



The Faint Young Sun Paradox

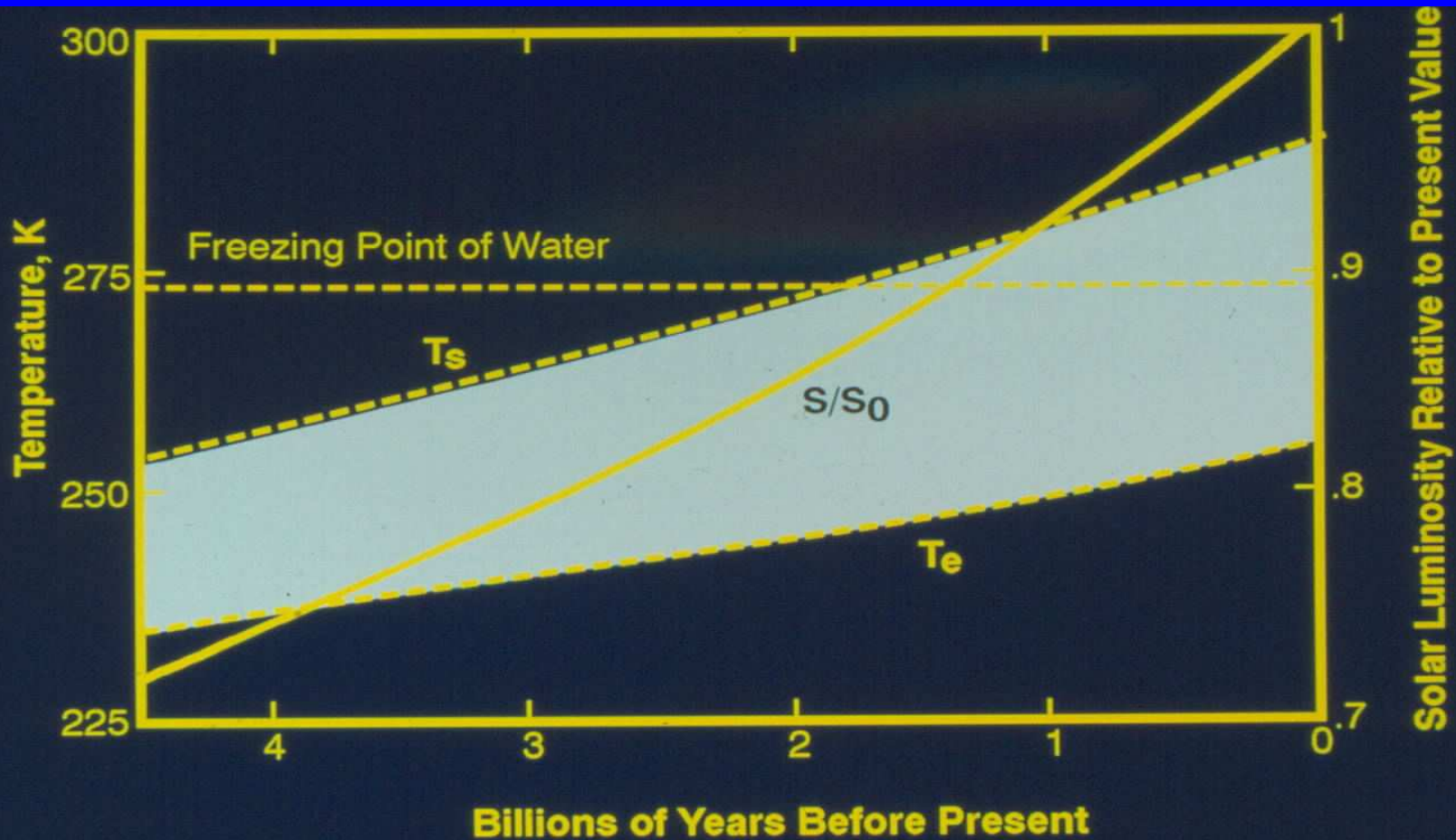
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Astrophysics & Montana State University

Thanks to Jim Kasting (Penn State), Richard
Linzen (MIT), and Ed Guinan (Villanova),
John Priscu (MSU)

The Faint Young Sun Paradox

The Sun was about 30% less luminous when life developed on Earth, yet geological and biological evidence points to a warm young Earth, 60 to 70 C

A Faint Young Sun Leaves the Earth Frozen Solid



Kasting et al, Scientific American, 1988

Where to look for a solution?

- Astrophysical Solutions: Young Sun was not faint
- Early Earth Atmosphere: Much more greenhouse gases
- Geology: Much more geothermal energy
- Biology: Life developed on a cold planet
- Fundamental Physics: e.g., gravitational constant has varied

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	900
		MIDDLE	1600
		EARLY	2500
	ARCHEAN	LATE	3000
		MIDDLE	3400
		EARLY	3800
HADEAN		4600	

⇐ First shelly fossils (Cambrian explosion)

⇐ Snowball Earth ice ages

} Warm

⇐ Rise of atmospheric O₂ (Ice age)

⇐ Ice age (?)

} Warm (?)

Biological Solution

- Early earth was cold and frozen over, yet life developed under unusual circumstances (John Priscu, MSU)



~4.5 Ga



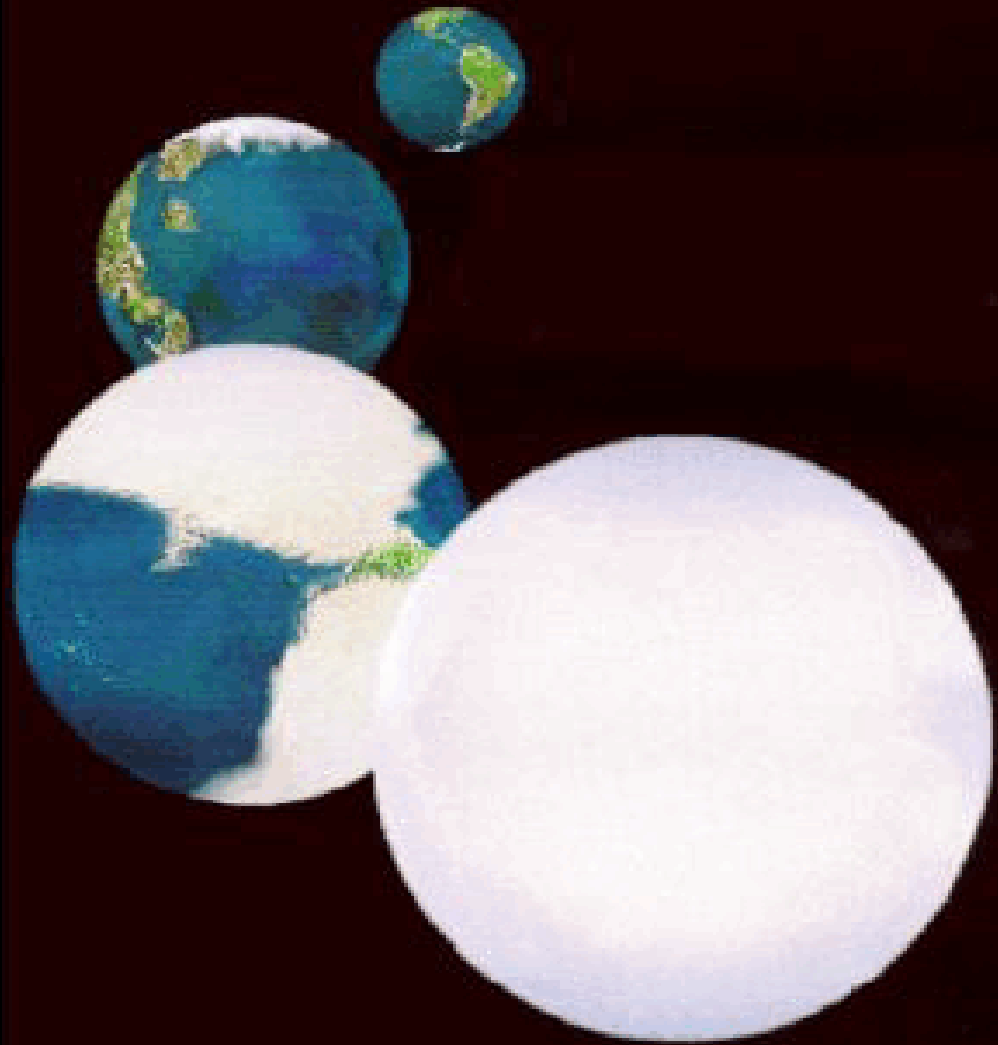
LHB
3.8-4.0 Ga



3.5 Ga

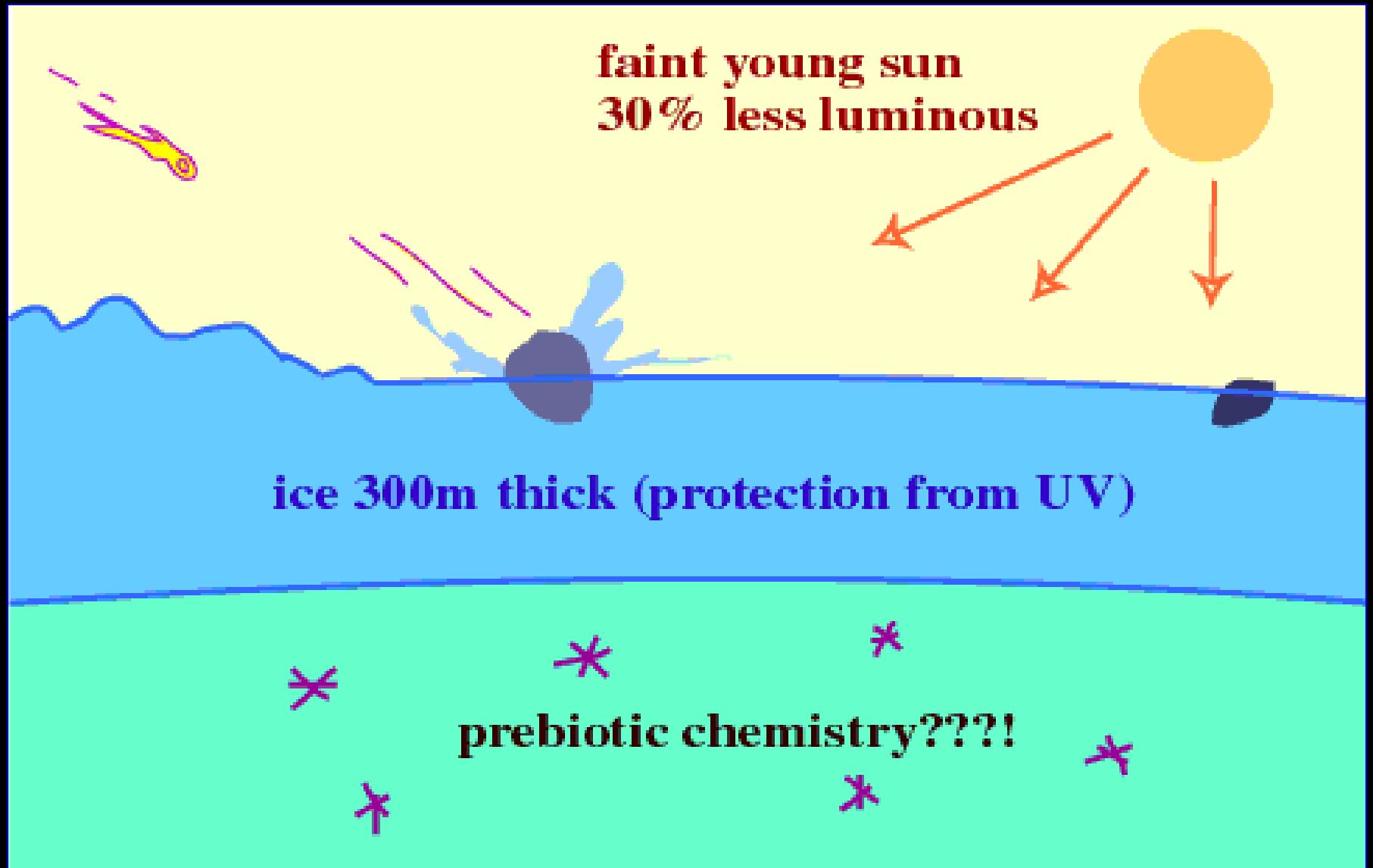


Snowball Earth



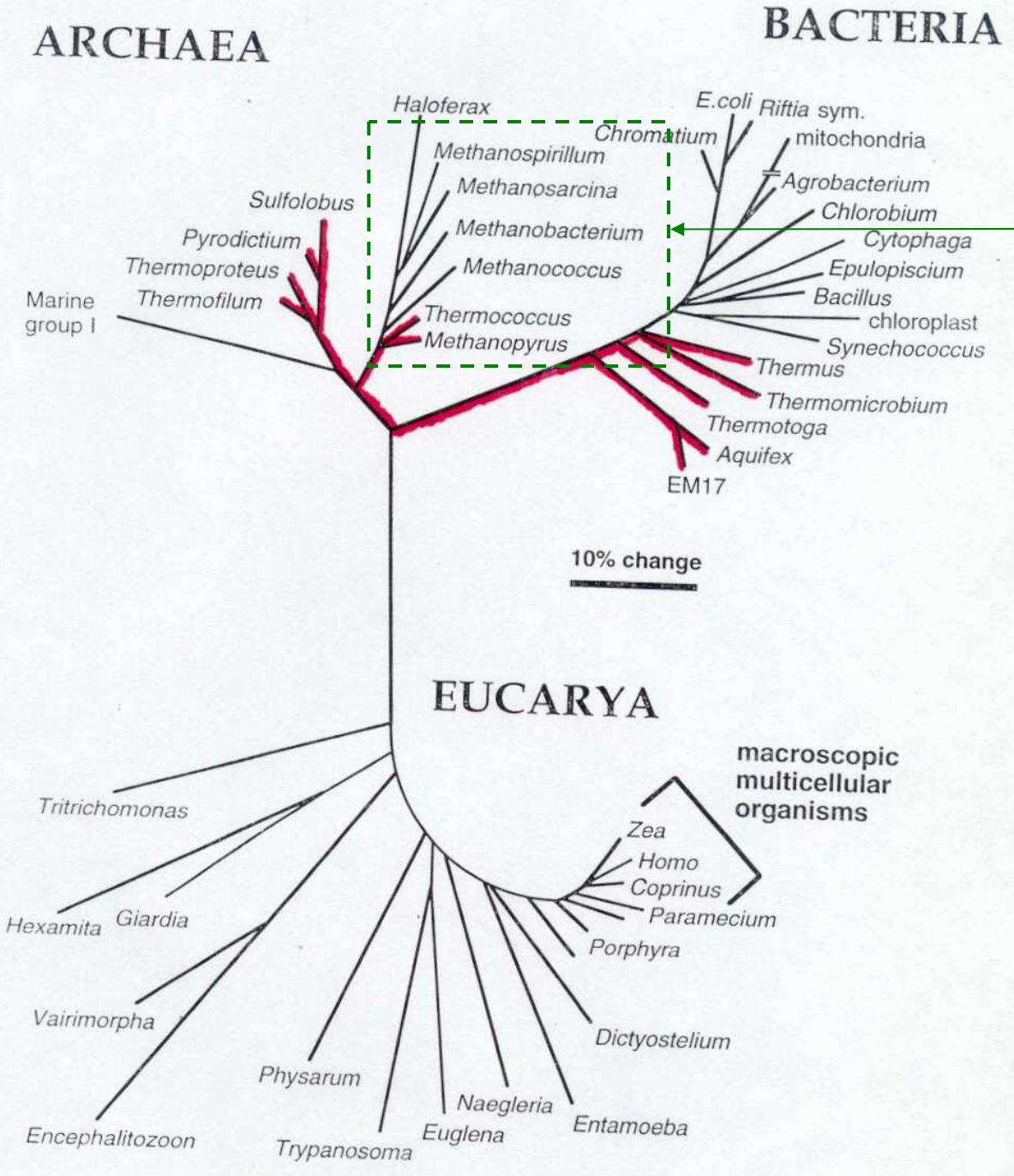
Lubick, N., 2002, *Nature*, 417:12-13

Frozen Ocean on Early Earth?



Bada *et al.* 1994, PNAS, 91:1248-1250.

Image: http://www.chem.duke.edu/~jds/cruise_chem/Exobiology/sites.html



Methanogenic
bacteria

“Universal”
(rRNA) tree
of life

Courtesy of
Norm Pace

Early Earth Life Forms Still Exist



Lake Thetis Stromatolites (Ruth Ellison)

Stromatolites go back at least 3.5 Gyr

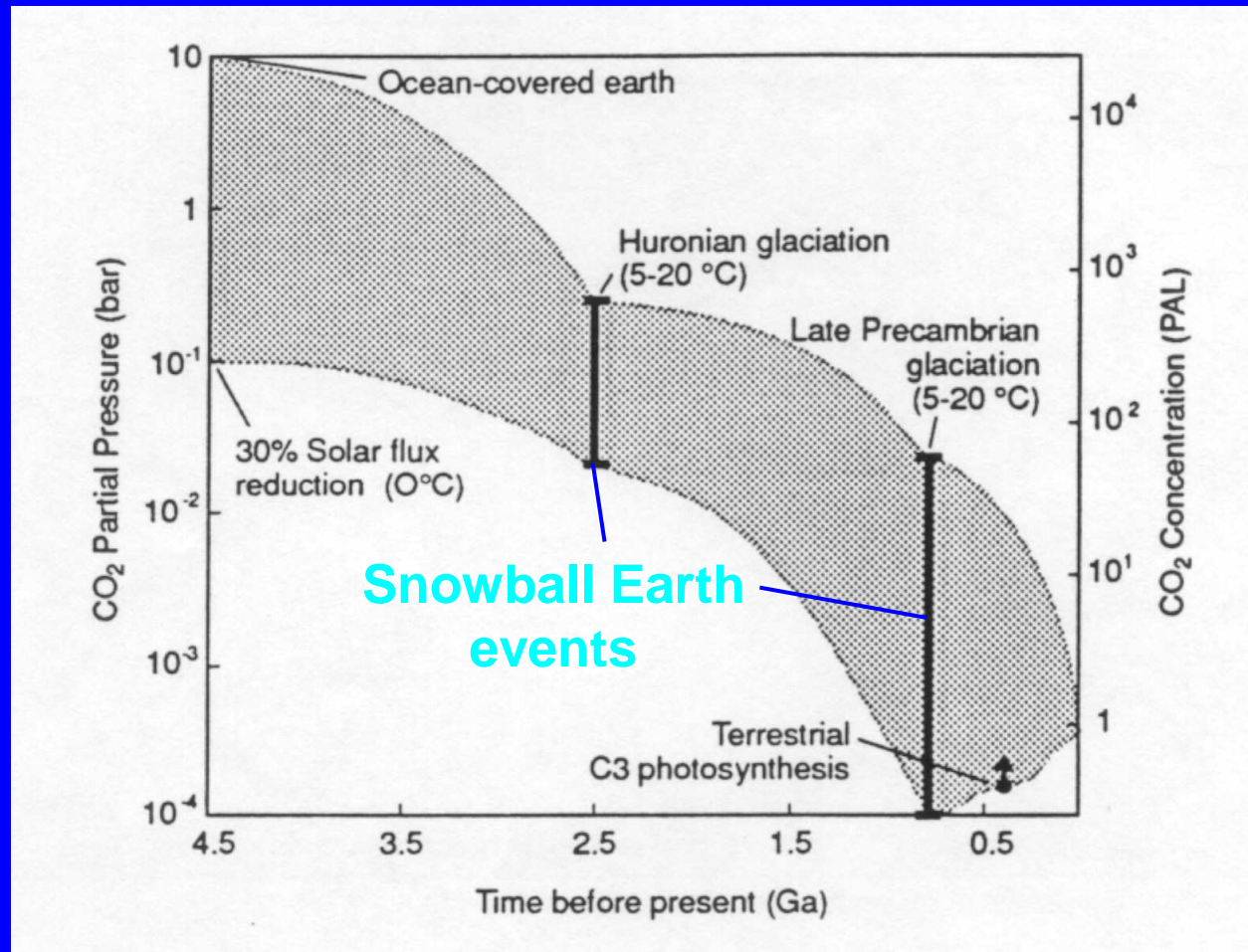


Precambrian stromatolite fossils from Glacier National Park

Problems with Cold Genesis

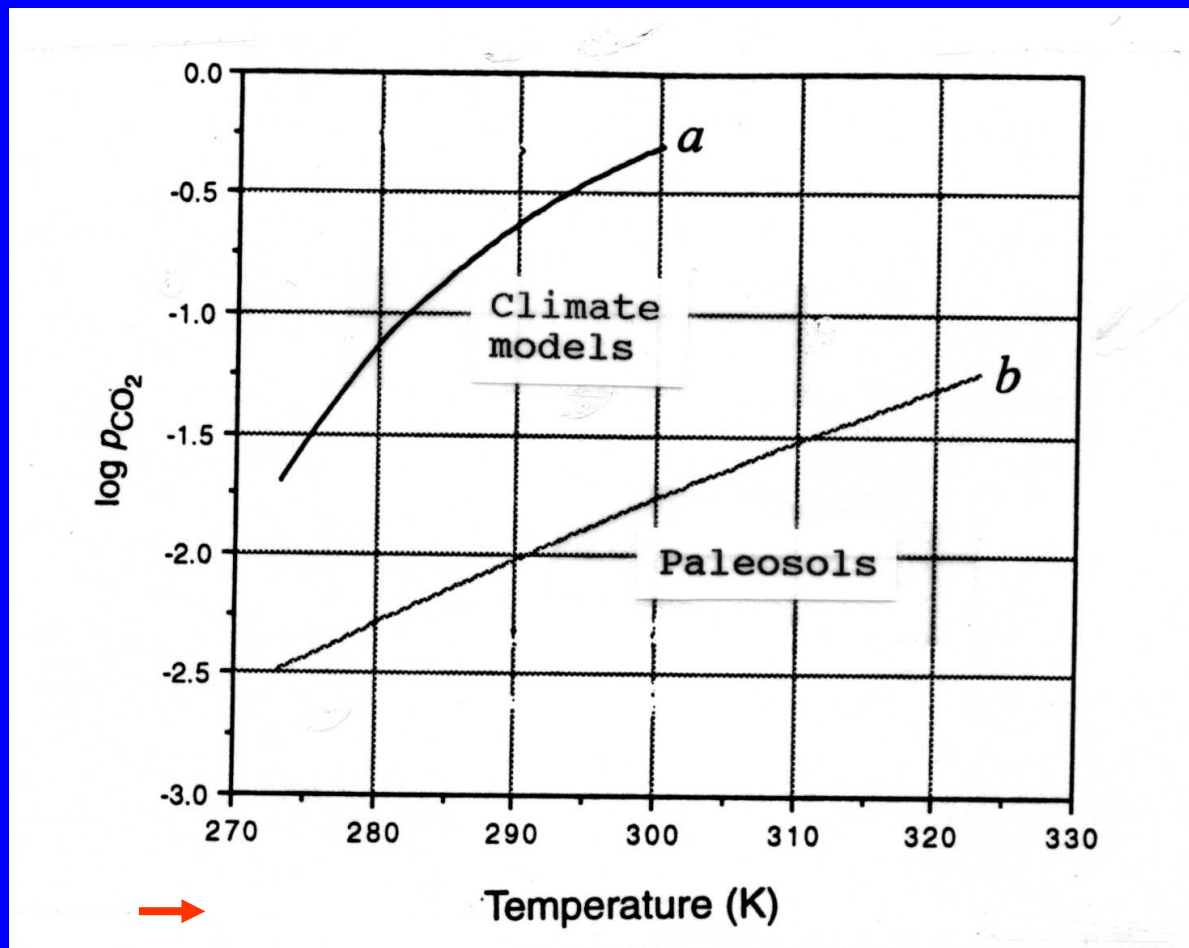
- Evidence for liquid water on continents
- Stromatolites live on surface

CO₂ vs. time *if* no other greenhouse gases (besides H₂O)



J. F. Kasting, *Science* (1993)

pCO₂ from Paleosols (2.8 Ga)



Absence of siderite (FeCO₃) places upper bound on pCO₂

⇒ May need other greenhouse gases (CH₄?)

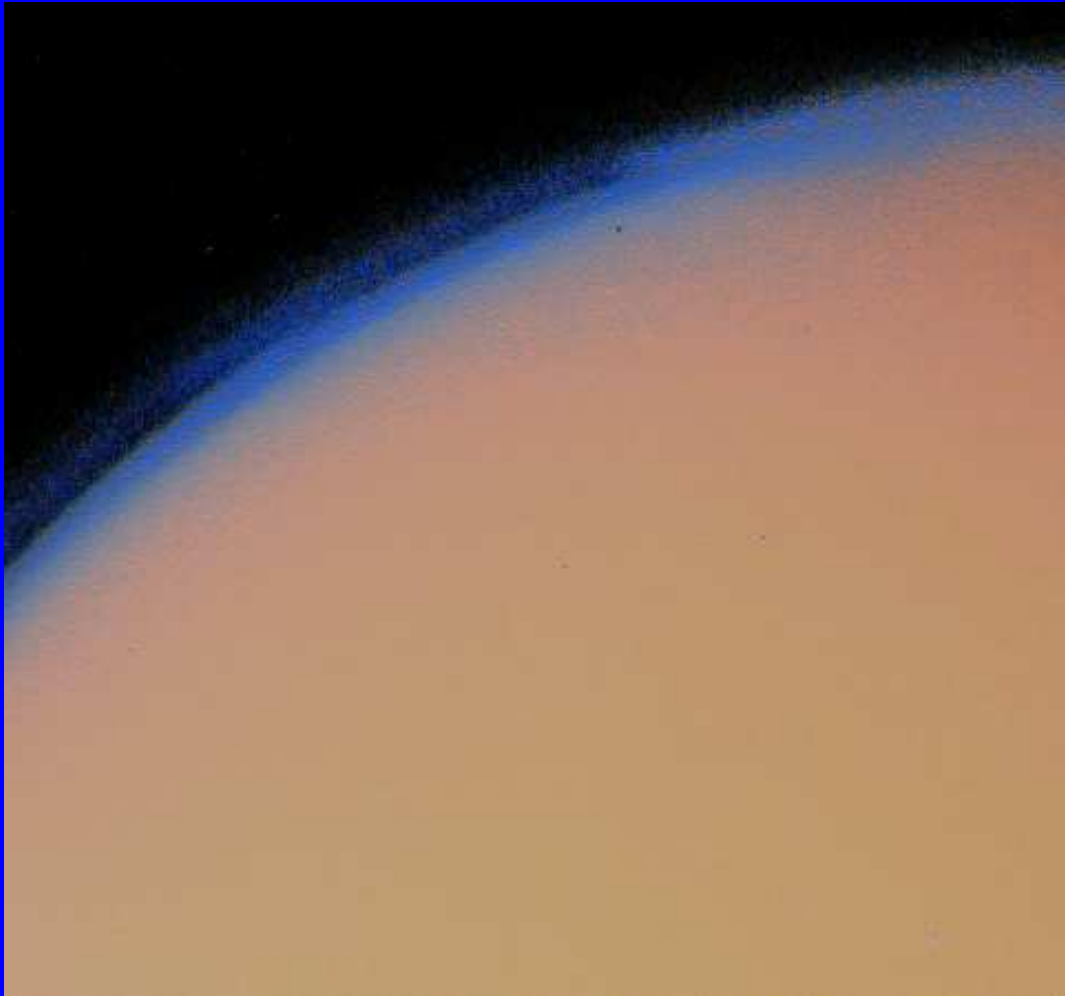
Today's CO₂ level (3×10⁻⁴ atm)

Rye et al., *Nature* (1995)

But

- If CH_4 becomes more abundant than CO_2 , **organic haze** begins to form... Which constitutes an Anti-Greenhouse agent.
- So the limit on CO_2 is an effective limit on CH_4

Titan's organic haze layer



Haze is thought to form from photolysis (and charged particle irradiation) of CH_4

(Picture from Voyager 2)

Climate Science Solution (Richard Linzen, MIT)

- Stratospheric clouds in nitrogen/methane atmosphere can produce sufficient greenhouse shielding to obtain high temperatures (albedo effect minor)
- How can this be verified from observations?

Albedo Effects?



National Aeronautics and
Space Administration

Apollo 17 View of Earth

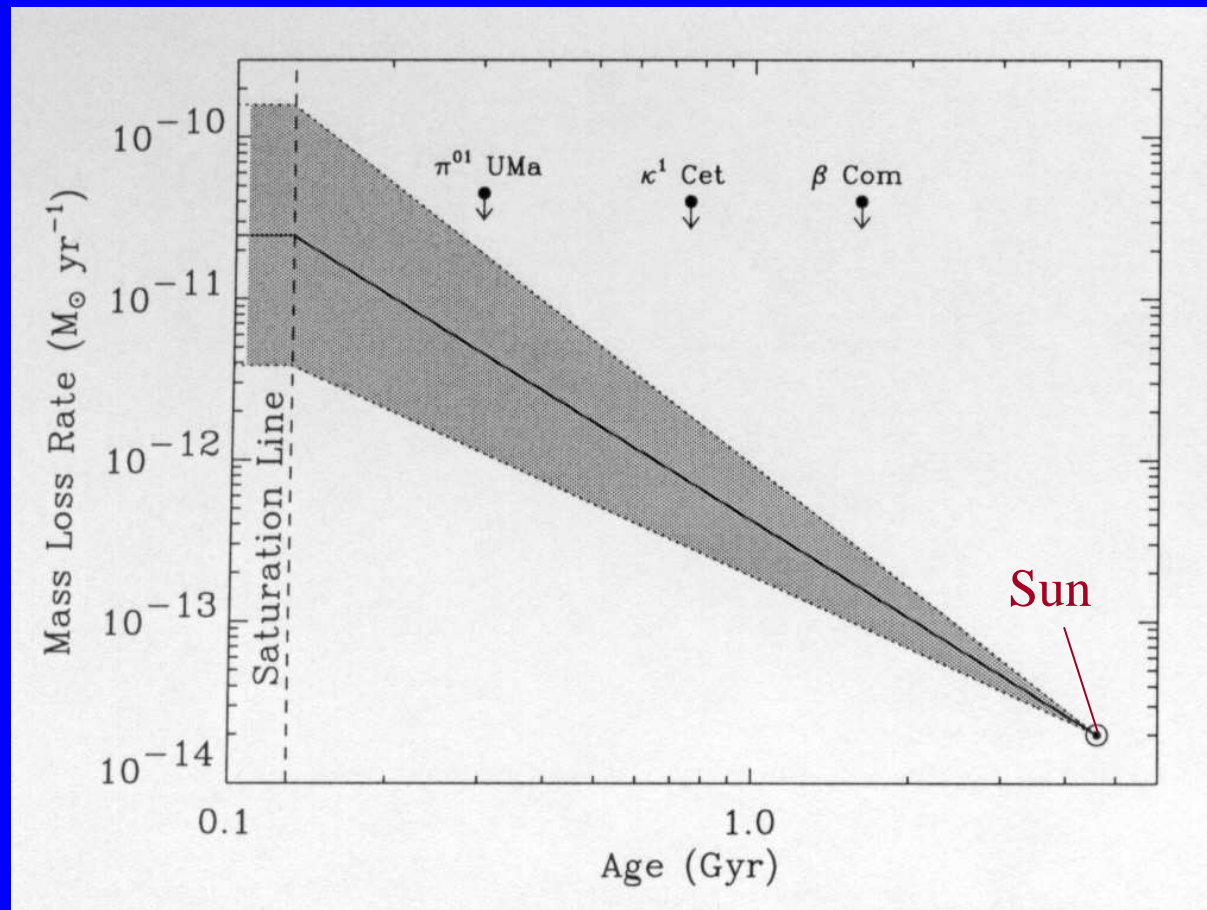


Was the young Sun really faint?

- Solar luminosity is a strong function of solar mass: $L_{\odot} \sim M_{\odot}^4$
- Planetary orbital distance varies inversely with solar mass: $a \sim M_{\odot}^{-1}$
- Solar flux varies inversely with orbital distance: $S \sim a^{-2}$
- Flux to the planets therefore goes as

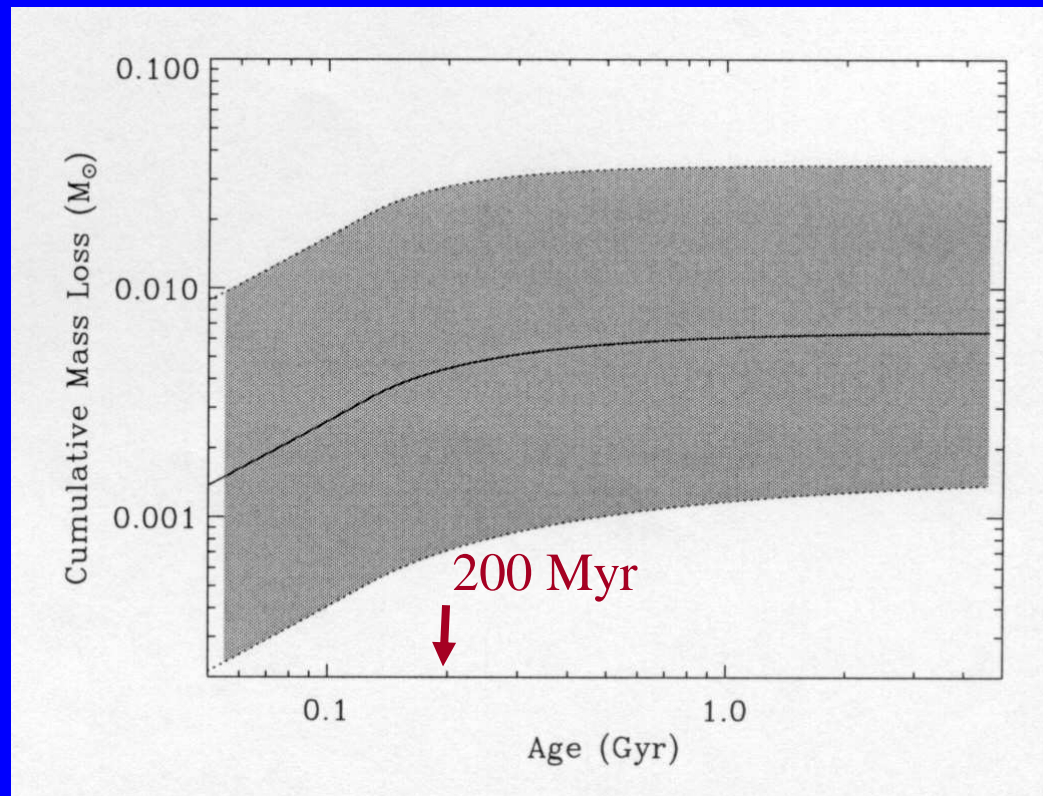
$$S \sim M_{\odot}^6$$

Estimated mass loss rate vs. stellar age



Wood et al. (2002)

Integrated mass loss vs. time



% Changes

Mass

<u>loss</u>	<u>ΔS</u>
0.6	3.6
1.0	6.0
2.0	13
3.0	19

Wood et al. (2002)

⇒ The Sun was probably back on the standard solar evolution curve by ~4.4 Ga (*i.e.*, 4.4 Gyr ago)

Summary

- Young Sun was probably less luminous, yet its UV, EUV and X-ray emission was an order of magnitude larger
- Young Earth was probably warmer than today, and single-cell organisms were present from very early on
- No silver bullet has devised yet to reconcile these results

The Future: Faint Young Sun problem requires a truly interdisciplinary approach

- Paleo-climatology
- Geology
- Biology
- Solar Physics
- Solar-stellar connection
- Atmospheric chemistry

This is so
much fun!