The Life Span and Detectability of Biospheres

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Geologic Time

EON	ERA	Duration in millions of years	Millions of years ago
PHANEROZOIC	CENOZOIC	65	65
	MESOZOIC	183	248
	PALEOZOIC	295	543
PRECAMBRIAN – PROTEROZOIC	LATE	357	900
	MIDDLE	700	1600
	EARLY	900	2500
PRECAMBRIAN – ARCHEAN	LATE	500	3000
	MIDDLE	400	3400
	EARLY	400	3800
PRECAMBRIAN – HADEAN		800	4600

You

Dinosaurs

First shelly fossils (Cambrian explosion)

Snowball Earth ice ages

Warm

Rise of atmospheric oxygen (Ice age)

Ice age (?)

Warm (?)

Origin of life

Stars brighten steadily during their adult life

Three billion years ago, the Sun was about 20% less luminous than today…

…but the Early Earth appears to be at least as warm as today! This is known as the *faint young sun paradox*

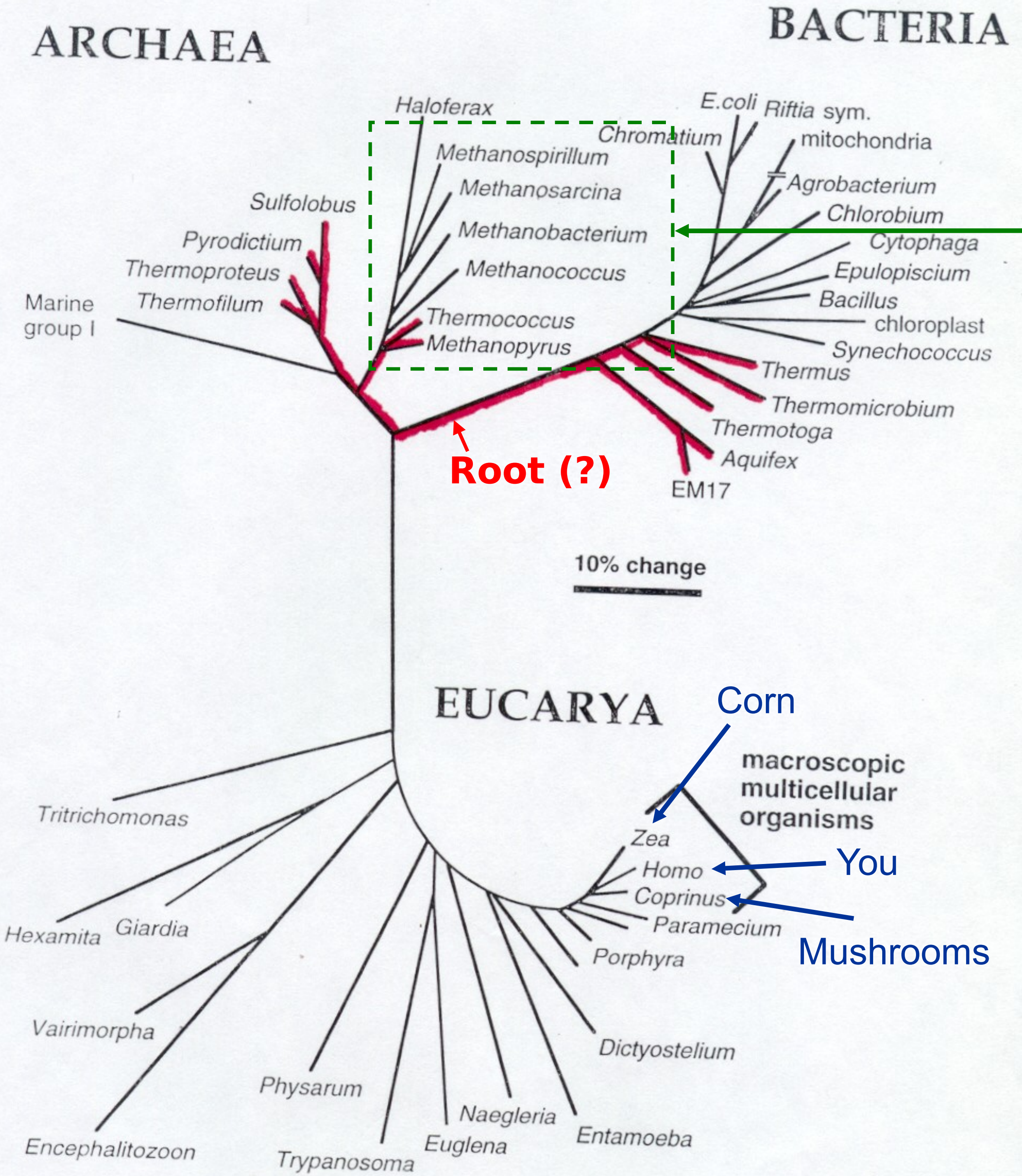
Greenhouse Gas Warming

Greenhouse gases are transparent to most incoming visible solar radiation and absorb and re-radiate much of the outgoing infrared radiation

Significant greenhouse gases on Earth today include carbon dioxide, water vapor, and methane

The decrease in solar radiation during the Early Earth could have been offset with an increase in atmospheric carbon dioxide, methane, or other greenhouse gases

Without greenhouse gas warming, the temperature of Earth would be 20 degrees below freezing!



Methanogenic bacteria

RNA Tree of Life

Courtesy of Norm Pace

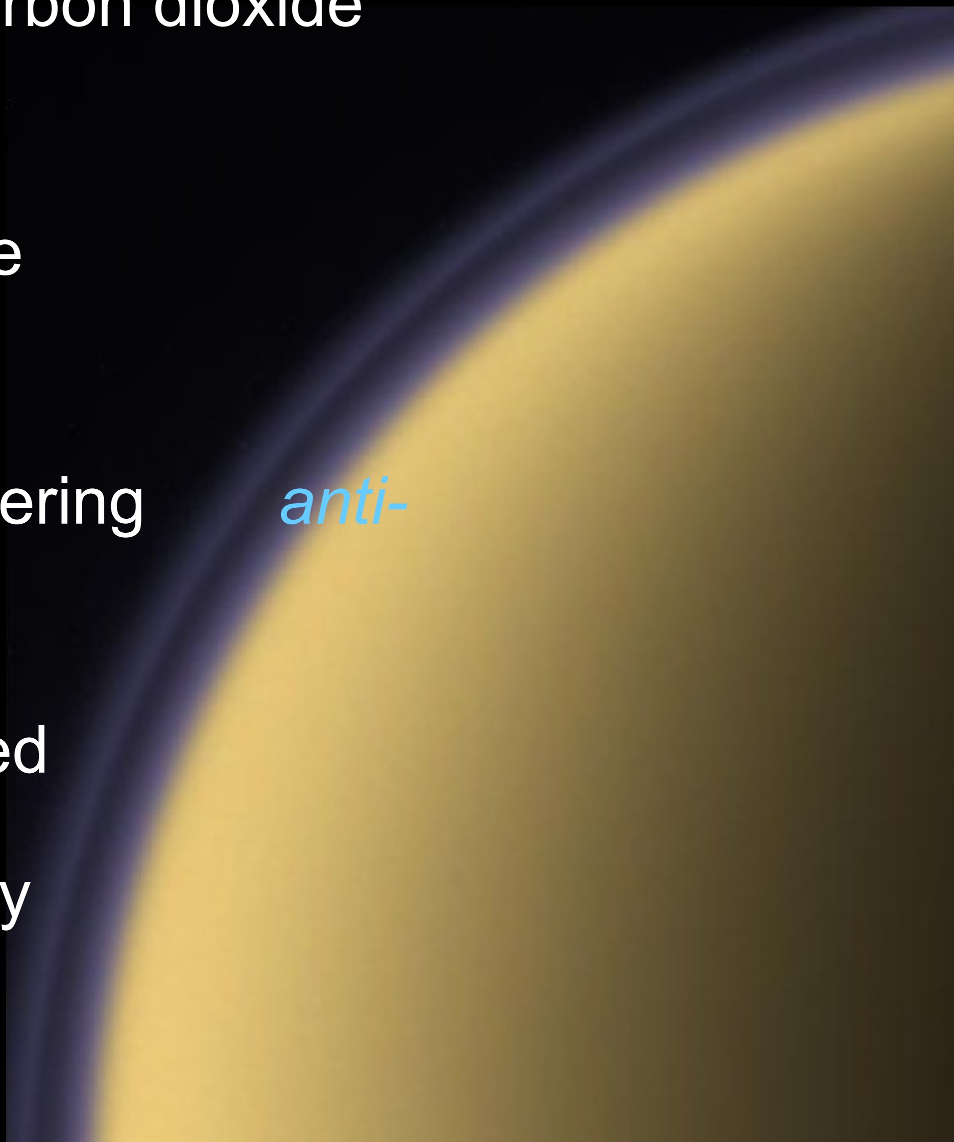
Organic Haze on Early Earth

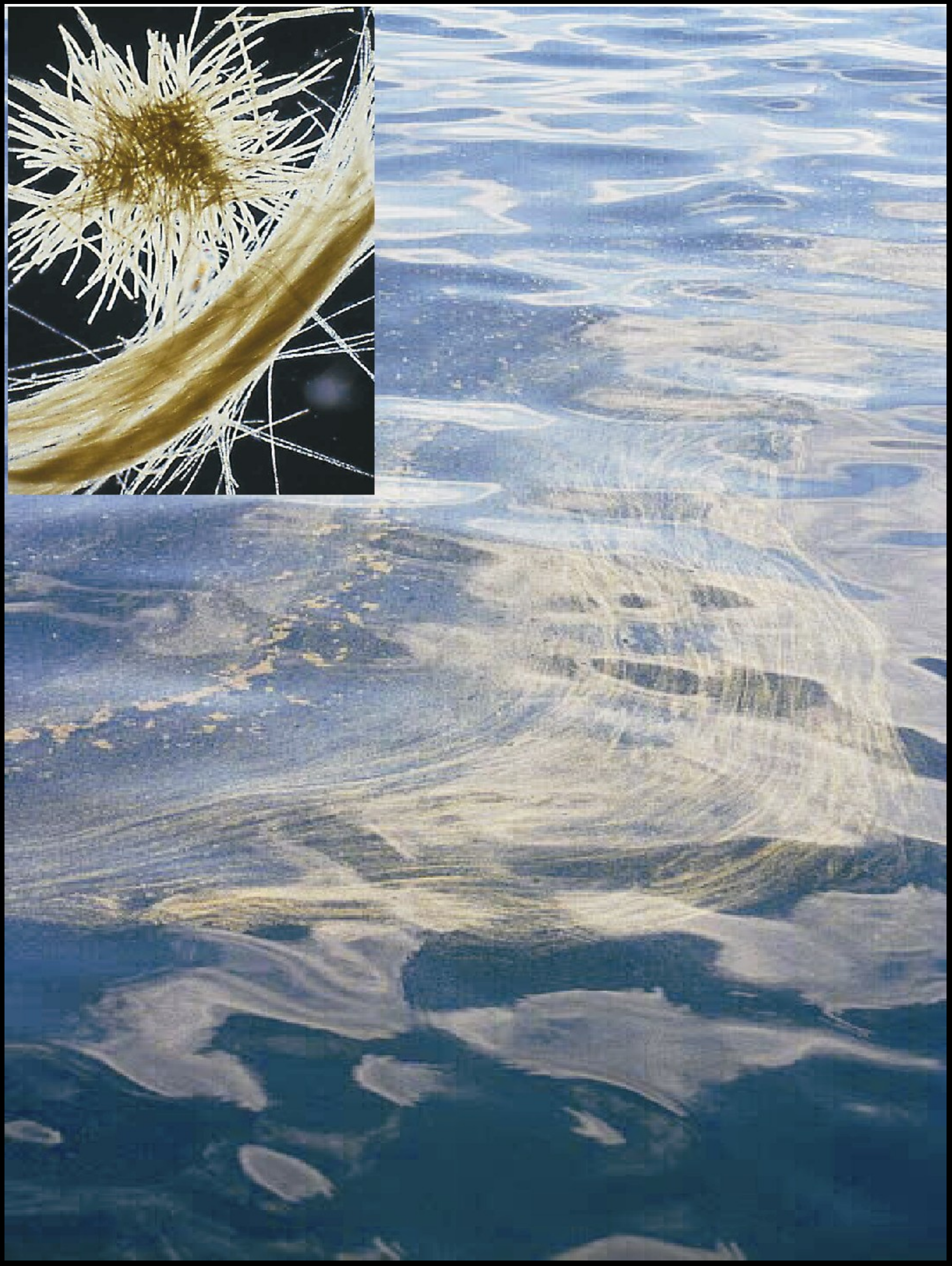
Haze forms in a methane/carbon dioxide atmosphere

Thin haze may provide some ultraviolet shielding

Thick haze produces a scattering *anti-greenhouse effect*

Haze thickness is constrained by a negative feedback loop between methanogen activity and temperature

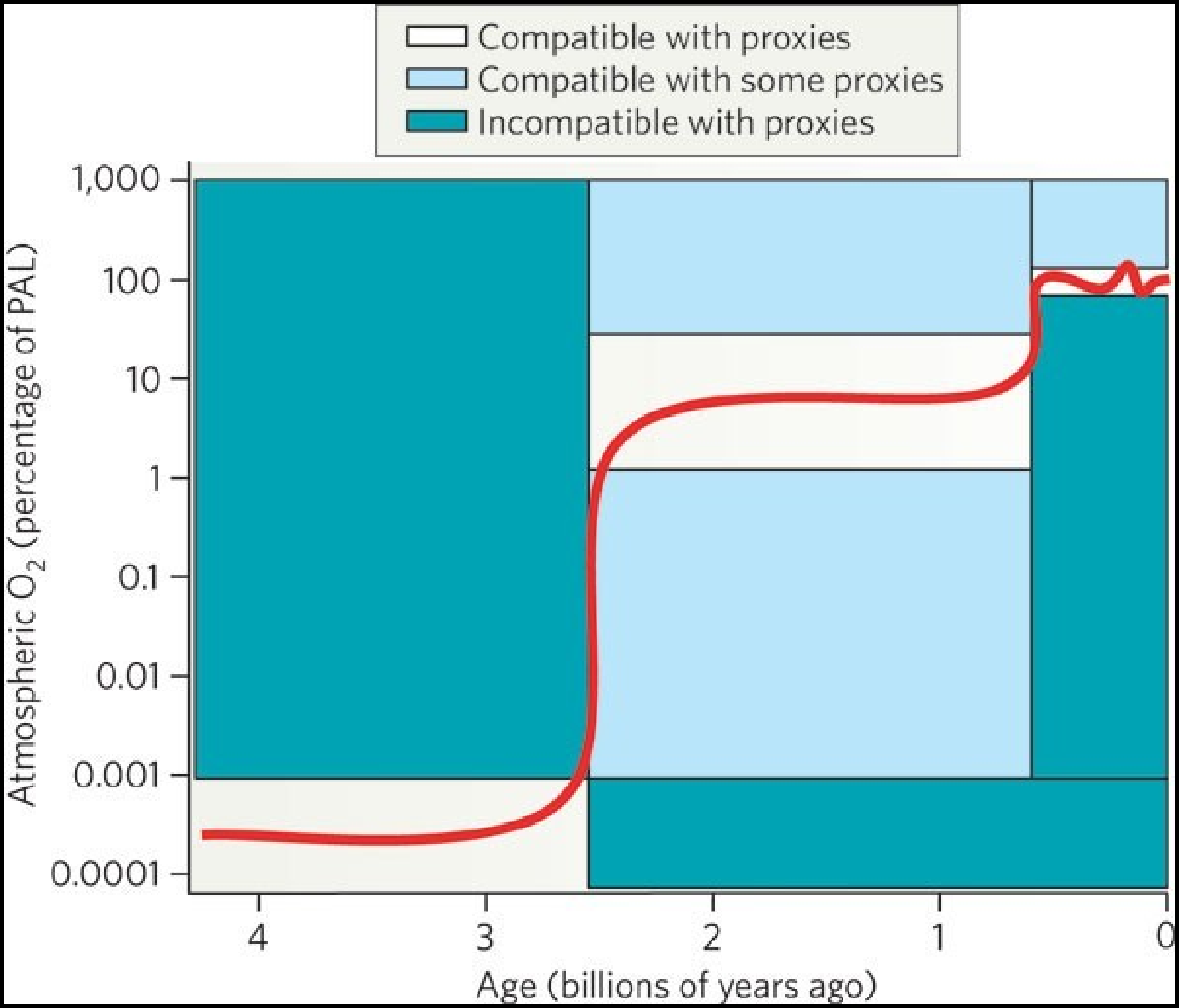




Trichodesmium

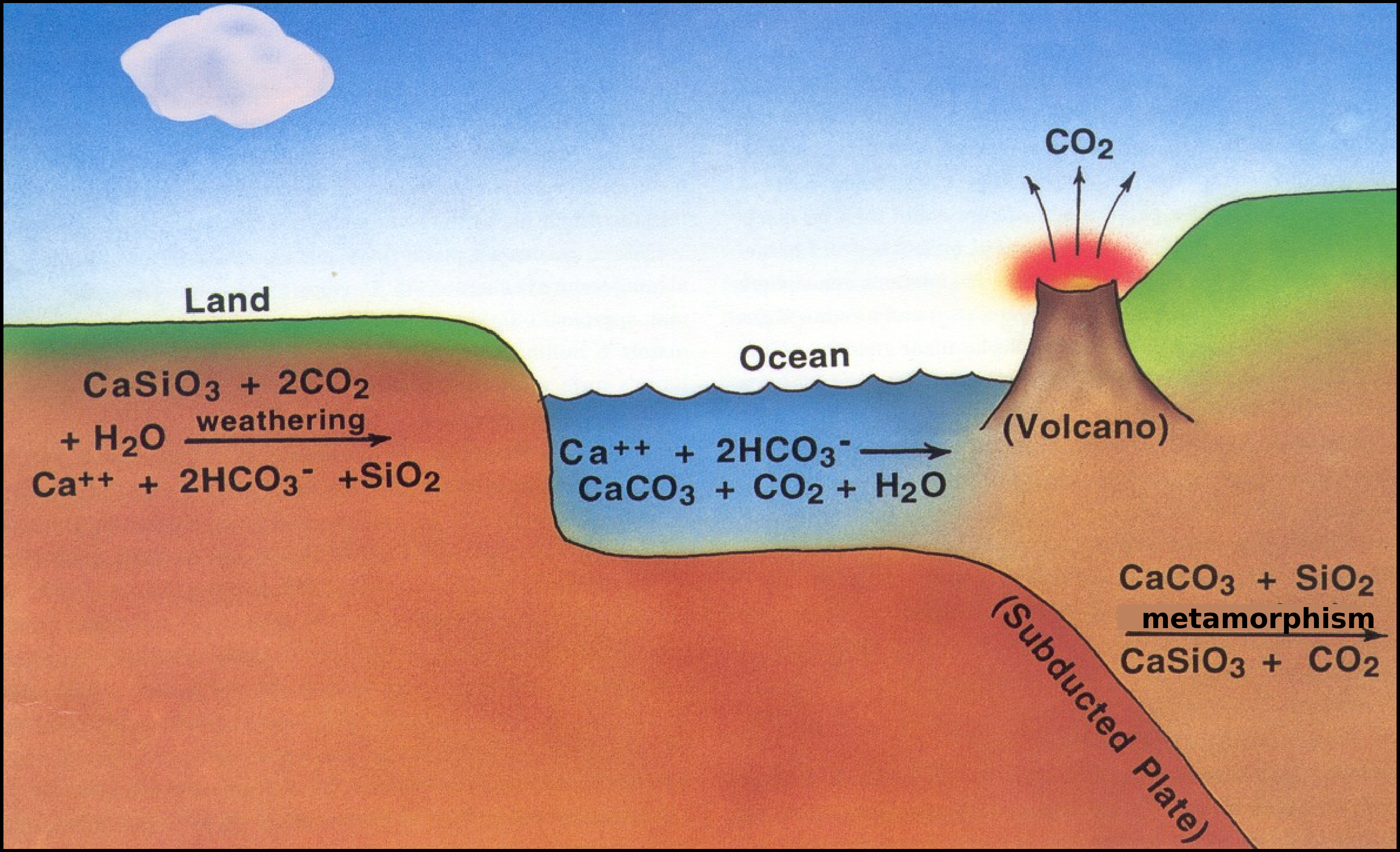
Rise of Atmospheric Oxygen

- Loss of methane greenhouse
- Ecological catastrophe
- Development of a shielding ozone layer



Kump, L.R. (2008) The rise of atmospheric oxygen. *Nature* 451: 277-278.

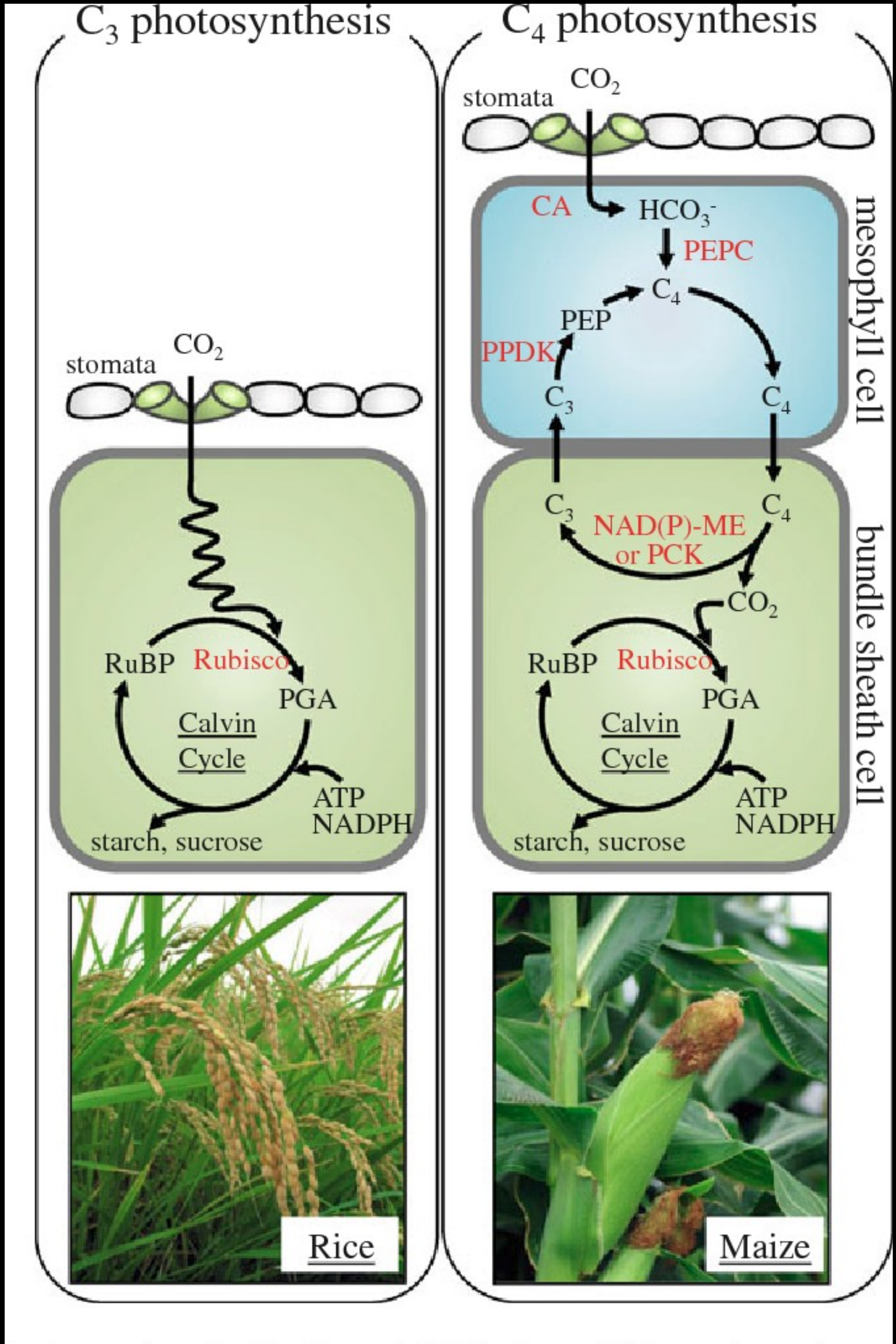
How has Earth managed to remain habitable over its entire history?



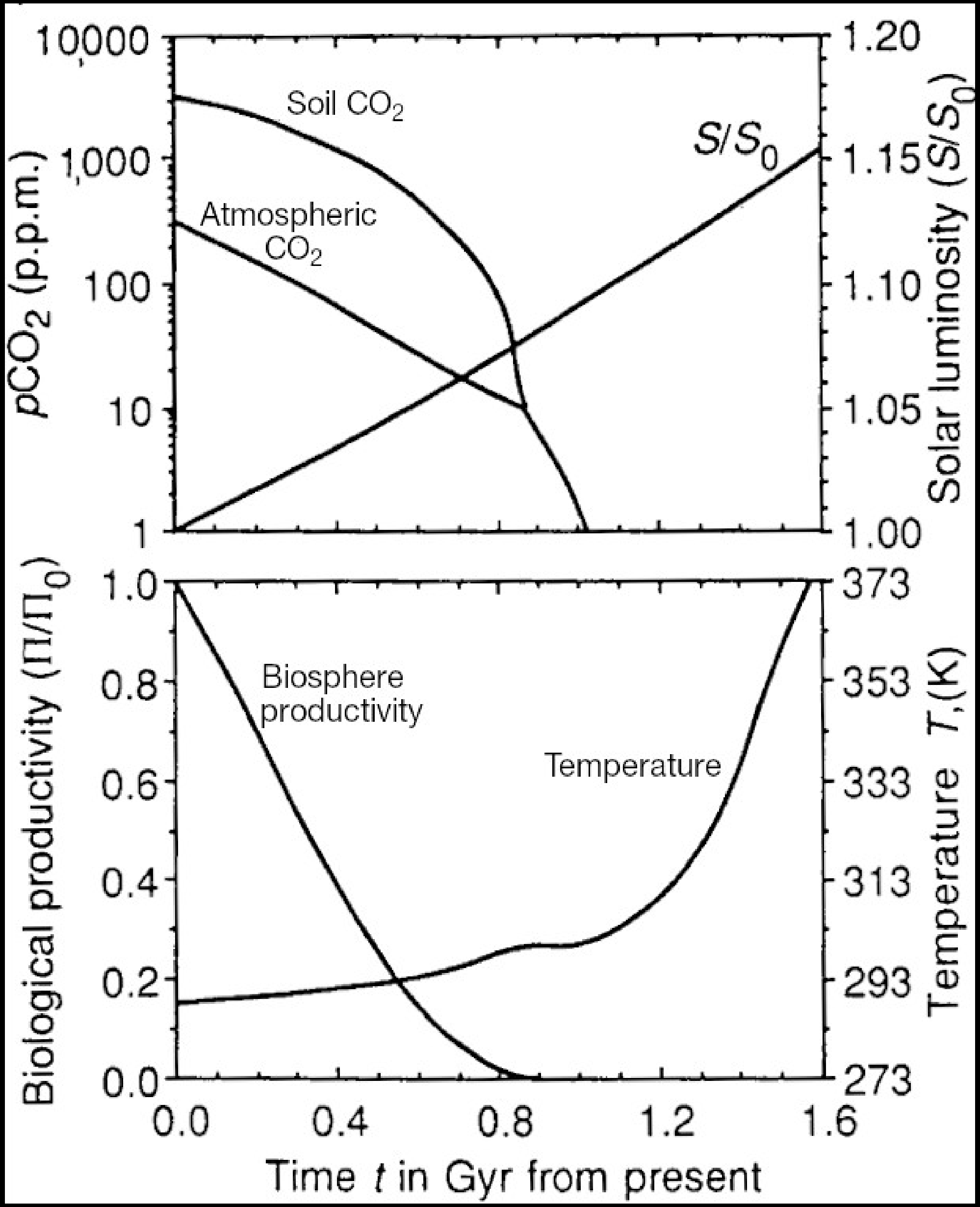
Walker, J.C.G., Hays, P.B., & Kasting, J.F. (1981) A negative feedback mechanism for the long-term stabilization of Earth's surface temperature, *Journal of Geophysical Research* 86: 9776–9782.

The carbonate-silicate cycle also places limits on the future habitability of Earth

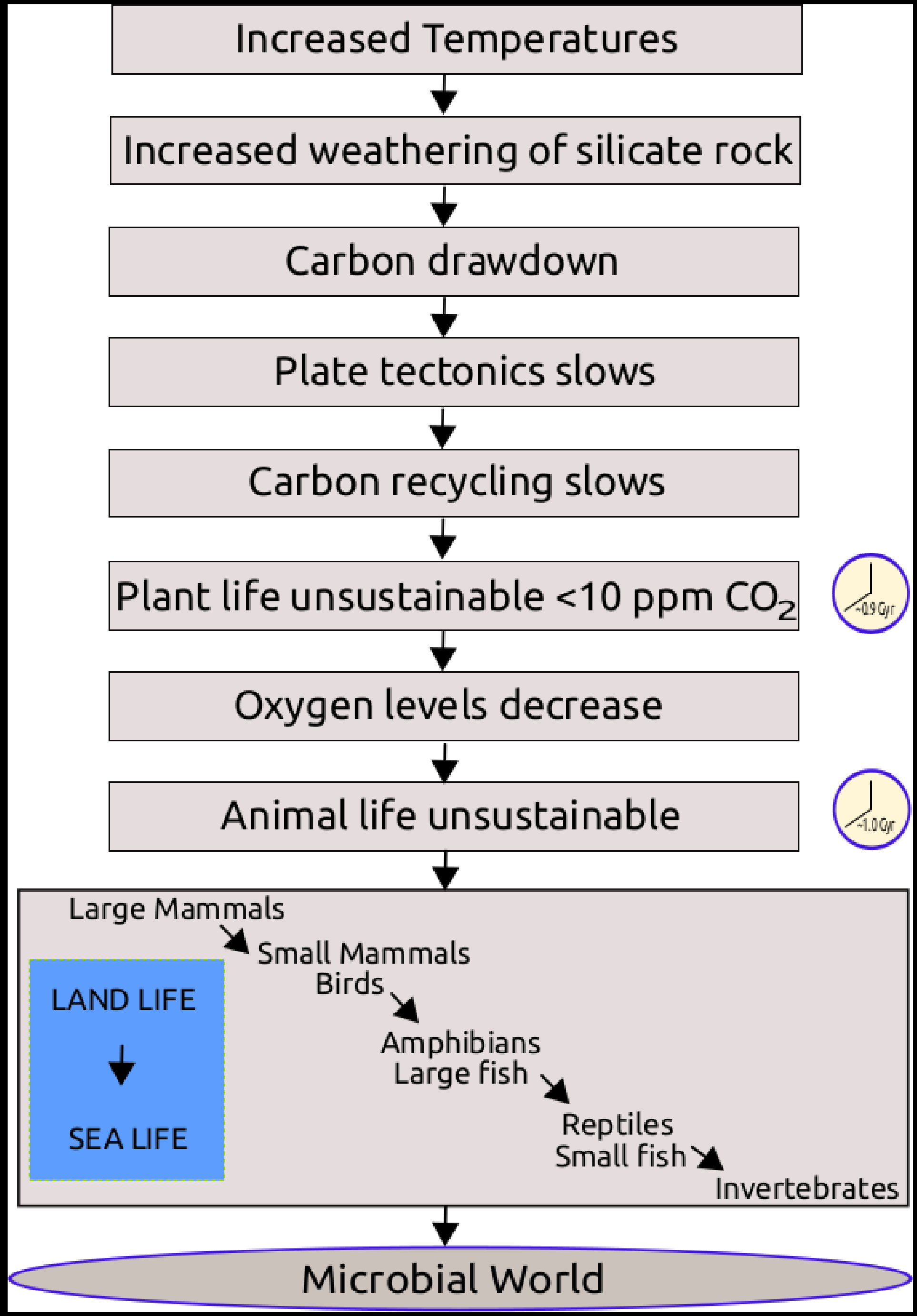
C3 Critical level
150 ppm CO_2



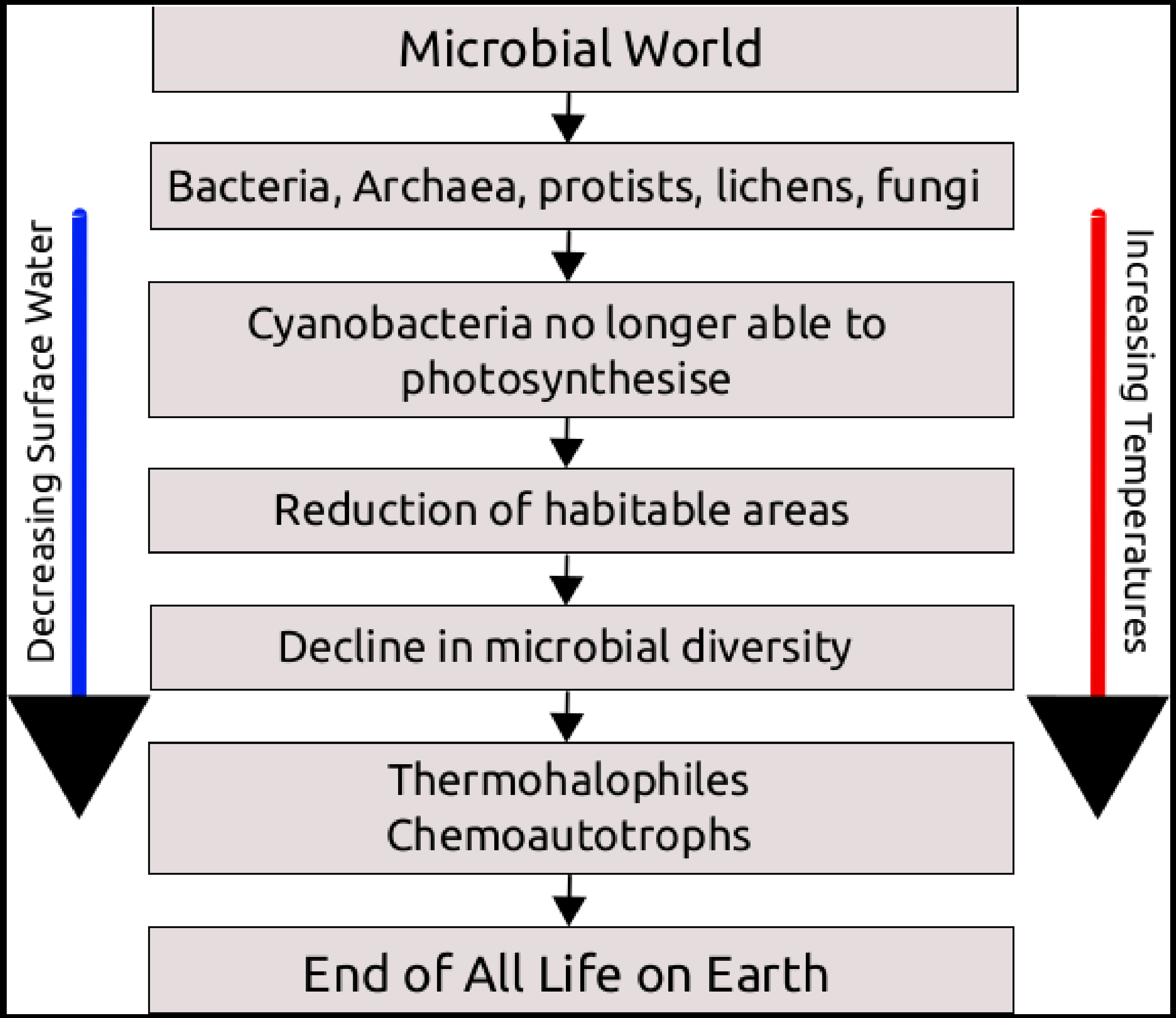
C4 Critical level
10 ppm CO_2



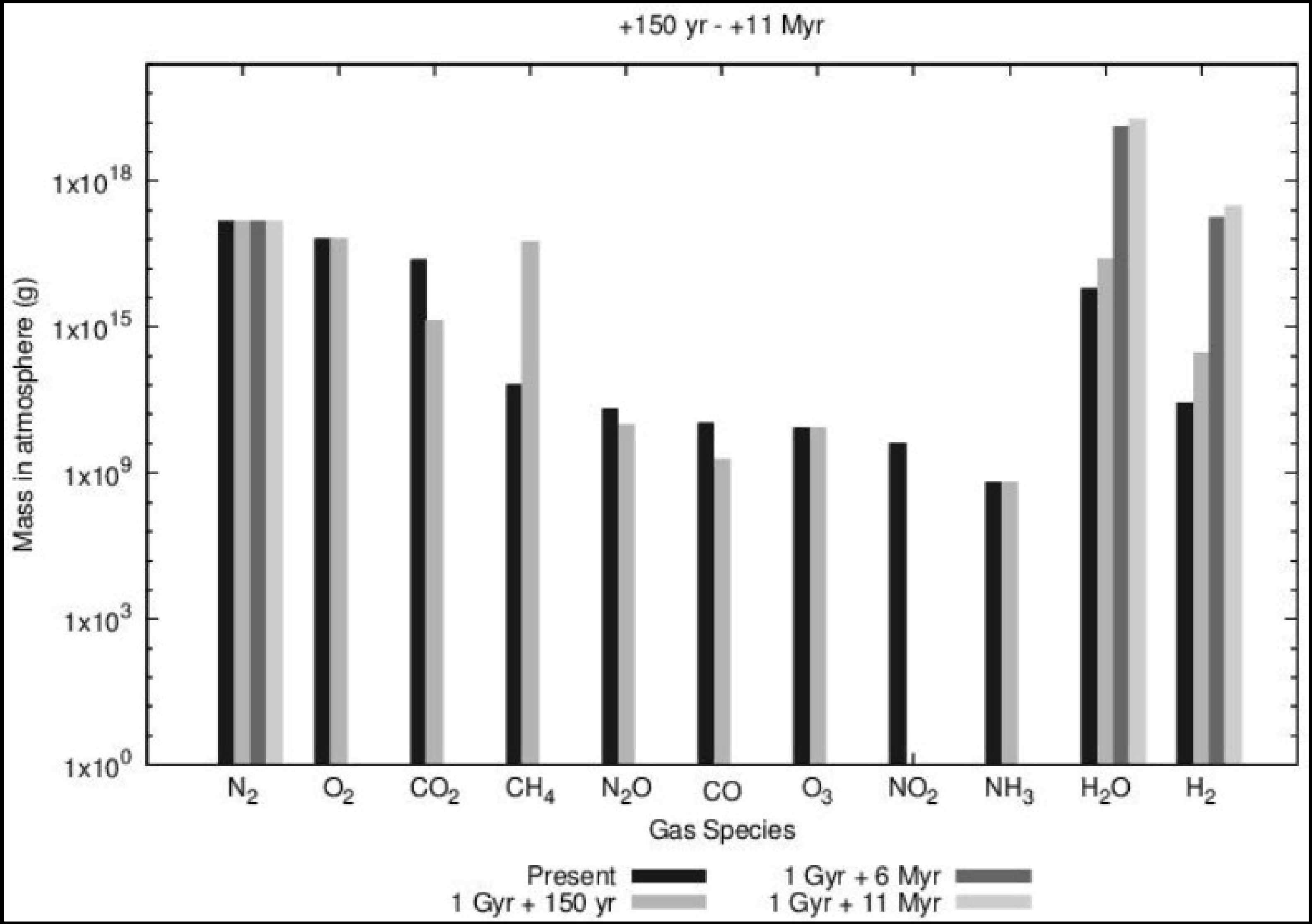
Caldeira, K., & Kasting, J.F. (1992) The life span of the biosphere revisited. *Nature* 360: 721-723.



Increased Temperatures
Increased weathering of silicate rock
Carbon drawdown
Plate tectonics slows
Carbon recycling slows
Plant life unsustainable <10 ppm CO_2
~0.9 Gyr
Oxygen levels decrease
Animal life unsustainable
~1.0 Gyr
Large Mammals
Small Mammals
Birds
Amphibians
Large fish
Reptiles
Small fish
Invertebrates
LAND LIFE
SEA LIFE
Microbial World

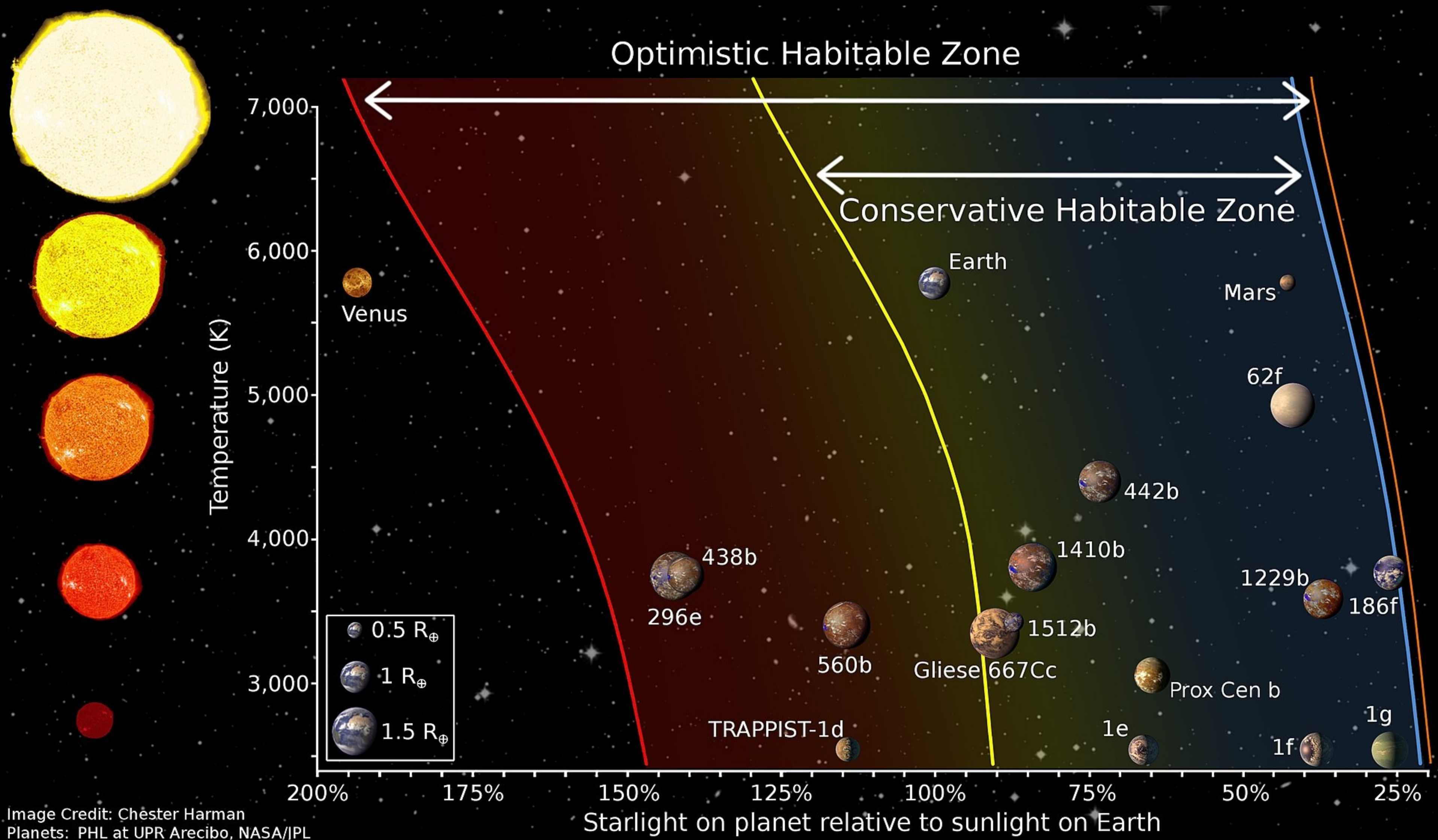


O'Malley-James, J.T., Greaves, J.S., Raven, J.A., & Cockell, C.S. (2013) Swansong biospheres: refuges for life and novel microbial biospheres on terrestrial planets near the end of their habitable lifetimes. *International Journal of Astrobiology* 12: 99-112.



O'Malley-James, J.T., Cockell, C.S., Greaves, J.S., & Raven, J.A. (2014) Swansong biospheres II: the final signs of life on terrestrial planets near the end of their habitable lifetimes. *International Journal of Astrobiology* 13: 229-243.

These limits to habitability from Earth also help to understand the habitability of extrasolar planets.



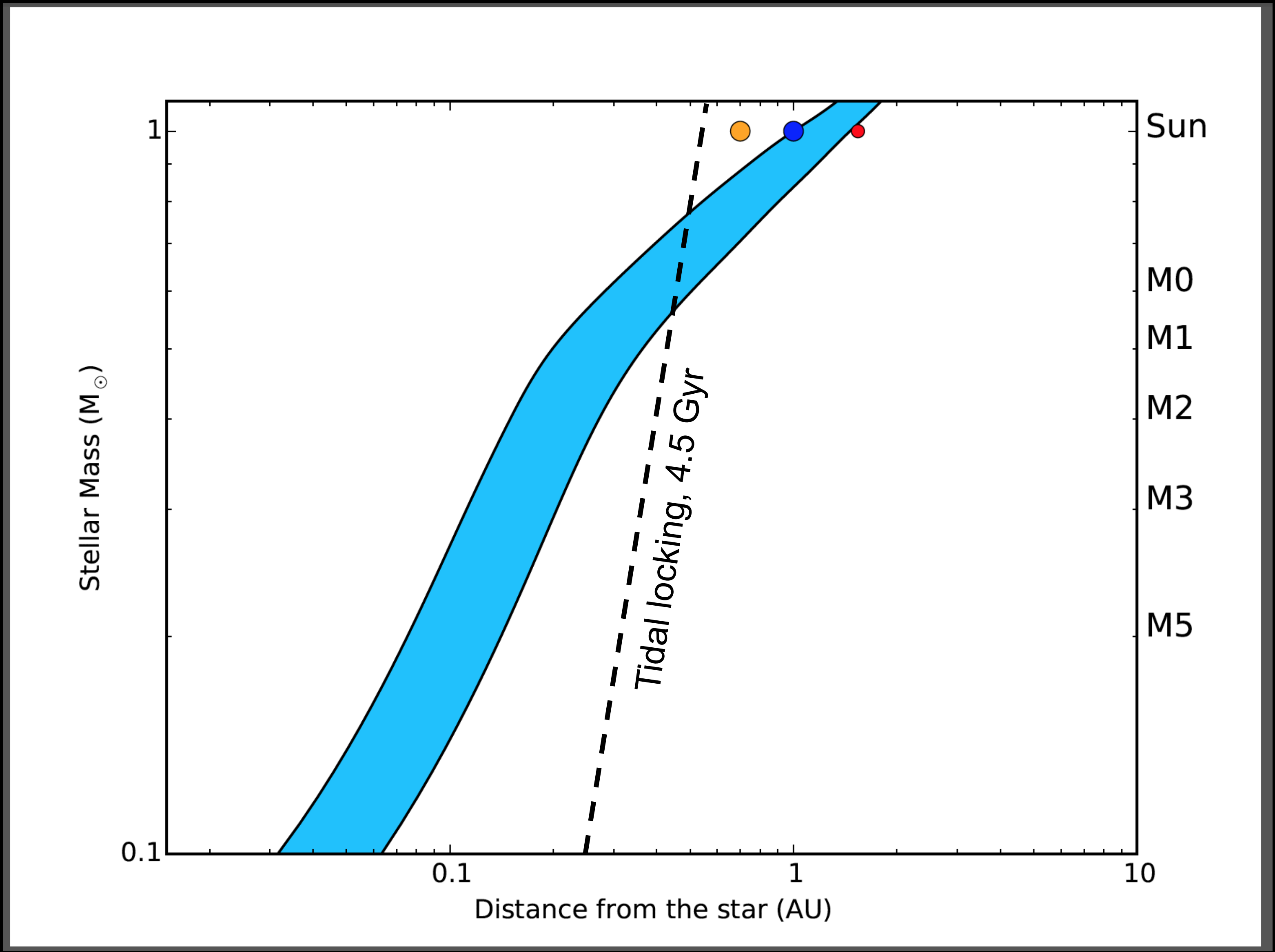
Kopparapu, R.K., Ramirez, R., Kasting, J.F., et al. (2013) Habitable zones around main sequence stars: New estimates. *The Astrophysical Journal* 765: 131.

The carbonate silicate cycle also defines what we call a Habitable Zone for planets around other stars:

A rocky planet with above-freezing temperatures

An atmosphere with N_2, H_2O, and CO_2

A mechanism for recycling volatiles (e.g. plate tectonics)



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Habitability problems have plagued M star systems:

Synchronous Rotation could cause the night side to freeze-out… (Dole 1964)

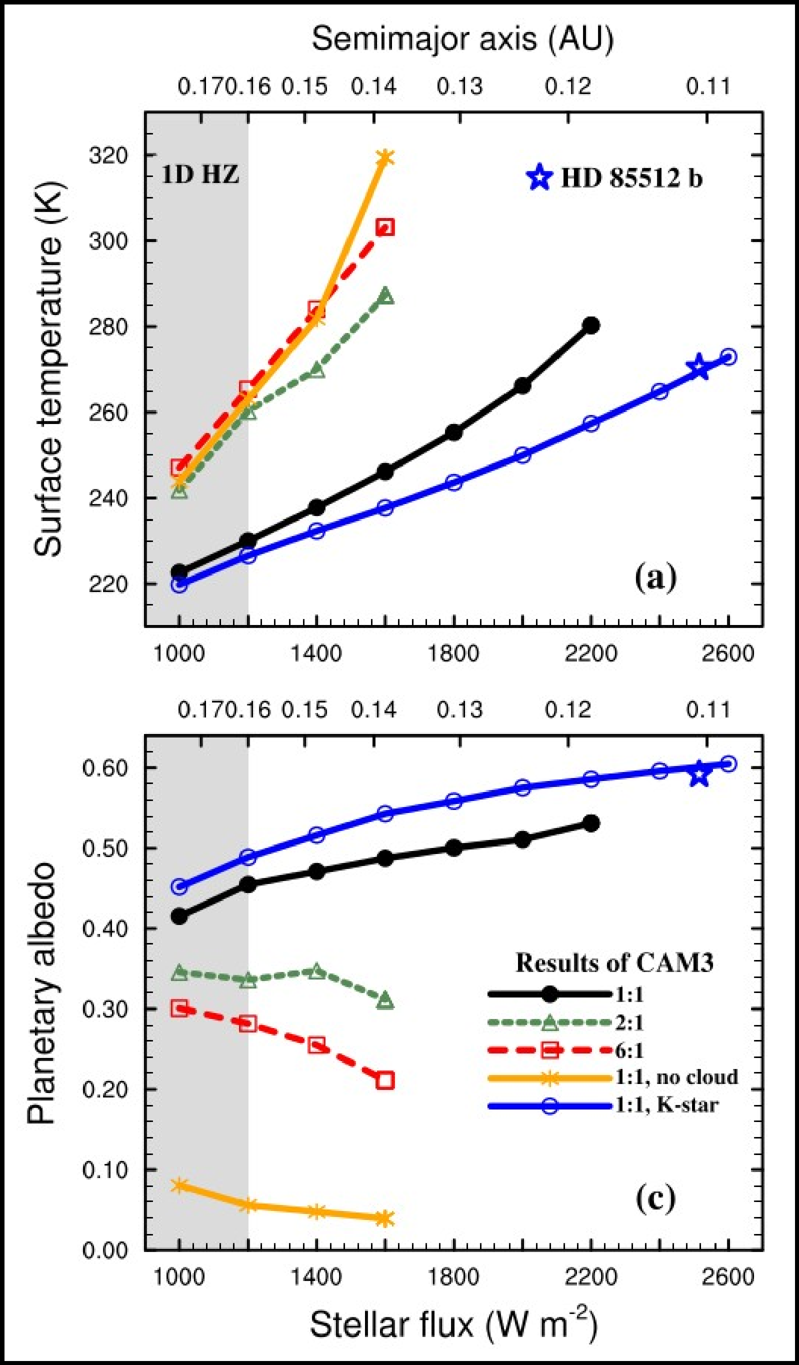
…but energy transport by atmospheric dynamics seems sufficient to prevent collapse (Joshi et al. 1997; Joshi 2003)

Water Loss during the pre-mail sequence phase could render a planet uninhabitable… (Ramirez & Kaltenegger 2014; Luger & Barnes 2015; Tian & Ida 2015)

…unless a planet begins with a large water inventory or acquires water later

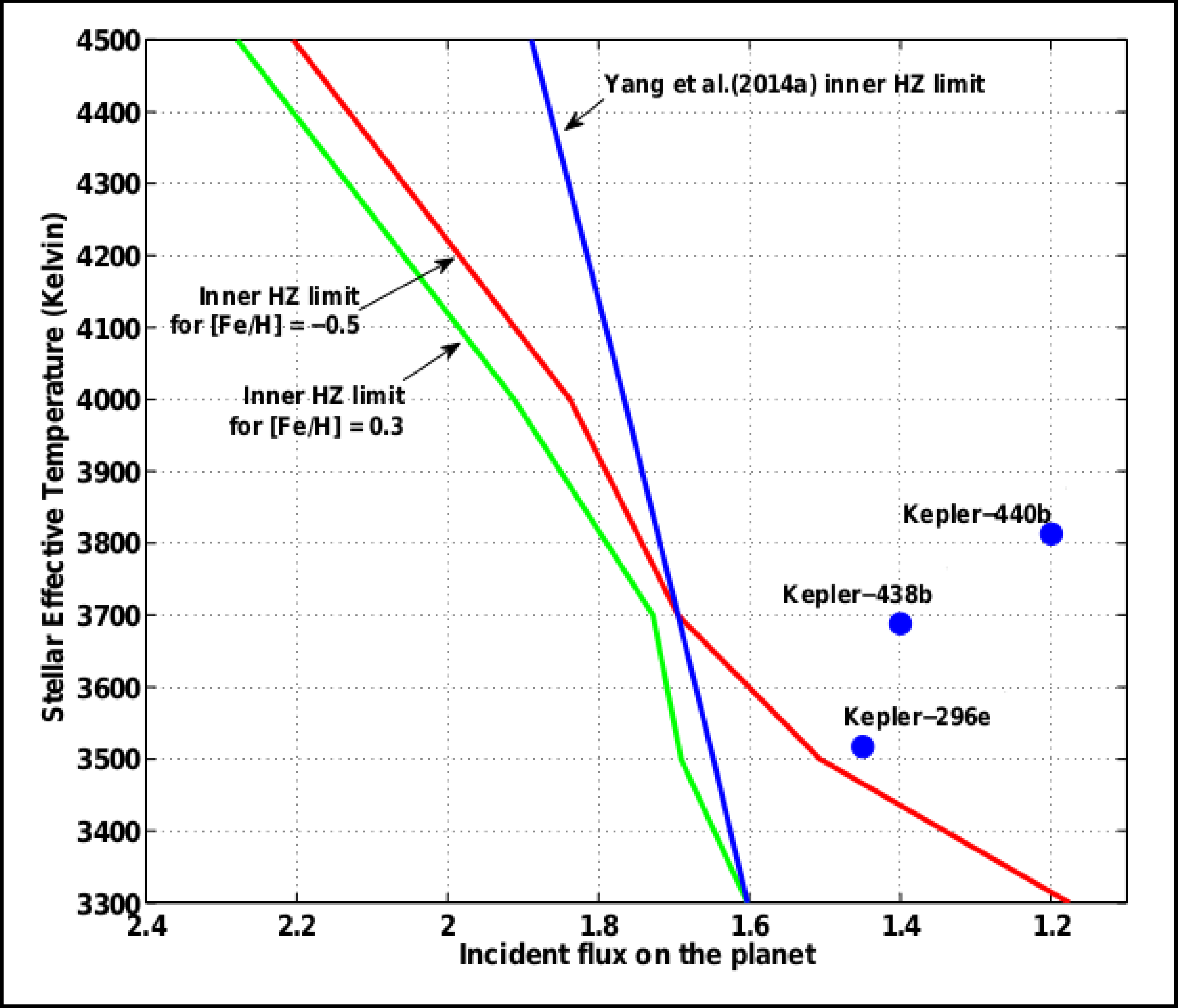
Solar Flares could cause damage both the atmosphere or any extant biology…

…unless a planet retains a thick atmosphere or protective ozone shield (Segura et al. 2003; Segura et al. 2010)



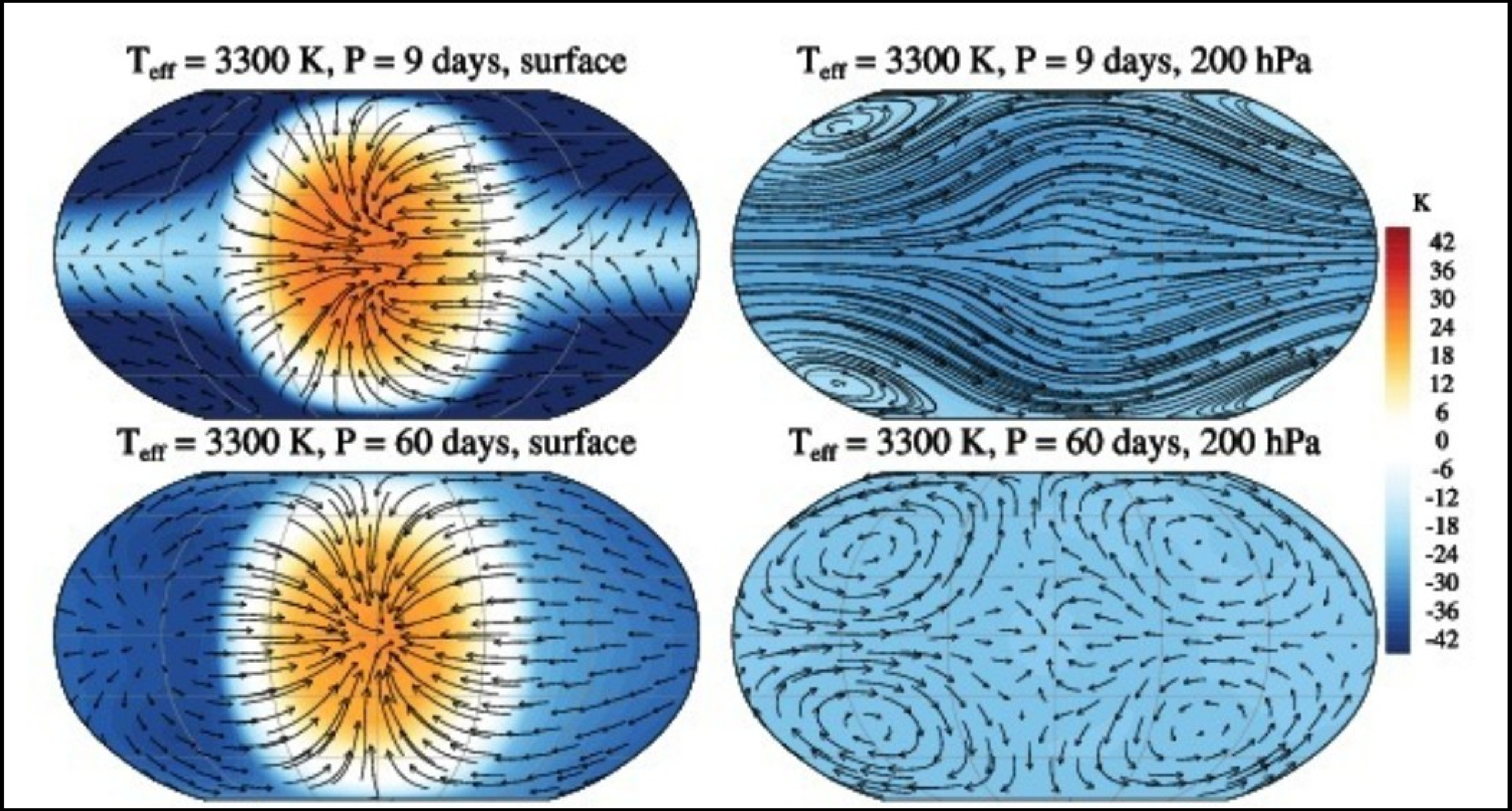
Planets in synchronous rotation can potentially remain stable longer than rapidly rotating planets near the inner edge of the HZ

Yang, J., Cowan, N.B. & Abbot, D.S. (2013) Stabilizing cloud feedback dramatically expands the habitable zone of tidally locked planets, *The Astrophysical Journal* 771: L45.



…but this effect is reduced when we account for self-consistent orbital periods

Kopparapu, R.K., Wolf, E.T., Haqq-Misra, J., et al. (2016) The inner edge of the habitable zone for synchronously rotating planets around low-mass stars using general circulation models, *The Astrophysical Journal* 819: 84.



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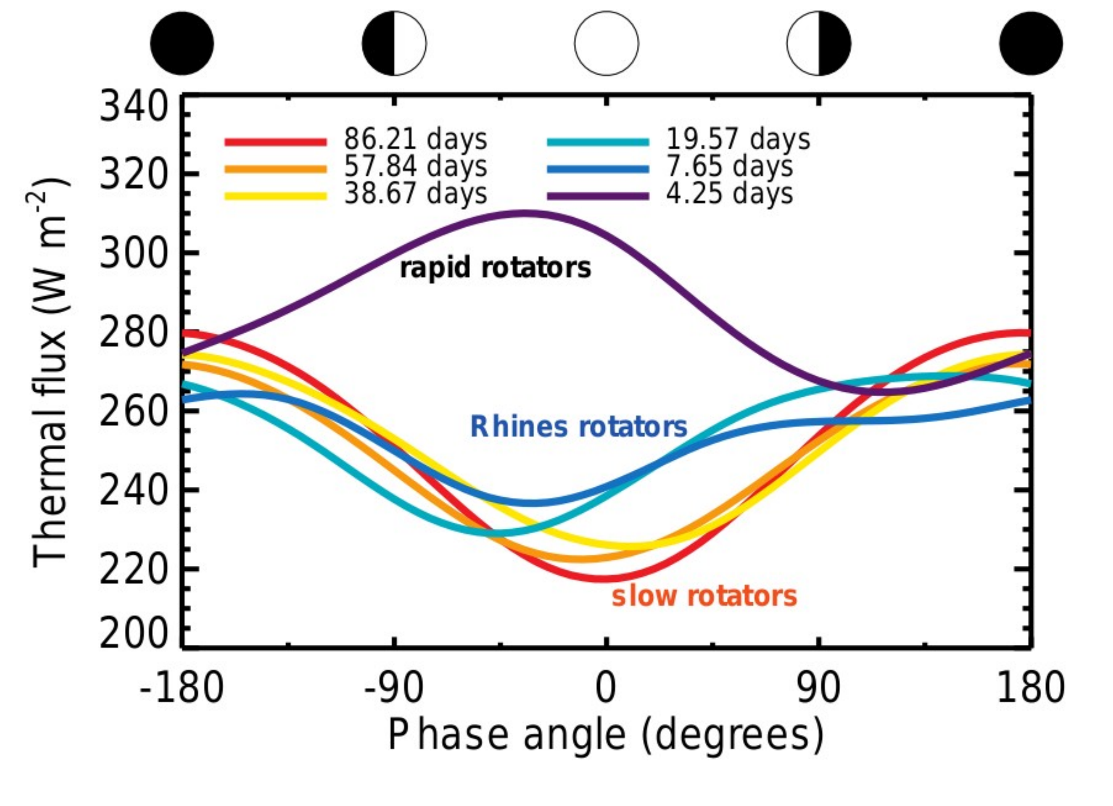
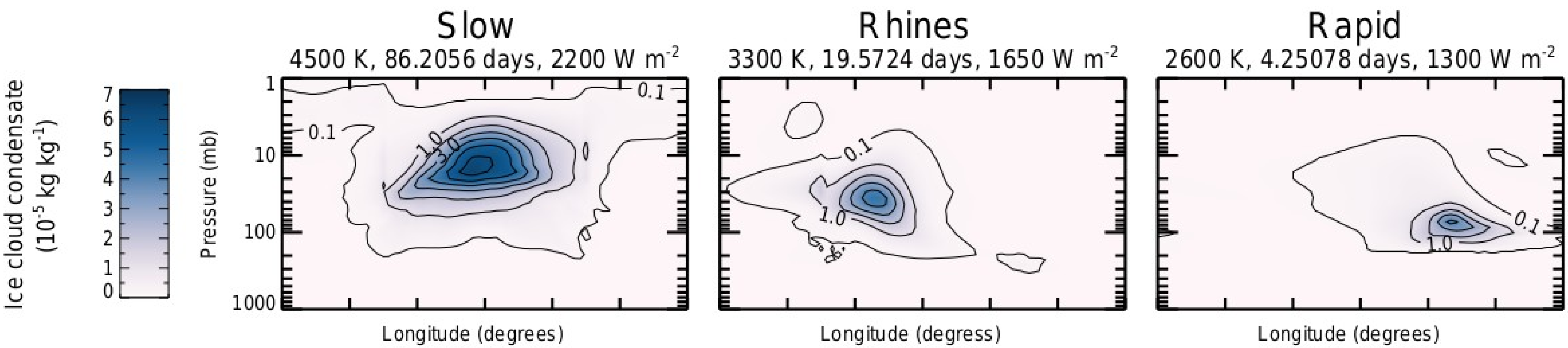


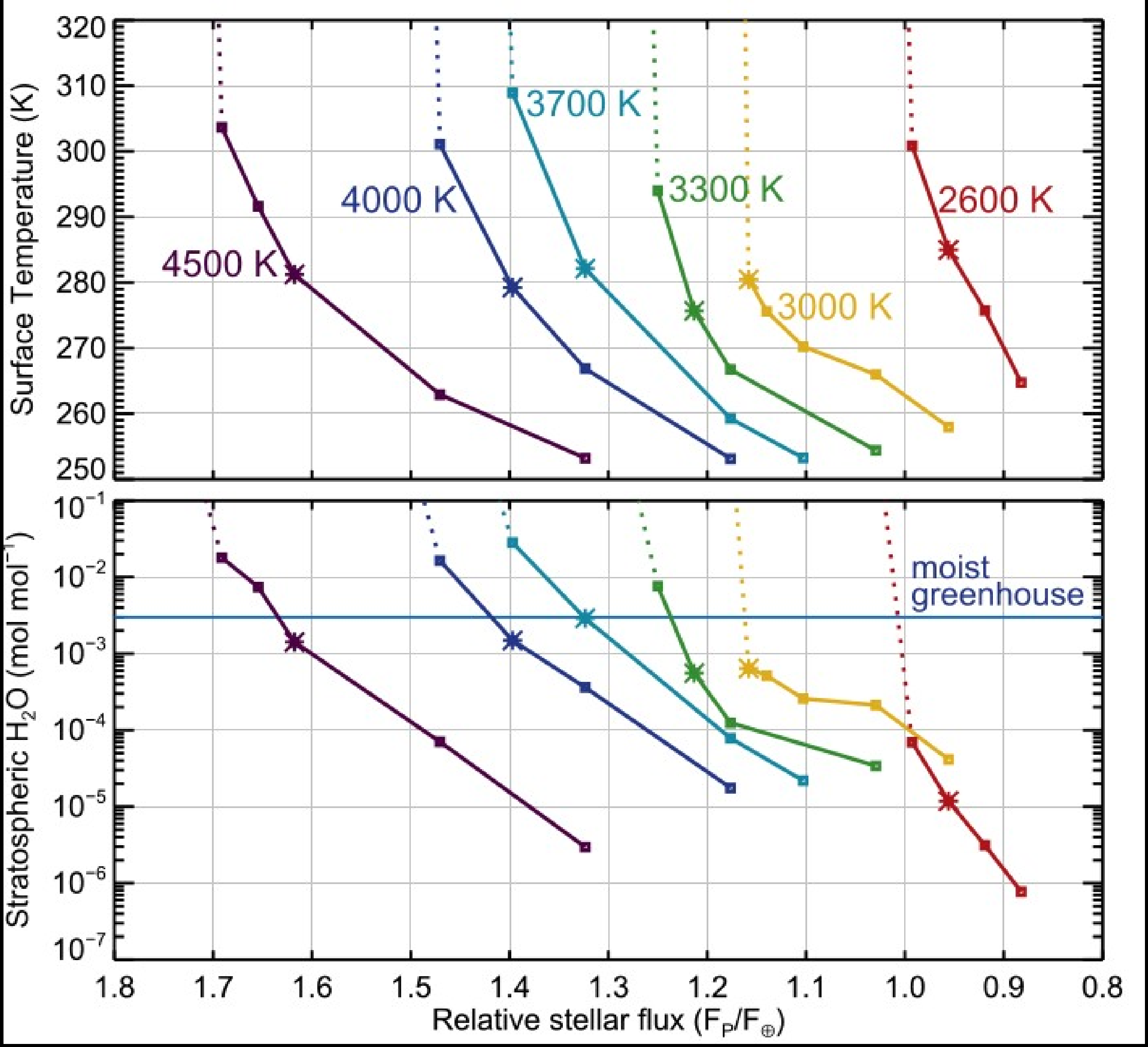


Haqq-Misra, J. Wolf, E.T., Kopparapu, R.K., et al. (2017) Demarcating circulation regimes of synchronously rotating terrestrial planets within the habitable zone, *The Astrophysical Journal* 852: 67.

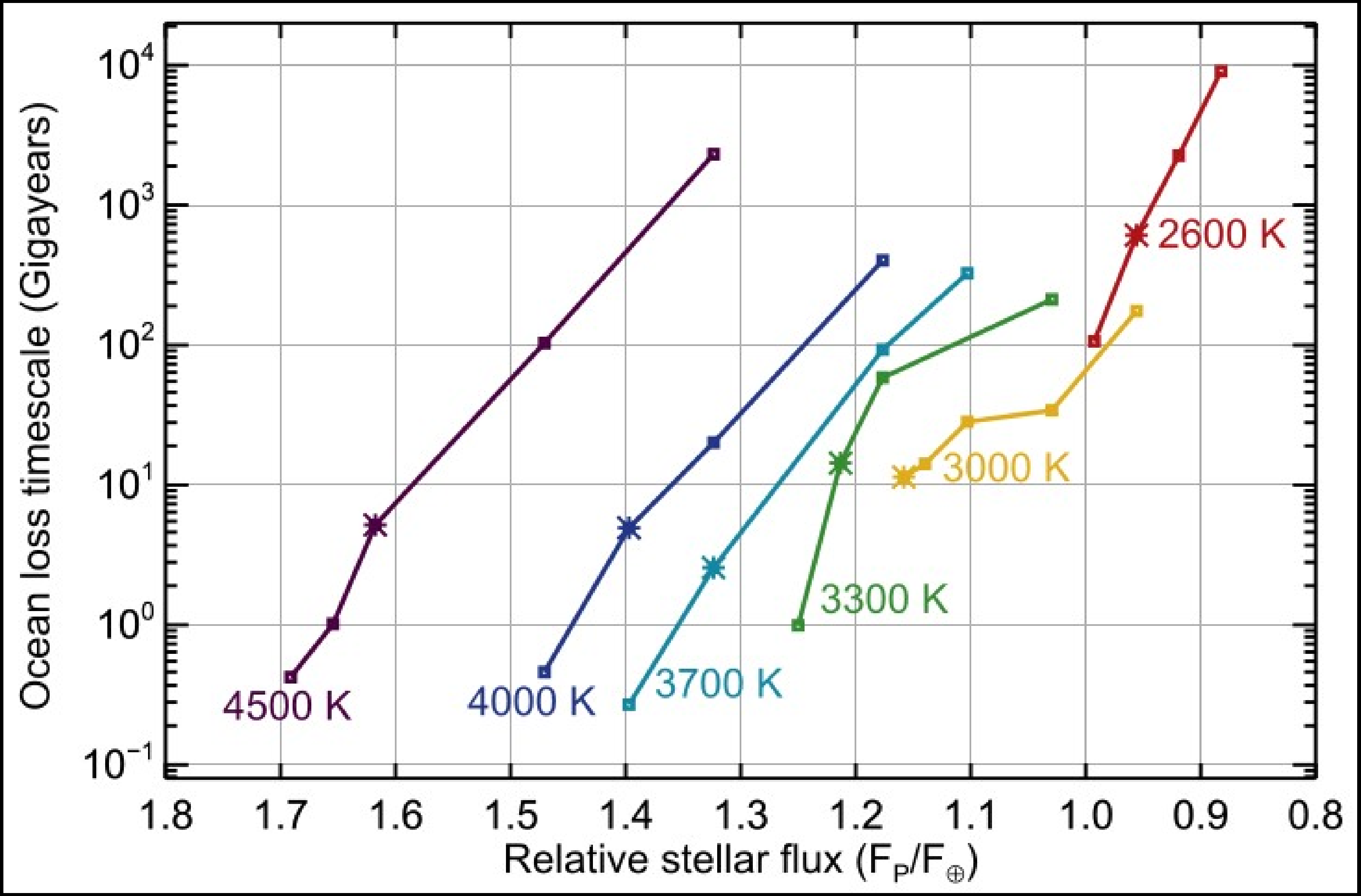
Water loss at the inner edge of the HZ:

Runaway Greenhouse - warming leads to increased evaporation of the oceans and more greenhouse warming from water vapor

Moist Greenhouse - water vapor saturates the troposphere and is dissociated in the stratosphere, where it is gradually lost to space



Kopparapu, R.K., Wolf, E.T., Arney, G., Batalha, N.E., Haqq-Misra, J., Grimm, S.L., & Heng, K. (2017) Habitable moist atmospheres on terrestrial planets near the inner edge of the habitable zone around M dwarfs. *The Astrophysical Journal* 845: 5.



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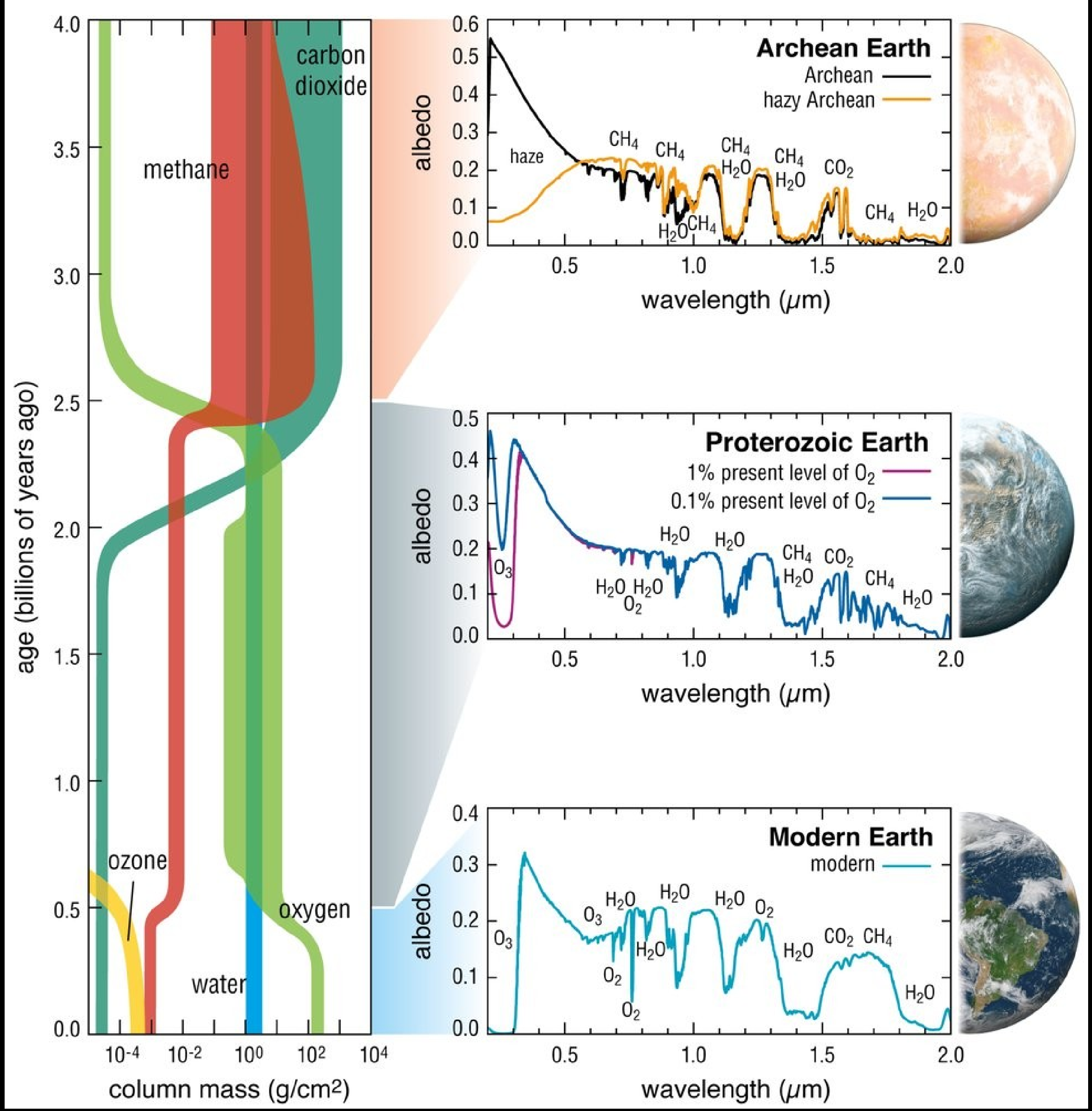
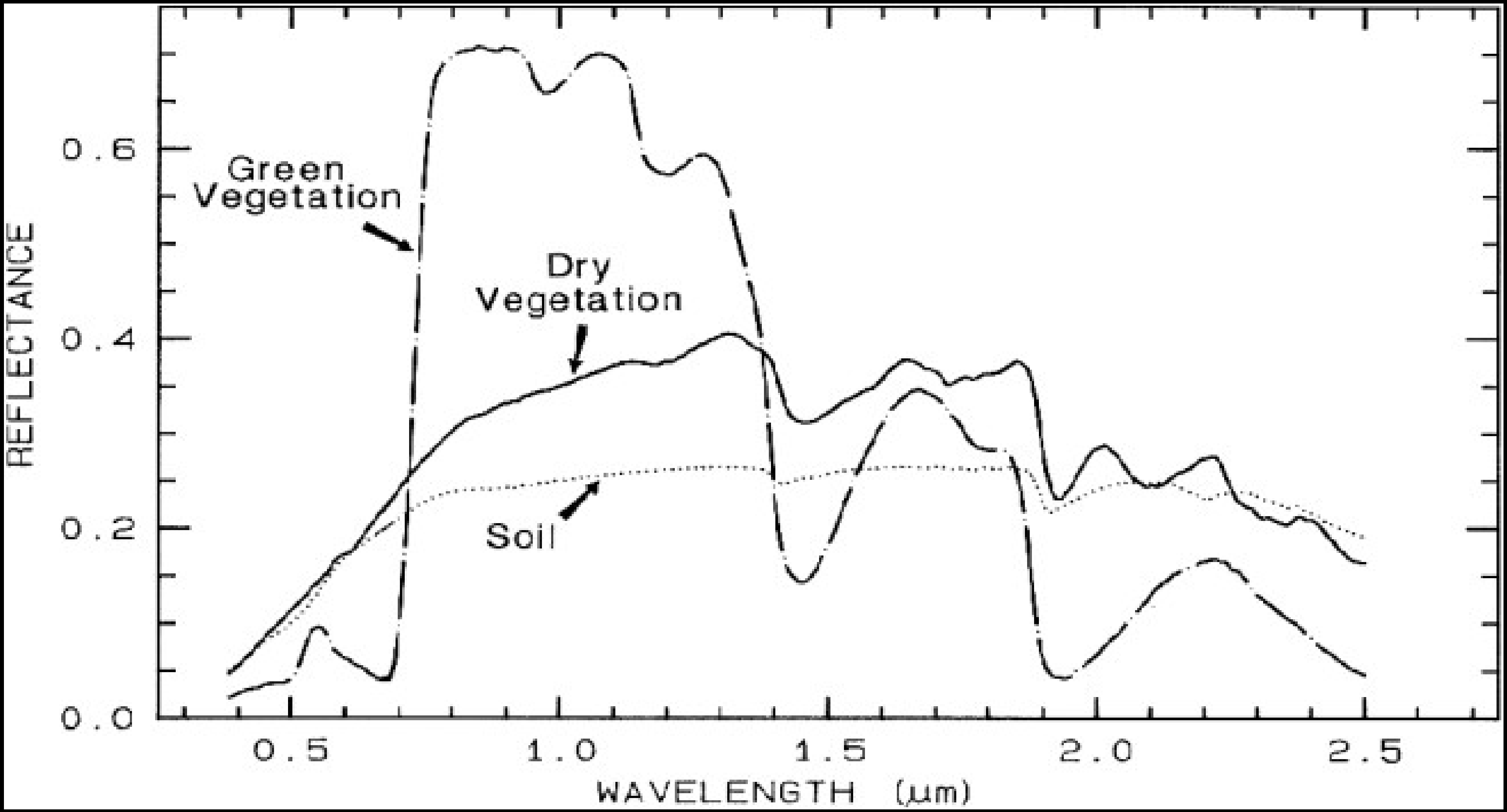
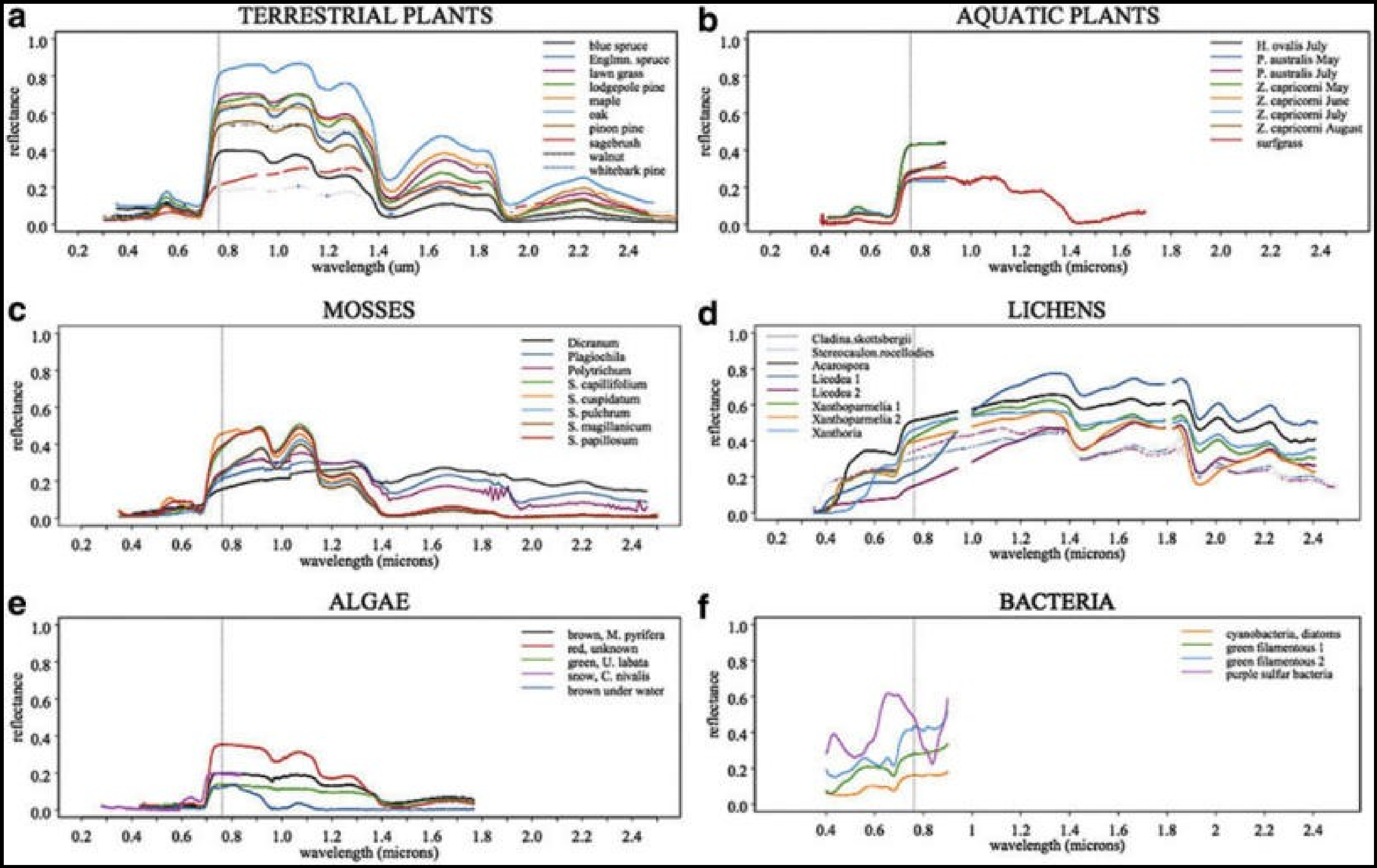
How can we search for evidence of biospheres on other planets?



age (billions of years ago)
column mass (g/cm2)
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
carbon dioxide
methane
ozone
oxygen
water
Archean Earth
Archean
hazy Archean
haze
CH_4
H_2O
CO_2
Proterozoic Earth
1% present level of O_2
0.1% present level of O_2
O_3
O_2
Modern Earth
modern
albedo
wavelength (μm)

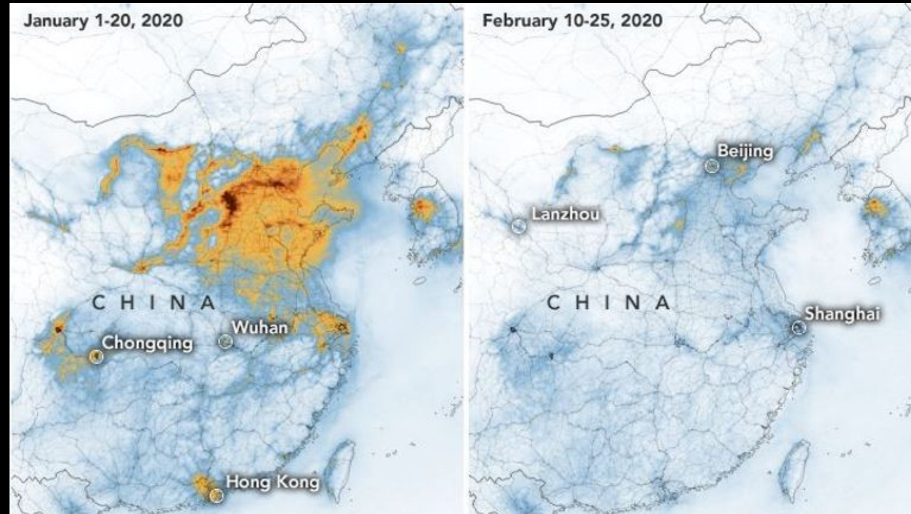


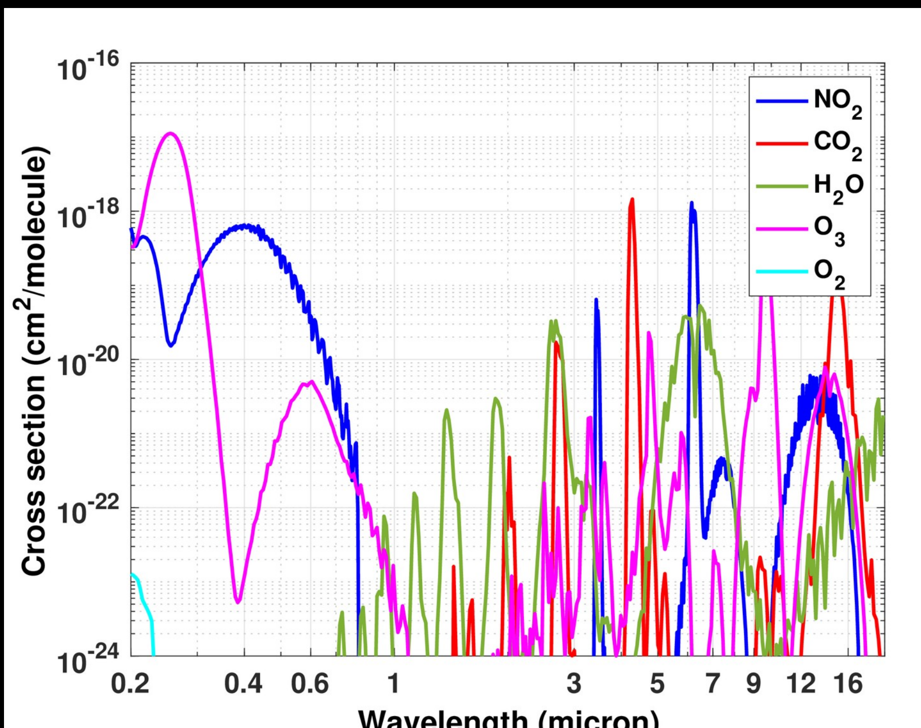
Arnold, L. (2008) Earthshine Observation of Vegetation and Implication for Life Detection on Other Planets. *Space Science Reviews* 135: 323-333.

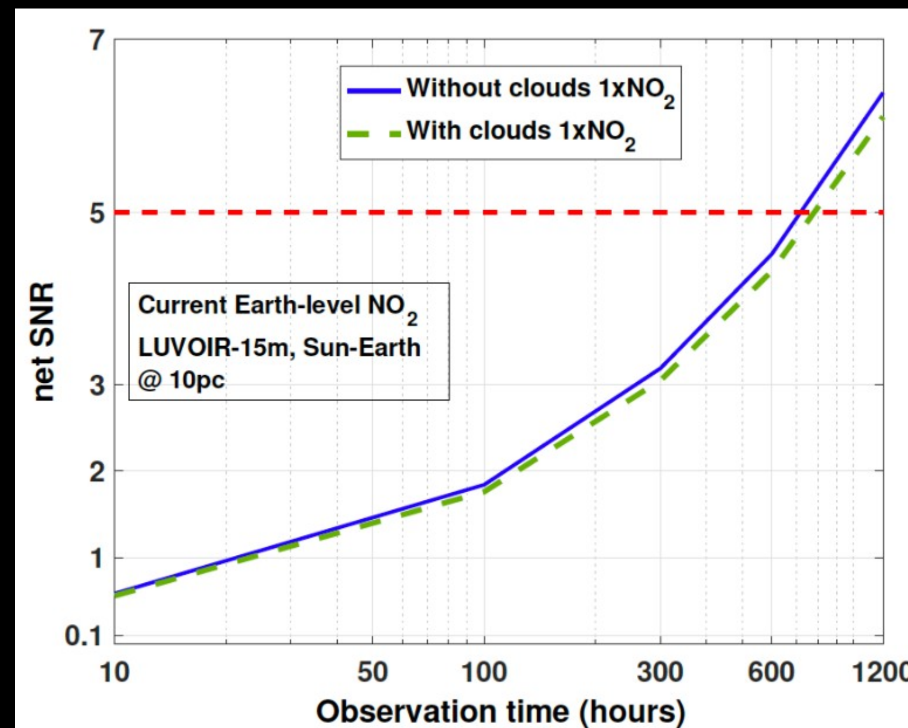


Schwieterman, E. W., Kiang, N. Y., Parenteau, M. N., Harman, C. E., DasSarma, S., et al. (2018) Exoplanet biosignatures: a review of remotely detectable signs of life. *Astrobiology* 18: 663-708.

NO_2 as a Technosignature

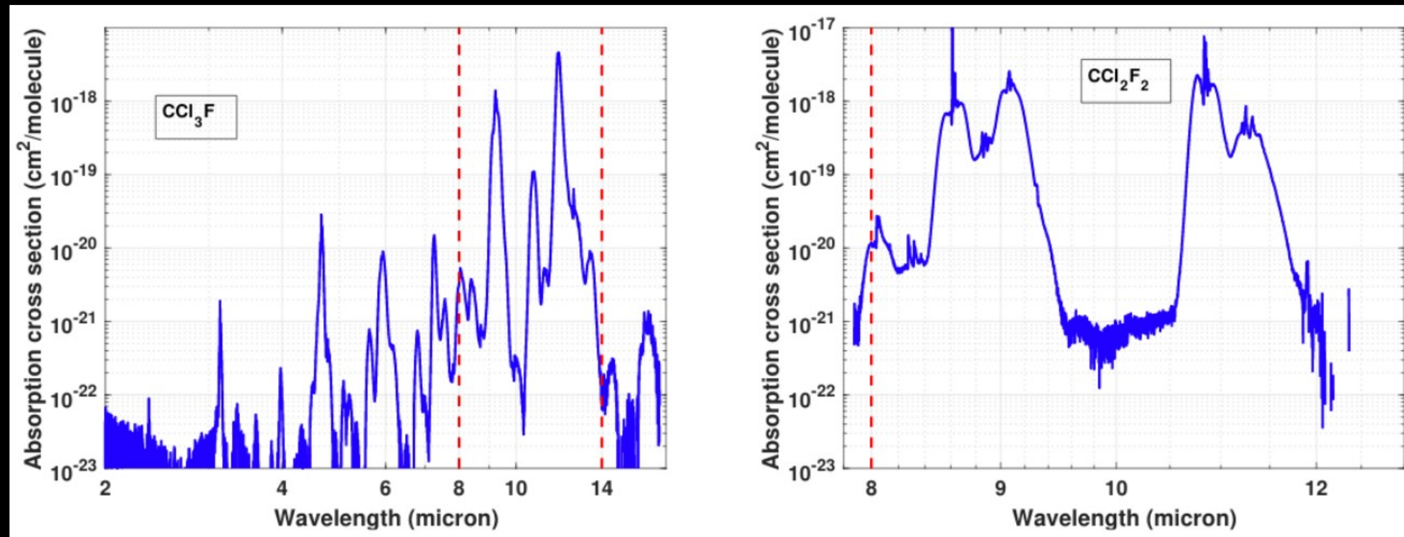


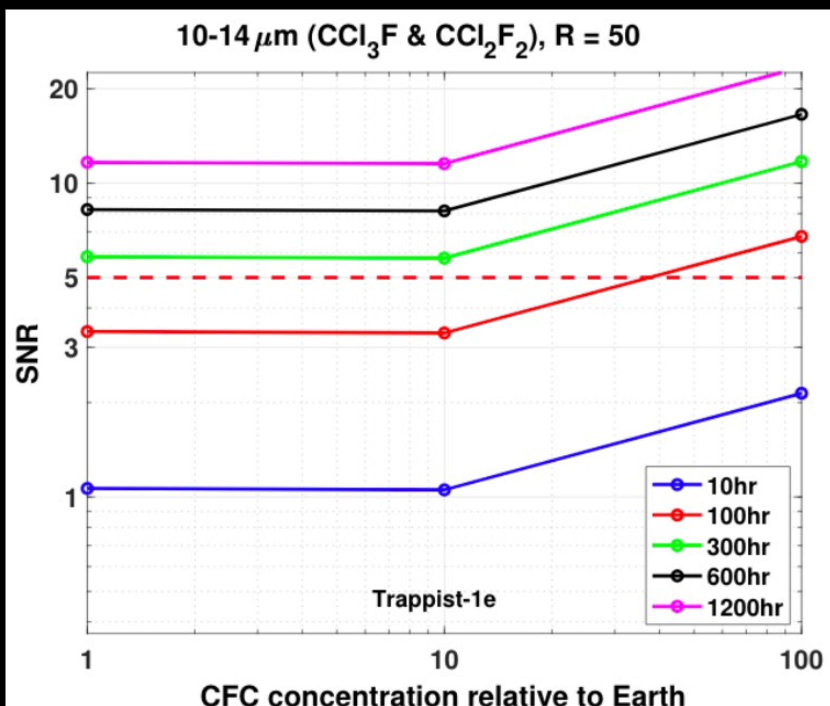




Kopparapu, R.K., Arney, G., Haqq-Misra, J., Lustig-Yaeger, J. & Villanueva, G. (in review) Nitrogen dioxide pollution as a signature of extraterrestrial technology. *The Astrophysical Journal*

CFCs as a Technosignature





CFCs on TRAPPIST-1e could be detectable with less than ~300 hr of JWST time at present Earth levels

This is less time than needed for some biosignature gases!

Kopparapu, R.K., Arney, G., Haqq-Misra, J., Lustig-Yaeger, J. & Villanueva, G. (in review) Nitrogen dioxide pollution as a signature of extraterrestrial technology. *The Astrophysical Journal*

Summary

Earth has remained continuously habitable for most of its history with the carbonate-silicate cycle providing a long-term thermostat for climate.

The carbonate-silicate cycle and runaway greenhouse define the limits of the habitable zone, which provide search constraints for exoplanet habitability.

Spectral biosignatures such as O_2/CH_4 or a vegetation red edge on a habitable planet could reveal an extraterrestrial photosynthetic biosphere.

Spectral technosignatures such as NO_2 or CFCs on a habitable planet could be evidence of an extraterrestrial technosphere

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