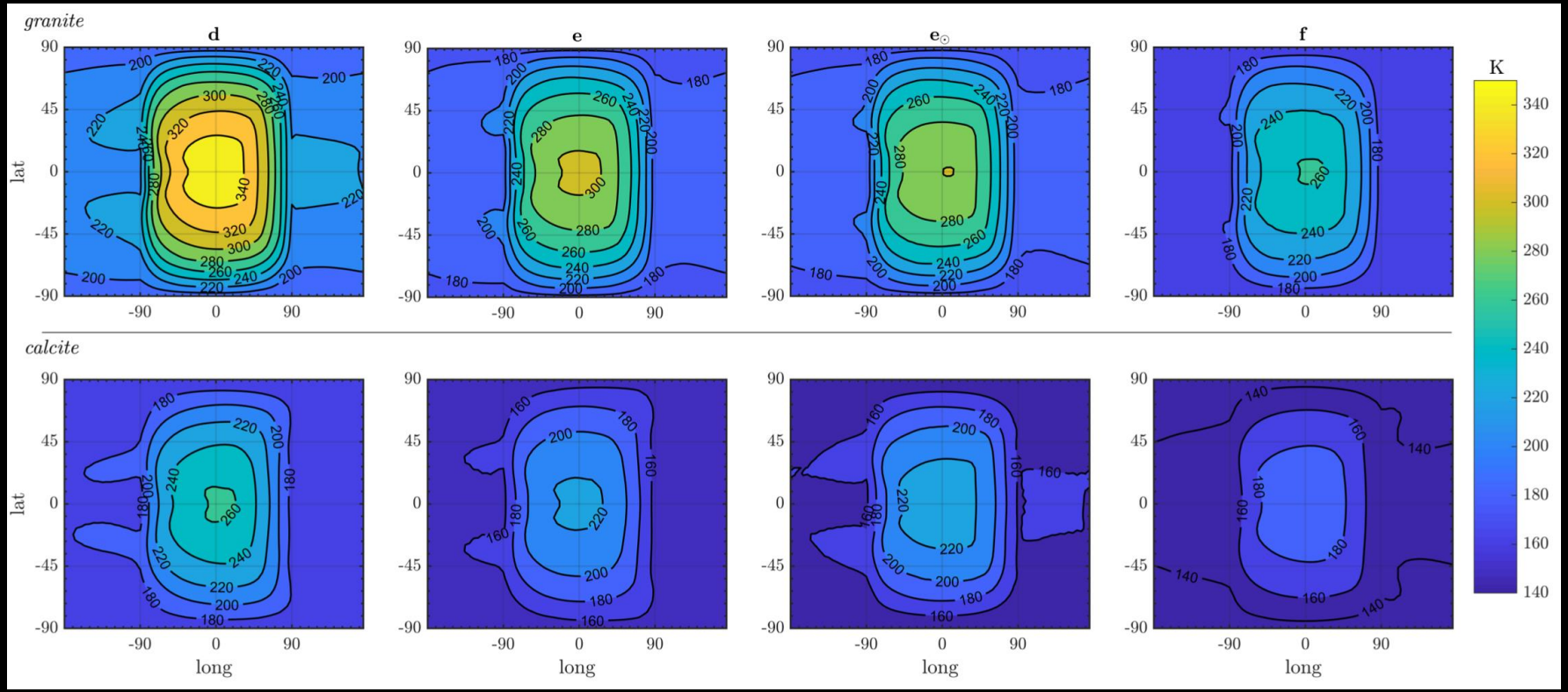


Differences of 50 K across lowest (granite) to highest (calcite) albedo land surface

Rushby, Shields, Wolf, et al. *ApJ,* in review

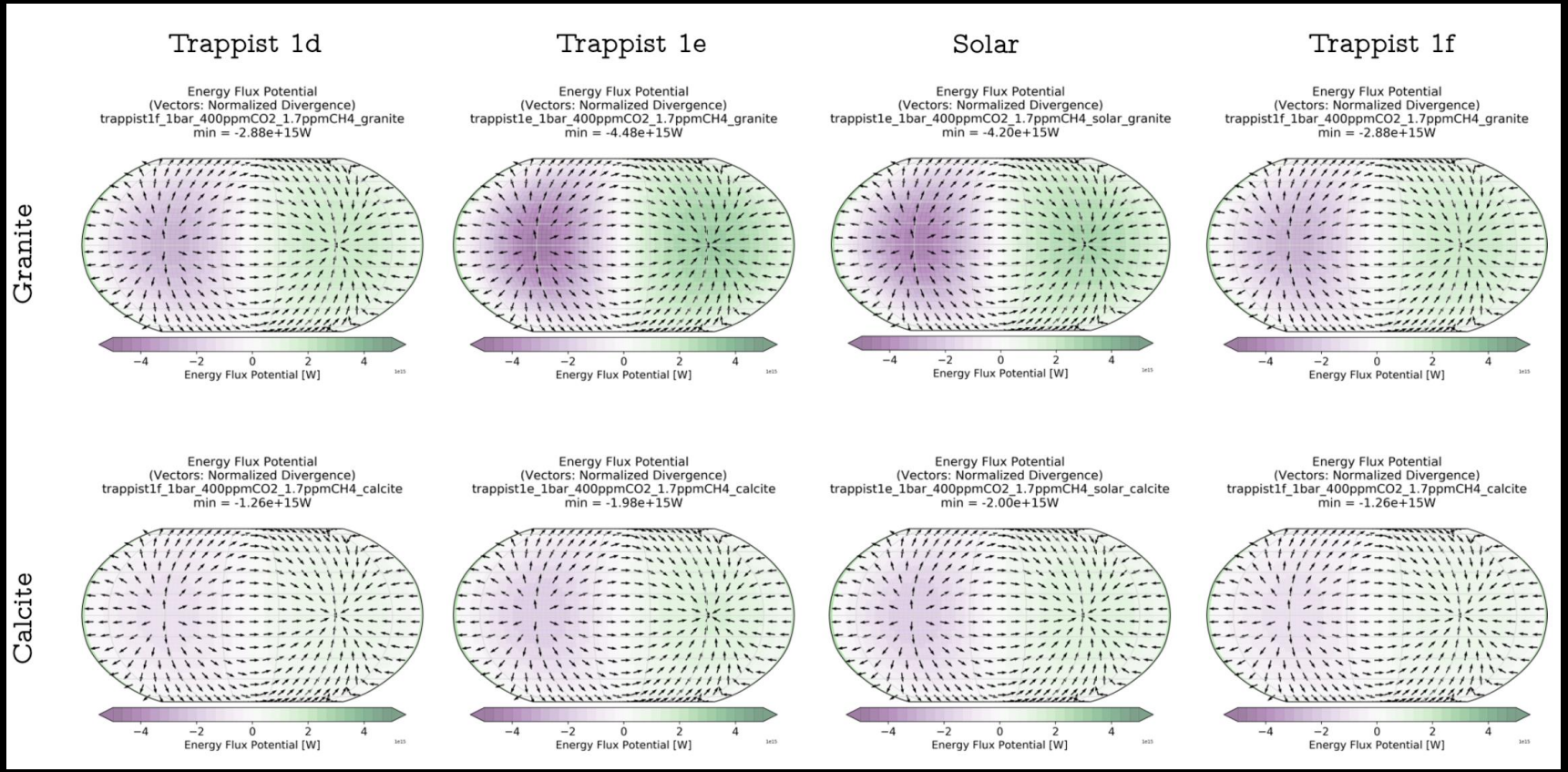
Surface Temperature

TRAPPIST-1d most capable of supporting life (with low albedo surface (ex. igneous rock)



Rushby, Shields, Wolf, et al. *ApJ*, in press

cross-equatorial energy transport increased for lower-albedo planets



Rushby, Shields, Wolf, et al. *ApJ*, in press

Aomaw e World

Take –away points

- Surface composition affects planetary climate and habitability
- Important to incorporate spectral dependence of ice, snow, salt, and land albedos into GCMs
- Allows for more realistic assessments of possible climates and habitability of exoplanets

Acknowledgments

- UCI
- National Science Foundation
- NASA Habitable Worlds Program
- Clare Boothe Luce Foundation
- UC President's Postdoctoral Fellowship Program
- Virtual Planetary Laboratory
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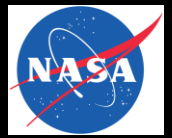
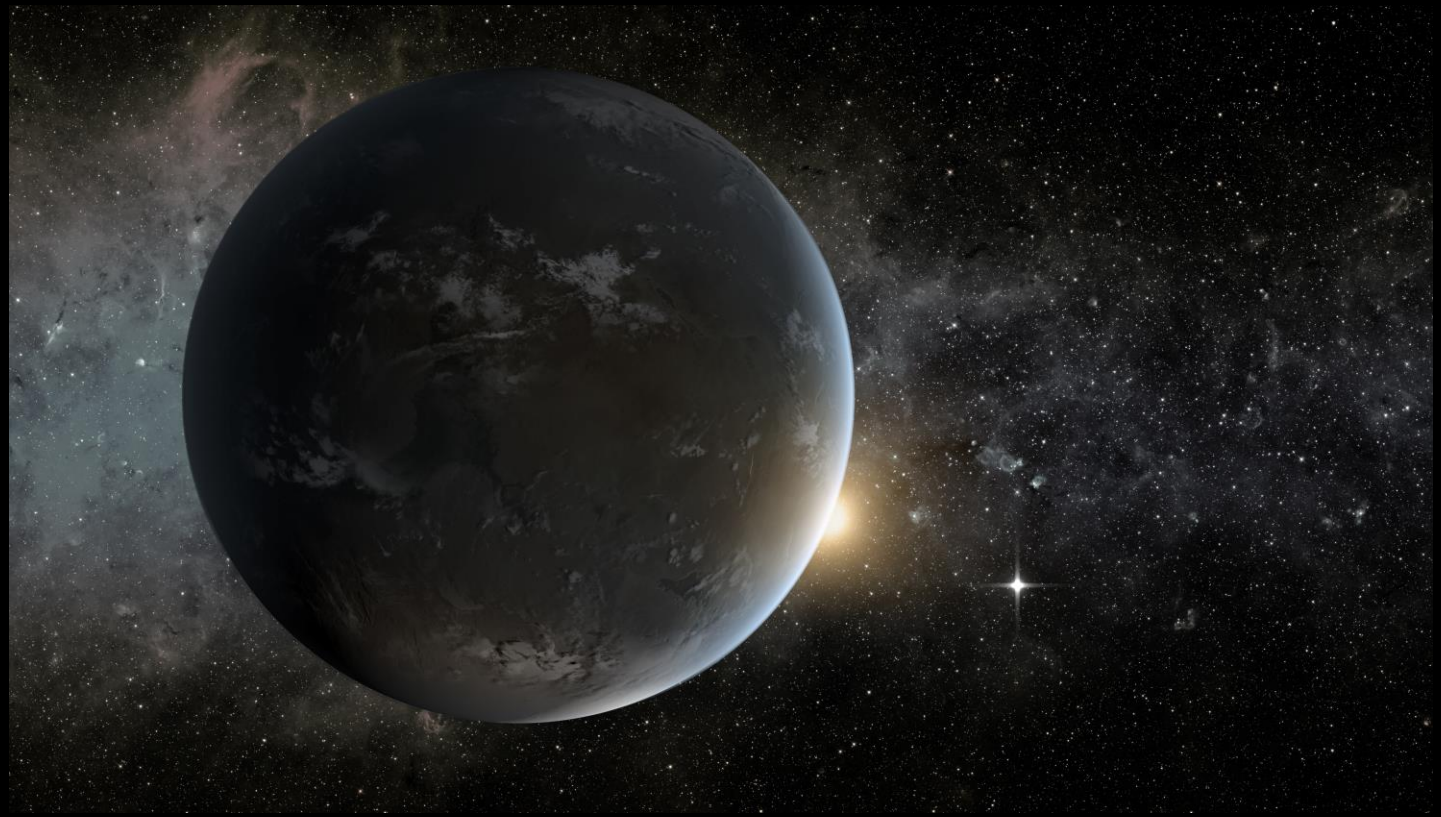


Thank you!



NASA Ames/JPL-Caltech/Tim Pyle

Take –away points

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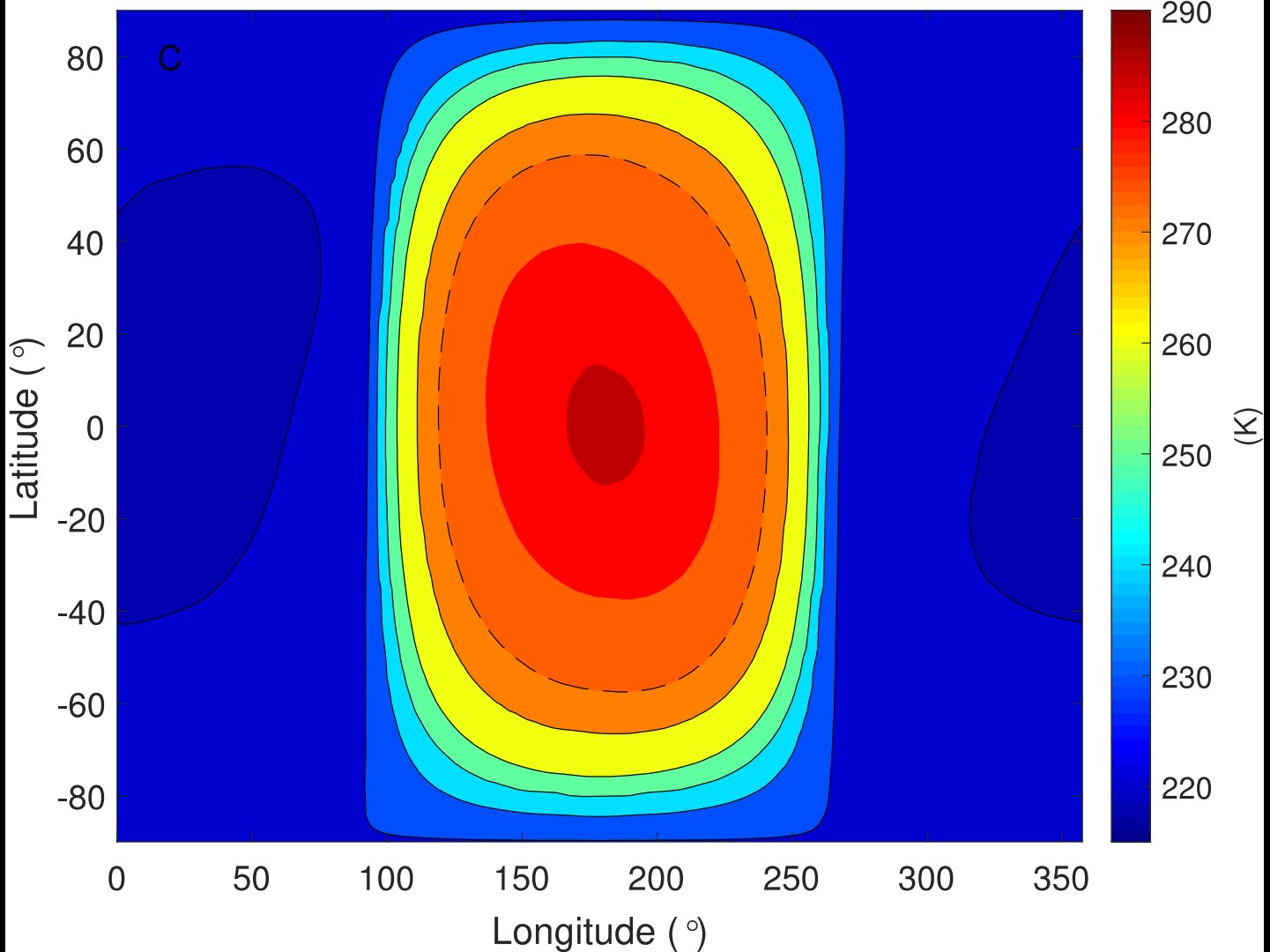
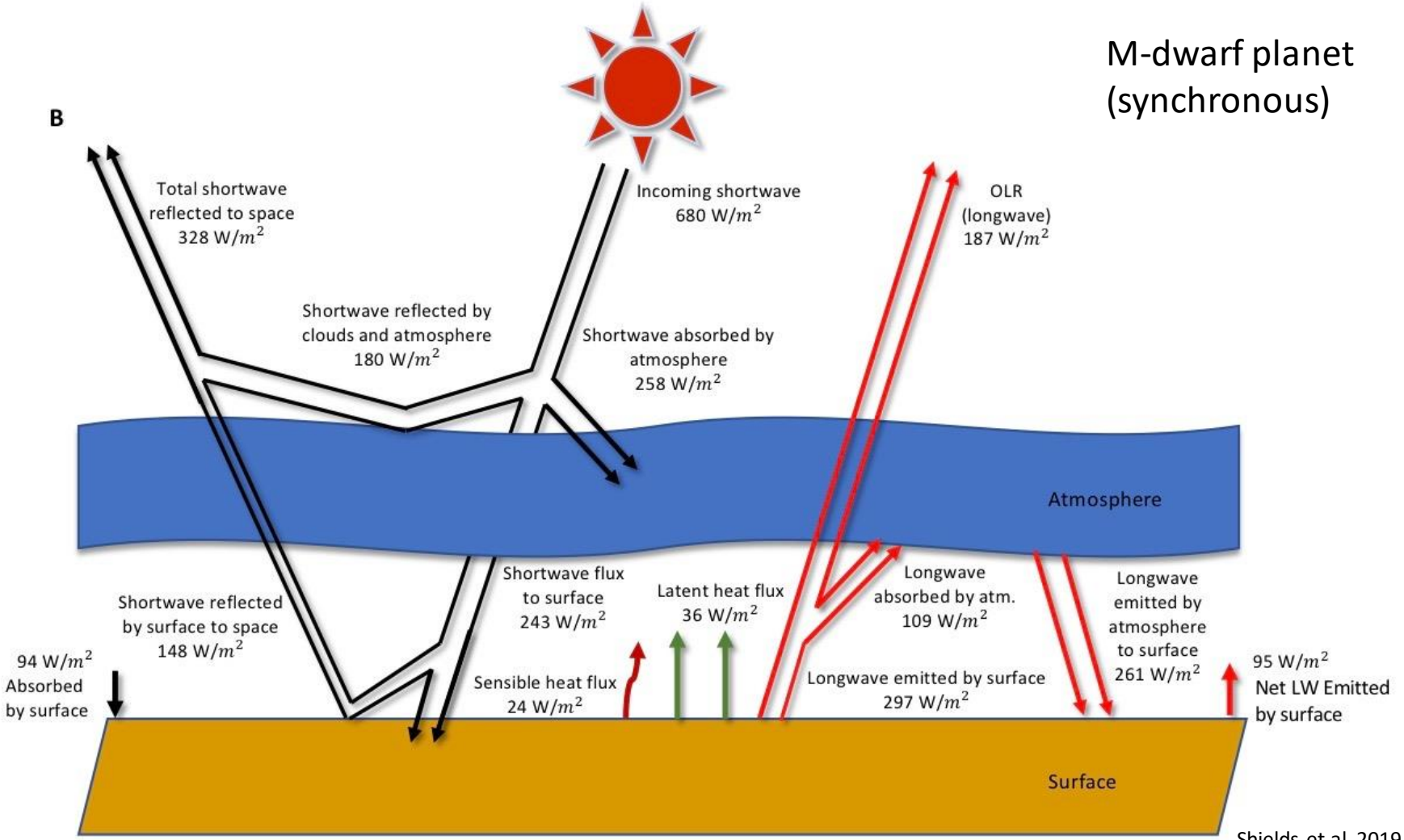
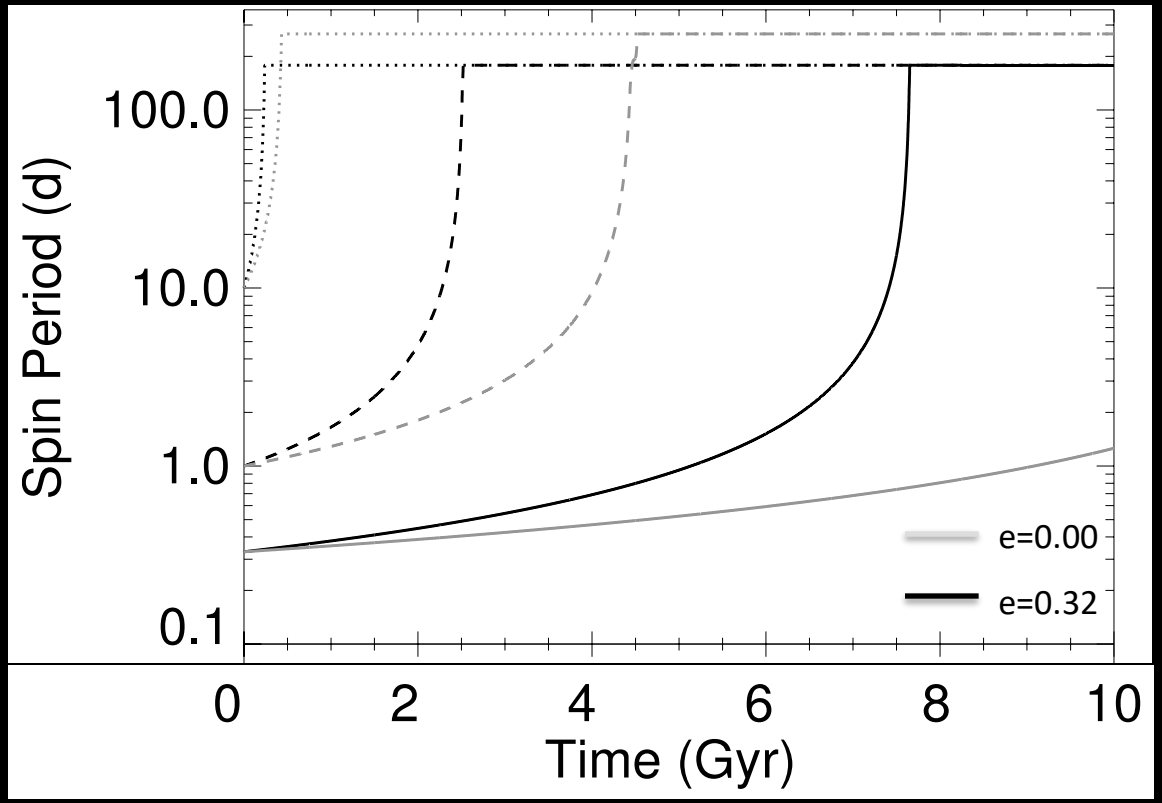

C
80
60
40
20
0
-20
-40
-60
-80
Latitude (°)
0
50
100
150
200
250
300
350
Longitude (°)
290
280
270
260
250
240
230
220
(K)

M-dwarf planet (synchronous)



Shields et al. 2019

Synchronous rotation is possible for Kepler-62f

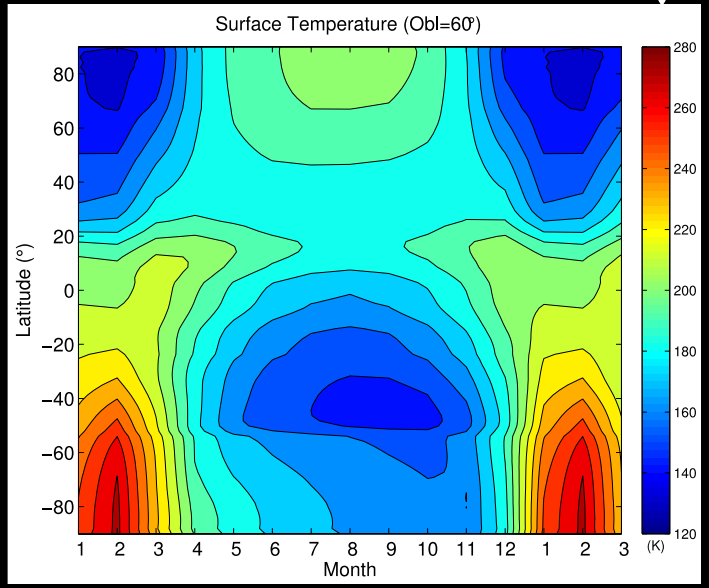


Shields et al. (2016a)

Surface Temperature

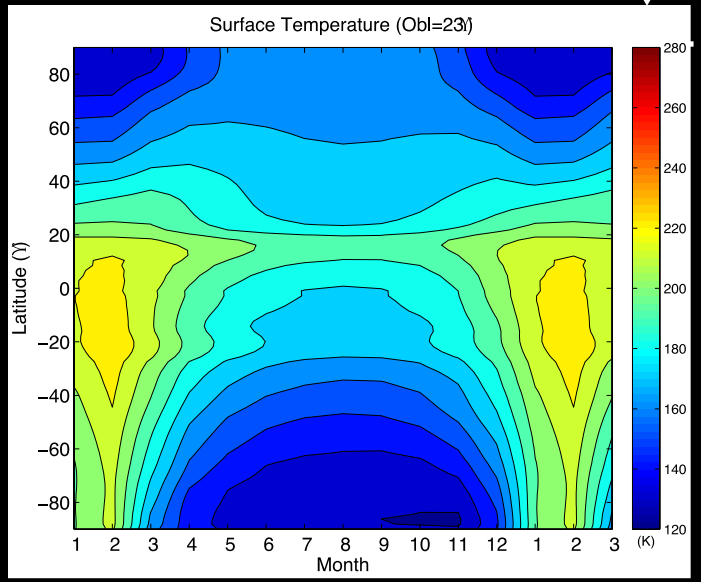
freezing point

Obliquity = 60°



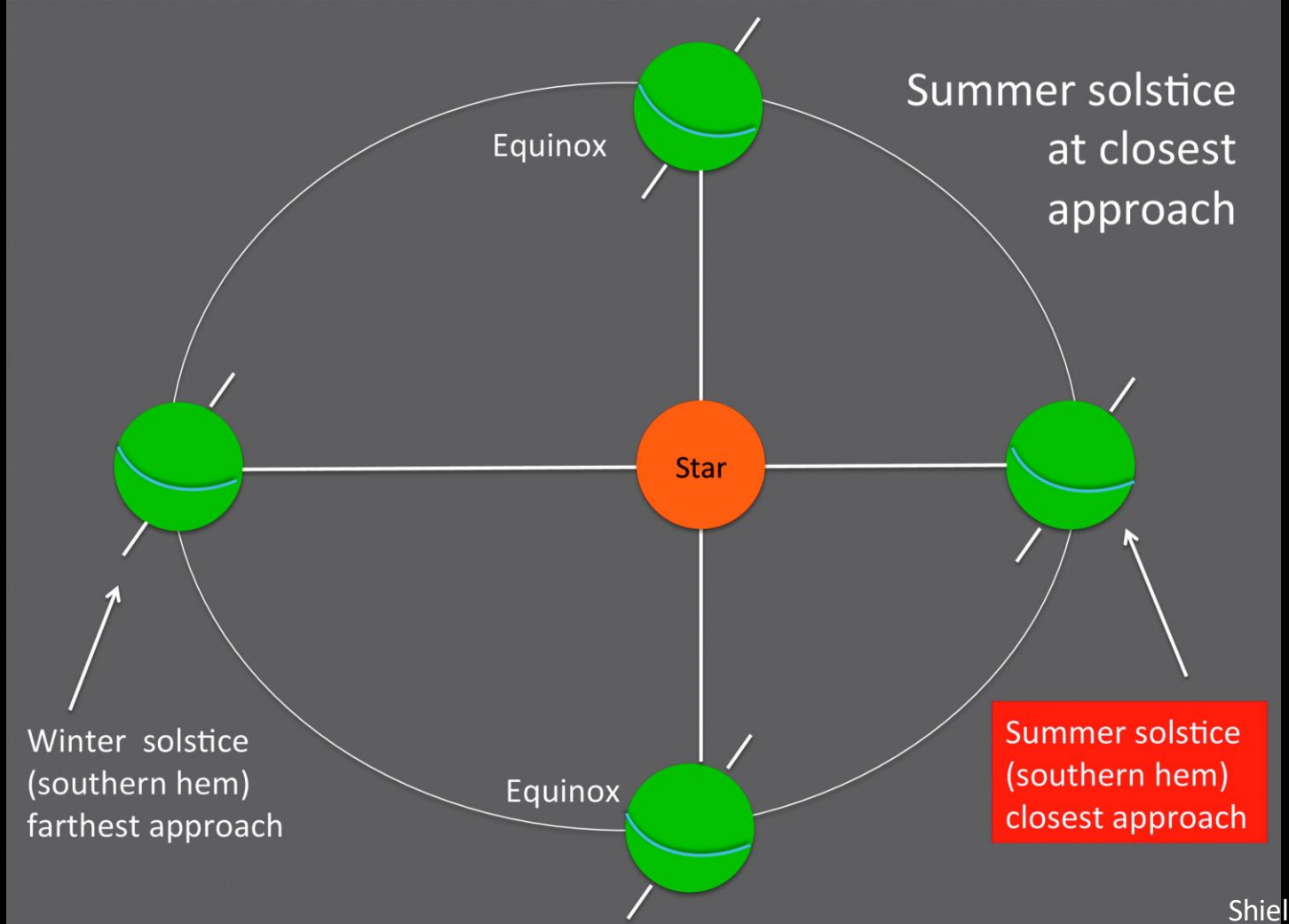
freezing point

Obliquity = 23°



Shields et al. (2016a)

Southern hemisphere summer



Shields et al. (2016a)

Rising Stargirls

RISING STARGIRLS

STARS SHINE IN MANY COLORS.