The Climates of Other Worlds:
Exoplanet Climatology as a Pathway to Accurate Assessments of Planetary Habitability

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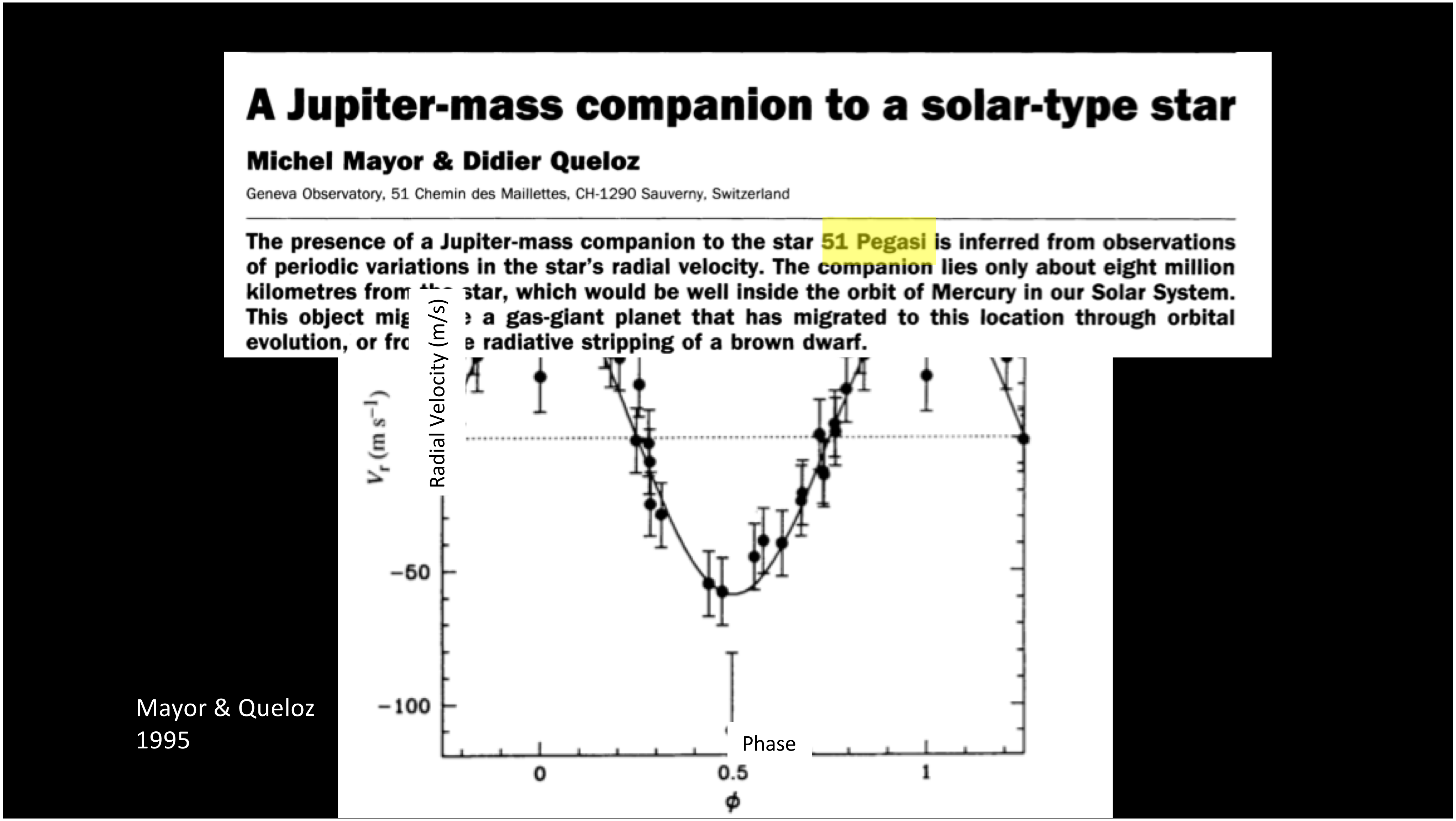
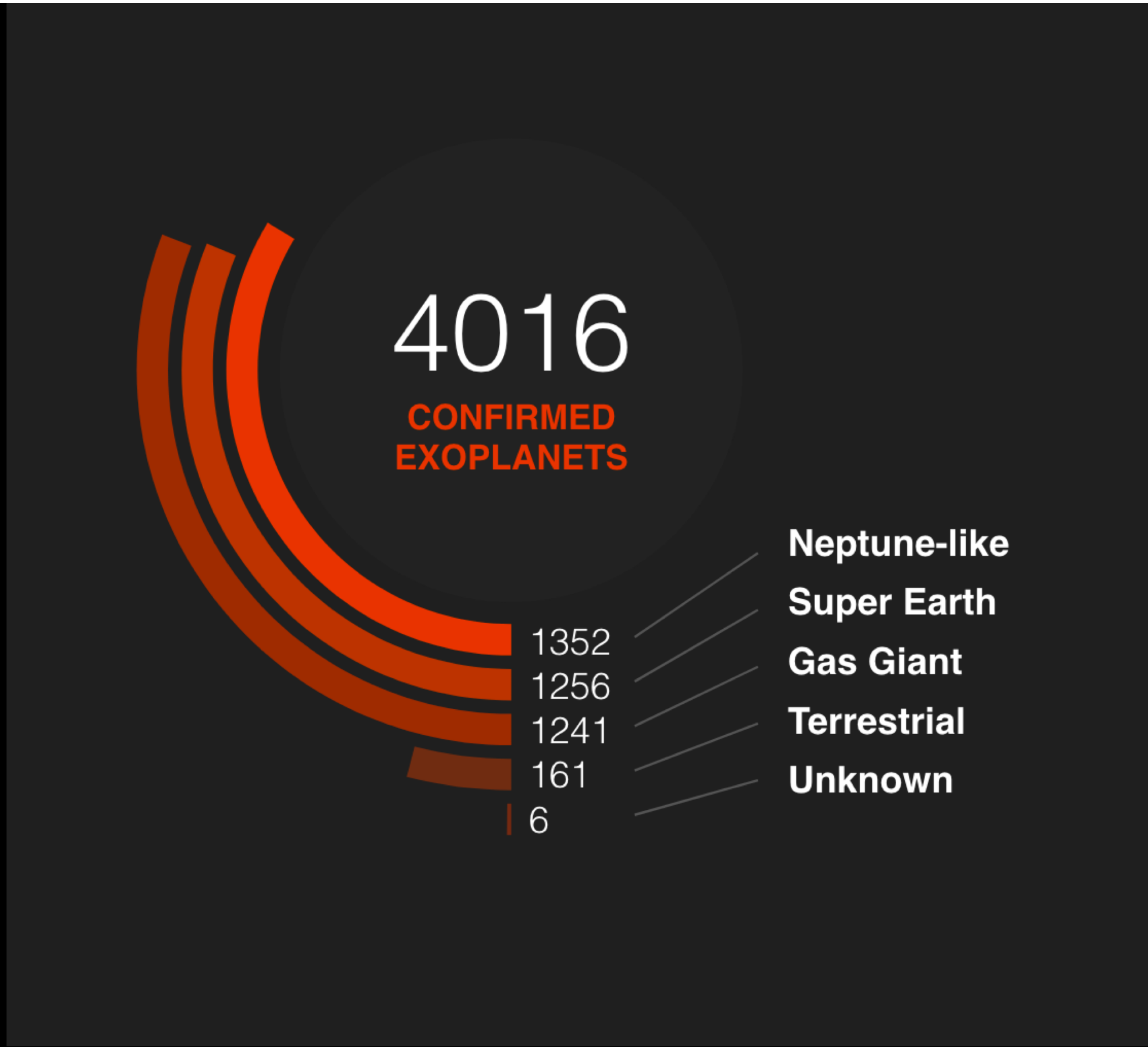
University of California, Irvine

Sagan Exoplanet Summer Workshop

July 18, 2019

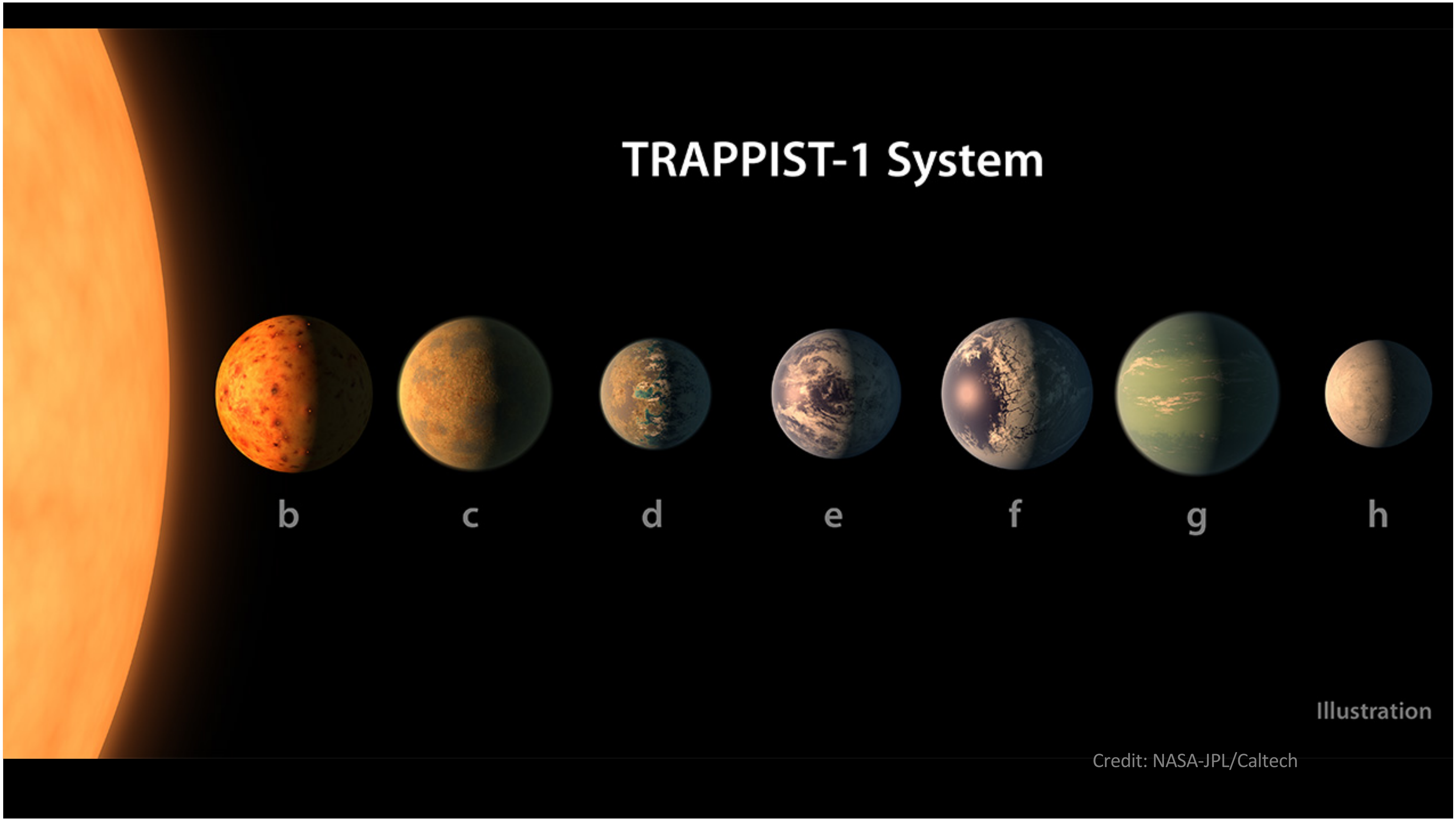

WE'RE LIVING
IN A WHOLE NEW UNIVERSE NOW...


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
star, which would be well inside the orbit of Mercury in our Solar System.
This object mig
a gas-giant planet that has migrated to this location through orbital
evolution, or fro
e radiative stripping of a brown dwarf.
Radial Velocity (m/s)
−50
−100
Phase
0
0.5
1
ϕ
Mayor & Queloz
1995



https://exoplanets.nasa.gov/

As of July 17, 2019


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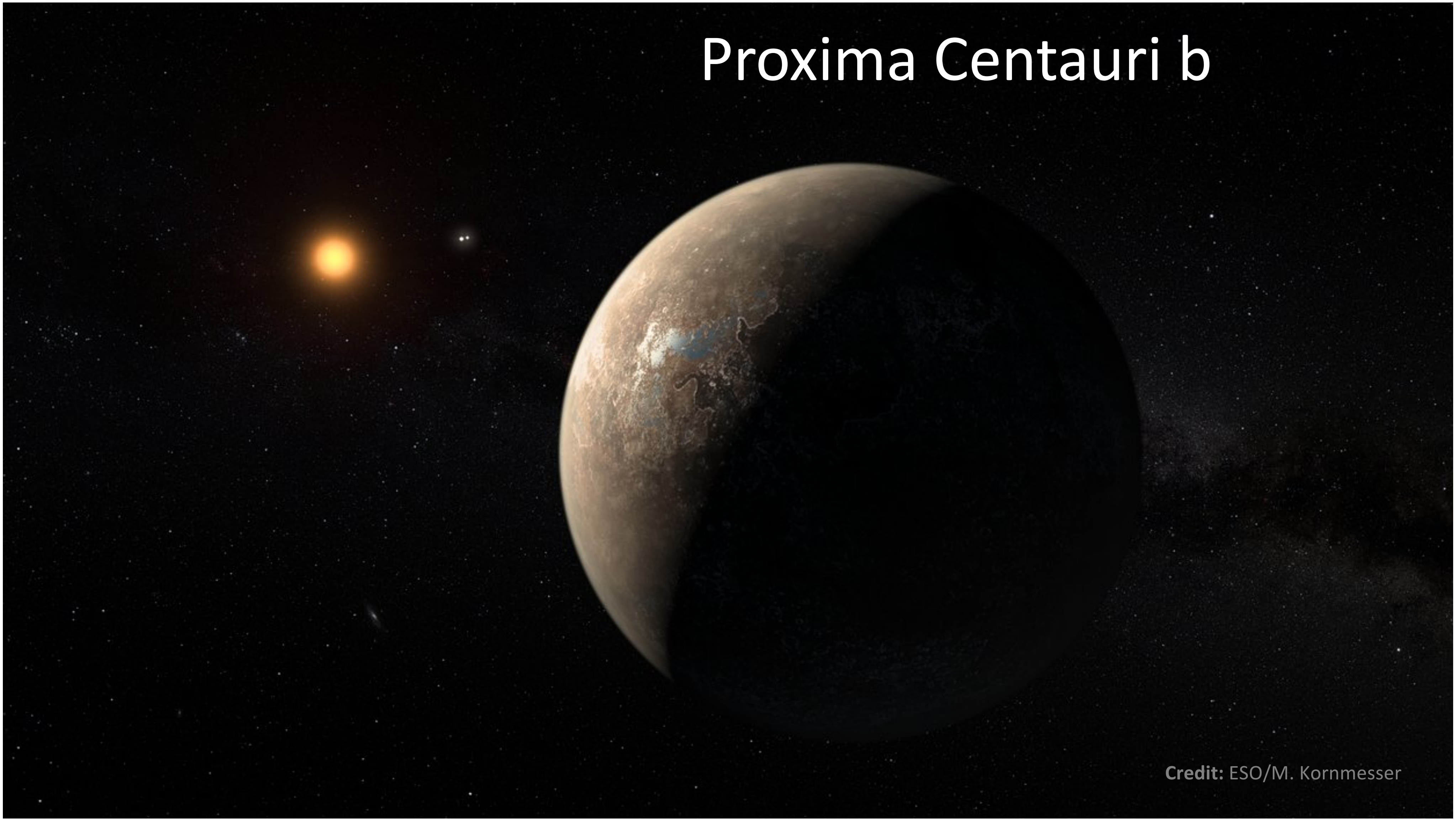
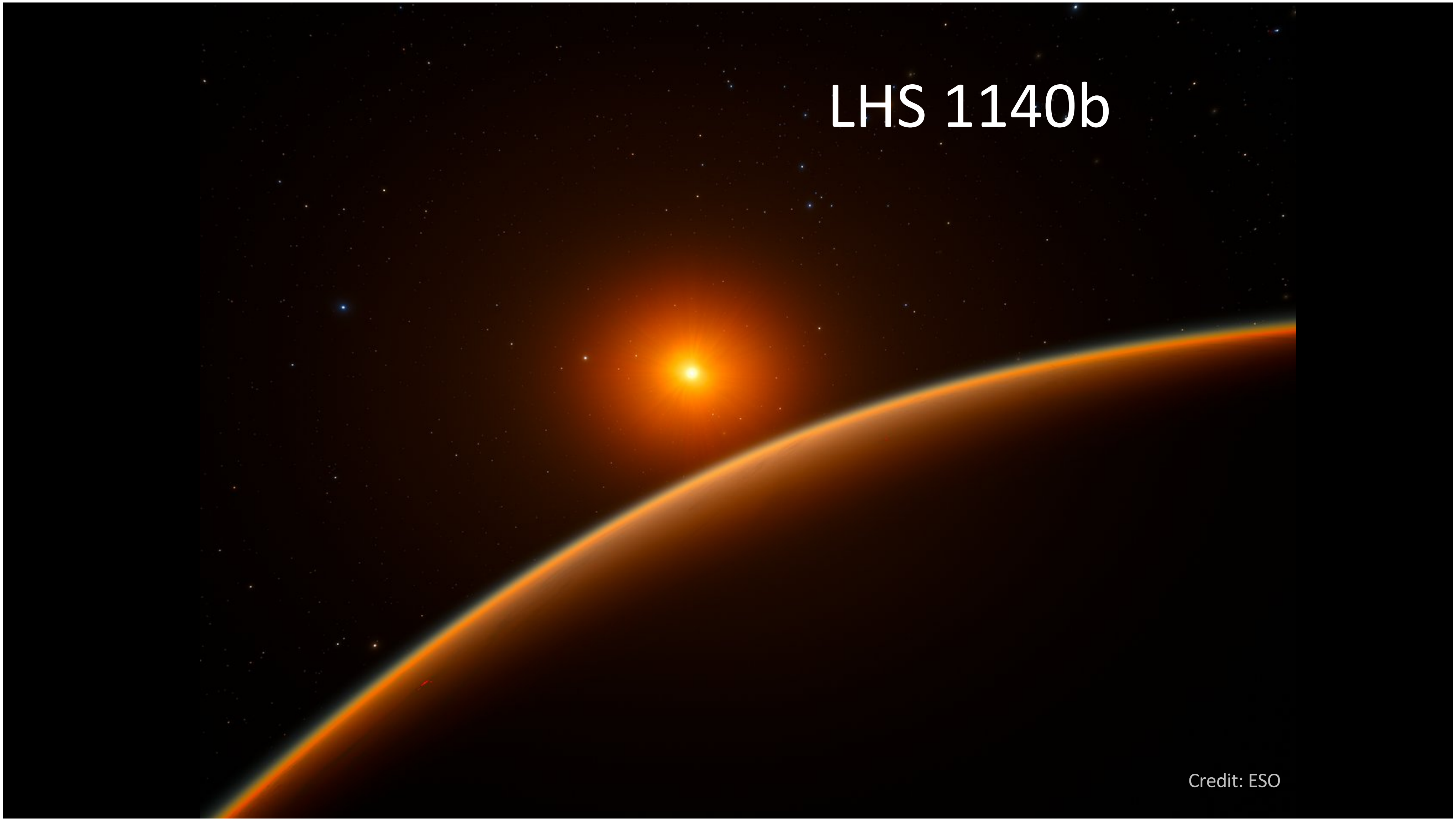
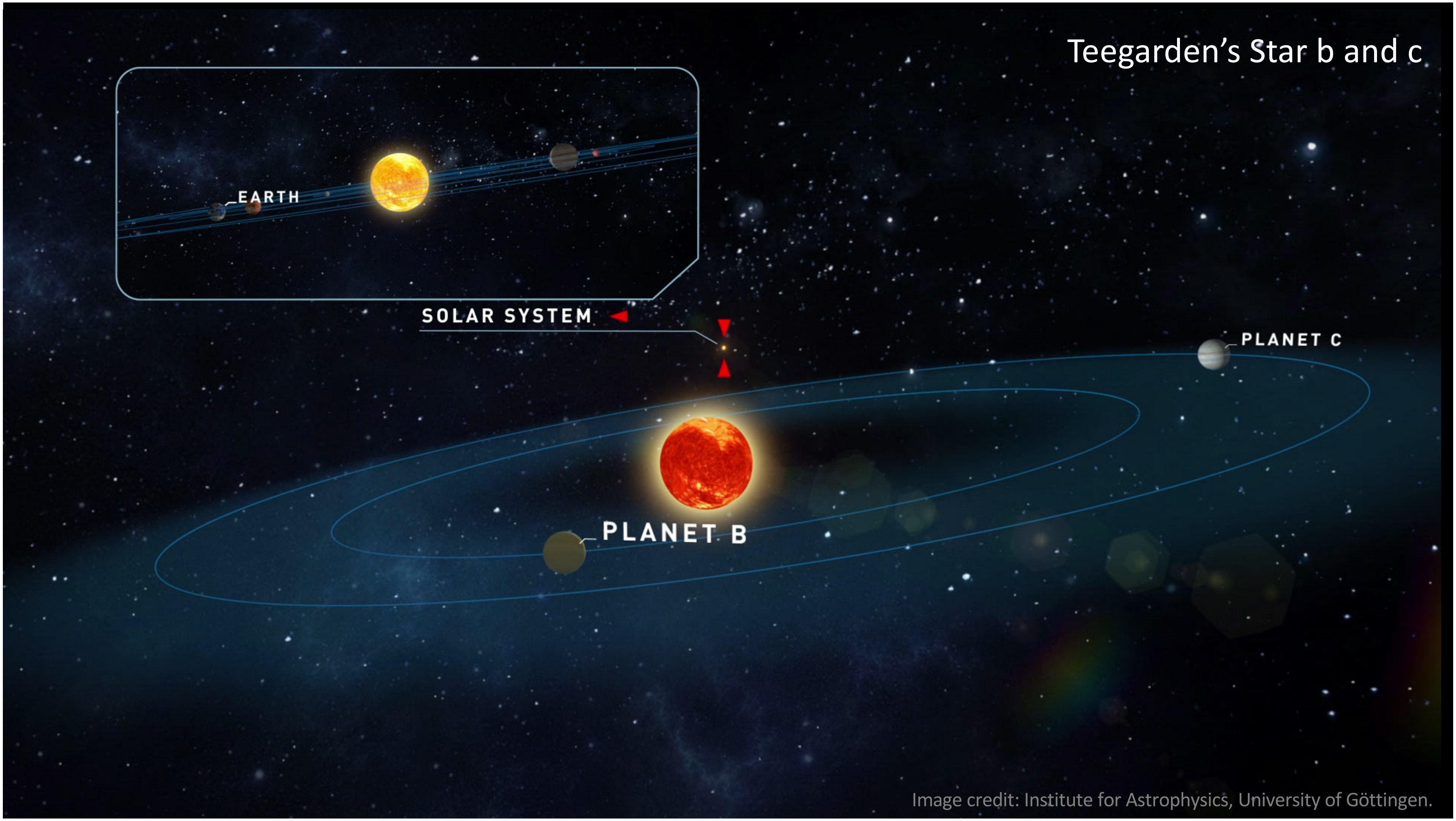
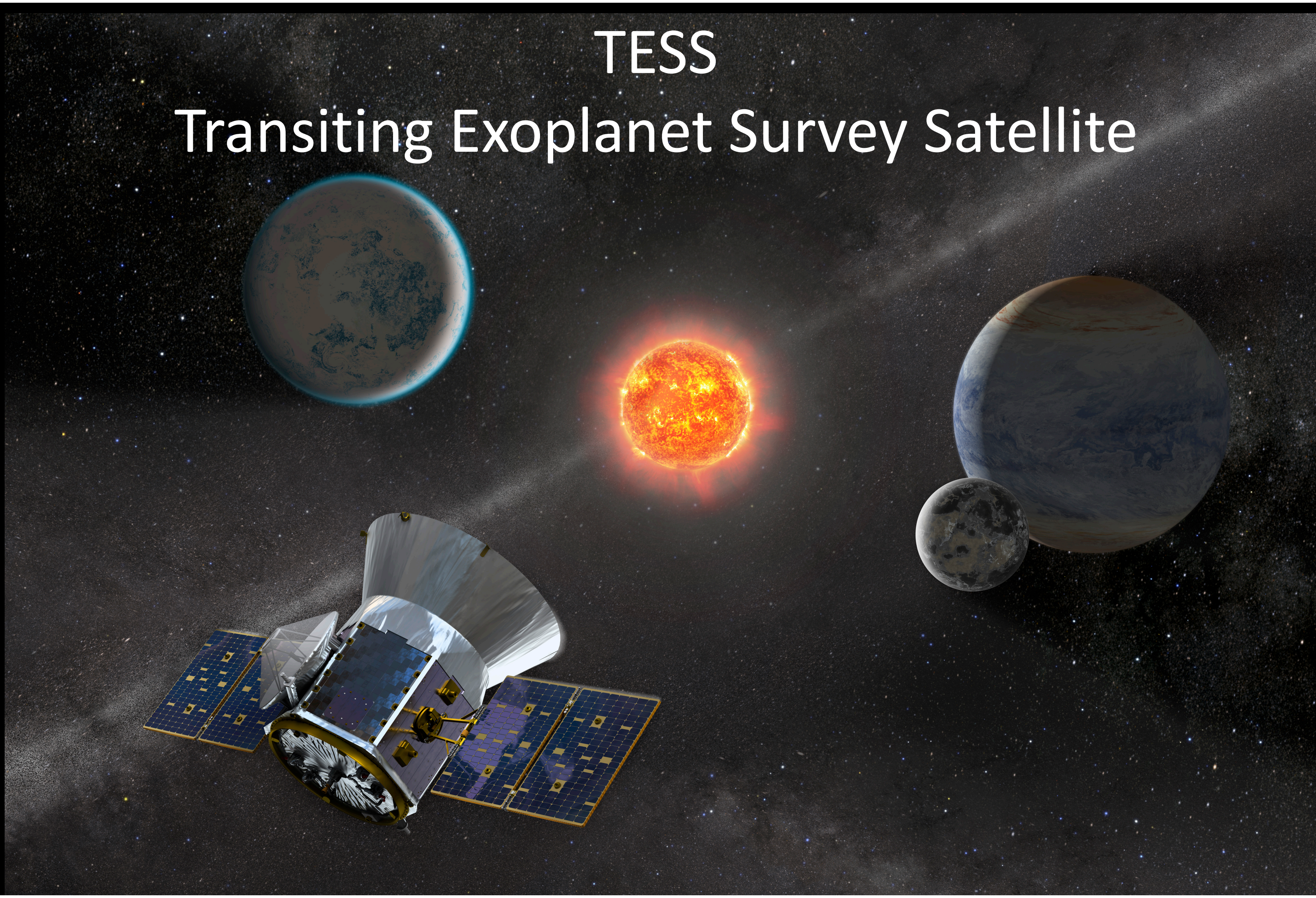
h
Illustration
Credit: NASA-JPL/Caltech


Proxima Centauri b
Credit: ESO/M. Kornmesser

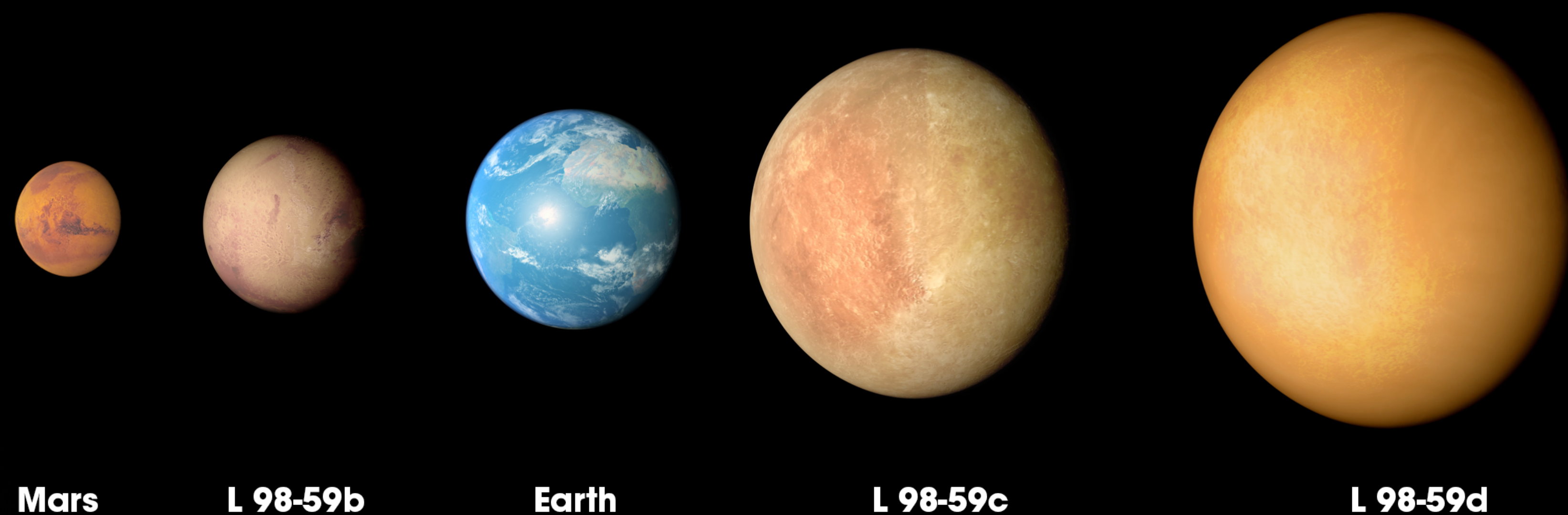

LHS 1140b
Credit: ESO


Teegarden's Star b and c
EARTH
SOLAR SYSTEM
PLANET C
PLANET B
Image credit: Institute for Astrophysics, University of Göttingen.


NASA's *Kepler* Mission

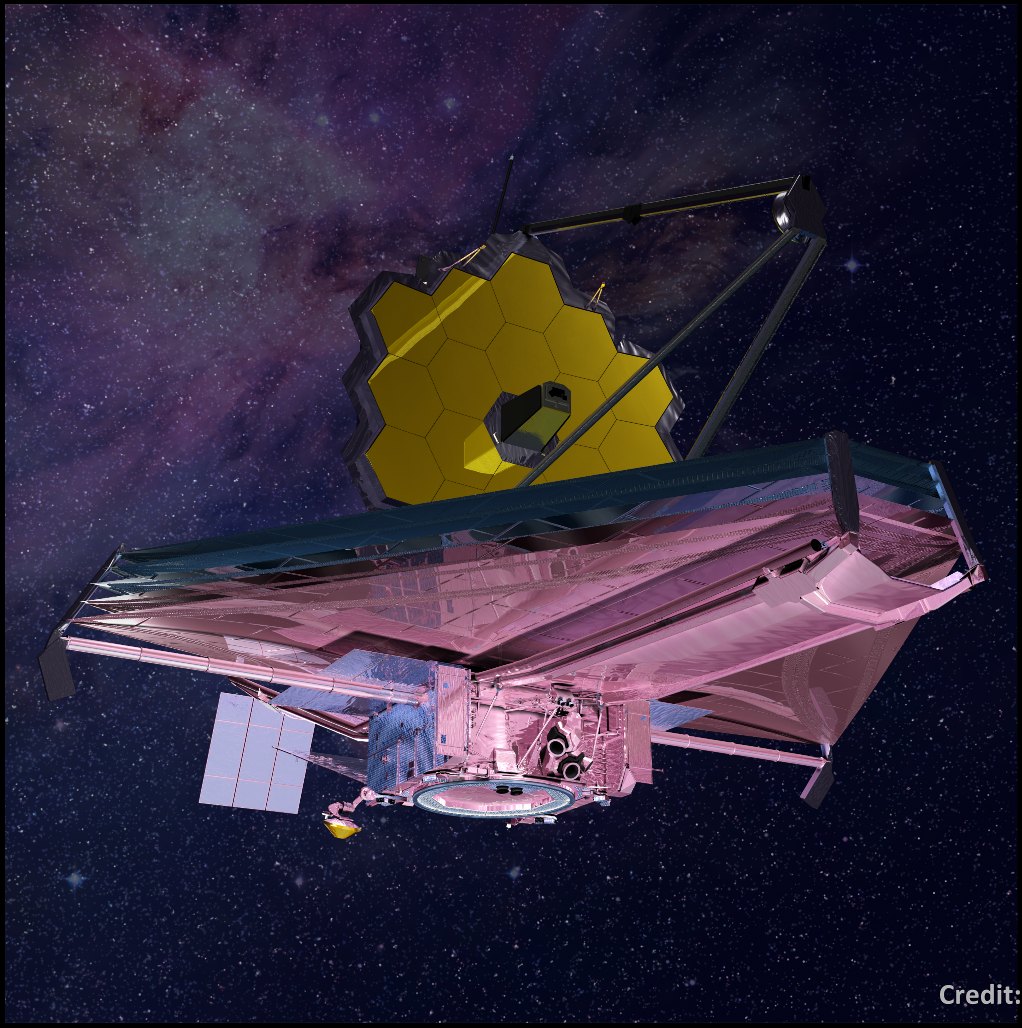

TESS
Transiting Exoplanet Survey Satellite

TESS planets in the Earth-sized regime



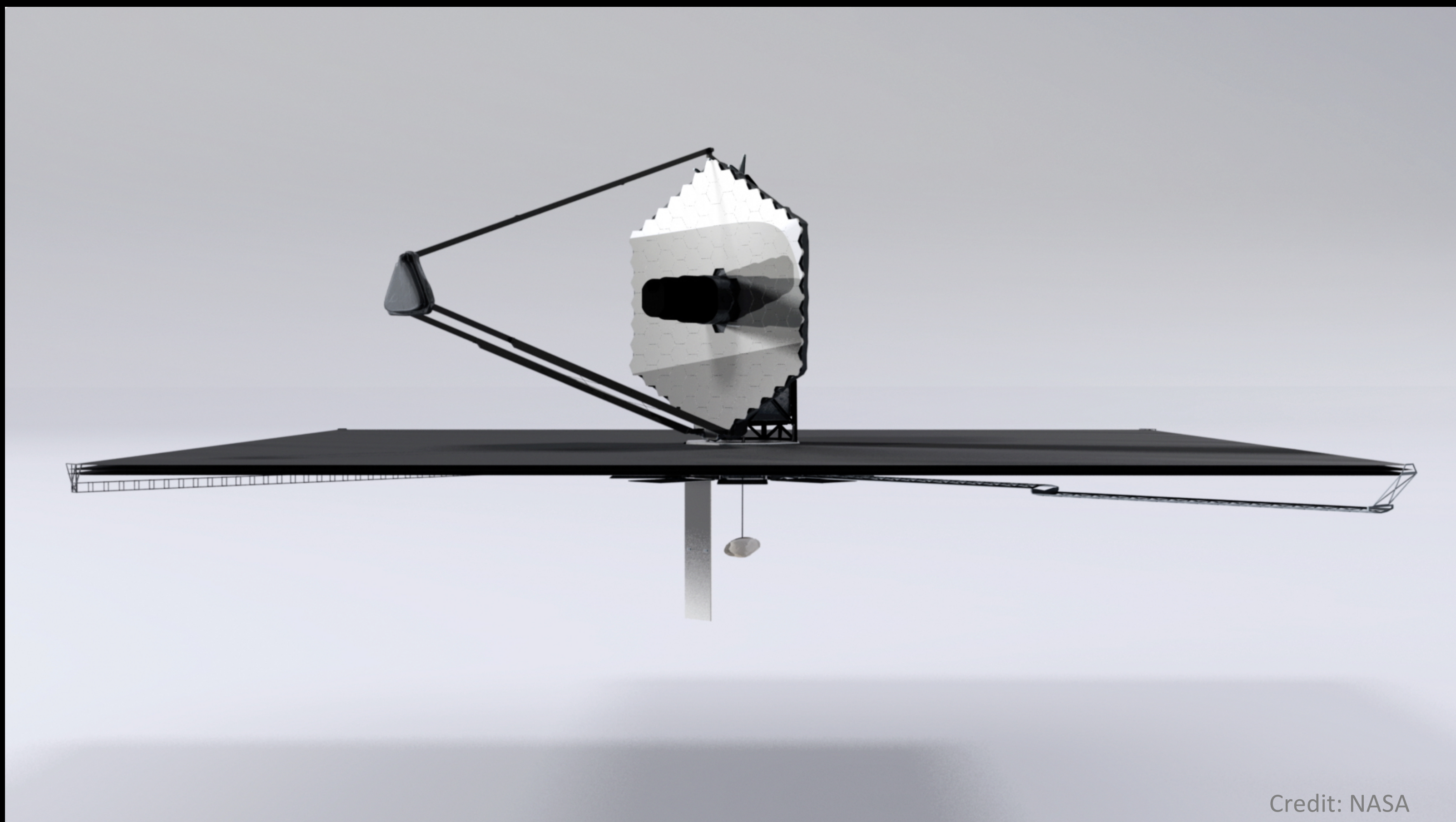
Credit: NASA's Goddard Space Flight Center

James Webb Space Telescope

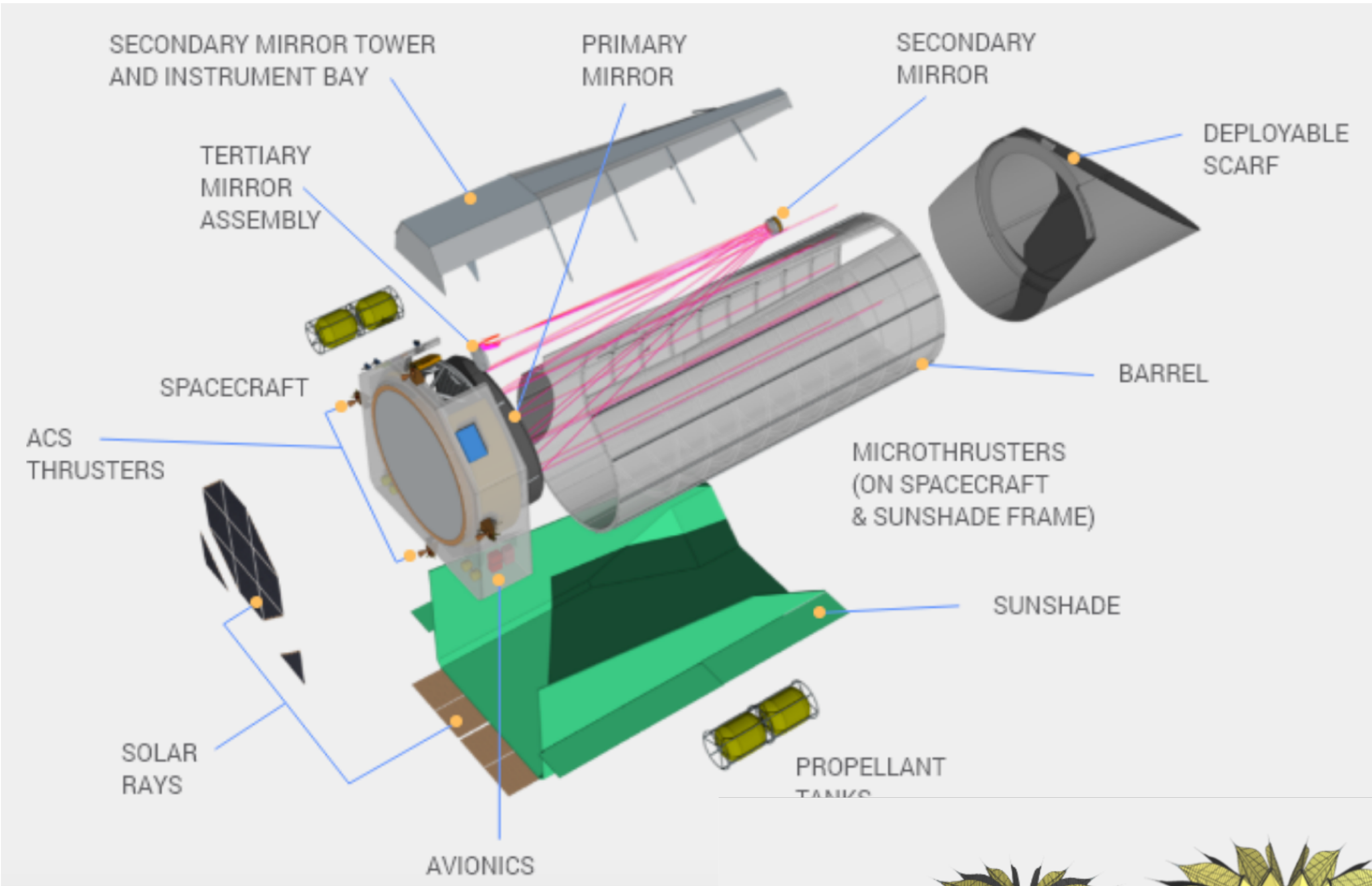


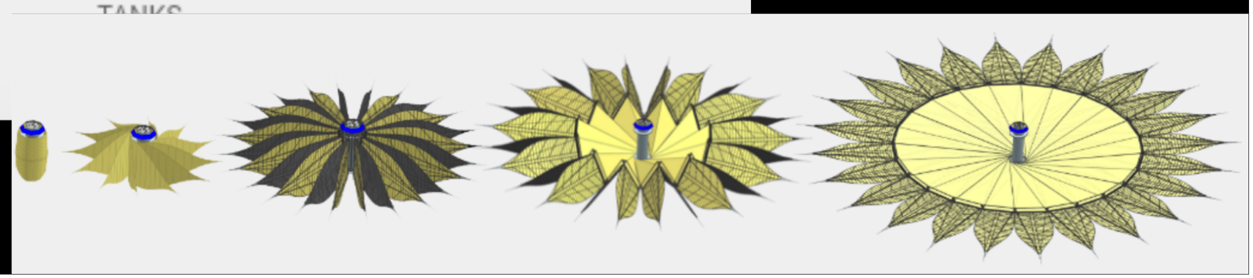
Credit: Northrop Grumman

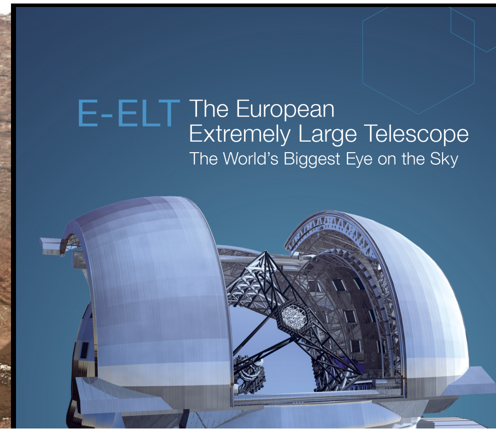
LUVOIR
(Large UV/Optical/IR Surveyor)



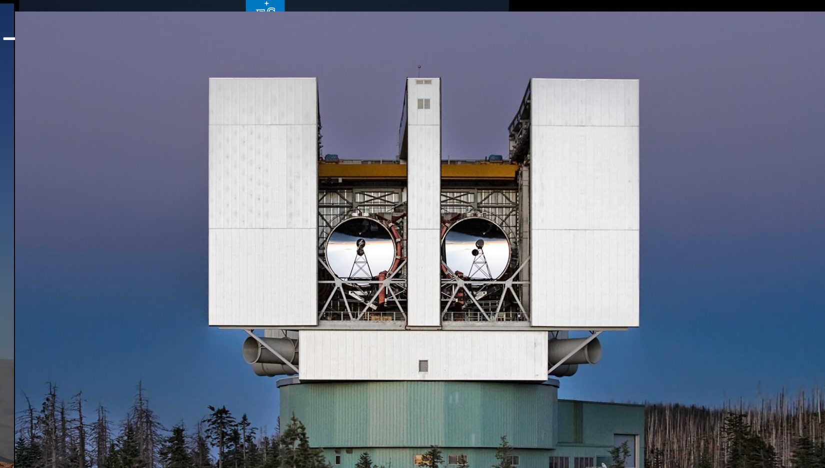
HabEx (Habitable Exoplanet Observatory)



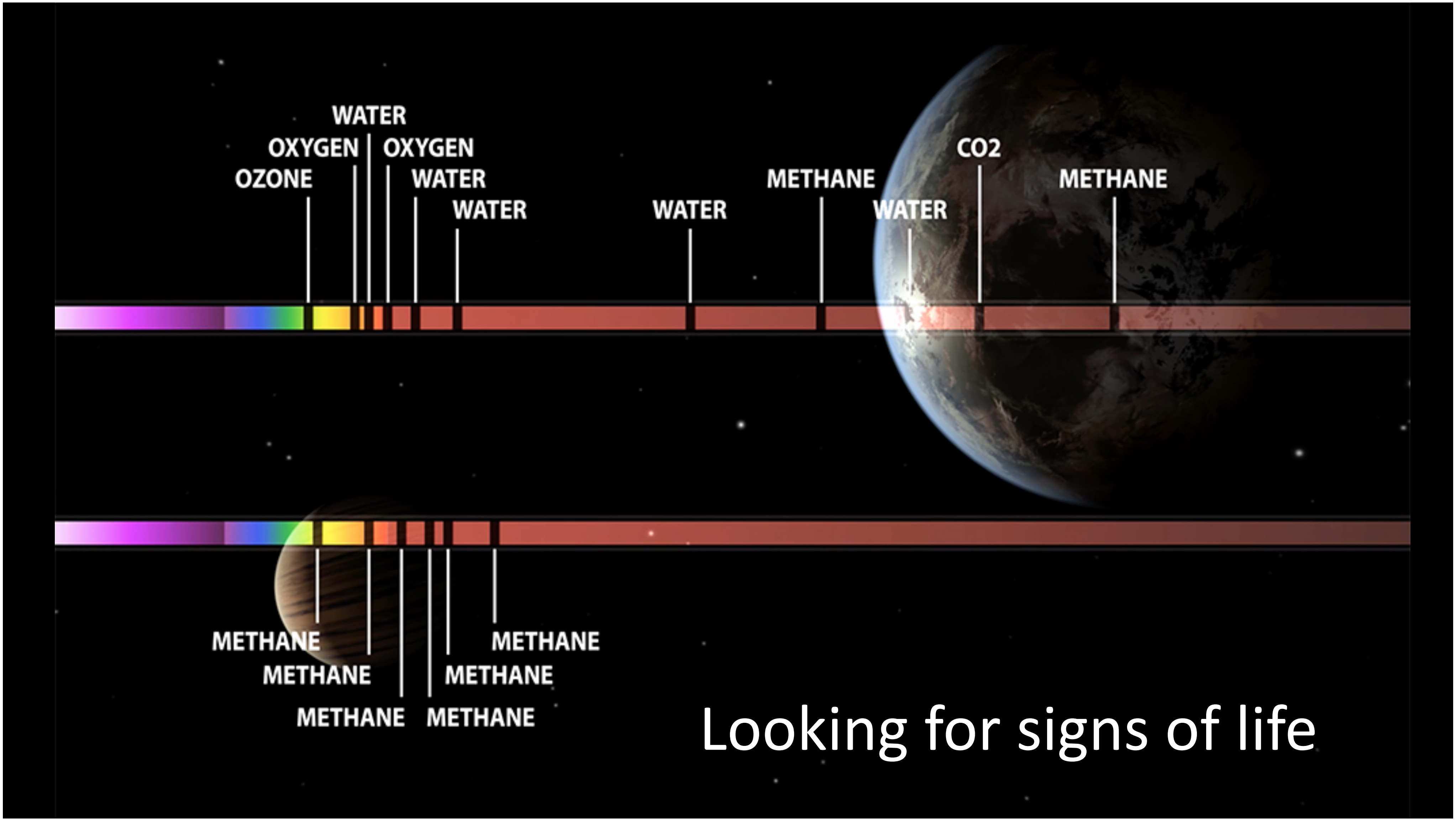




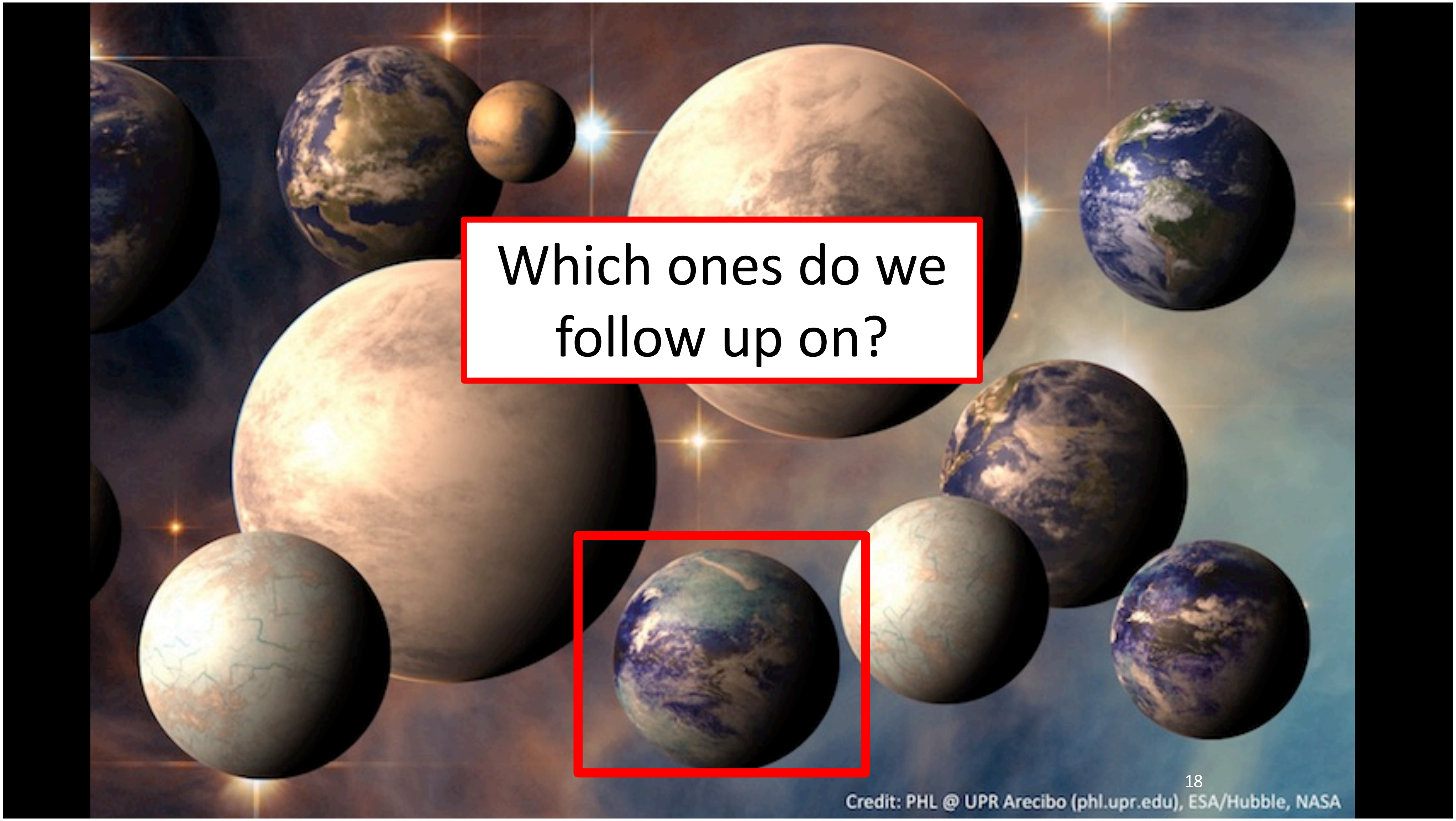
Extremely Large Telescopes



Large Binocular Telescope



Looking for signs of life


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

Contact (1997)

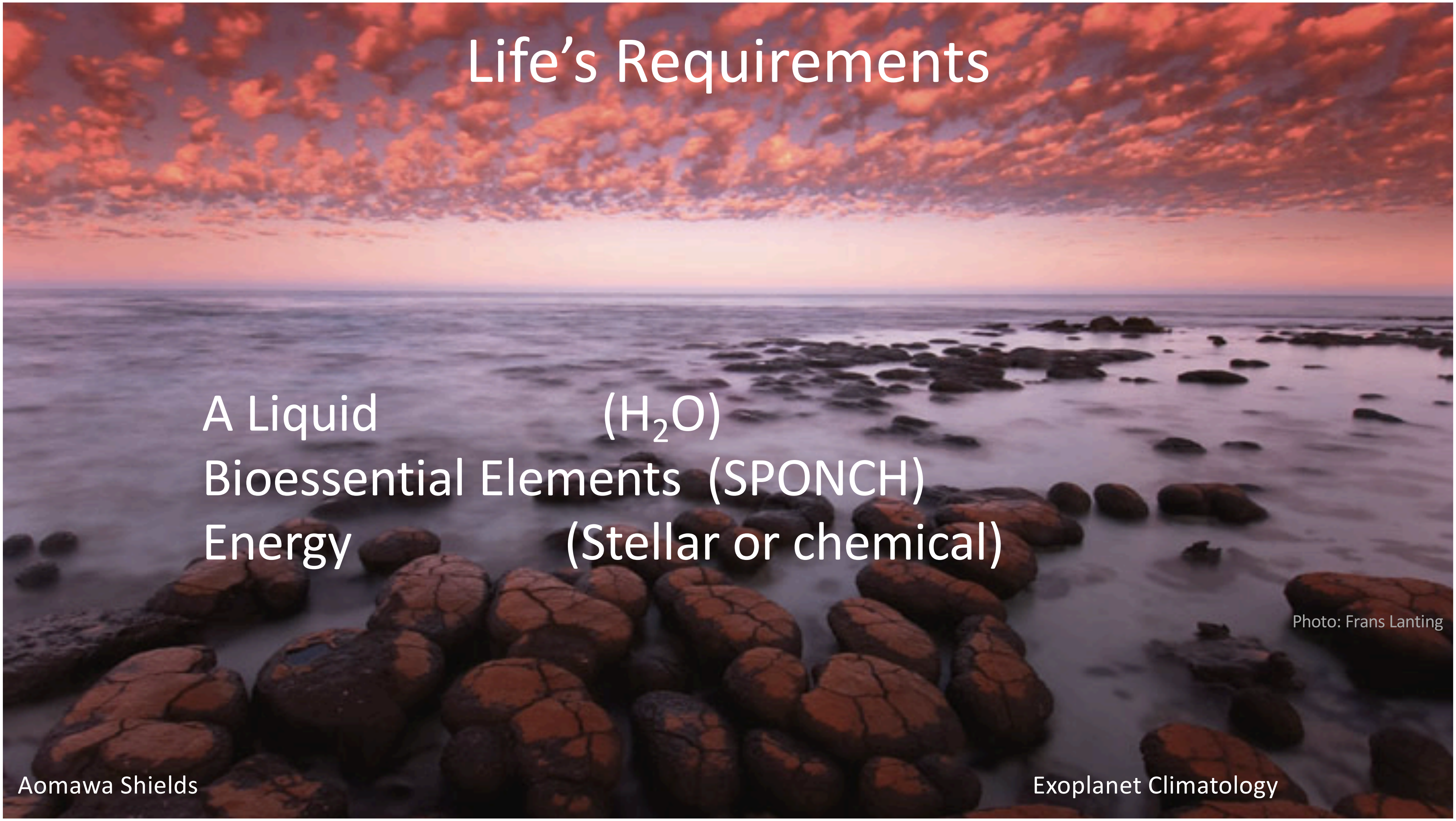
New era, new approach

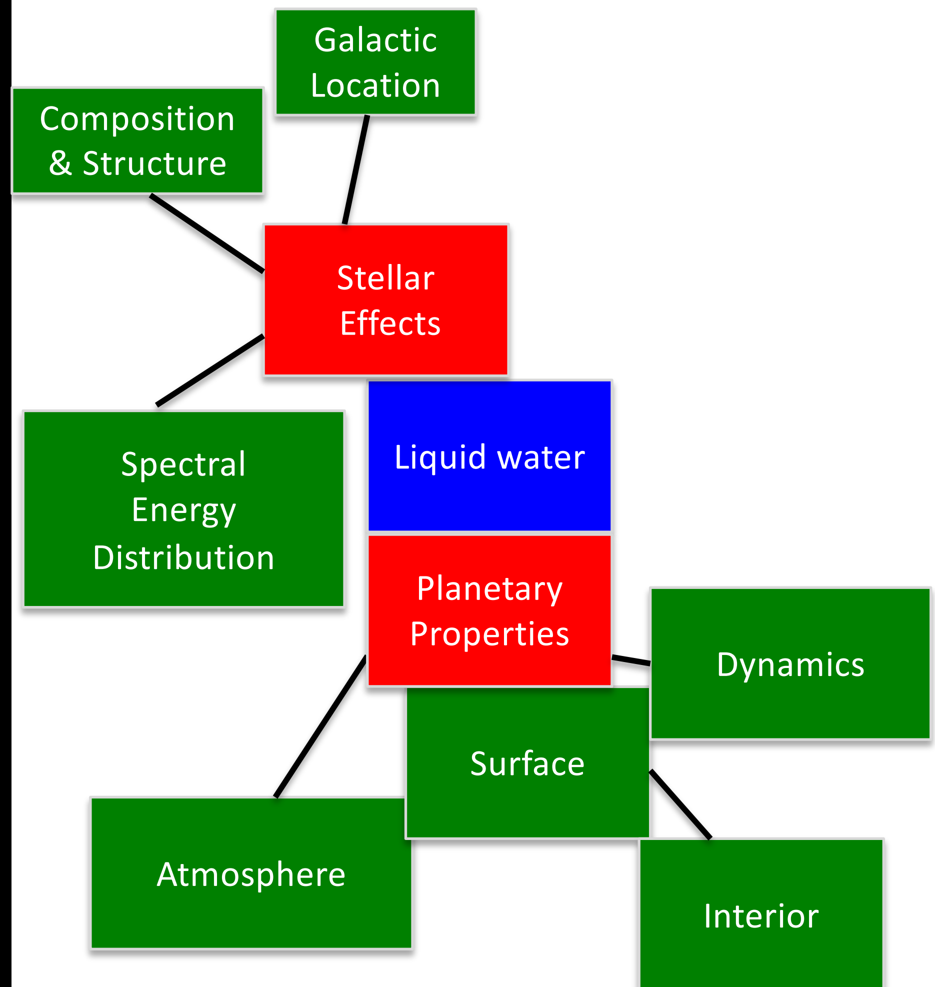
- Observational data AND computer models

NASA

+

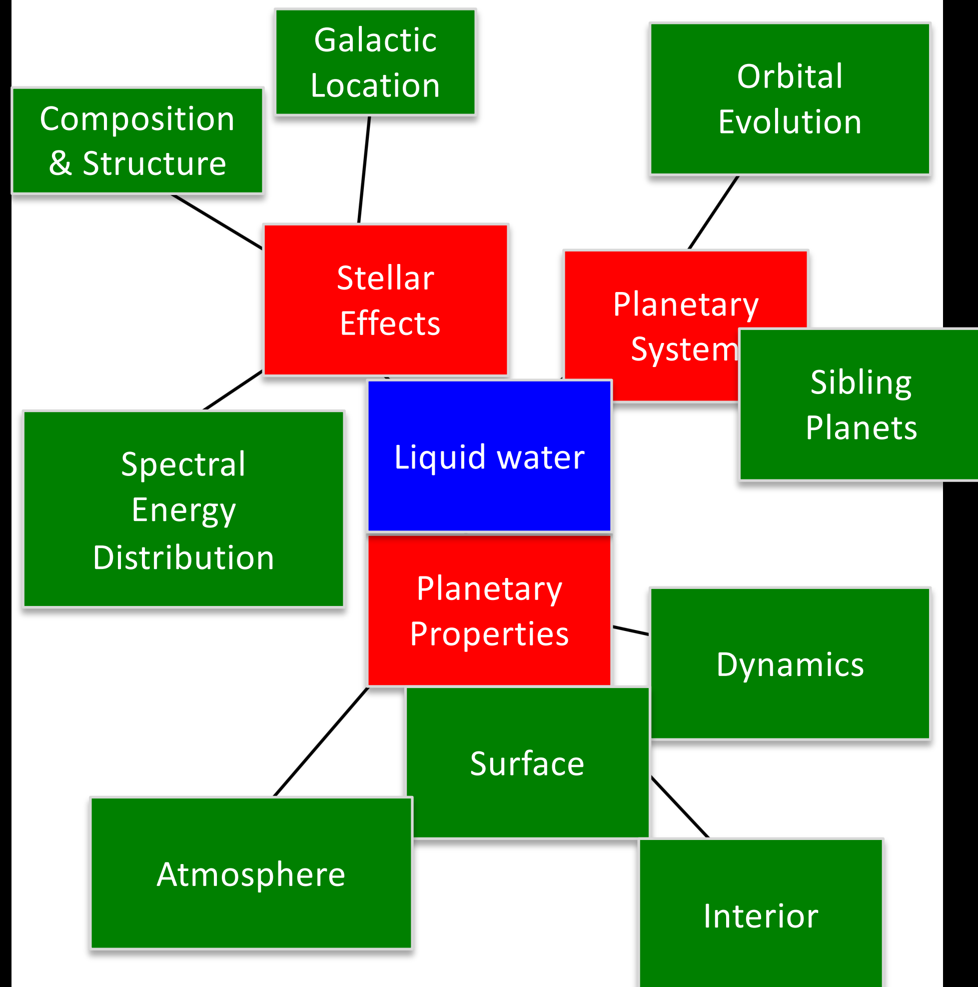
Koshland Science Museum


Life’s Requirements
A Liquid (H2O)
Bioessential Elements (SPONCH)
Energy (Stellar or chemical)
Photo: Frans Lanting
Aomawa Shields
Exoplanet Climatology

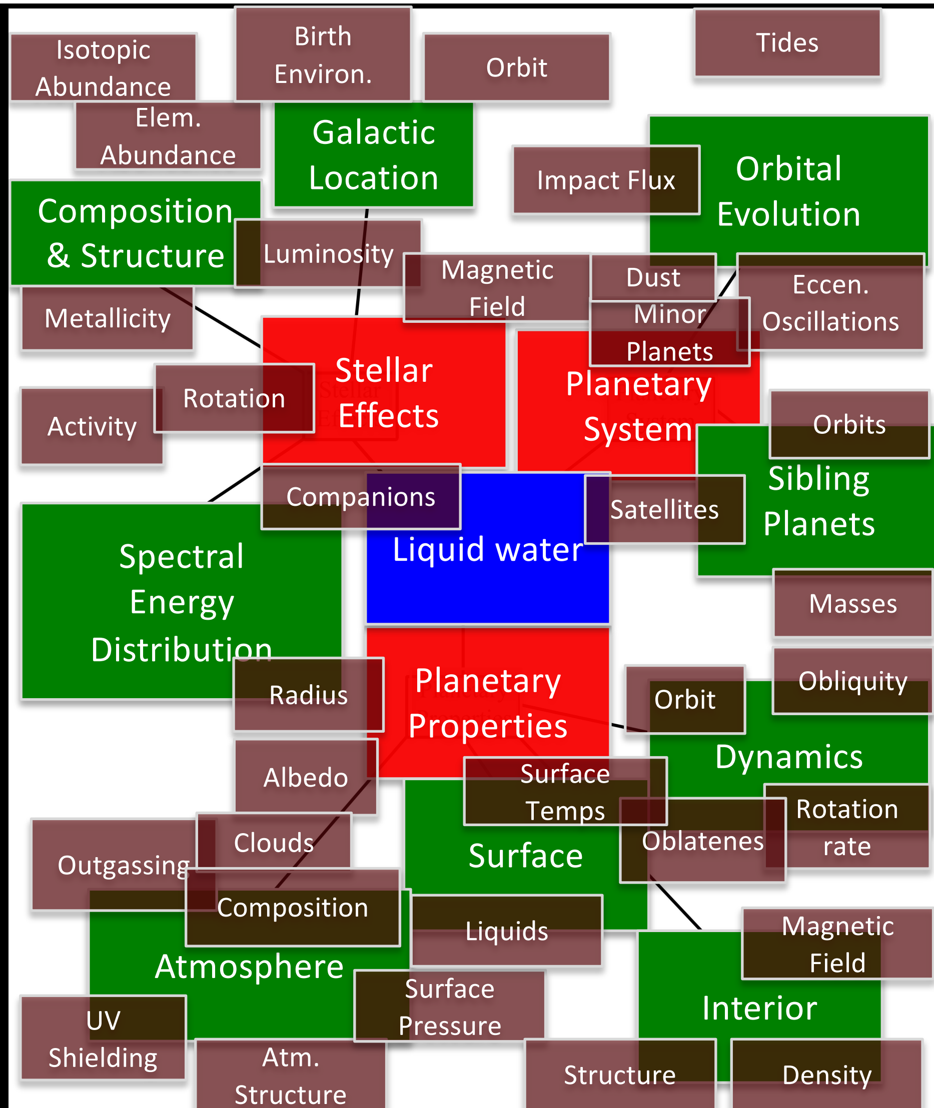


Aomawa Shields

Exoplanet Climatology



Credit: After Meadows and Barnes 2018



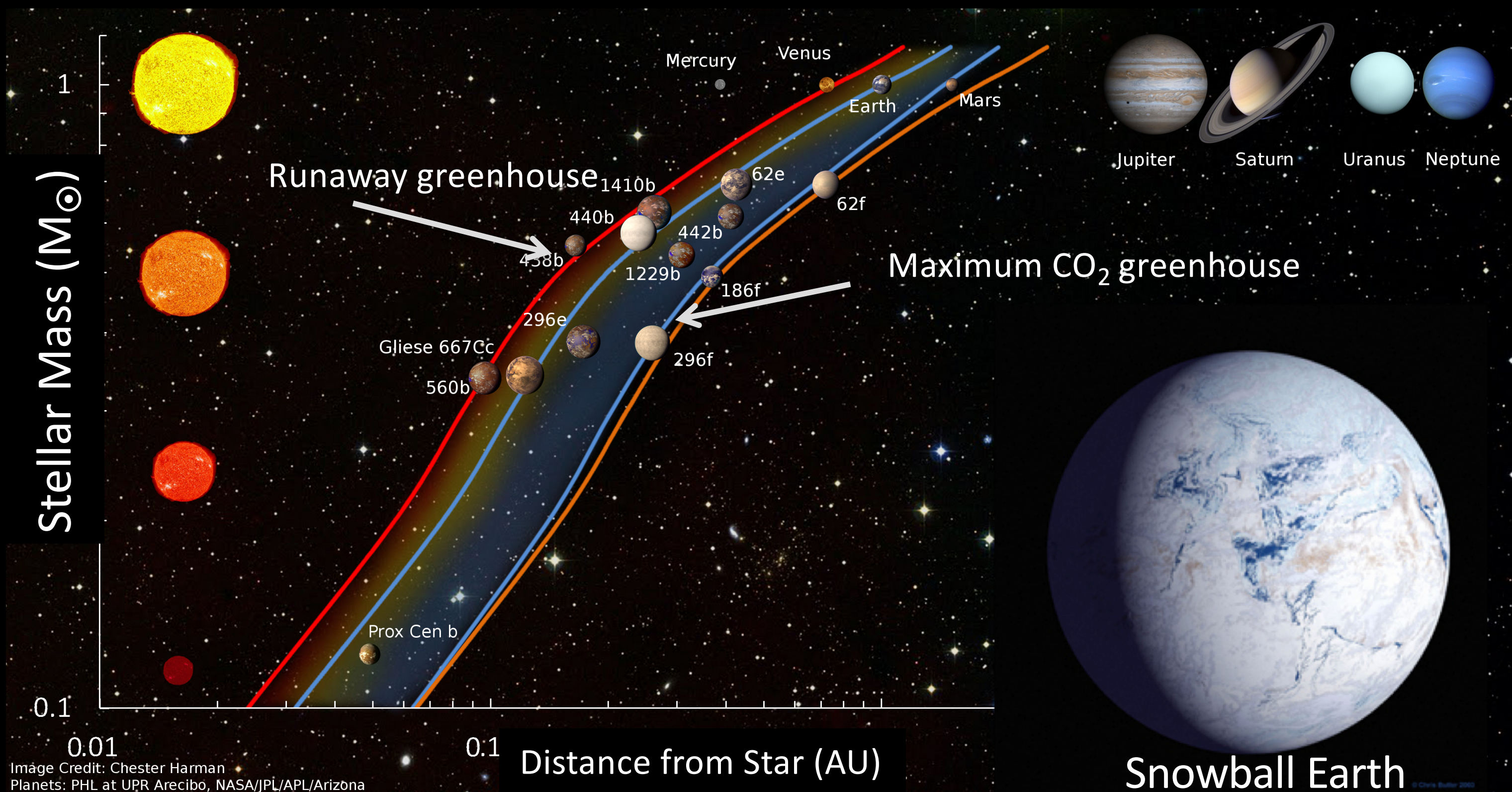
Credit: After Meadows and Barnes 2018

Aomawa Shields

Exoplanet Climatology

The Habitable Zone

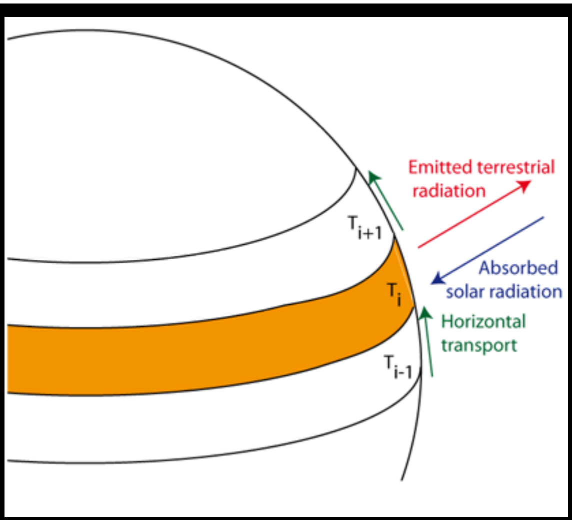
(Kasting et al. 1993, Kopparapu et al. 2013)



Many factors can affect planetary habitability

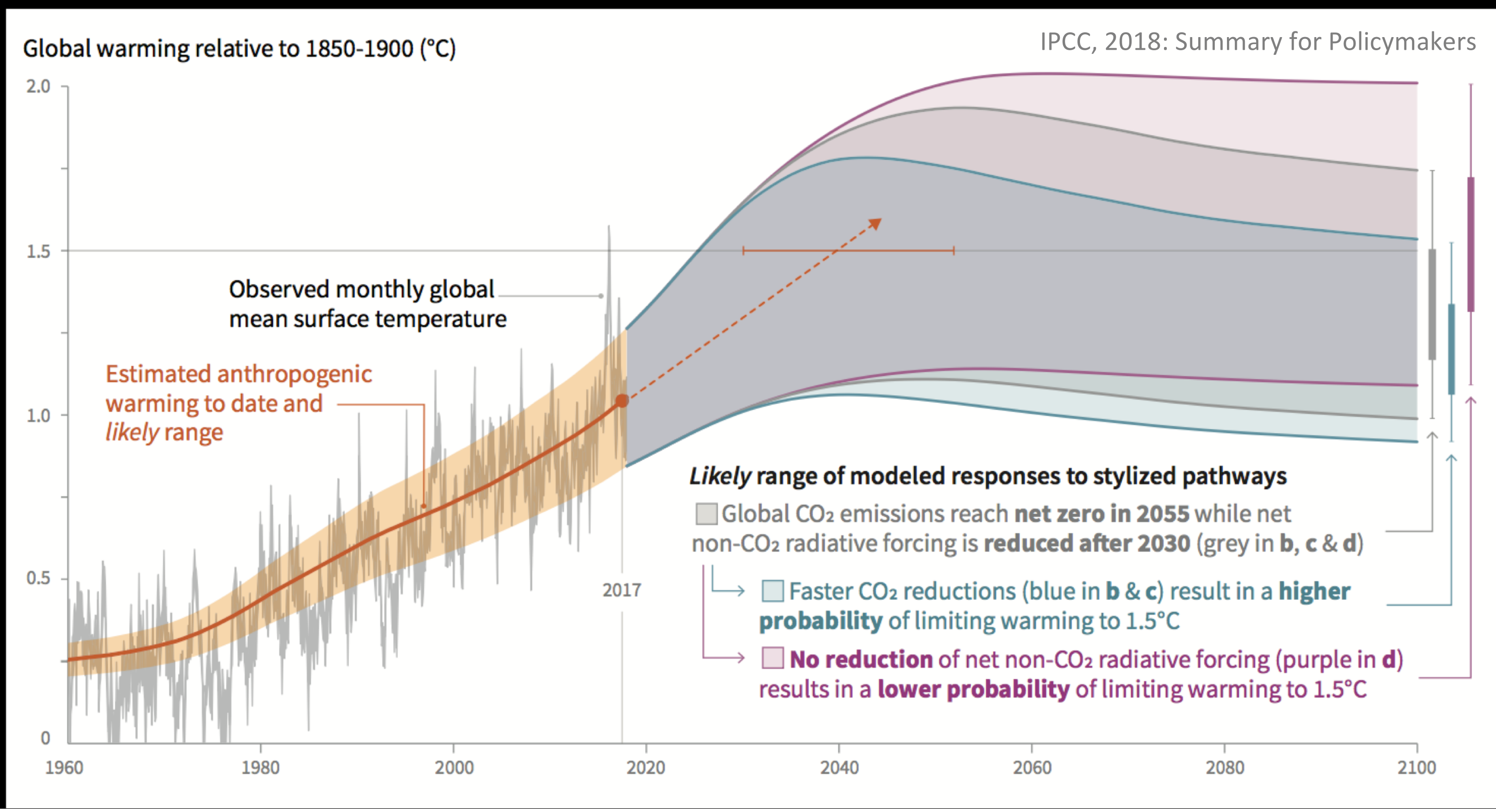
Models

- 1-D line-by-line radiative transfer models
  - 1-D in height
  - Atmospheric gas absorption
- Radiative convective climate models
- Energy Balance Models (EBMs)
  - 0-D or 1-D (in latitude) usually
- 3-D General Circulation Models (GCMs)
  - Sophisticated treatment of atmospheric circulation, ocean-atmosphere processes

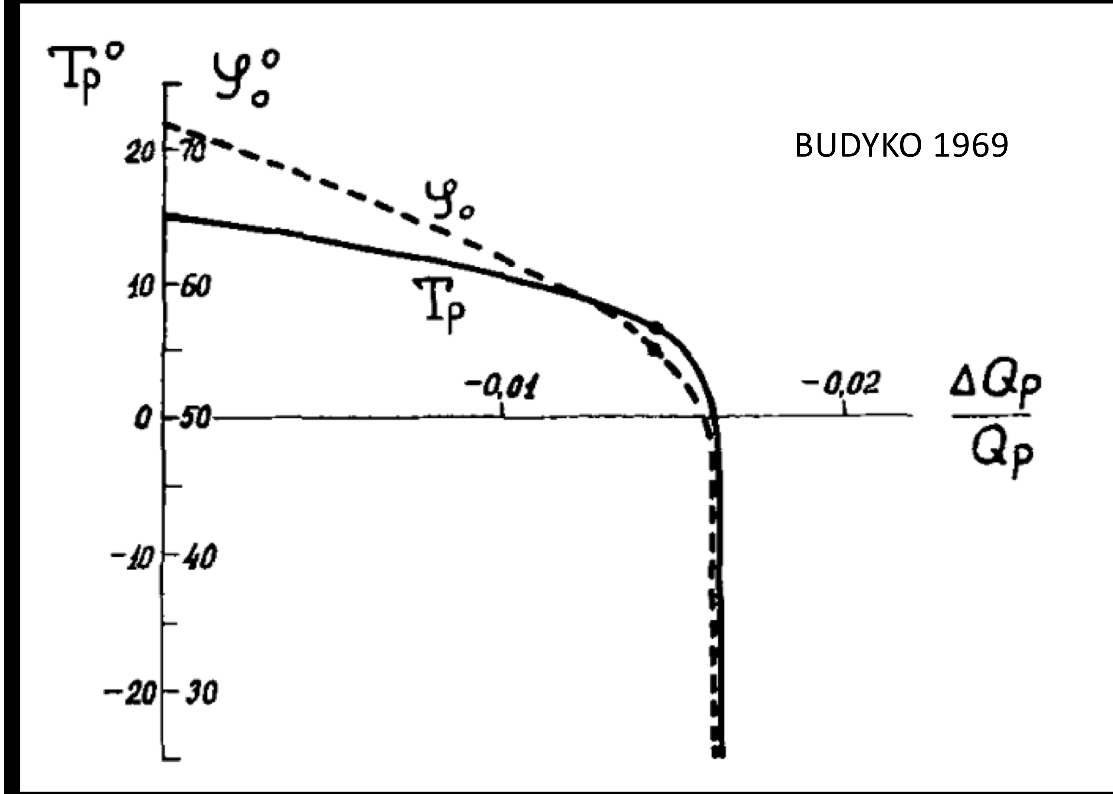


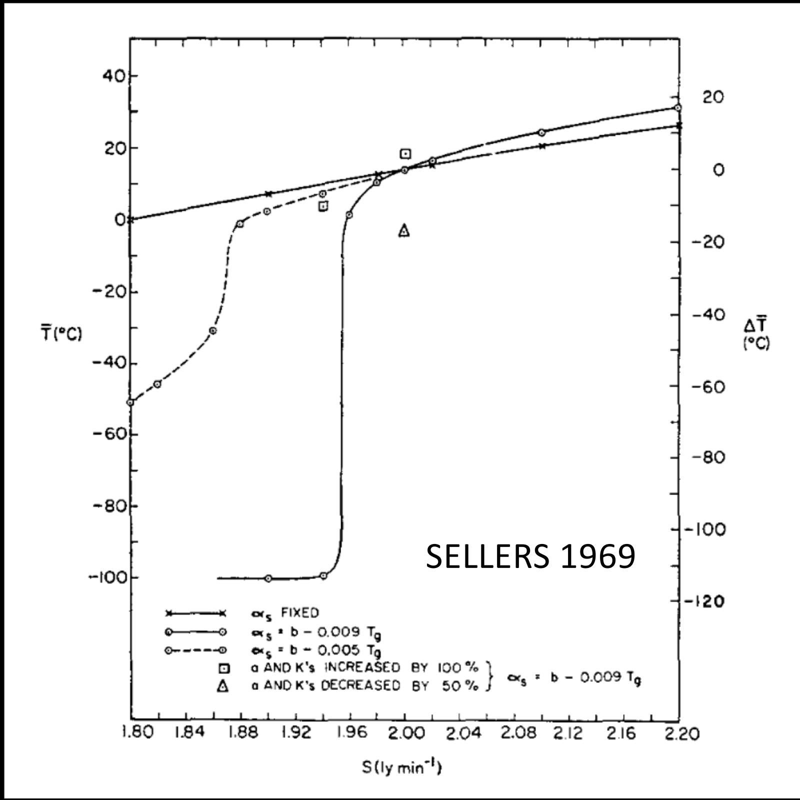
PREDICTING FUTURE CLIMATE ON EARTH

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



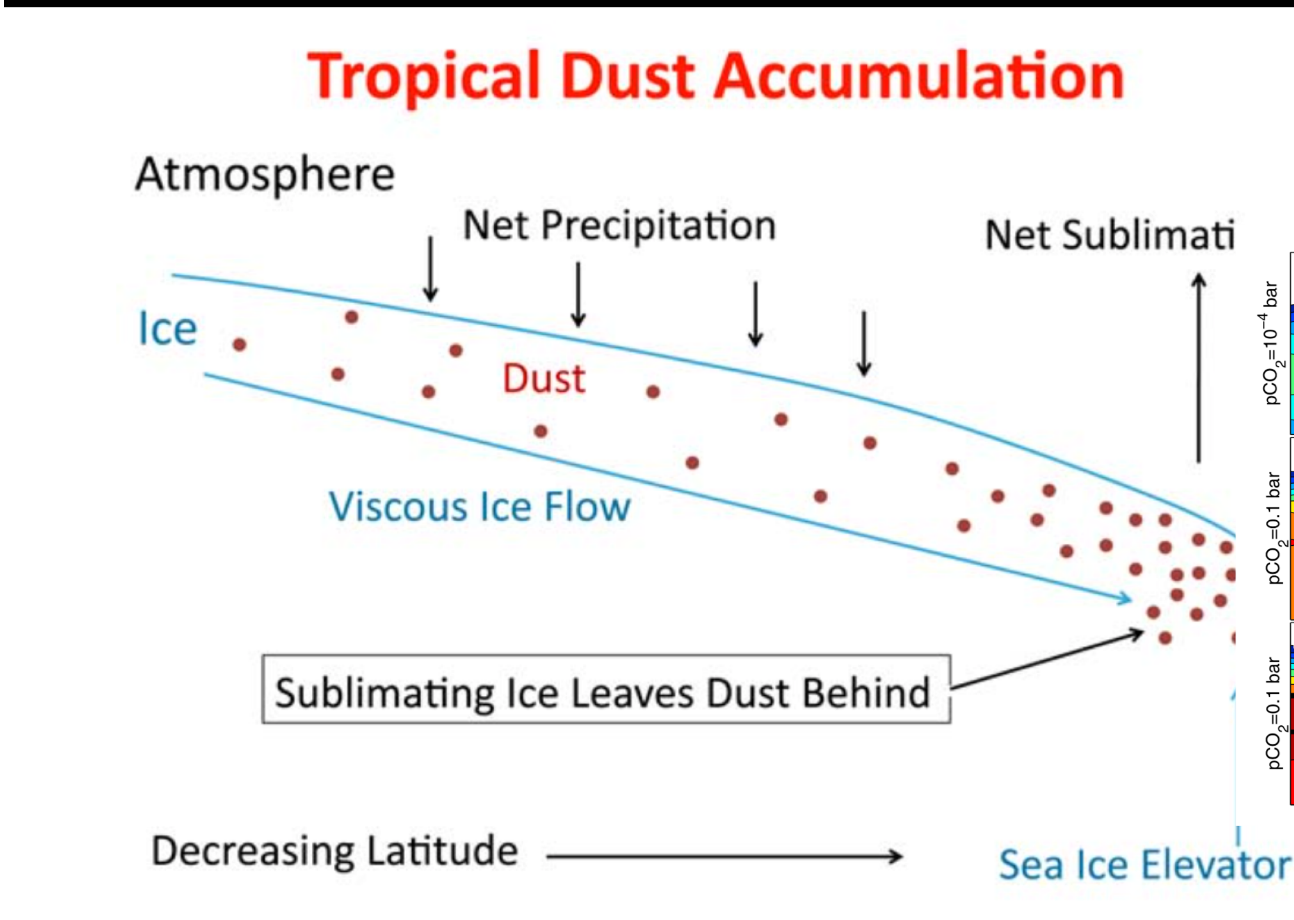
EFFECT OF SOLAR VARIATIONS ON TEMPERATURE AND ICE EXTENT

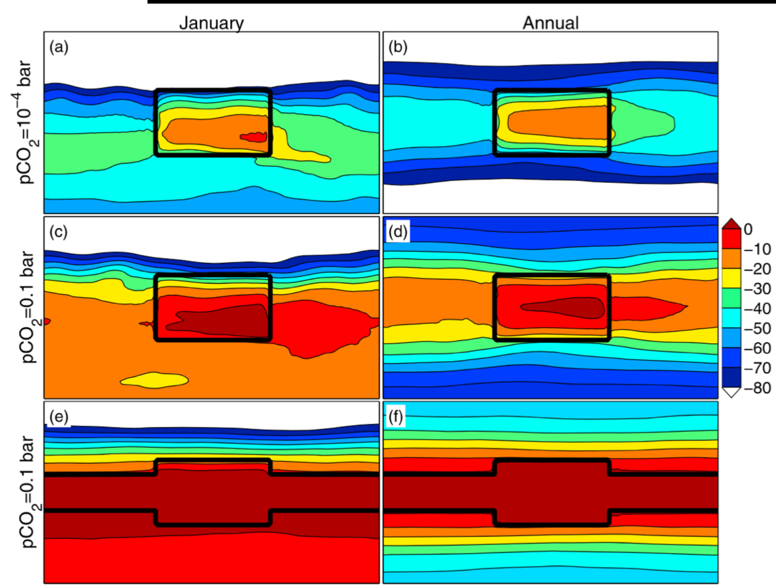




Exploring thaw criteria for Snowball Earth

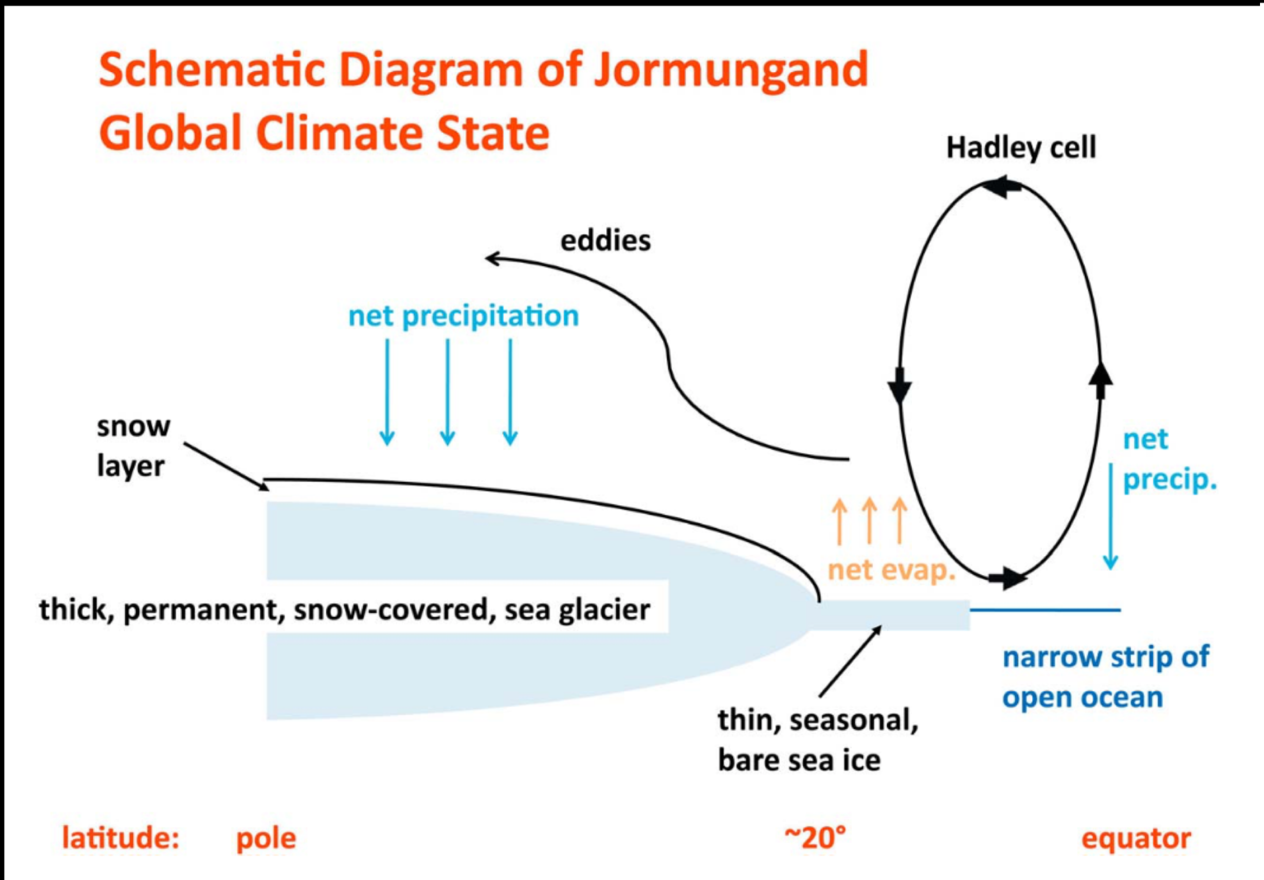
Abbot and Pierrehumbert 2010

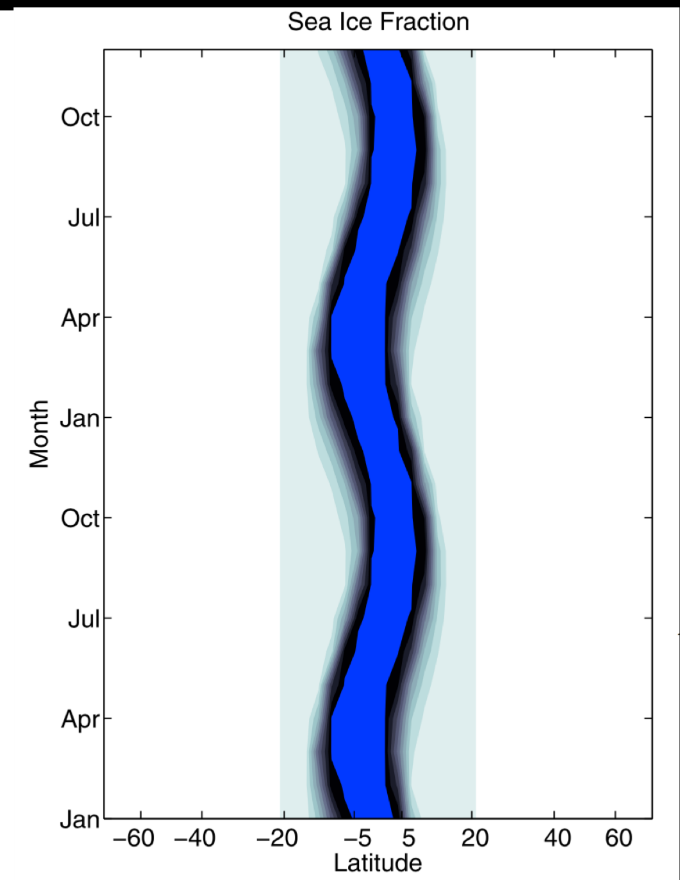


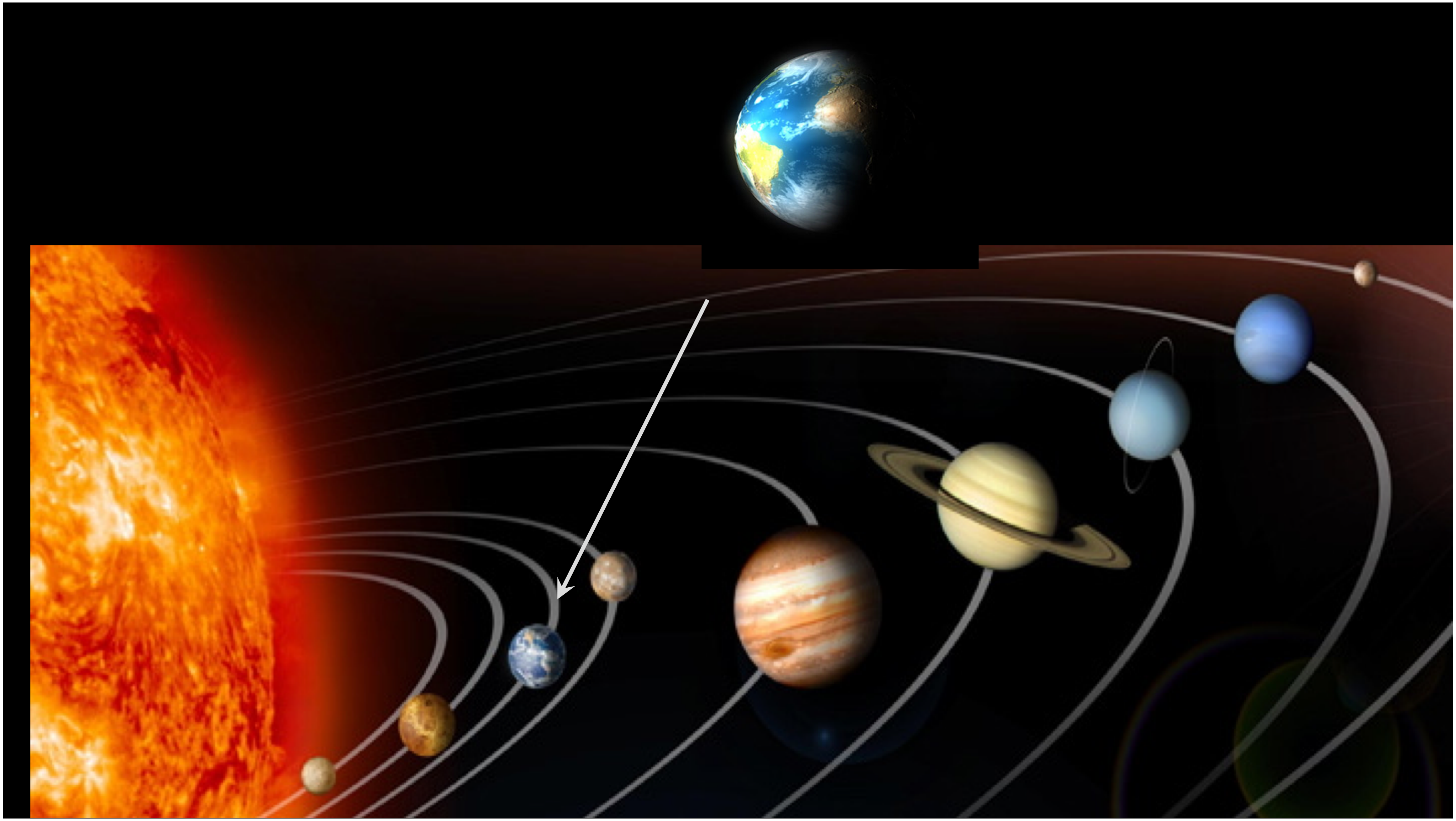


Waterbelt Snowball Earth as refuge for photosynthetic life

Abbot et al. 2011

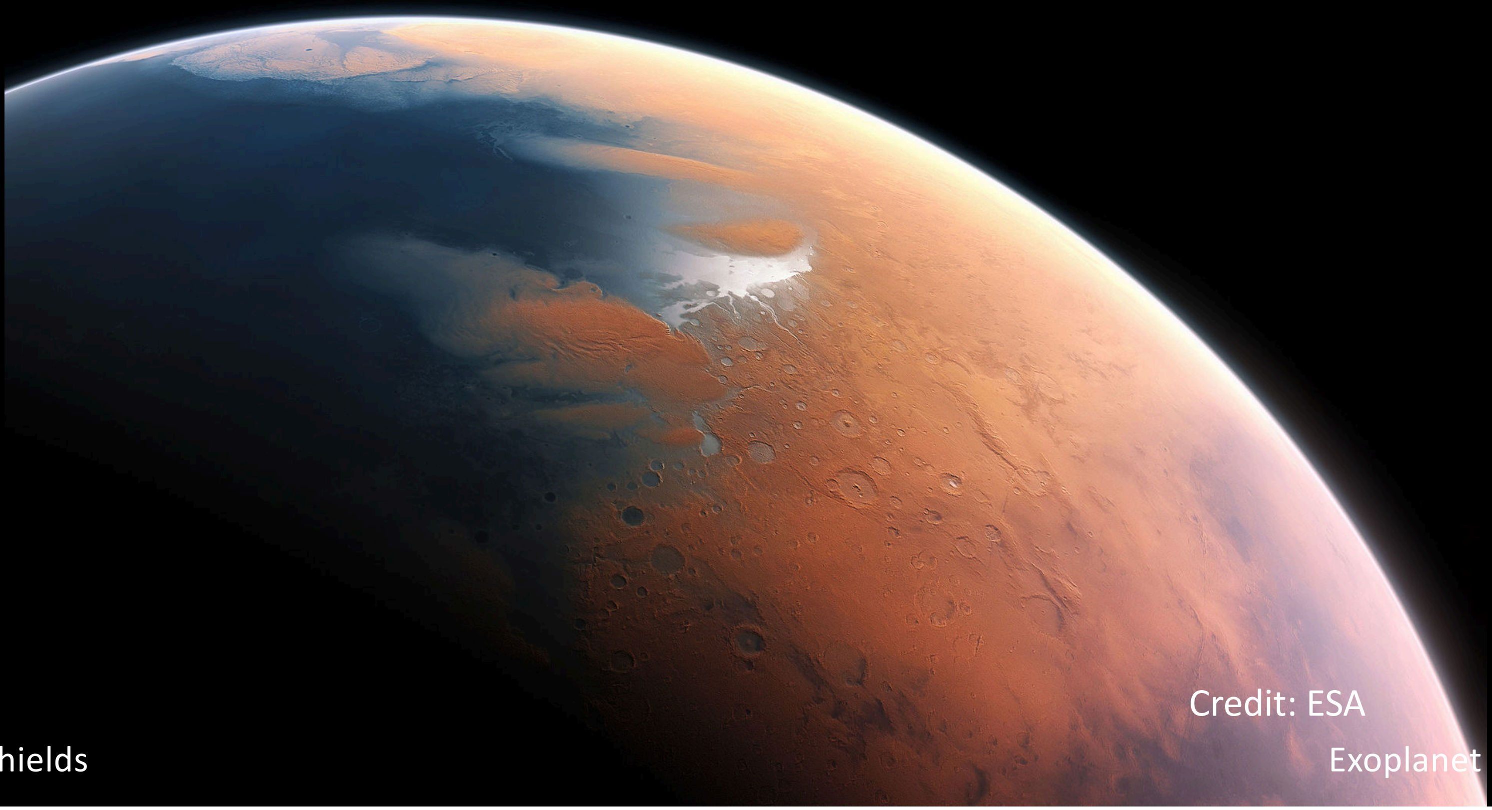






Warming Early Mars

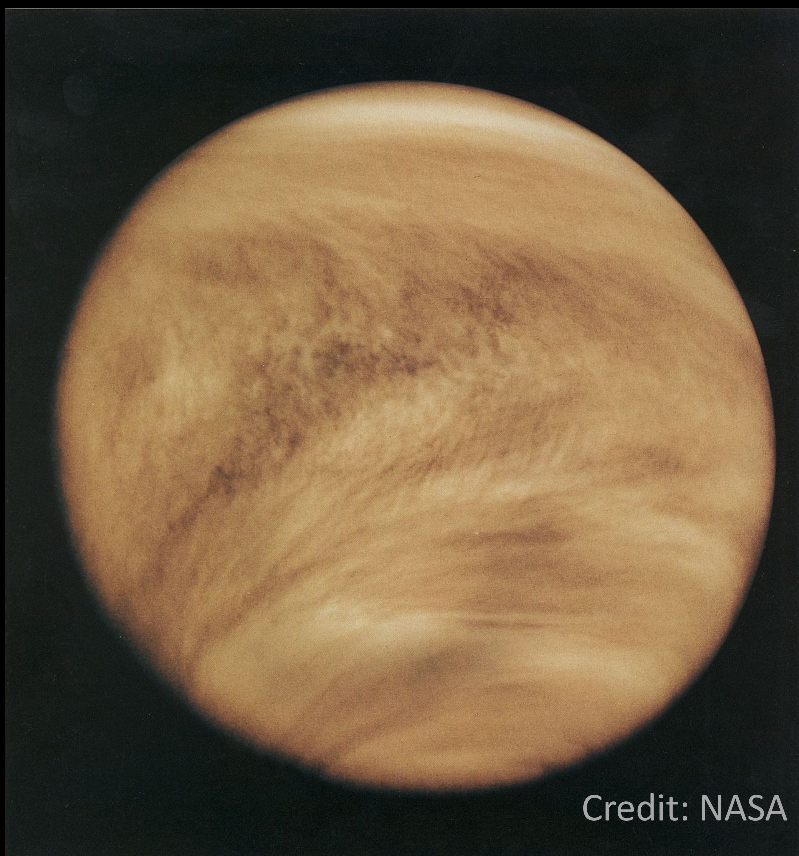
Forget and Pierrehumbert 1997, Colaprete & Toon 2003,
Forget et al. 2013, Kitzmann 2016, Wordsworth et al. 2017



Credit: ESA

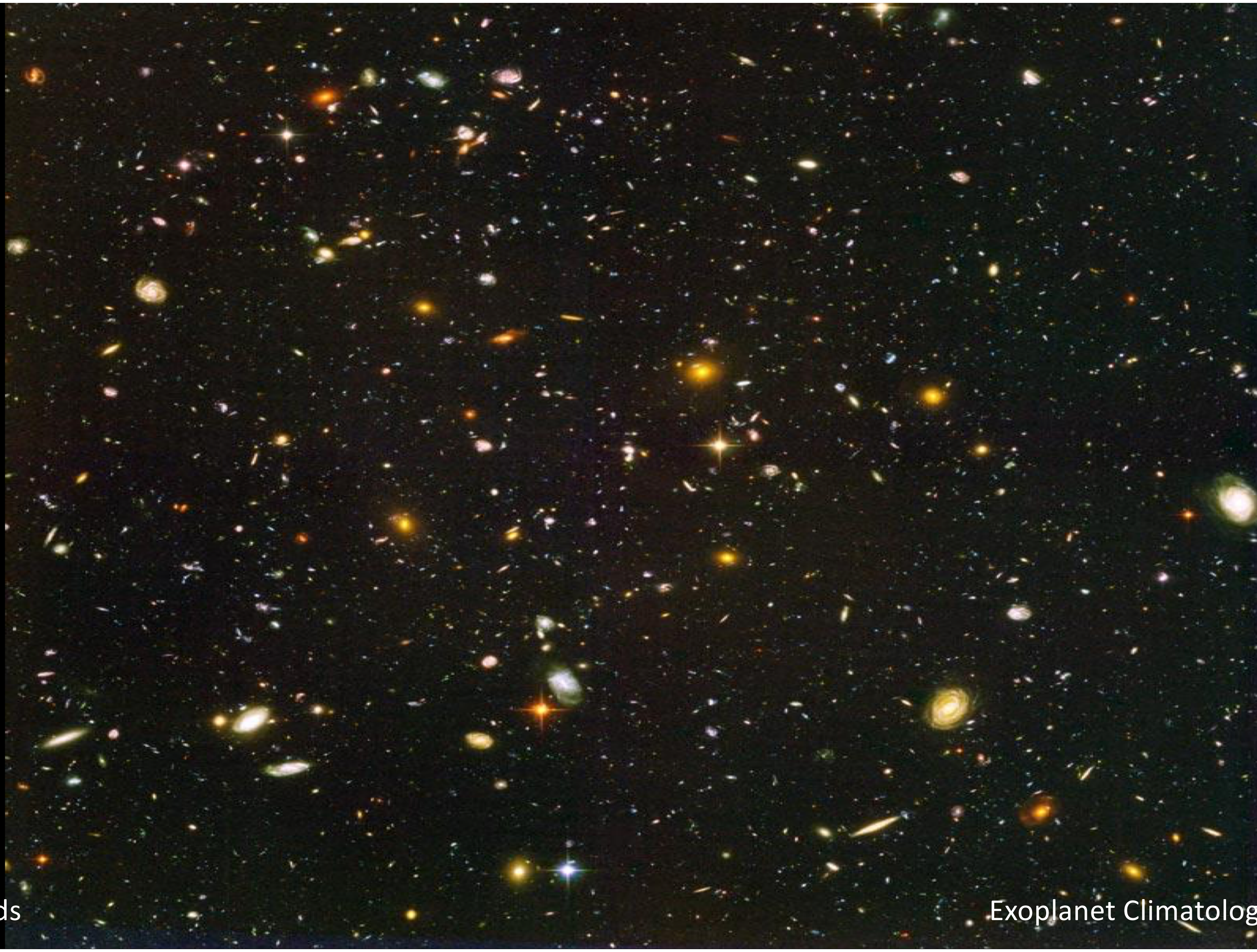
Constraining zonal wind patterns on Venus

(e.g., Lebonnois et al. 2010)



Credit: NASA

Credit: Spitzer Space Telescope



Credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team


Aomawa Shields
Exoplanet Climatology

M-dwarf planets

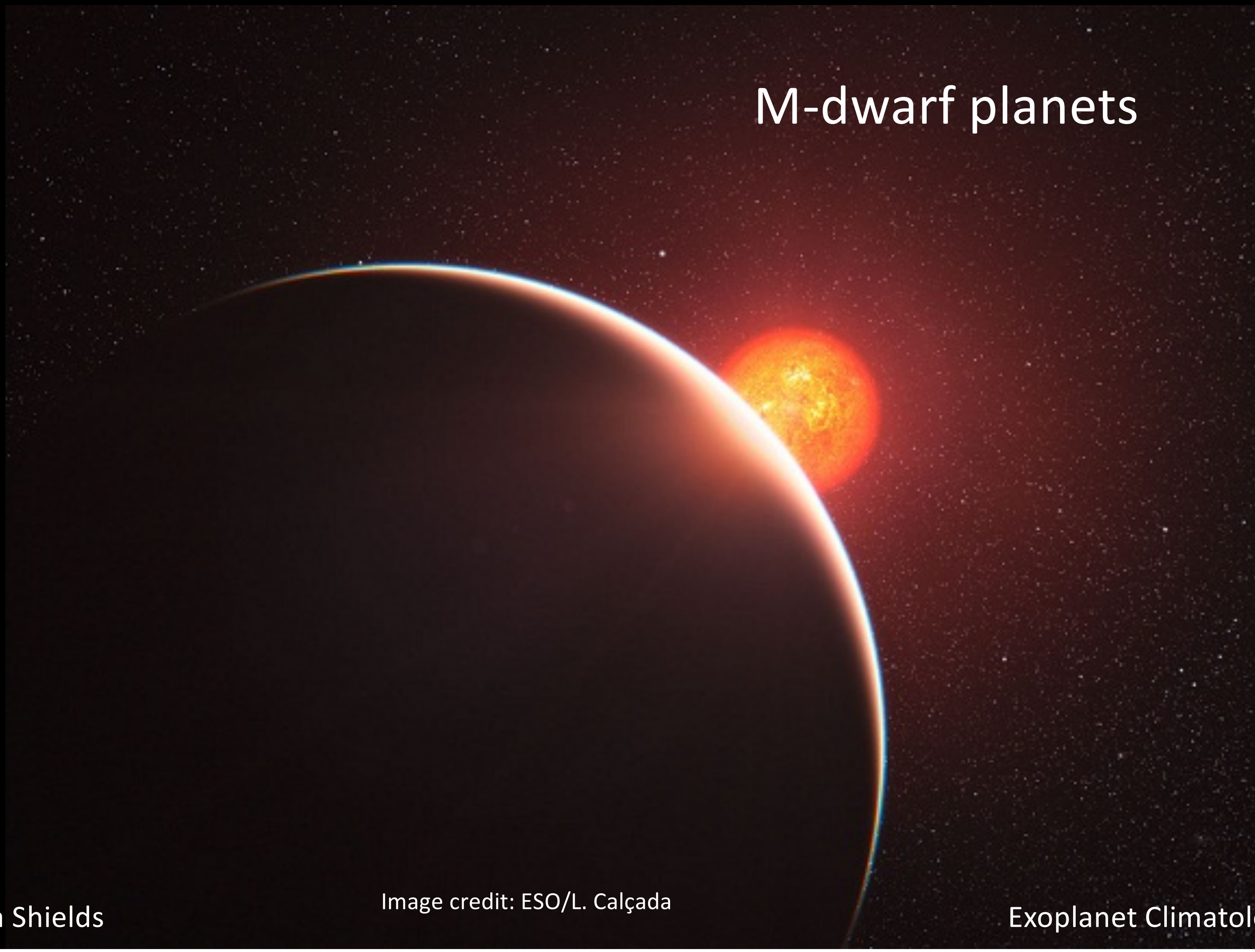


Image credit: ESO/L. Calçada

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Physics Reports

Volume 663, 5 December 2016, Pages 1–38

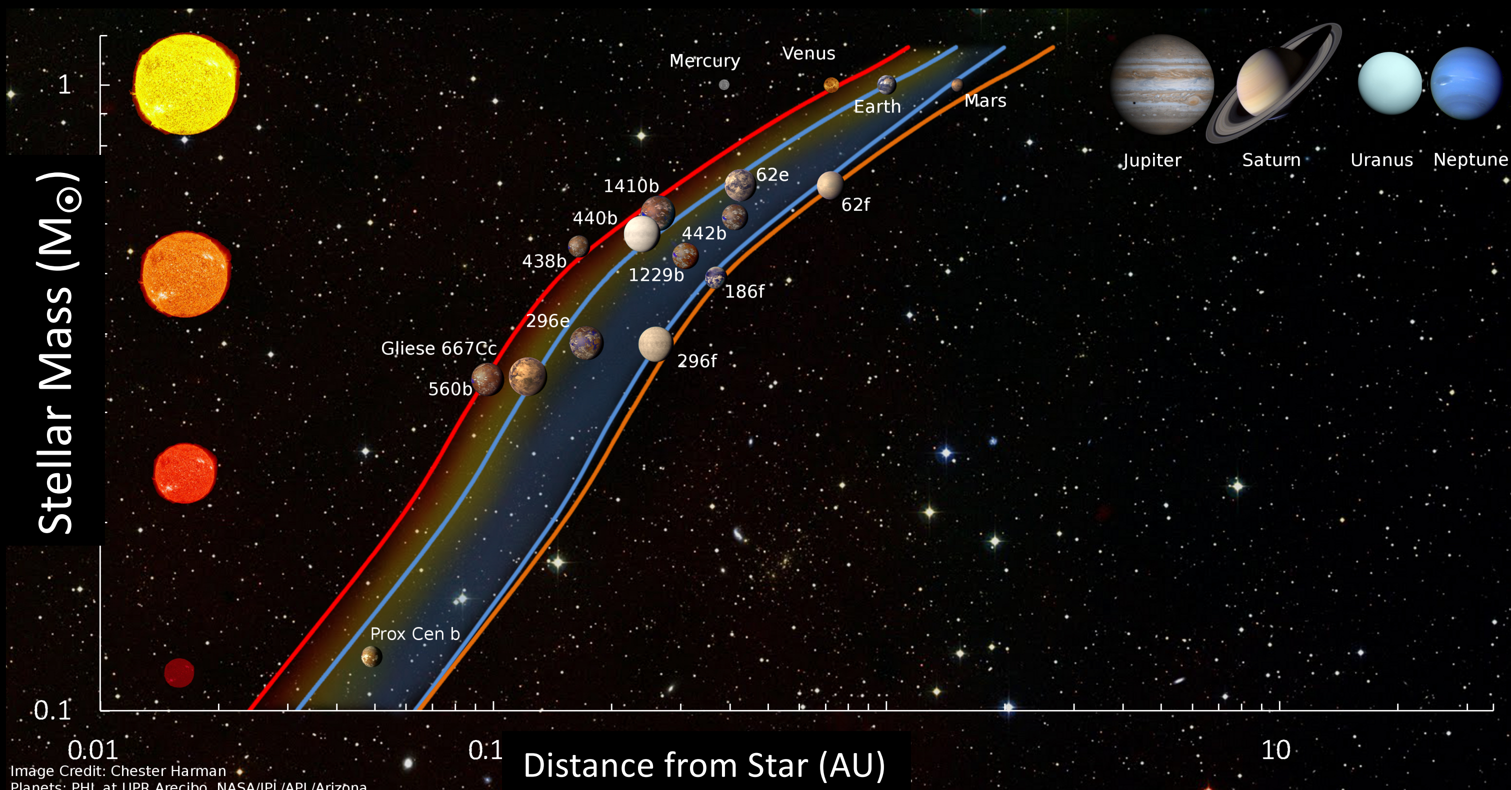
The habitability of planets orbiting M-dwarf stars

Aomawa L. Shields[a, b, d], Sarah Ballard[c], John Asher Johnson[d]

Show more

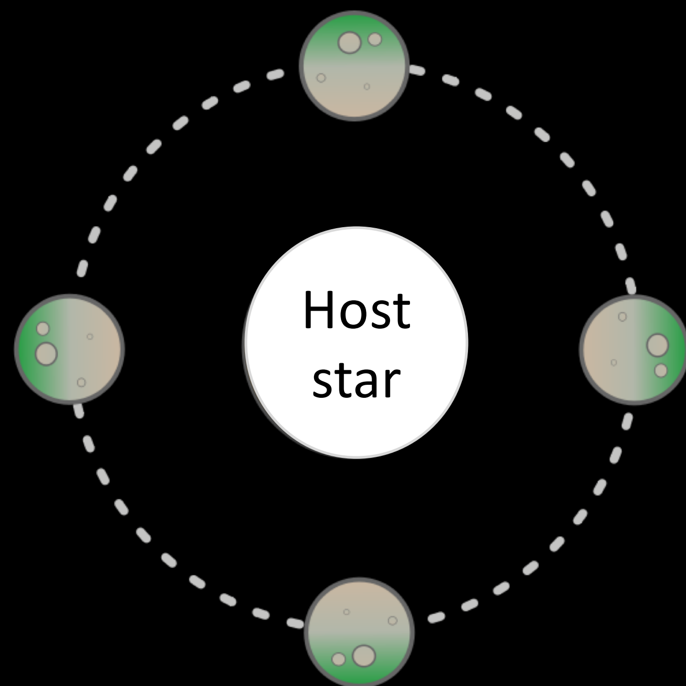
http://dx.doi.org/10.1016/j.physrep.2016.10.003

The Habitable Zone

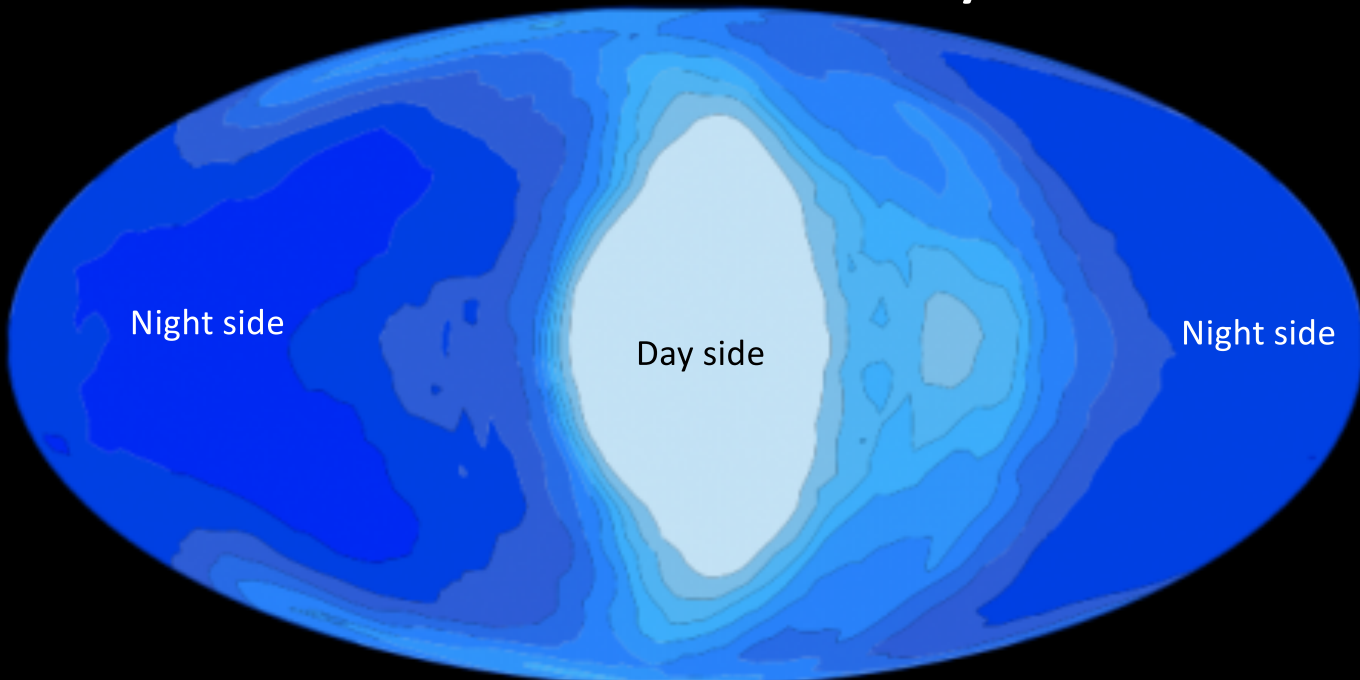


Synchronous rotation and surface pressure

(Joshi, Haberle, and Reynolds 1997)

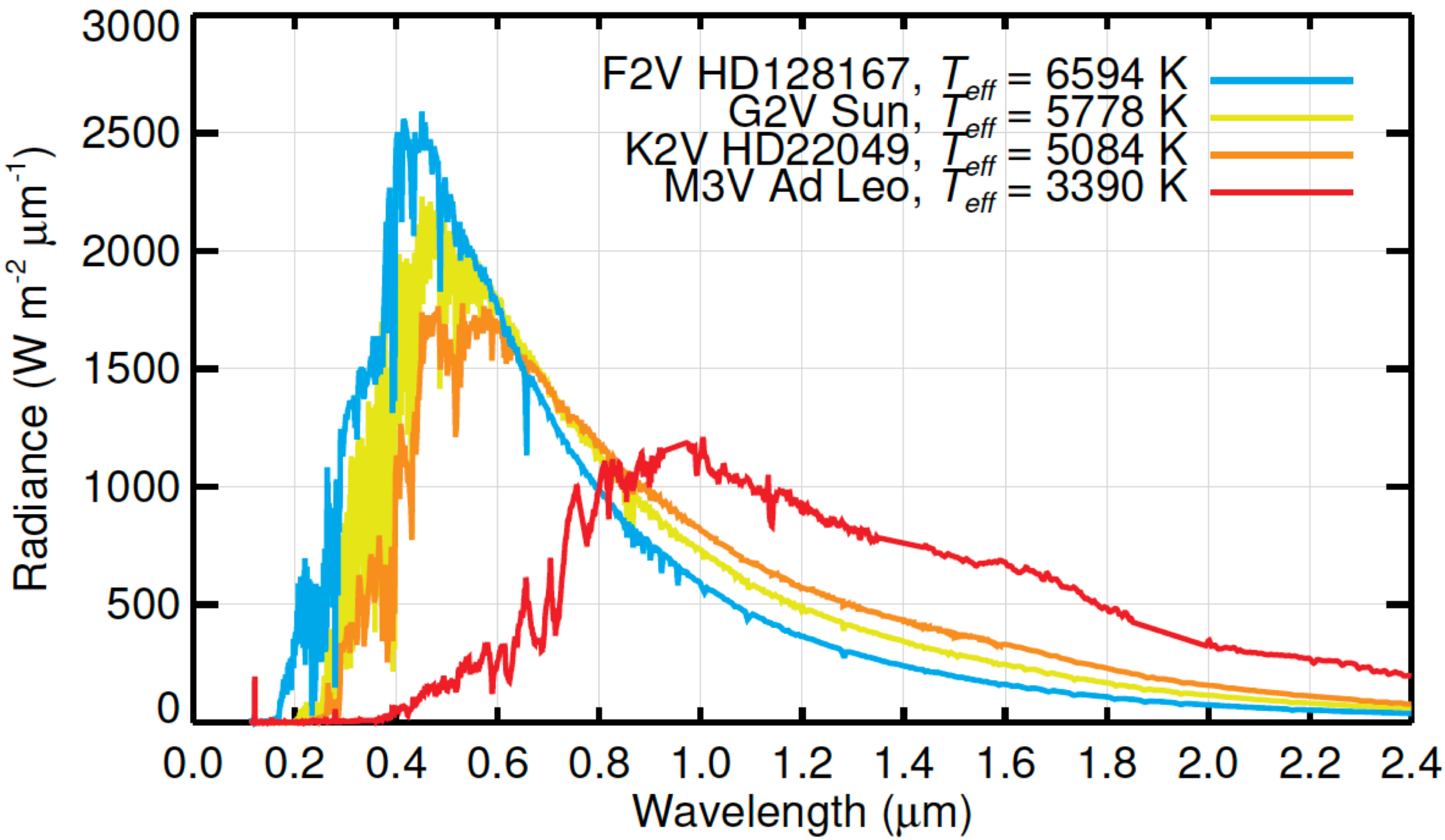


Synchronous rotation can be a benefit for climate and habitability (Yang et al. 2013)



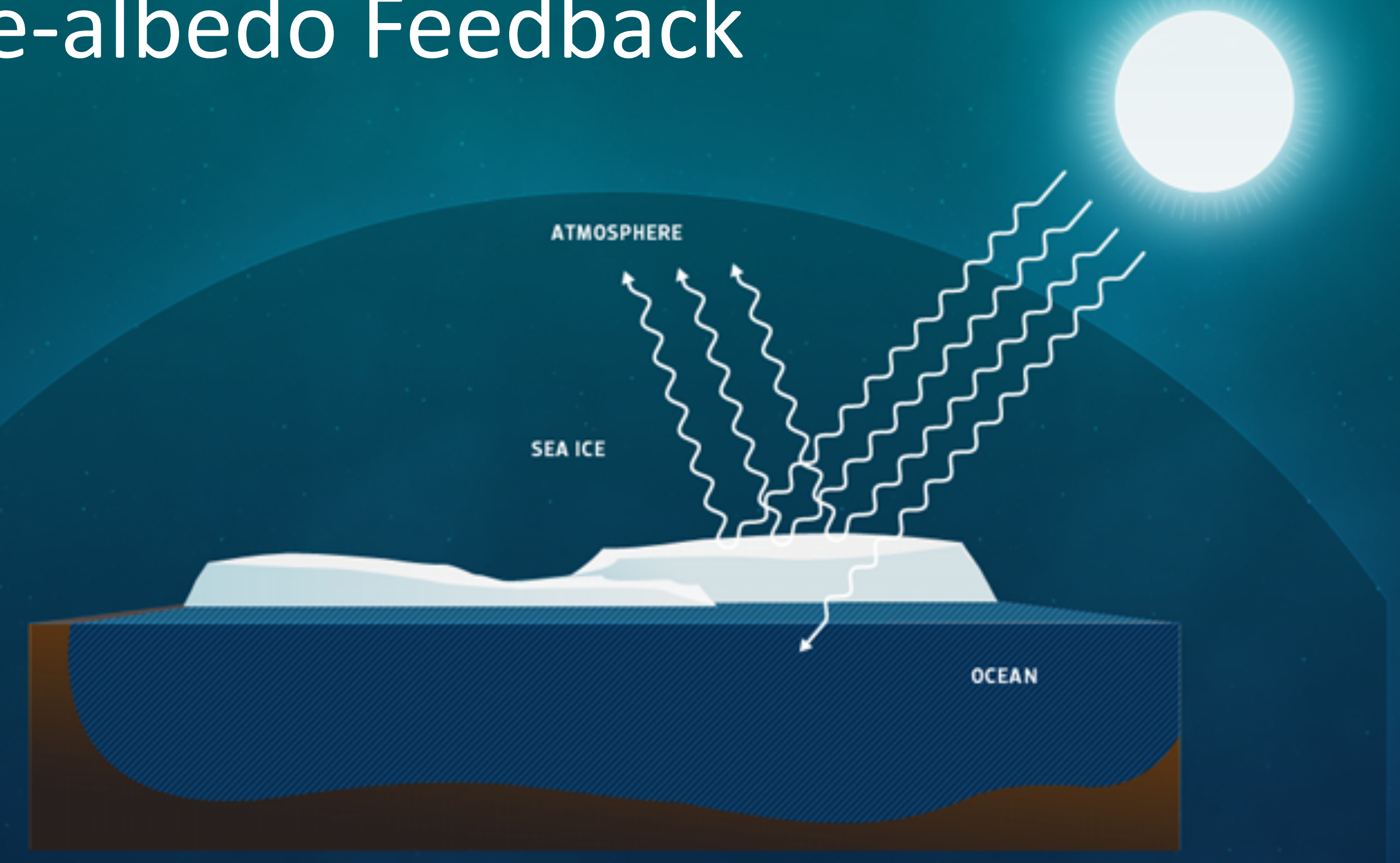
Credit: Jun Yang


Starlight

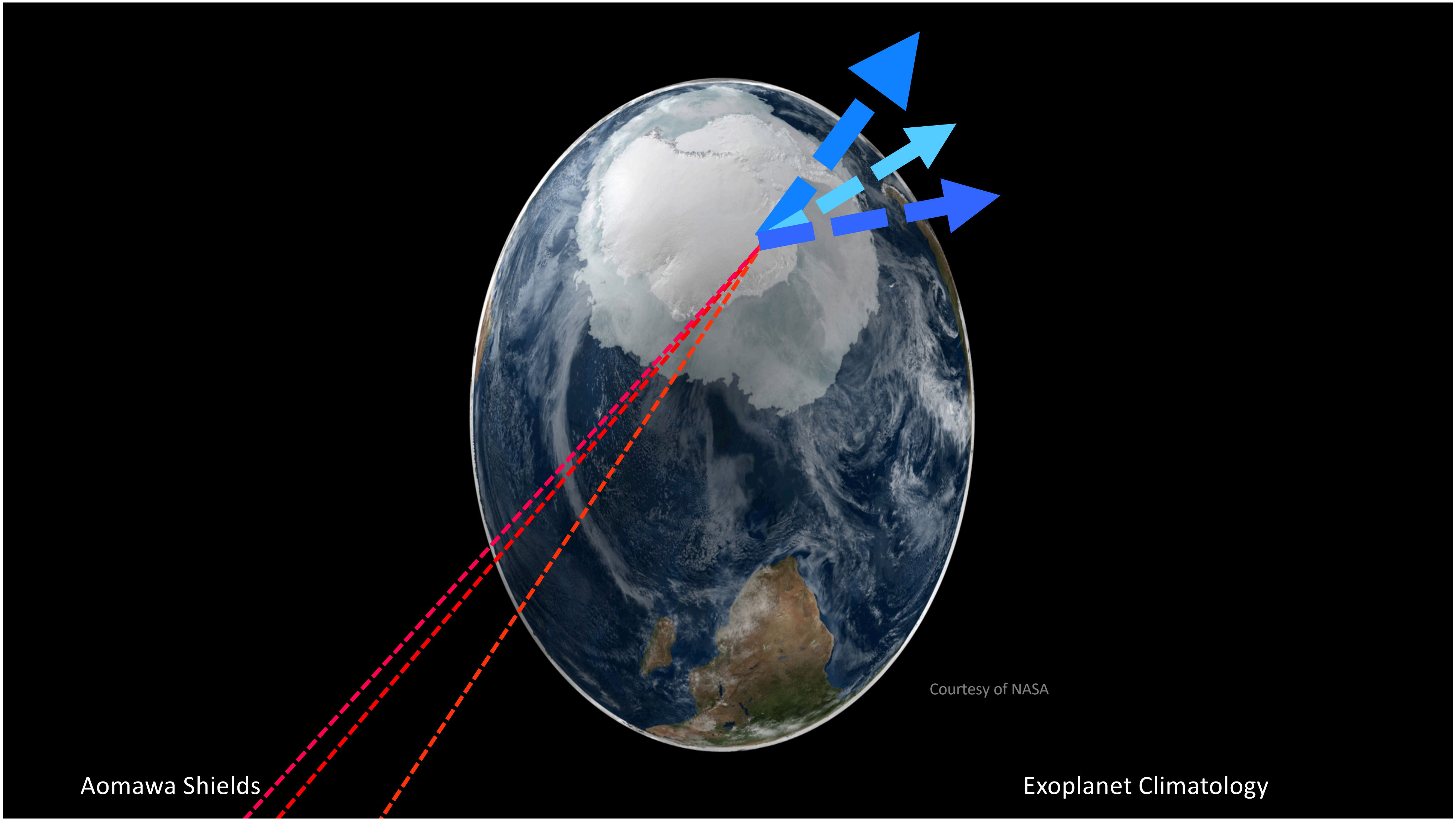


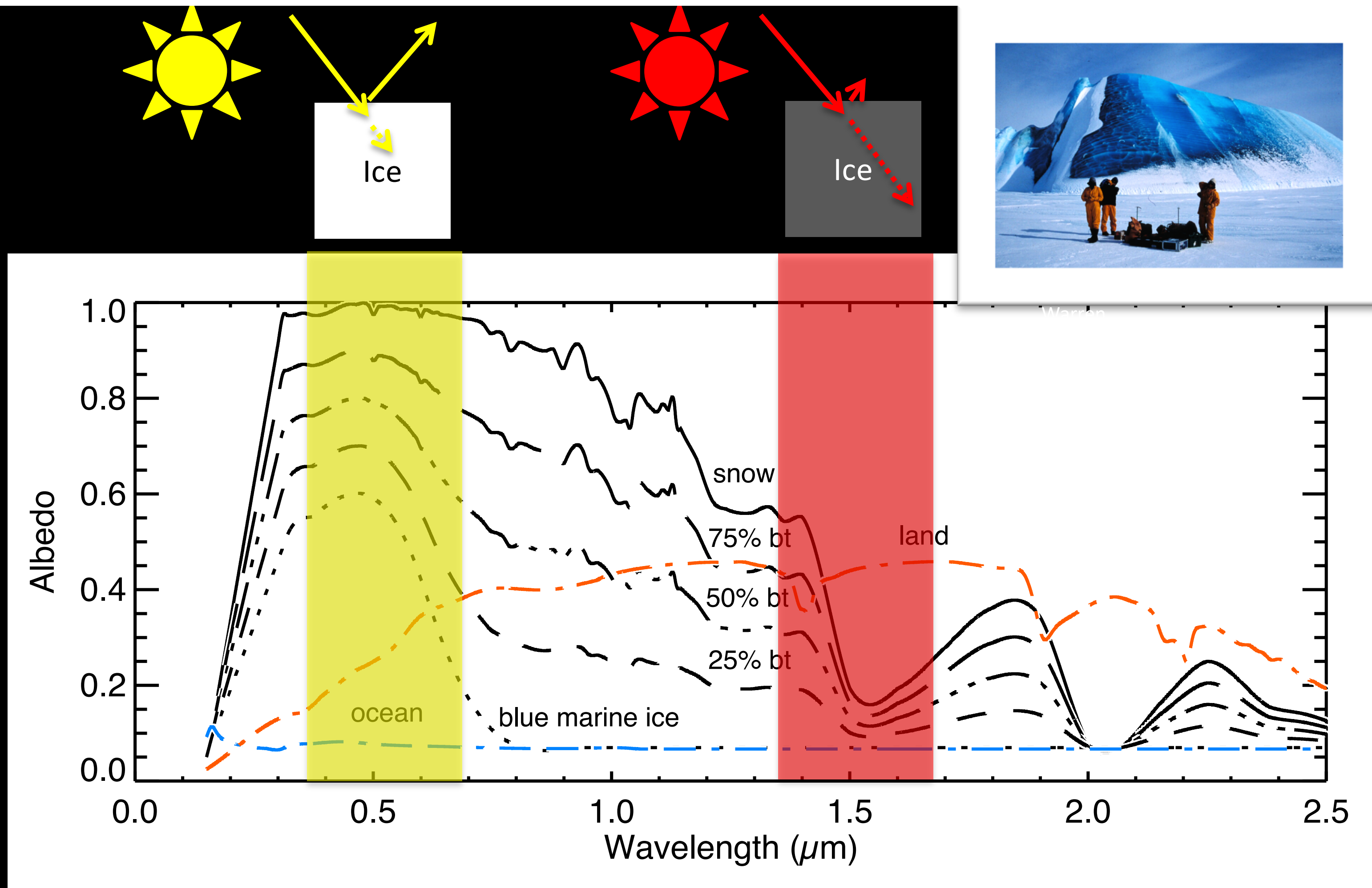
Credit: Based on Wolf, Shields et al. 2017a

Ice-albedo Feedback



KOSHLAND SCIENCE MUSEUM

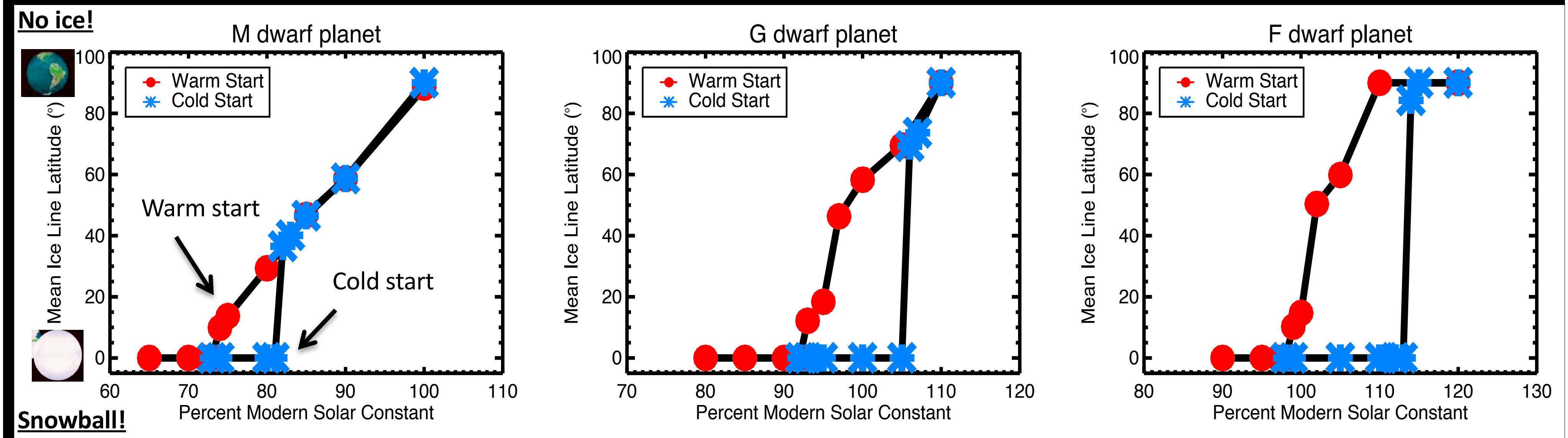

Courtesy of NASA
Aomawa Shields
Exoplanet Climatology



Ice absorbs where M-dwarfs emit strongly

Shields et al. (2013)
Warren et al. (2002)
Grenfell et al. (1994)

Climate Stability

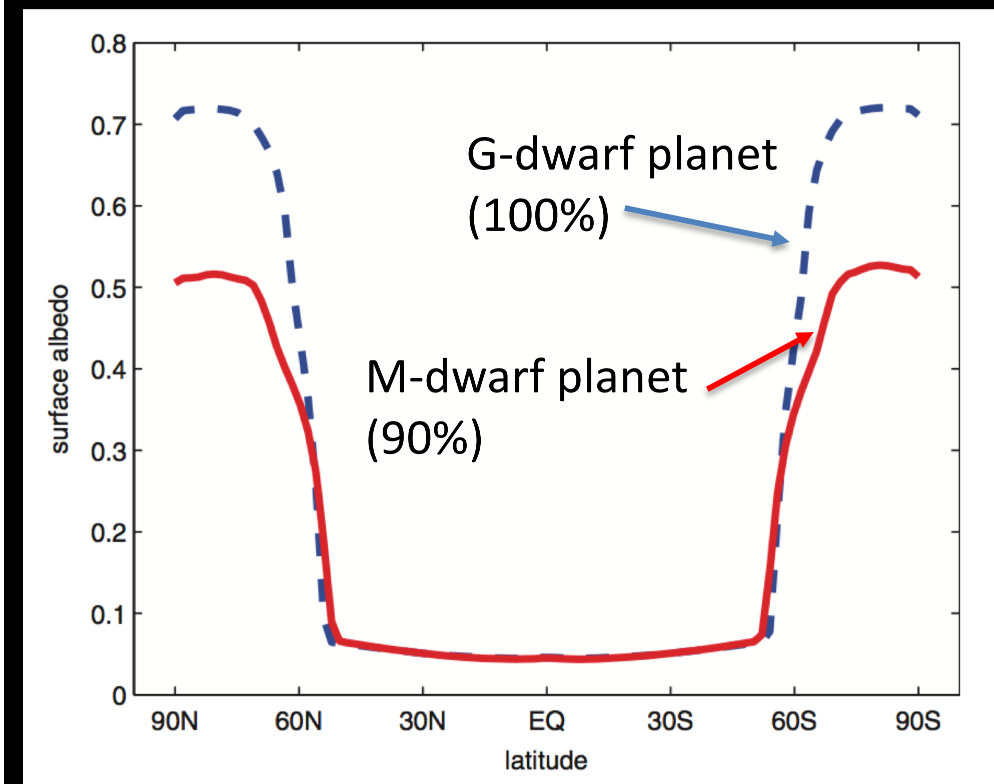


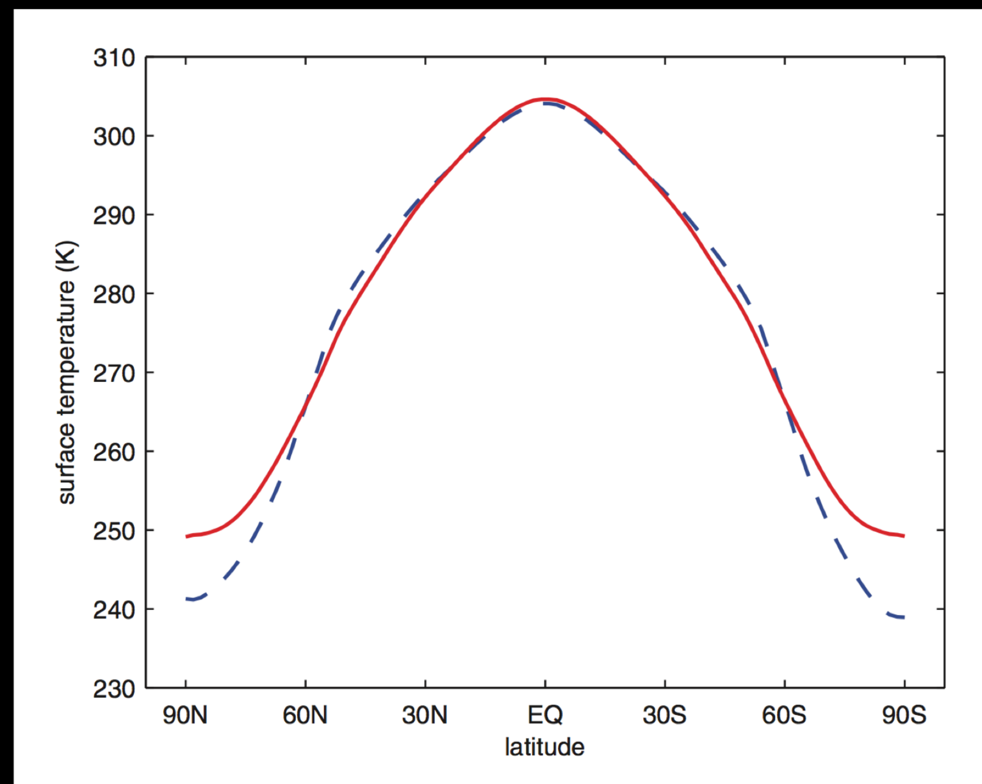
Shields et al. (2014)

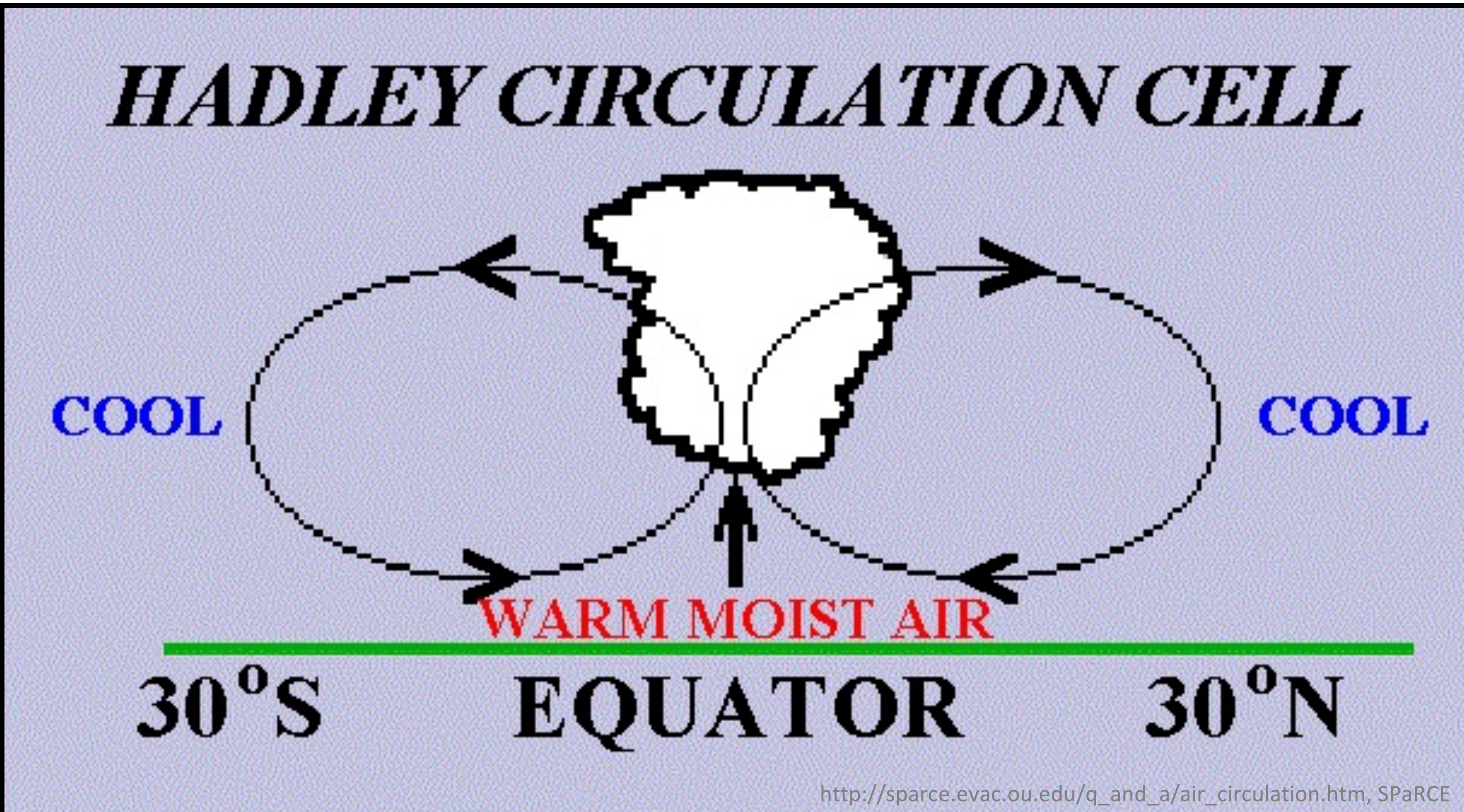
Albedo

Surface Temperature

Shields et al. (2013)

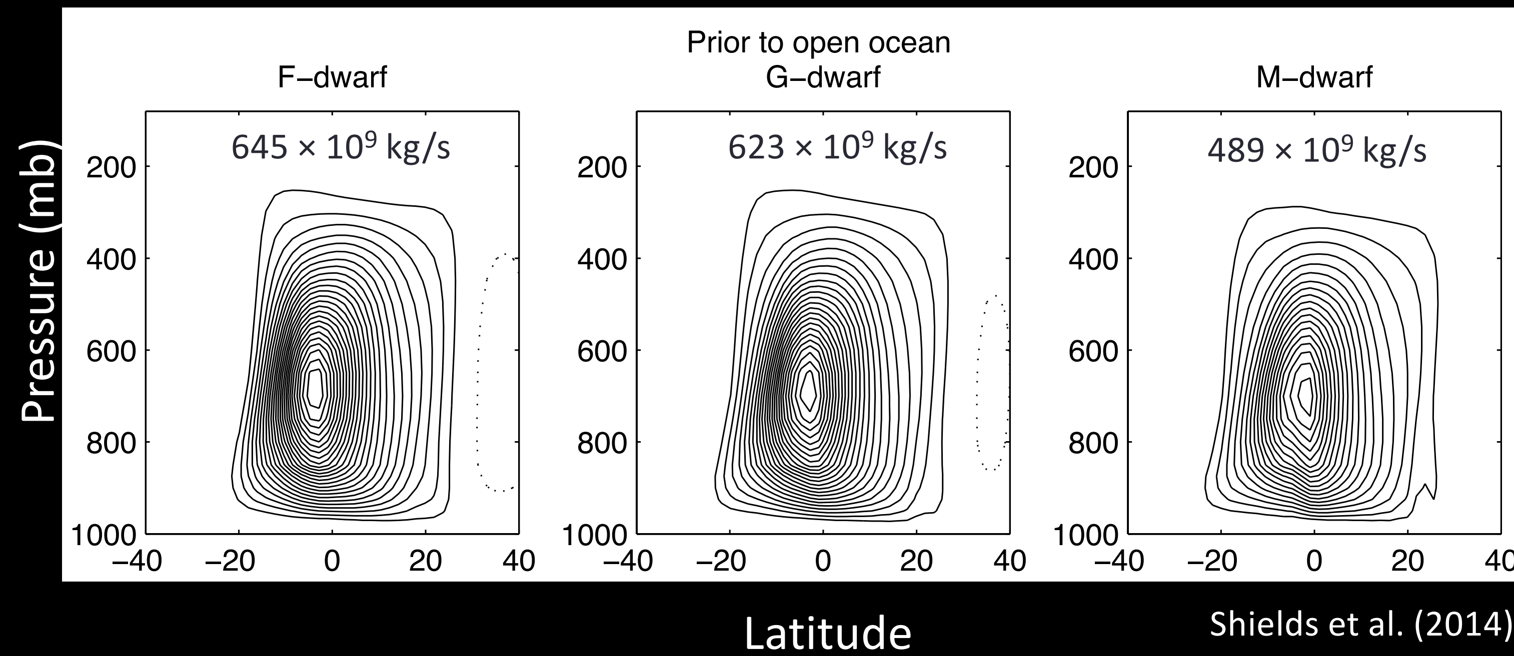






Transports heat from equator to higher latitudes

Hadley circulation on deglaciating planets
Northern hemisphere winter

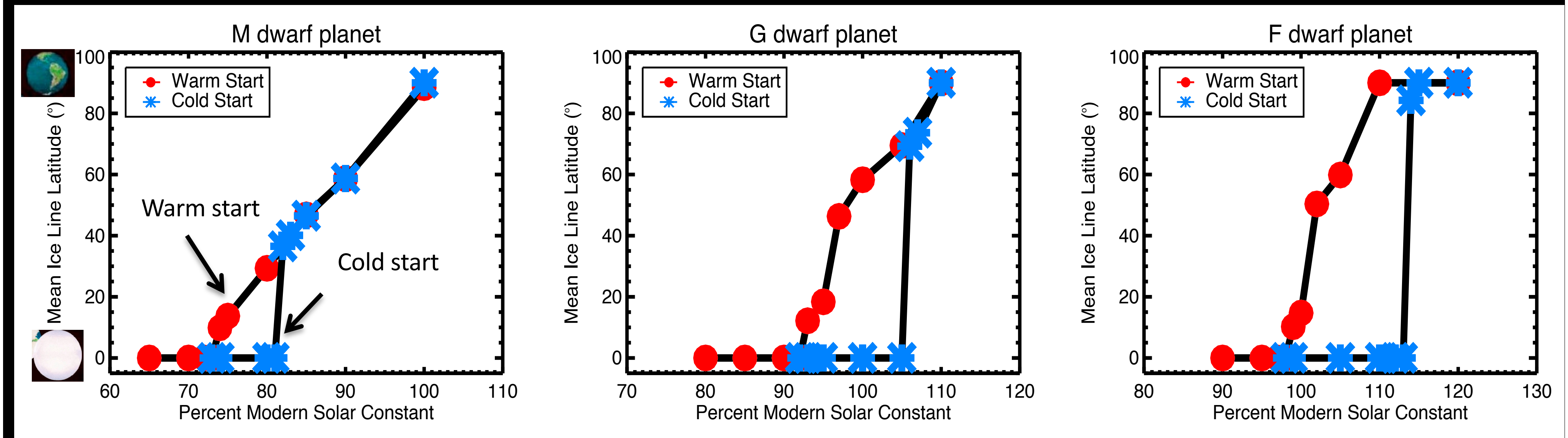


Shields et al. (2014)

Weaker Hadley circulation helps M-dwarf planet thaw more easily

Climate Stability

Shields et al. (2014)



Shorter jump in ice line

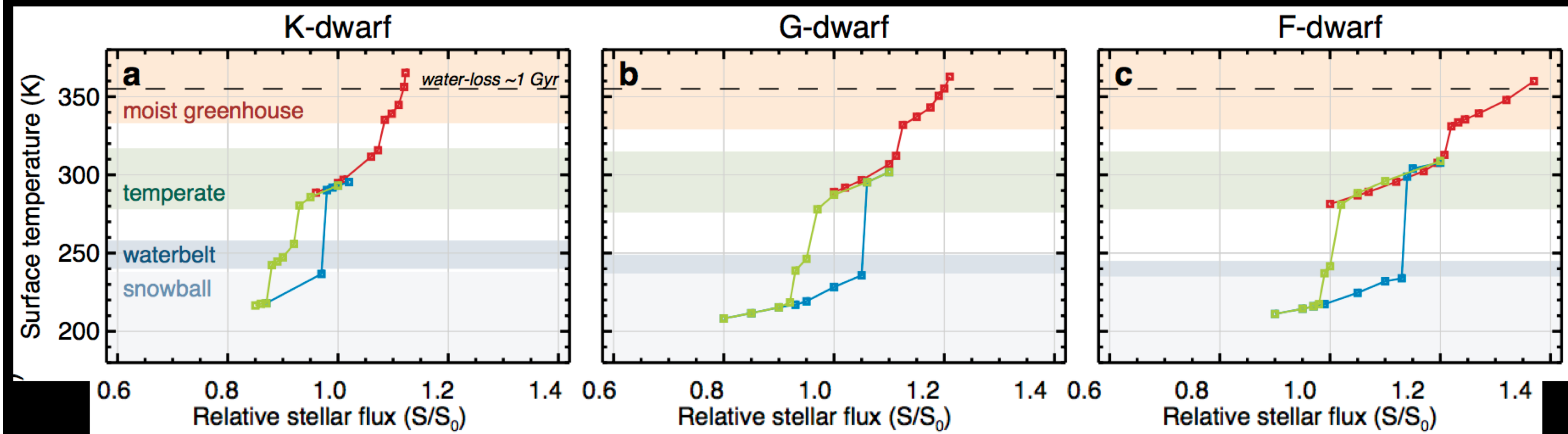
Higher jump in ice line

Better for life?

Aomawa Shields

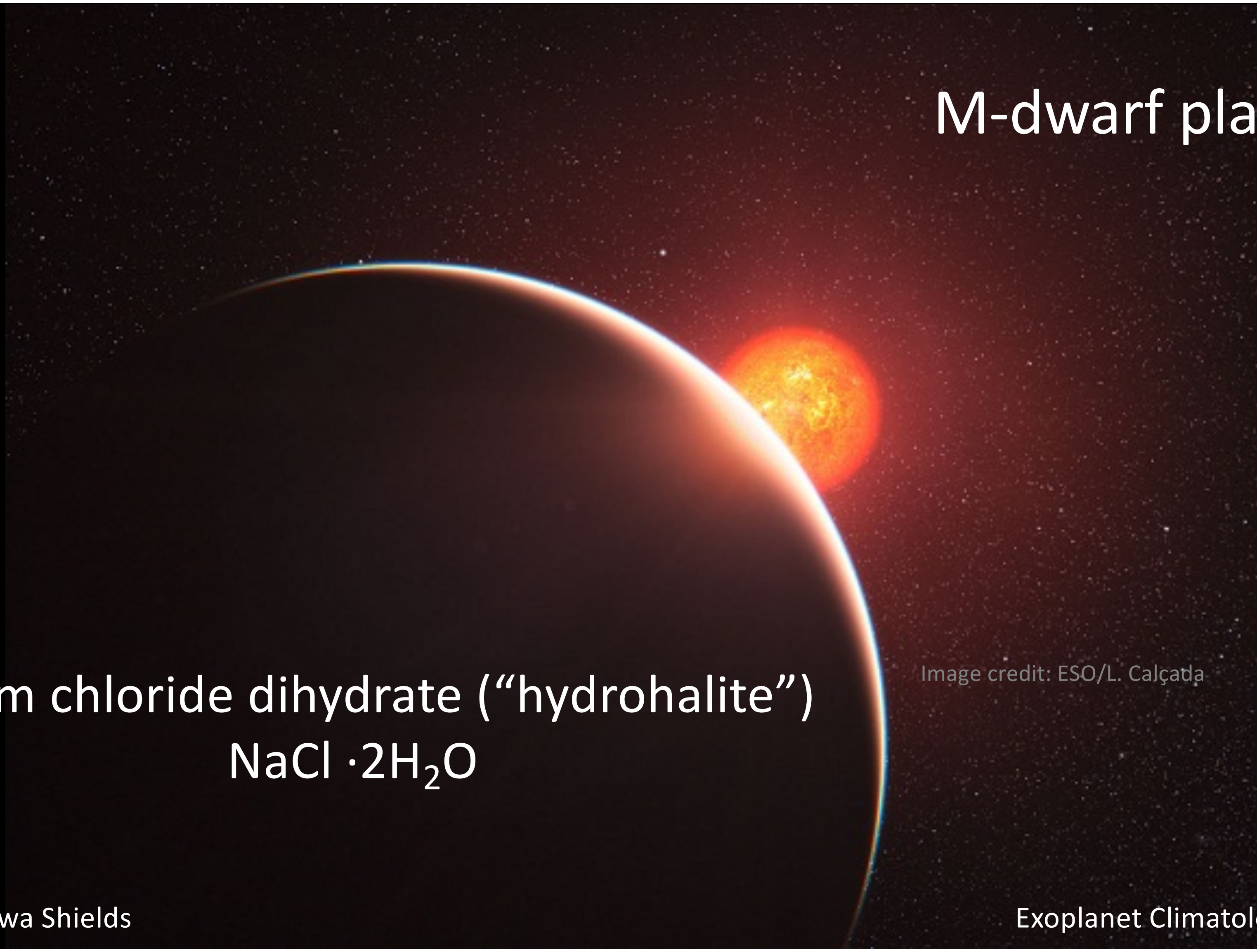
Exoplanet Climatology

Identifying Multiple Possible Climate Regimes



Wolf, Shields+ (2017)

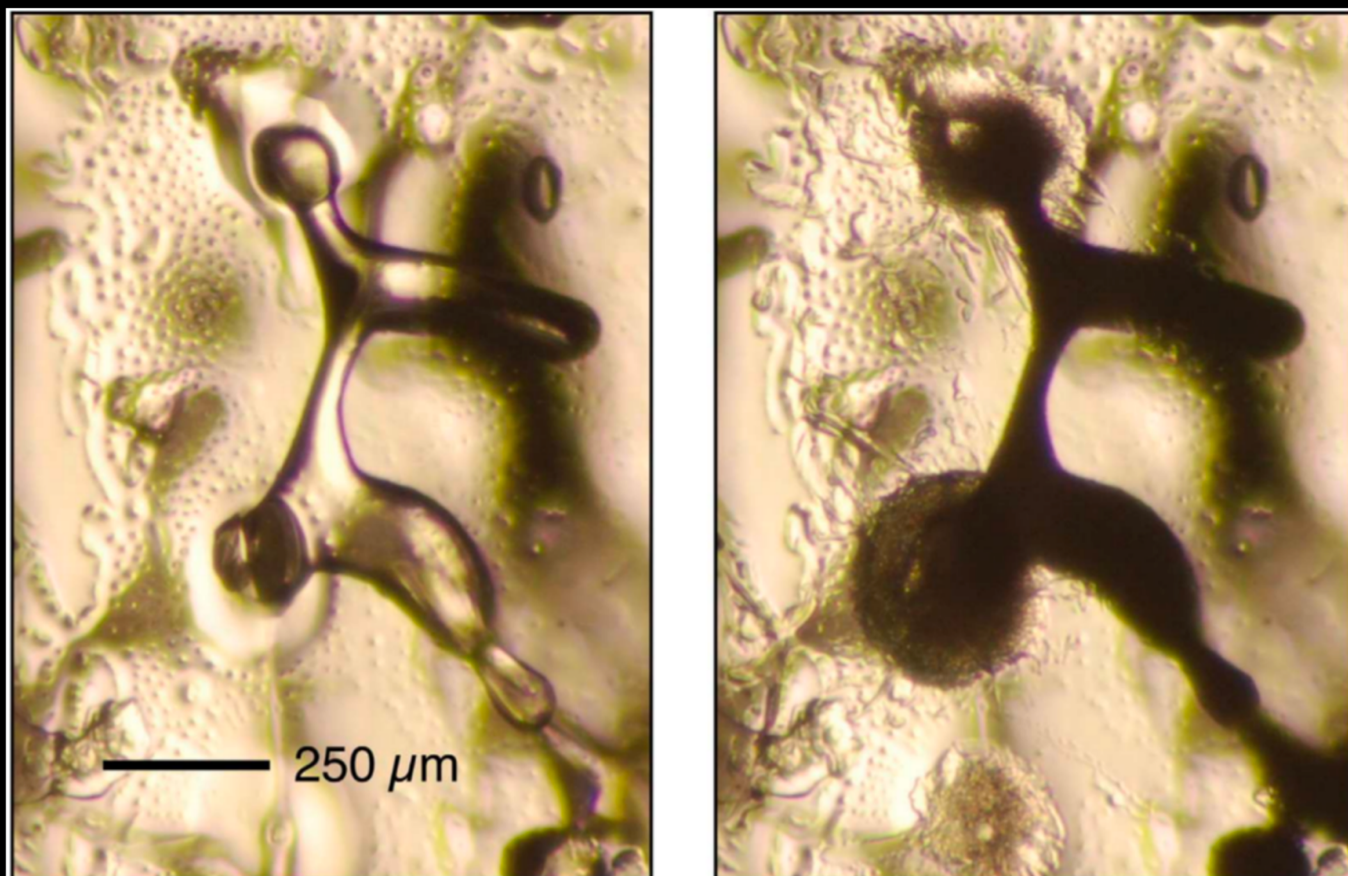
M-dwarf planets



Sodium chloride dihydrate ("hydrohalite")

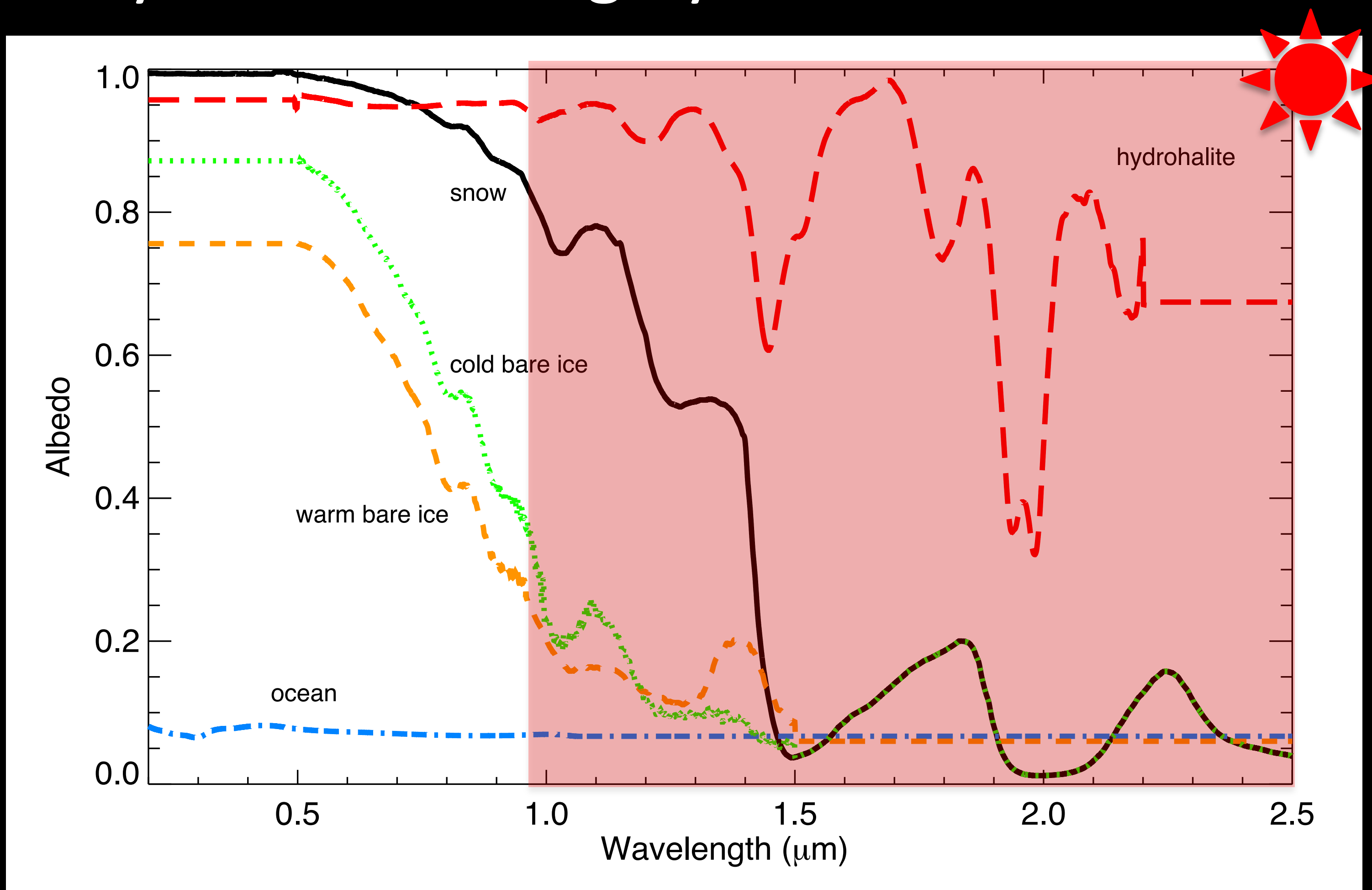
$NaCl \cdot 2H_2O$

Hydrohalite precipitation in sea ice
T < -23° C



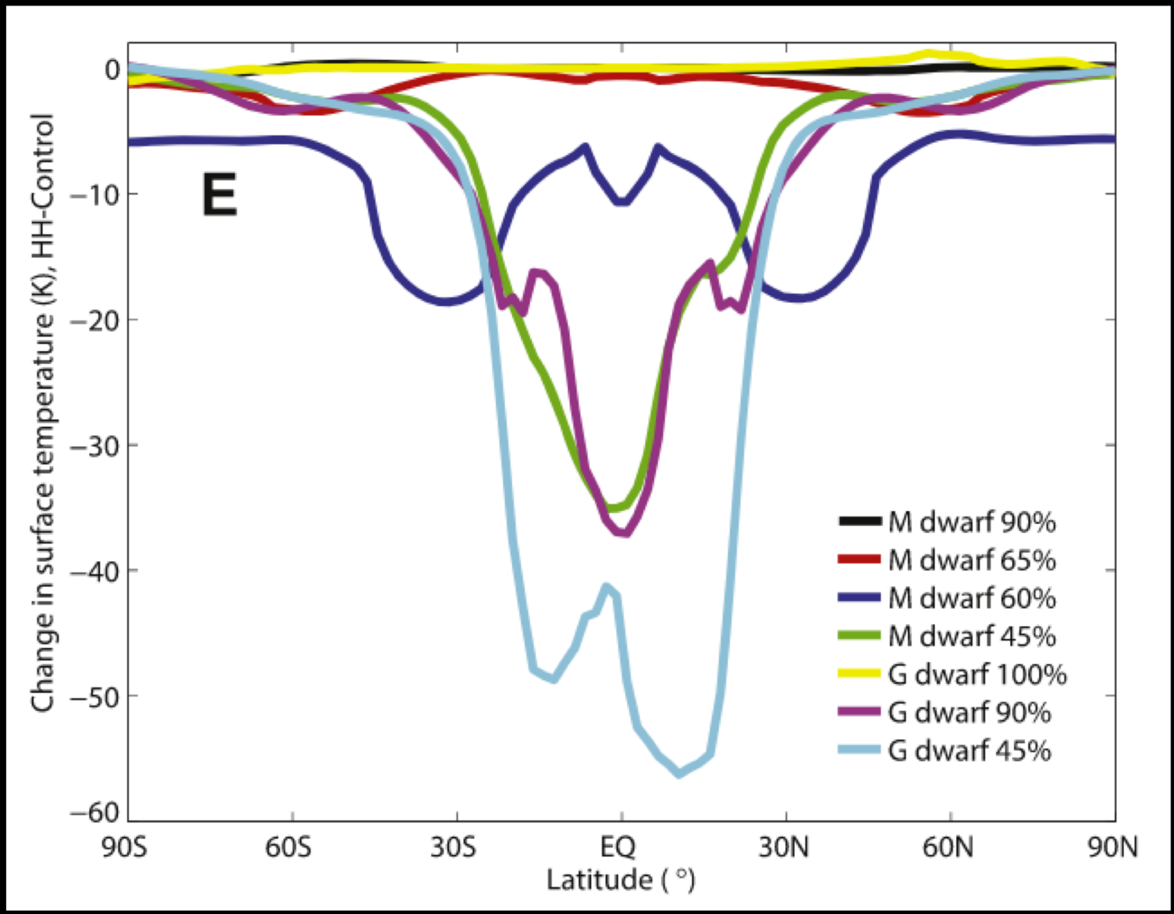
Carns et al. 2015

Hydrohalite is highly reflective in the IR



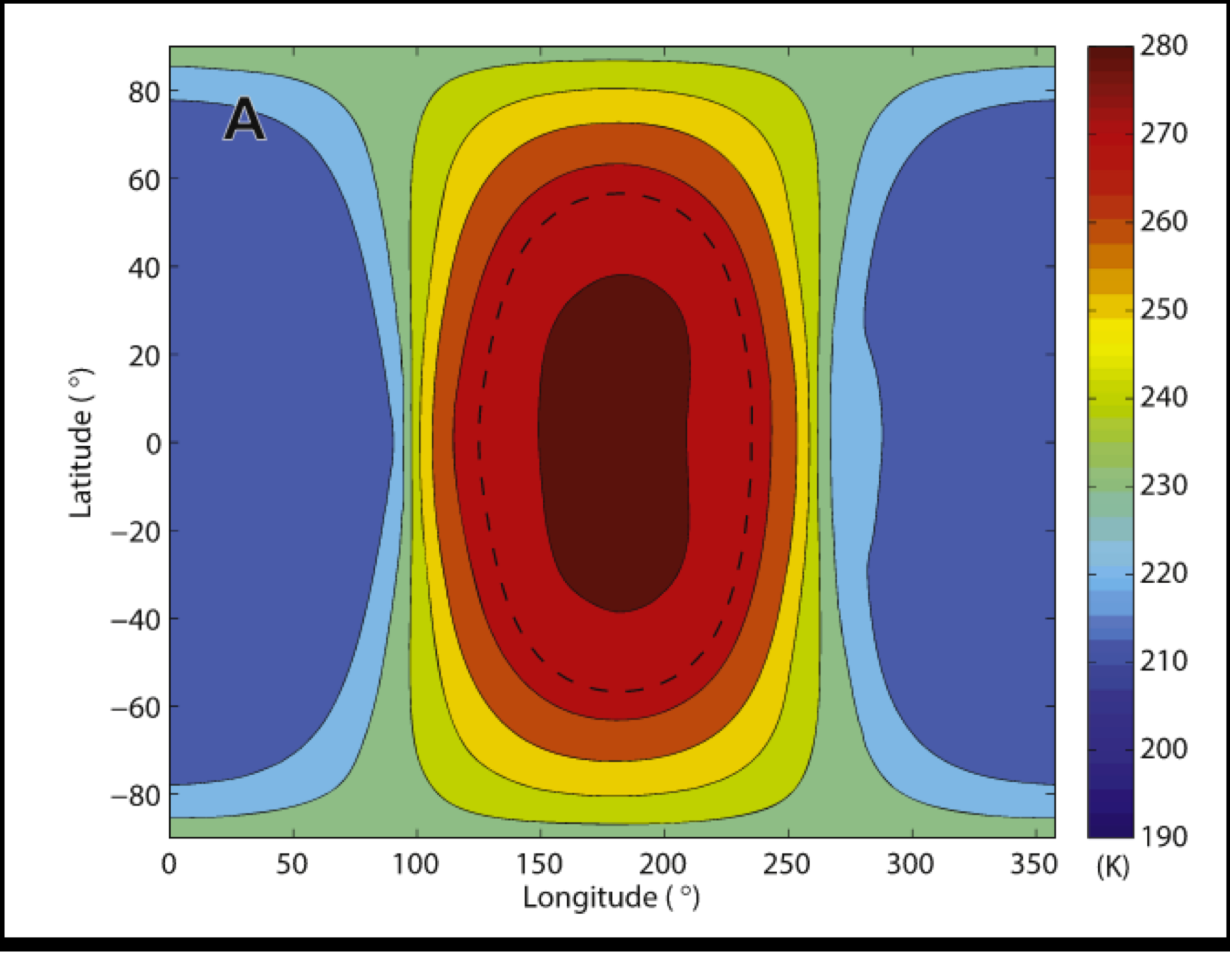
Shields and Carns 2018

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

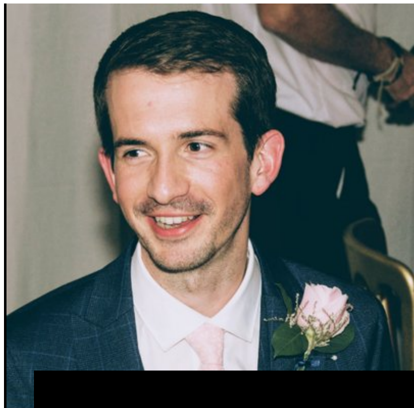


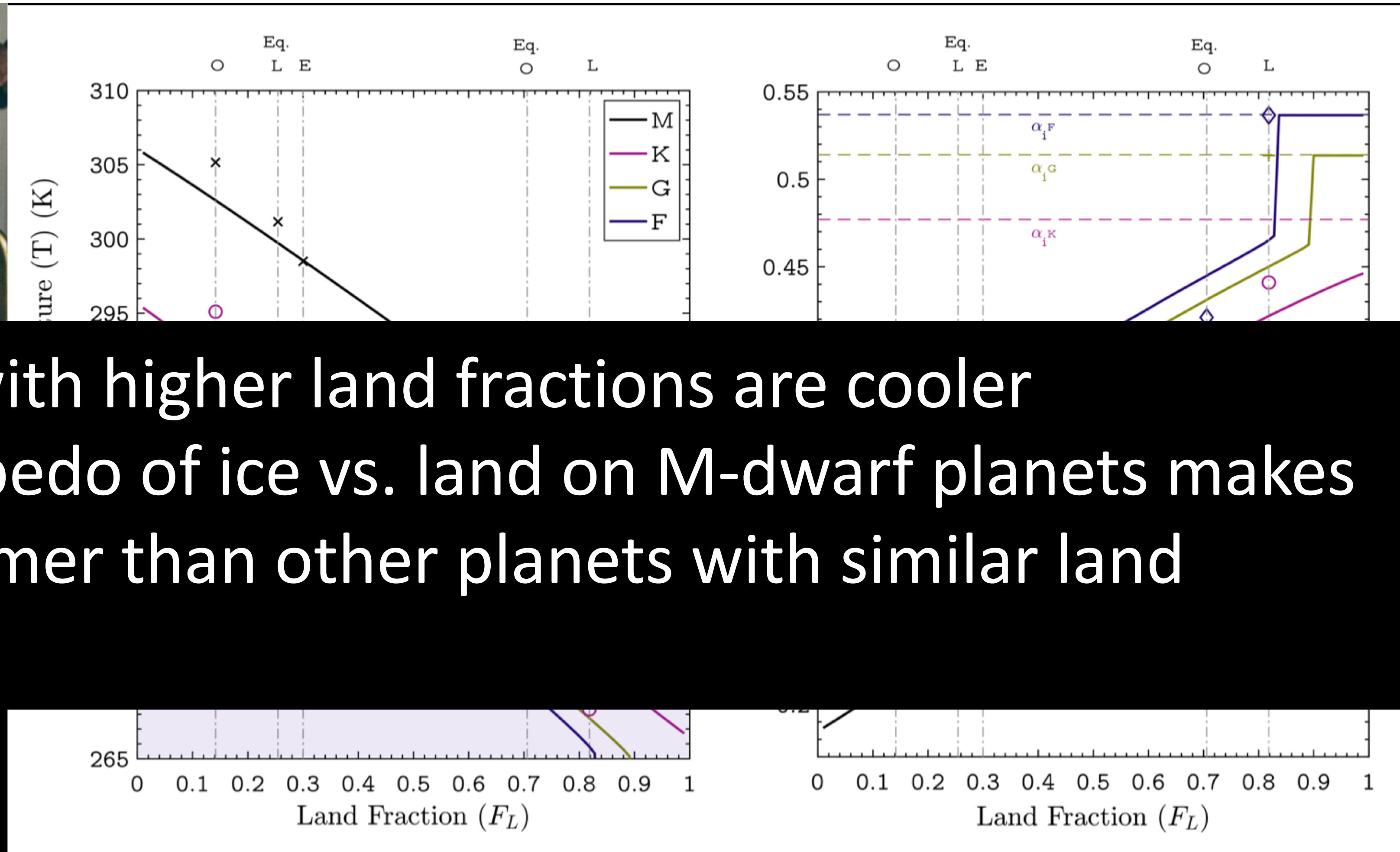
Shields and Carns 2018

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



Shields and Carns 2018





-Planets with higher land fractions are cooler

-Lower albedo of ice vs. land on M-dwarf planets makes them warmer than other planets with similar land fraction

Rushby, Shields, and Joshi, in review

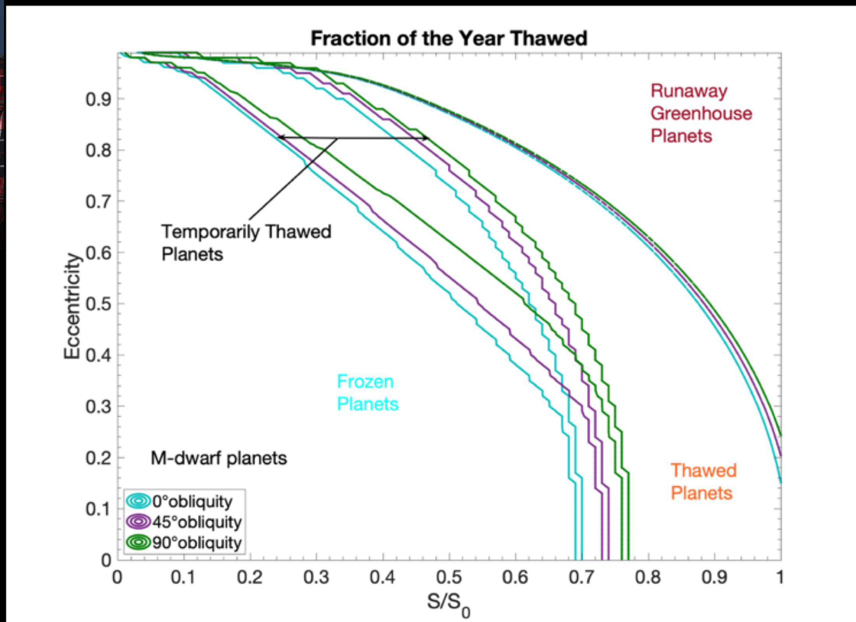
Igor Palubski

Temporal habitability and water loss on eccentric planets

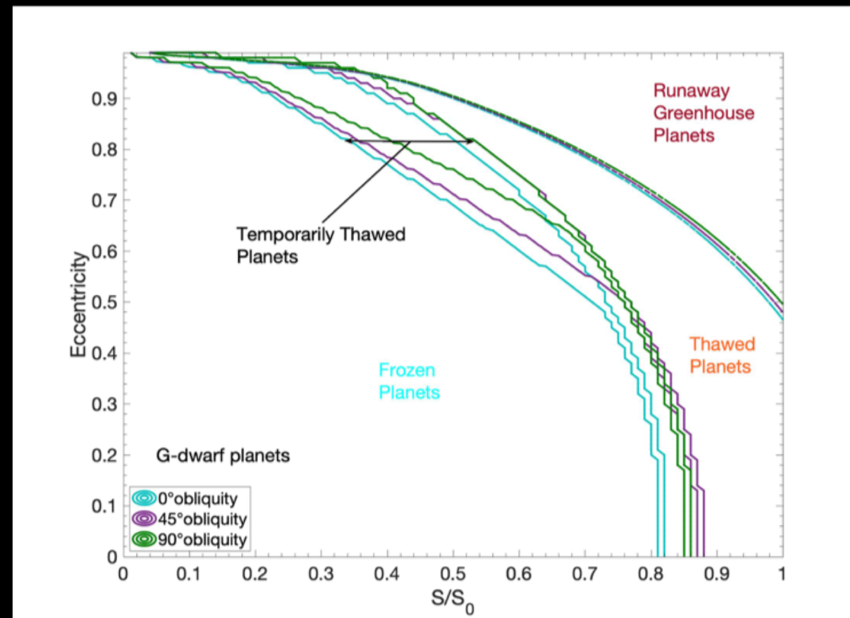
Exoplanet Climatology

Igor Palubski

M-dwarf planets



G-dwarf planets



Palubski, Shields, and Deitrick, in prep

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

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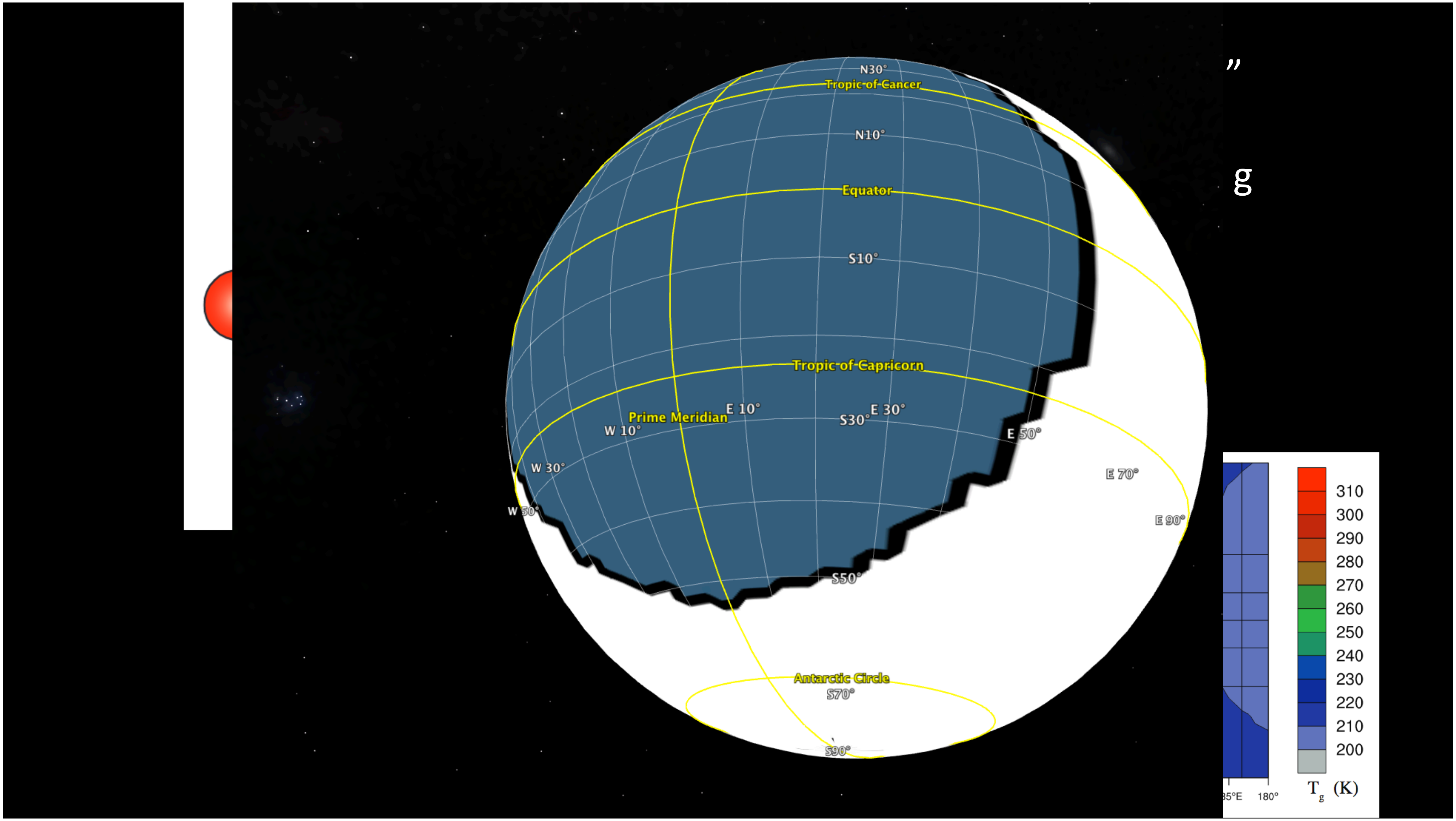
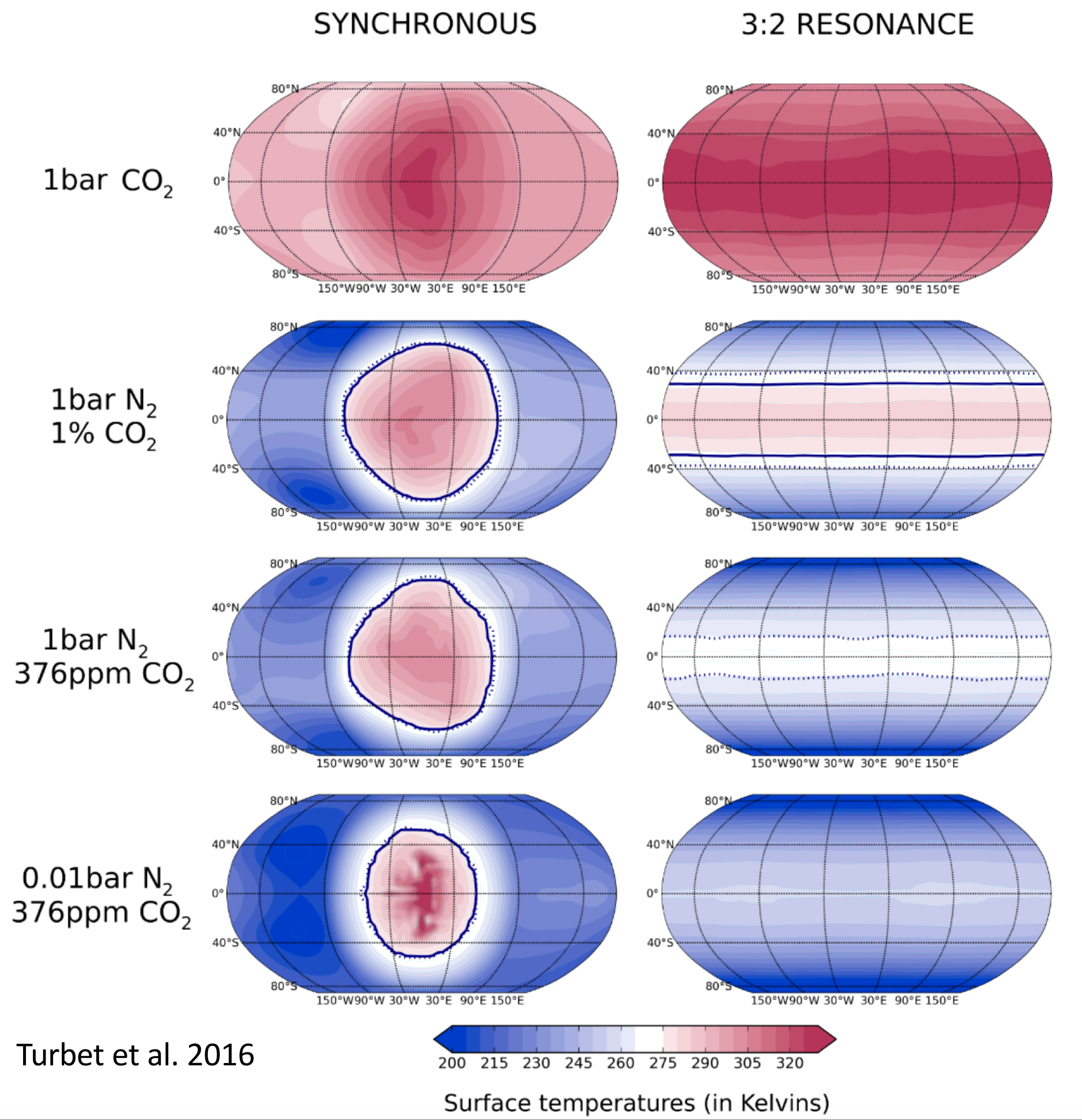
Targeted planet studies

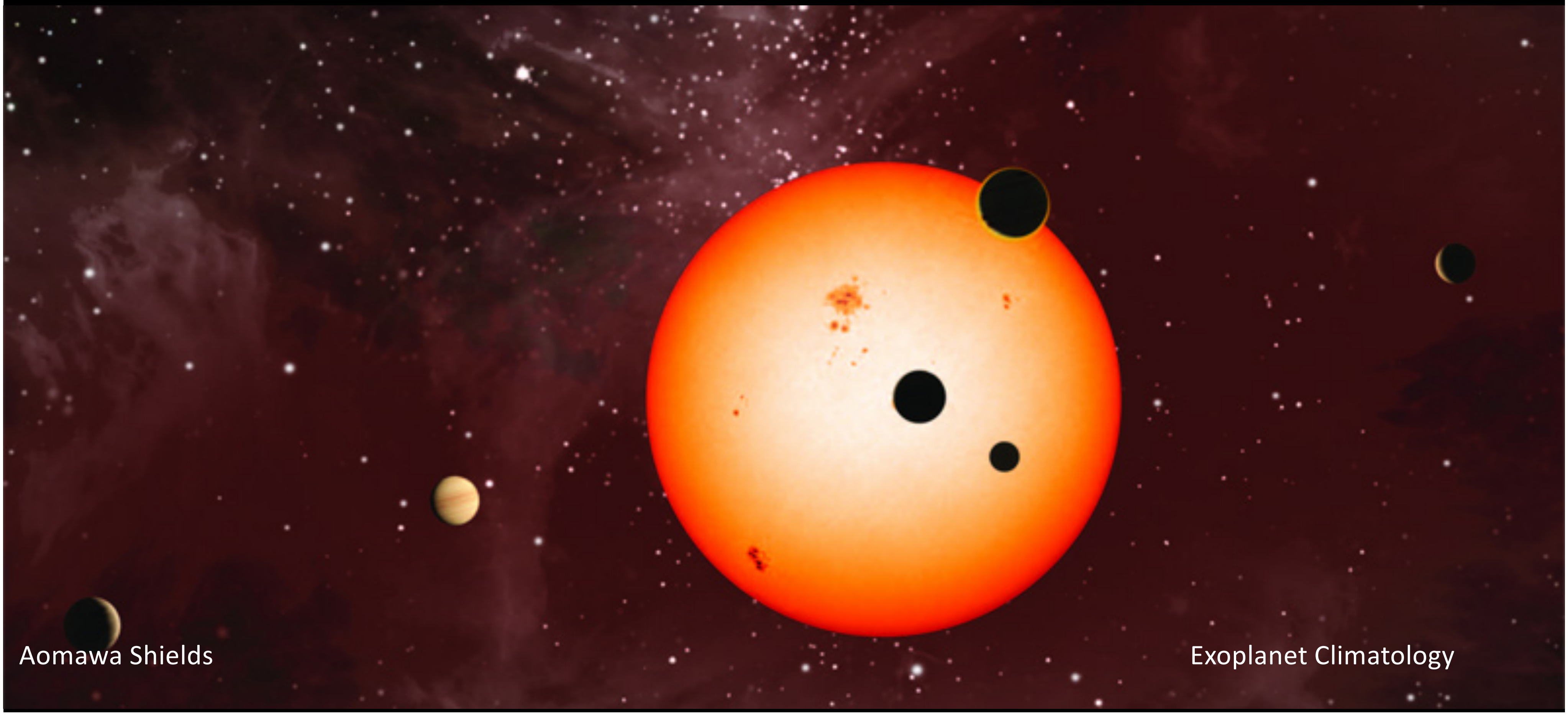

N30°
Tropic of Cancer
N10°
Equator
S10°
Tropic of Capricorn
Prime Meridian
E 10°
W 10°
S30°
E 30°
E 50°
W 30°
W 50°
E 70°
E 90°
S50°
Antarctic Circle
S70°
S90°
”
g
310
300
290
280
270
260
250
240
230
220
210
200
180°
T g (K)

Habitable climates on Proxima Centauri b



Turbet et al. 2016

Multiple-planet systems



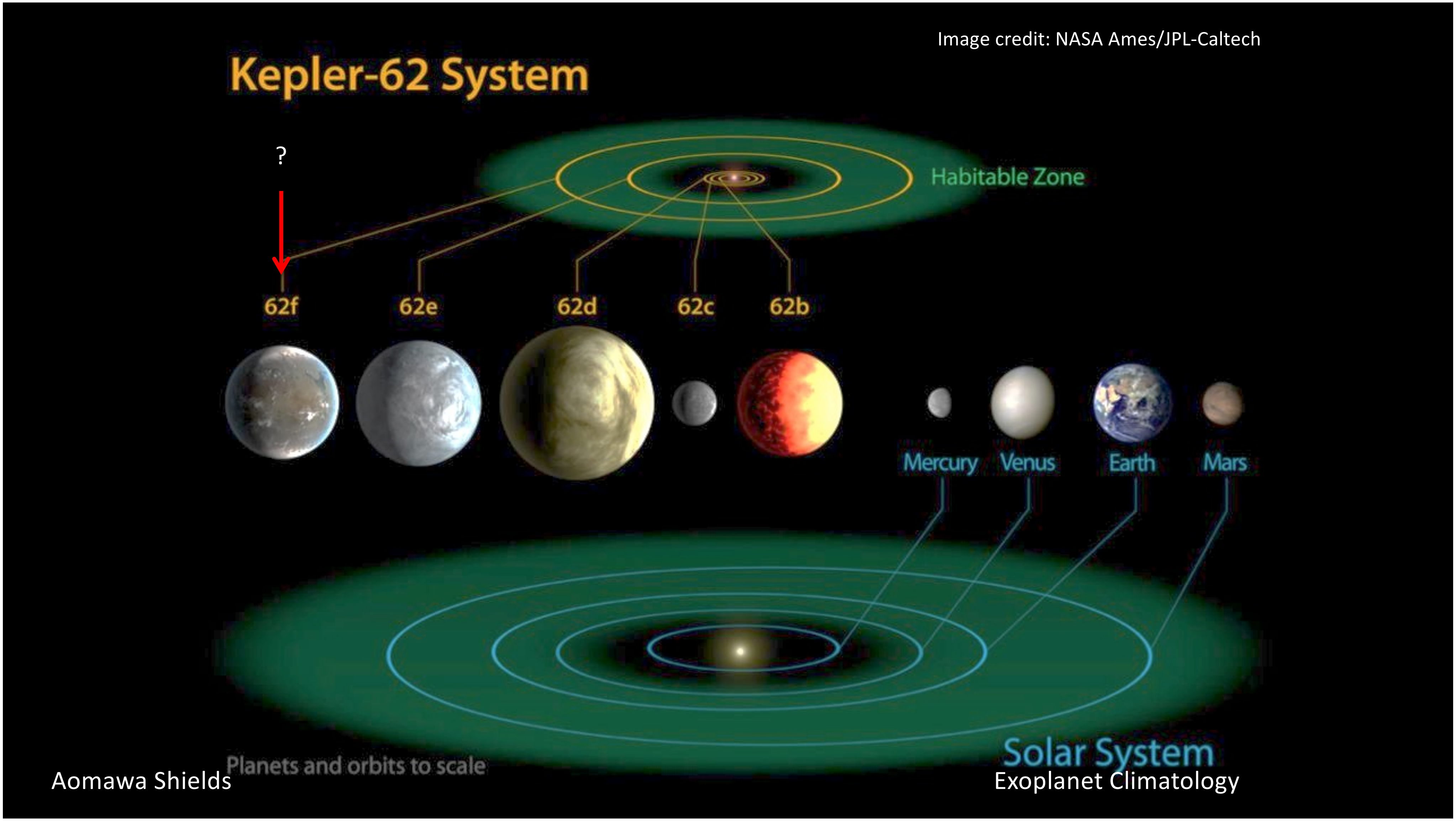
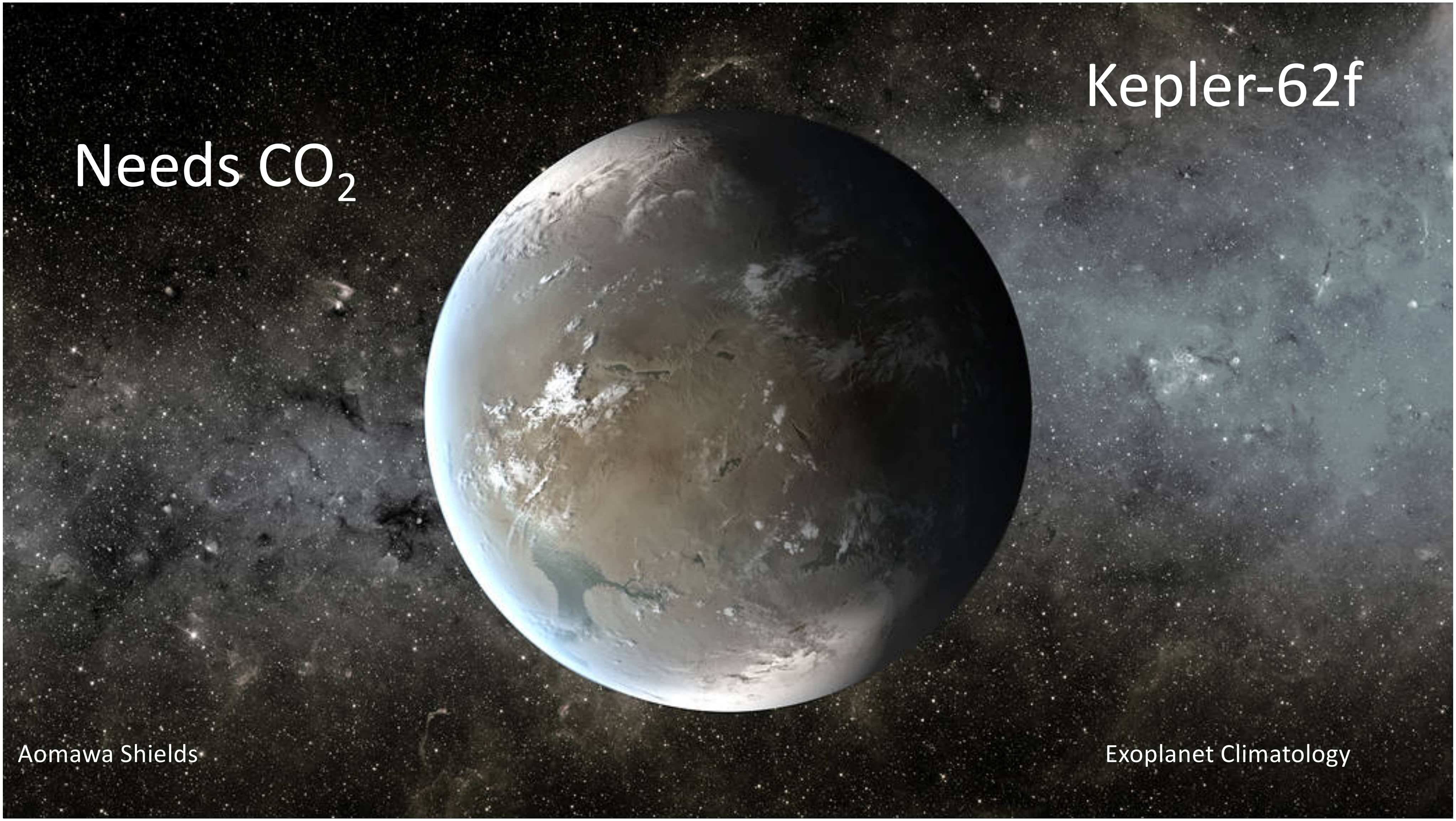
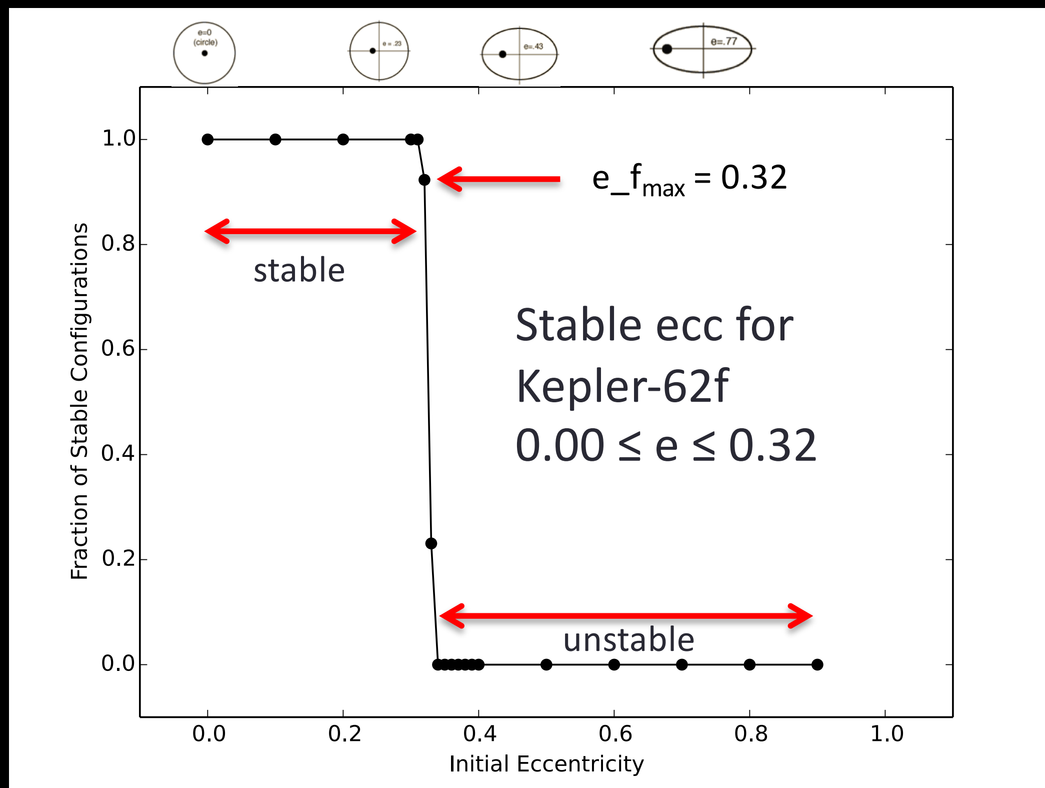


Image credit: NASA Ames/JPL-Caltech
Kepler-62 System
?
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale
Aomawa Shields
Exoplanet Climatology


Kepler-62f
Needs CO_2
Aomawa Shields
Exoplanet Climatology

Stable eccentricities



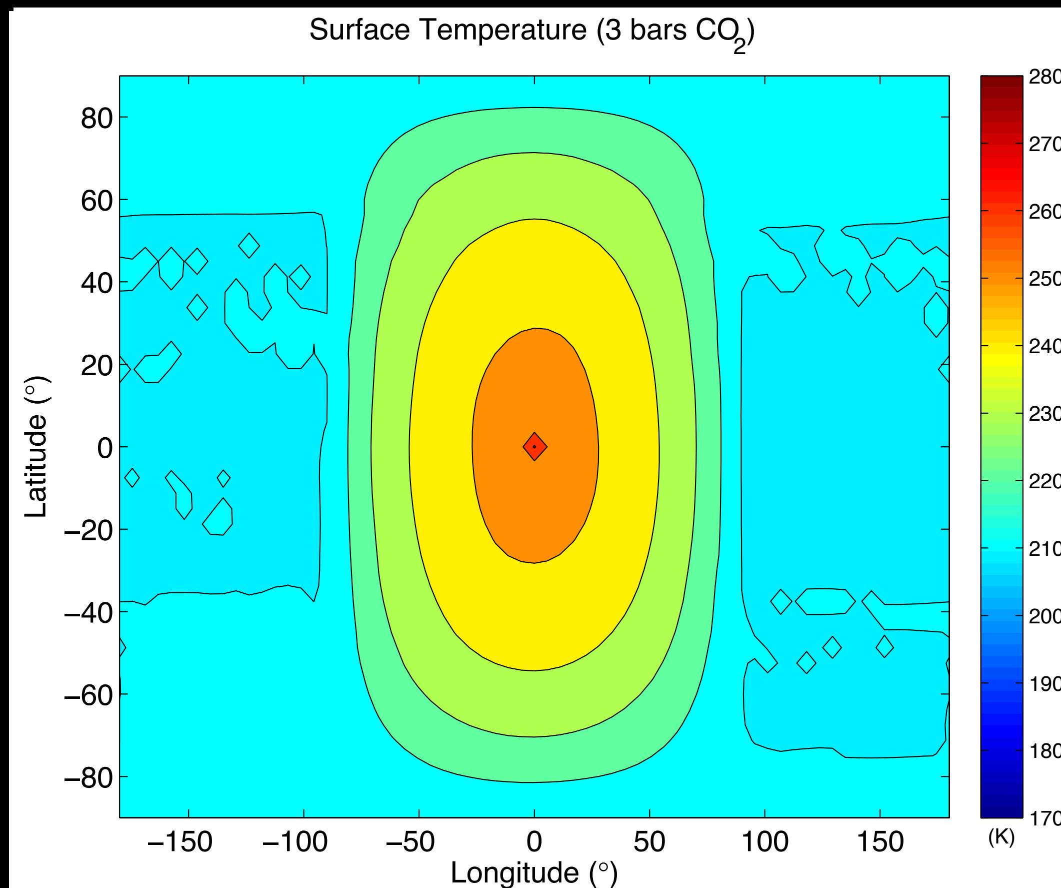
Shields et al. (2016a)

Surface Temperature, 3 bar CO_2

High CO_2

Earth-like axial tilt

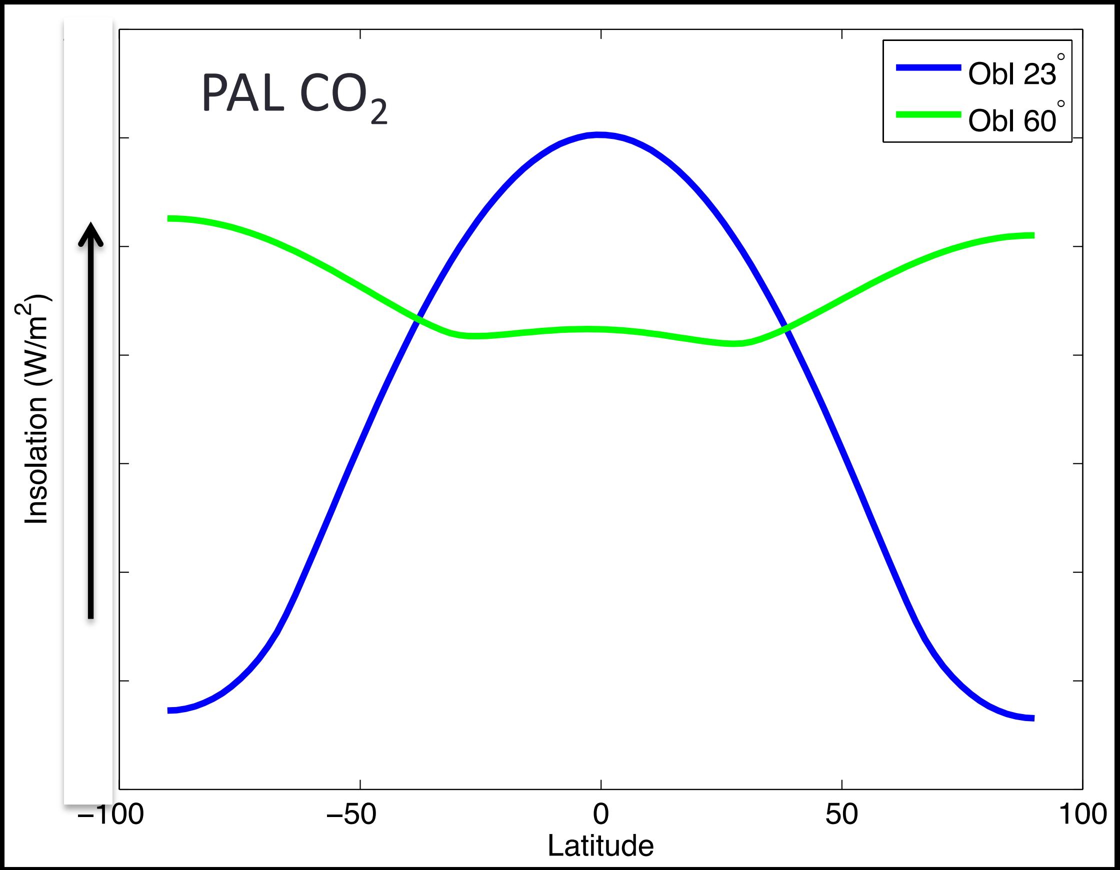
Circular orbit



Shields et al. 2016a

Global mean surface temps similar to Earth!

Insolation

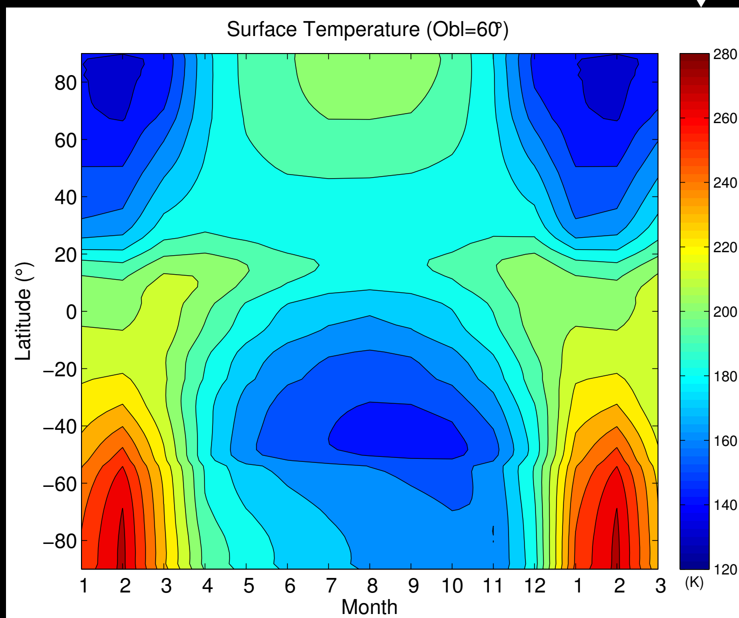


Shields et al. 2016a

Surface Temperature

Obliquity = 60°

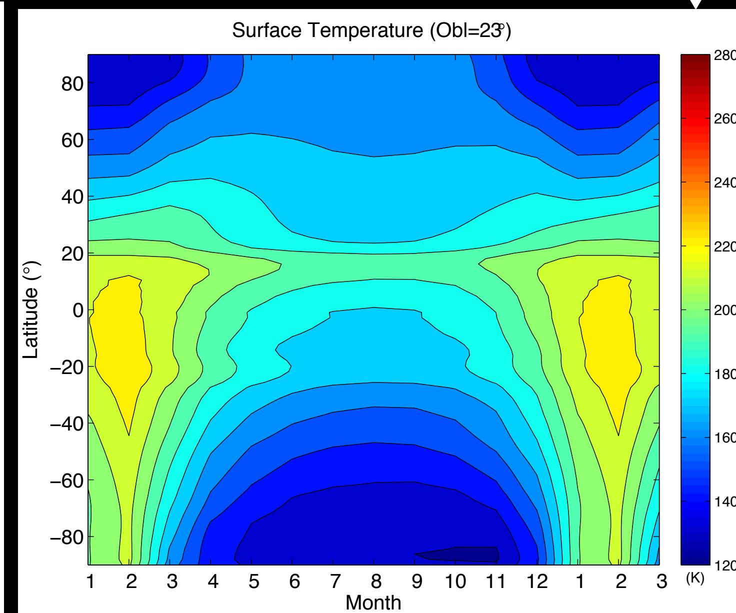
freezing point



Southern hemisphere summer

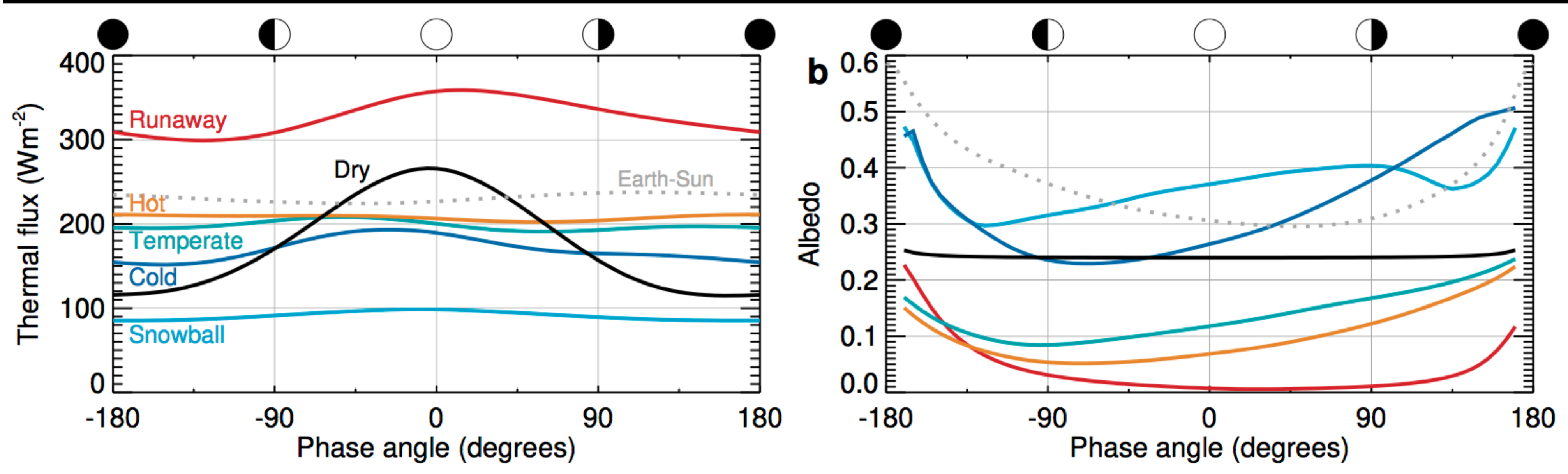
Obliquity = 23°

freezing point



Shields et al. (2016a)

Linking theory to observations



Credit: Eric T. Wolf

The Climates of Other Worlds:
A Review of the Emerging Field of Exoplanet Climatology

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ABSTRACT

The discovery of planets orbiting stars other than the Sun has accelerated over the past decade, and this trend will continue as new space- and ground-based observatories employ next-generation instrumentation to search the skies for habitable worlds. However, many factors and processes can affect planetary habitability, and must be understood to accurately determine a planet's habitability potential. While climate models have long been used to understand and predict climate and weather patterns on the Earth, a growing community of researchers has begun to apply these models to extra-solar planets. This work has provided a better understanding of how orbital, surface, and atmospheric properties affect planetary climate and habitability, how these climatic effects might change for different stellar and planetary environments, and how the habitability and observational signatures of newly-discovered planets might be influenced by these climatic factors. This review summarizes the origins and evolution of the burgeoning field of exoplanet climatology, discusses recent work using a hierarchy of computer models to identify those planets most capable of supporting life, and offers a glimpse into future directions of this quickly evolving subfield of exoplanet science.

Aom logy

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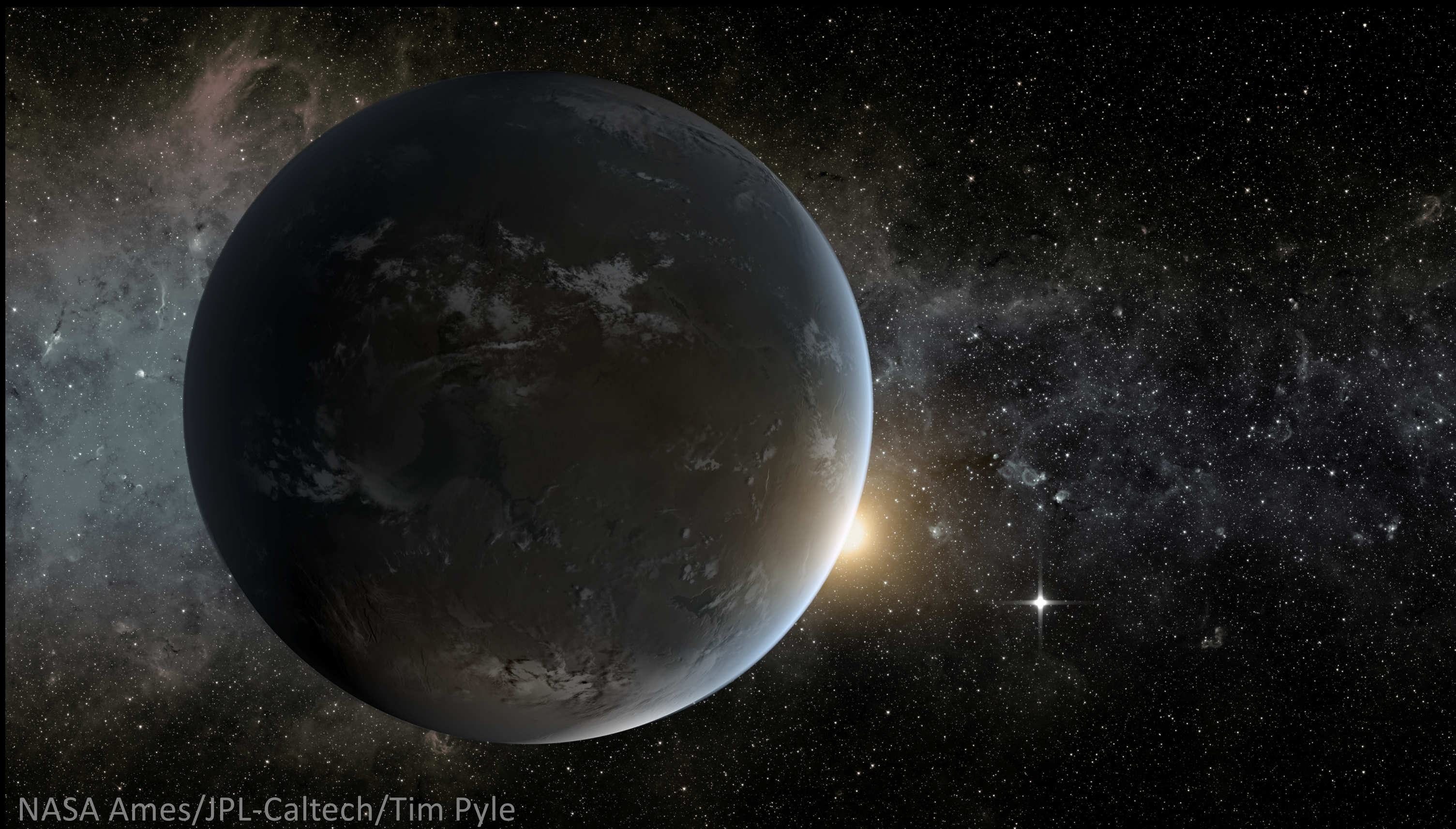
Thank you!



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Aomawa Shields

Take away point

Combining observations AND theory

=

How we will most accurately assess planetary habitability