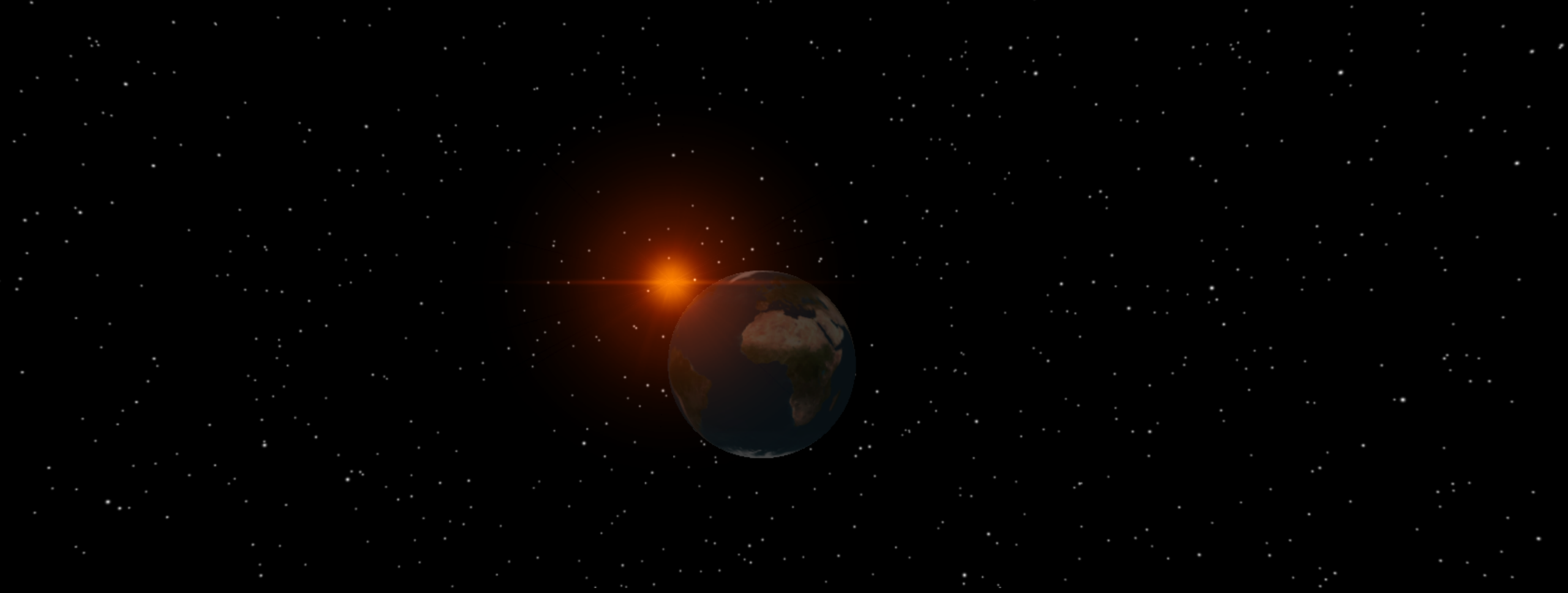

Life is Present but not Detectable: The Productivity of Oxygenic Photosynthesis around Cool M Dwarf Stars

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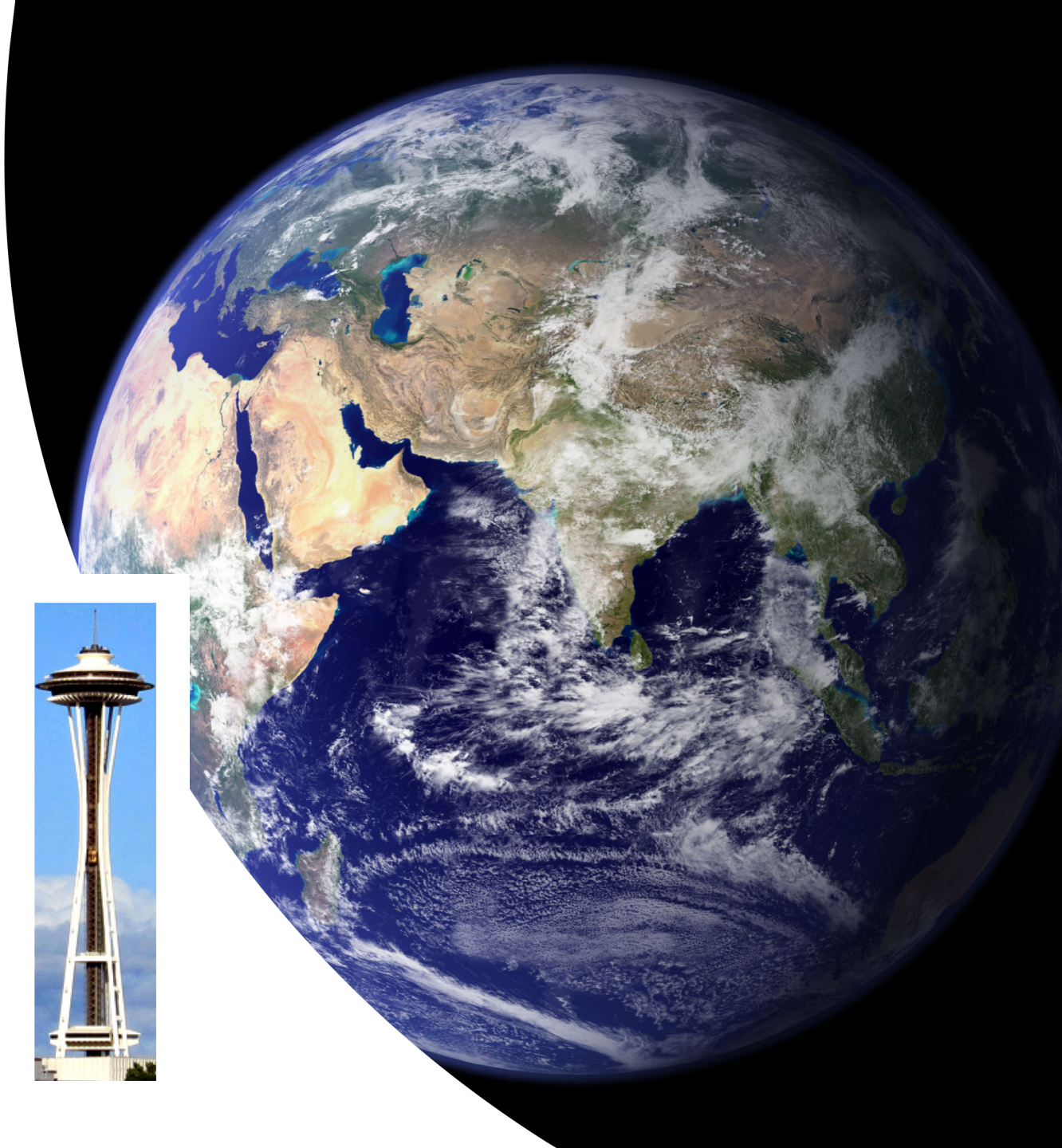
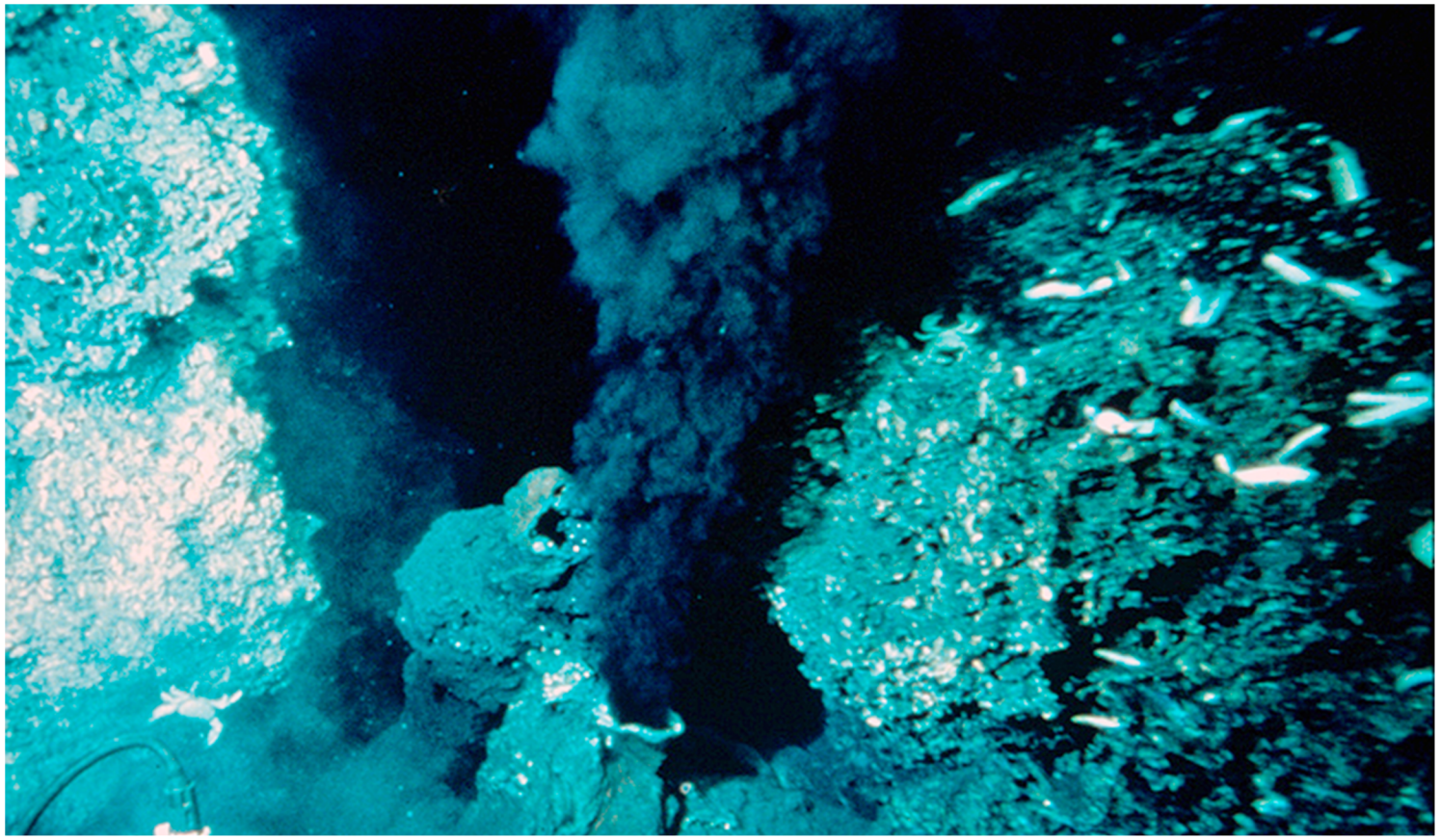
The Modern Earth

- Annual biomass productivity: ~10^{14} kg yr^{-1}
- Solar flux: ~1361 W m^{-2}
- Biomass production largely limited by P/N availability
- 10 million Space Needle masses!



Biomass Production

- 50% of production on land
- 50% in the oceans
- How will this differ around cooler stars?



Biospheres with only chemical energy could be less detectable

- Internal energy from Earth is only ~0.03% that of energy from the Sun
- Before oxygenic photosynthesis Earth's productivity may have been just 0.01% modern

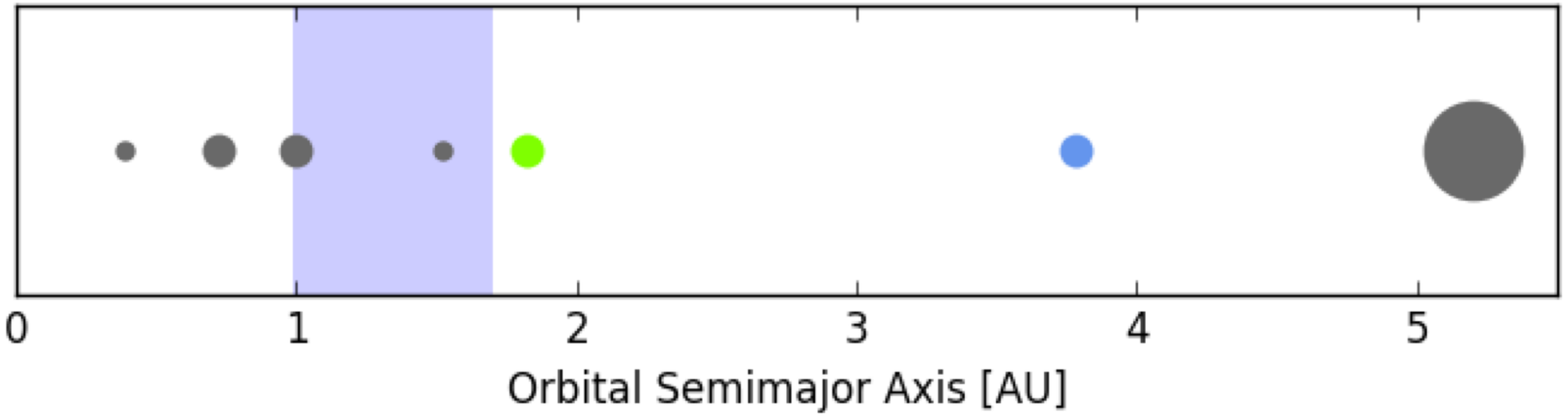
$CO_2 + 2H_2O + h\nu \rightarrow CH_2O + H_2O + O_2$

$\sim 10^{14}$ kg yr^{-1} total biomass production on the modern Earth

~7% photon use in oceans, ~31% on land (Field et al., 1998)

Oxygenic Photosynthesis

Could the Earth be growth limited by light?



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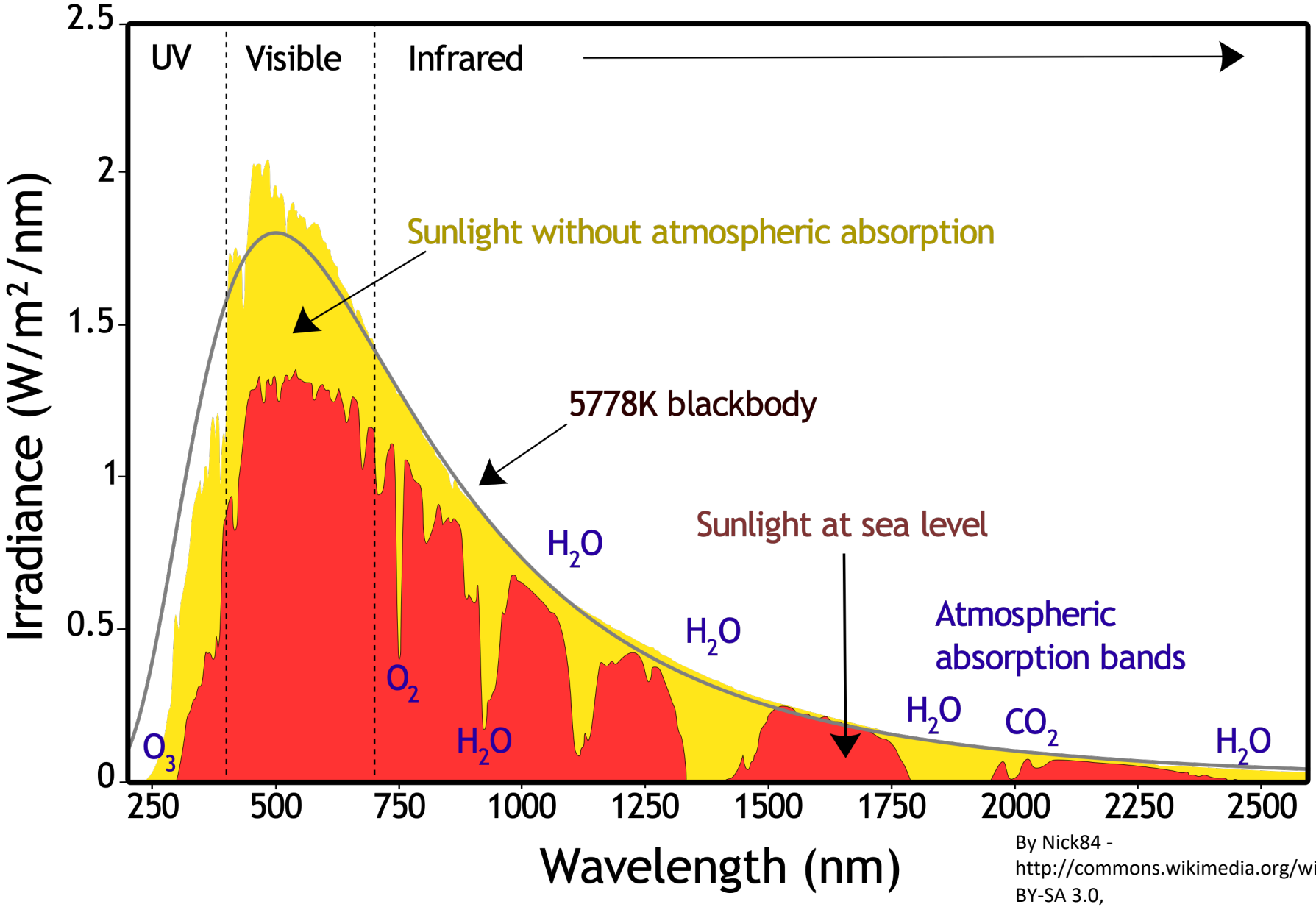
Spectrum of Solar Radiation (Earth)



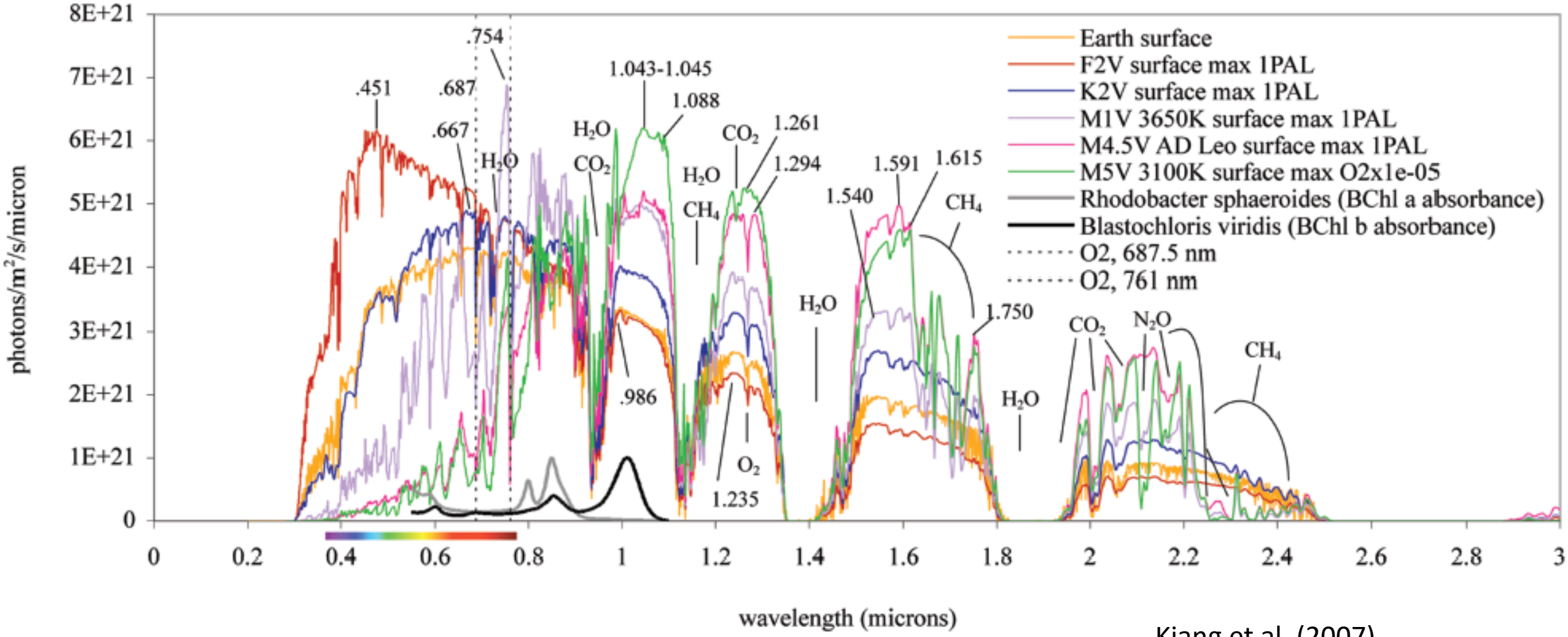
Photon Requirements for Oxygenic Photosynthesis

Lower wavelength limit at ~400 nm

Upper wavelength limit at ~750 nm

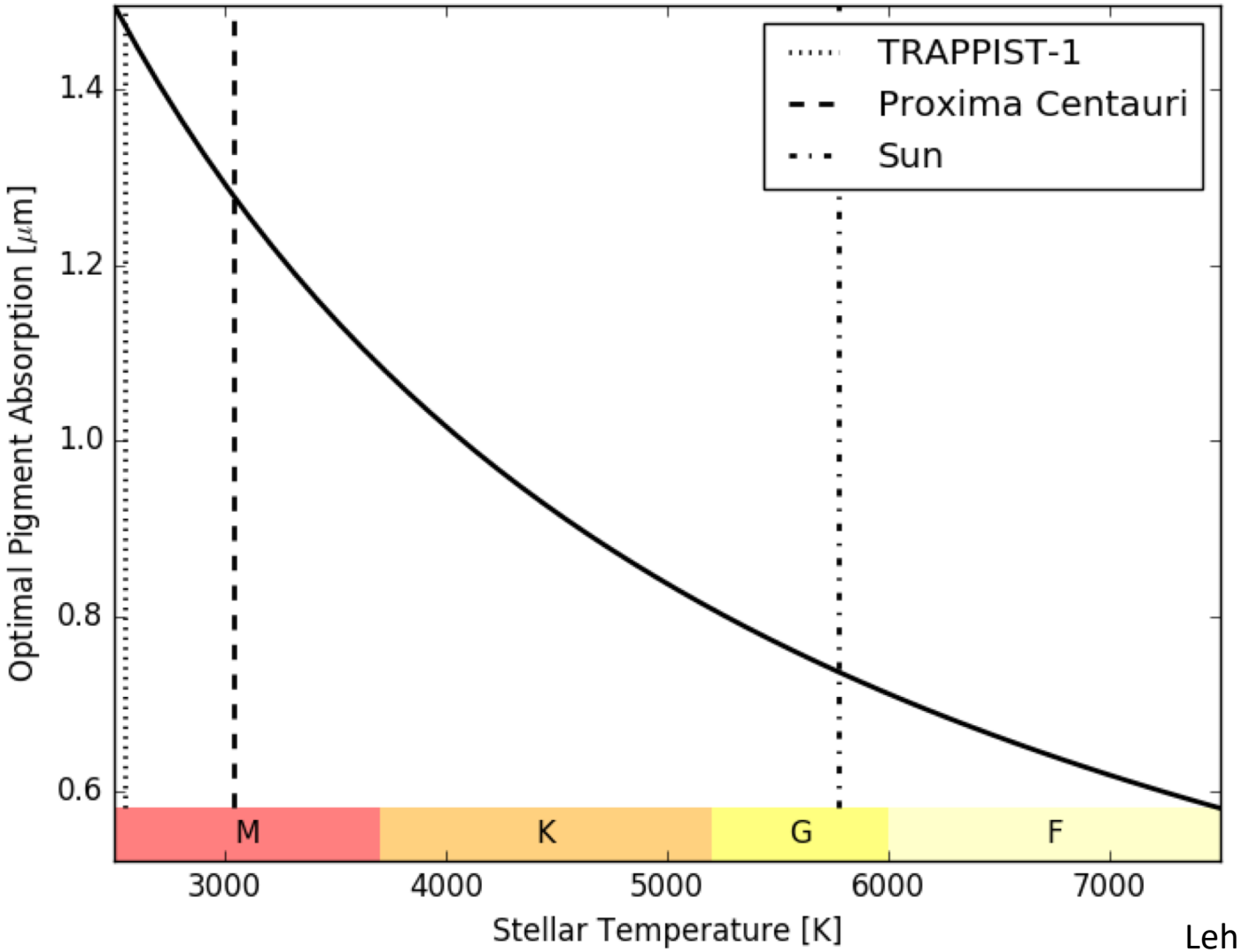
Absolute upper limit for oxygenic photosynthesis is unknown

Available Photons Around Other Stars



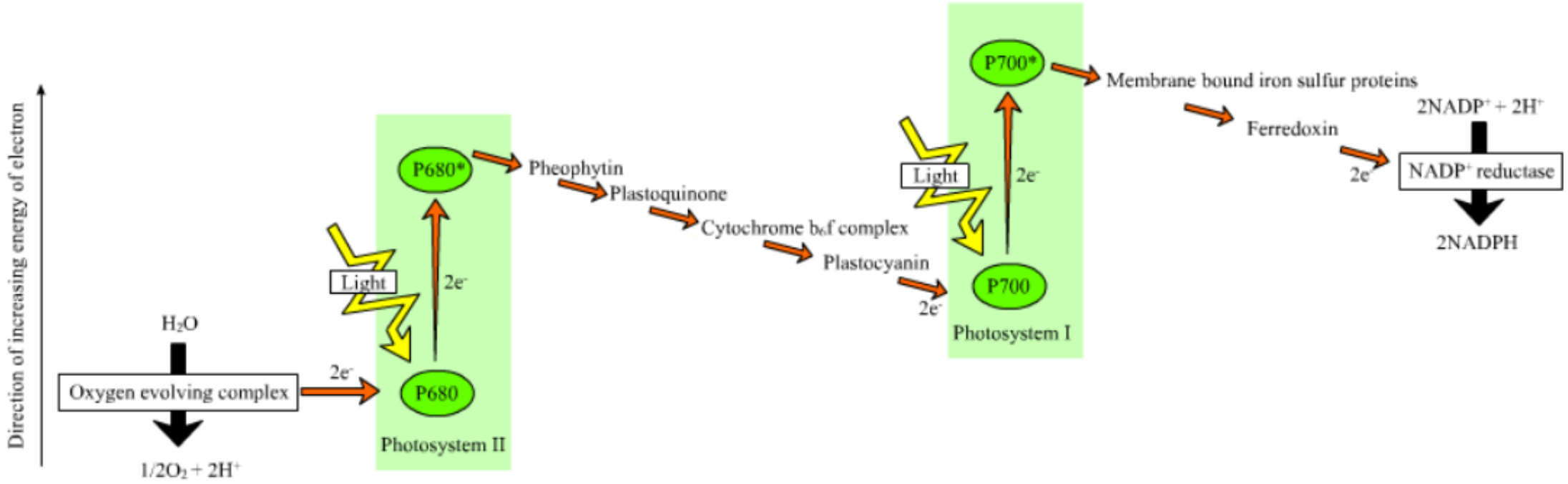
Kiang et al. (2007)

Optimal absorption wavelength around other stars

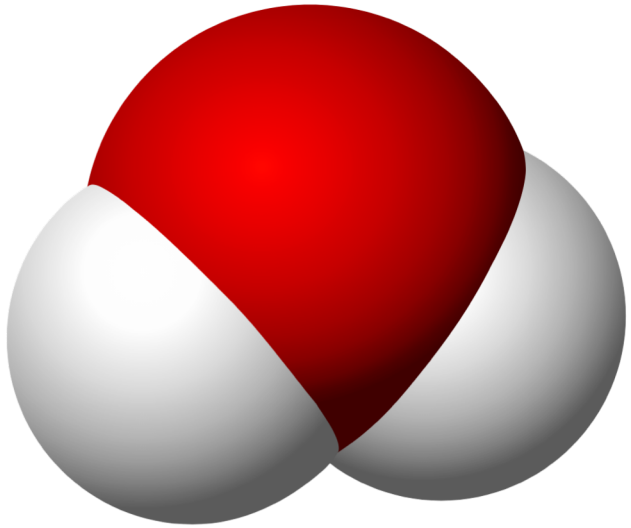


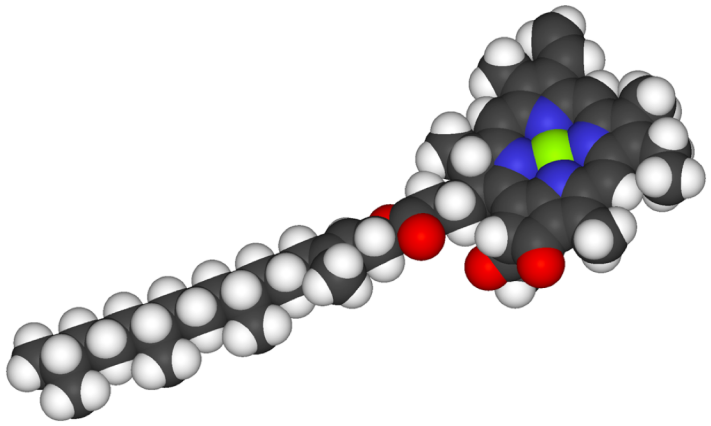
Lehmer et al. 2018

2 Step Z-Scheme



http://commons.wikimedia.org/wiki/File:Z-scheme.png





How long can a photon wavelength be for oxygenic photosynthesis?

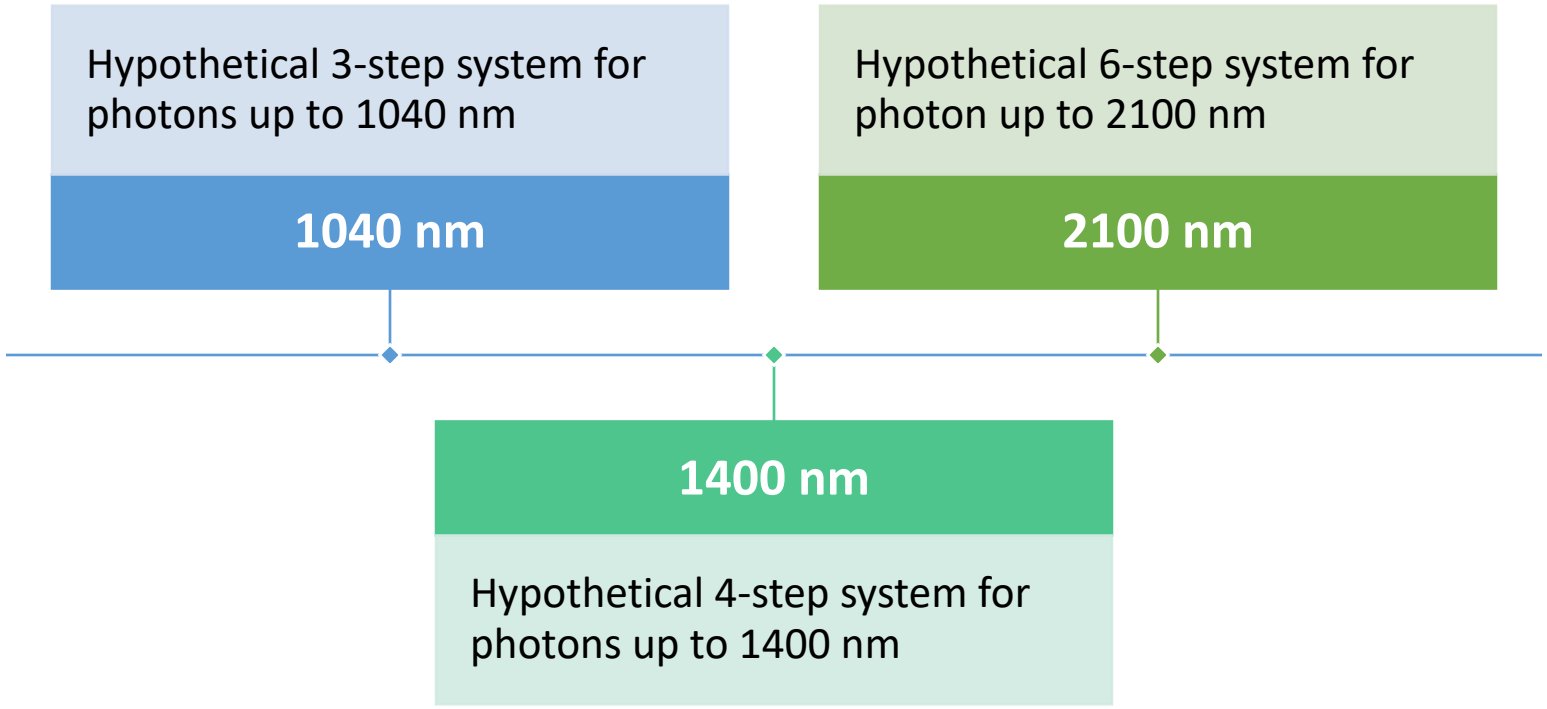
misconception

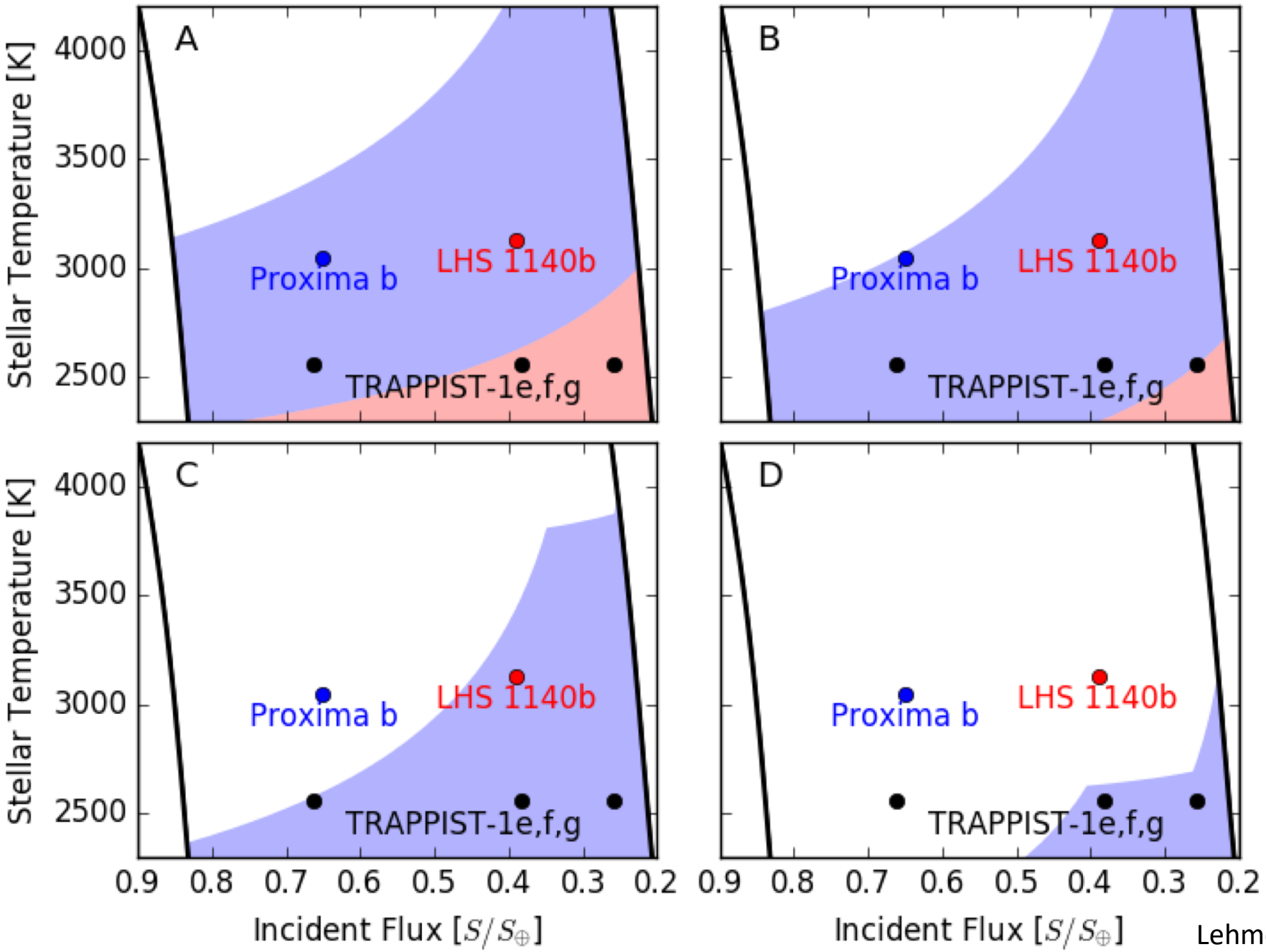
- A water molecule t… quires ~1.23 eV to split, c… g to a photon of ~1 µm… upper limit for oxygenic photos…sis?
- An electronic excitation must occur
- Total energy must be comparable

Upper Wavelength Limits for Oxygenic Photosynthesis

1. 750 nm is the observed limit for the modern Earth
2. van Grondelle and Boeker (2017) found a limit of 900 nm
3. ~1100 nm is the limit of a detectable electronic transition
4. 1500 nm is beyond the optimal pigment absorption wavelength of the coolest M dwarf stars

Photon Energy at Long Wavelengths





Upper limit for oxygenic photosynthesis:

A. 750 nm
B. 900 nm
C. 1100 nm
D. 1500 nm

Red shaded region:

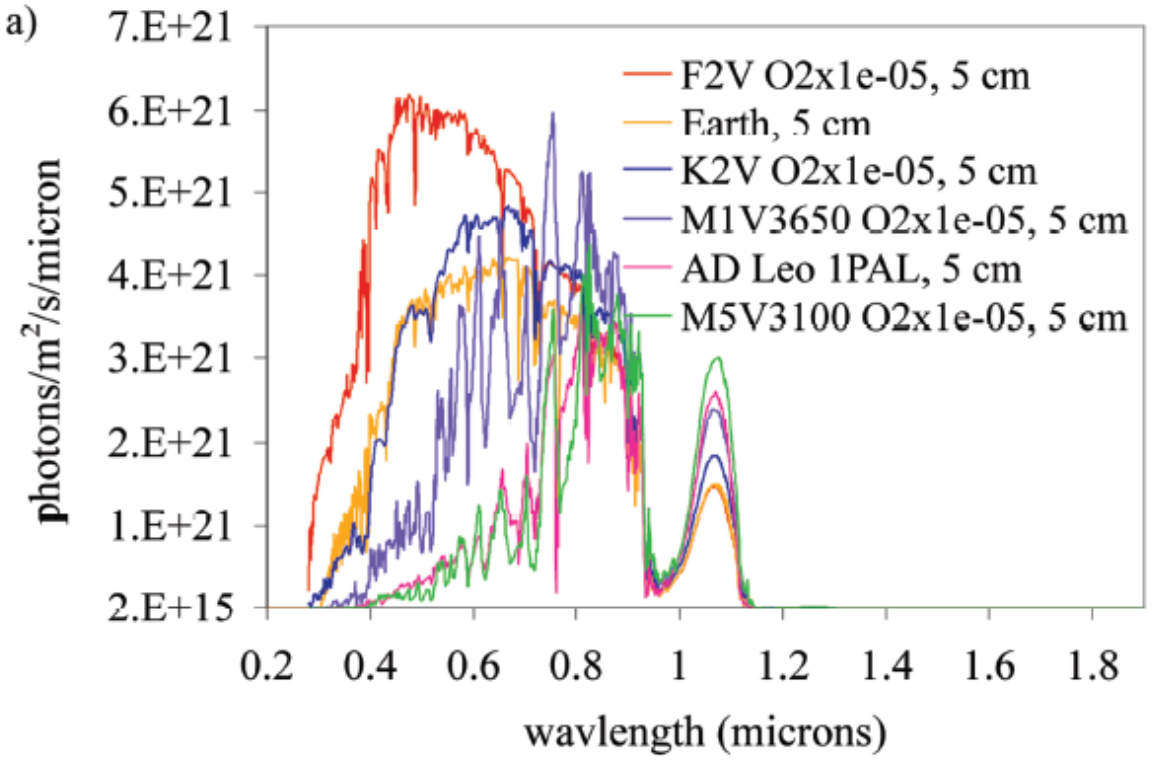
below ocean photon use

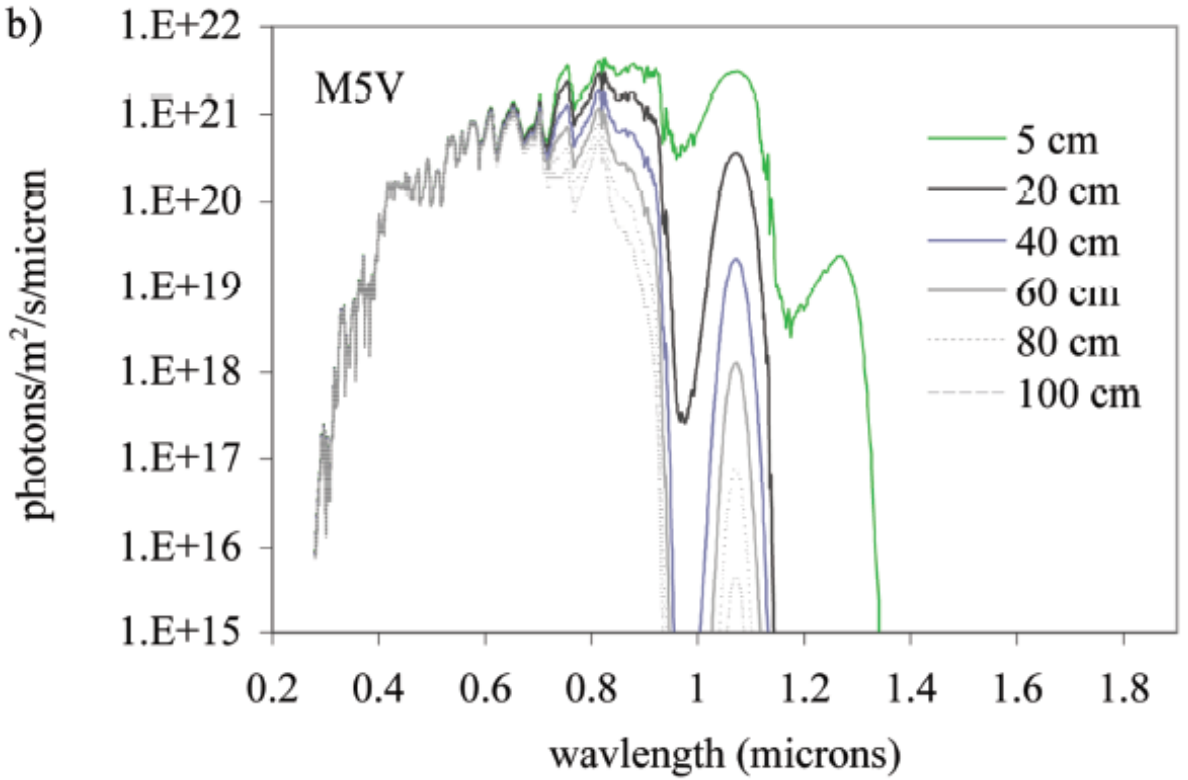
Blue shaded region:

below terrestrial photon use

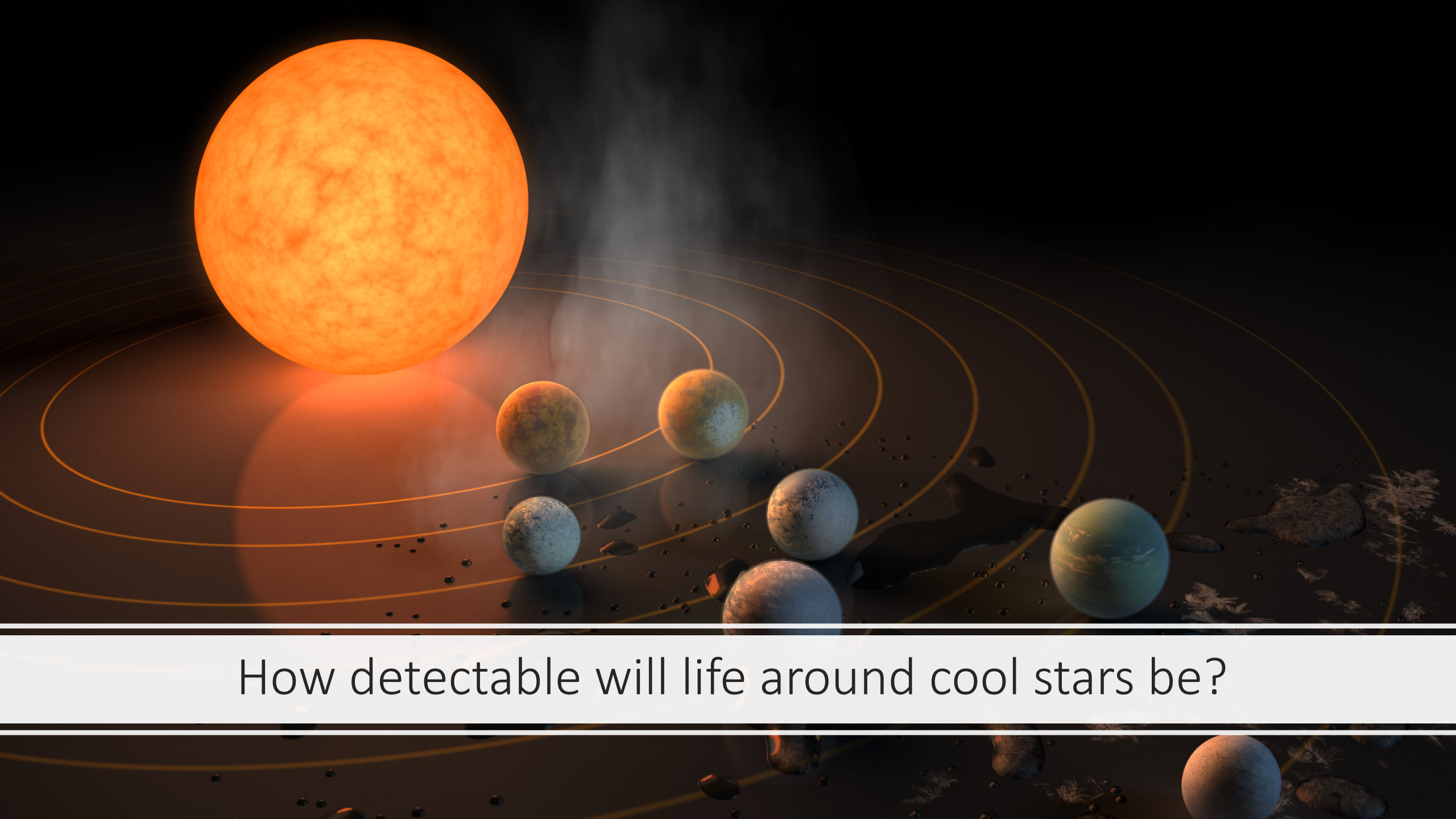
Lehmer et al. 2018

Available Photons Around Other Stars (in water)





Kiang et al. (2007)



How detectable will life around cool stars be?

Flux of O_2 on the Modern Earth

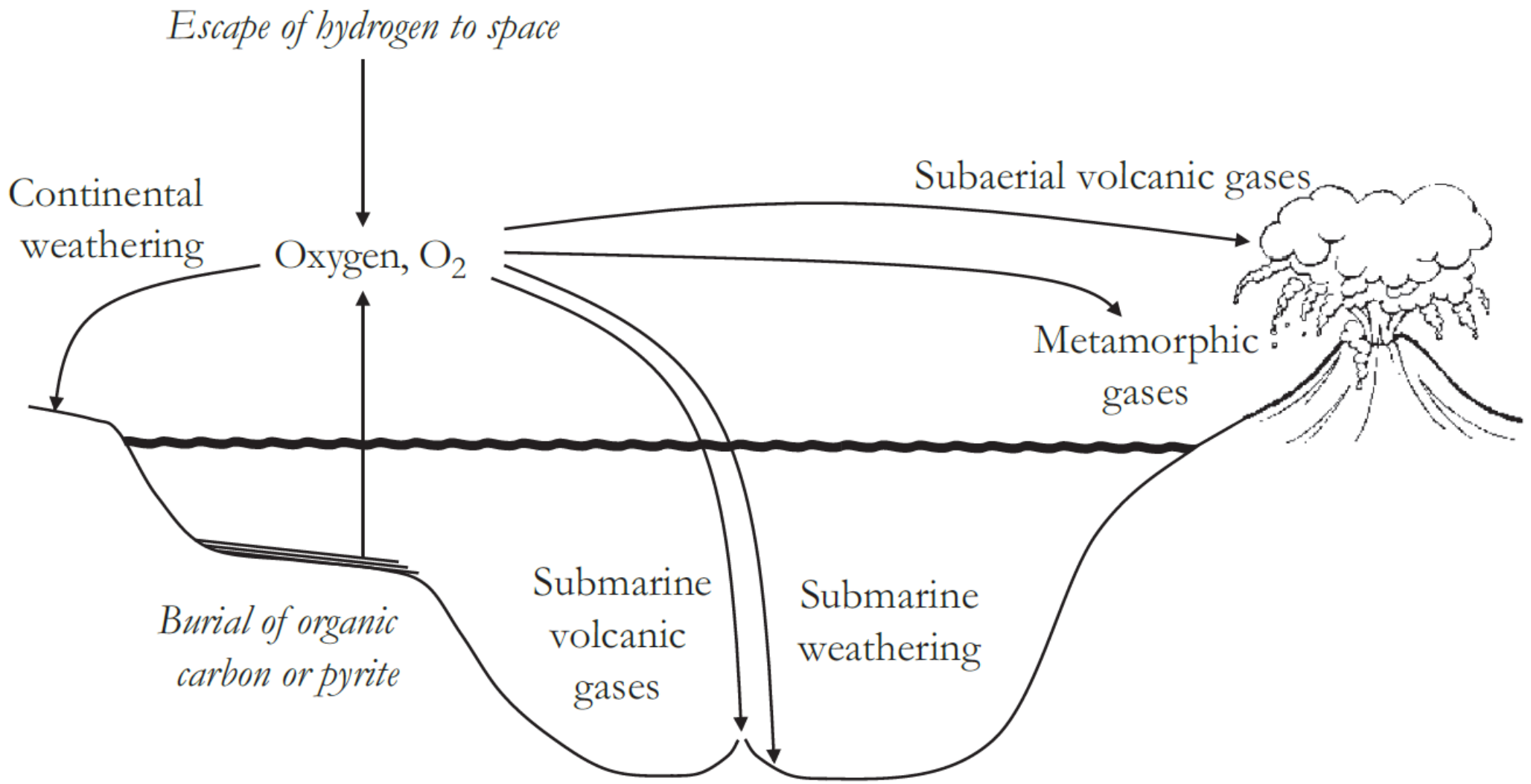
Nearly all O_2 produced from oxygenic photosynthesis is consumed on short timescales by respiration or oxidative decay

Less than 1% of biomass produced from oxygenic photosynthesis is buried

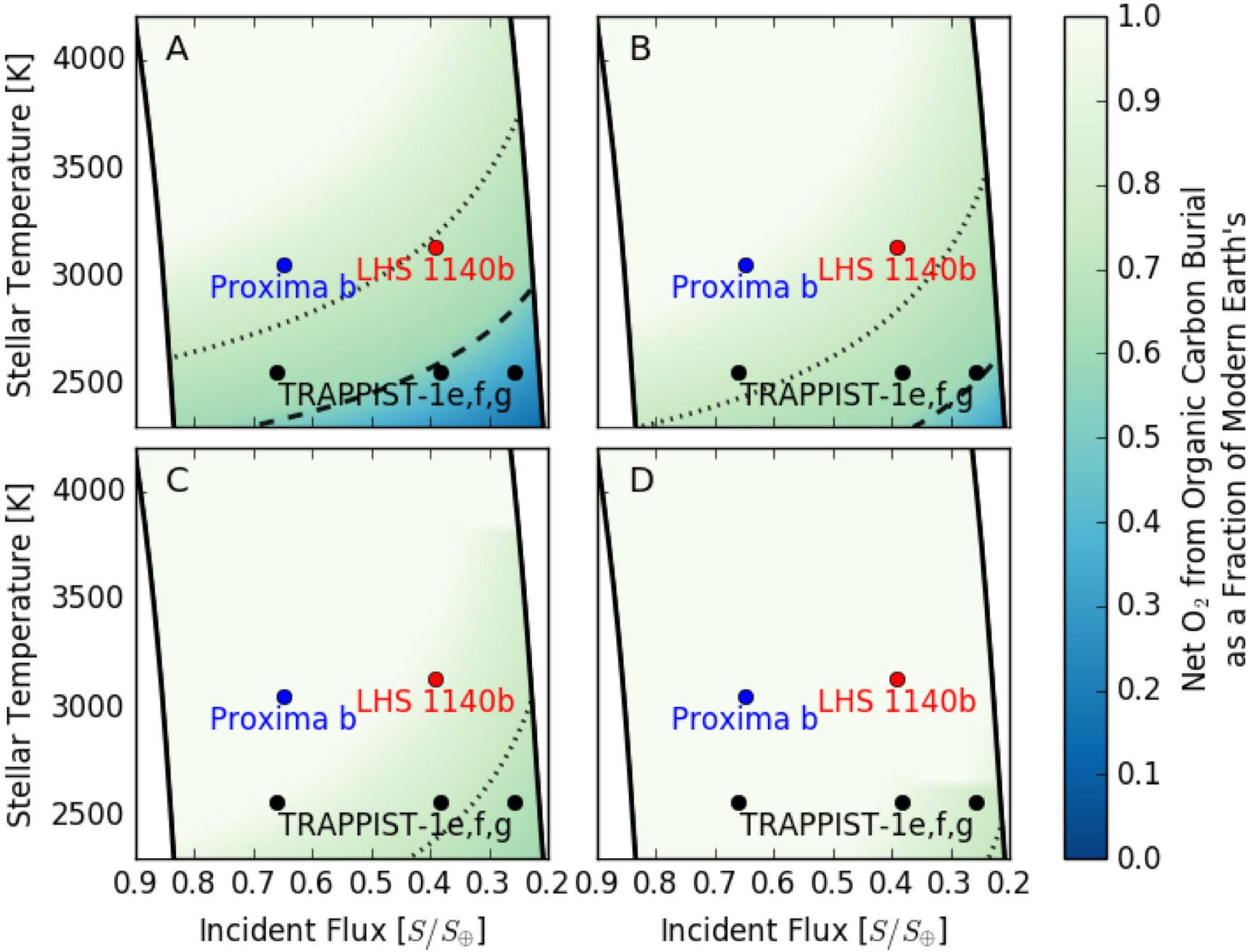
Burial estimates span 5.6-10.0 Tmol yr^{-1} (0.16-0.30%)

O_2 flux is partially consumed by kinetically rapid reactions with reducing gases (e.g., H_2, CO, H_2S, SO_2, etc.) – 5.7±1.2 Tmol yr^{-1} O_2 equivalent

Remaining O_2 flux is consumed via oxidative weathering



Catling and Kasting, (2017) p. 261



- Dashed line shows burial rate of 0.3% (Earth's upper limit)
- Dotted line shows burial rate of 0.23% (median burial rate)

A. 750 nm
B. 900 nm
C. 1100 nm
D. 1500 nm

Surface reservoirs for O_2

- The Earth's crust is more oxidized than the mantle
- Total O_2 sink for the modern Earth is ~10^{10} Tmol
- Modern O_2 from organic C burial is ~10 Tmol yr^{-1}

Image Credit: Candida Savage

When did oxygenic photosynthesis evolve?

~2.7 Ga – stromatolites indicative of oxygenic photosynthesis (and others)

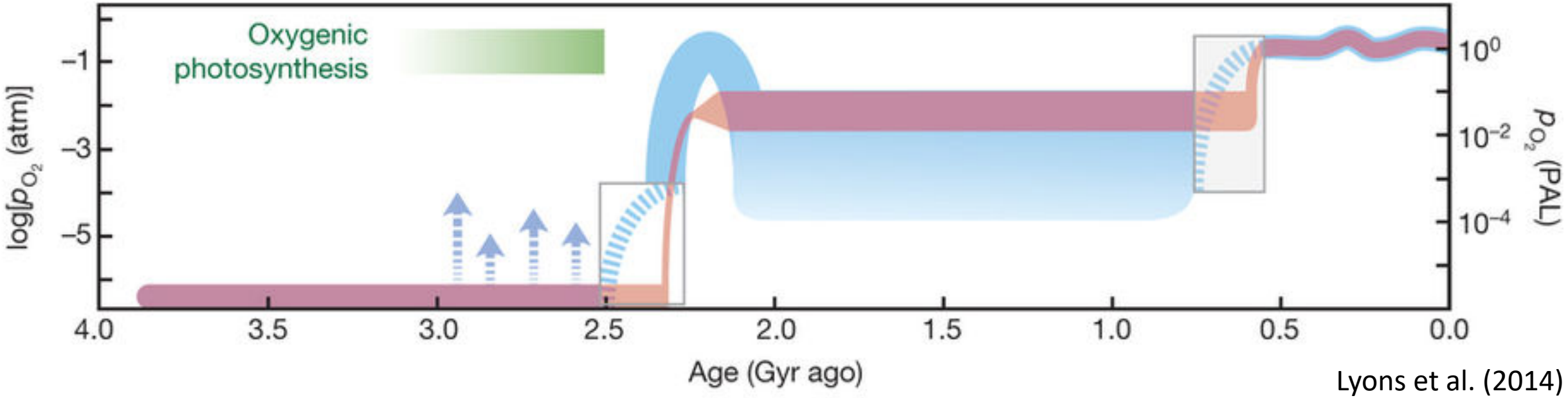
2.95 Ga - Mo isotopes

3.2 Ga - kerogen-rich shales consistent with oxygenic phototrophs

3.7-3.8 Ga - Cr isotopes and U/Th ratios

Great Oxidation Event

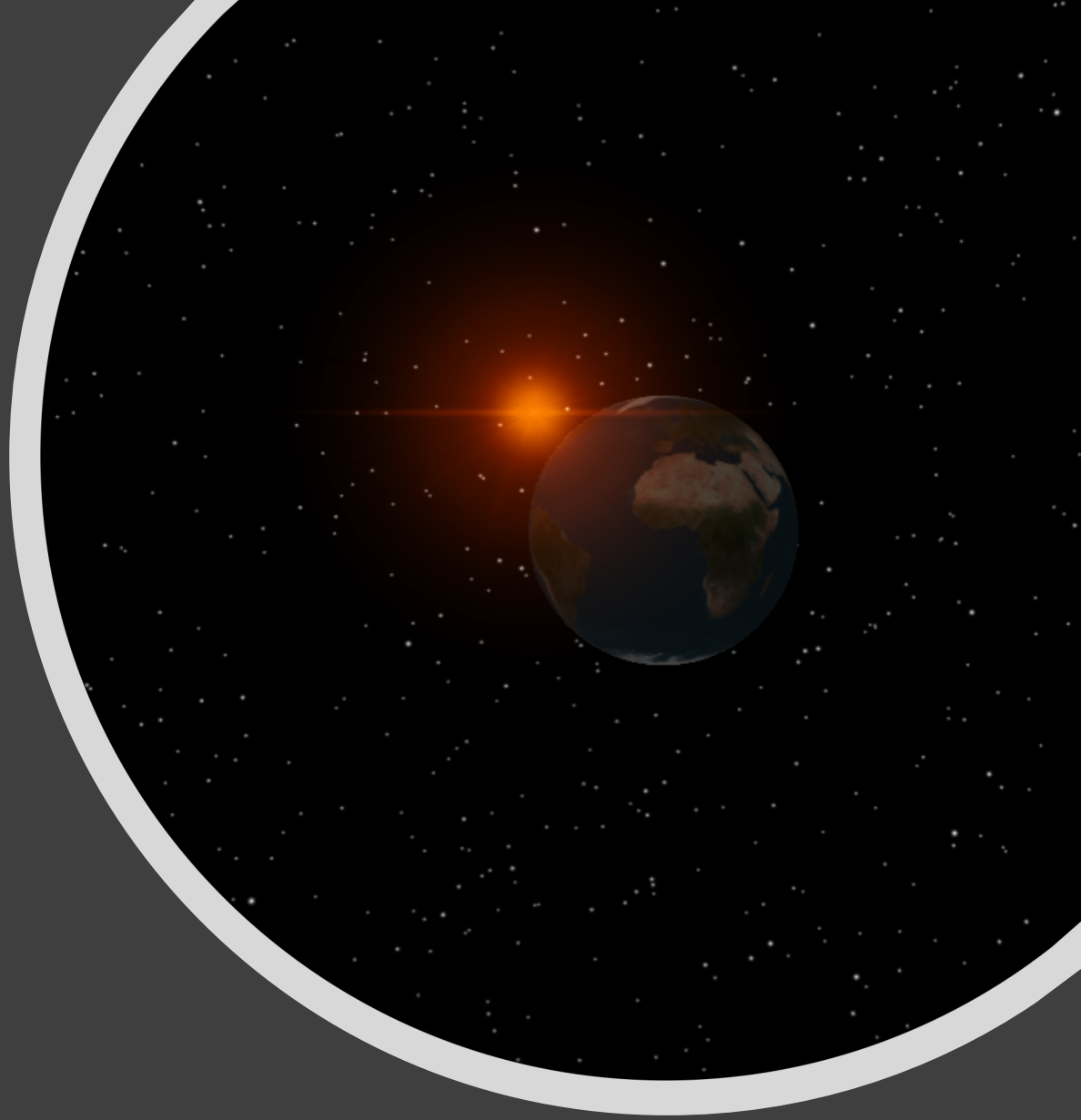
- Earth's atmosphere became oxygenated at ~2.4 Ga
- Geochemical evidence suggests oxygenic photosynthesis evolved by 2.7-3.2 Ga, possibly earlier, before even 3.4-3.8 Ga
- 300 Myr or more may have passed between the advent of oxygenic photosynthesis and the Great Oxidation Event



Lyons et al. (2014)

Biospheres around cool stars could be growth limited

- Energy limitations could limit biomass productivity to just a few percent of modern Earth's
- Outgassing rates must not overwhelm biological fluxes
- Crustal sinks could delay biological signals for billions of years

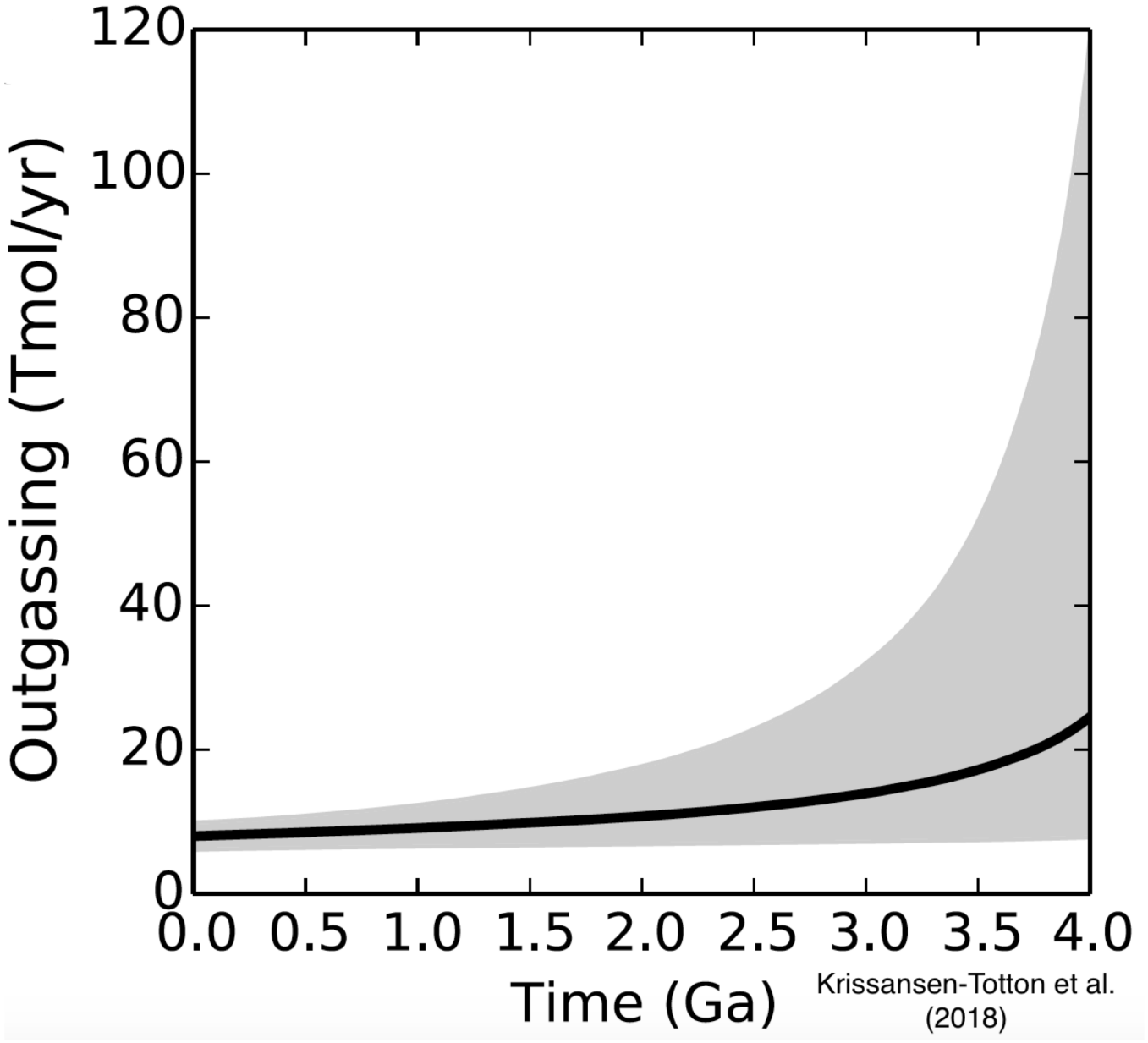


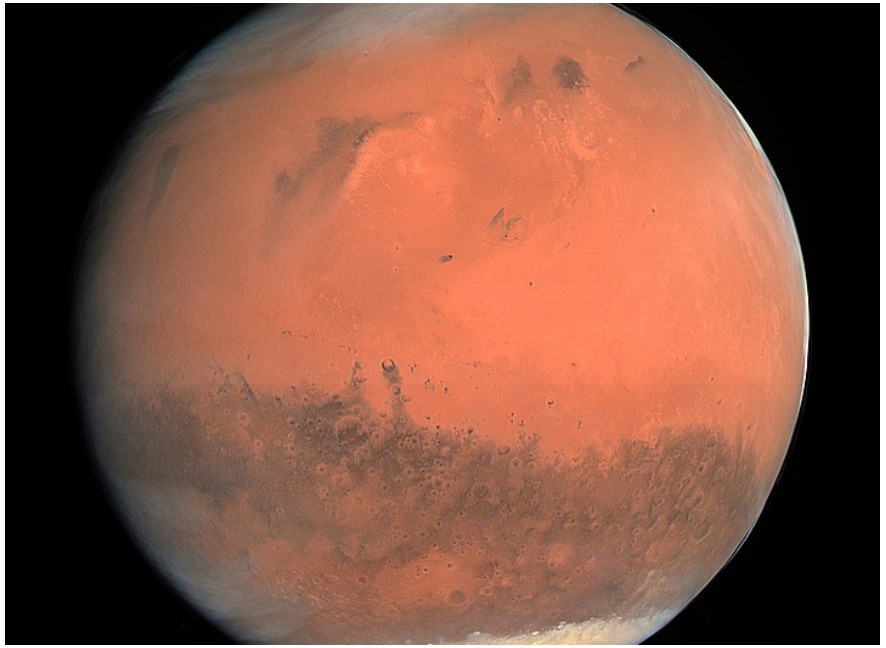
Even if life is present, it may not be detectable on some worlds

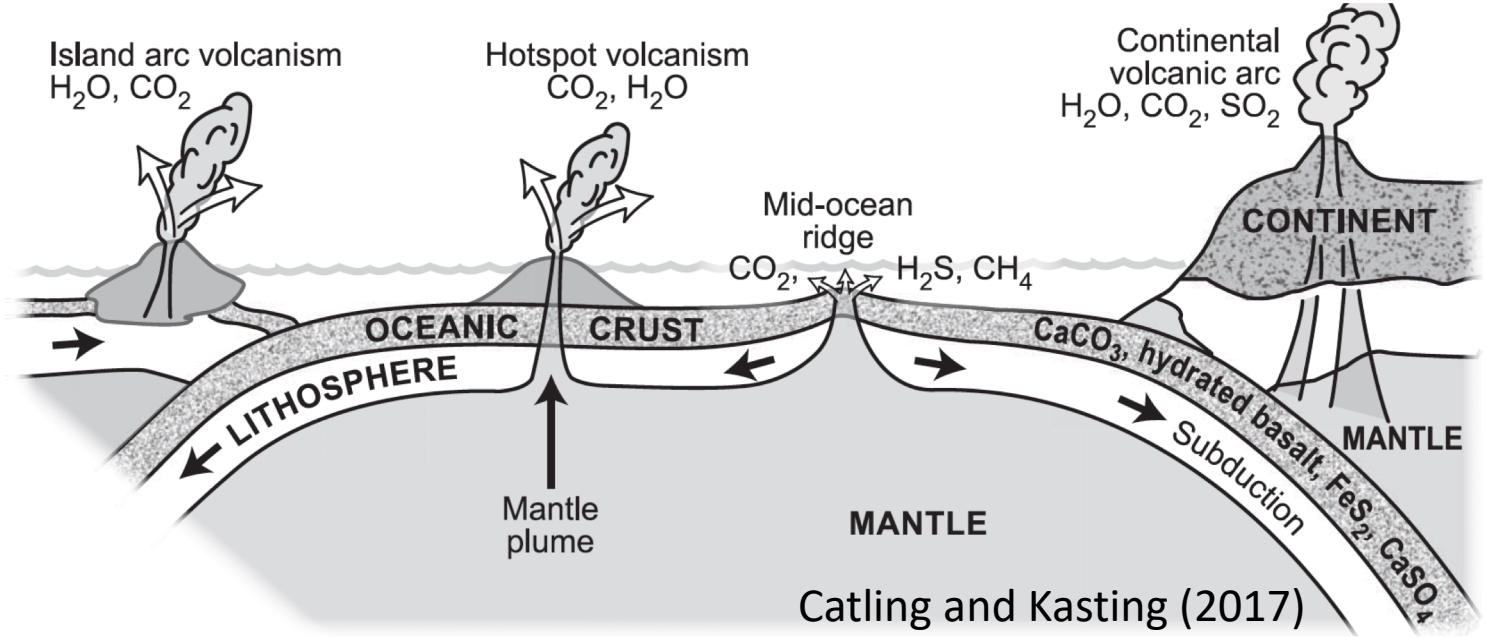
- How can this inform target selection?
  - For stellar temperatures below ~3000 K an Earth-like planet may be unable to overcome planetary fluxes
  - Water-rich worlds may be particularly impacted around cool stars
  - Planets in a non-synchronous orbits could be growth limited
  - FGK stars may provide the best targets to unambiguously find evidence for life

Outgassing on Earth

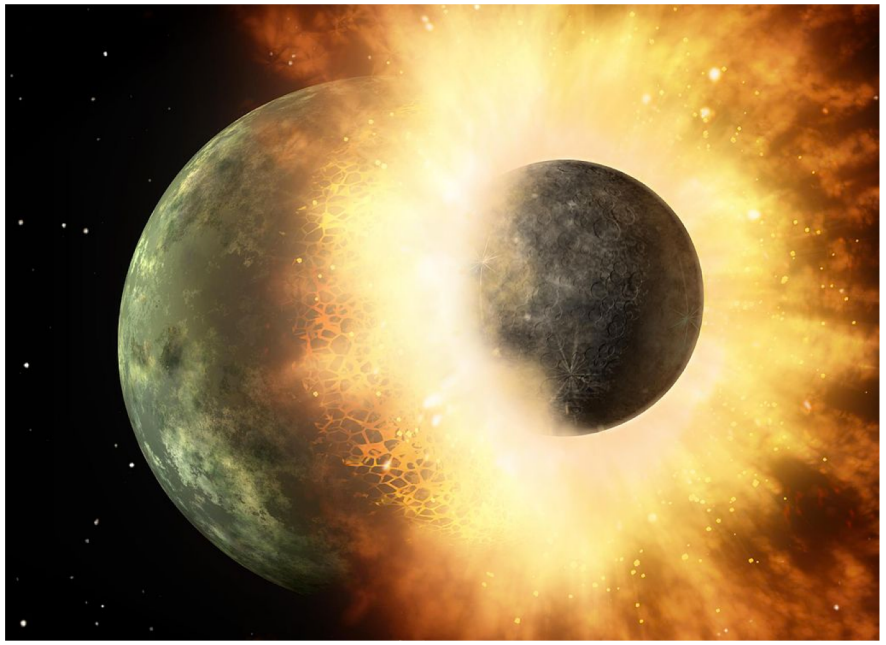
Composition is thought be be roughly constant through time







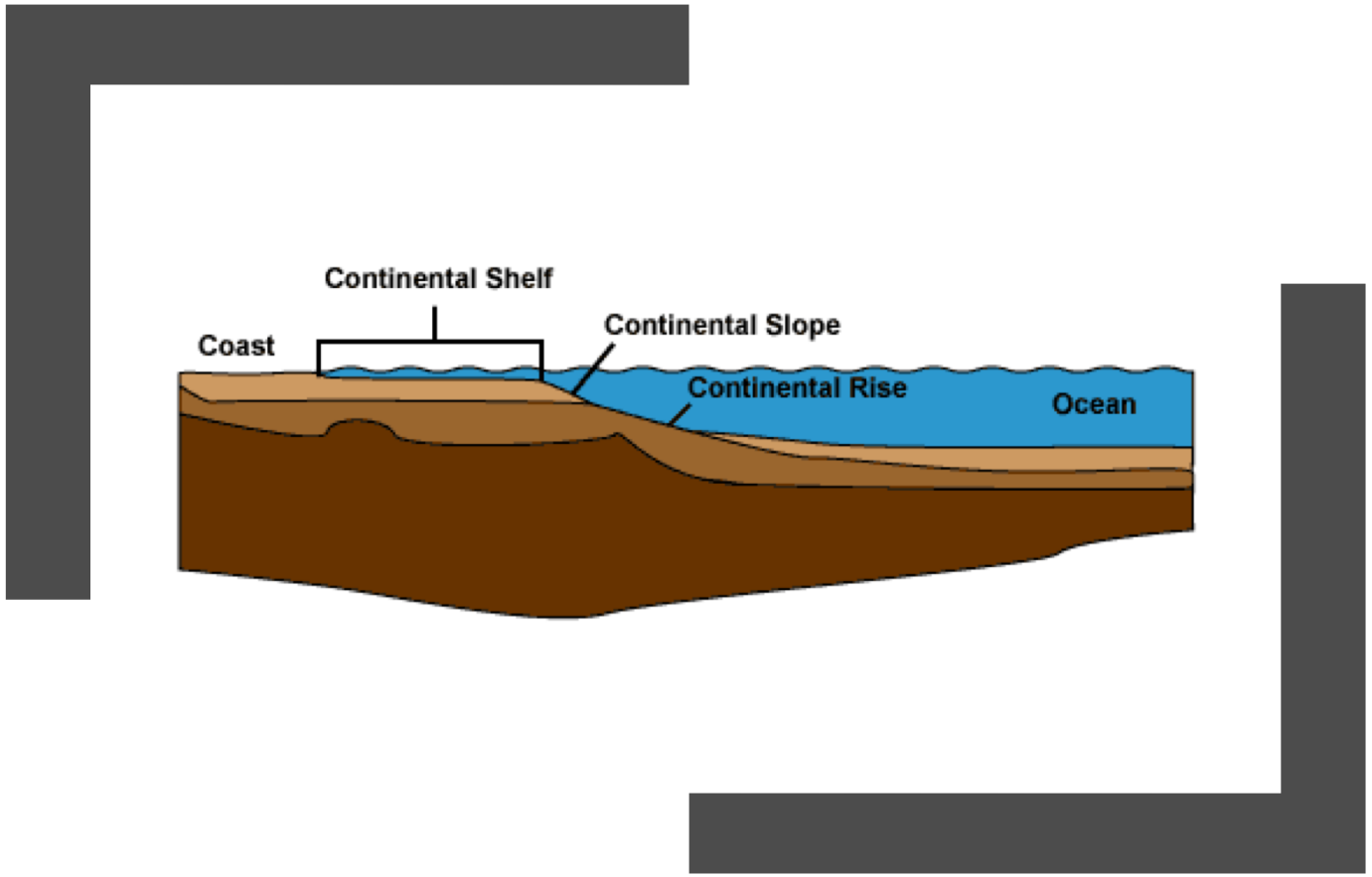
Catling and Kasting (2017)



Will exoplanets have similar outgassing rates/compositions?

Volcanic outgassing could scale as the square of heat flow

Organic C burial on Earth



- ~97% of organic C is buried in the coastal ocean margin (modern Earth)

Will organic C burial be the same on other planets?

- Biomass production on the early Earth may have been orders of magnitude smaller than modern
- Anoxic conditions