The diversity of Earth's past (and future) atmospheres

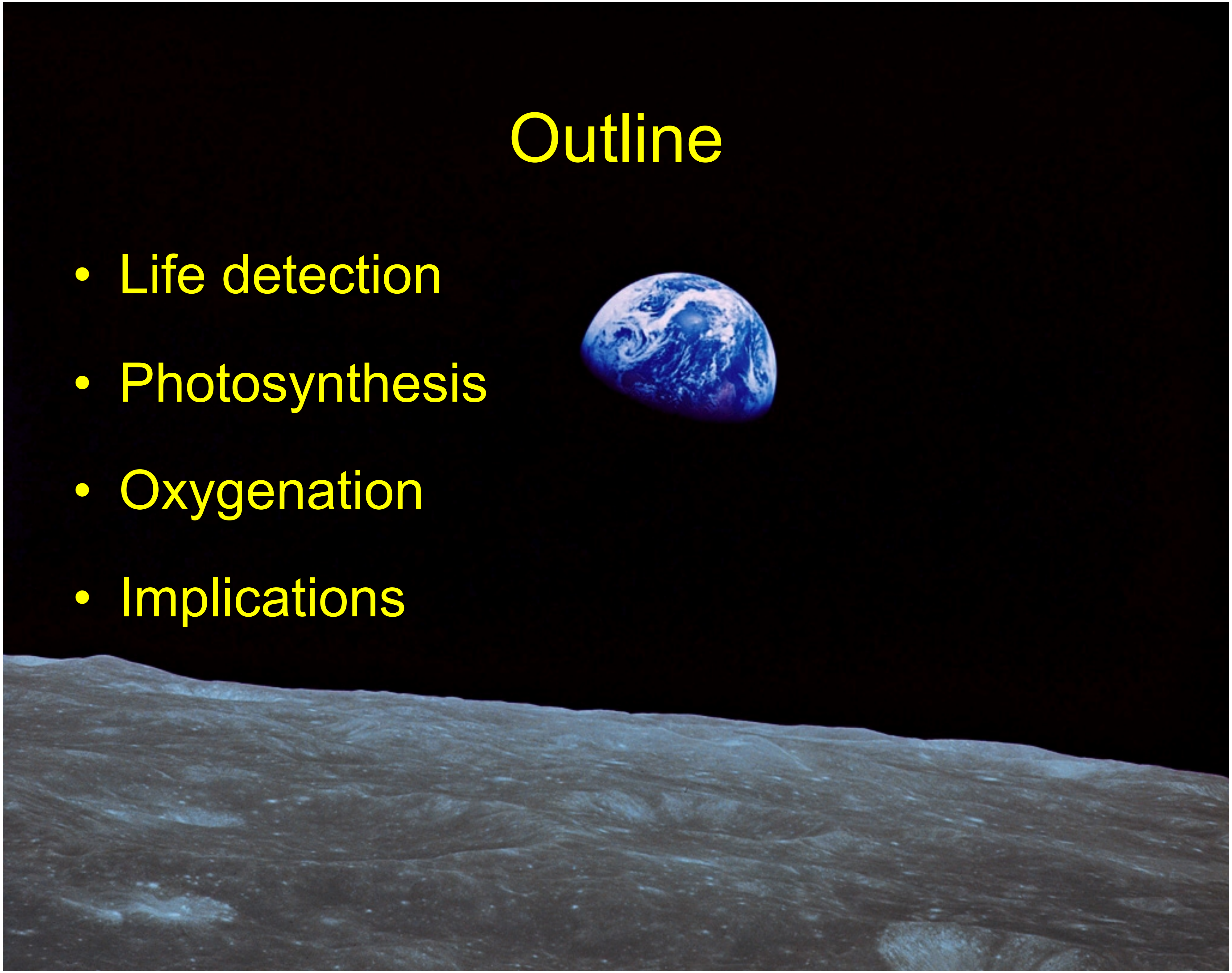
Tim Lenton

School of Environmental Sciences, University of East Anglia, Norwich, UK

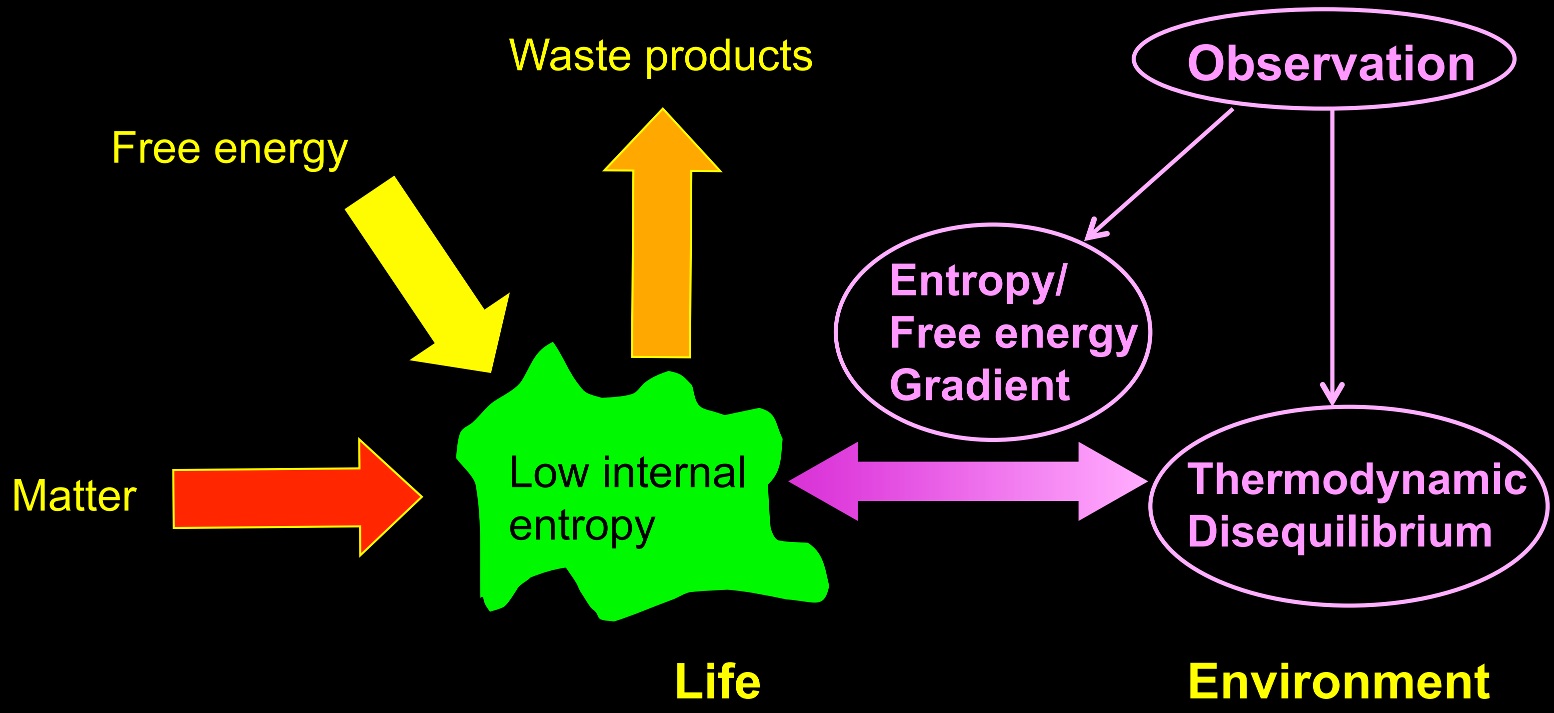
Thanks to Andy Watson, Colin Goldblatt, Jim Lovelock

Outline

- Life detection
- Photosynthesis
- Oxygenation
- Implications

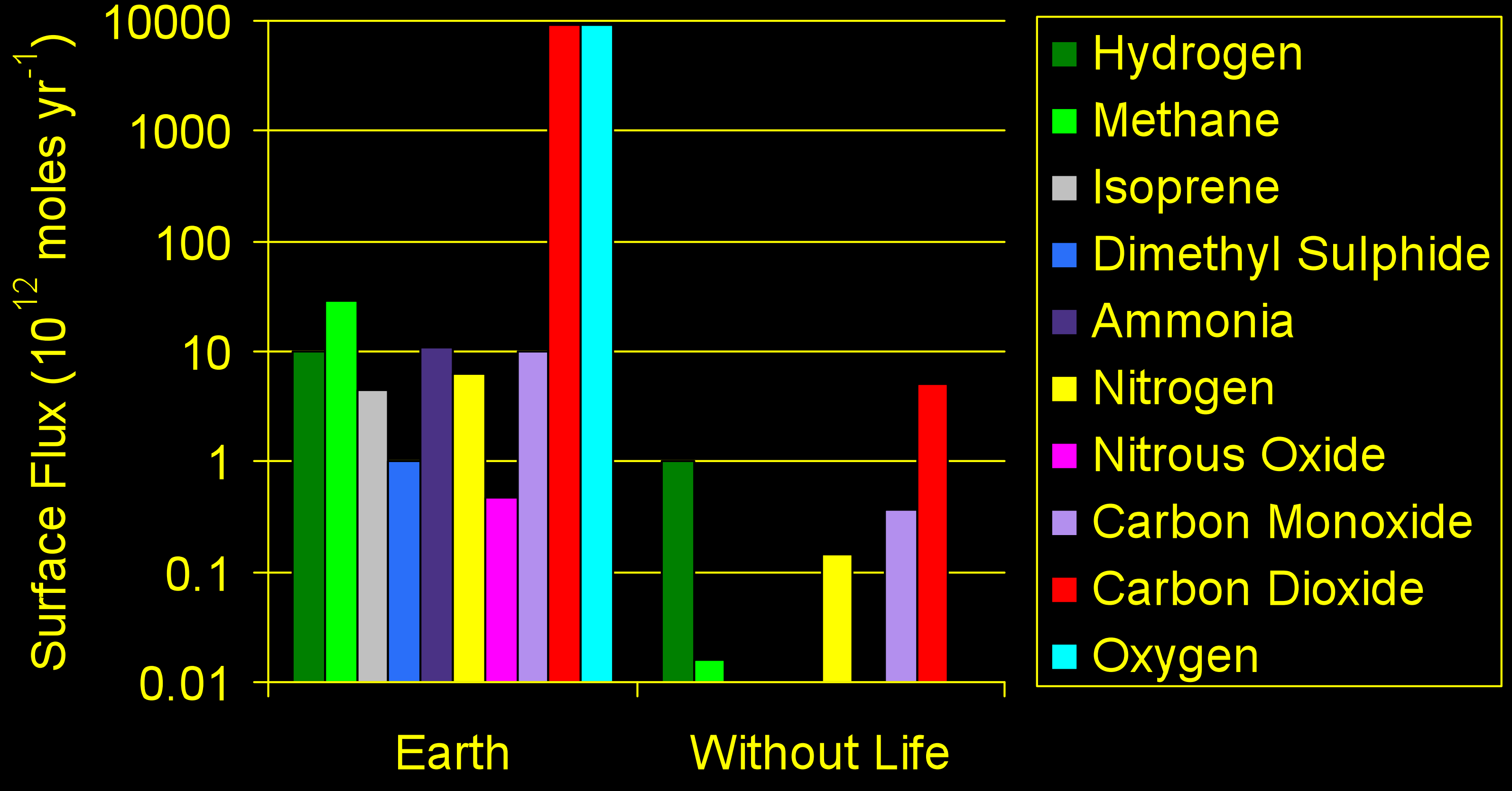


Life detection

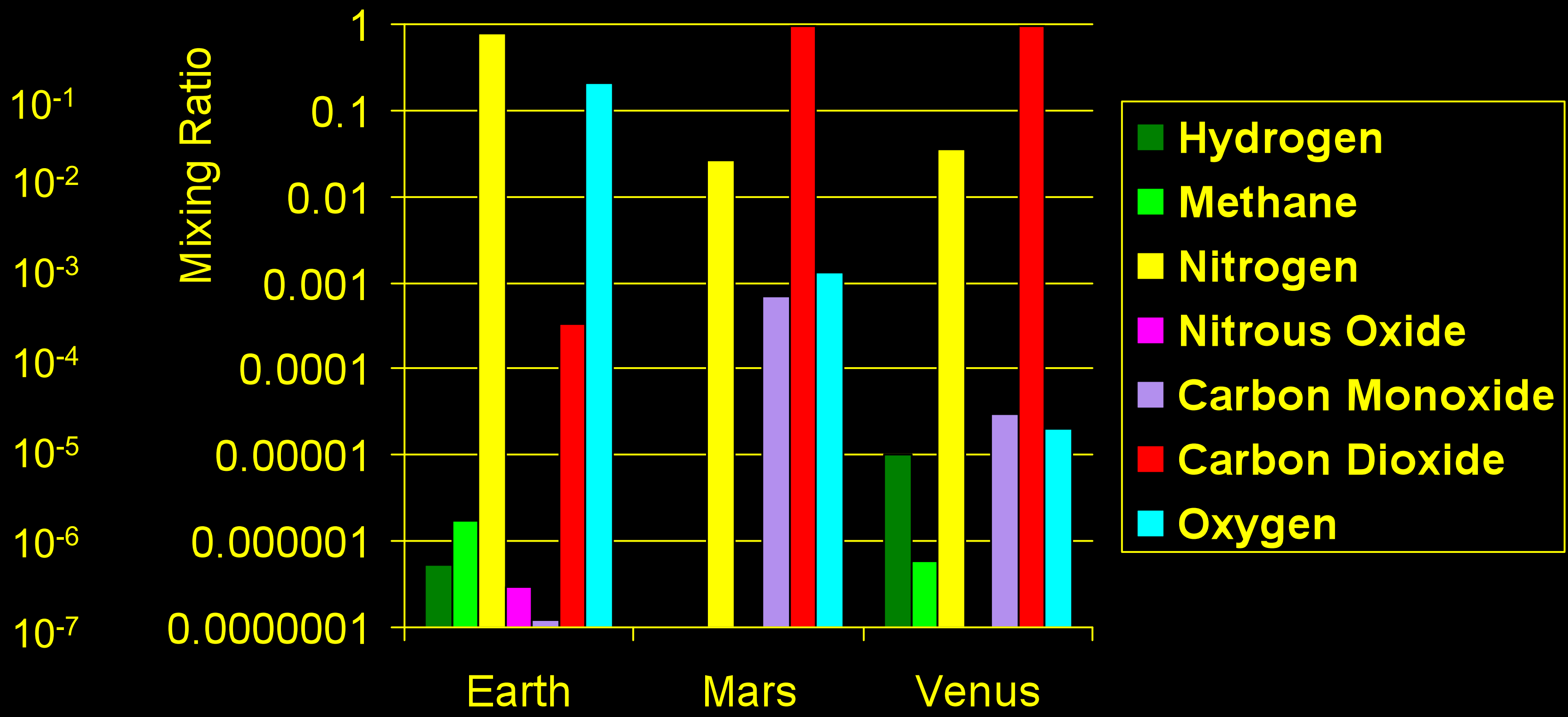


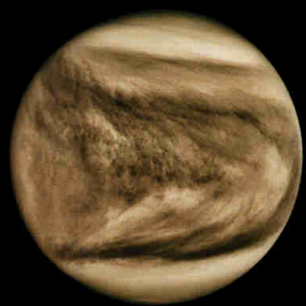
J. E. Lovelock (1965) Nature 207: 568-570

Fluxes of gases

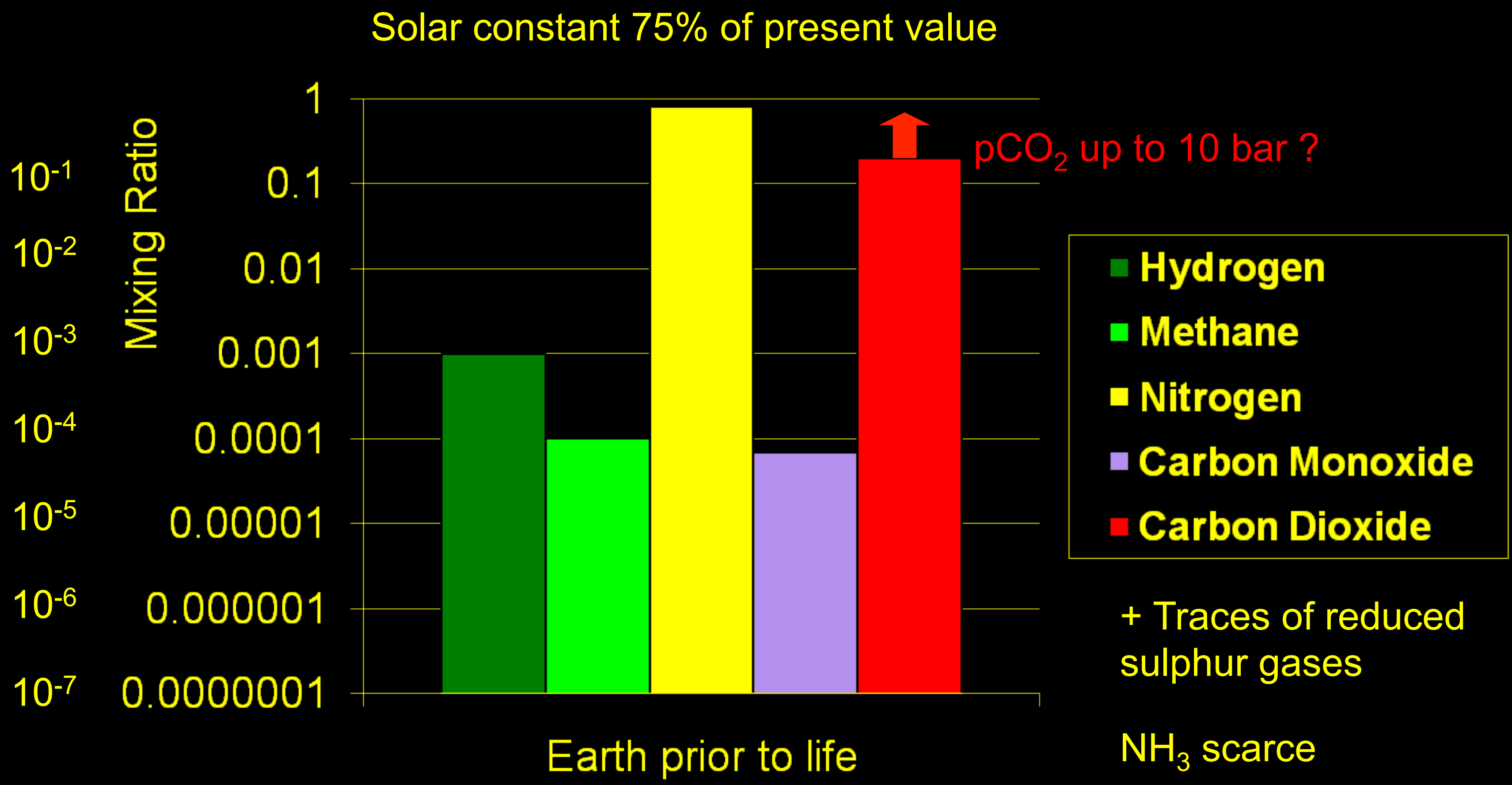


Atmospheric compositions





Atmosphere prior to life (~4 Ga)



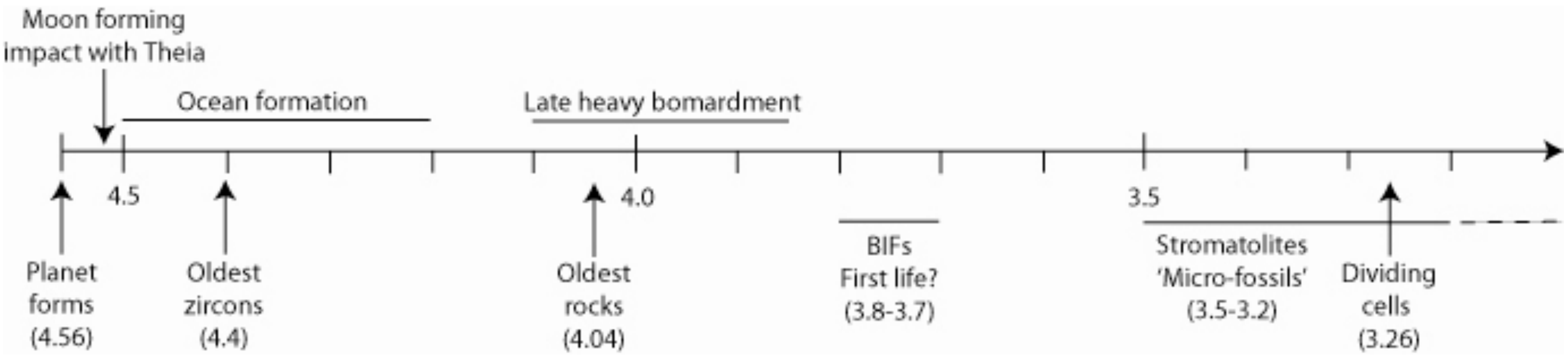
+ Traces of reduced sulphur gases

NH_3 scarce

Oxygen was virtually absent ($<10^{-13}$)

Kasting (1993)

The first billion years or so

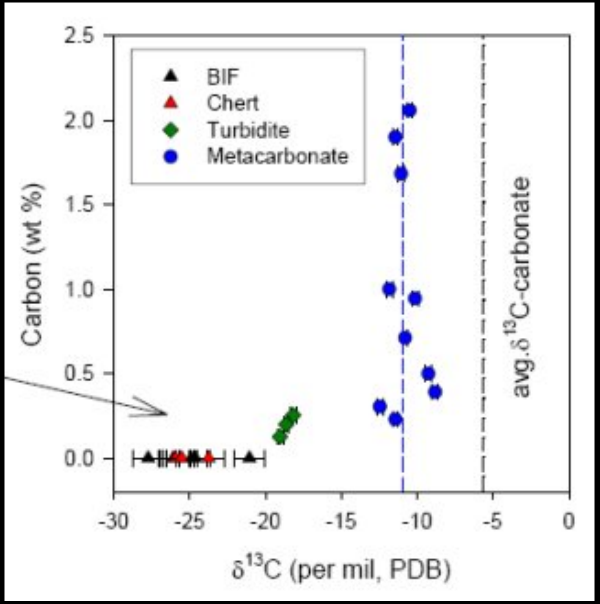


Lenton & Watson 'Revolutions that made the Earth' OUP (2011)

Oldest reduced carbon ~3.8 Ga

- Rare turbidite in Isua supracrustal group, Western Greenland
- Reduced carbon in the form of graphite, tiny granules a few microns across
- Remarkable $\delta^{13}C$ ~ -20 ‰ indicates carbon fixation by Rubisco
- Suggests photosynthesis but not necessarily *oxygenic* photosynthesis

Outcrop of turbidite containing graphite



Types of photosynthesis

- General equation for photosynthesis:

  $CO_2 + 2\ H_2A + h\nu \rightarrow (CH_2O)_n + H_2O + 2A$

  carbon dioxide + electron donor + light energy → carbohydrate + water + oxidized donor

- Many anoxygenic forms:
  - electron donors: H_2, H_2S, S^0, SO_3^{2-}, $S_2O_3^{2-}$, Fe^{2+}

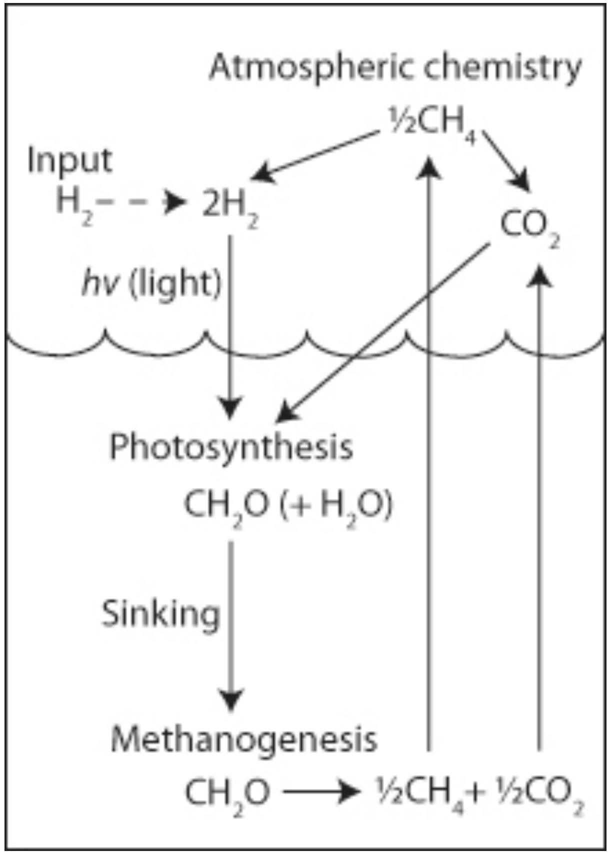
- Oxygenic photosynthesis:

  $CO_2 + 2\ H_2O + h\nu \rightarrow (CH_2O)_n + H_2O + O_2$

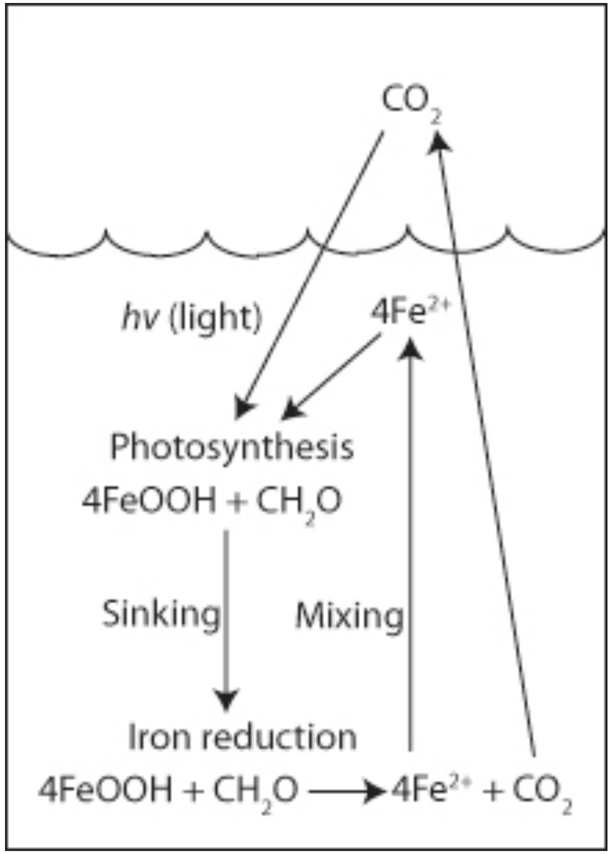
  carbon dioxide + water + light energy → carbohydrate + water + oxygen

Early recycling biospheres

Hydrogen fuelled



Iron fuelled



Lenton & Watson ‘Revolutions that made the Earth’ OUP (2011)

Why use water?

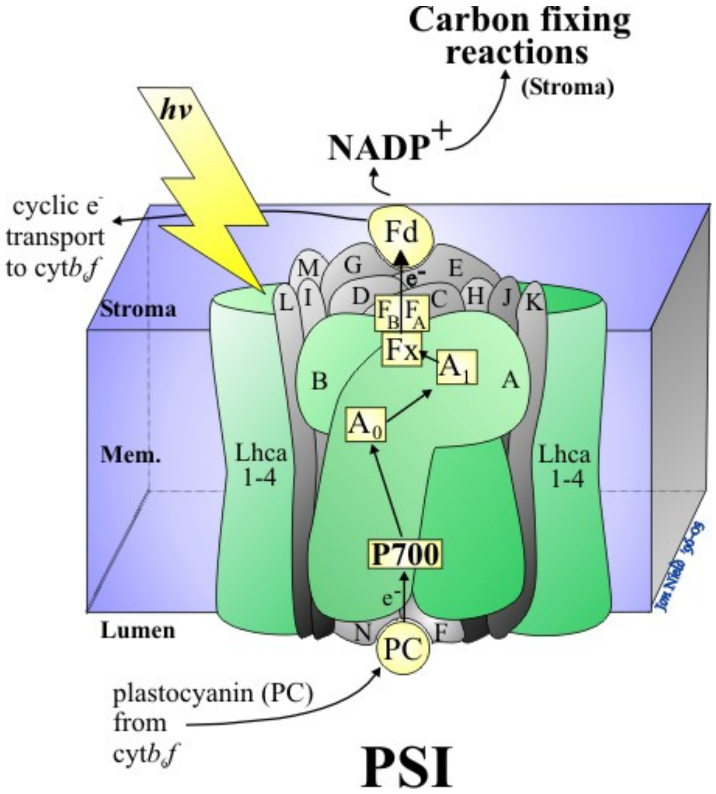
- Need to exhaust other donors that are easier to extract electron from (H_2, H_2S, Fe^{2+}…)

- Requires an unusual environment
  - Microbial mat
  - Sulphur deficient lake
  - After a bloom in the surface ocean

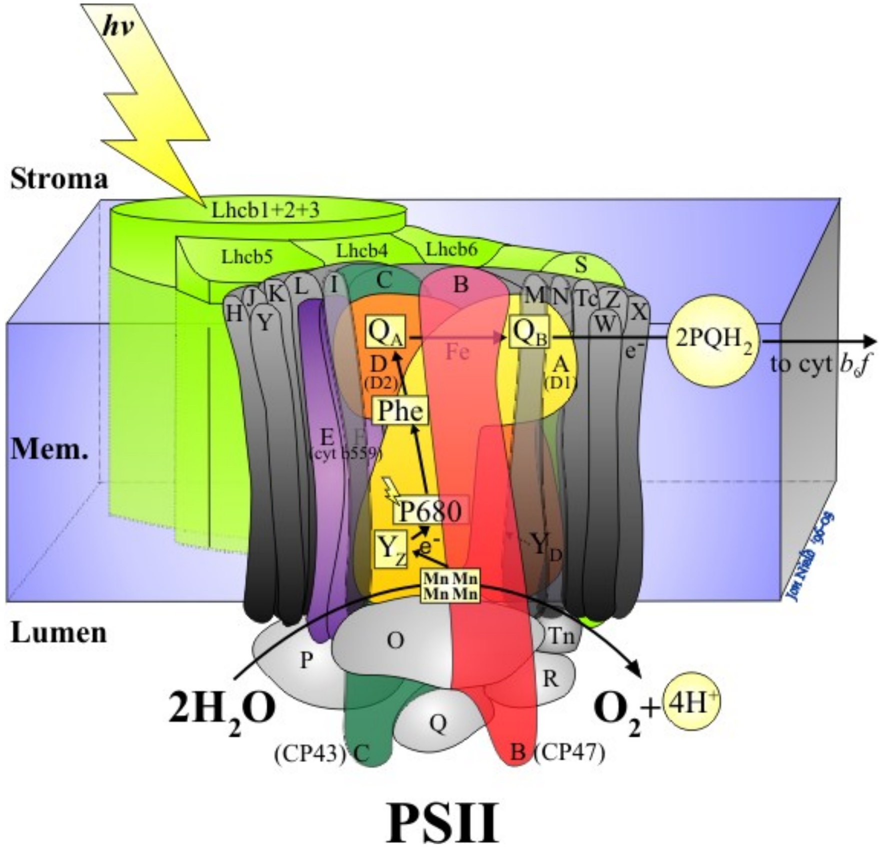
- Need to get enough energy to split water
  - This is a major challenge…

Photosystem I and Photosystem II

Photosystems of each type are found separately in different anoxygenic photosynthesisers
But they are linked together in oxygenic photosynthesis (cyanobacteria)

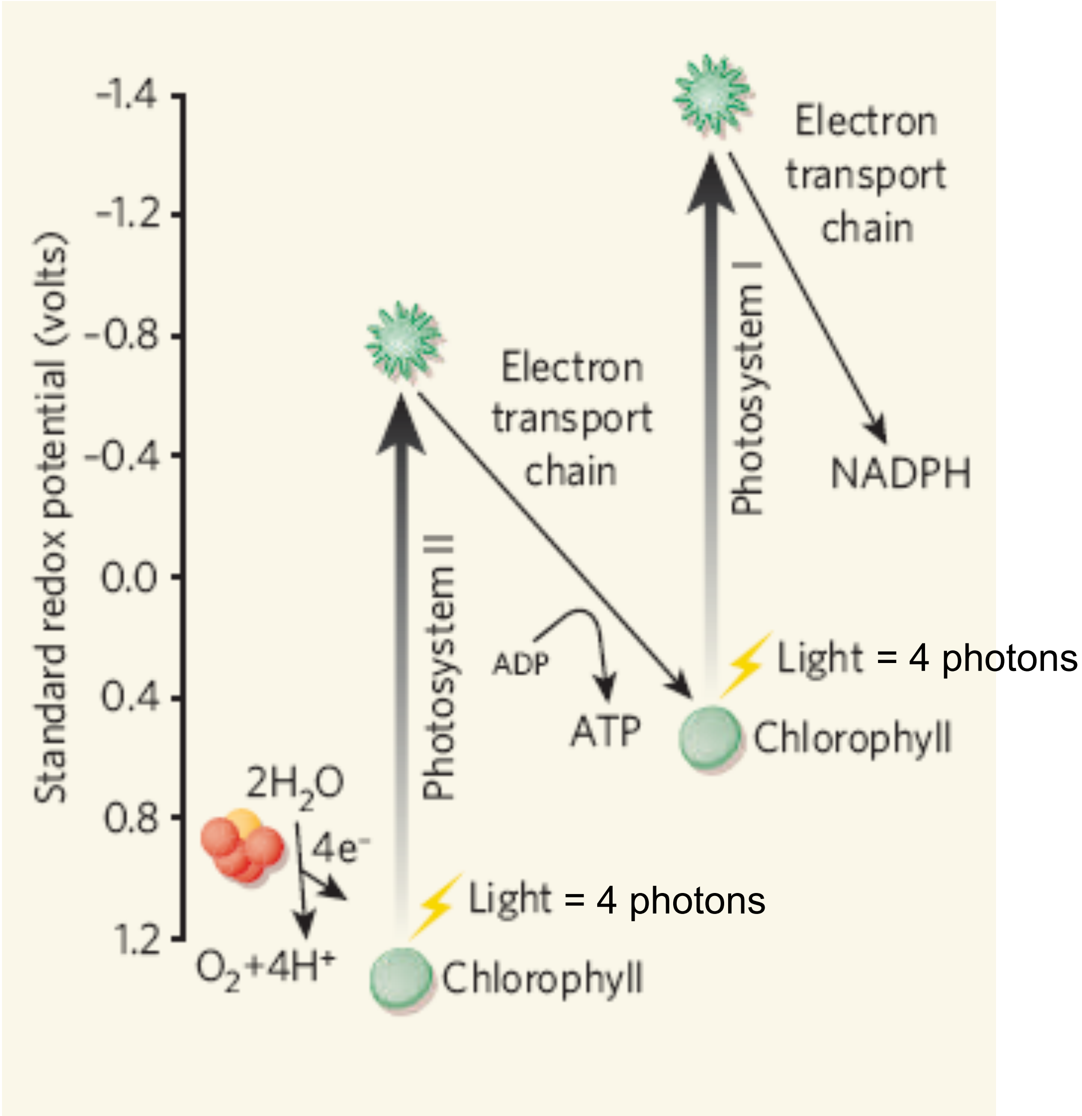


Type-I photosystems generally have cyclic electron transport



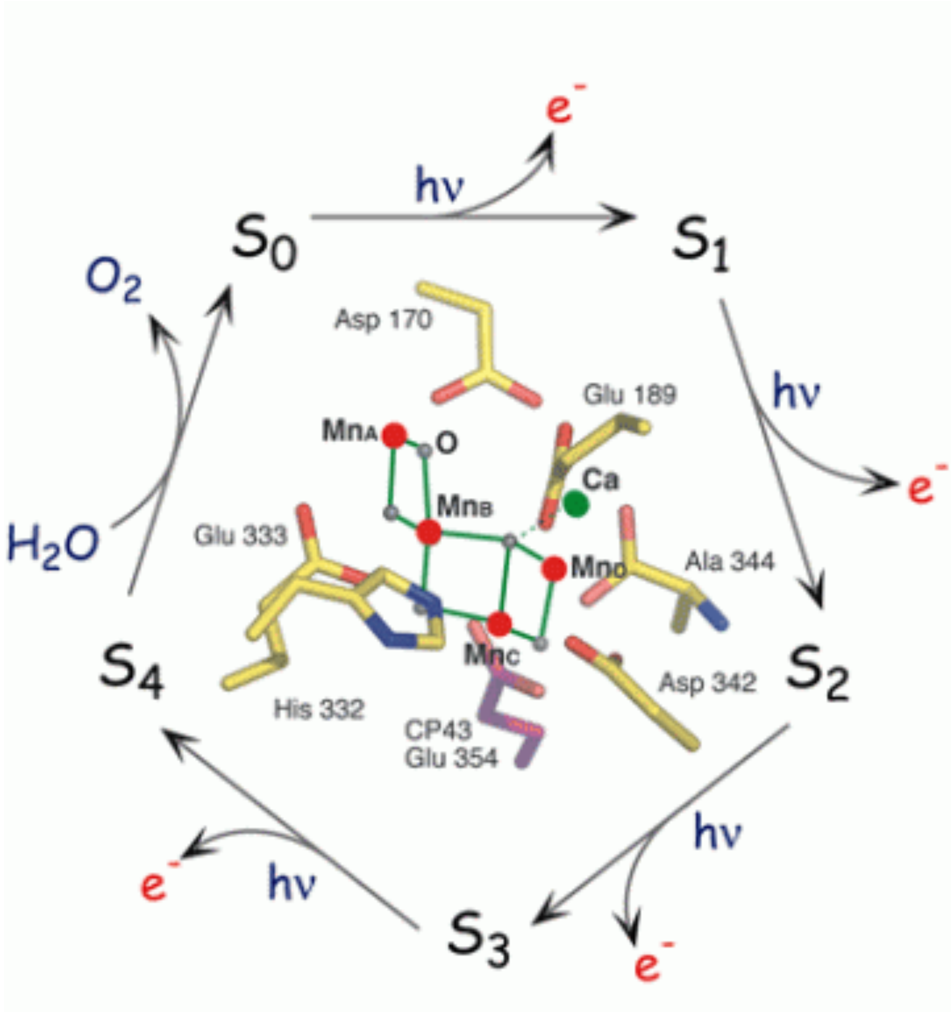
Type-II photosystems generally have linear electron transport

The 'Z' scheme



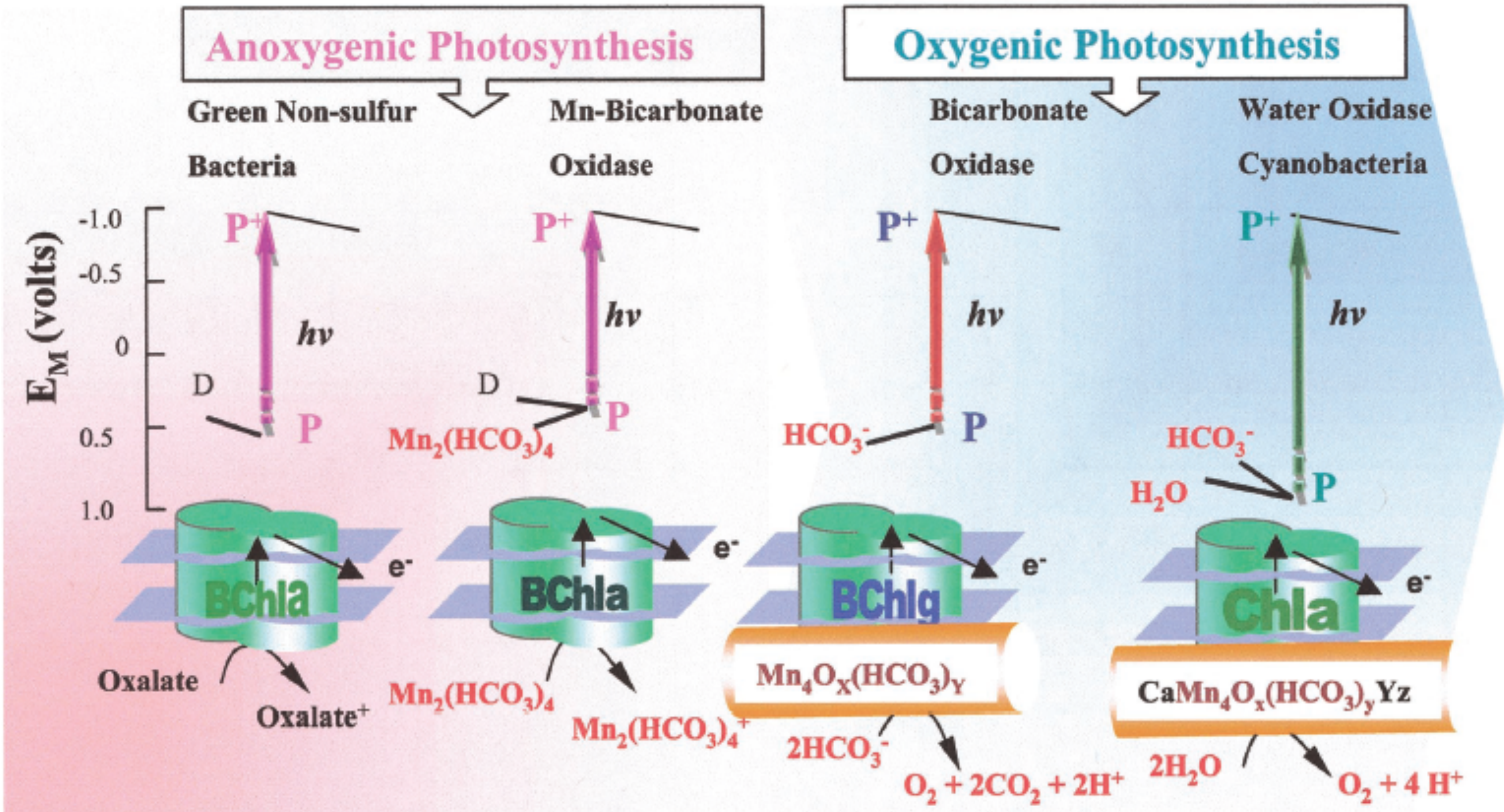
Allen & Martin (2007) *Nature* 445: 610-612

Water-splitting reaction centre



Yano *et al.* (2006) *Science* 314: 821-825

Bicarbonate (HCO_3^-) scenario

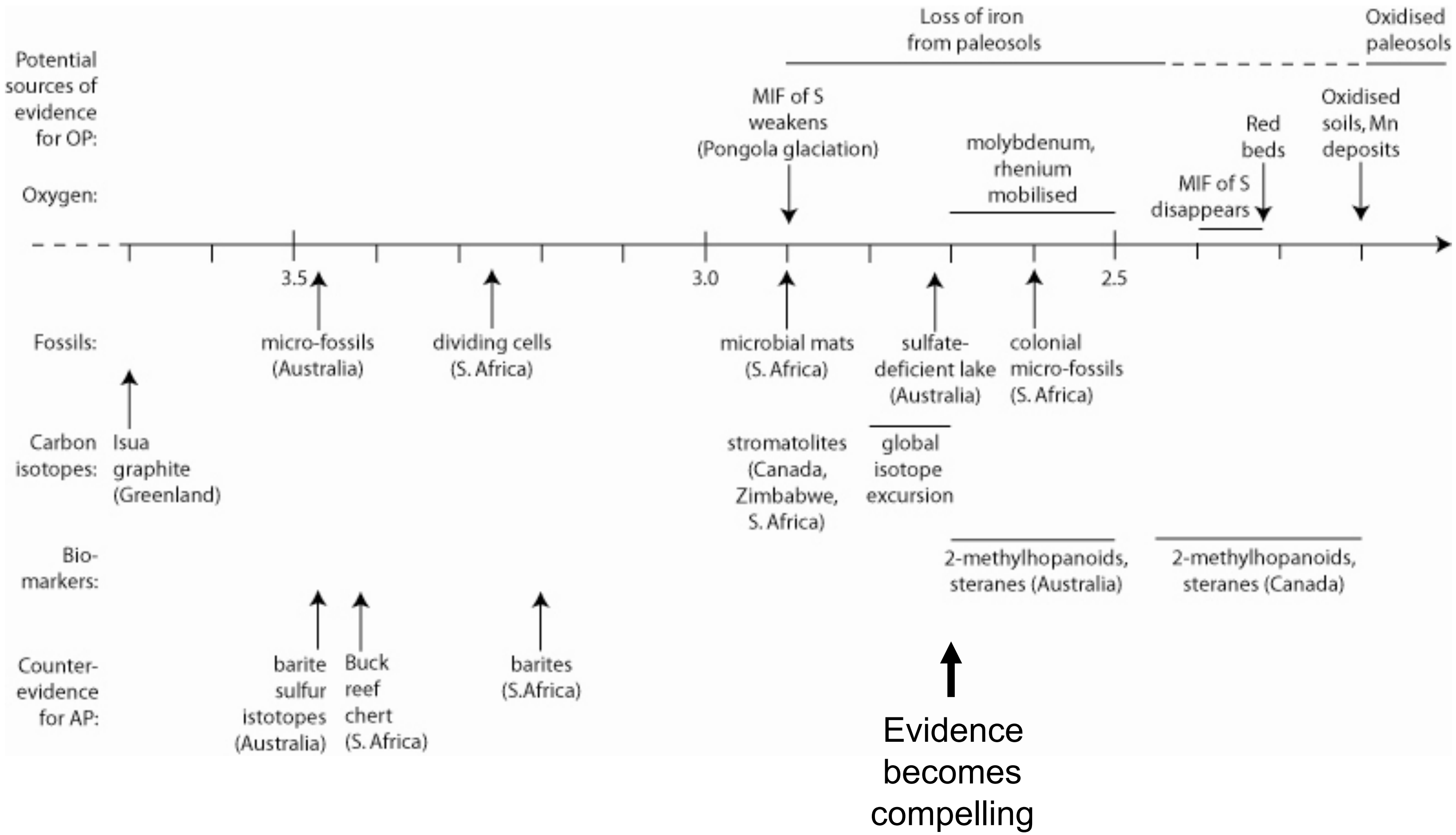


Dismukes *et al.* (2001) *PNAS* 98(5): 2170-2175

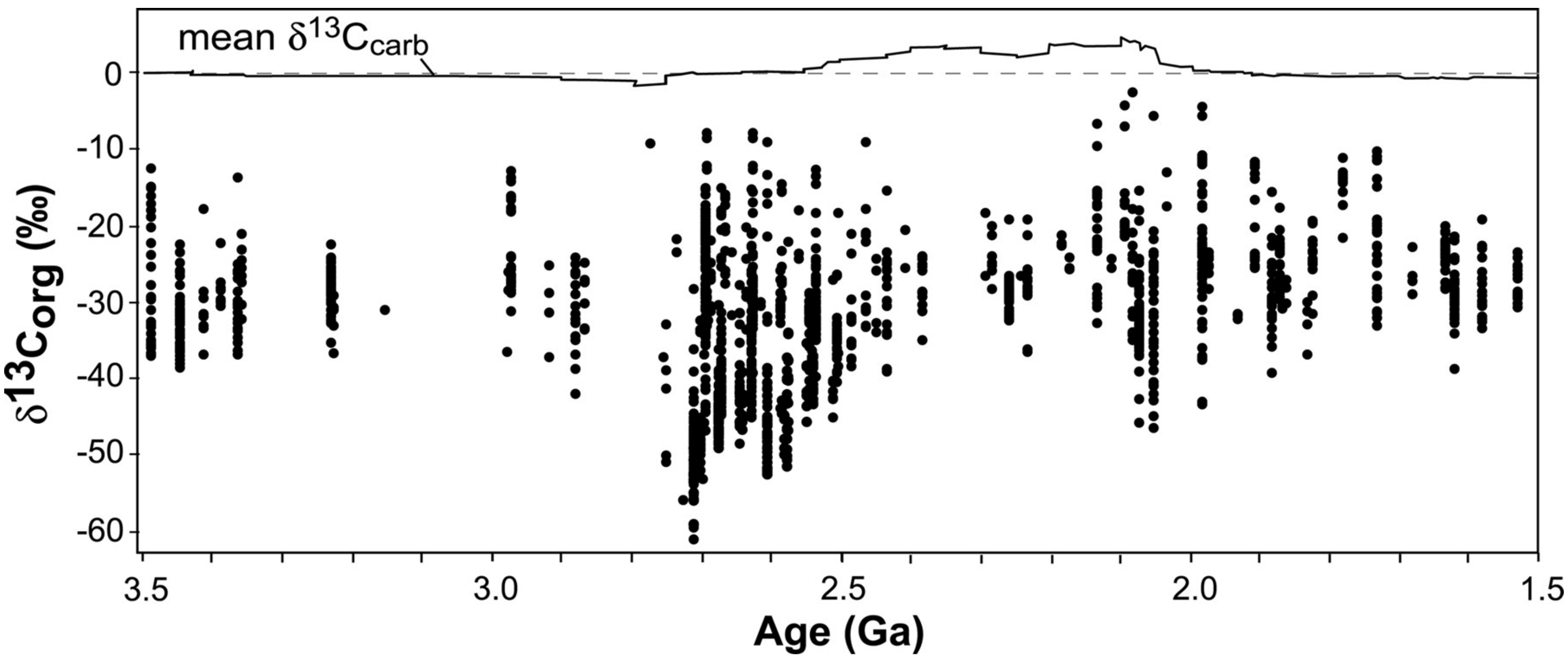
A critical step in evolution?

- A number of things all had to evolve and come together in one organism:
  - Both type-I and type-II photosystems
    - Plus the linkage between them such that a current flows
  - The water splitting complex
  - High energy light harvesting
- Each step along the way had to confer a selective advantage
  - (or at least not too much disadvantage)
- Achieving all this is inherently improbable

Origin of oxygenic photosynthesis

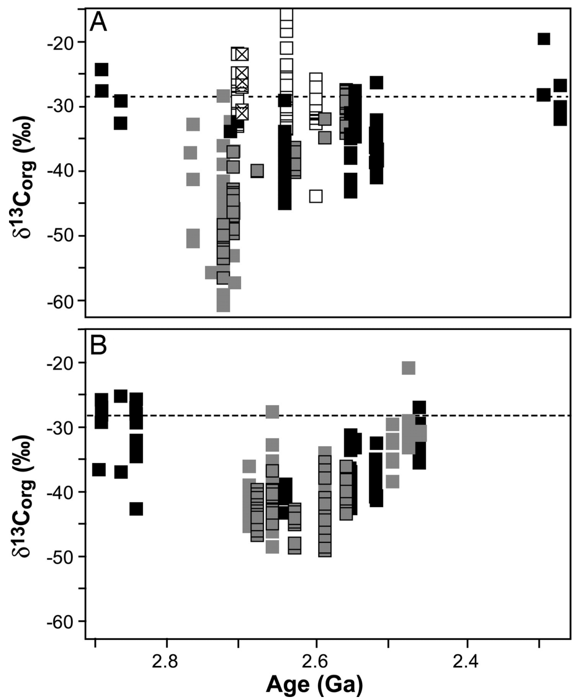


Lenton & Watson 'Revolutions that made the Earth' OUP (2011)



Shallow waters

Deep waters



Methanotrophy interpreted as producing most negative $\delta^{13}C_{org}$ values in oxygenated surface waters

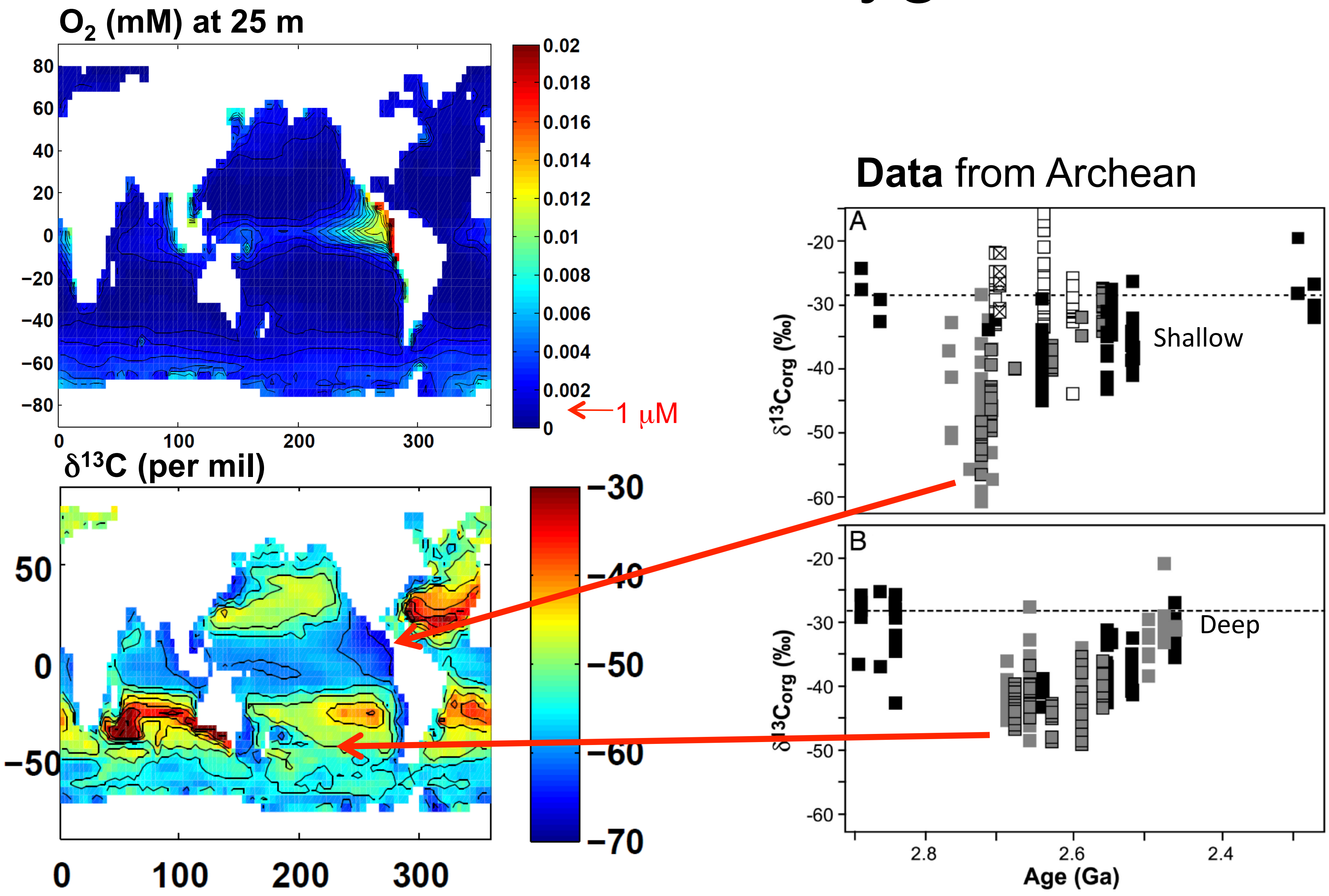
Less negative $\delta^{13}C_{org}$ trend over time interpreted as due to rise of aerobic respiration

Eigenbrode & Freeman (2006) *PNAS* 103: 15759-15764

Oxygen oases

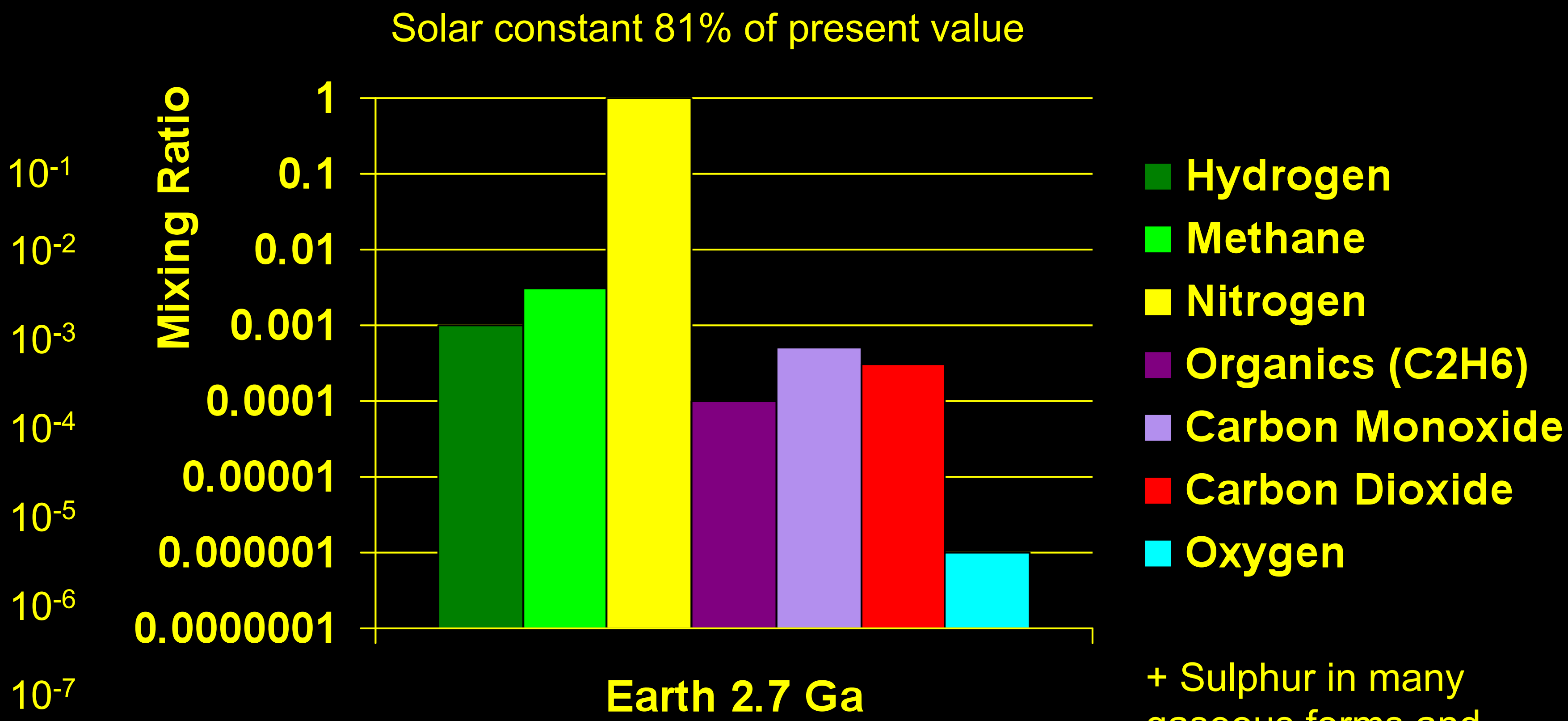
Model: MIT GCM

Atmospheric O_2 restored to zero



Stuart Daines

Archæan atmosphere ~2.7 Ga

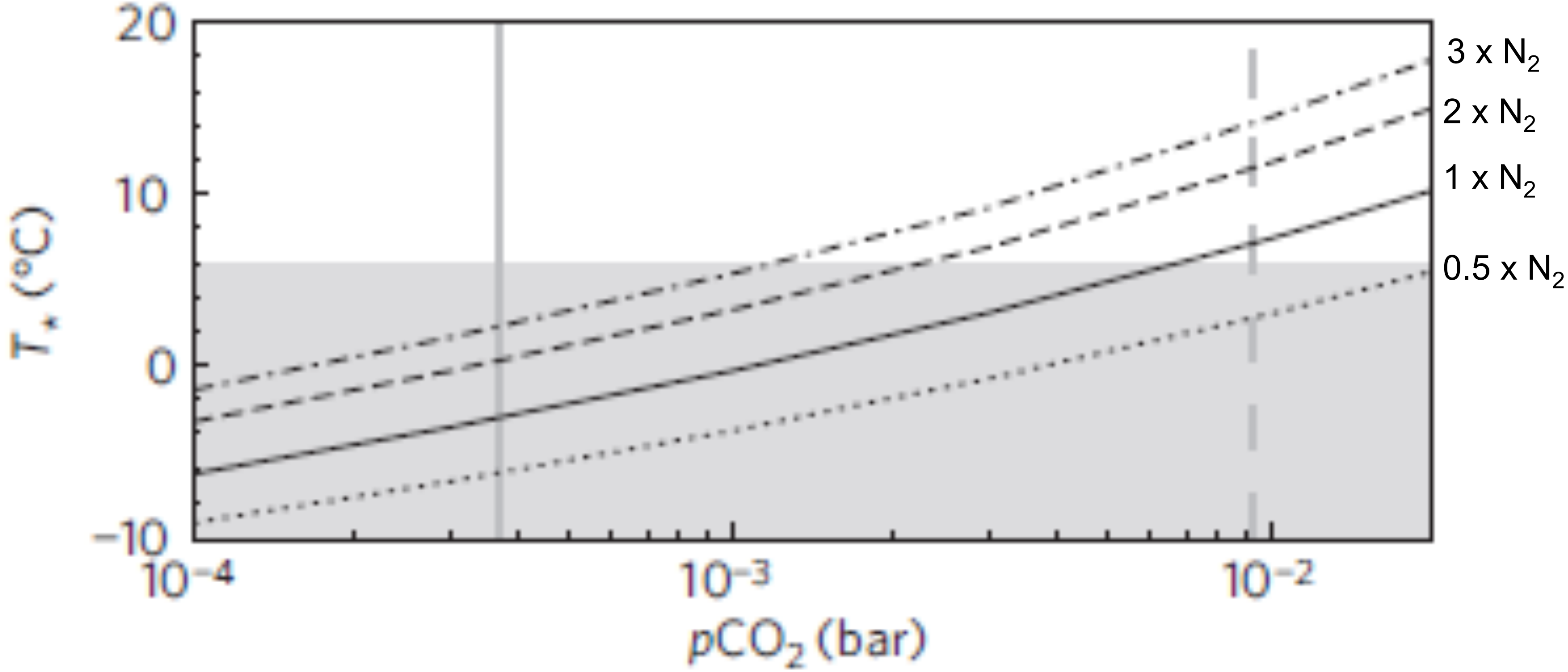


+ Sulphur in many gaseous forms and oxidation states

Detection problem: O_2 too low?

Kasting et al. (1983)
Rye et al. (1995)
Pavlov et al. (2000)

Nitrogen-enhanced warming?

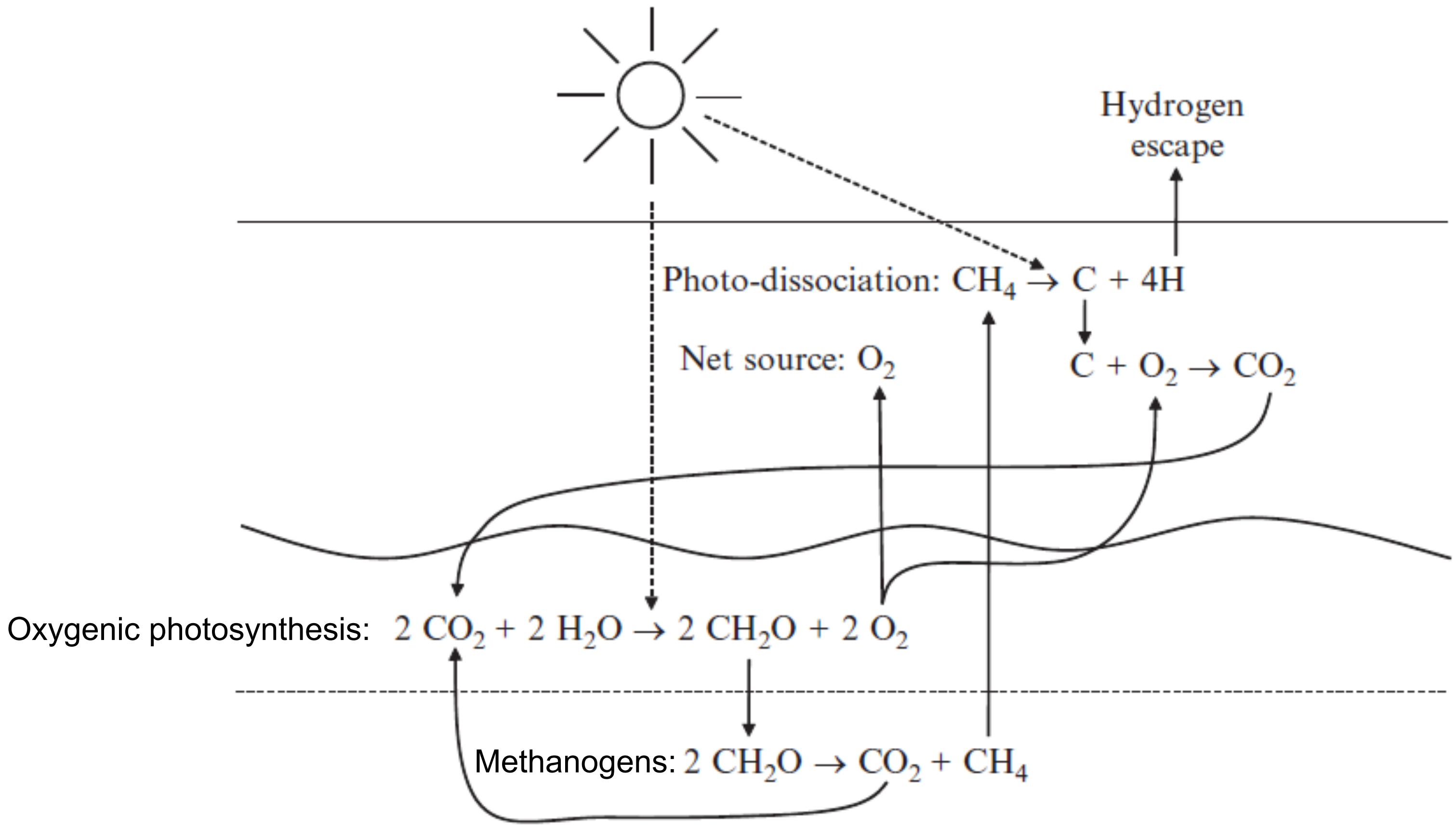


On today's Earth there is 0.5 x present atmospheric N_2 (PAN) in the crust and >1.4 x PAN in the mantle, which was once in the atmosphere

Goldblatt et al. (2009) Nature Geoscience

Hydrogen escape

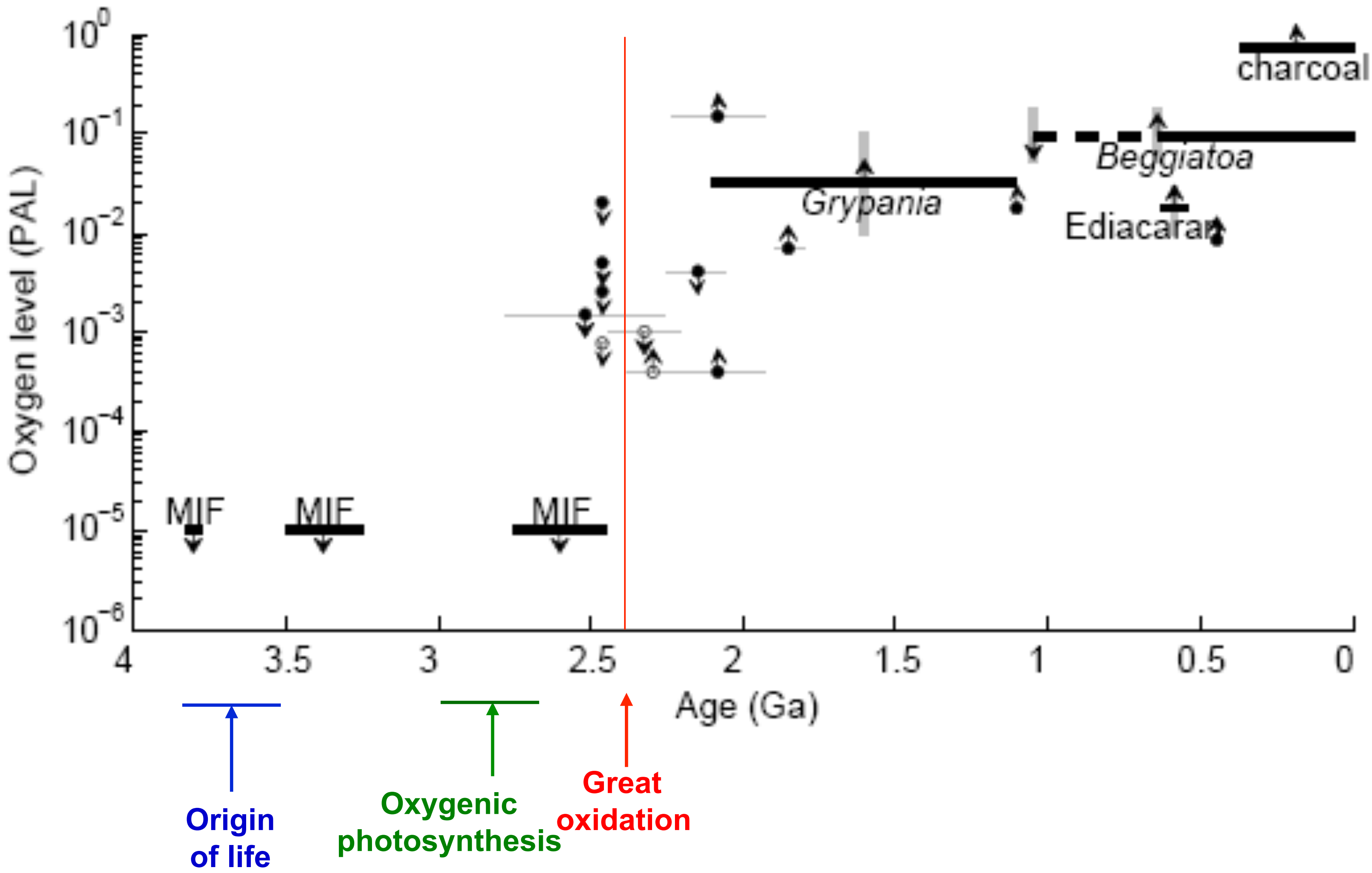
Overall reaction: $2\ H_2O \rightarrow O_2 + 4H(\uparrow space)$



Catling et al. (2001)

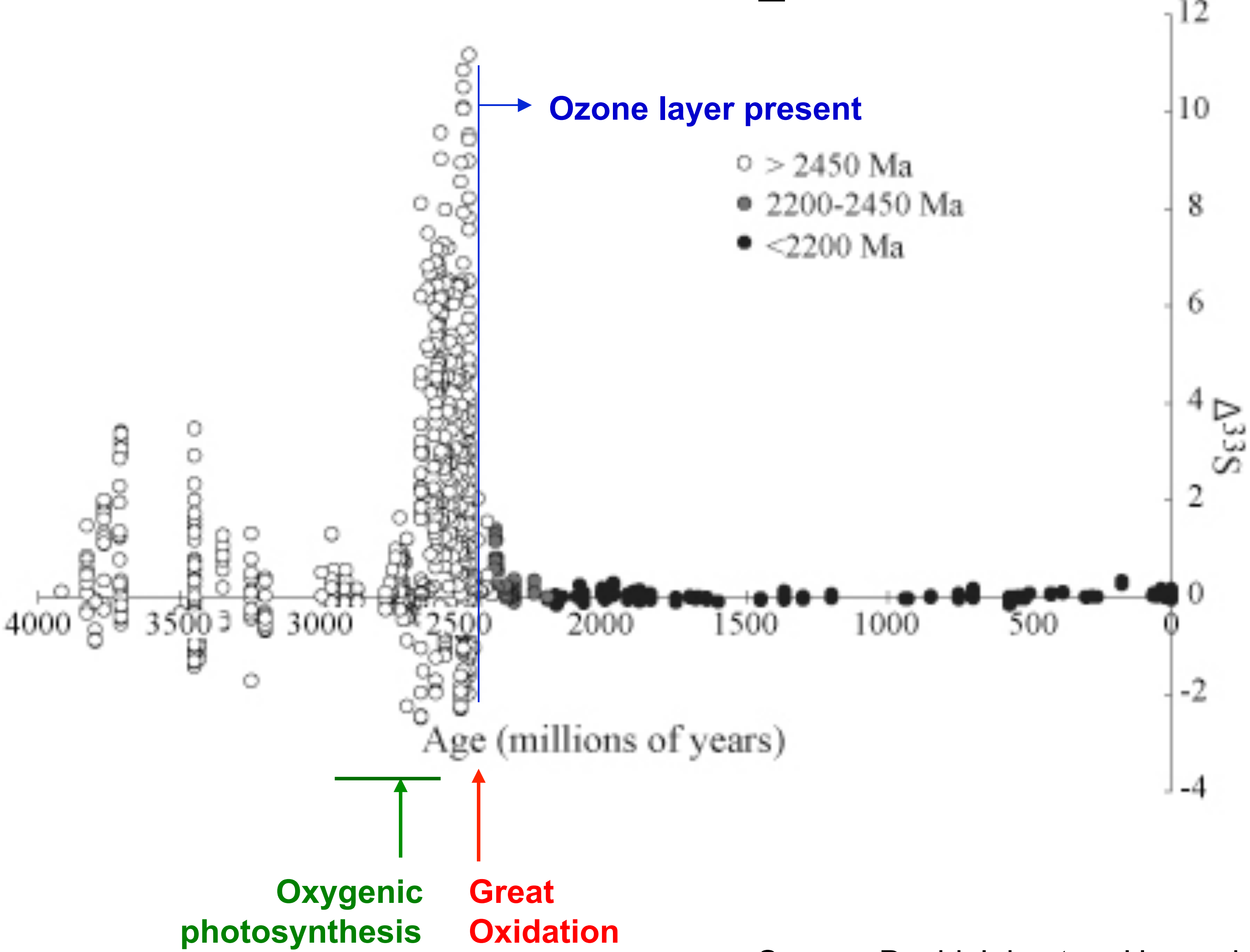
History of atmospheric oxygen

PAL = Present Atmospheric Level



Goldblatt, Lenton, Watson (2006) *Nature*

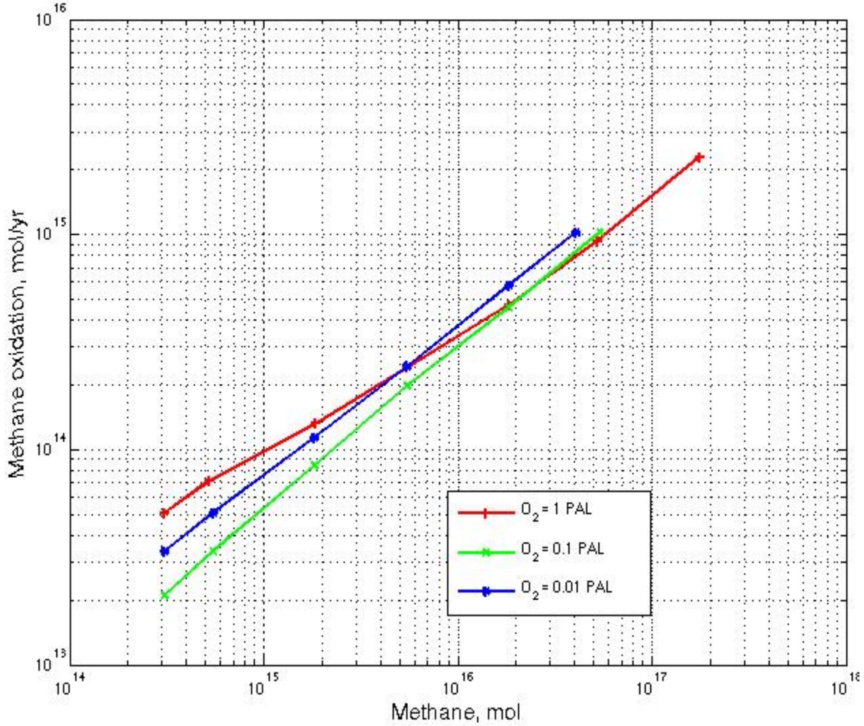
Mass Independent Fractionation (MIF) of sulphur indicates $O_2 < 10^{-5}$ PAL

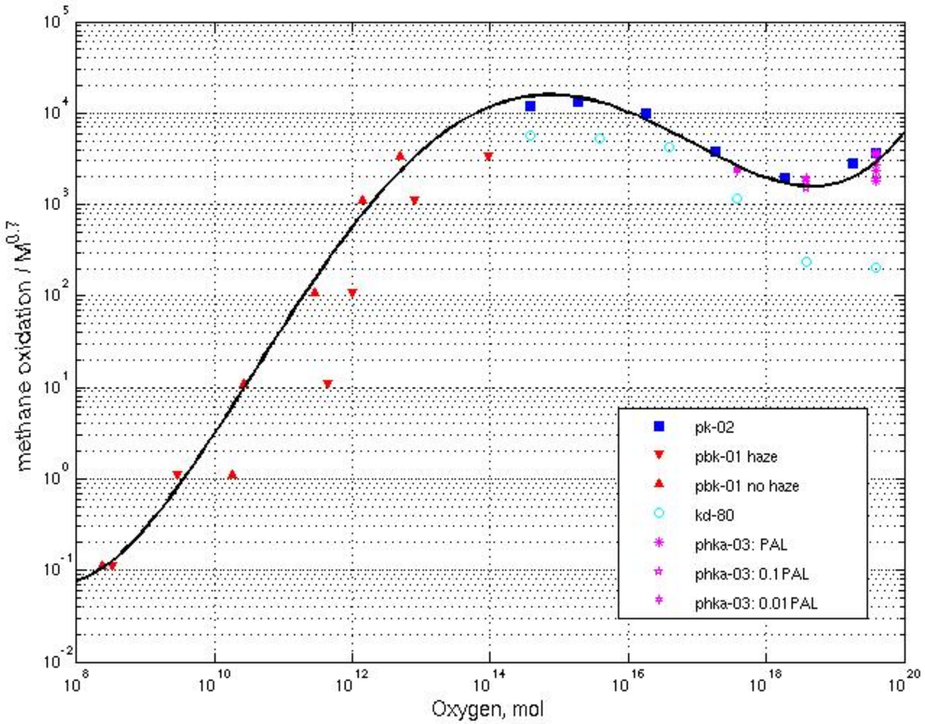


Source: David Johnston, Harvard University

Photochemical methane oxidation

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$





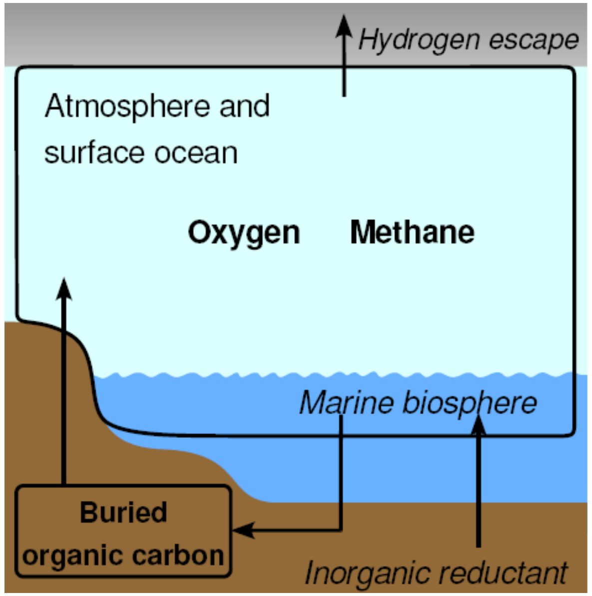
M^x: x = 0.58
x = 0.75
x = 0.70

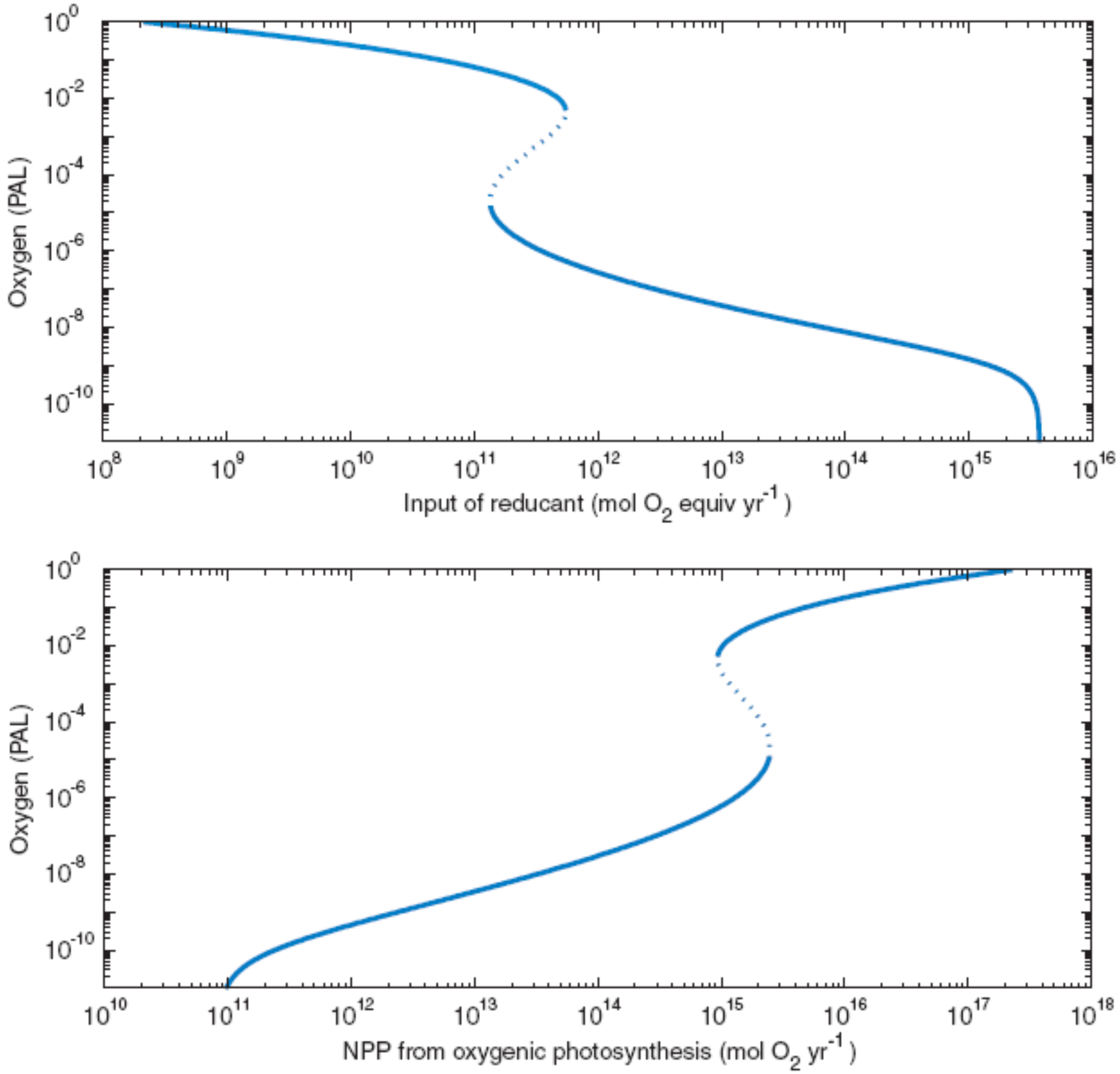
x = 0.7

Polynomial fit, $\Psi(O_2)$

Data are published results from Jim Kasting's 1D photochemical model

Bi-stability of atmospheric oxygen

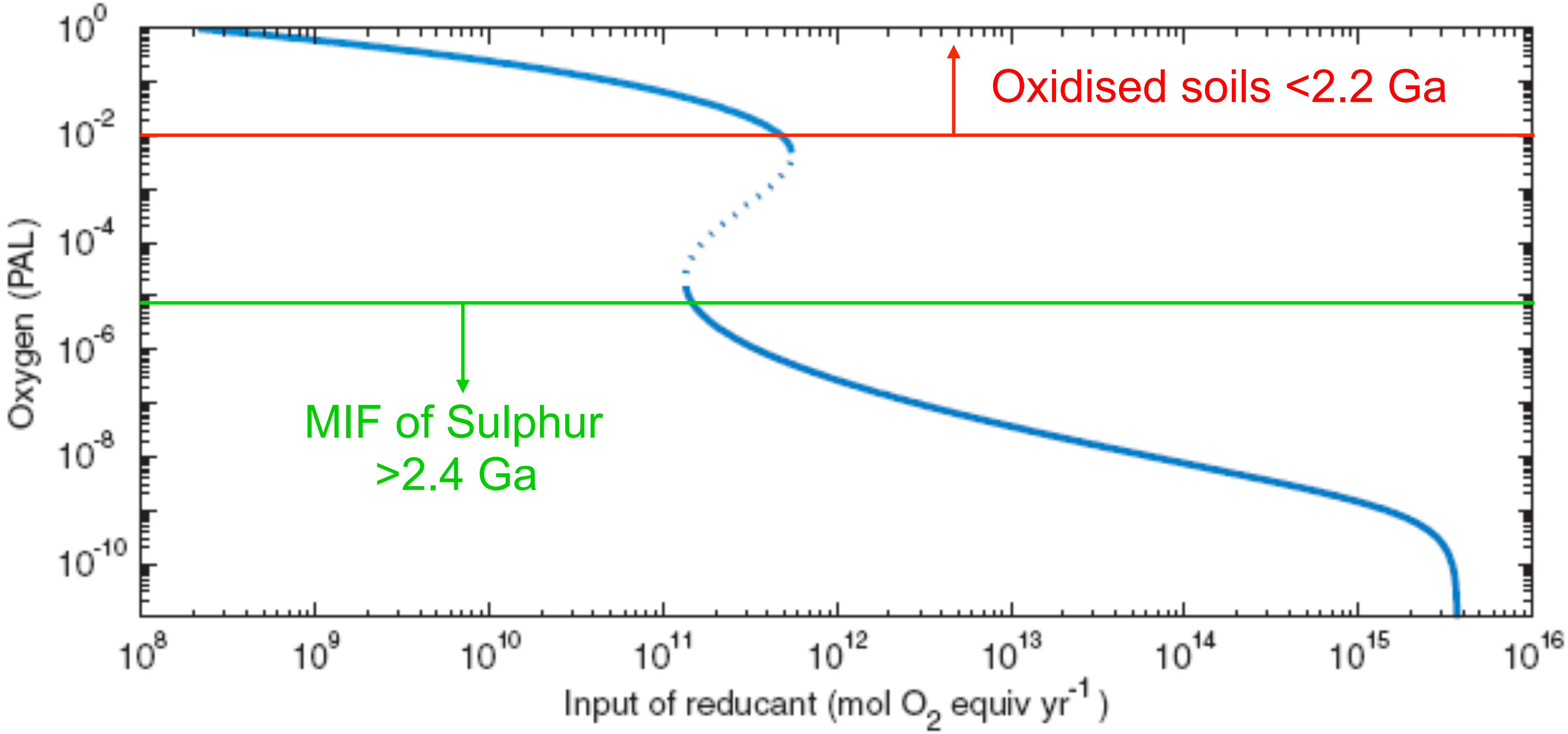




Steady states are separated by formation / loss of an ozone layer

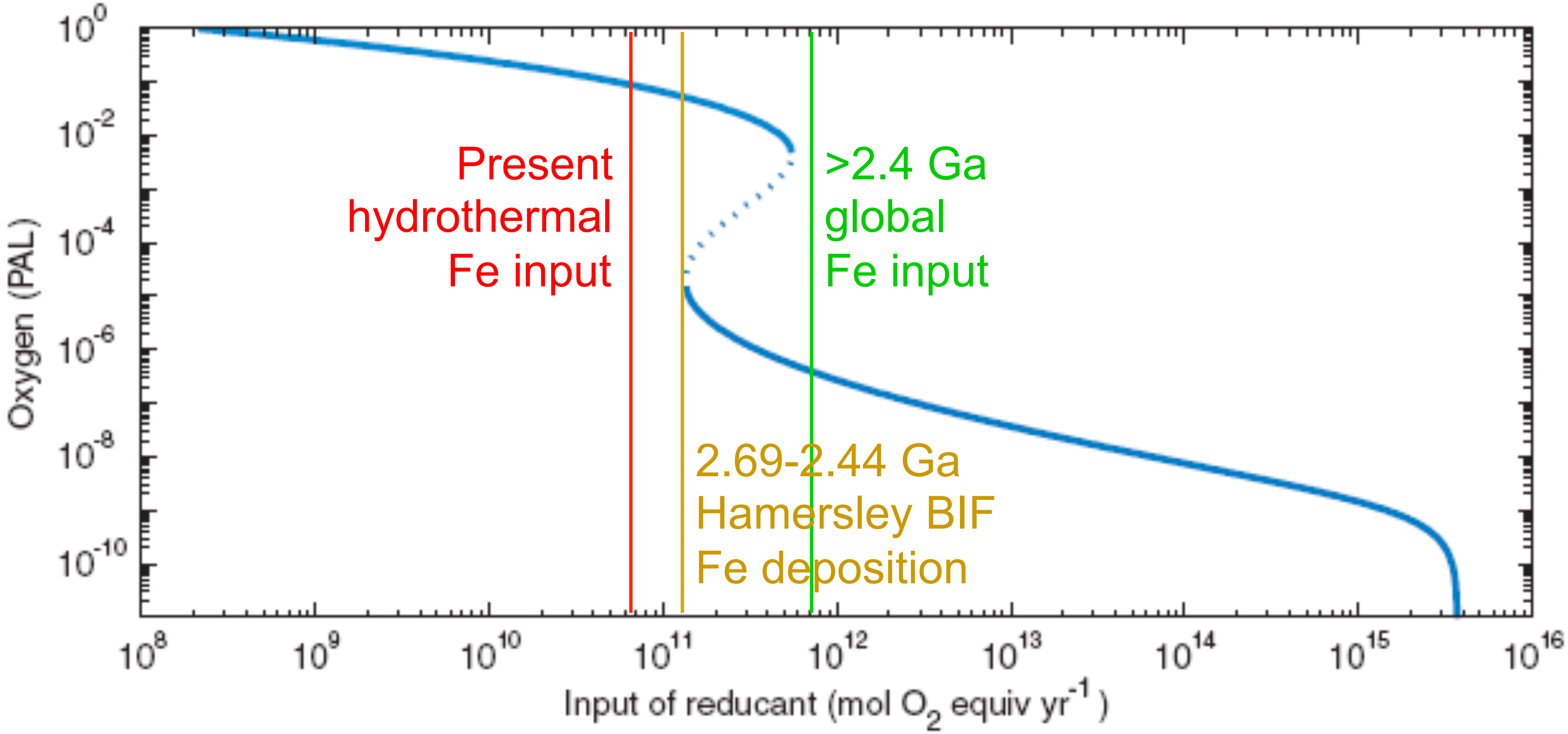
Goldblatt, Lenton, Watson (2006) *Nature*

Bi-stability of atmospheric oxygen



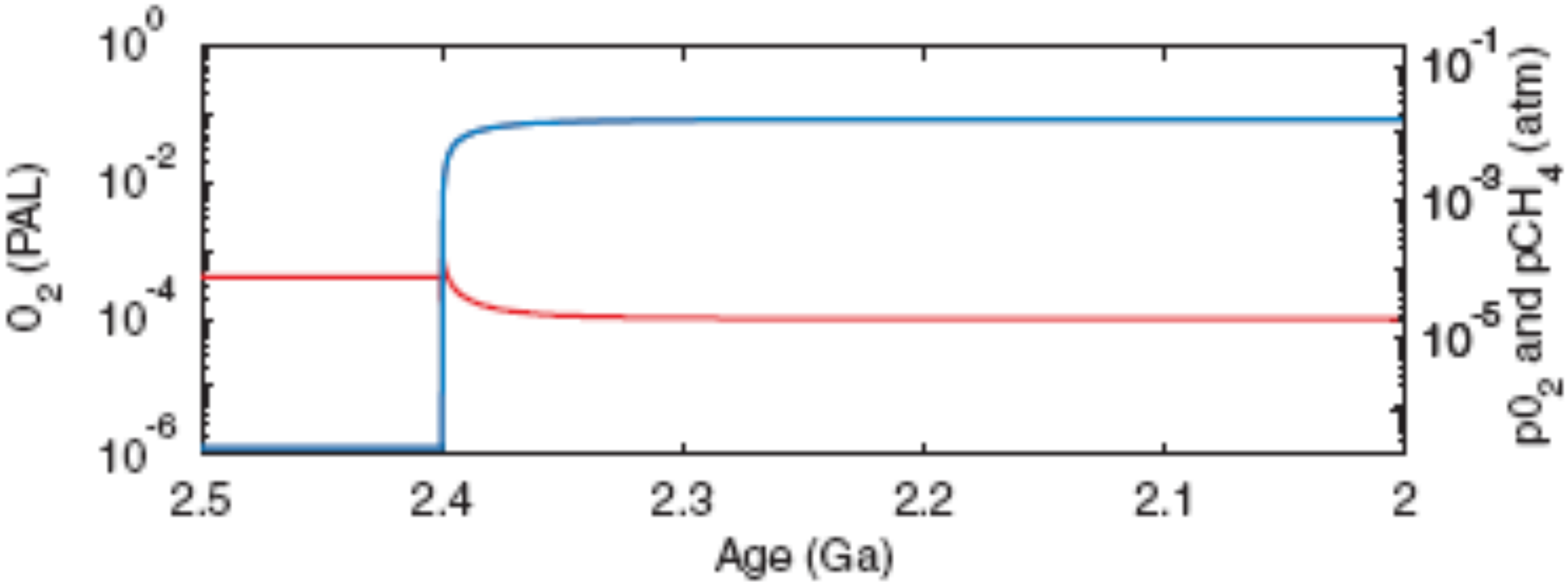
Goldblatt, Lenton, Watson (2006) *Nature*

Bi-stability of atmospheric oxygen



Goldblatt, Lenton, Watson (2006) *Nature*

The Great Oxidation

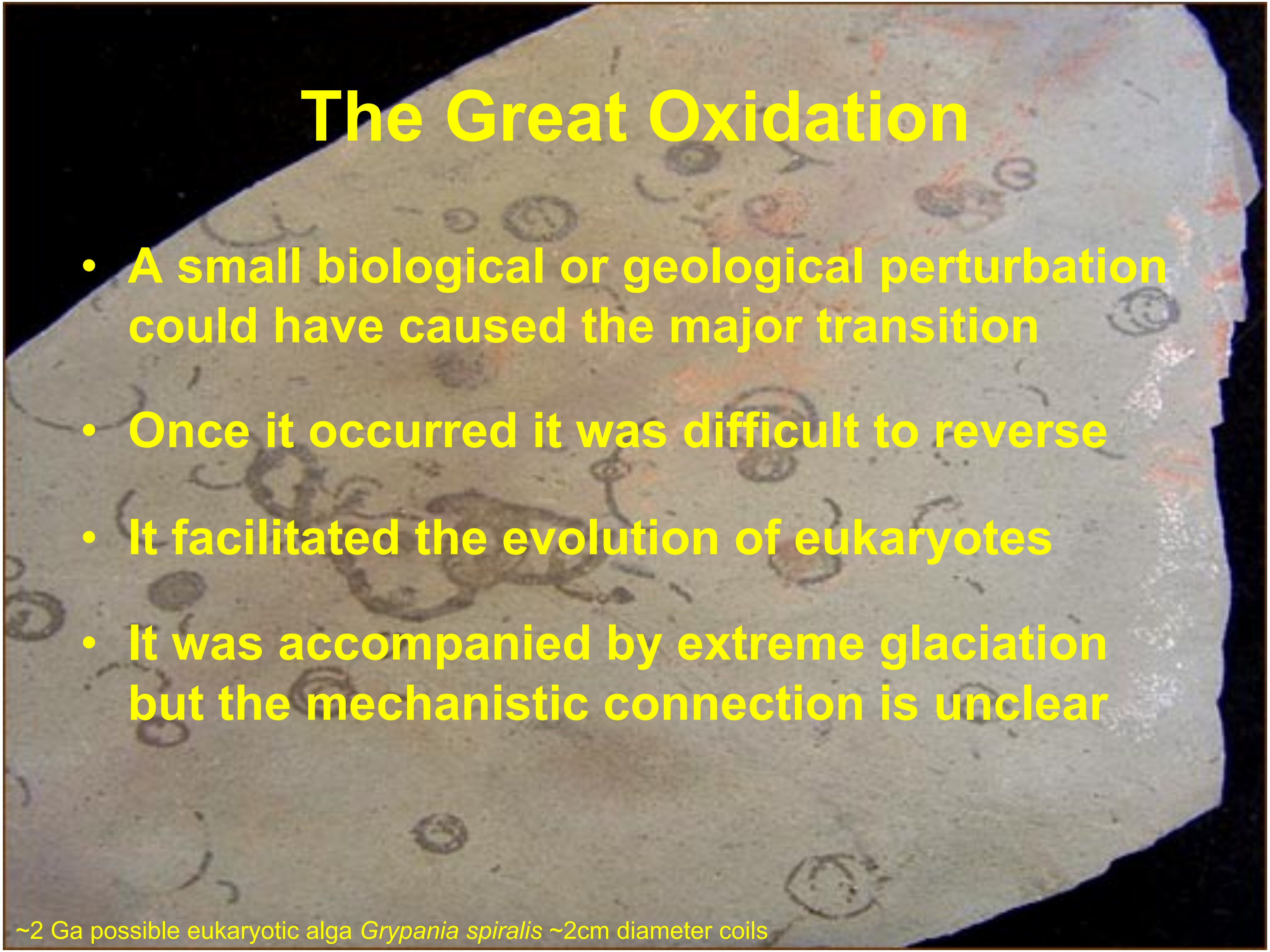


- Potential triggers:
  - A decline in reductant input from the mantle
  - An increase in net primary productivity
  - A pulse of net organic carbon burial
  - Hydrogen escape to space

Goldblatt, Lenton, Watson (2006) *Nature*

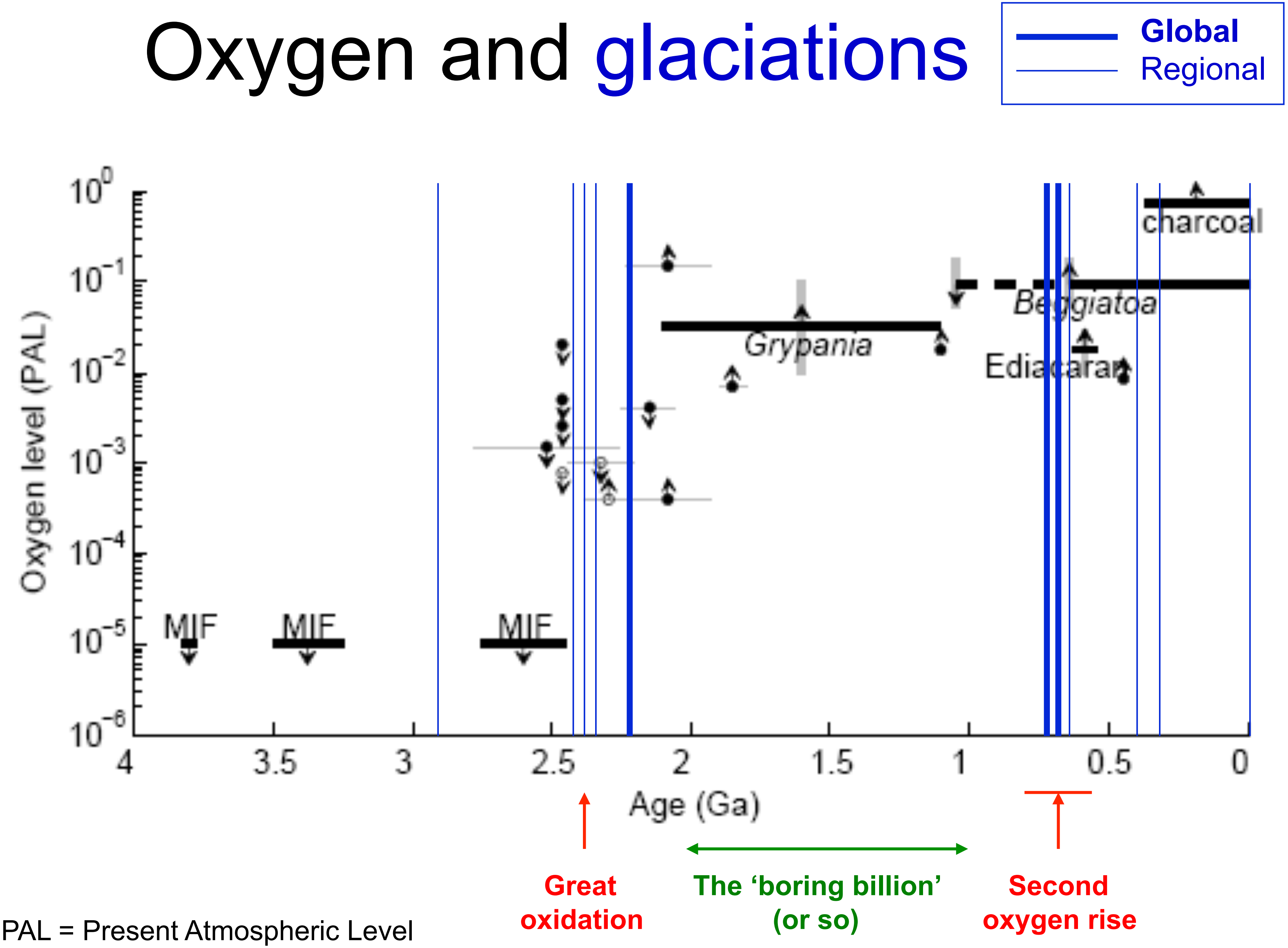
The Great Oxidation

- A small biological or geological perturbation could have caused the major transition
- Once it occurred it was difficult to reverse
- It facilitated the evolution of eukaryotes
- It was accompanied by extreme glaciation but the mechanistic connection is unclear



~2 Ga possible eukaryotic alga *Grypania spiralis* ~2cm diameter coils

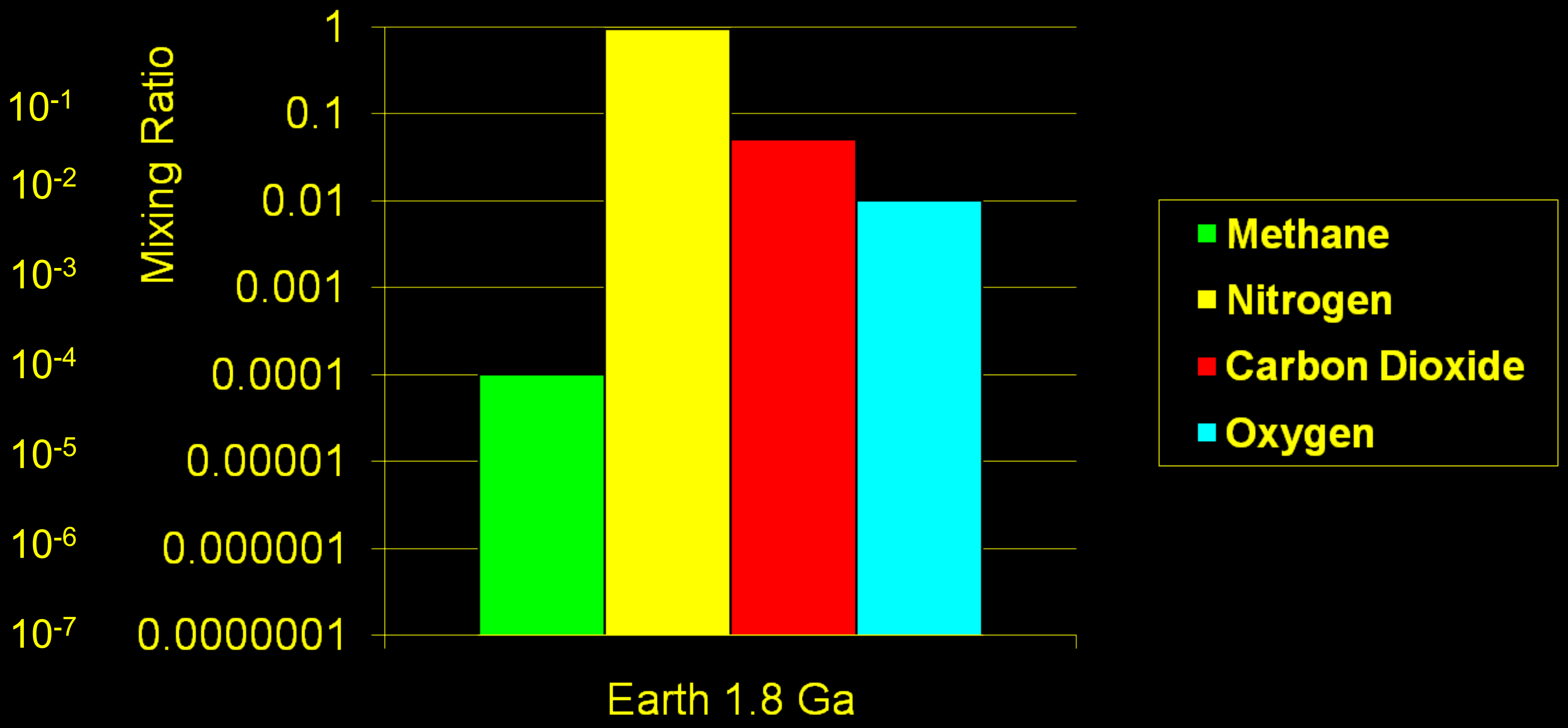
Oxygen and glaciations



PAL = Present Atmospheric Level

Major gases ~1.8 Ga

Solar constant 87% of present value



Ozone layer has formed

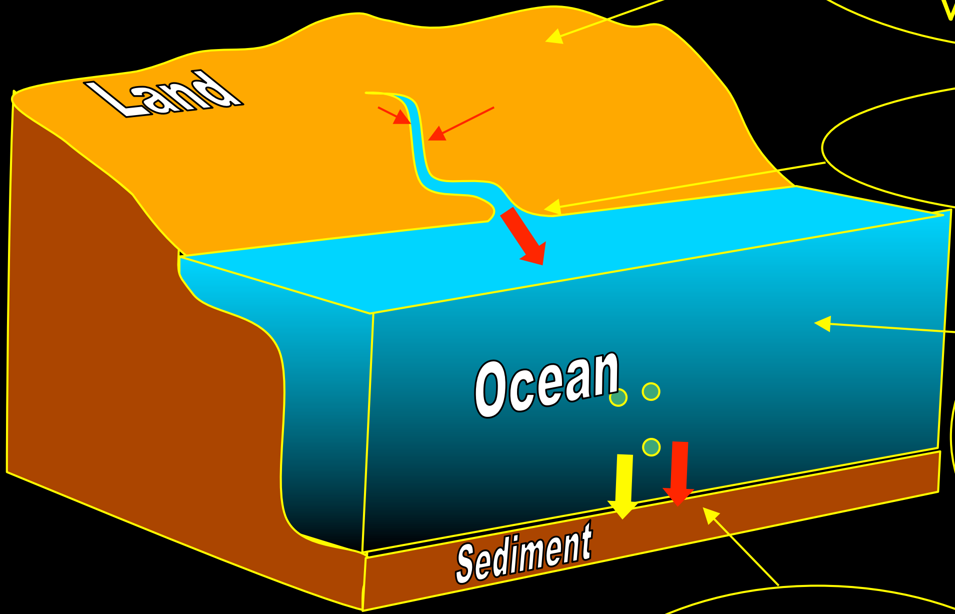
Disequilibrium of CH_4 and O_2 detectable!

Segura et al. (2003) Astrobiology

The Canfield ocean

Oxygen in the atmosphere converts sulphide to sulphates, which are very soluble.

SO_4 is washed to the oceans



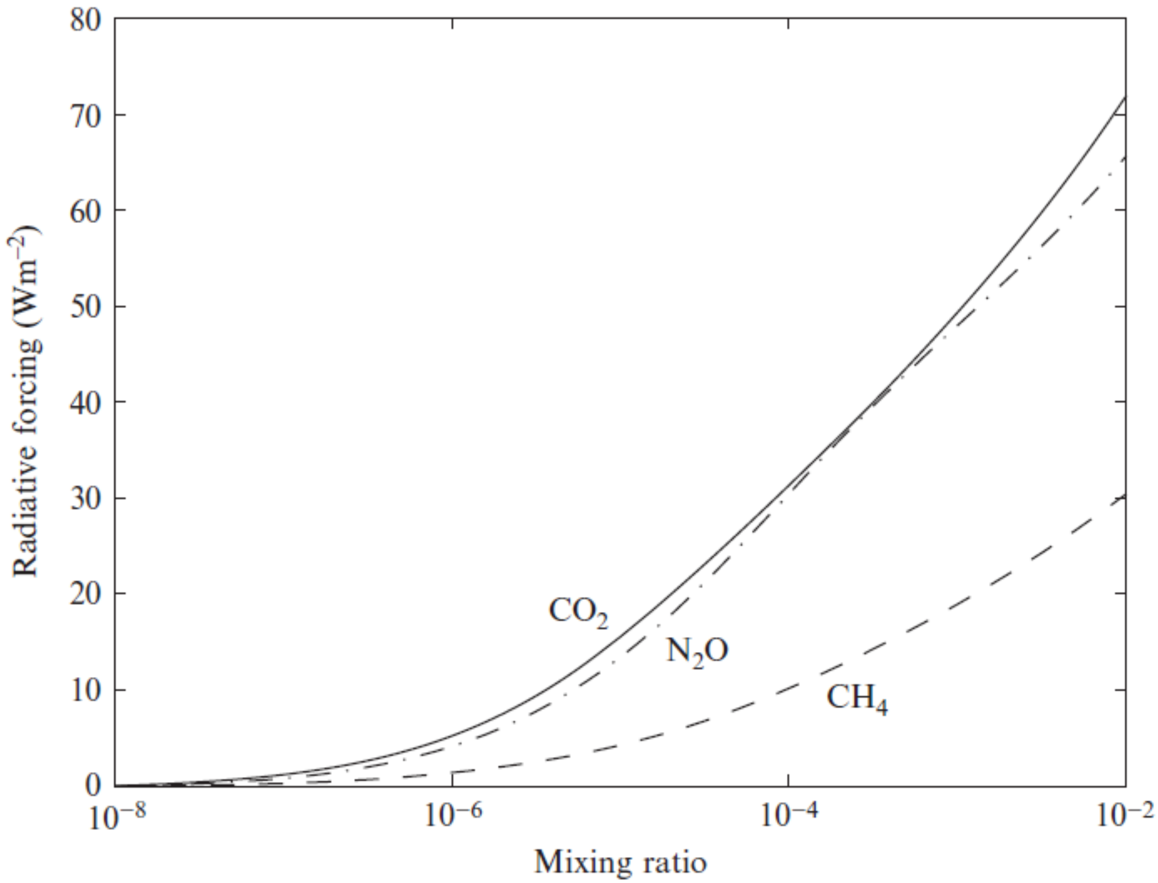
S is converted back to HS^-, and H_2S by bacteria in the low-oxygen oceans

It reacts with Fe^{2+} and removes it to sediments as FeS_2

Possible H_2S outgassing, widespread denitrification…

Canfield (1998) Nature **396**: 450-453.

Laughing gas atmosphere?

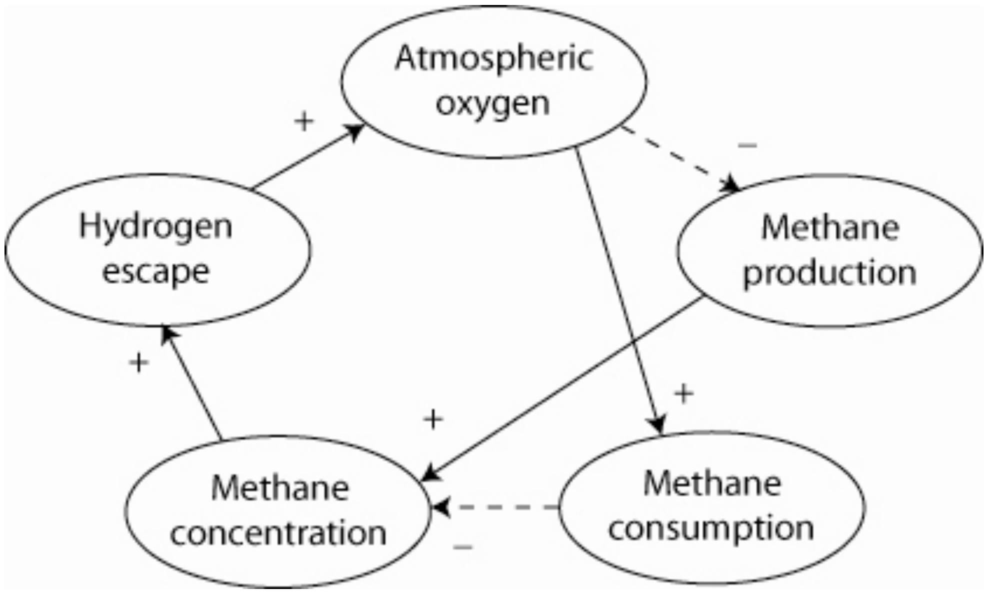


Radiative forcing calculated by a line-by-line model relative to 10^{-8} of each gas

Suggestion of Roger Buick

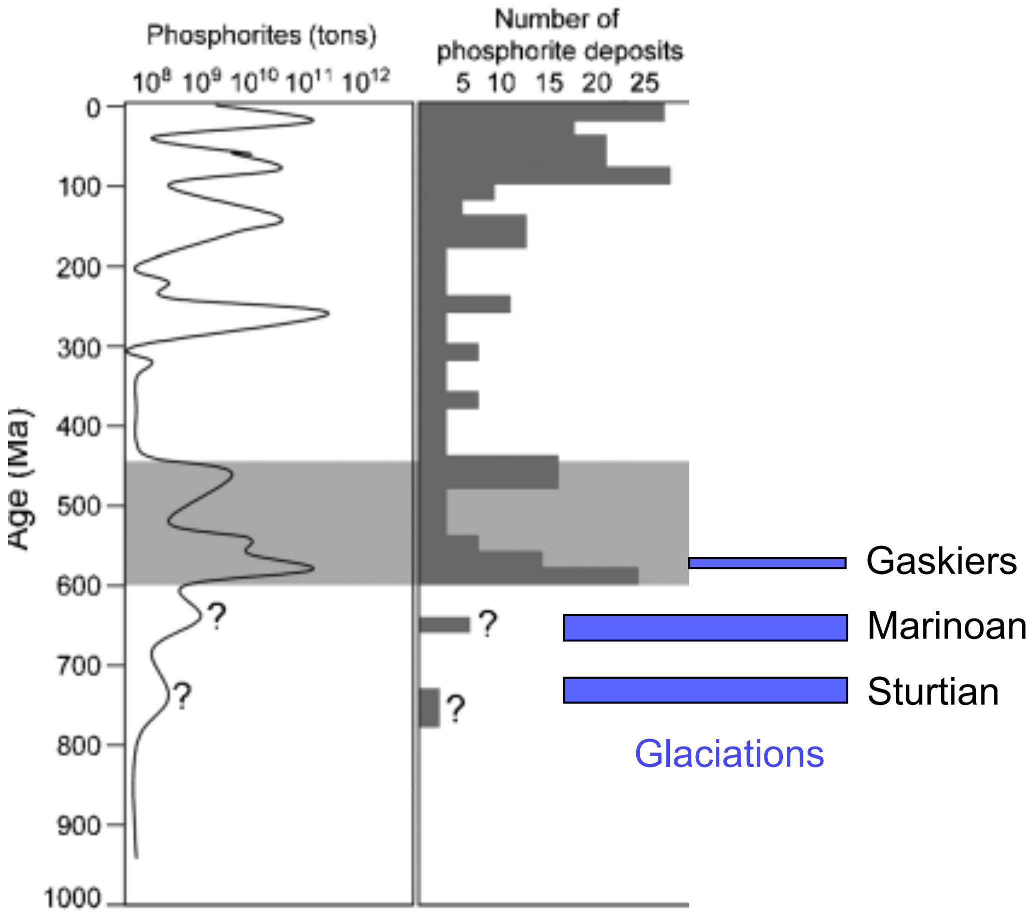
Results from Colin Goldblatt

Why did oxygen remain at an intermediate level for >1 Gyr?



There was still a lot of methane in the atmosphere and oxygen was influenced by much higher-than-today rates of hydrogen escape

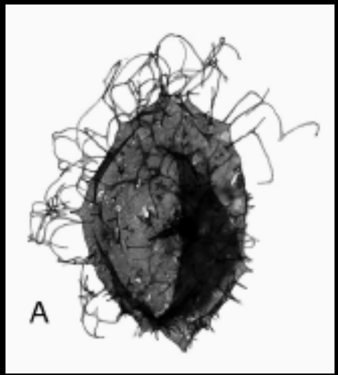
What caused O_2 to rise at the end of the Proterozoic?



- **Hypothesis: Increased P supply to the oceans**
- There are no phosphorite (phosphorus-rich rock) deposits prior to the Neoproterozoic
- There are small quantities near-simultaneous with the early snowballs.
- Numerous large deposits around 600 million years ago, nearly continuous since that time.

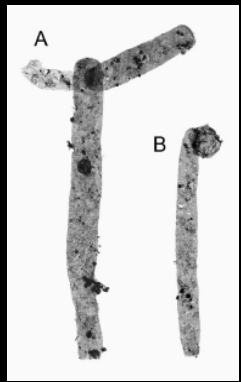
Hypothesised trigger: Land colonisation

Fungi ~1430 Ma

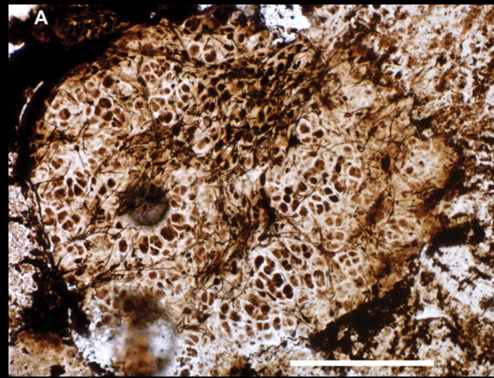


Cyanobacteria ~850 Ma

Algae ~750 Ma

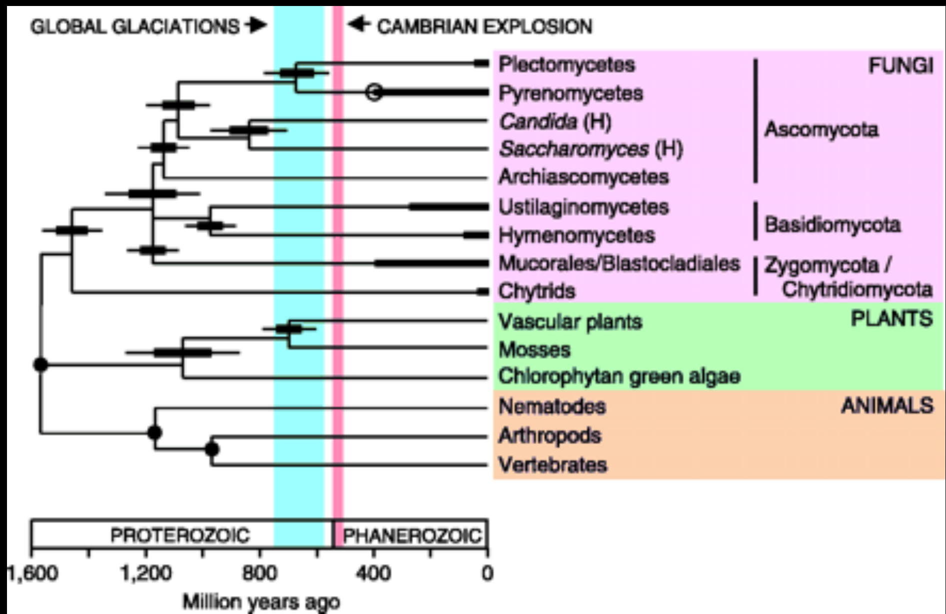


Lichens ~600 Ma



Butterfield (2005) *Paleobiology* 31: 165-182
House et al. (2000) *Geology* 28: 707-710
Butterfield (2004) *Paleobiology* 30: 231-252
Yuan *et al.* (2005) *Science* 308: 1017-1020

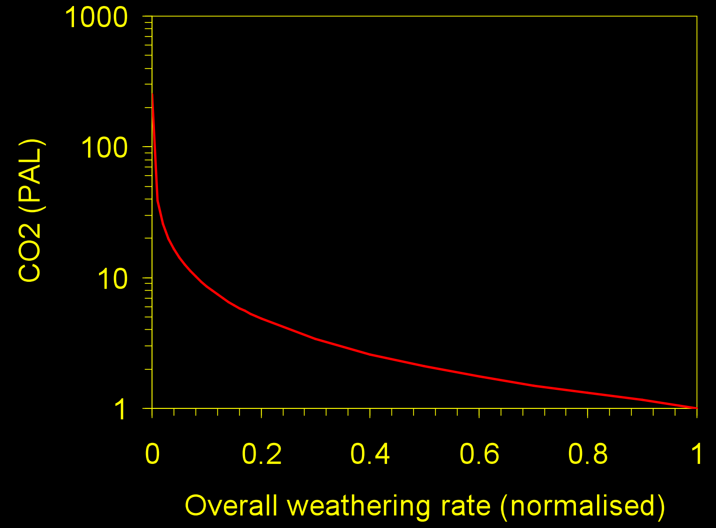
- Microfossils
- Molecular clocks
- Carbon isotope signature of photosynthetic microbial communities



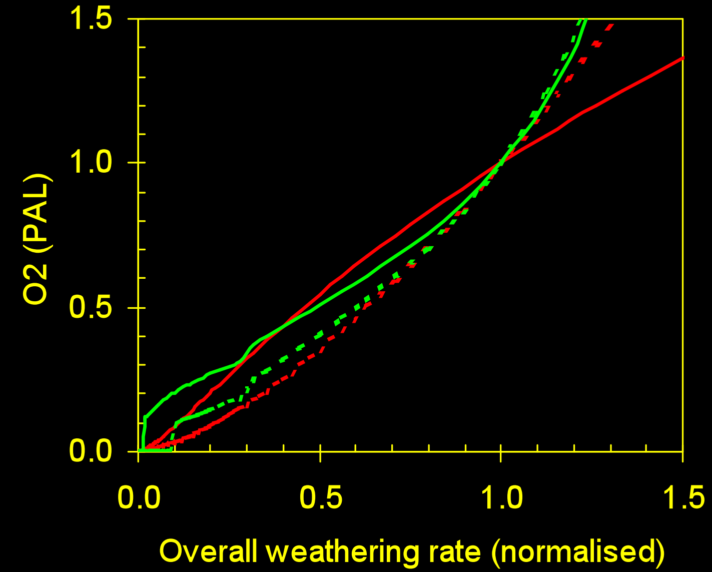
Heckman *et al.* (2001) *Science* 293: 1129-1133

Consequences of bio-weathering

- Silicates → Carbonates
  - Decrease in CO_2
  - 'Snowball Earth' events
    - ~0.74 Ga
    - ~0.59 Ga



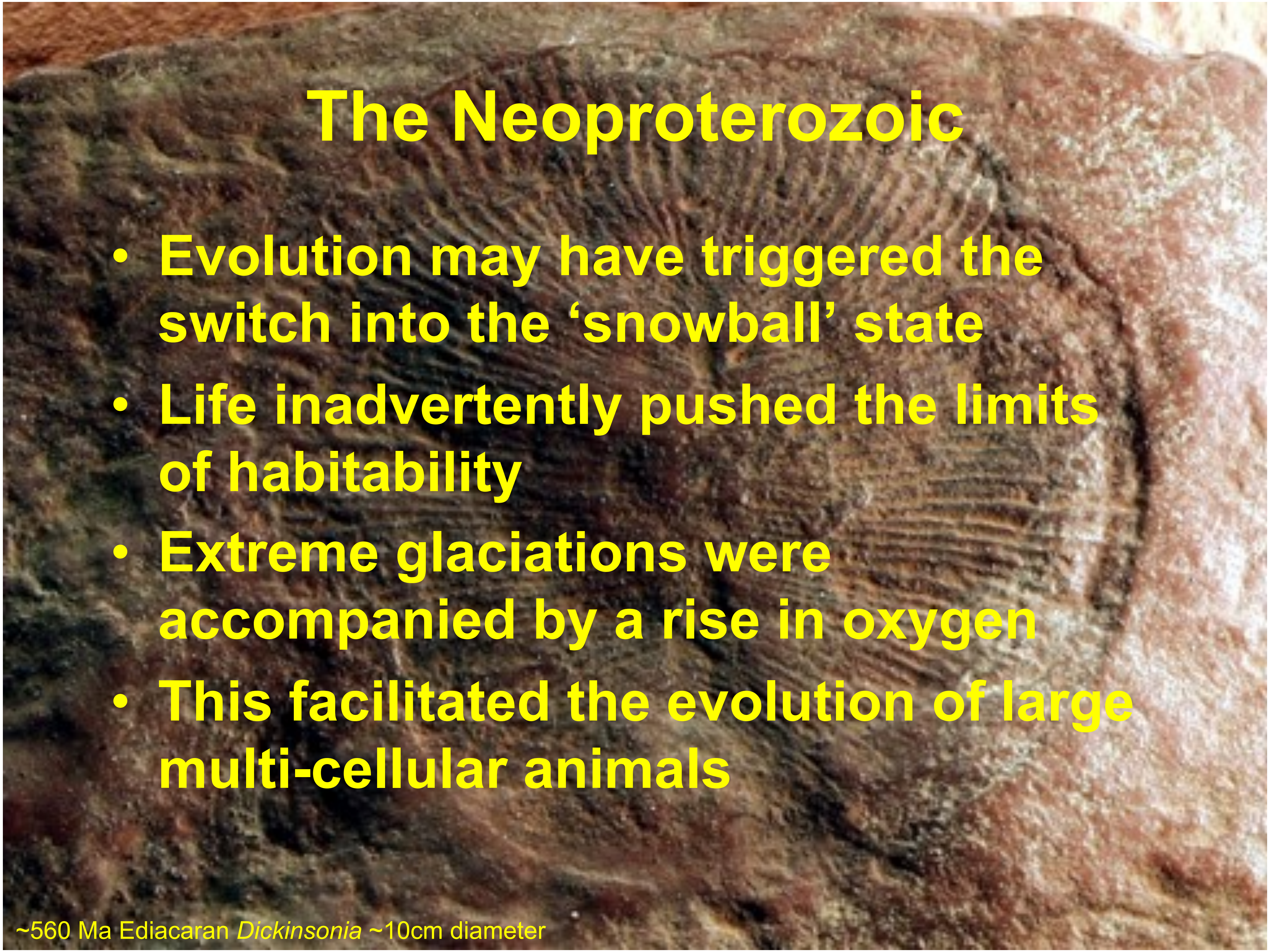
- Phosphorus → Organic C
  - Increase in O_2
  - Necessary for larger animals
    - Ediacara ~0.57 Ga
    - Cambrian 'explosion' ~0.54 Ga



Lenton & Watson (2004) *Geophys. Res. Lett.* 31: L05202

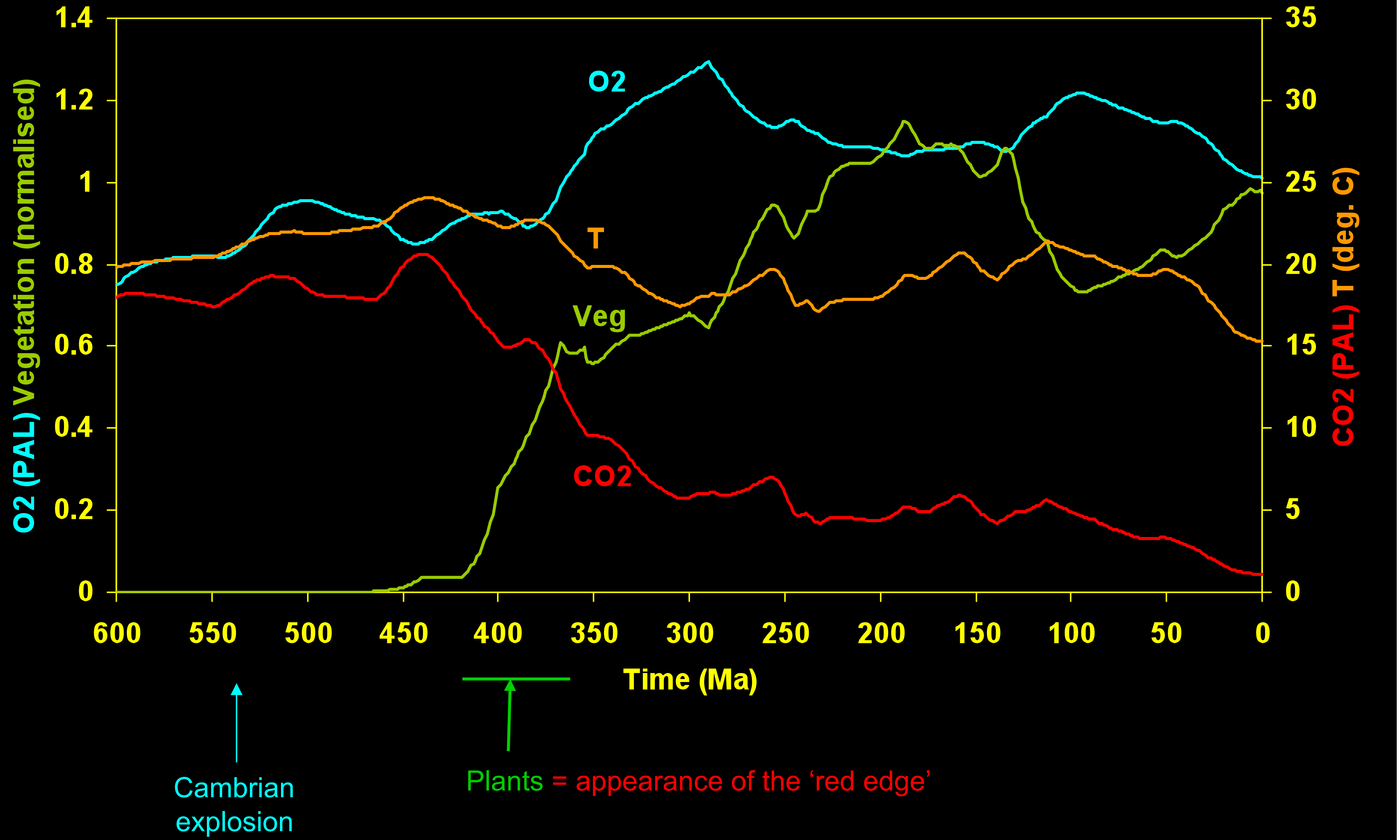
The Neoproterozoic

- Evolution may have triggered the switch into the ‘snowball’ state
- Life inadvertently pushed the limits of habitability
- Extreme glaciations were accompanied by a rise in oxygen
- This facilitated the evolution of large multi-cellular animals



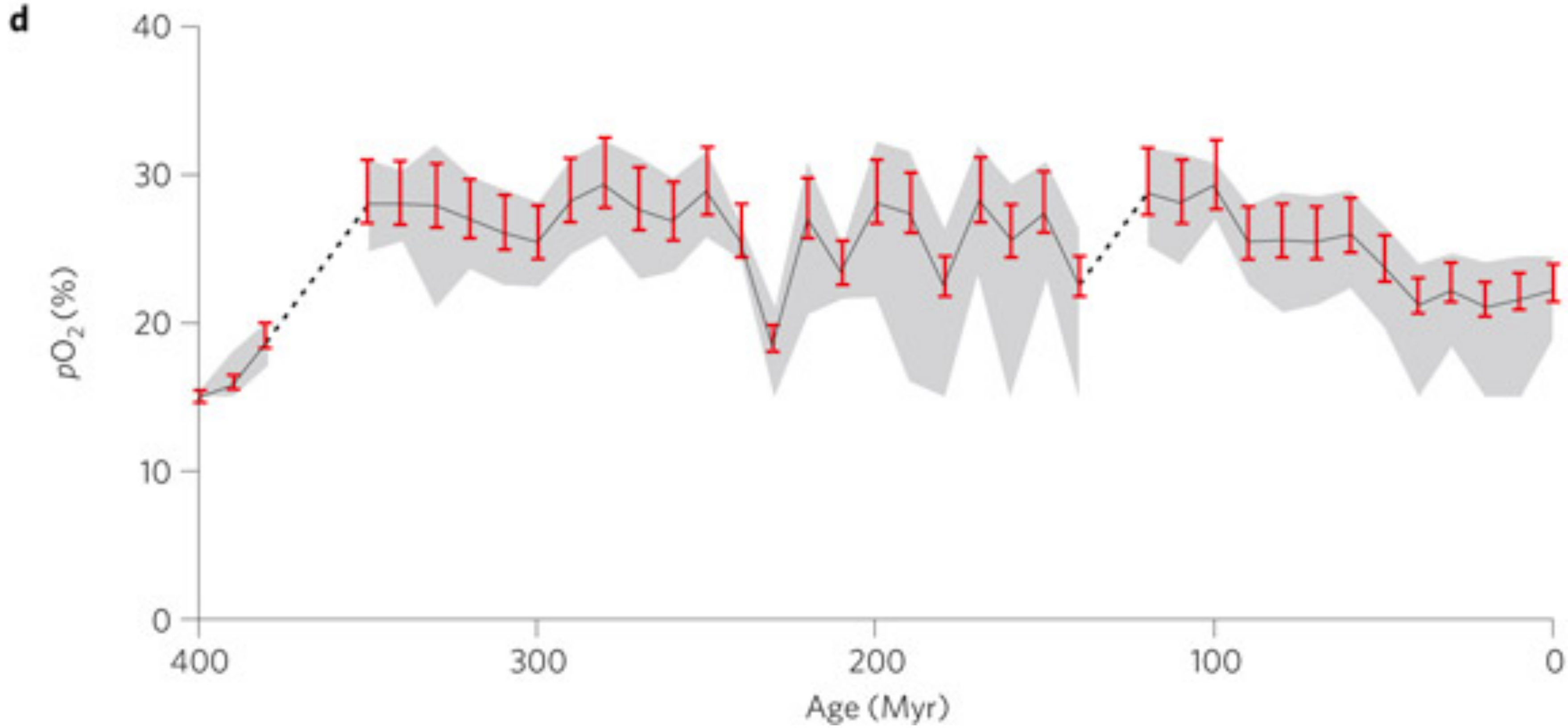
~560 Ma Ediacaran *Dickinsonia* ~10cm diameter

The Phanerozoic



COPSE model of Bergman, Lenton, Watson (2004) *Am. J. Sci.* 304: 397-437

Estimates of O_2 from the charcoal record (400-0 Ma)

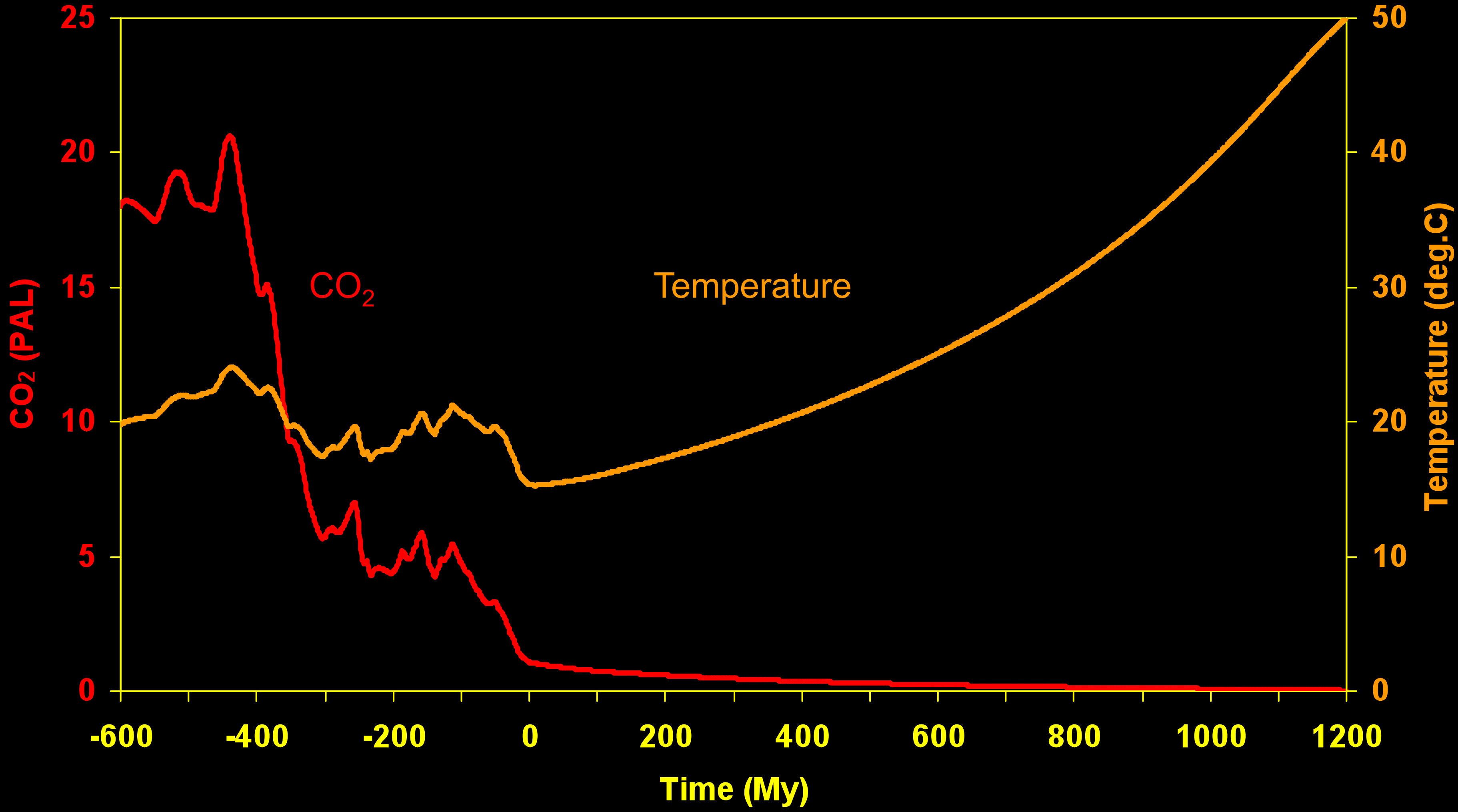


Glasspool & Scott (2010) *Nature Geoscience* **3**: 627-630

Earth future

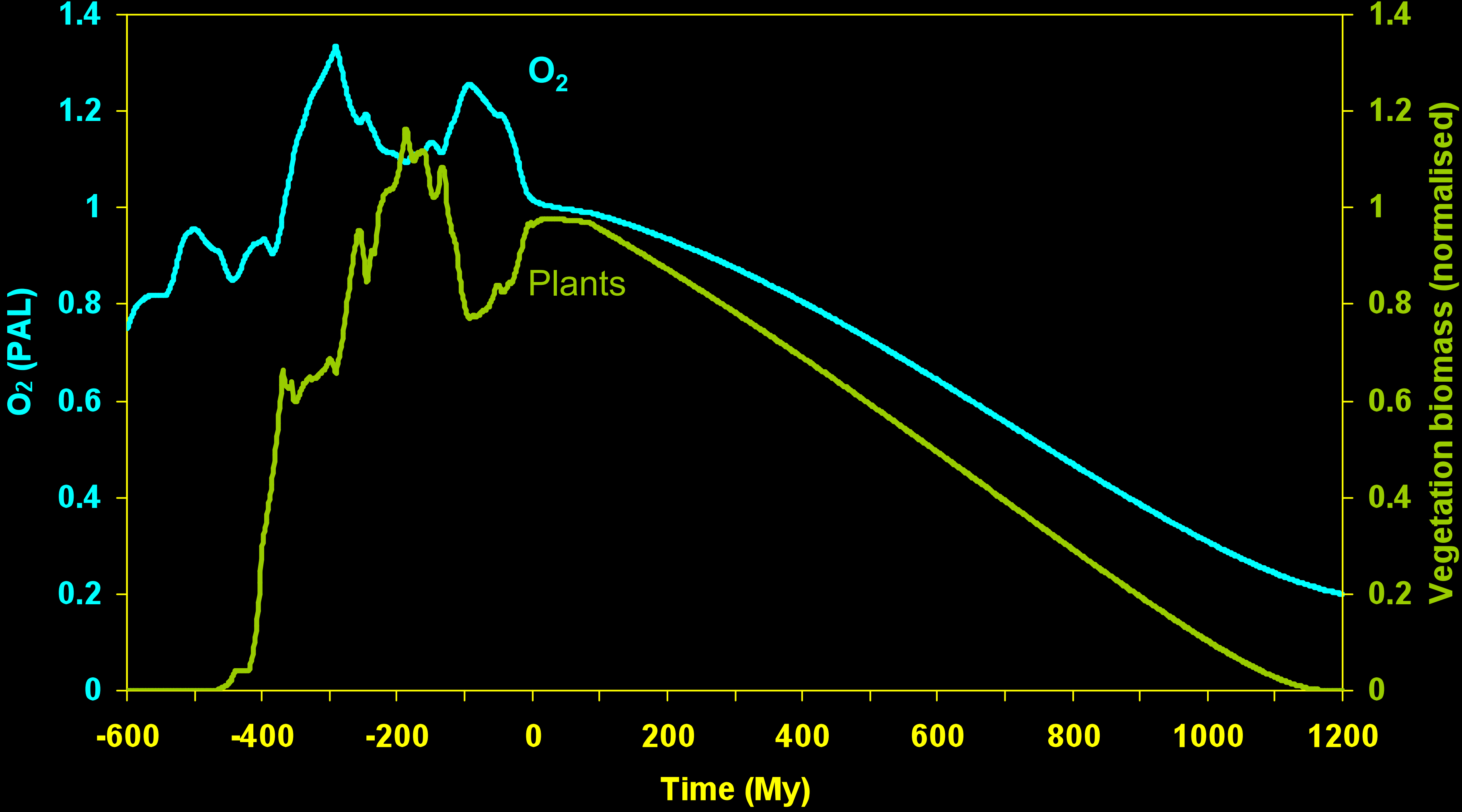
- Solar luminosity increasing ~1% per 100 My
- Long-term climate regulator removes CO_2
- CO_2 starvation:
  - C_3 plants CO_2 ~150 ppm
  - C_4 plants CO_2 ~10 ppm
- Overheating:
  - Eukaryotes ~50 ºC
- Loss of water via H-escape to space
- What will happen to O_2?

Past and future CO_2 and temperature



COPSE model of Bergman, Lenton and Watson

Past and future O_2 and plants

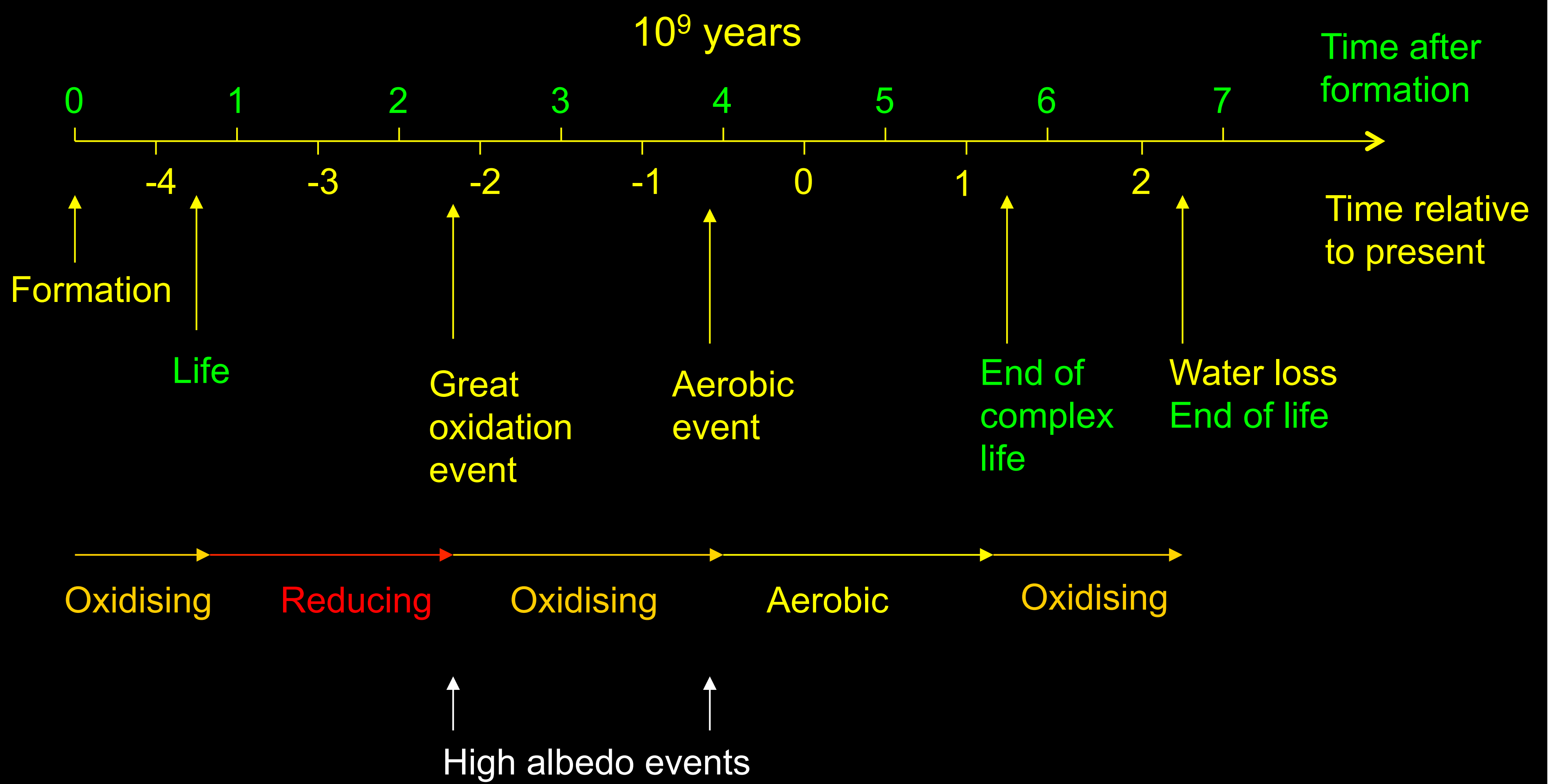


COPSE model of Bergman, Lenton and Watson

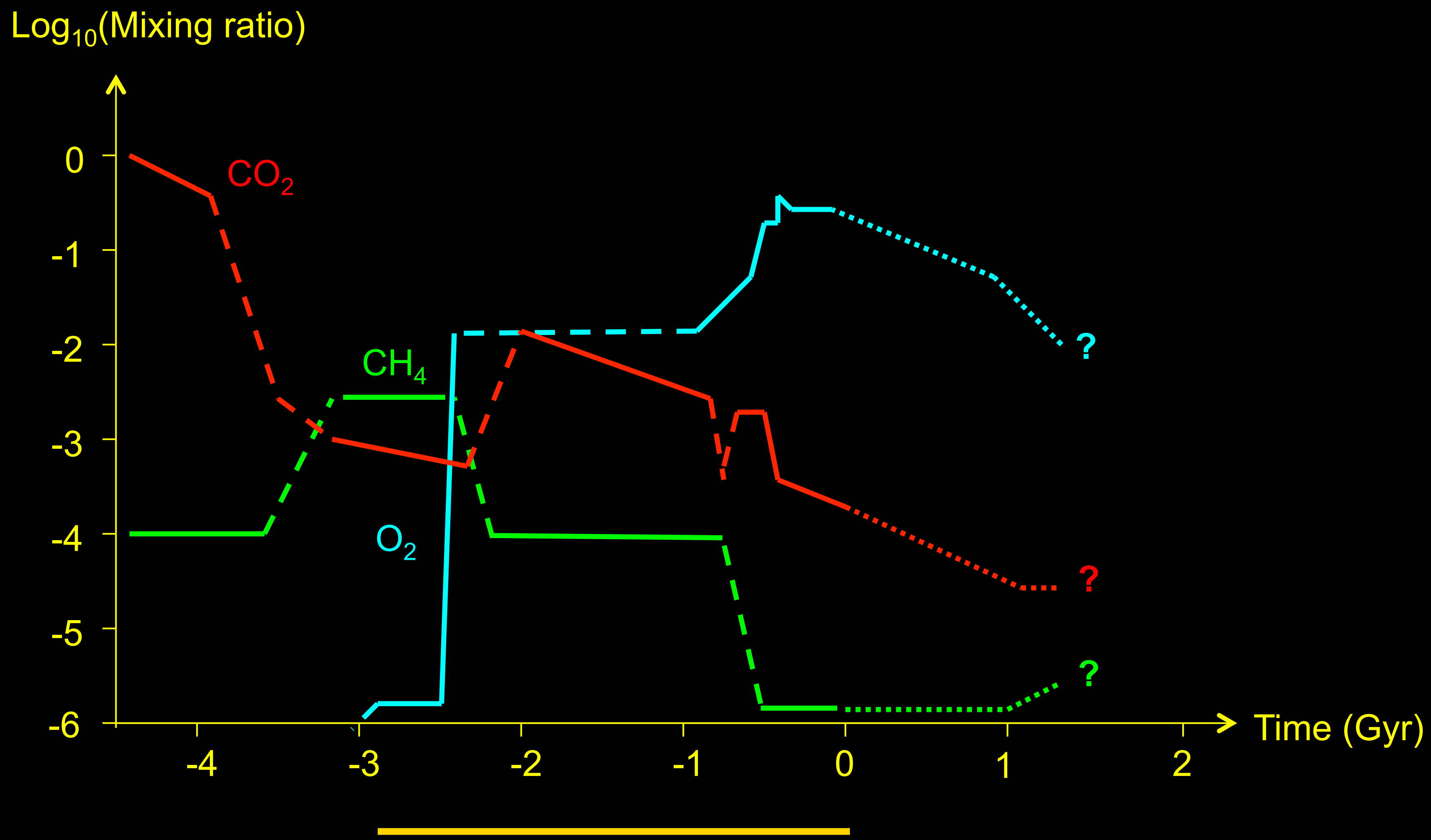
Four stages for oxygen

	>2.7 Ga	Oxygenic photosynthesis → ~2.7-2.4 Ga	Great Oxidation → ~2.3-1.0 Ga?	Neoproterozoic oxygenation → <0.6 Ga
Atmosphere	Reducing $O_2 < 10^{-12}$ atm	Reducing $O_2 \sim 10^{-6}$ atm	Oxidising $O_2 > 10^{-3}$ atm	Oxidising $O_2 \sim 10^{-1}$ atm
Surface Ocean	Anoxic	Oxygenated	Oxygenated	Oxygenated
Deep Ocean	Anoxic	Anoxic	Anoxic	Oxygenated

Earth timeline



Major gases

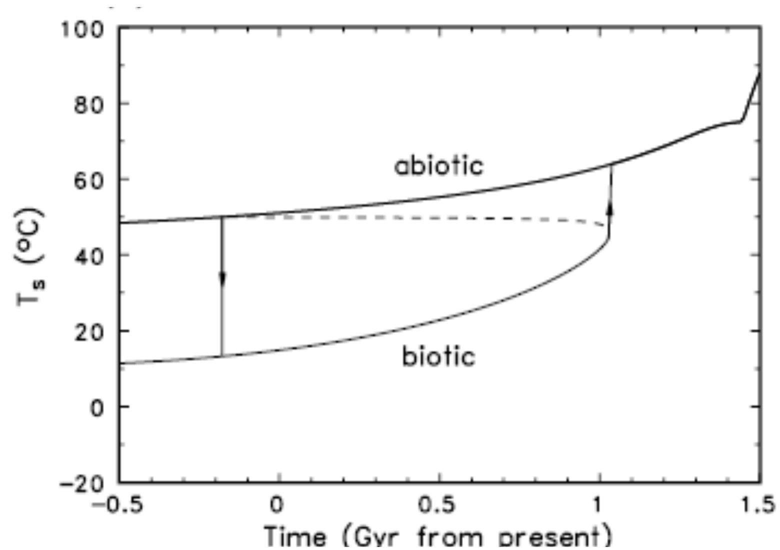


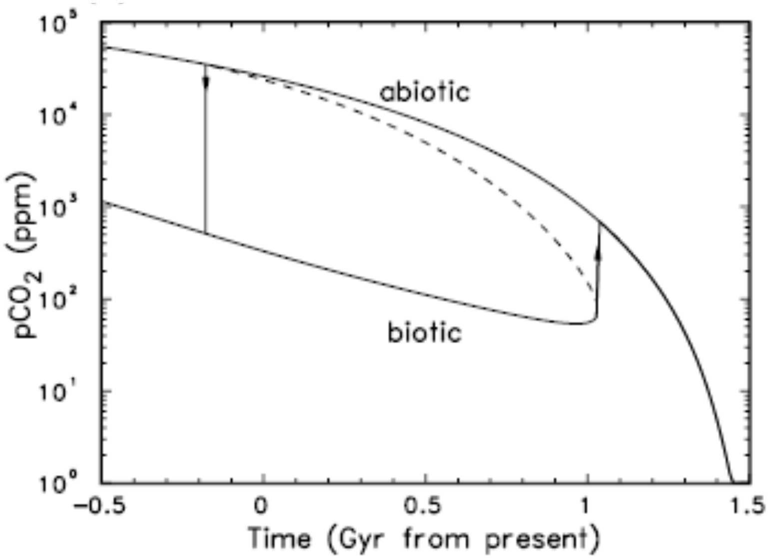
Interval of most extreme atmospheric disequilibrium
(~50% of life span of planet)

Generalising for O_2

- Oxygenic photosynthesis
  - So difficult to evolve that it might only occur on a tiny fraction of planets with life
- Oxygenation
  - Contingent on oxygenic photosynthesis but also dependent on hydrogen escape
- Aeration (high O_2)
  - Probably contingent on colonisation of the continents to increase phosphorus supply

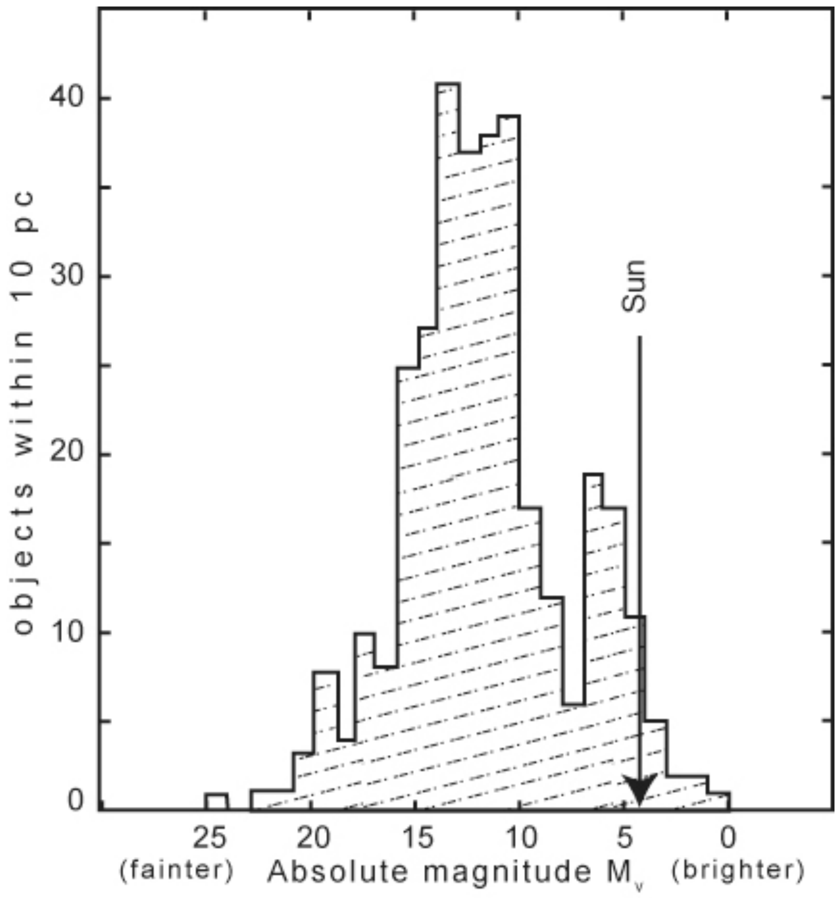
Bi-stability for CO_2 and temperature?





Lenton & von Bloh (2001) *Geophys. Res. Lett.* 28: 1715-1718

Violating the principle of mediocrity



- Conscious ‘observer’ species require lots of O_2 in the atmosphere
- Around a type-M star, splitting water (oxygenic photosynthesis) would require coupling 3 or 4 photosystems
- That makes it even harder to evolve

Data from RECONS www.recons.org

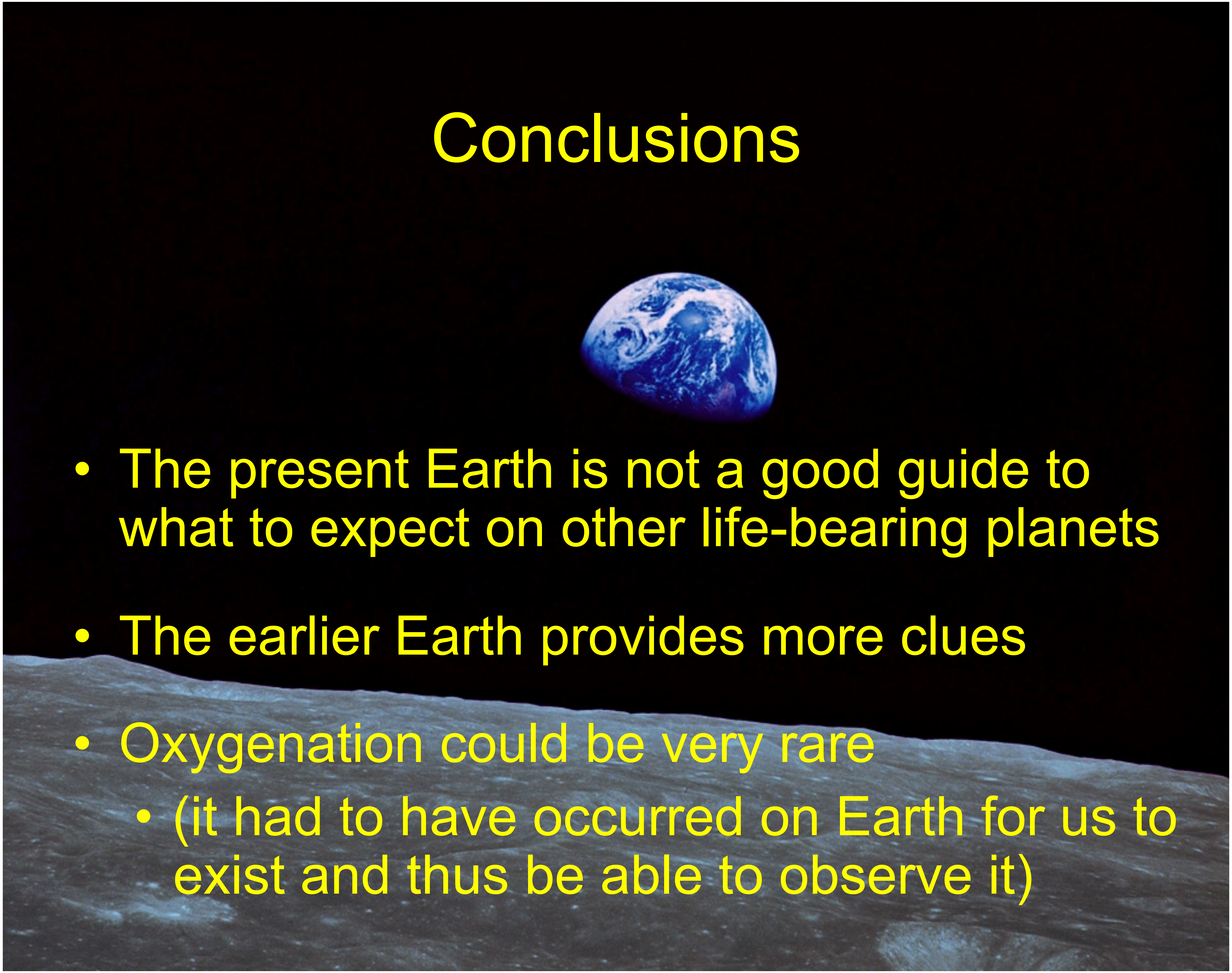
Wolstencroft & Raven (2002) *Icarus* **157:** 535

Goldilocks principle for oxygenation

Depends on planet size:

- Too small:
  - bulk atmospheric loss occurs
- Near Earth size:
  - diffusion limited H-escape increases with size
- Too large:
  - energetic limitation of H-escape delays oxidation beyond the habitable lifetime

Conclusions



- The present Earth is not a good guide to what to expect on other life-bearing planets
- The earlier Earth provides more clues
- Oxygenation could be very rare
  - (it had to have occurred on Earth for us to exist and thus be able to observe it)