Climate and Habitability of Earth-like Extrasolar Planets

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NASA Virtual Planetary Laboratory (VPL)

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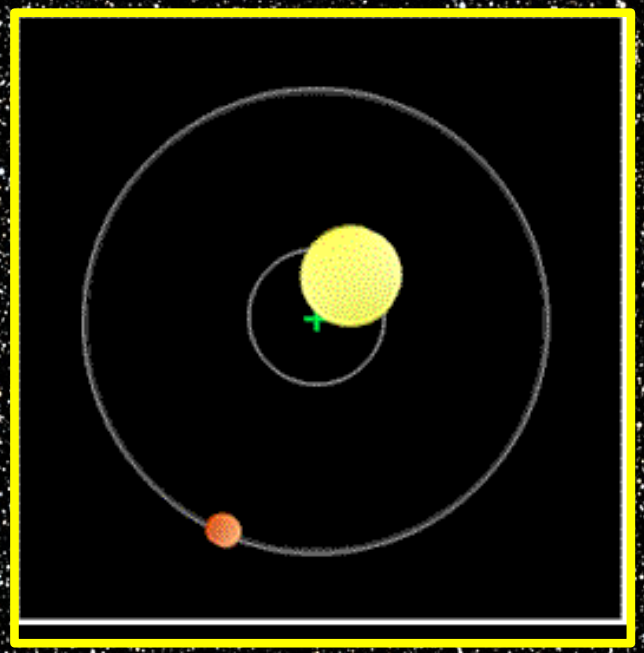
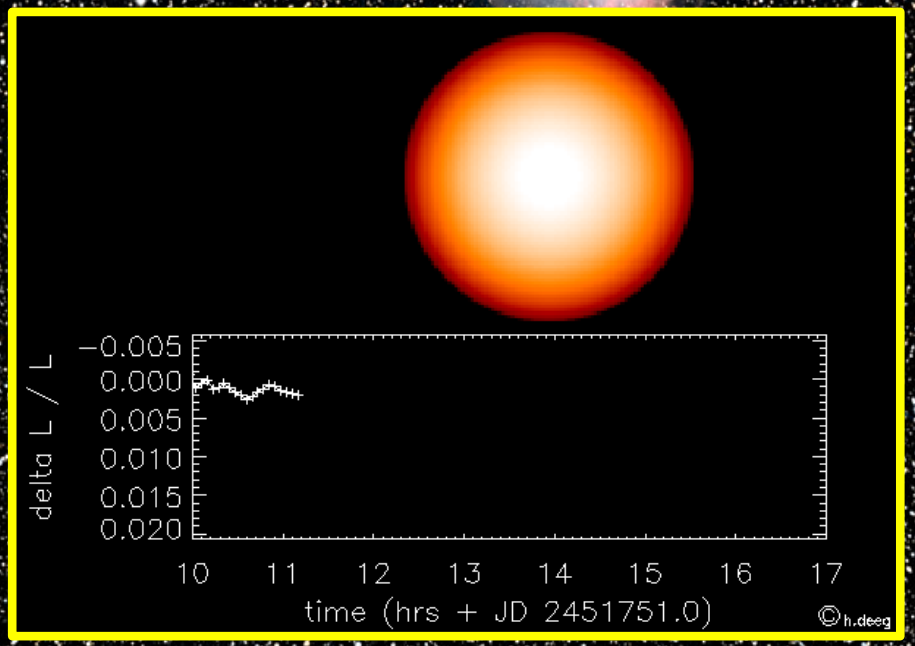
As of today there are…
3706 Confirmed Exoplanets

NASA Exoplanet Archive
http://exoplanetarchive.ipac.caltech.edu

radial velocity



transit photometry



Potentially habitable exoplanets:
53 – optimistic assumptions
13 – conservative assumptions

Habitable Exoplanets Catalog
Planetary Habitability Lab, University of Puerto Rico, Aceribo
http://phl.upr.edu/projects/habitable-exoplanets-catalog

What do we mean by a “habitable” planet?

A habitable planet is …

ocean covered.

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ocean covered.

This provides significant constraint on surface temperature.

freezing	*boiling*
273 K	373 K
0° C	100° C
32° F	212° F

A habitable planet is …

ocean covered.

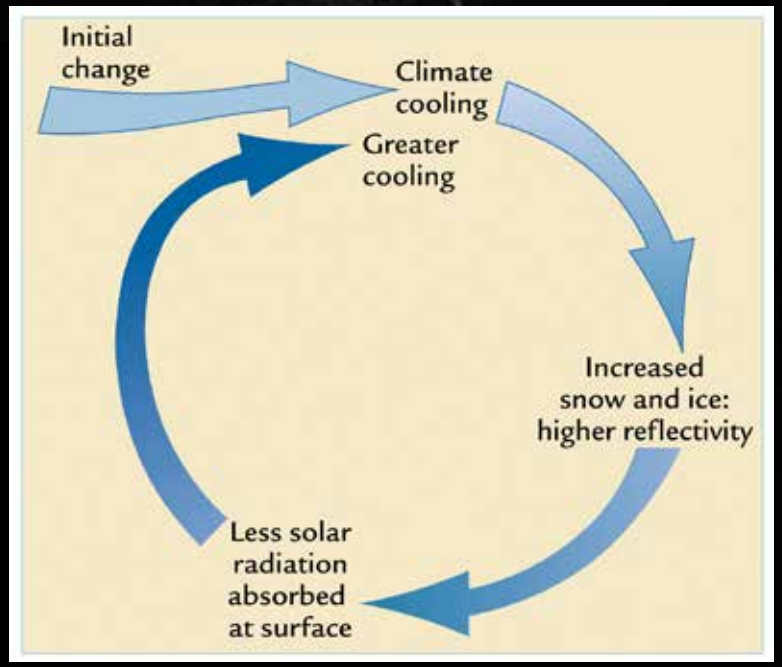
H_2O dominates climate

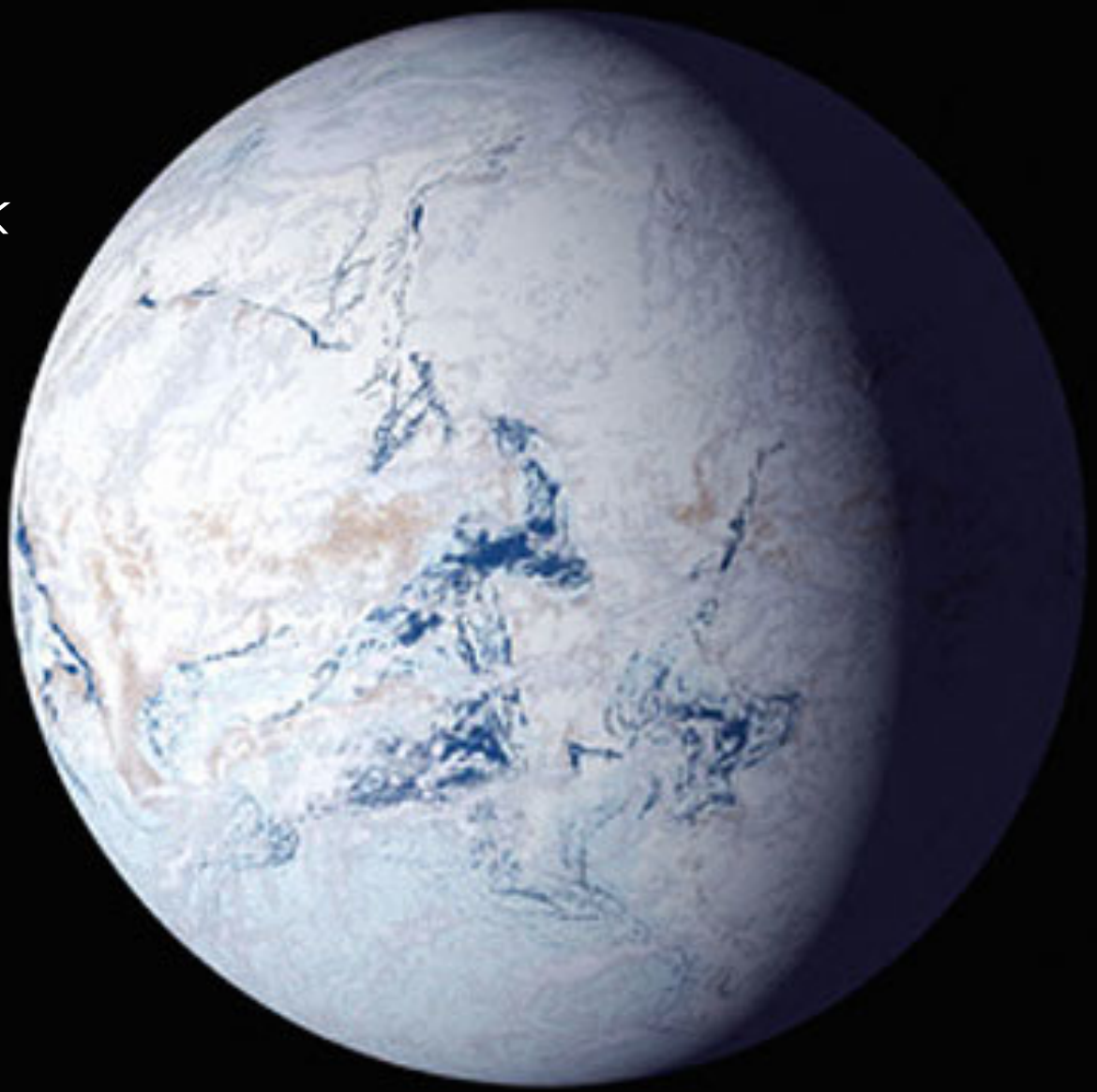
H_2O causes strong positive climatic feedbacks.

A habitable planet is *not* …

…a snowball Earth

Sea ice albedo feedback

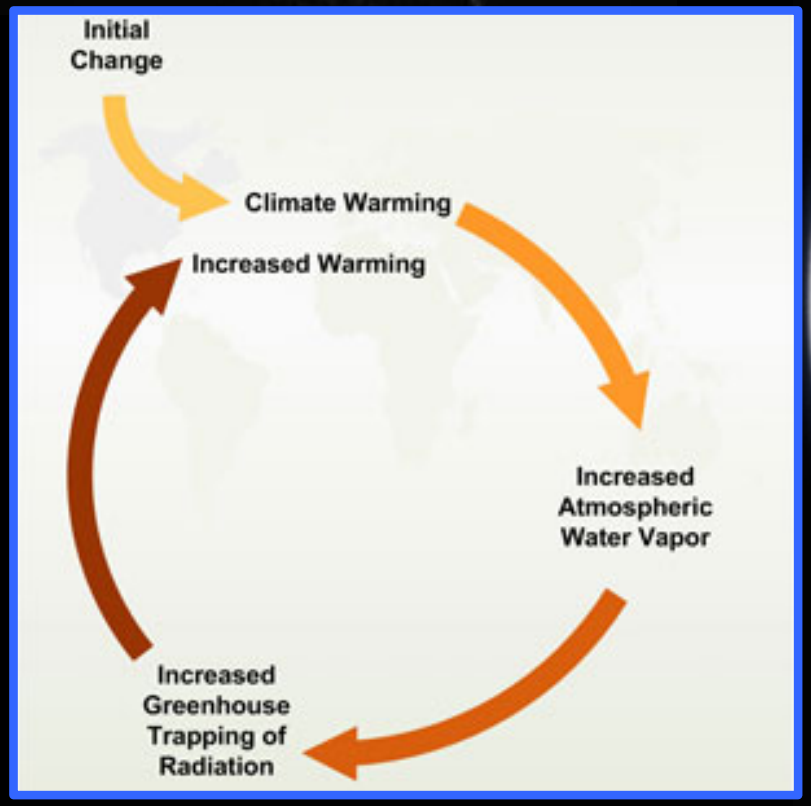




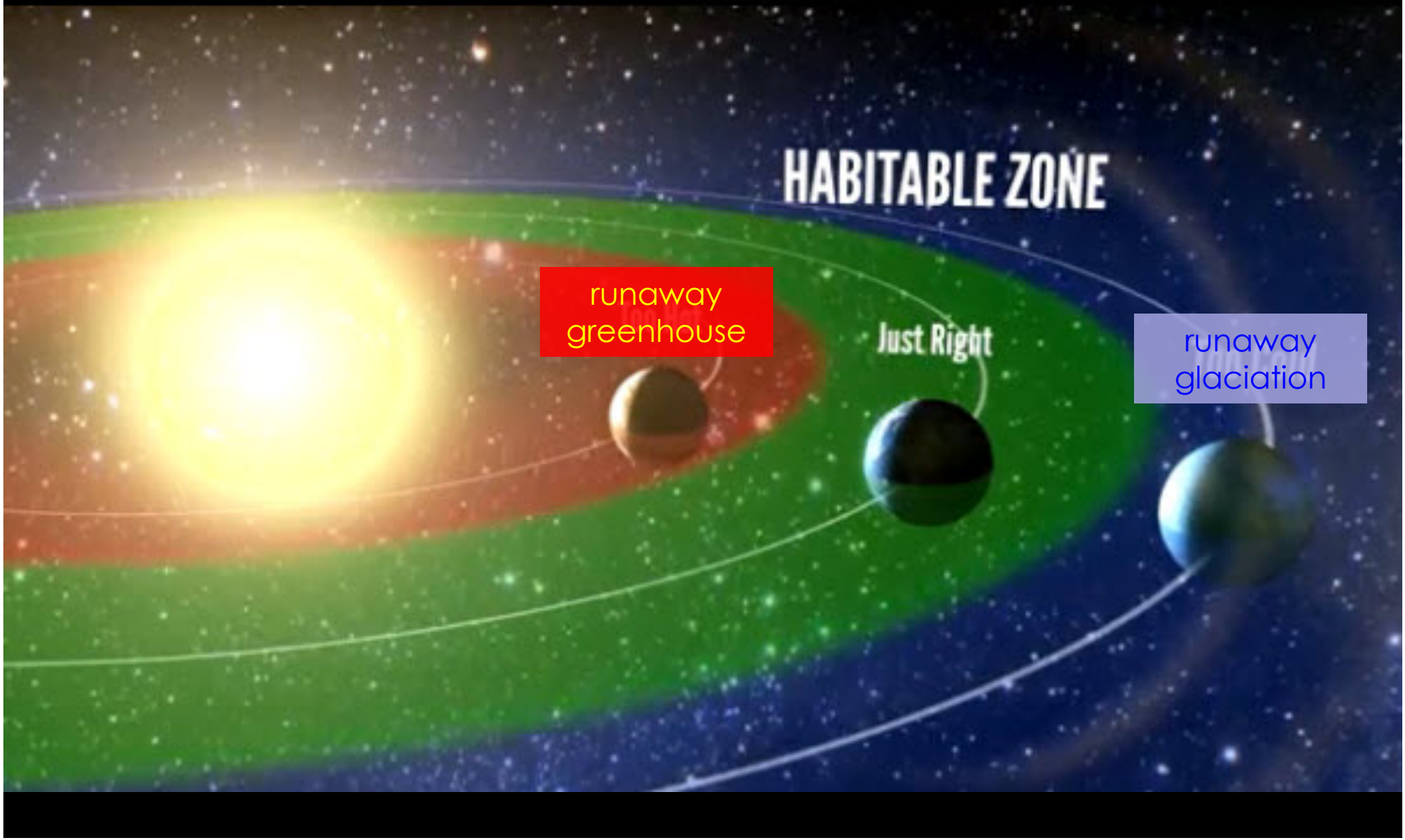
A habitable planet is *not* …

…a runaway greenhouse.

Water vapor greenhouse feedback



"Habitable Zone" -- the region in space surrounding a star where N_2-CO_2-H_2O composed atmospheres can sustain surface liquid water.



What do we know about habitable zone extrasolar planets?

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Things we know

mass
radius
orbital period
incident stellar flux
stellar spectra

Things we don't know

atmospheric composition
surface properties
rotation rate

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Things we know

mass
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Things we don't know

atmospheric composition **~ Earthy***
surface properties **~ ocean covered**
rotation rate **~ 24 hour diurnal cycle**

*For determining the habitable zone we assume an N_2 + H_2O + CO_2 composition

What do we know about habitable zone extrasolar planets?

Things we know

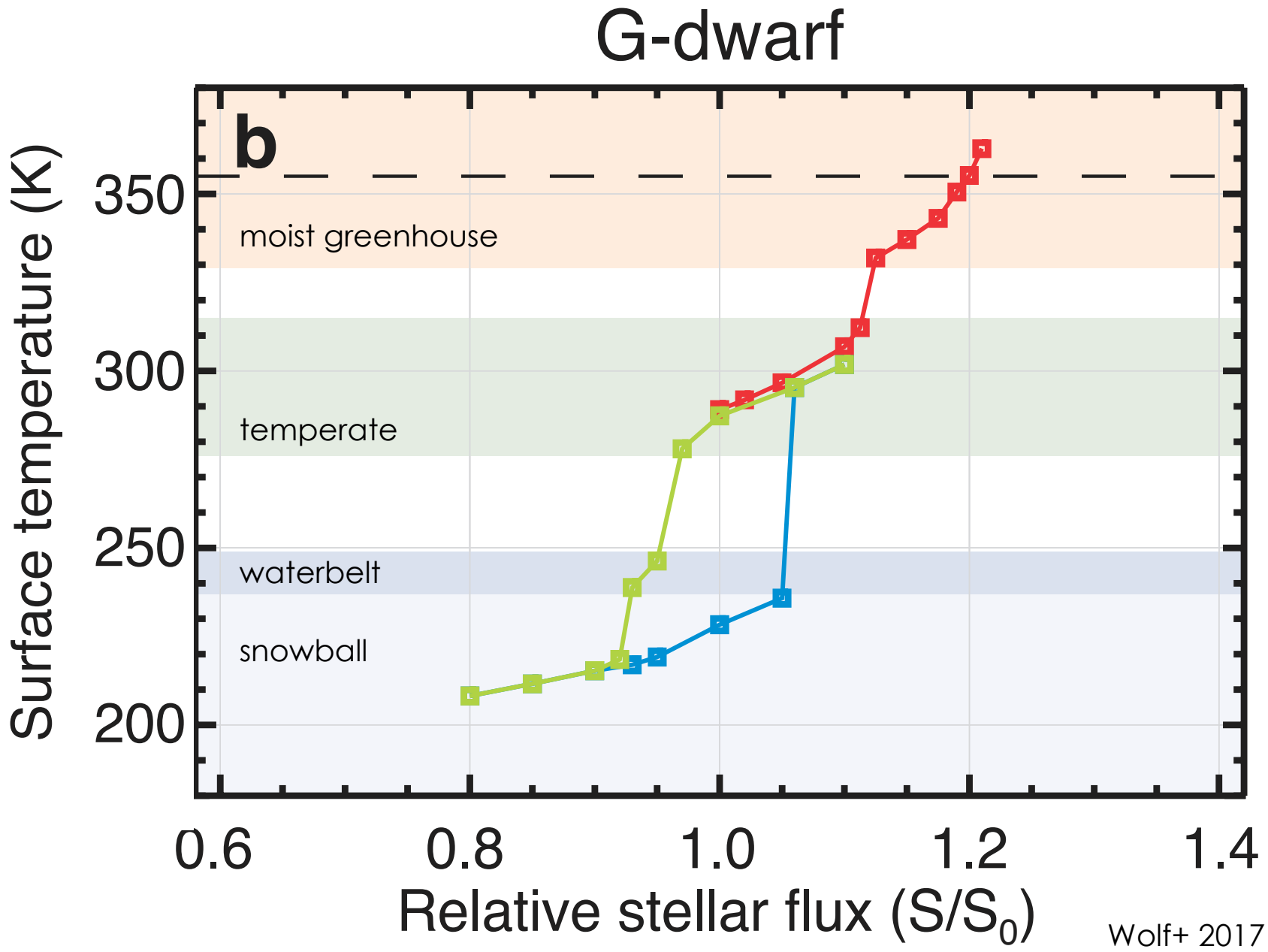
mass
radius
orbital period
incident stellar flux *Large changes in the solar input!!*
stellar spectra

Things we don't know

atmospheric composition **~ Earthy***
surface properties **~ ocean covered**
rotation rate **~ 24 hour diurnal cycle**

*For determining the habitable zone we assume an N_2 + H_2O + CO_2 composition

Let's start with the simplest possible problem…
Earth, modern CO_2, around the Sun, at various TSI



Wolf+ 2017

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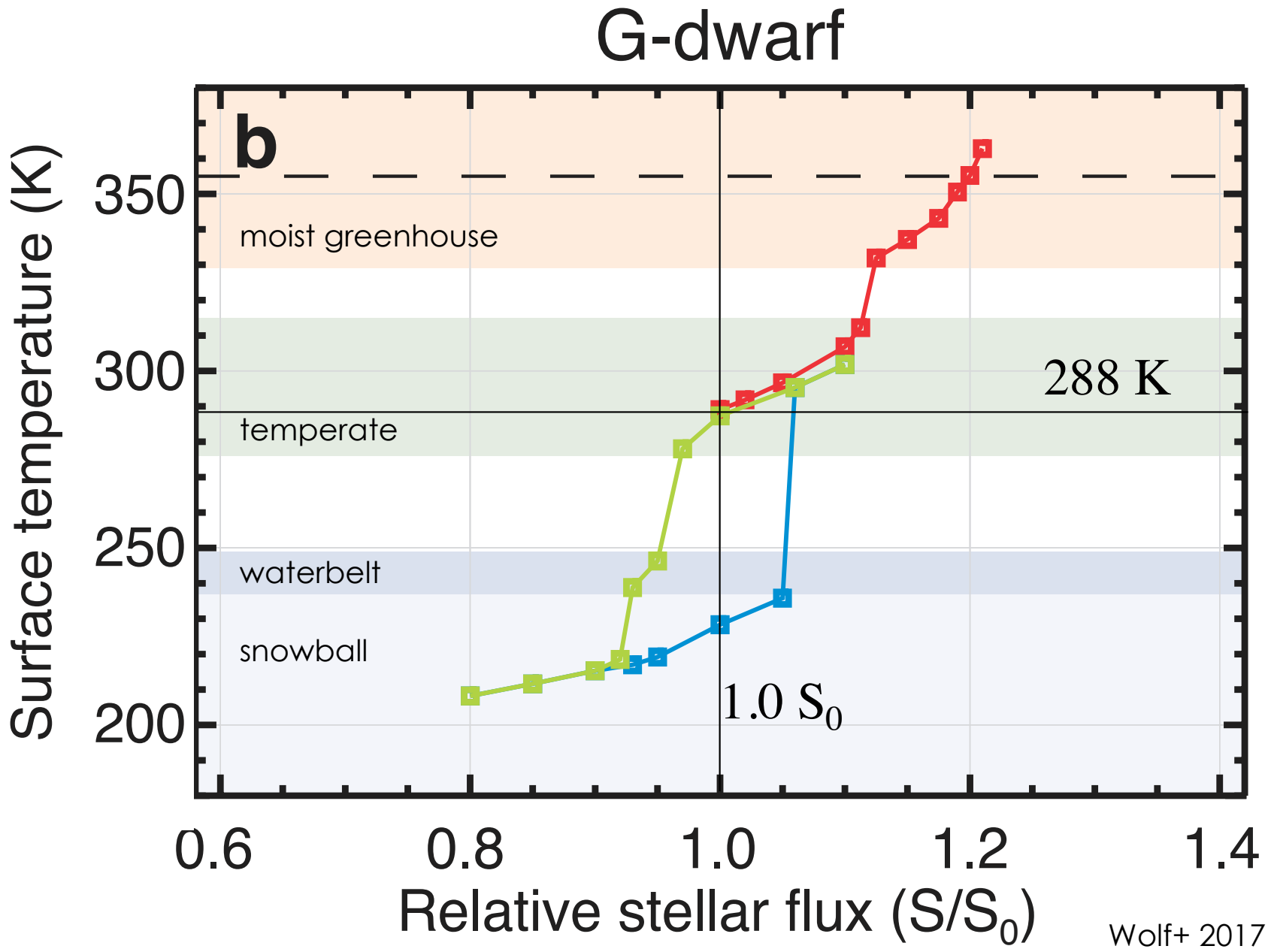

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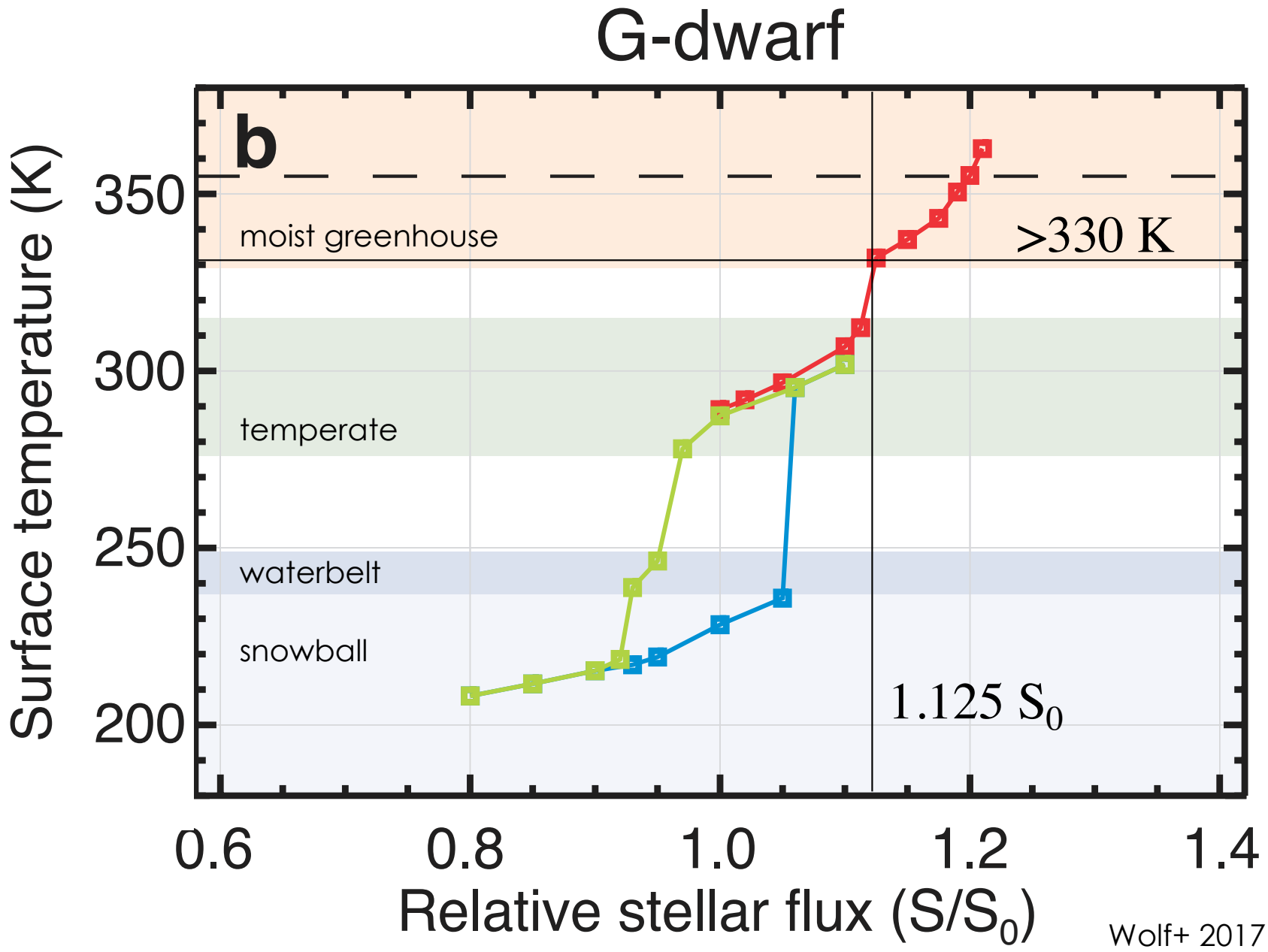

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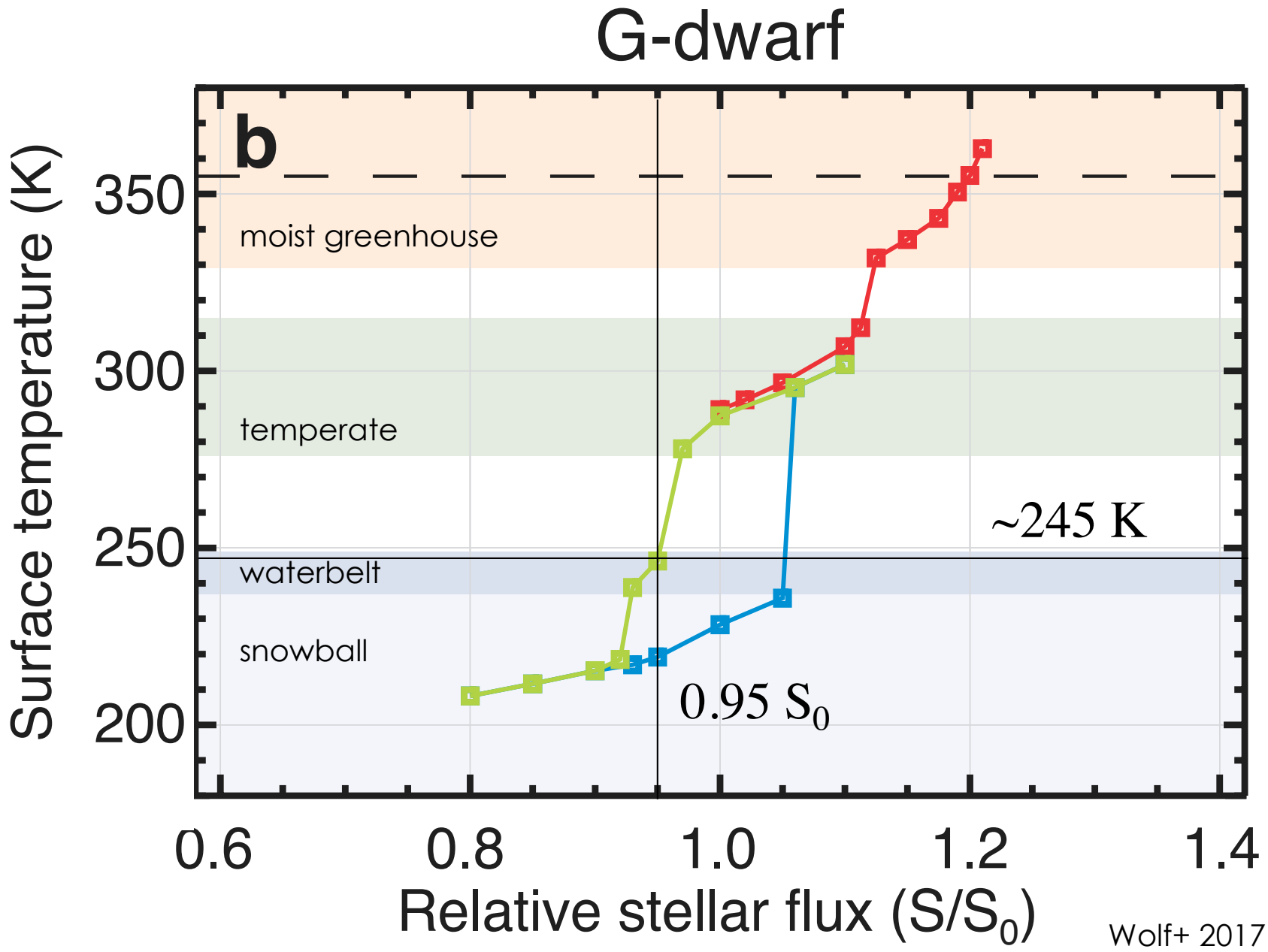

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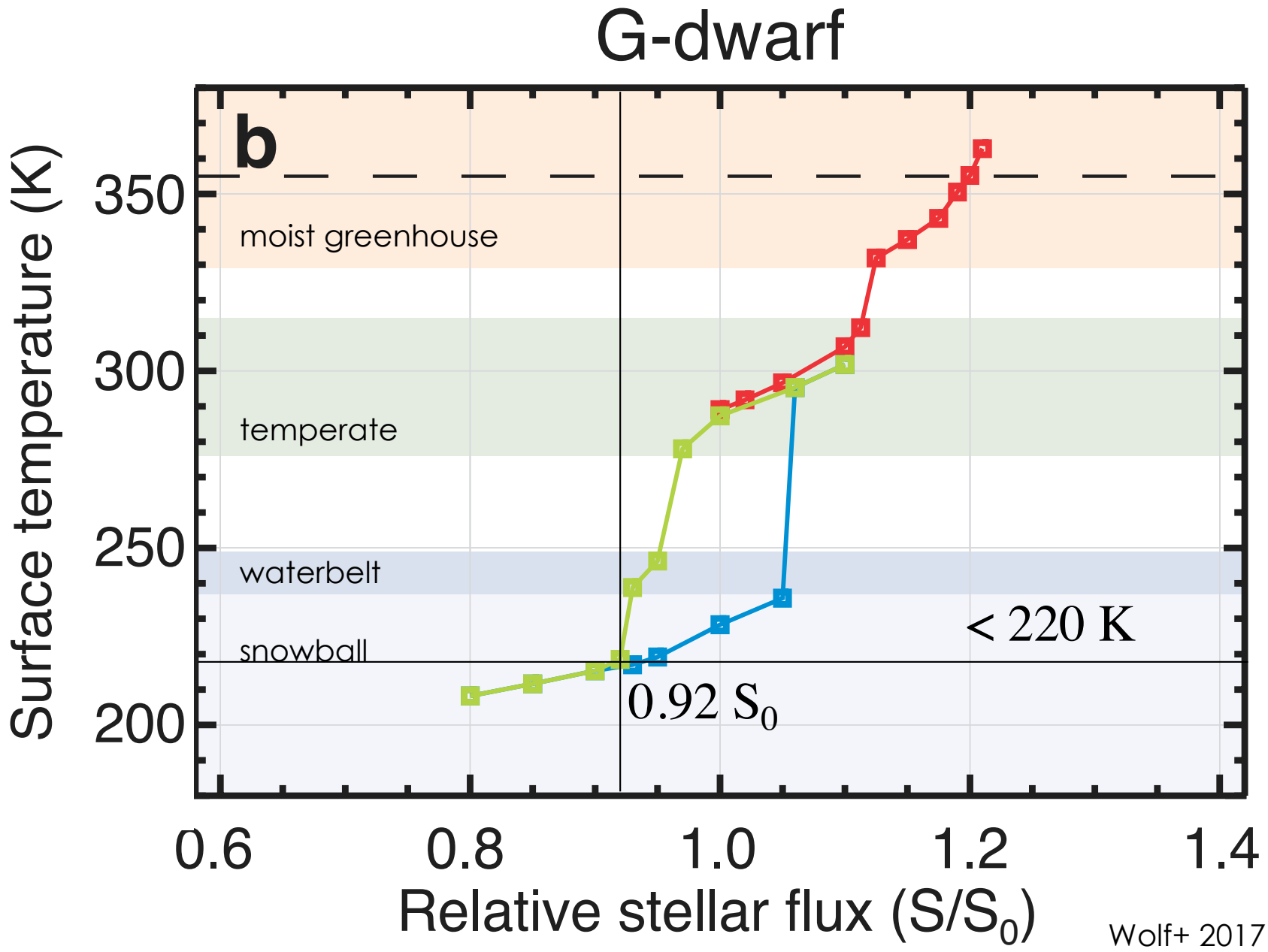

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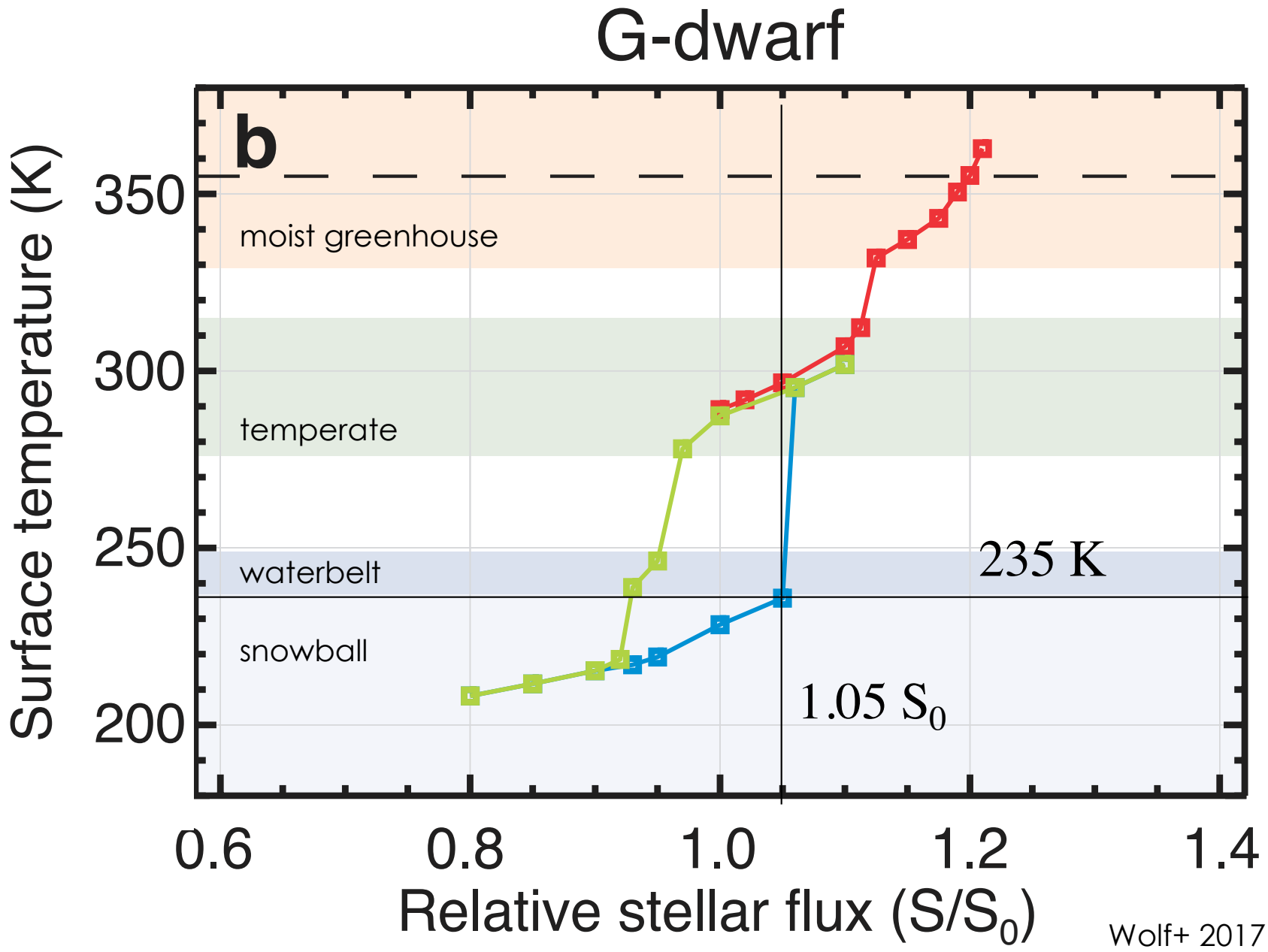

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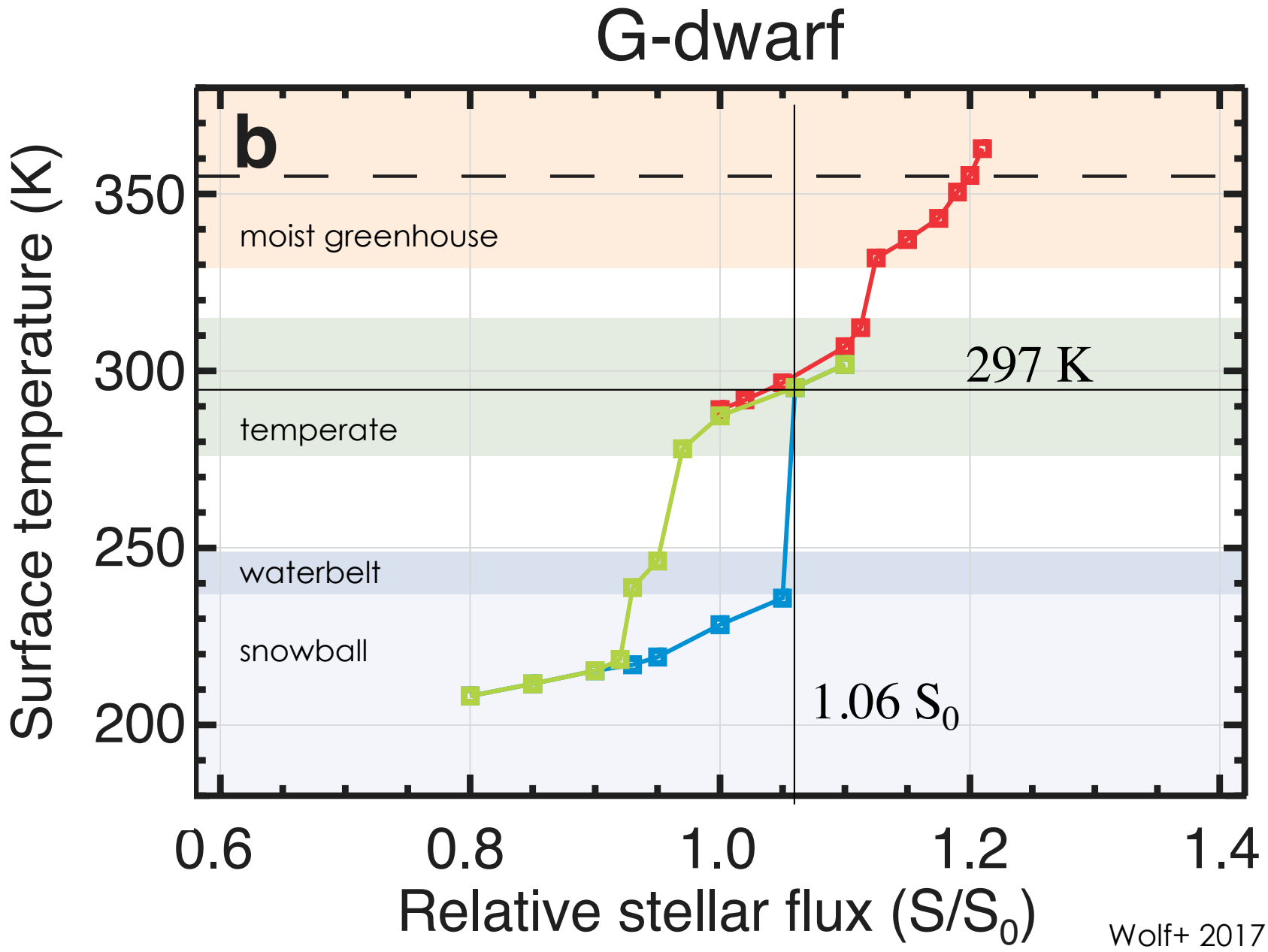

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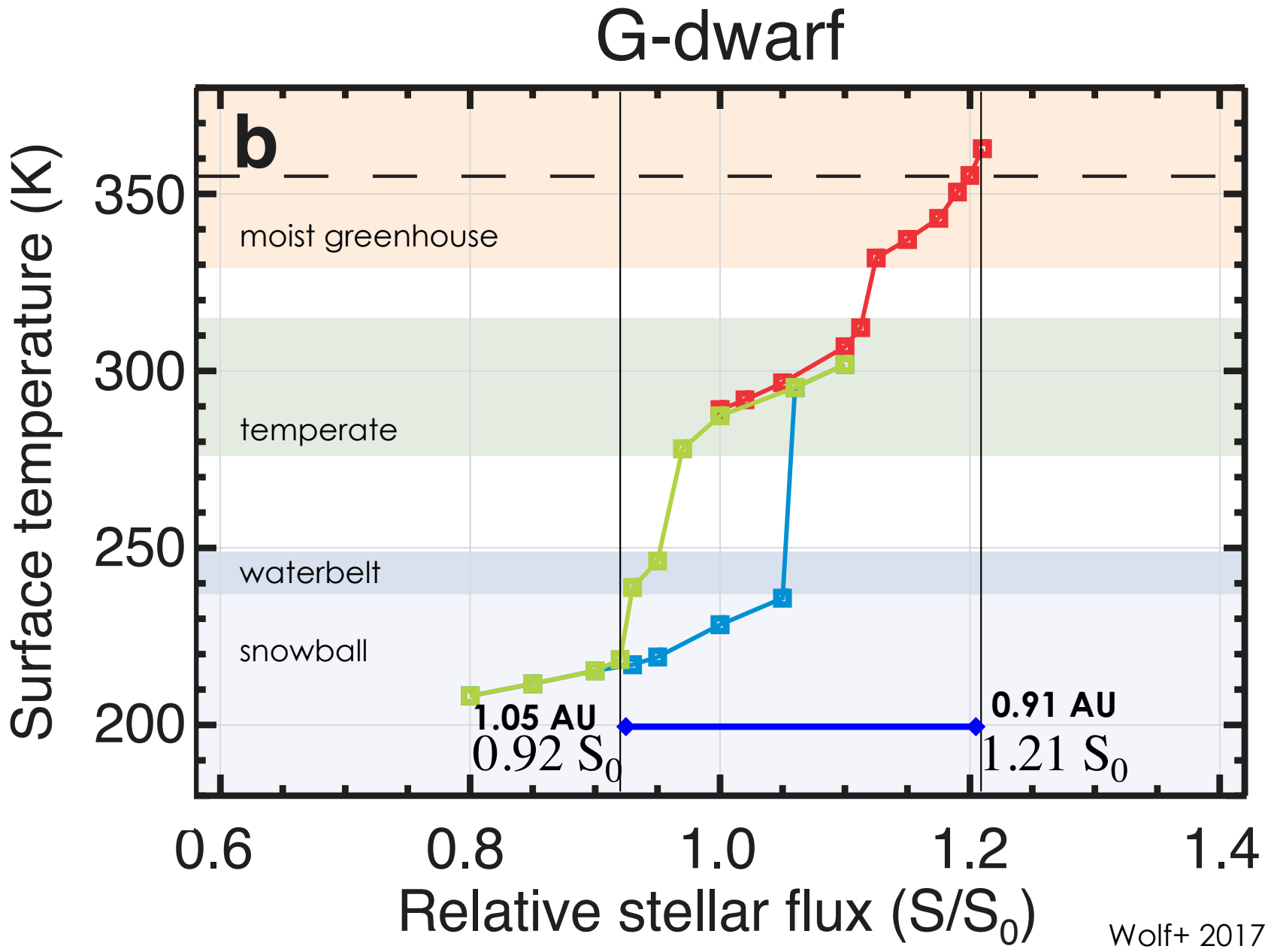

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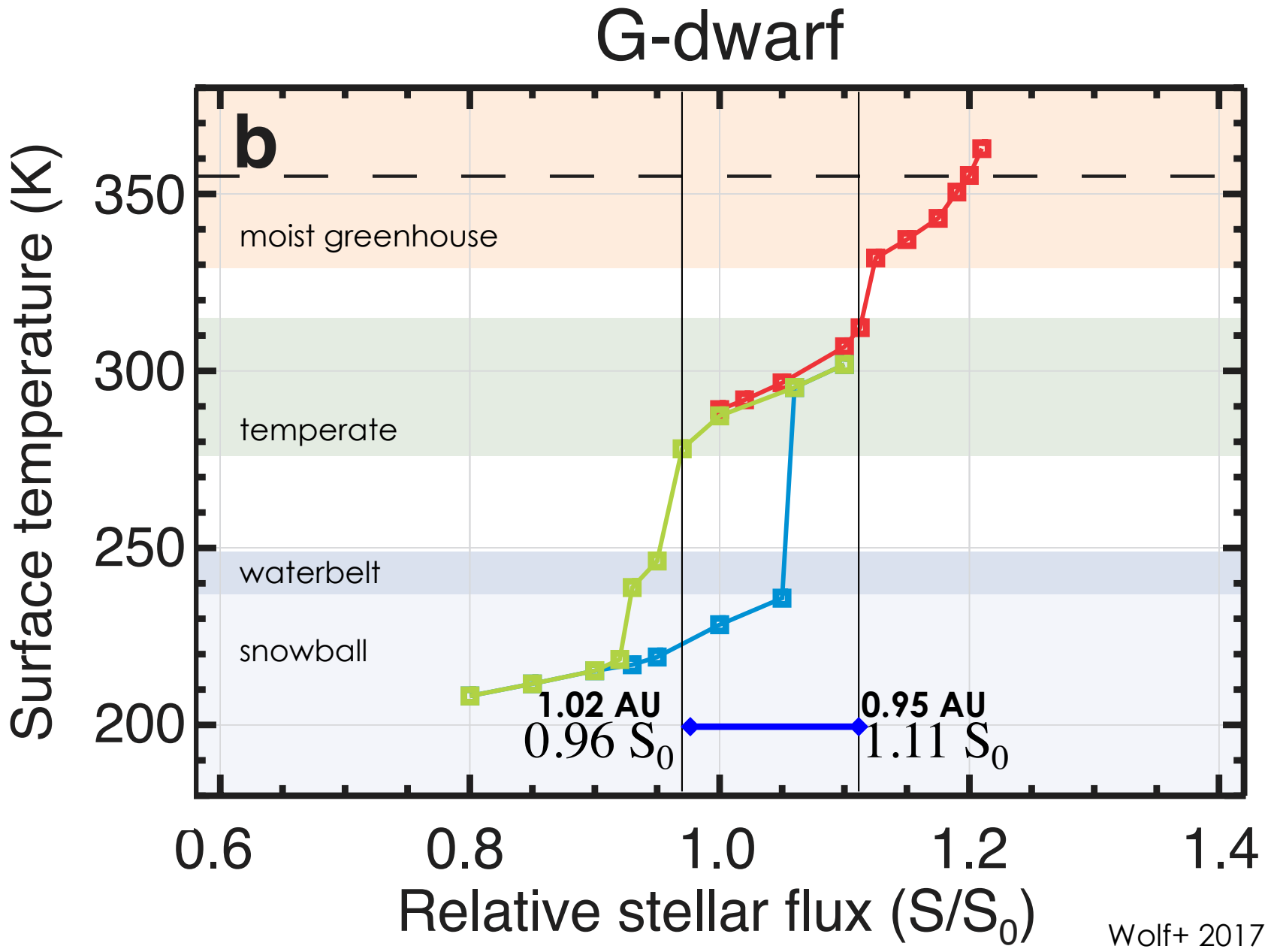

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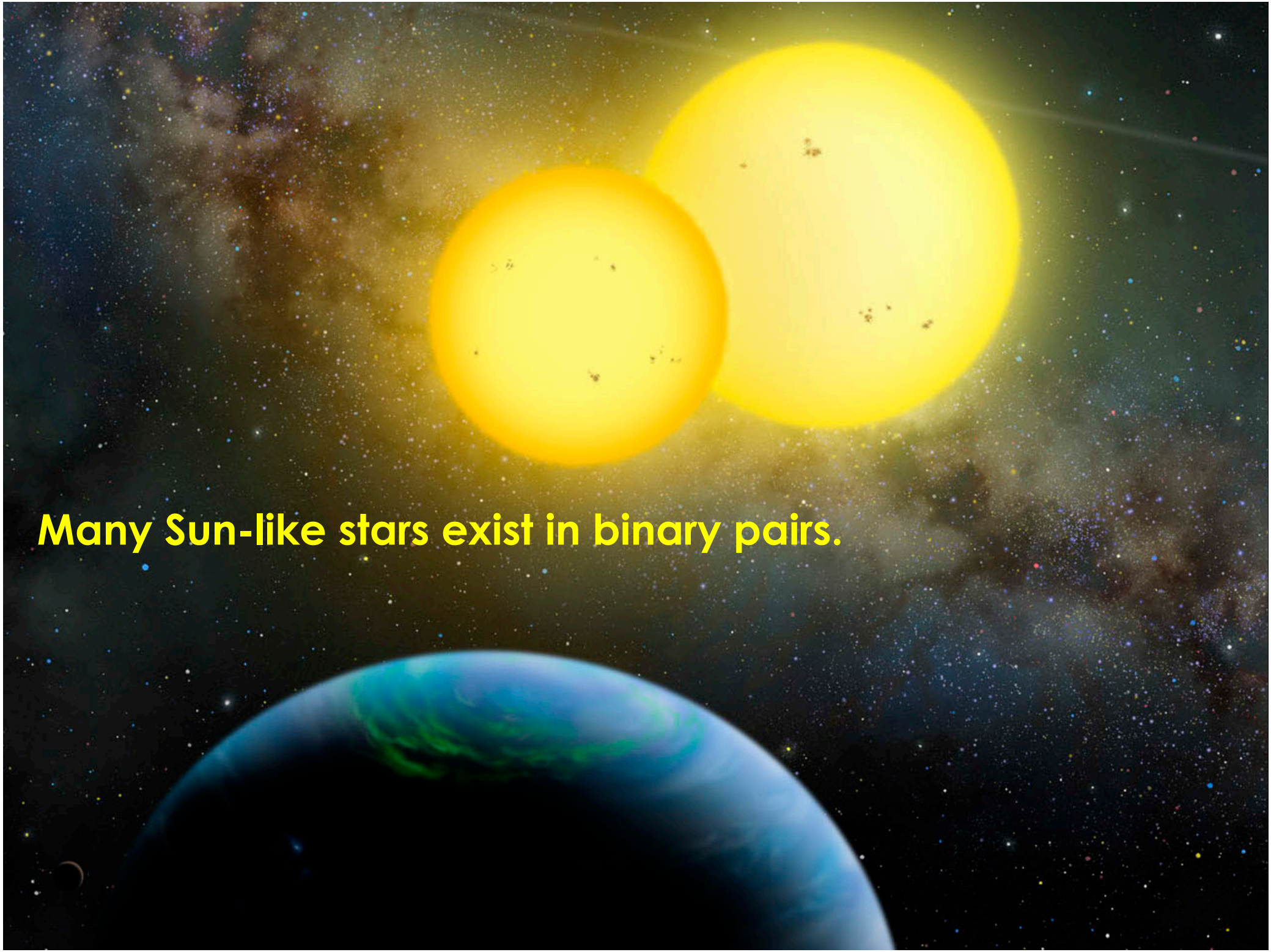
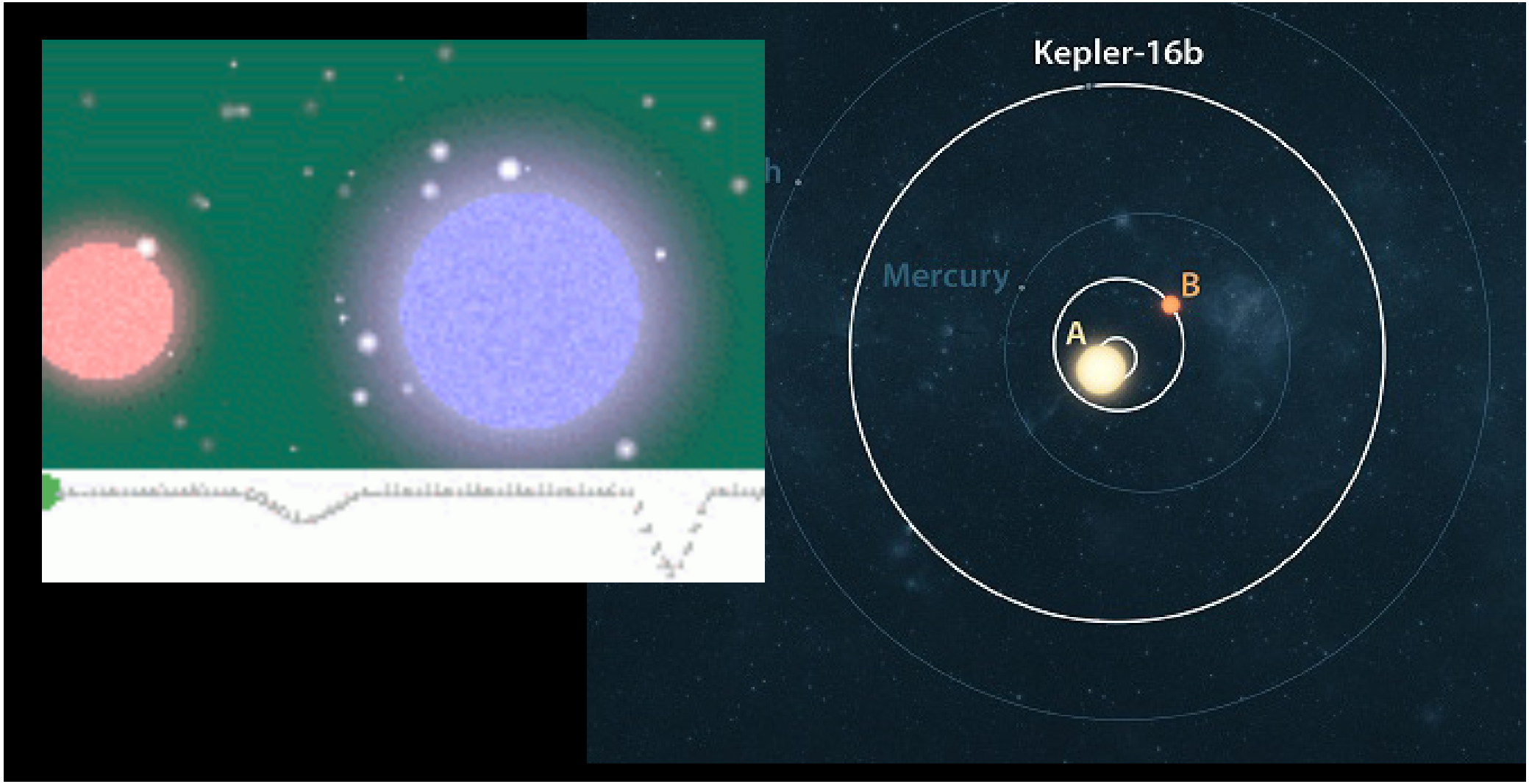
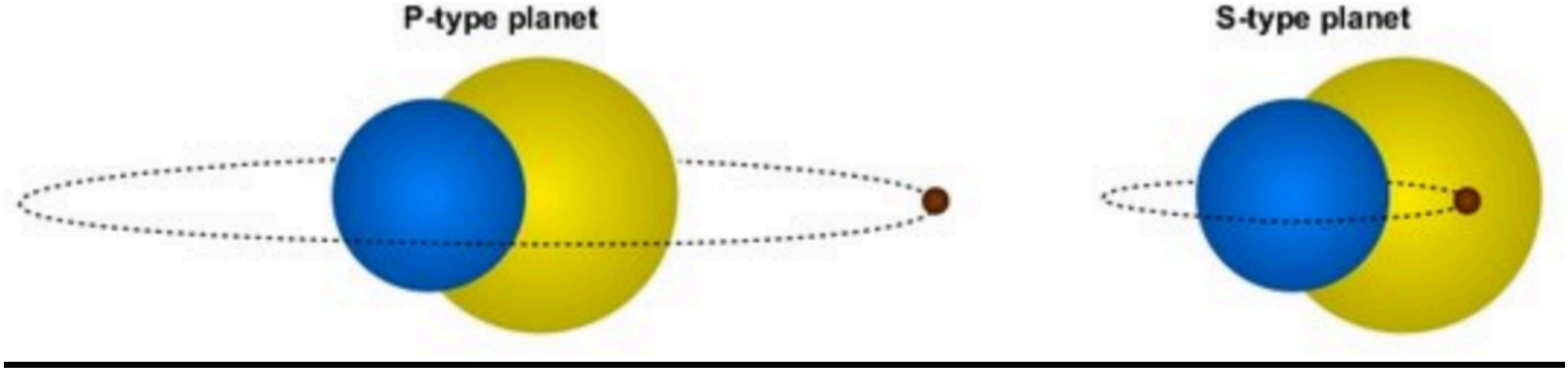
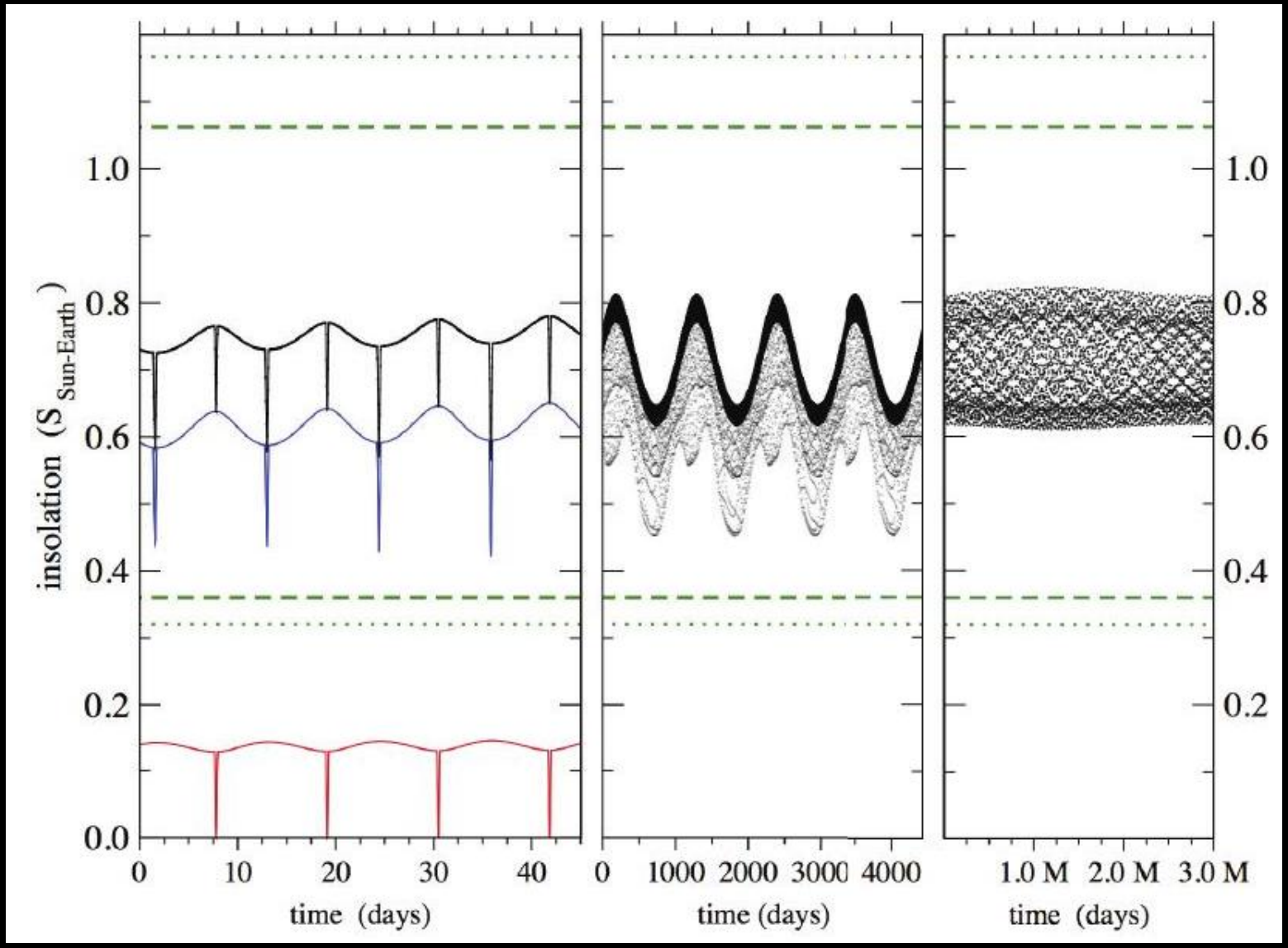

Many Sun-like stars exist in binary pairs.


Kepler-16b
Mercury
A
B


P-type planet
S-type planet

Variability of TSI in Kepler-1647 System (P-type)

Short term Medium term Long term



Kostov+ 2016

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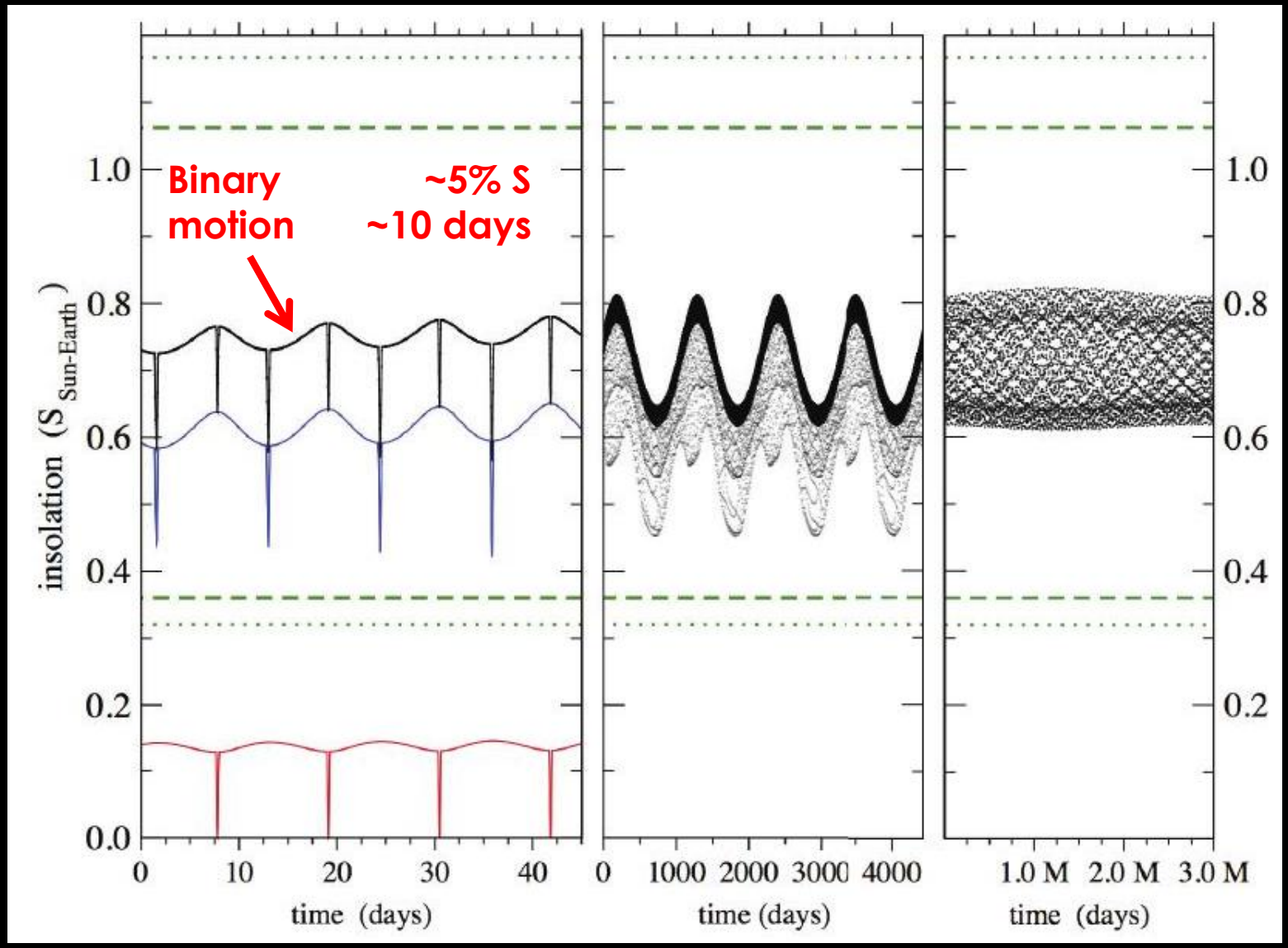

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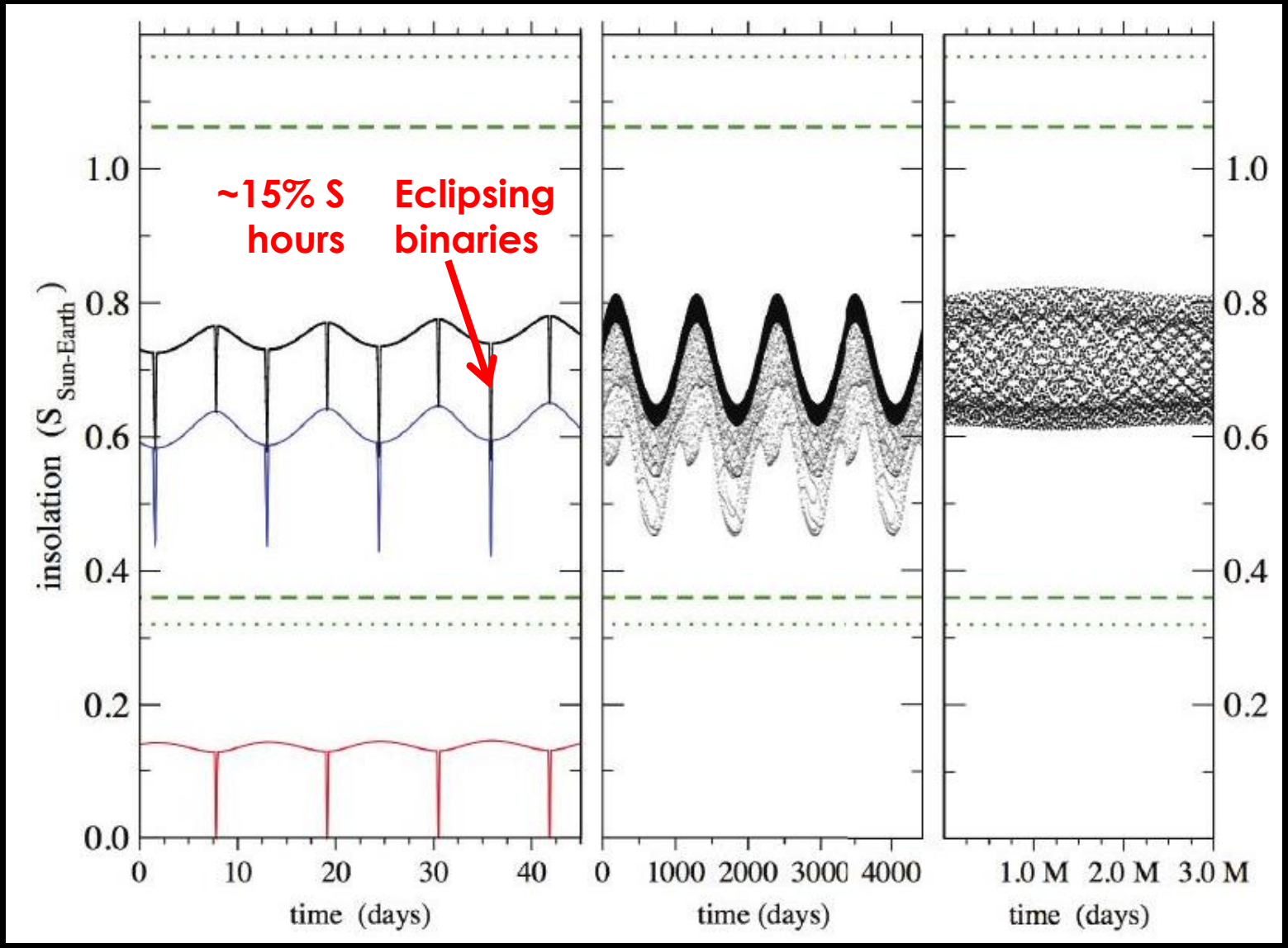
Variability of TSI in Kepler-1647 System (P-type)

Short term | Medium term | Long term



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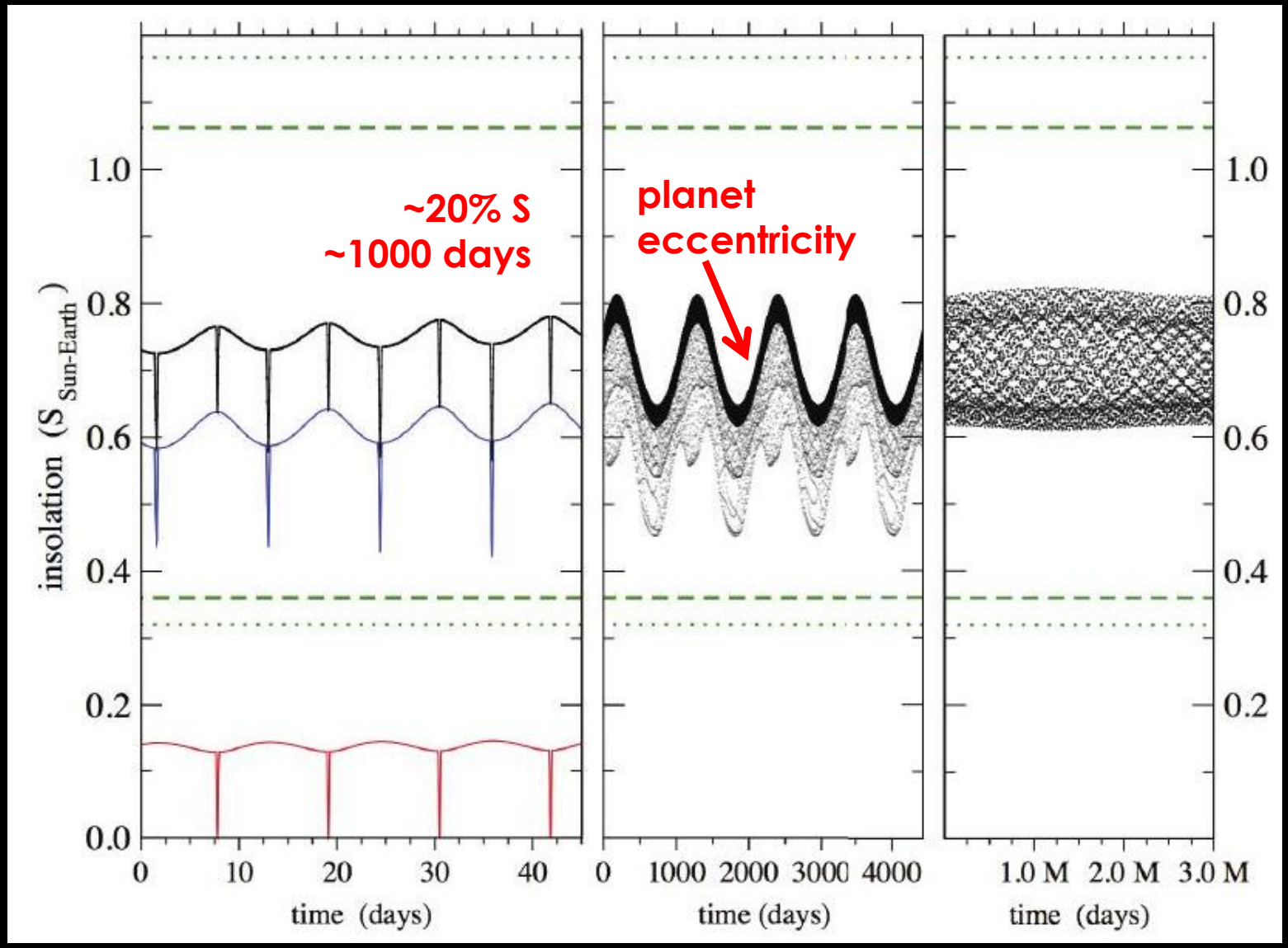
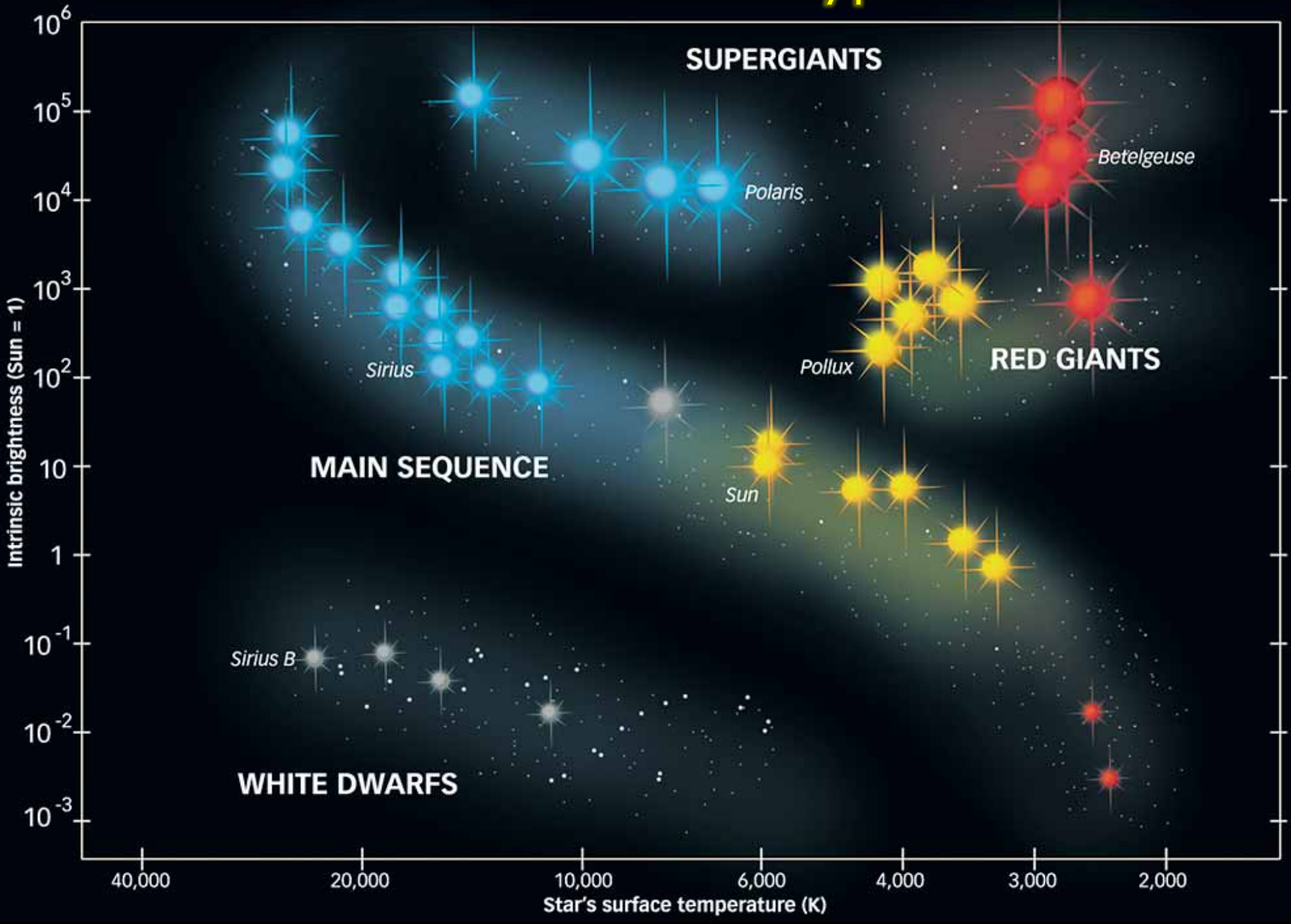


Kostov+ 2016

What about other stellar types?



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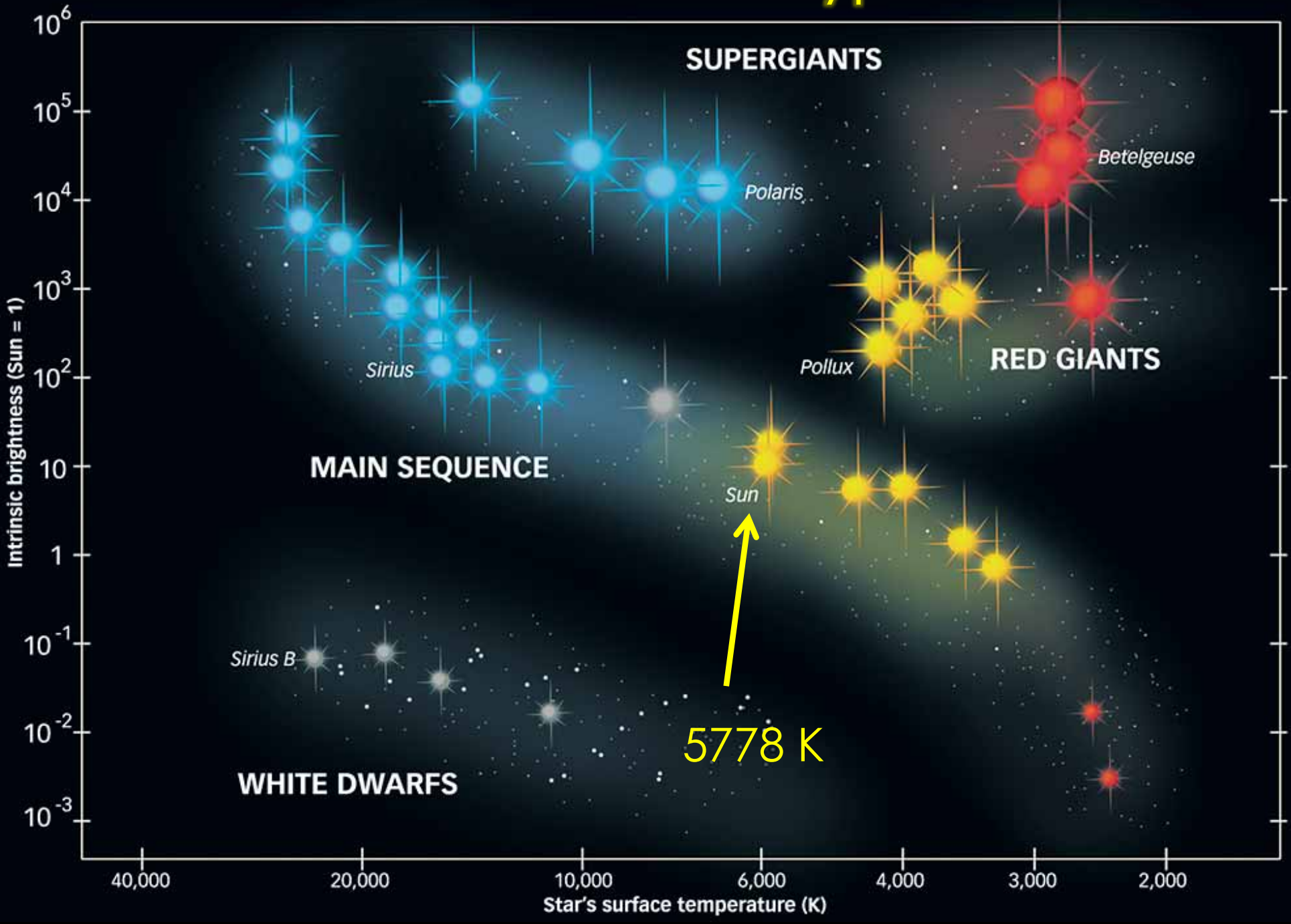

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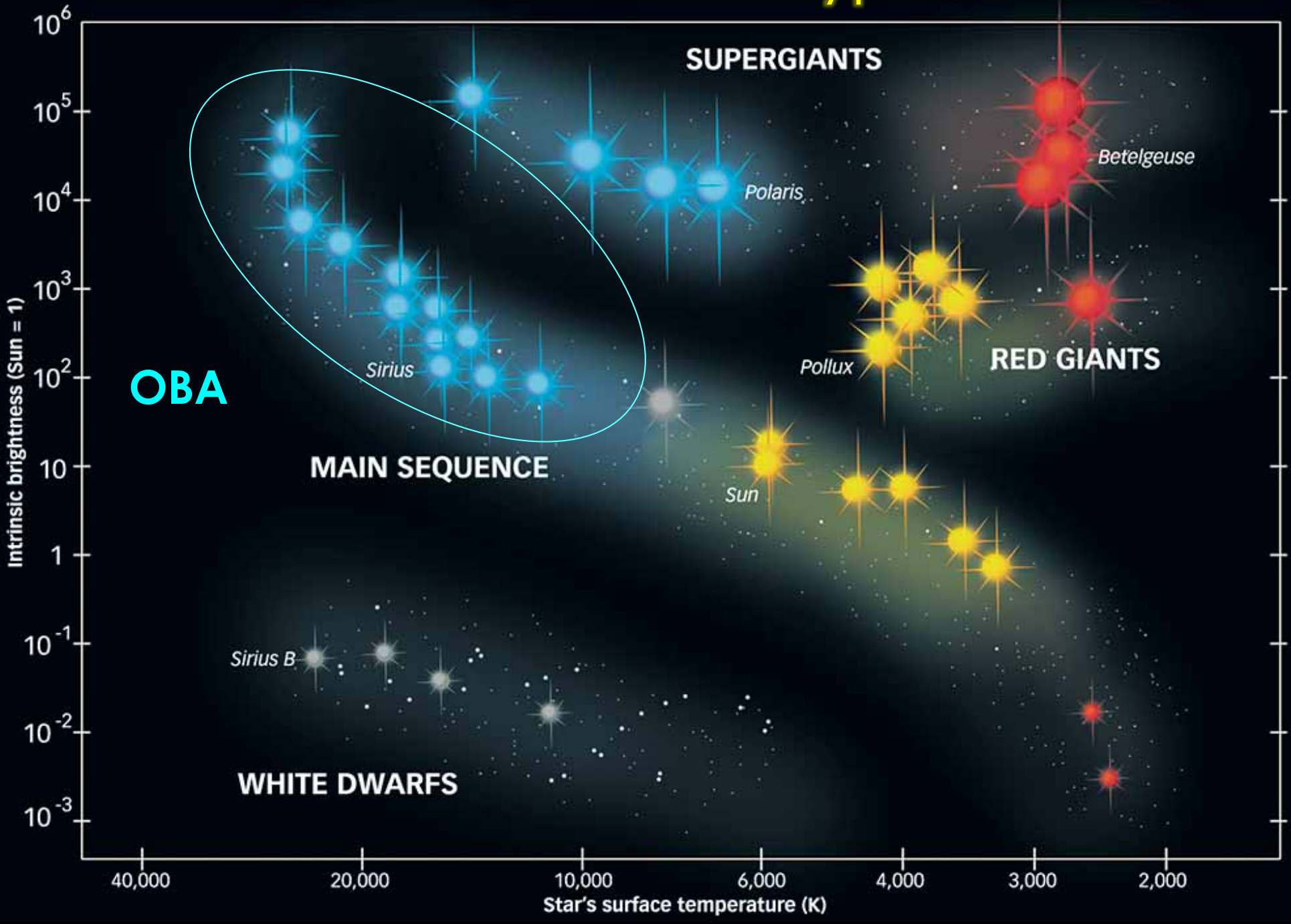

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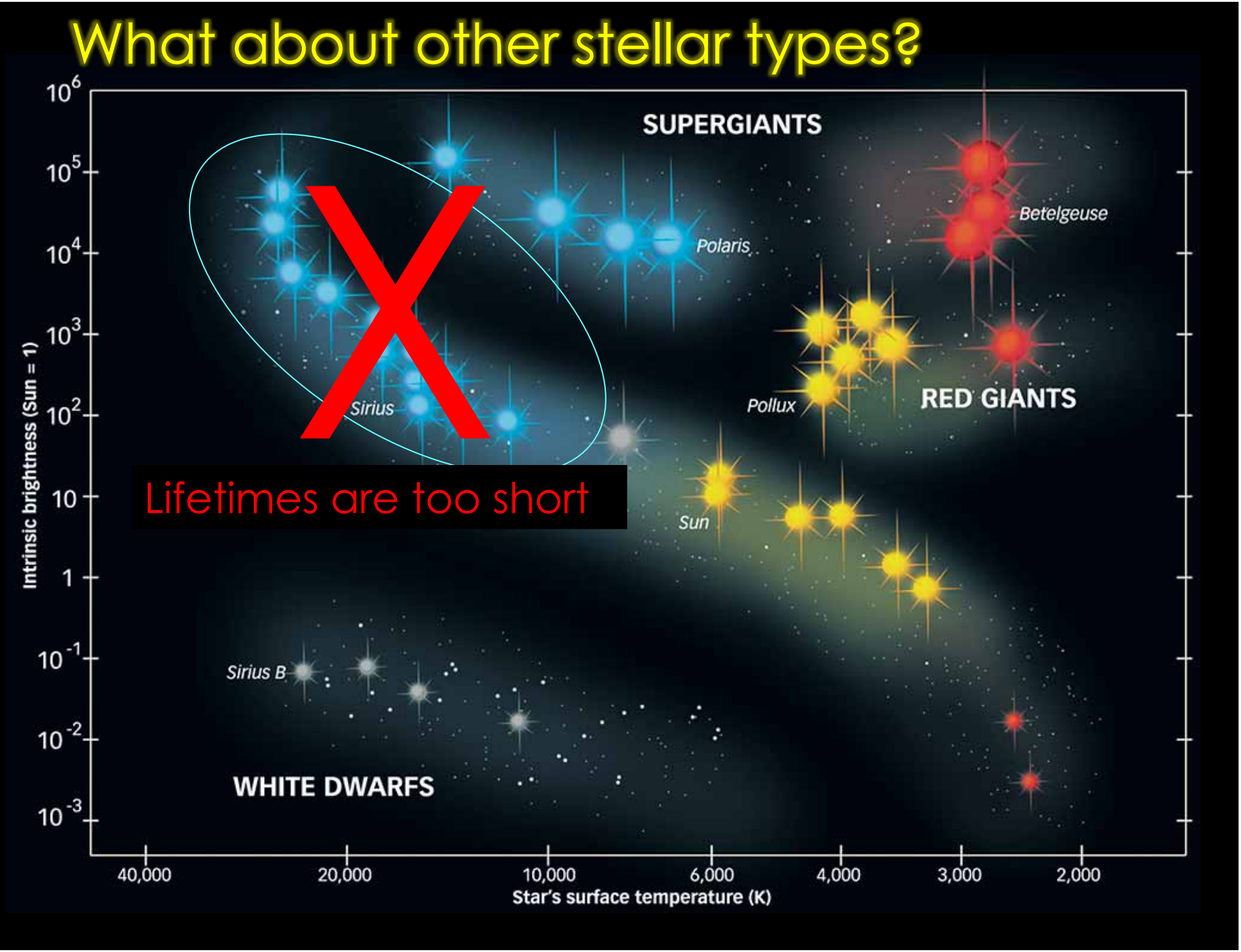

Lifetimes are too short

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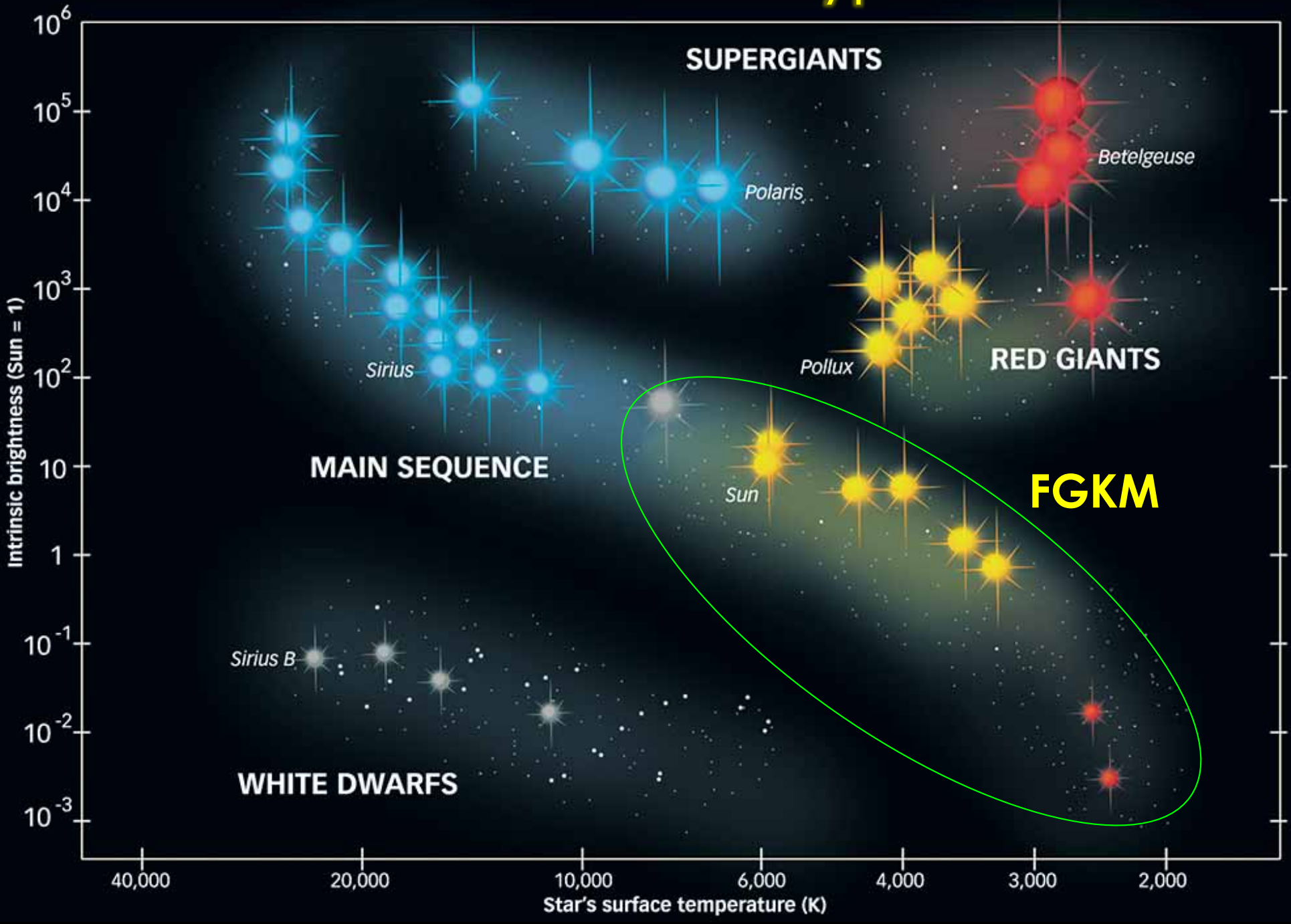

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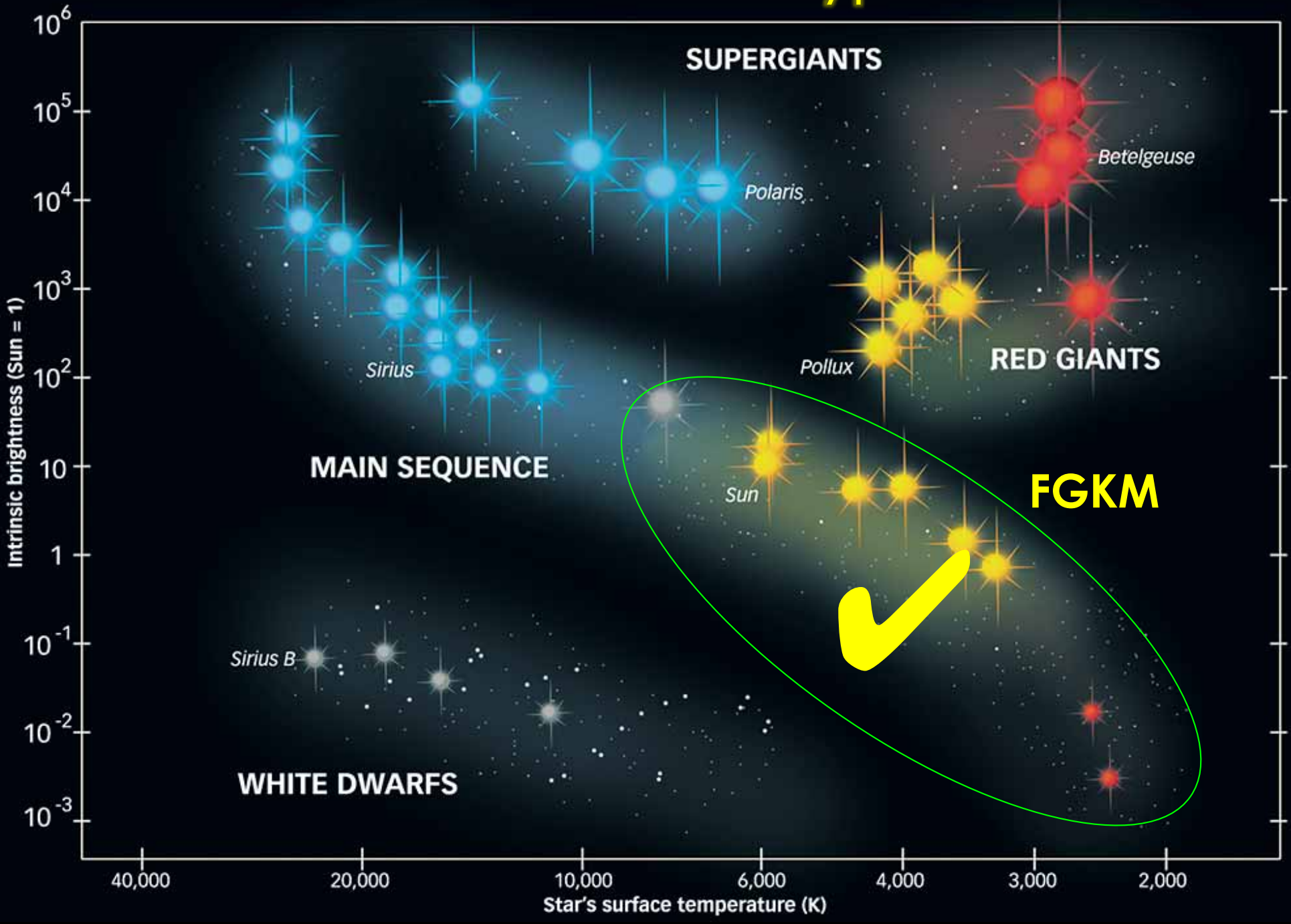
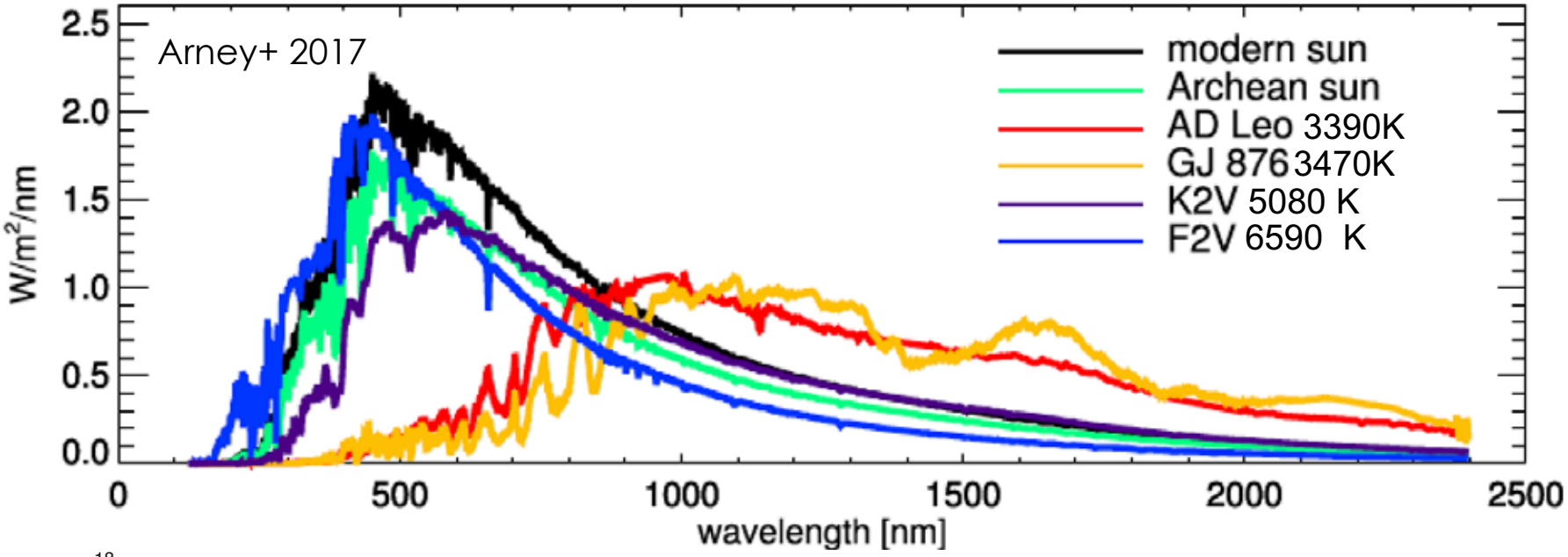
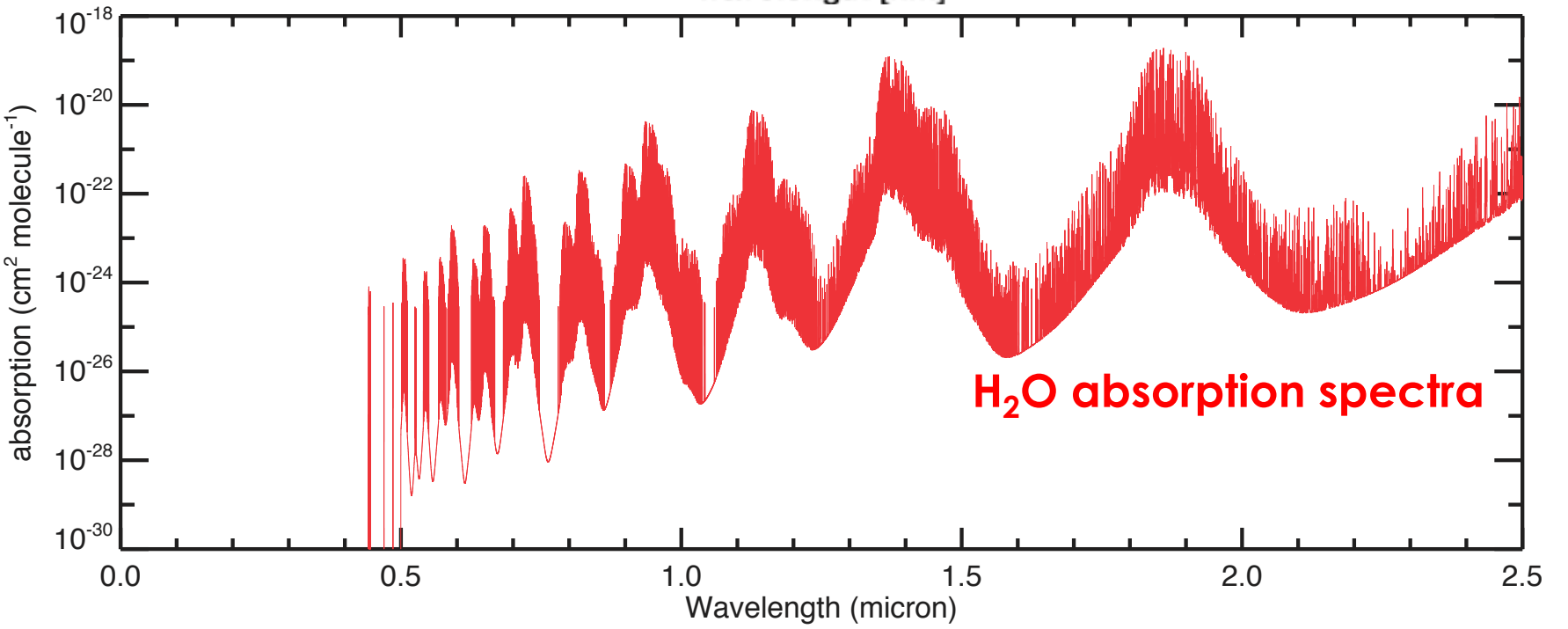


Shifts stellar spectra affects near-IR absorption by H_2O





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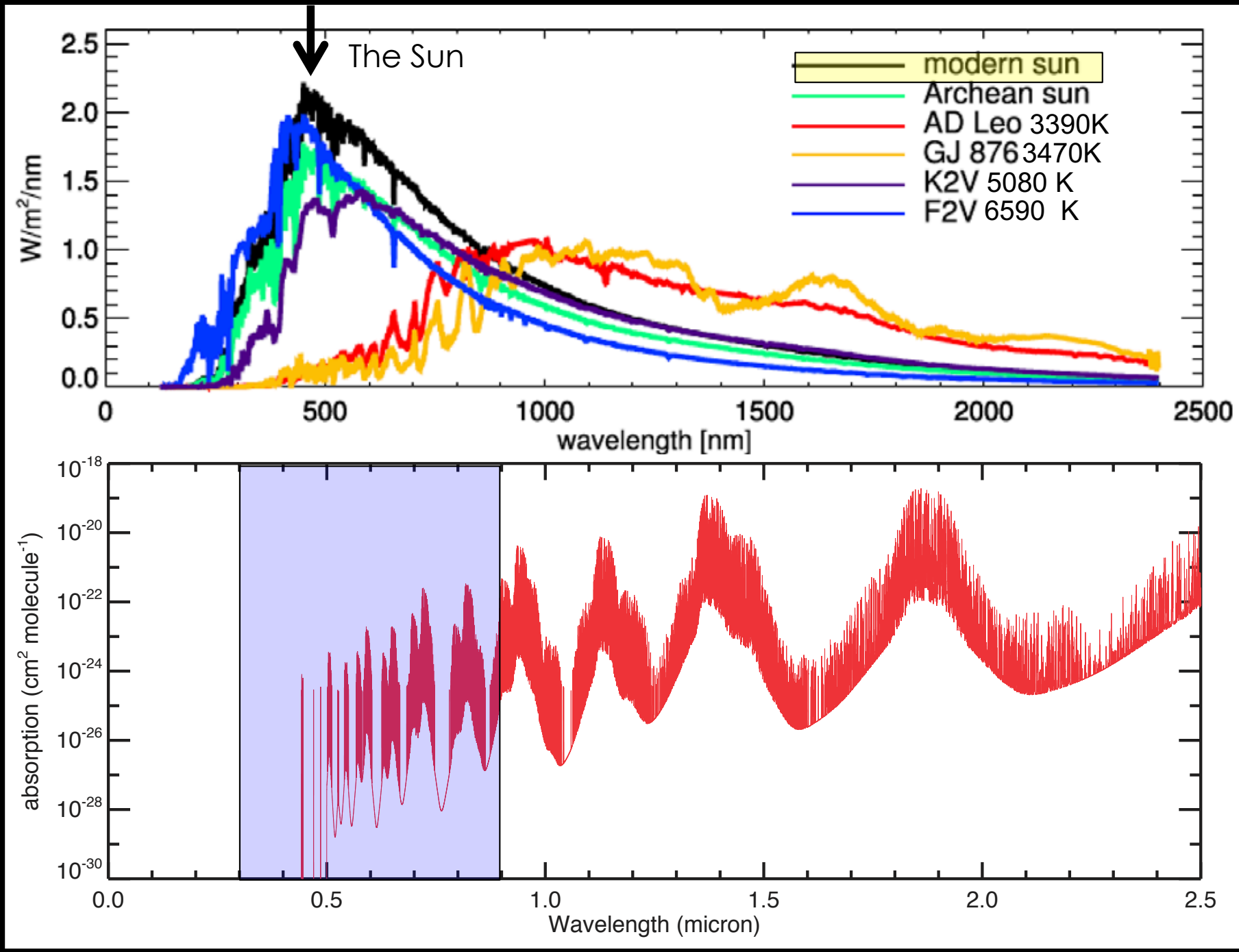

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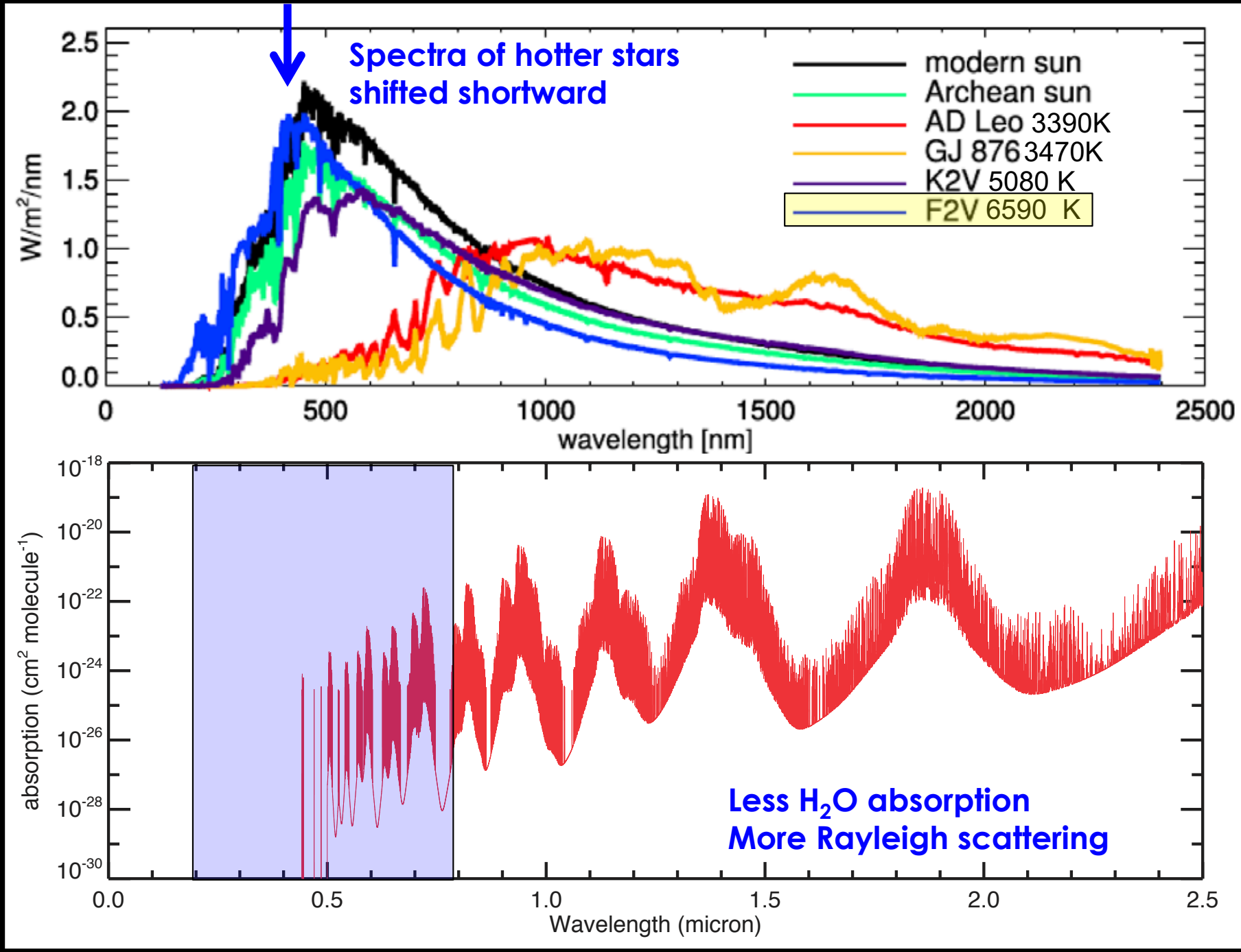

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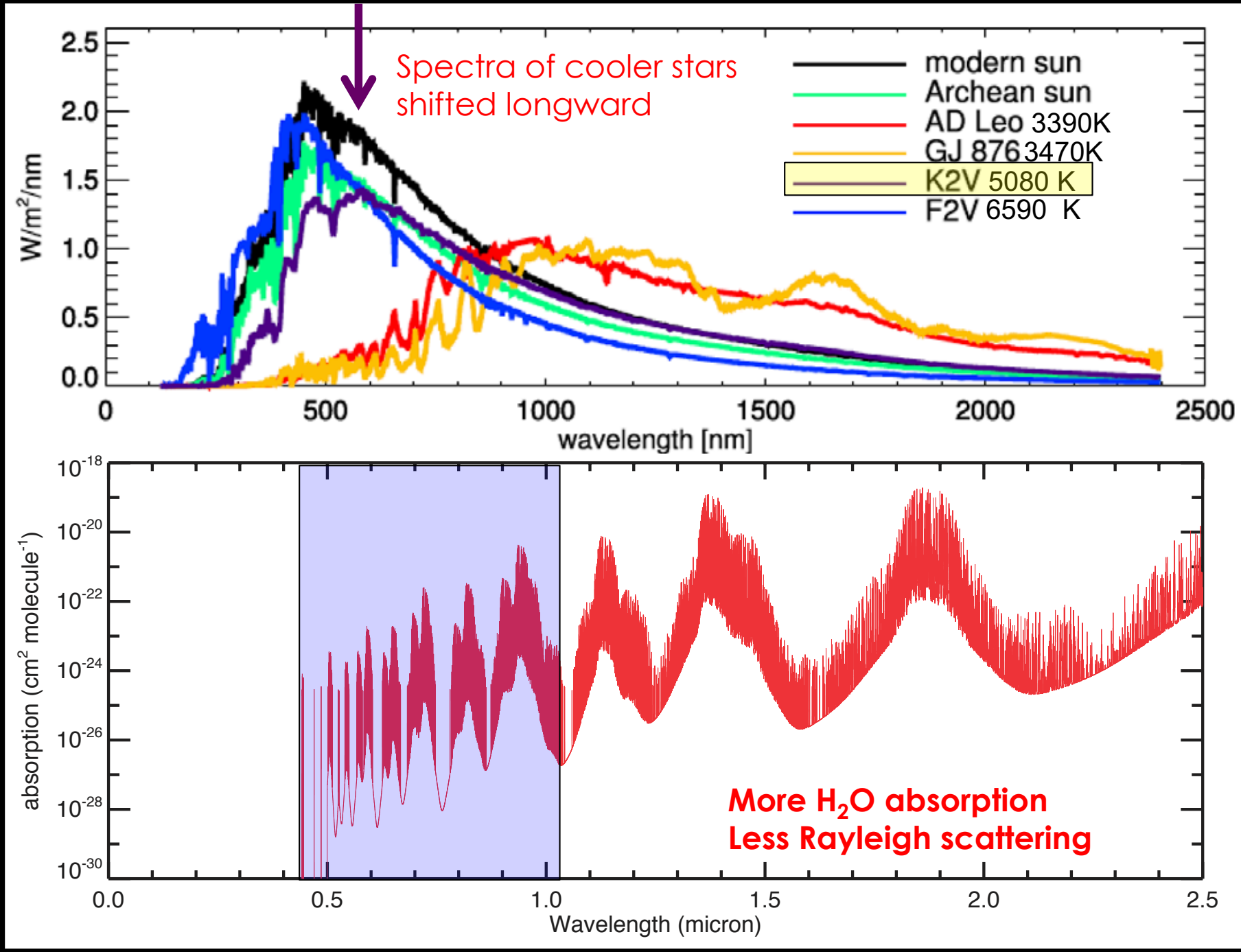

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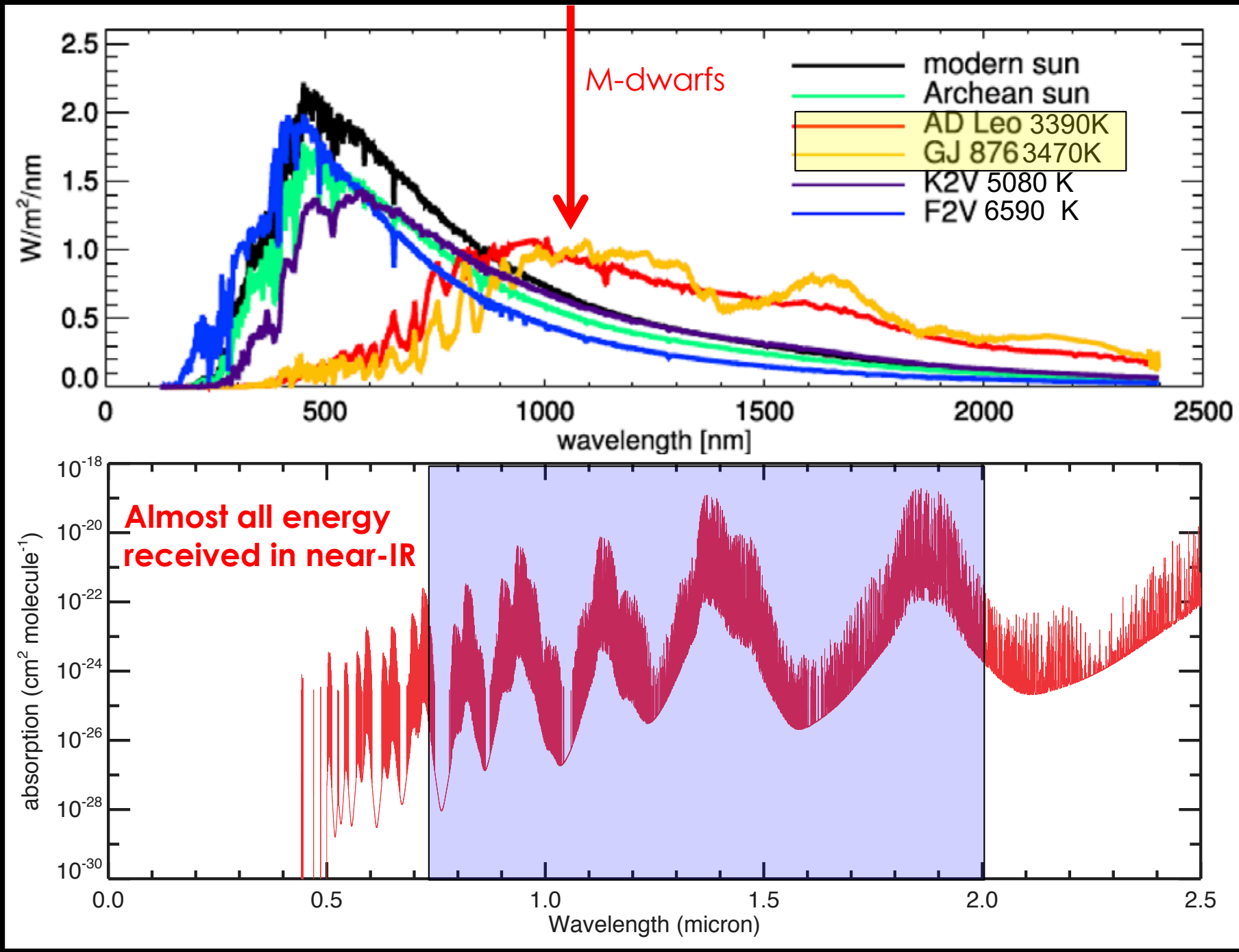
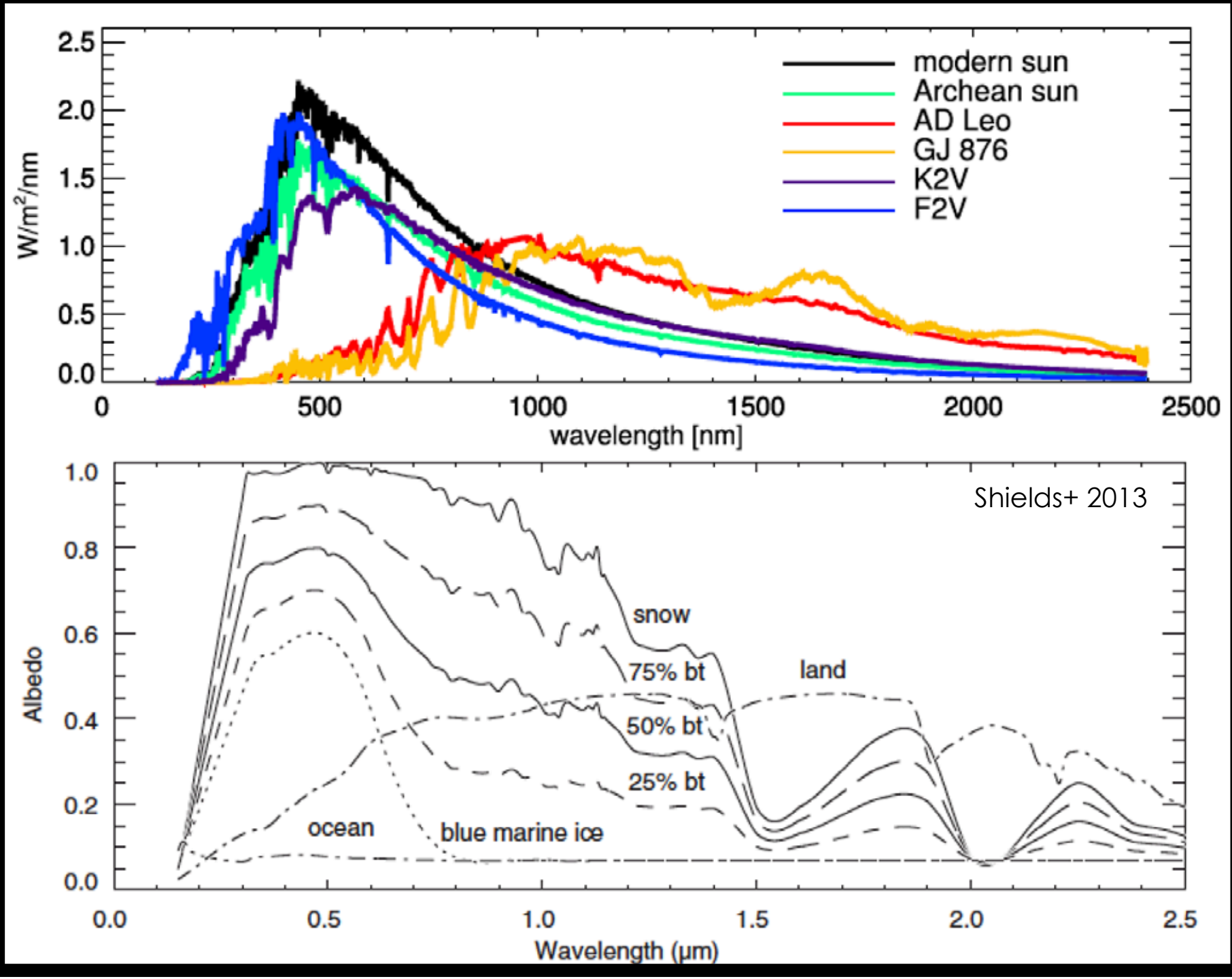


Shifts stellar spectra affects integrated surface albedo



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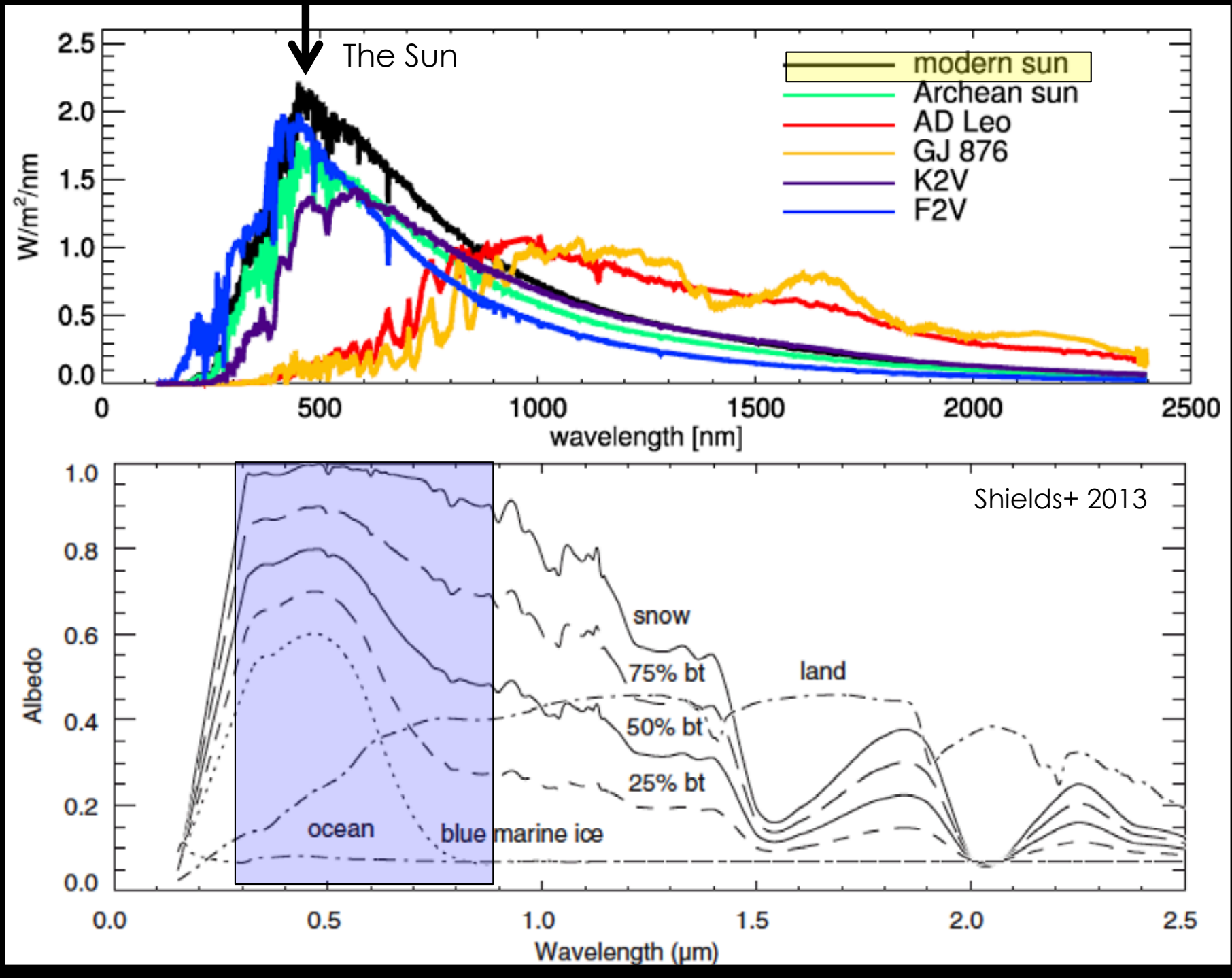

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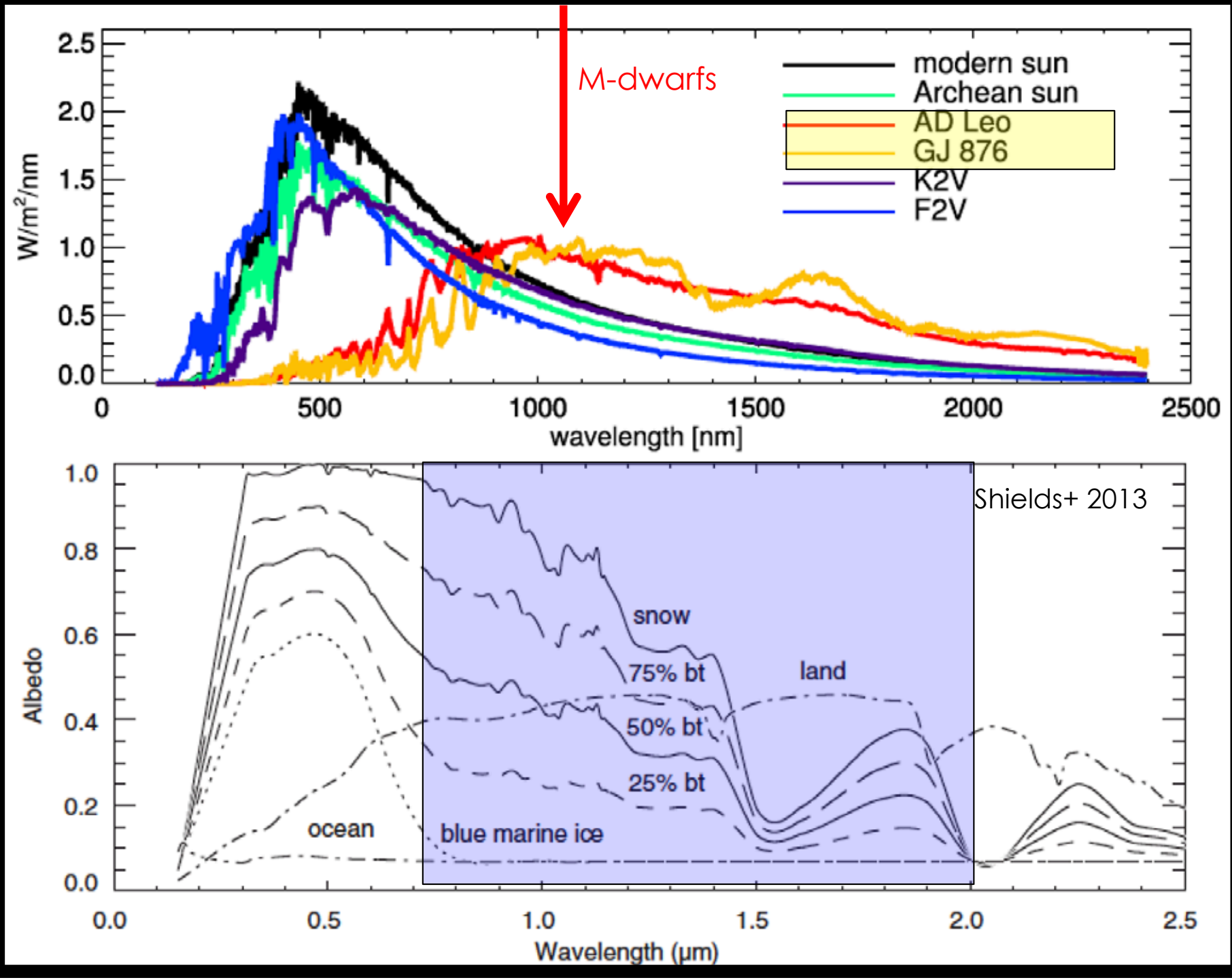
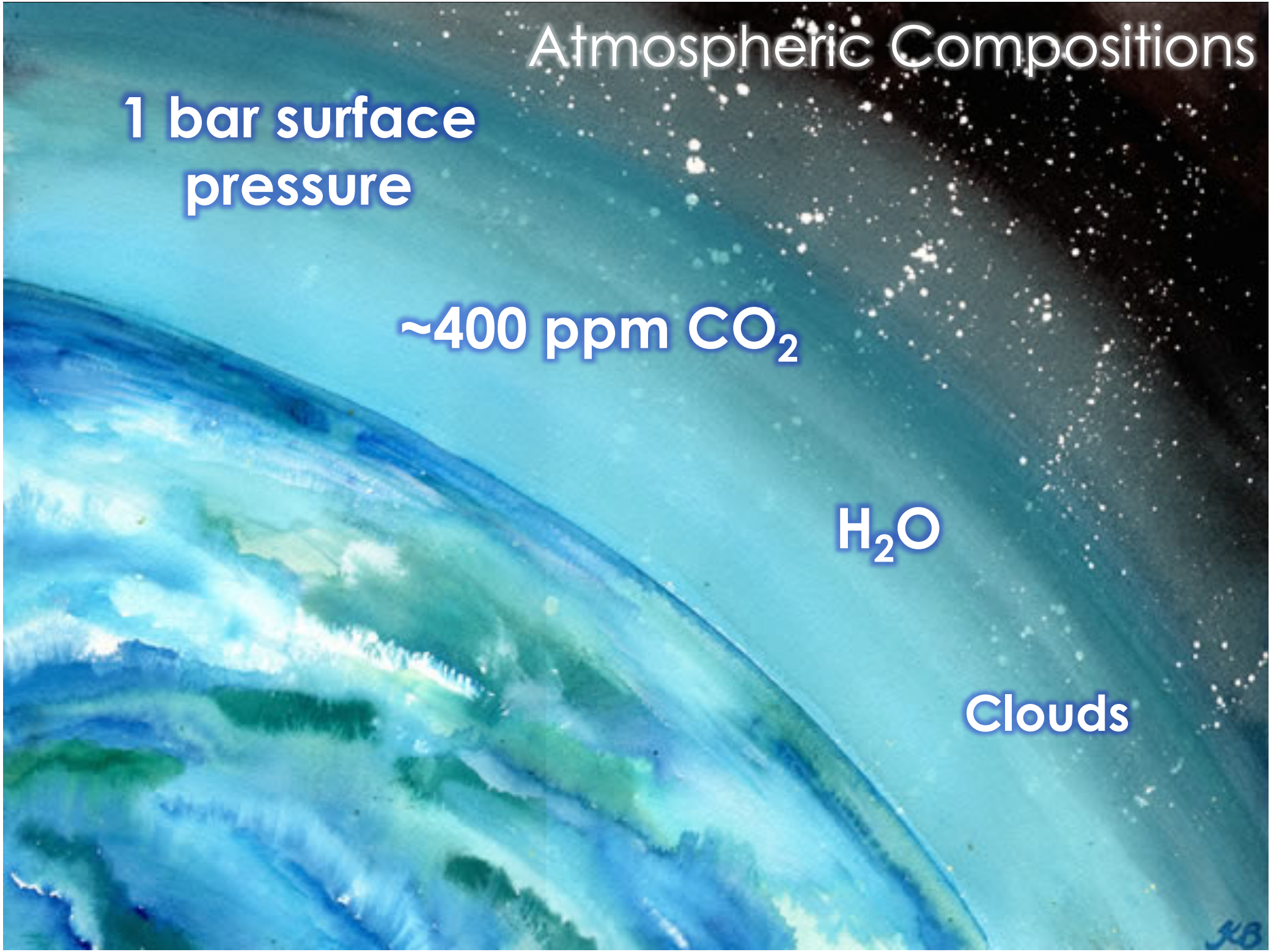
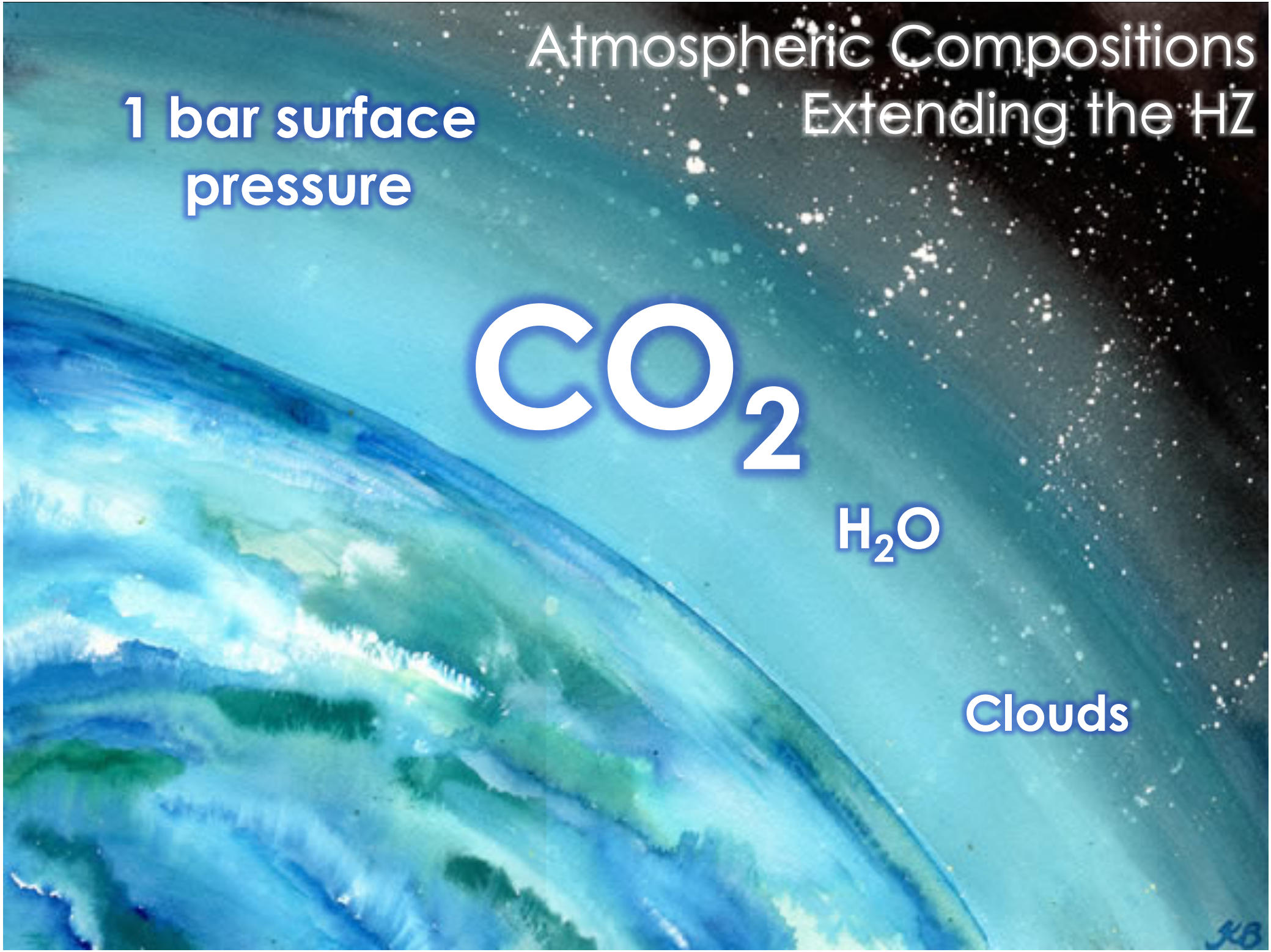
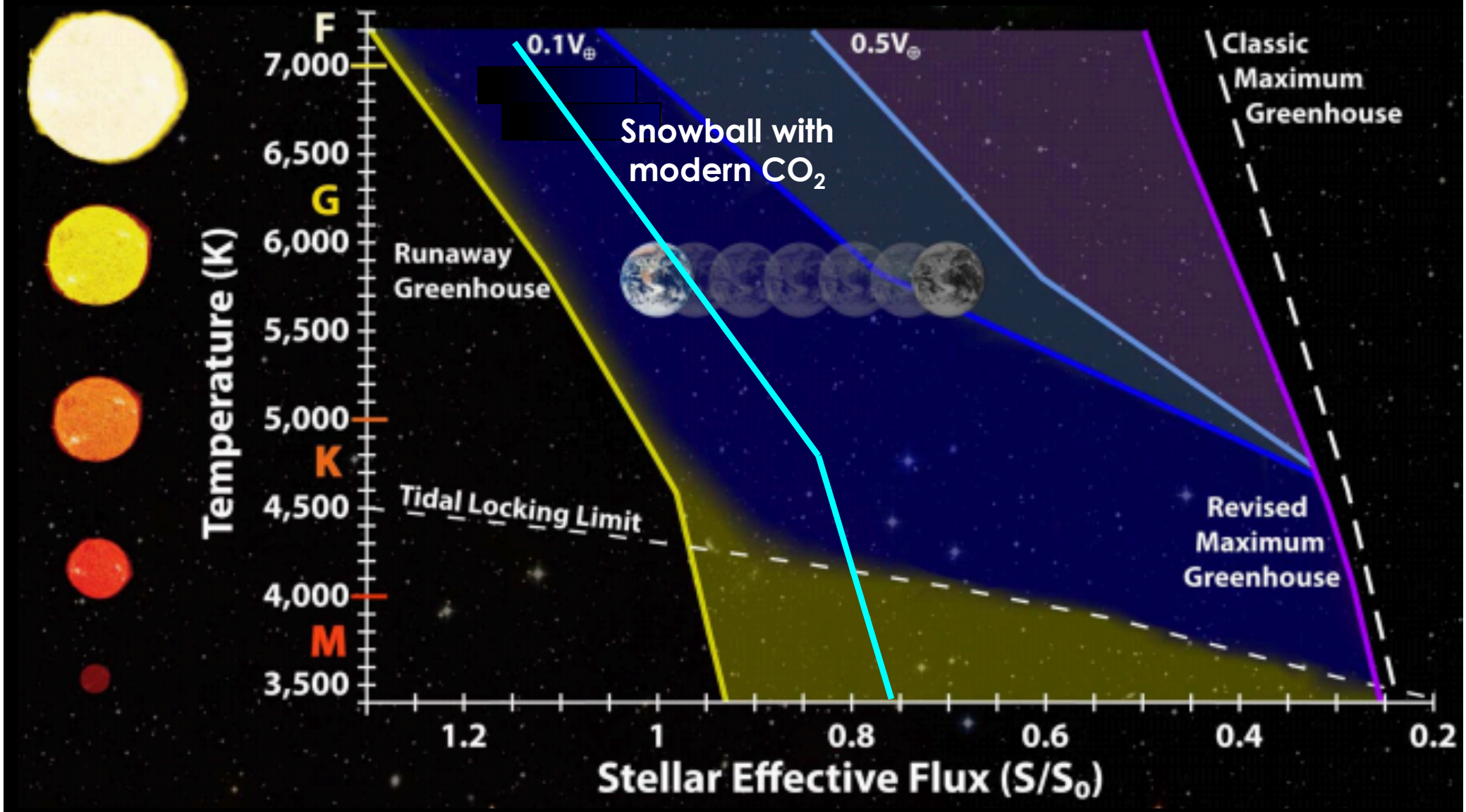



Atmospheric Compositions
1 bar surface pressure
~400 ppm CO_2
H_2O
Clouds


Atmospheric Compositions
Extending the HZ
1 bar surface pressure
CO_2
H_2O
Clouds

The outer edge of the habitable zone

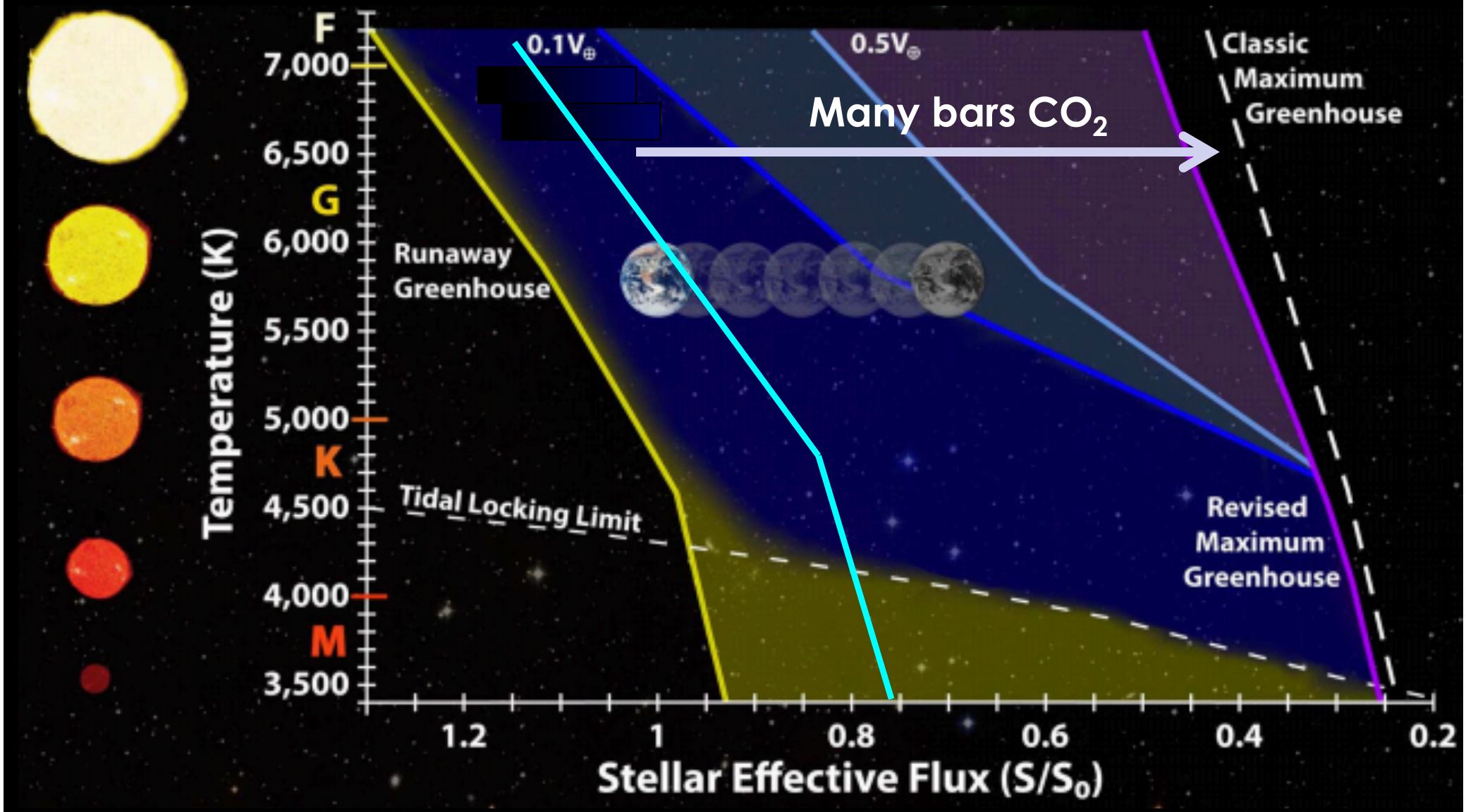
The Maximum CO_2 Greenhouse Limit



Haqq-Misra+ 2016

The outer edge of the habitable zone

The Maximum CO_2 Greenhouse Limit



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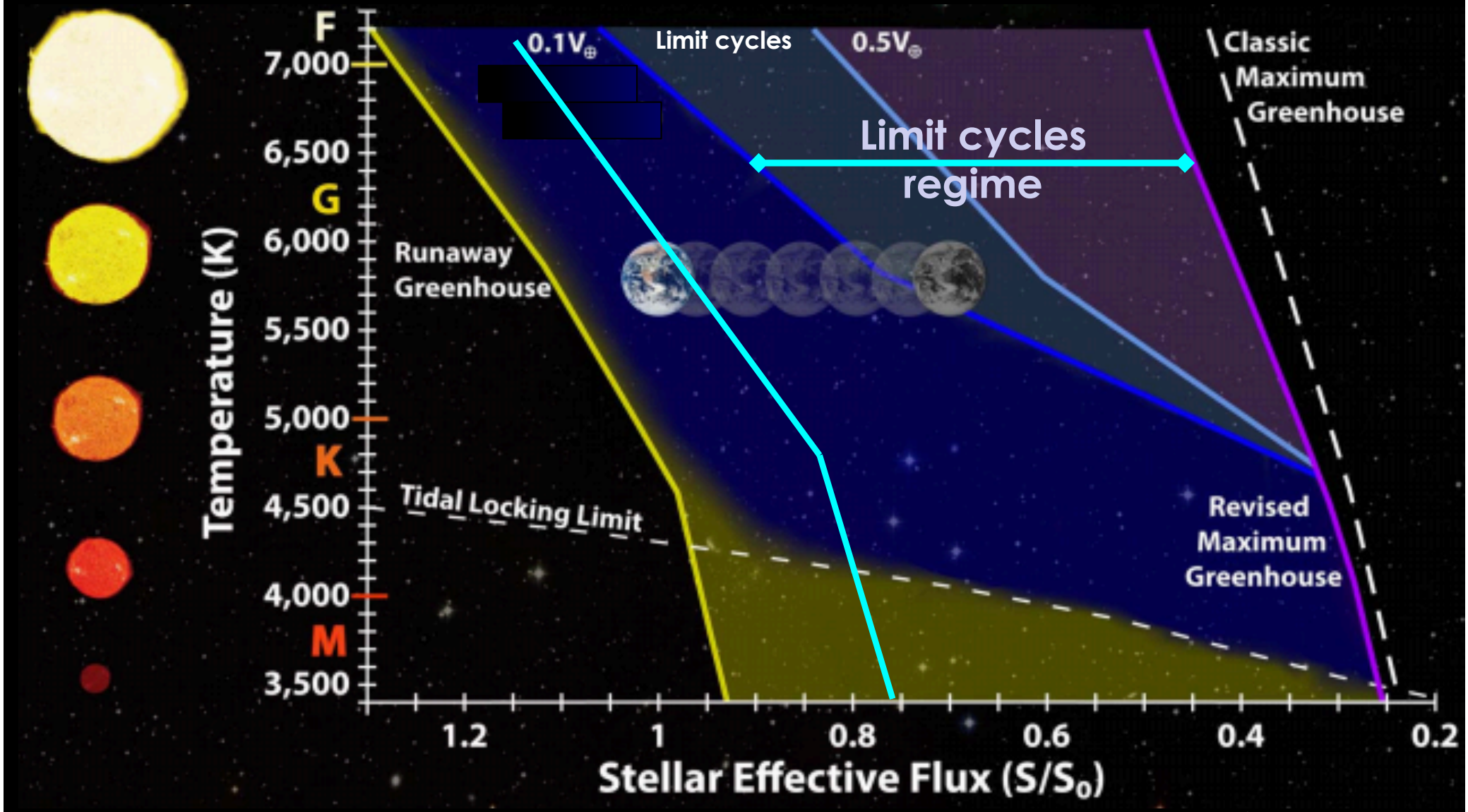
The outer edge of the habitable zone

Limit Cycles



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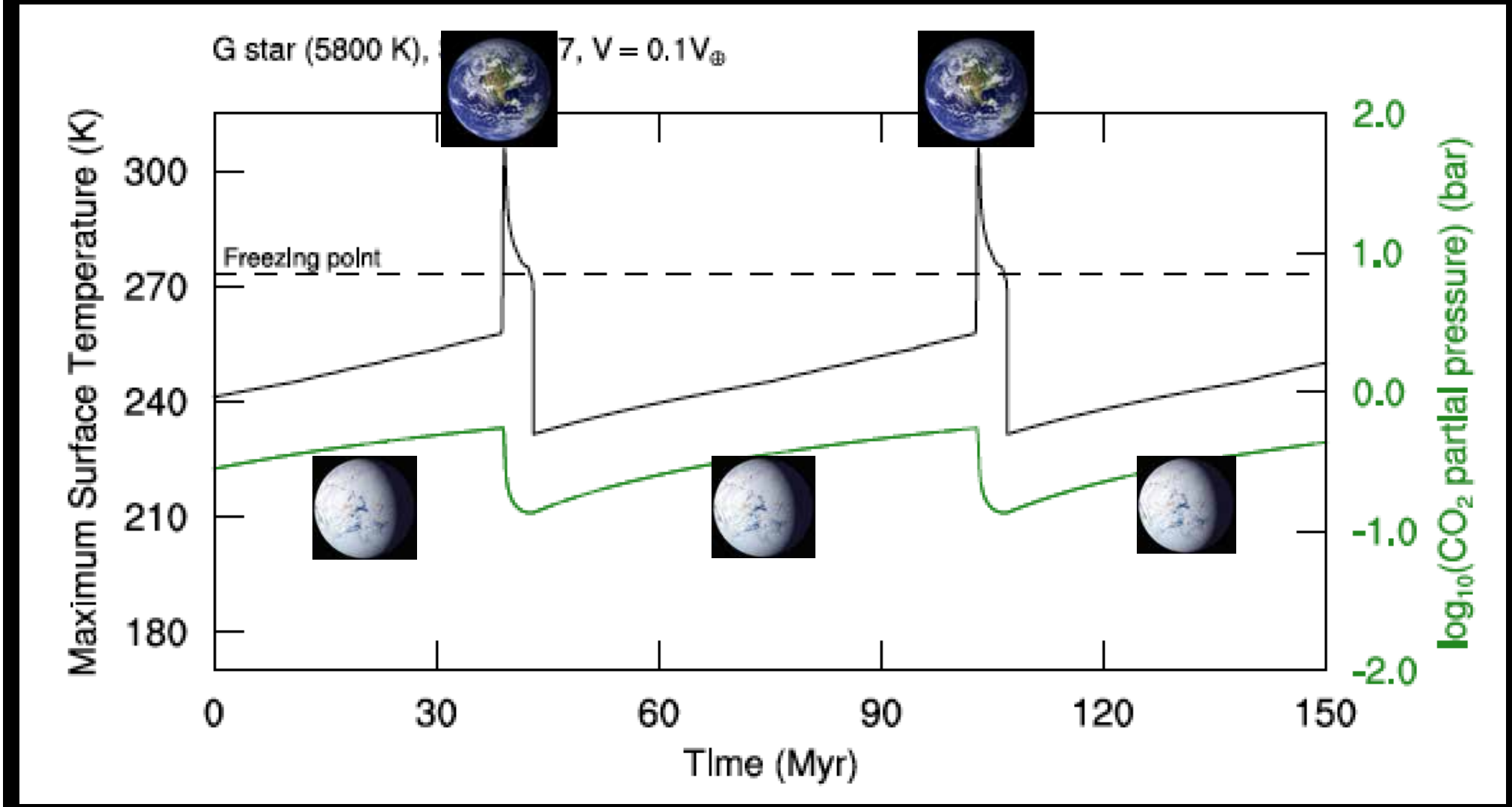

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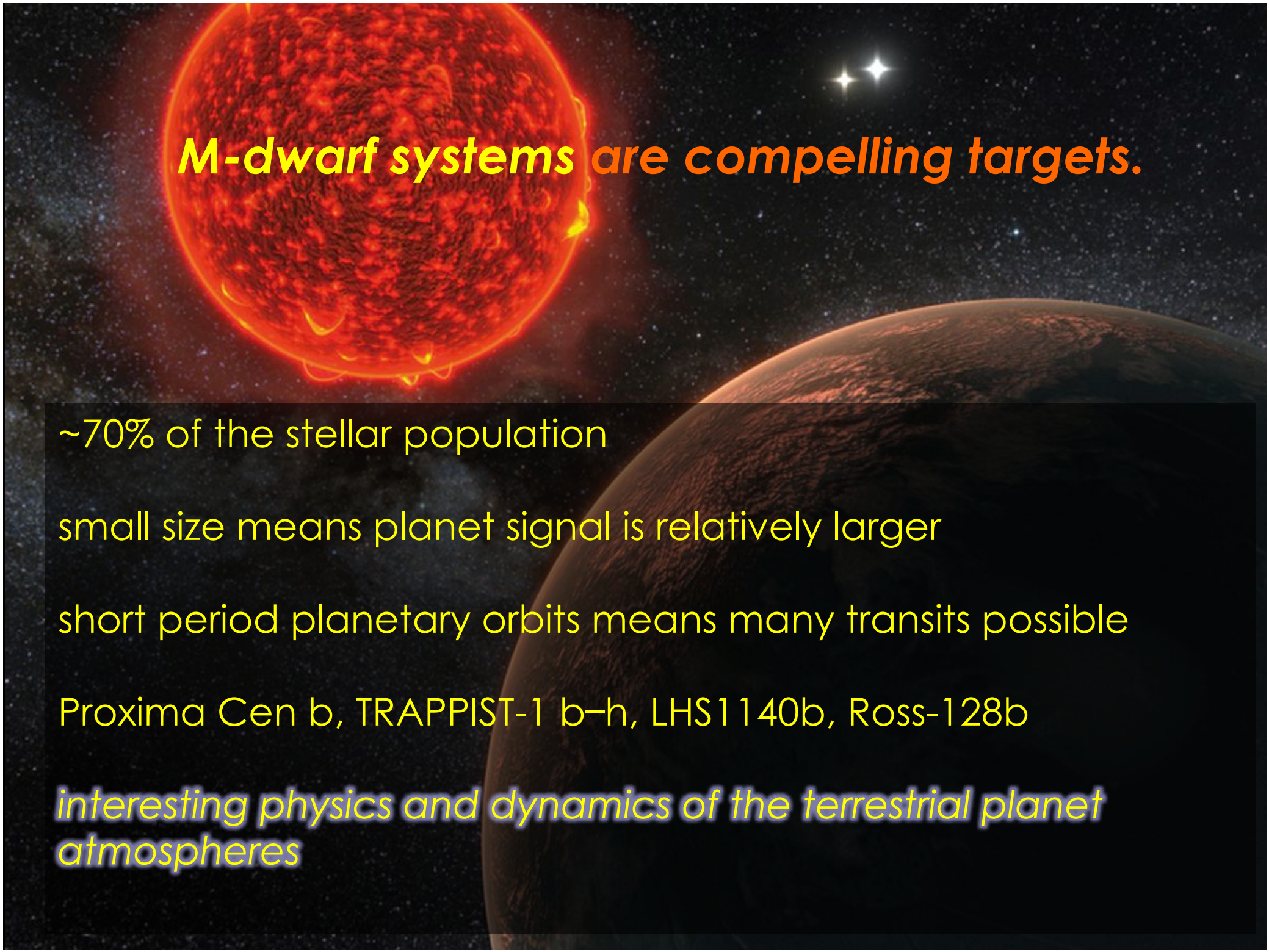
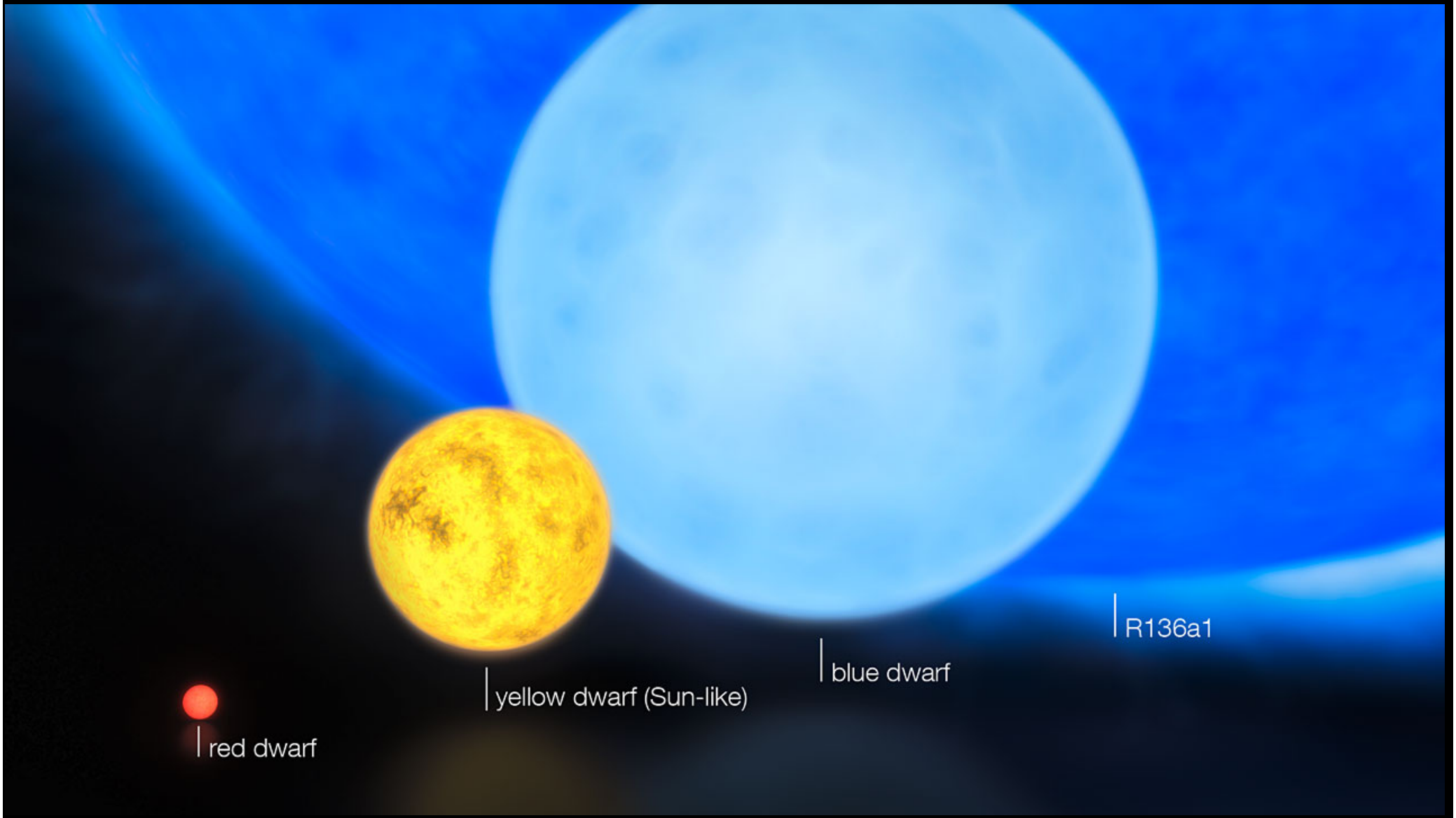
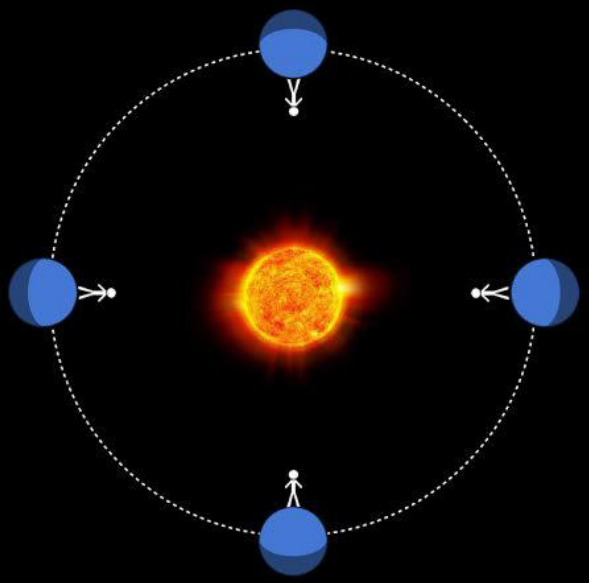

M-dwarf systems are compelling targets.
~70% of the stellar population
small size means planet signal is relatively larger
short period planetary orbits means many transits possible
Proxima Cen b, TRAPPIST-1 b–h, LHS1140b, Ross-128b
interesting physics and dynamics of the terrestrial planet atmospheres

M-dwarf stars are the smallest and most common in the universe

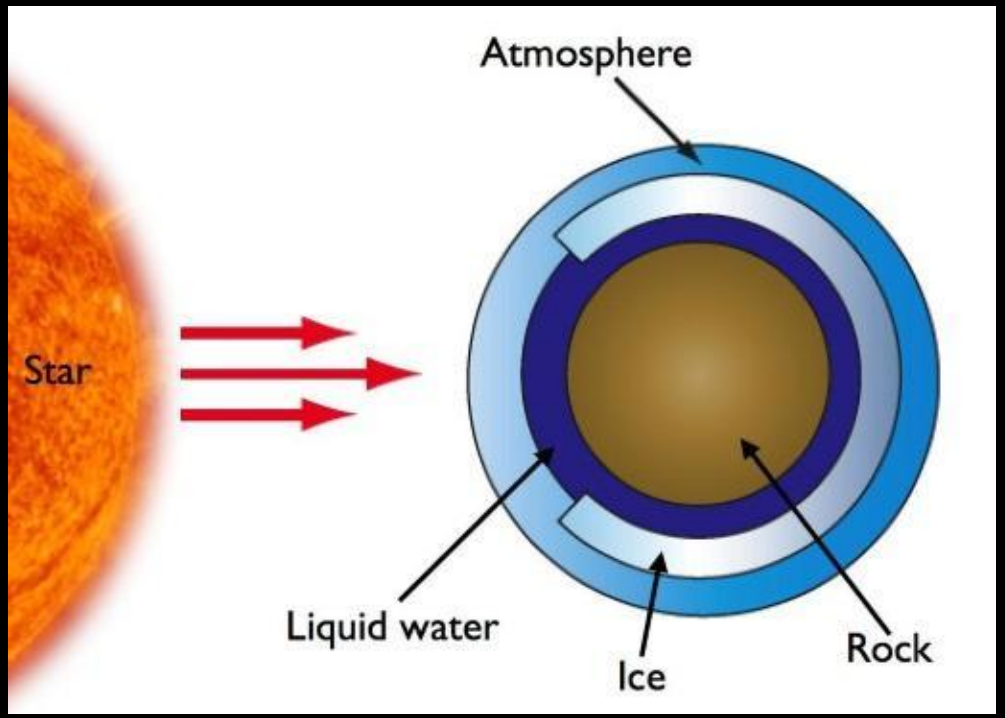


Consequences of tidal locking



→ rotation rate = orbital period
→ spatial variations in solar insolation
→ Strongly affects atmospheric dynamics and clouds

The "Eyeball" Climate State



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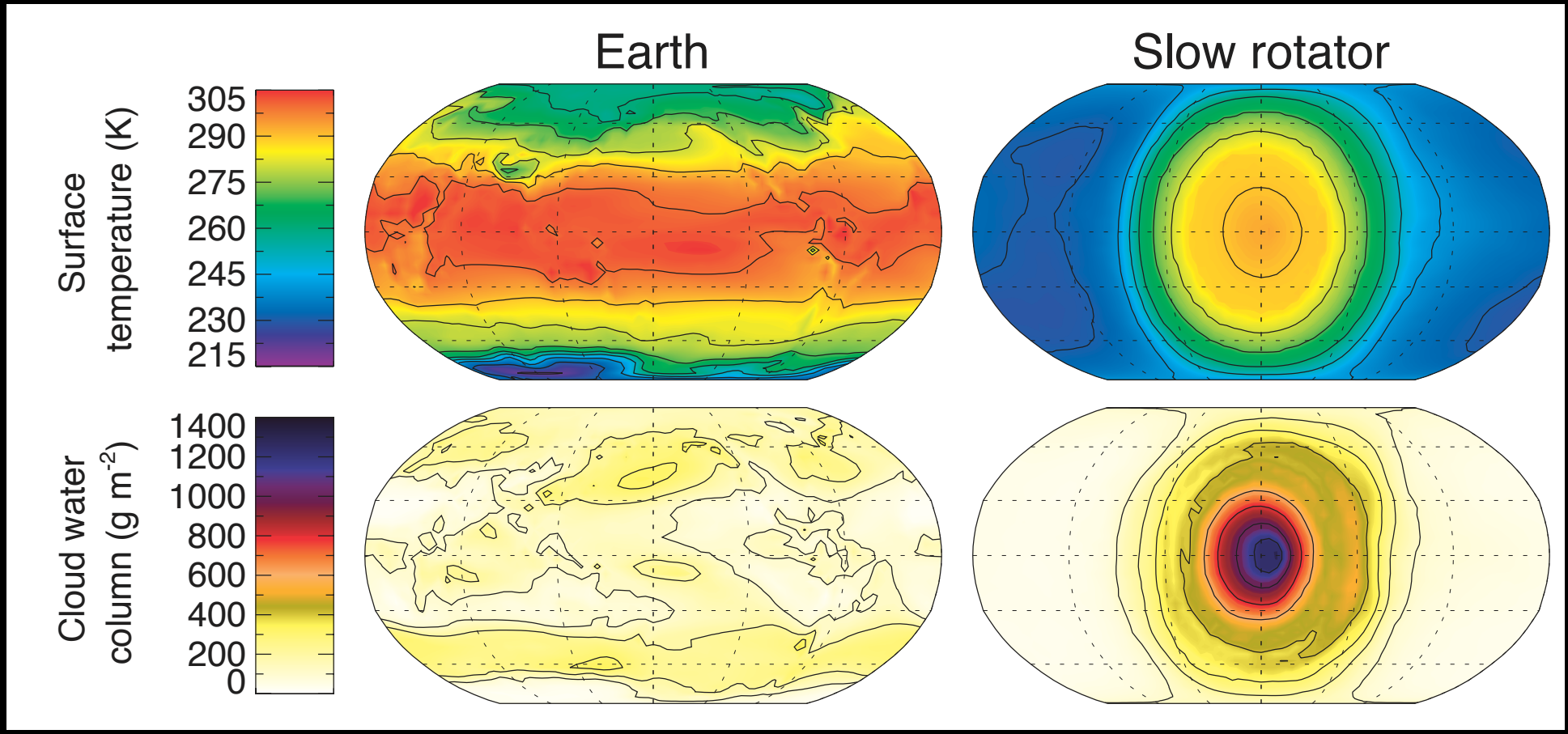
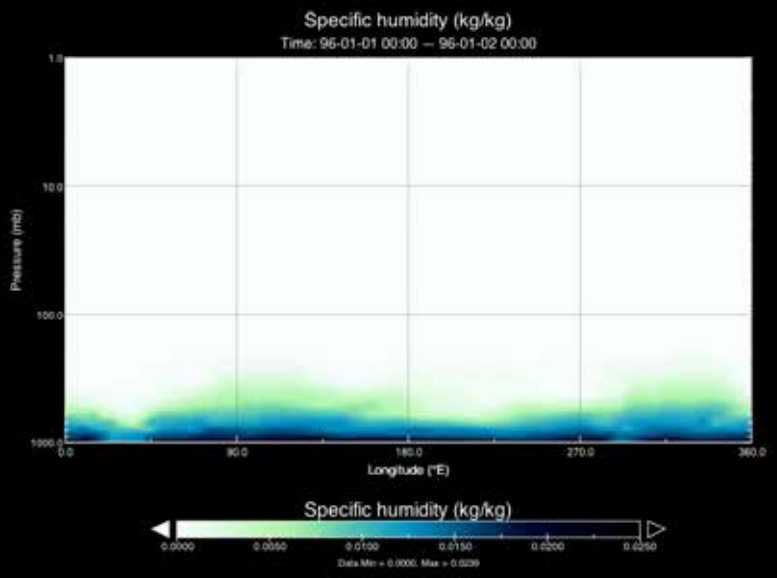


The albedo of slow rotators is greatly increased due to substellar clouds

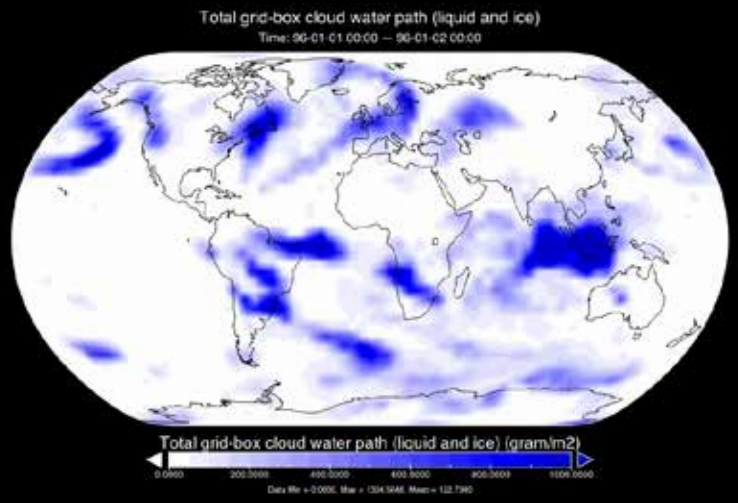
rapid rotator
24 hours non-synchronous

(translation… *Earth*)

water vapor

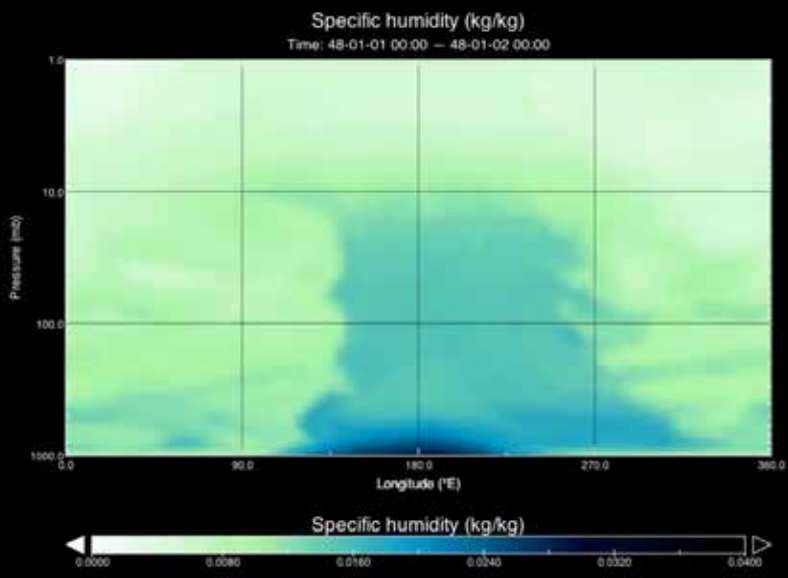


Cloud water column

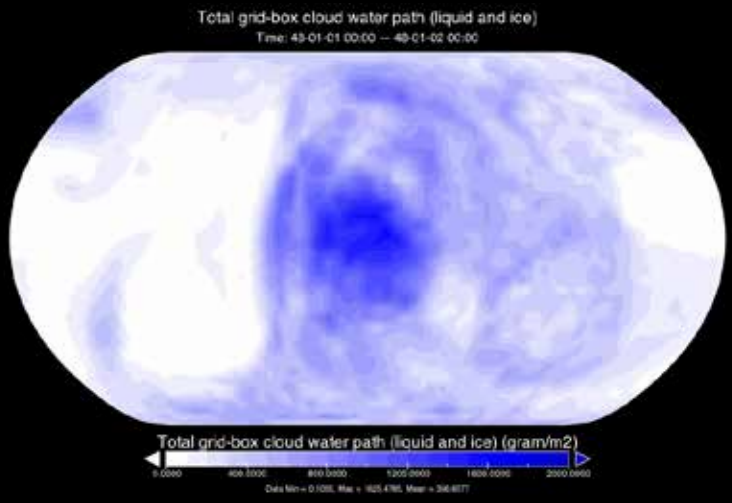


slow rotator
84.7 day, synchronous

water vapor

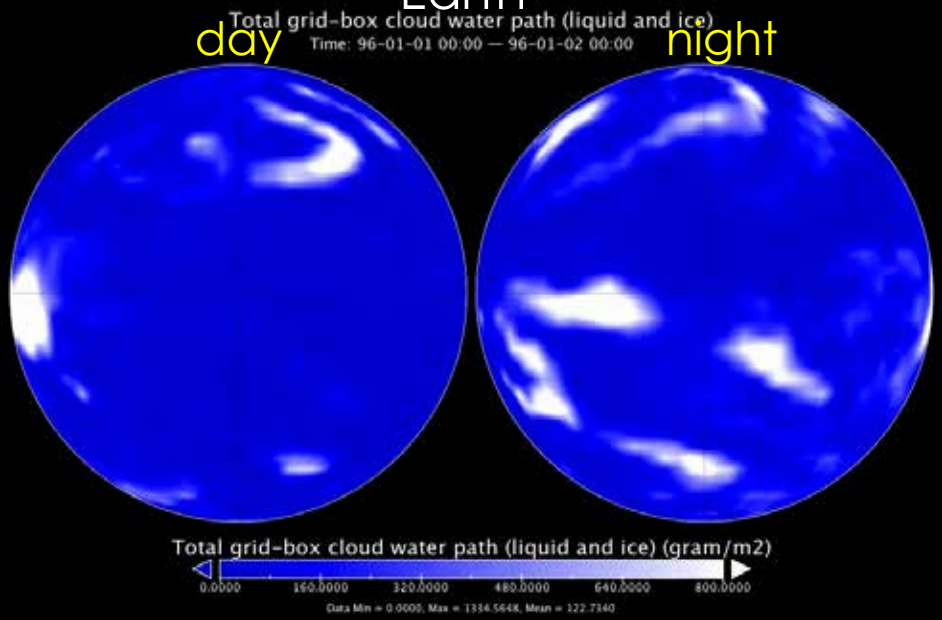


Cloud water column



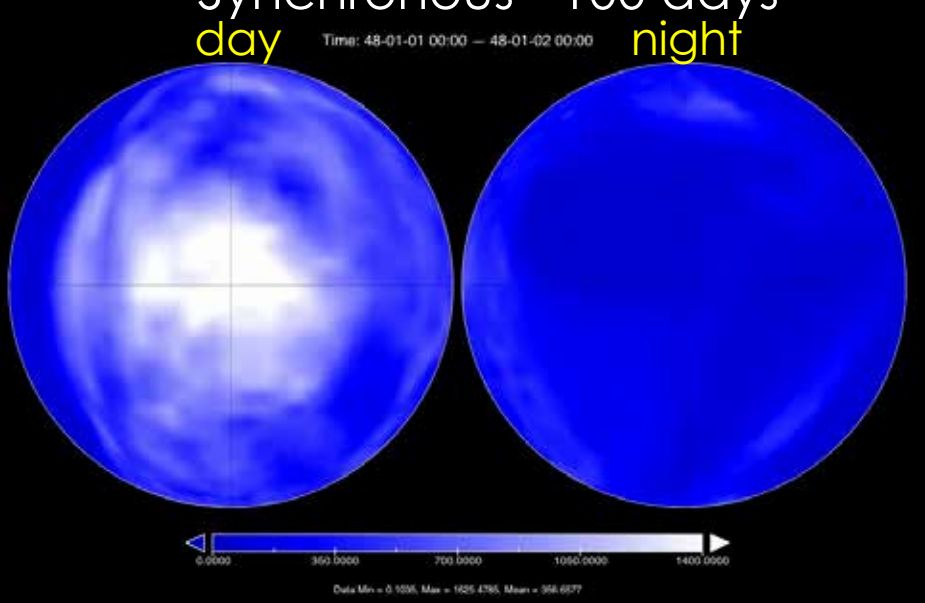
Earth

day night



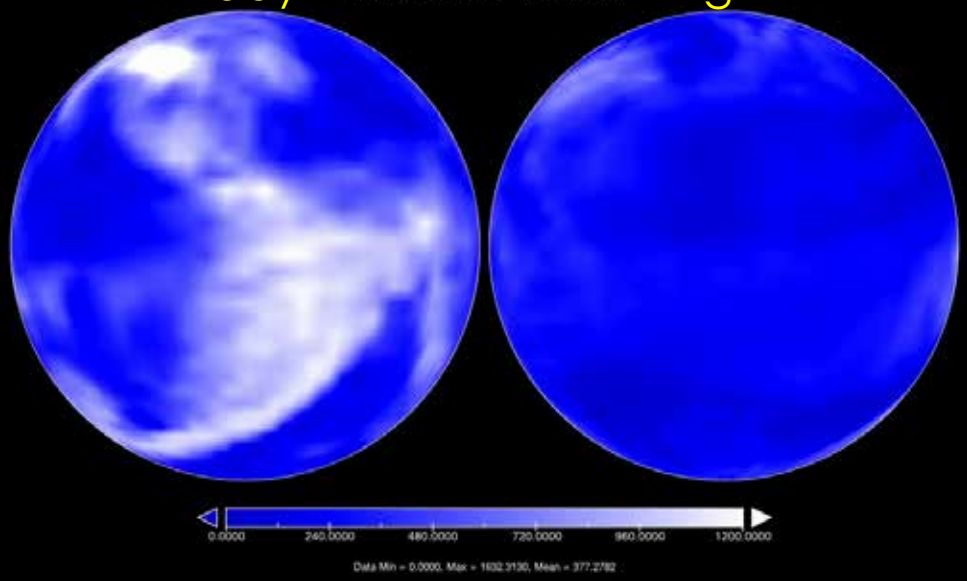
Synchronous ~100 days

day night



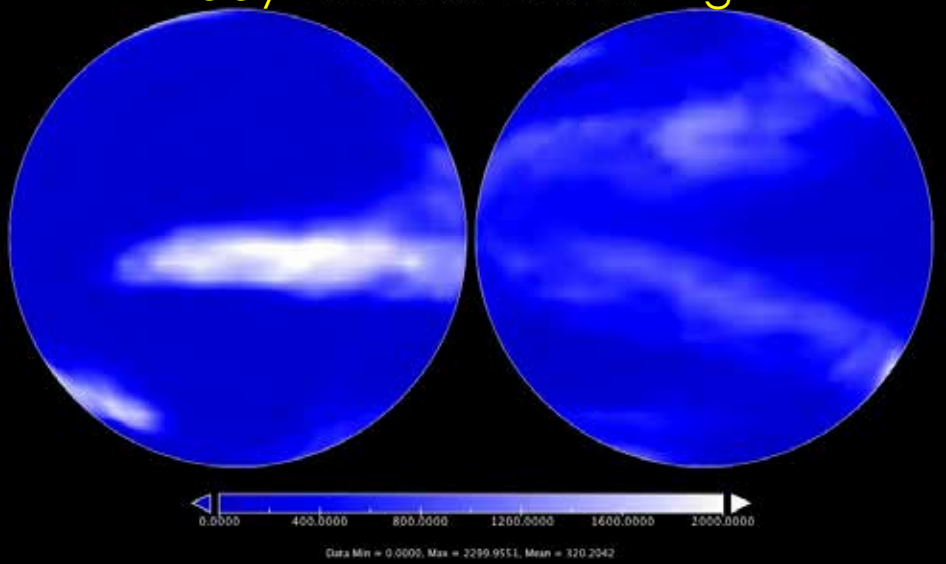
Synchronous ~8 days

day night



Synchronous ~4 days

day night



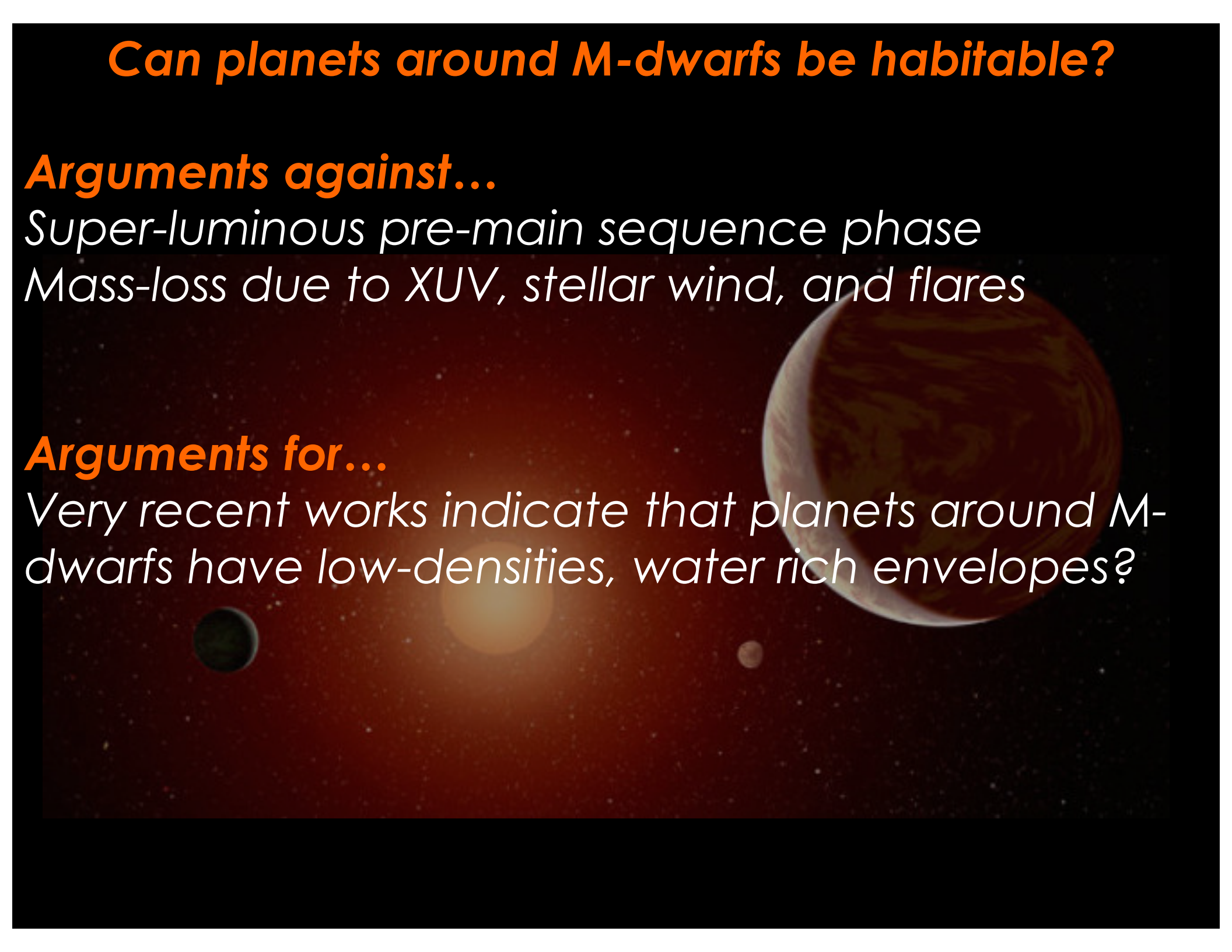
Can planets around M-dwarfs be habitable?

Arguments against…

Super-luminous pre-main sequence phase
Mass-loss due to XUV, stellar wind, and flares

Arguments for…

Very recent works indicate that planets around M-dwarfs have low-densities, water rich envelopes?



There are many things I didn't get to…

- *Habitability of non "Earth-like" planet-types*

  "Dune" planets, photochemical hazes, Intense volcanism on tidally locked planets, Super-Earths

- *Different greenhouse gases*

  CH_4, N_2-H_2 CIA

- *Atmospheric chemistry under different SEDs*
- *Surface UV radiation environments*
- *Different evolutionary paths*

  planetary migration, abiotic O_2 build up

- ***Relevance of climate states to transmission spectra, and thermal phase curves***

  Can we discriminate between them?

Transiting Exoplanet Survey Satellite

NASA

Launch date April 18th, 2018

The successor to Kepler

TESS: Delivered to Kennedy Space Center Feb. 19th, 2018

James Webb Space Telescope

NASA

Launch date Spring 2019

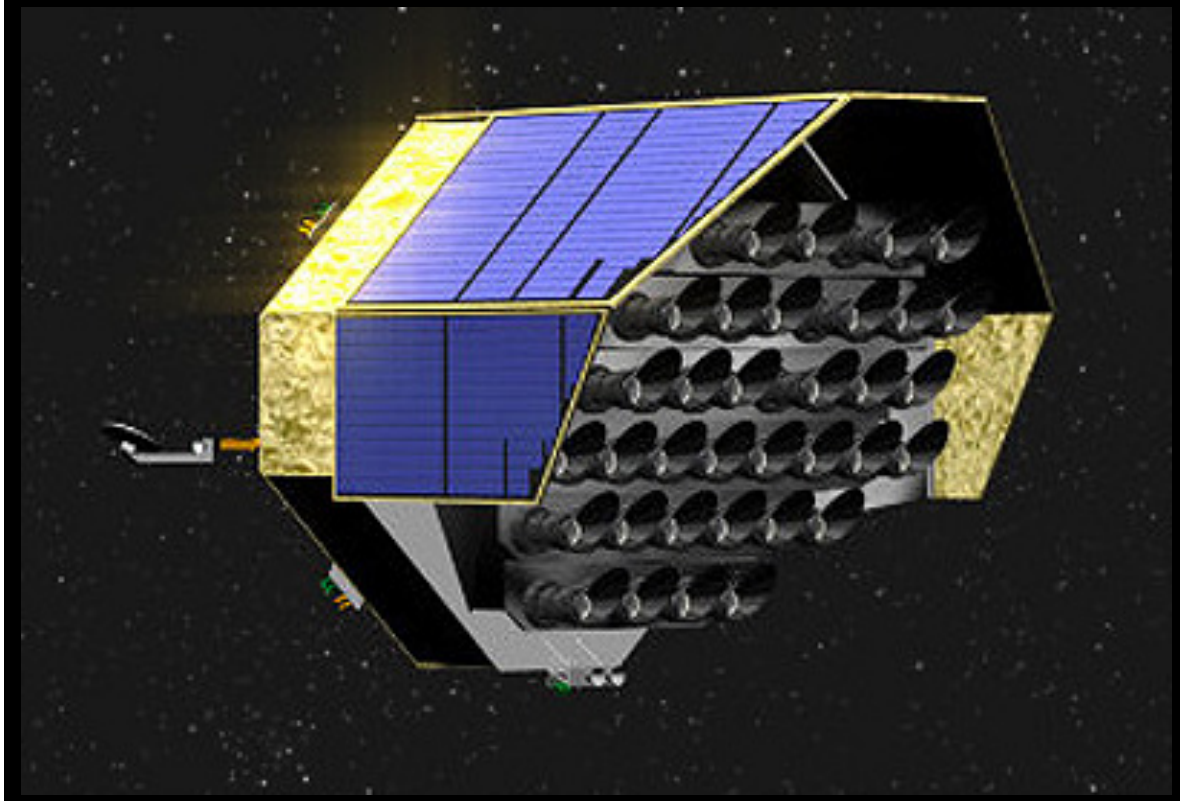
Infrared
0.6 to 28.5 µm

Designed to study the early universe, galaxies … and also exoplanets

PLA*netary* ***T****ransits and* ***O****scillations of stars*

ESA

Launch date 2026

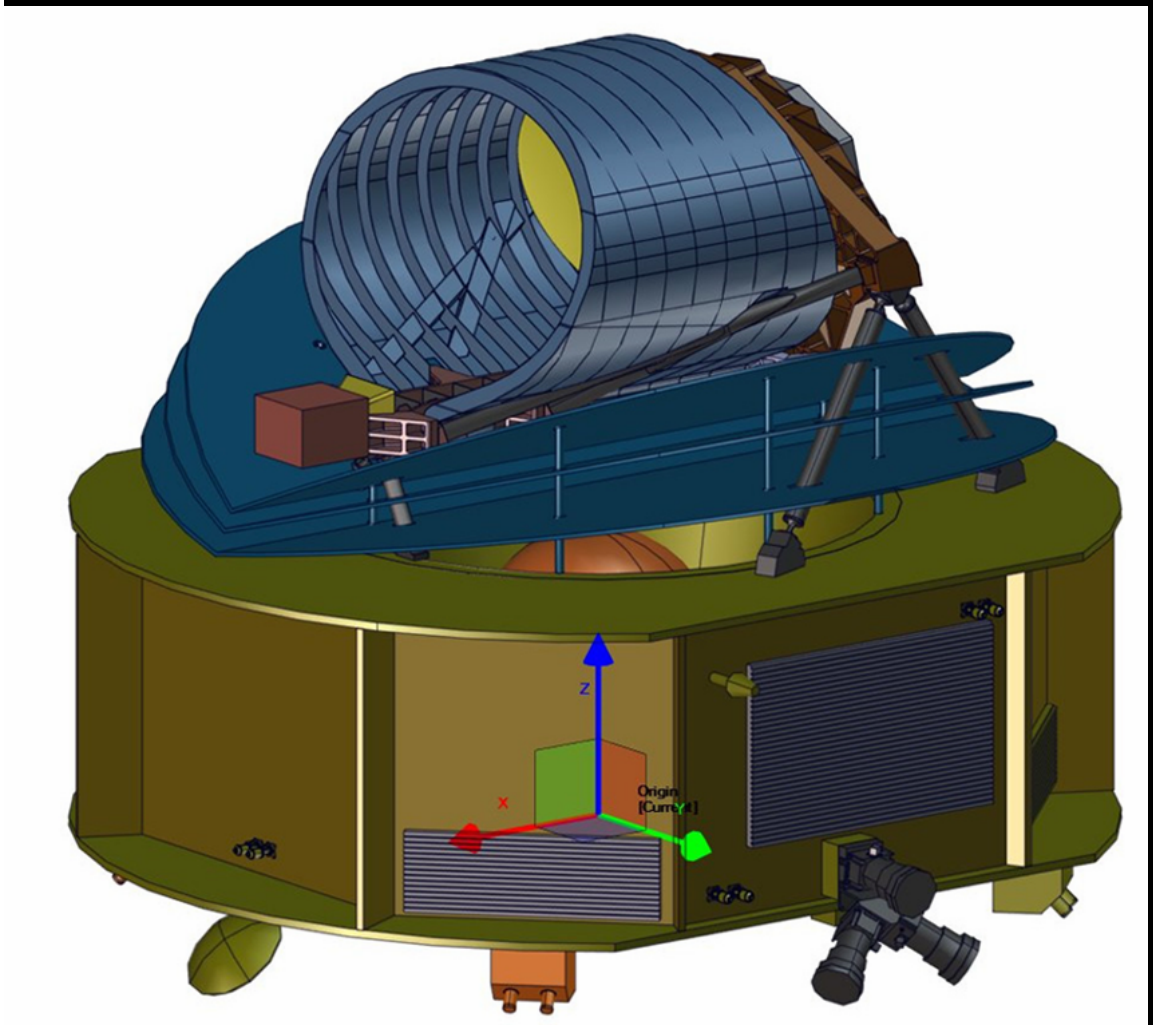


Designed to discover and characterize Earh-like planets around solar-type stars.

***A**tmospheric **R**emote-sensing **I**nfrared **E**xoplanet **L**arge-Survey*

ESA

Launch date 2026



Designed to probe atmospheres of hot exoplanets (500 K and hotter)

No habitable planets.

Thirty-Meter Class Ground Based Telescopes Late 2020s?

***T**hirty **M**eter **T**elescope*

***E**uropean **E**xtra **L**arge **T**elescope*

Decadal Survey Mission Concept Studies Late 2030s?

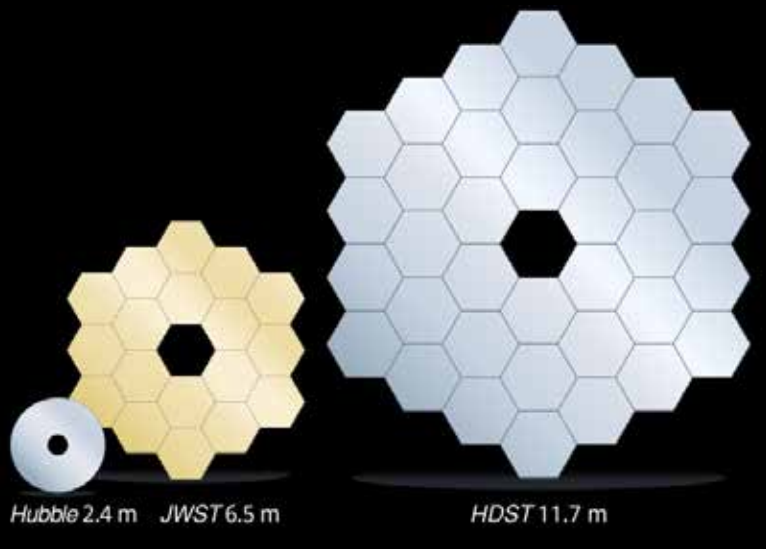
***L**arge **UV O**ptical **I**nfra**R**ed Surveyor (LUVOIR)*

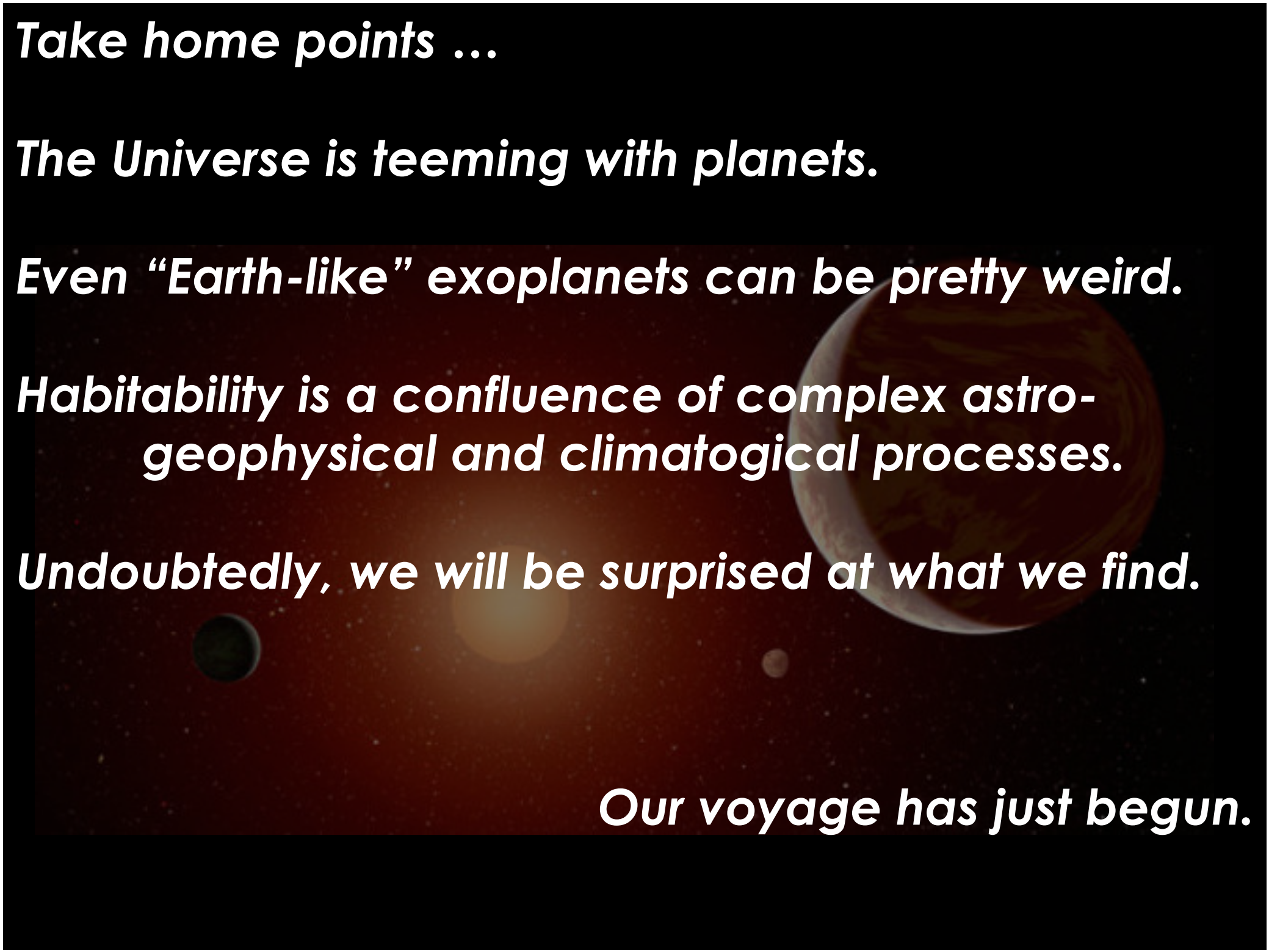
***O**rigins **S**pace **T**elescope*

***Hab**itable **Ex**oplanet Imaging Study (HabEx)*

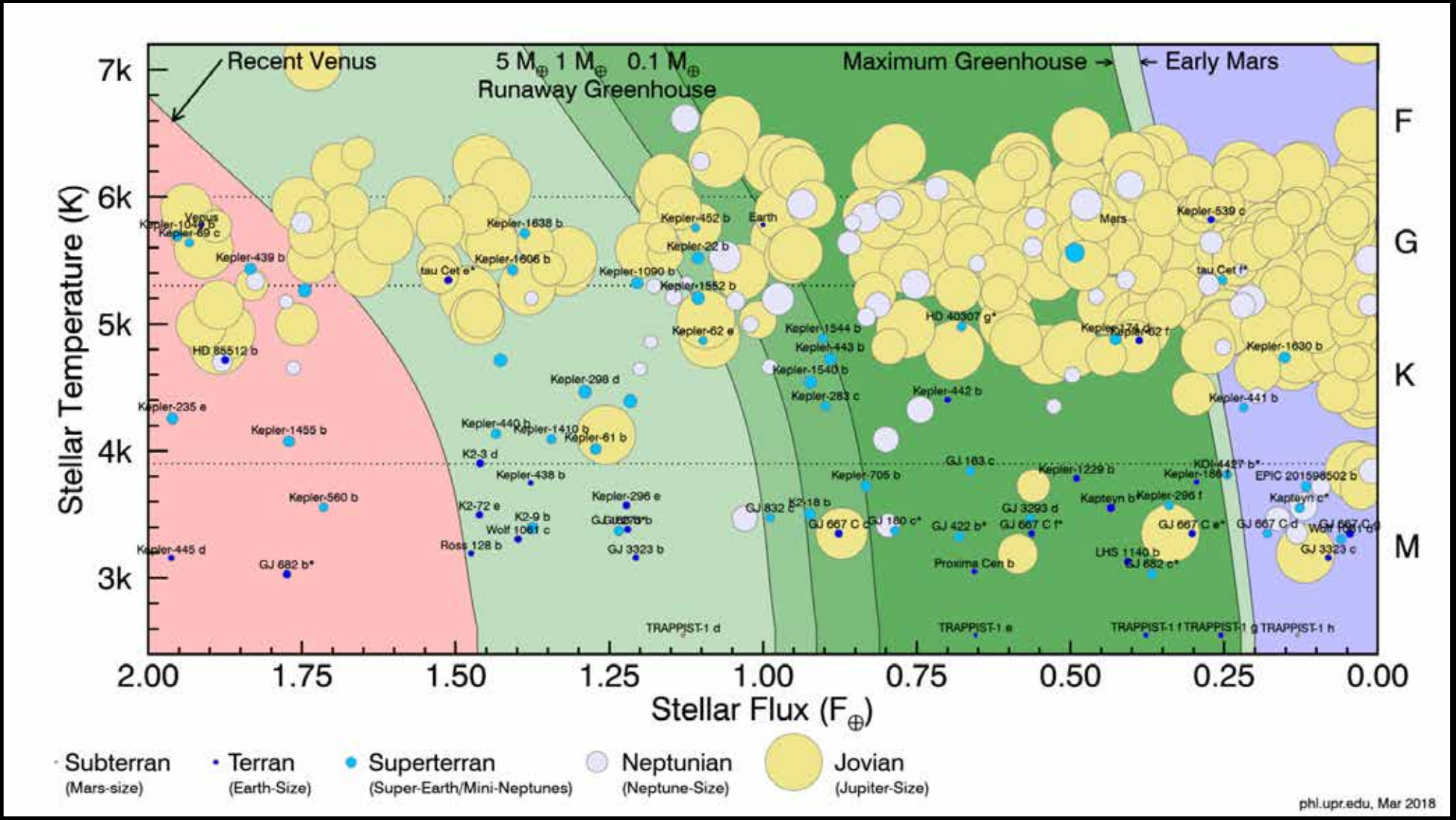
Lynx X-ray Observatory

For 3 out of the 4 have characterization terrestrial exoplanet atmospheres as the central plank in their design specifications.




Take home points …
The Universe is teeming with planets.
Even "Earth-like" exoplanets can be pretty weird.
Habitability is a confluence of complex astro-geophysical and climatogical processes.
Undoubtedly, we will be surprised at what we find.
Our voyage has just begun.

The Habitable Zone



Habitable Exoplanets Catalog
Planetary Habitability Lab, University of Puerto Rico, Aceribo
http://phl.upr.edu/projects/habitable-exoplanets-catalog