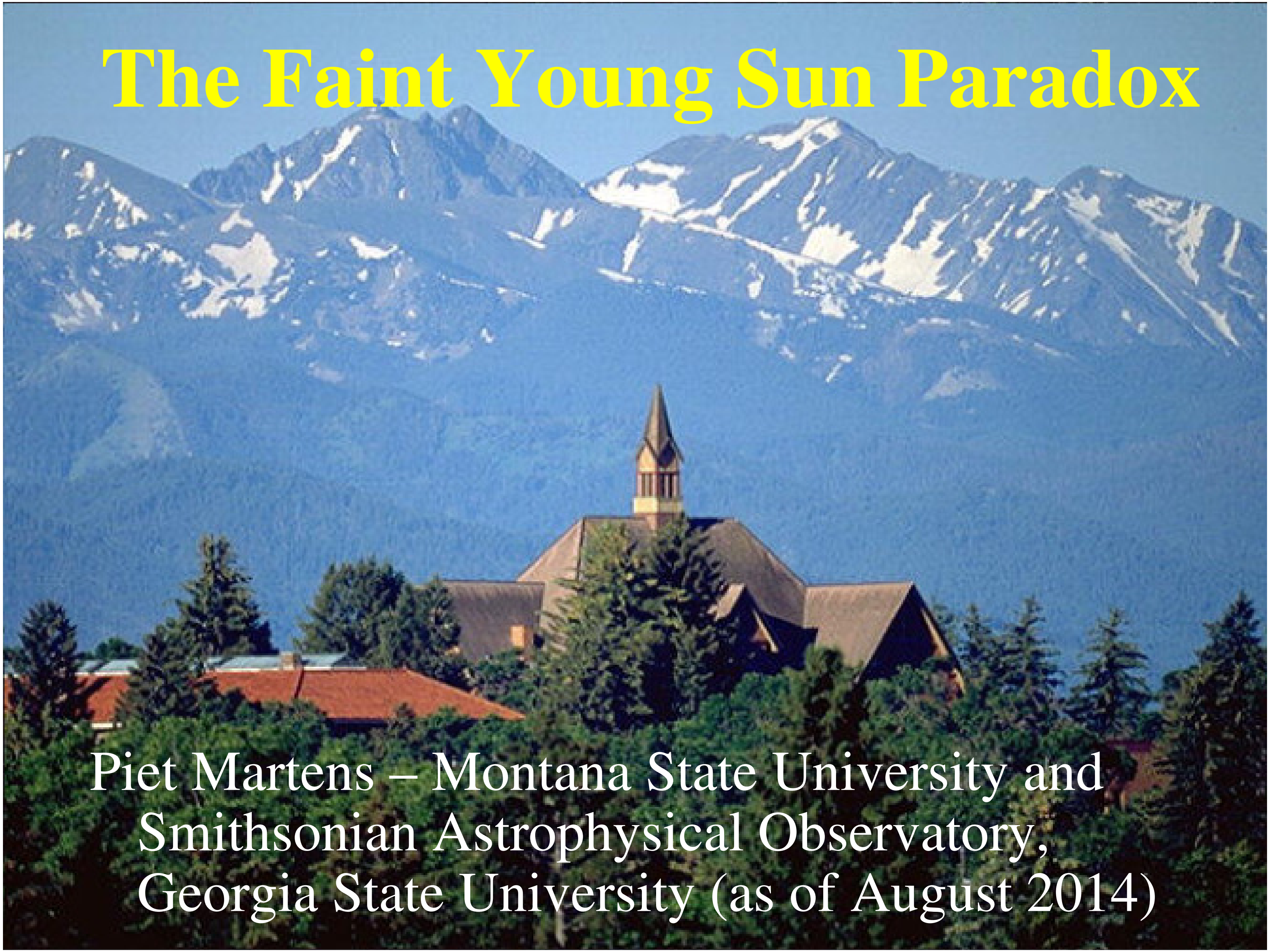
The Faint Young Sun Paradox



Piet Martens – Montana State University and
Smithsonian Astrophysical Observatory,
Georgia State University (as of August 2014)

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

Average Atmospheric Temperature: First Order Approximation

$$L(1-A)=4\sigma T_e^4$$

A = Earth's Albedo

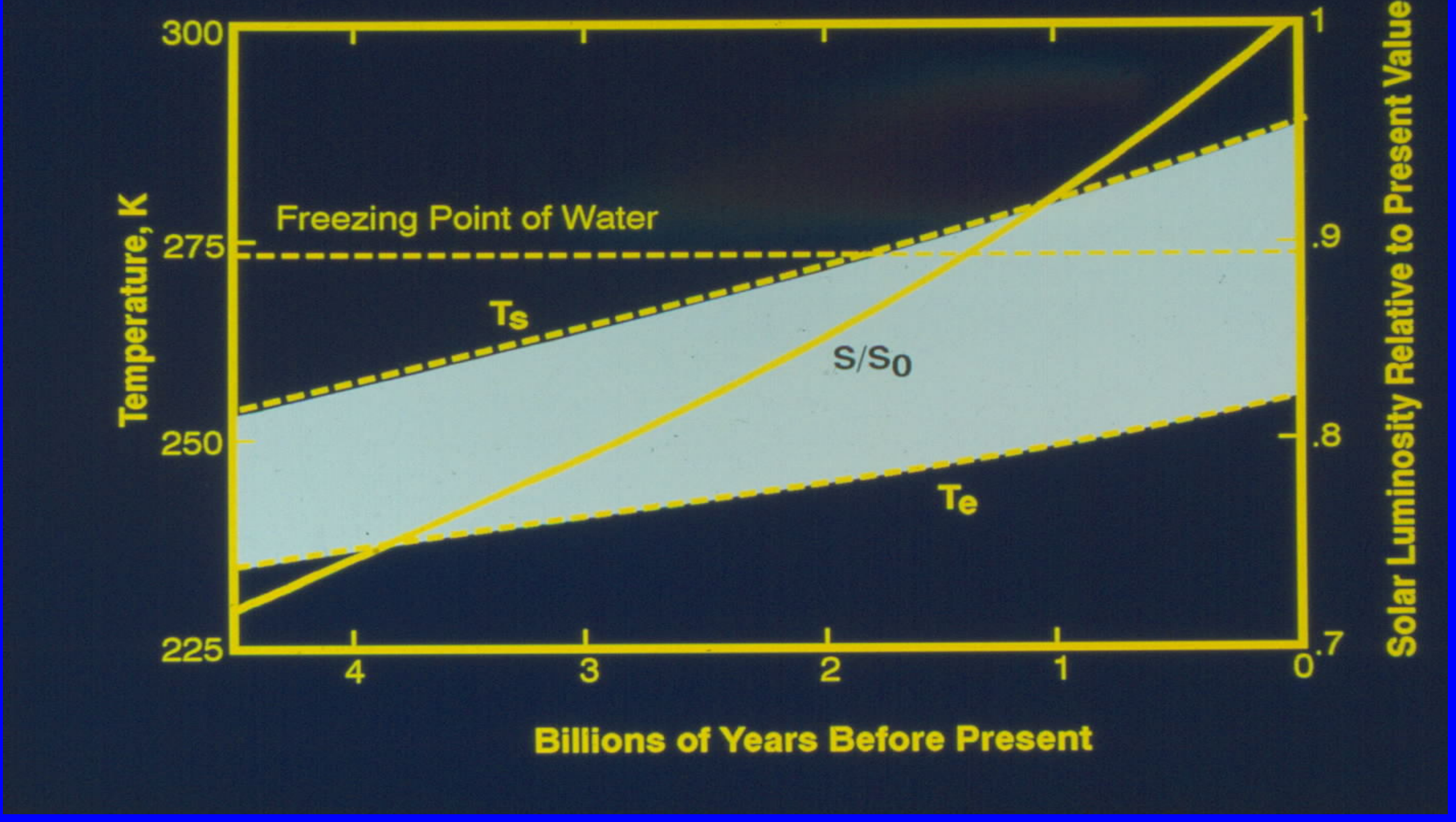
σ = Stefan Boltzmann Constant

T_e = Radiative Equilibrium Temperature

L = Solar Irradiance at Top of Earth's Atmosphere

$$T_{atm}=T_e+\Delta T_{greenhouse}$$

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	357	900
		MIDDLE	700	1600
		EARLY	900	2500
	ARCHEAN	LATE	500	3000
		MIDDLE	400	3400
		EARLY	400	3800
	HADEAN		800	4600

← First shelly fossils (Cambrian explosion)

← Snowball Earth ice ages

Warm

← Rise of atmospheric O_2 (Ice age)

← Ice age (?)

Warm (?)

Biological Solution

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

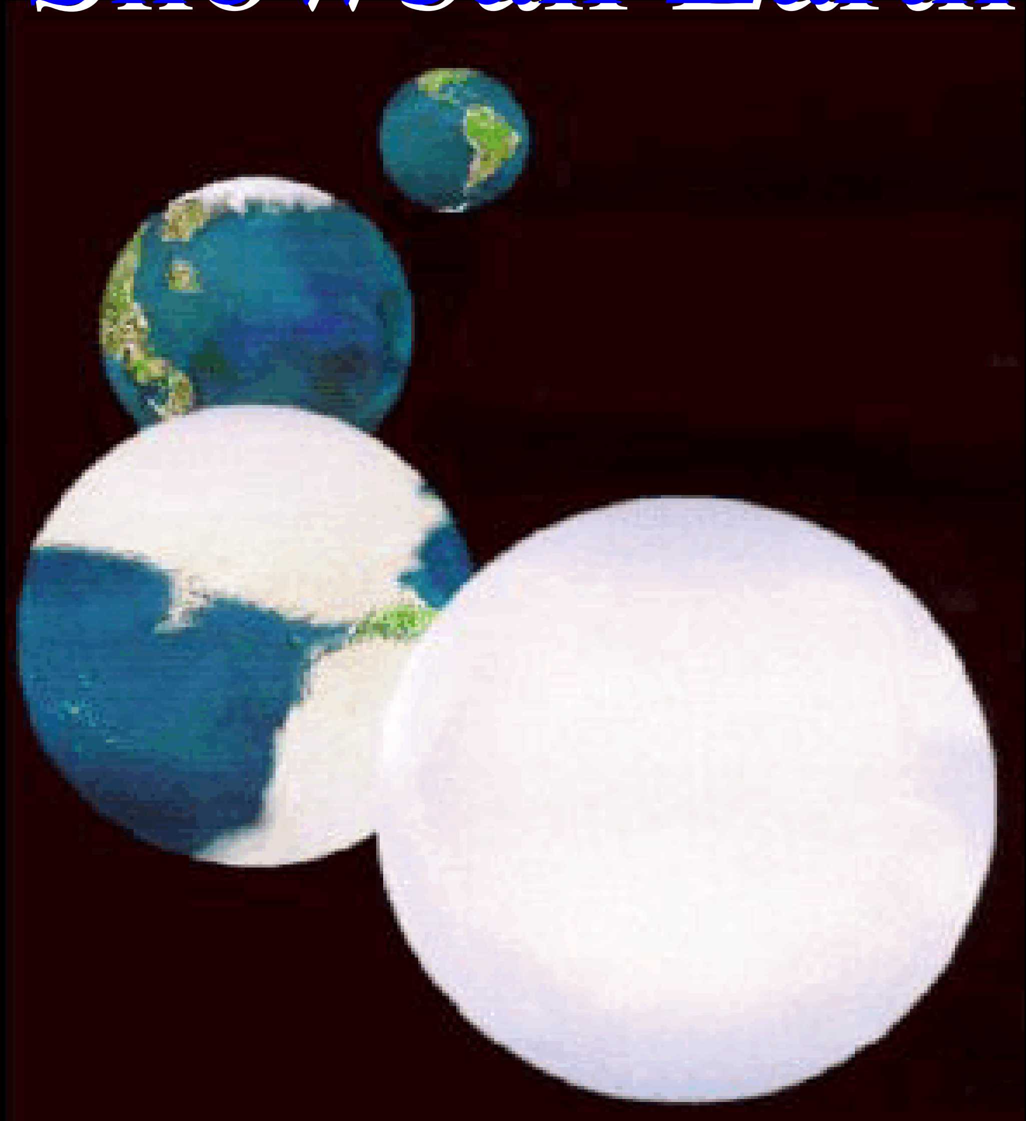
~4.5 Ga

LHB
3.8-4.0 Ga

3.5 Ga

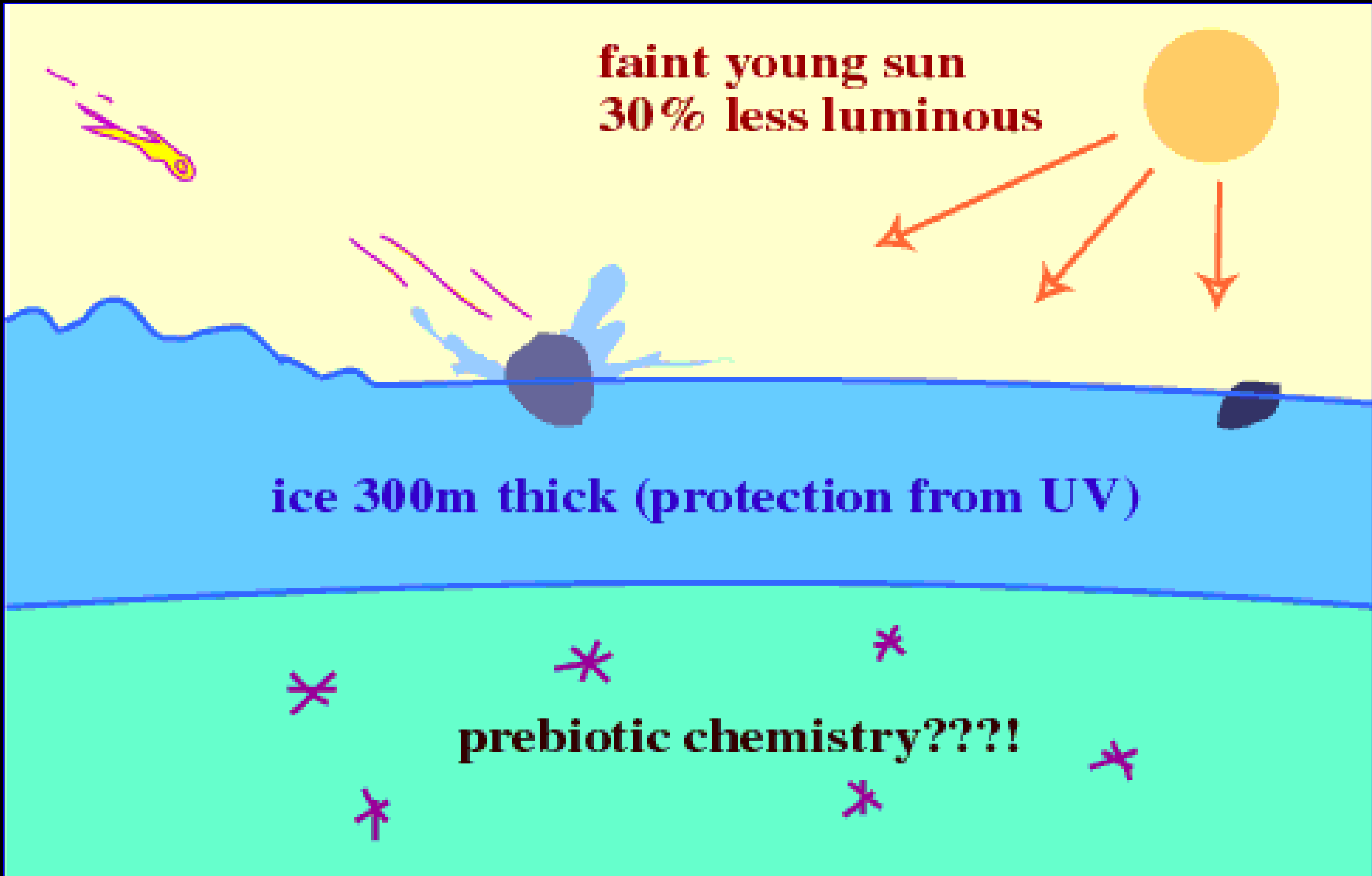
http://ircamera.as.arizona.edu/NatSci102/lectures/lifeform.htm
http://www.psi.edu/projects/moon/moon.html

Snowball Earth

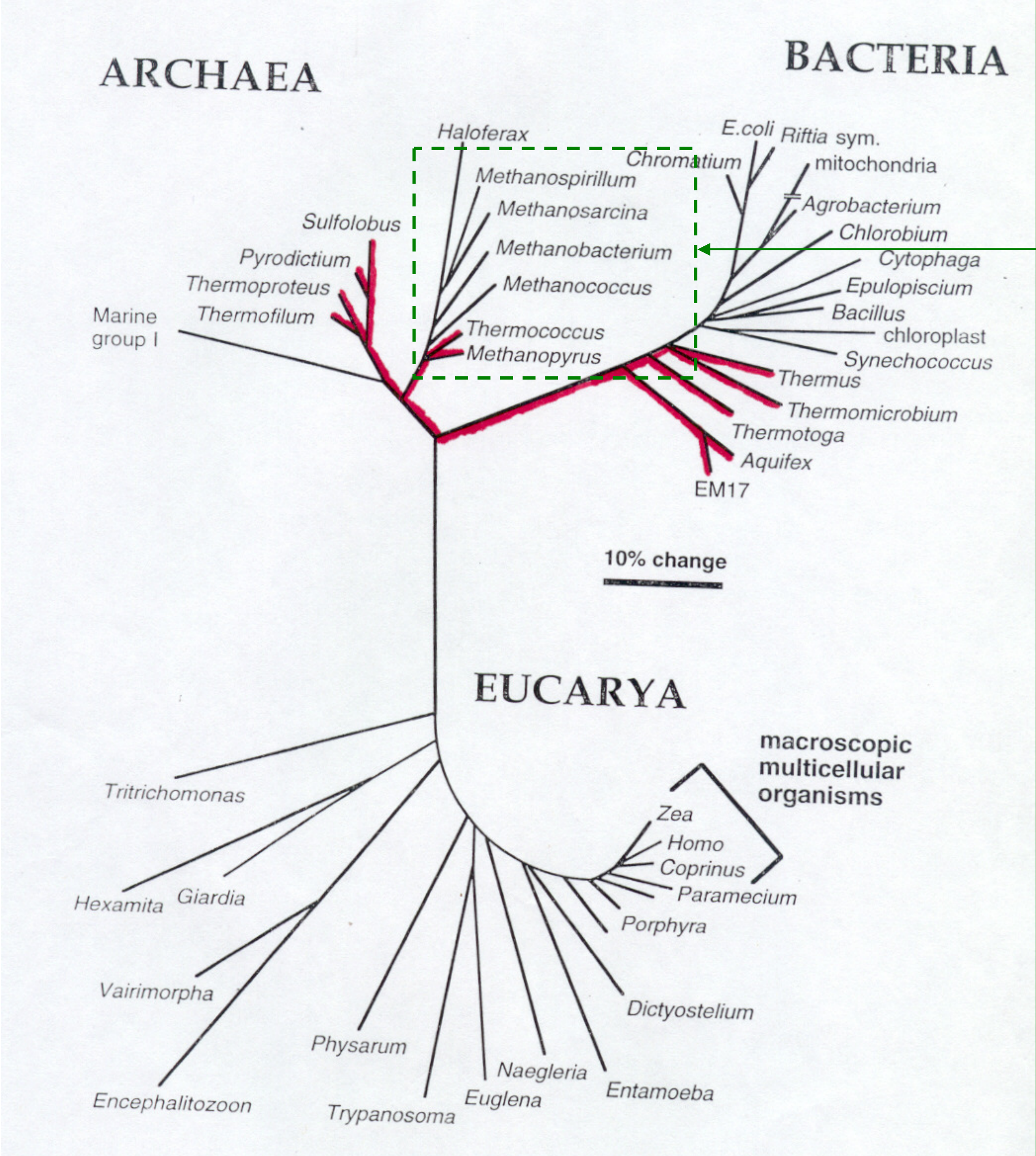


Lubick, N., 2002, *Nature*, 417:12-13

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)

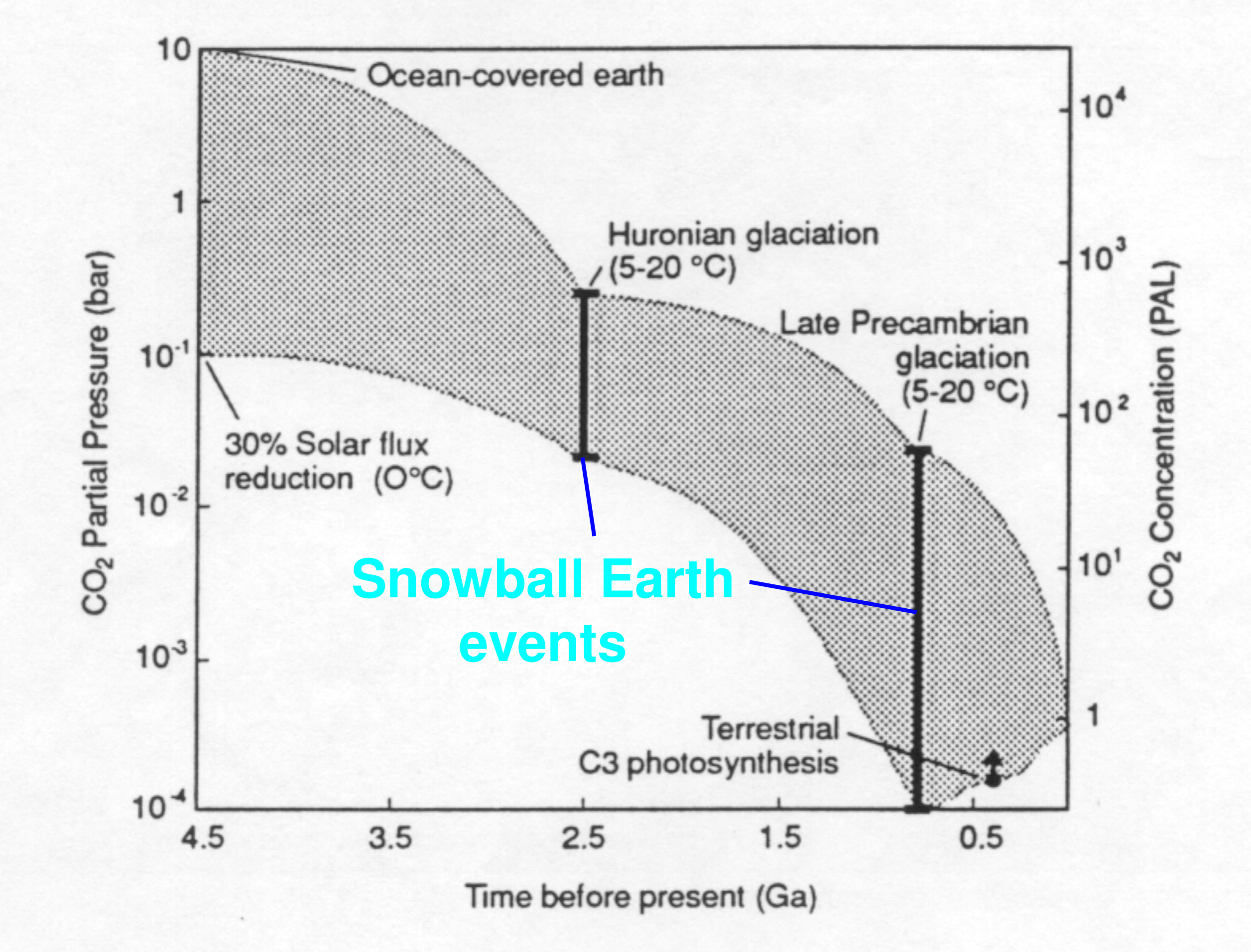
Stromatolites go back at least 3.5 Gyr

Precambrian stromatolite fossils from Glacier National Park

Problems with Cold Genesis

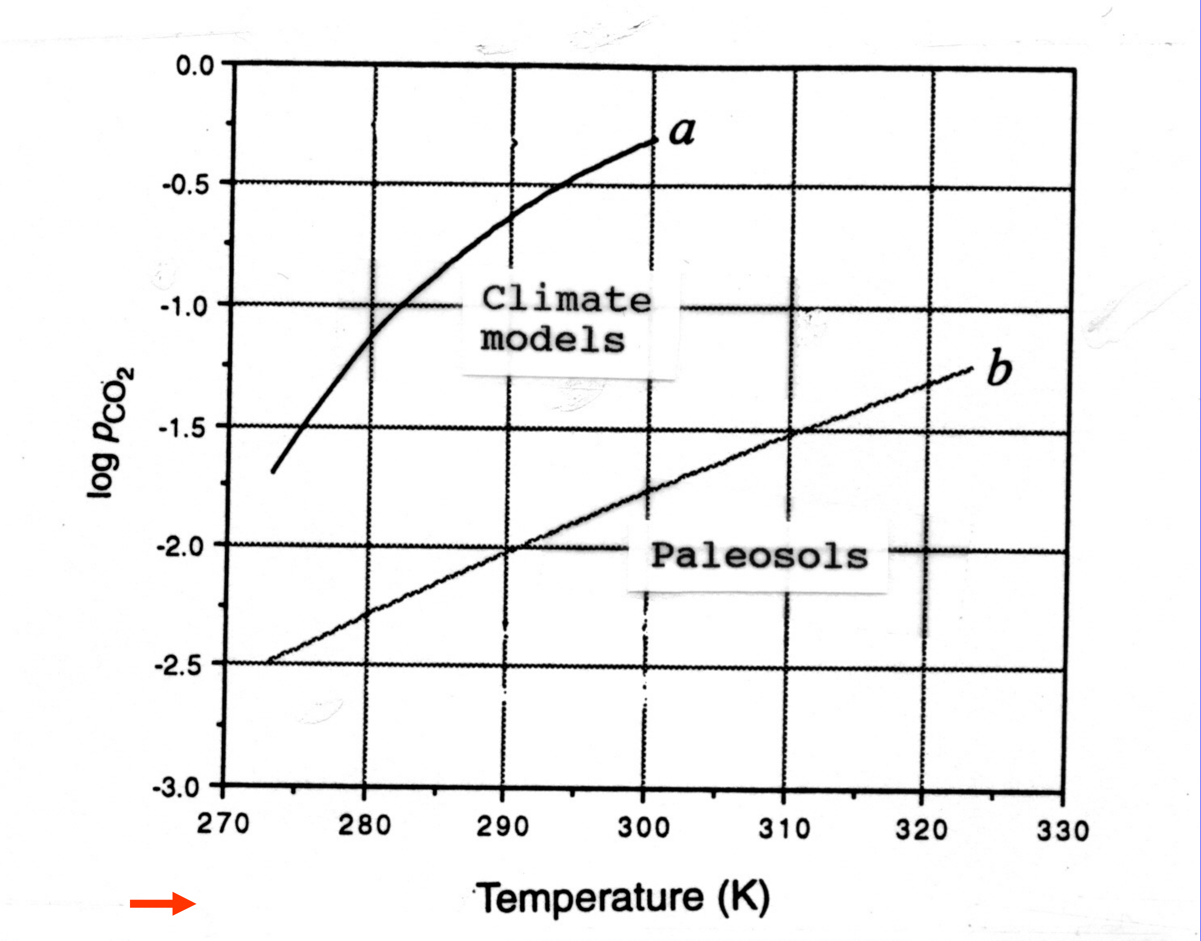
- Evidence for liquid water on continents
- Stromatolites live on surface

CO_2 vs. time *if* no other greenhouse gases (besides H_2O)



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

pCO_2 from Paleosols (2.8 Ga)



Absence of siderite ($FeCO_3$) places upper bound on pCO_2

⇒ May need other green-house gases (CH_4?)

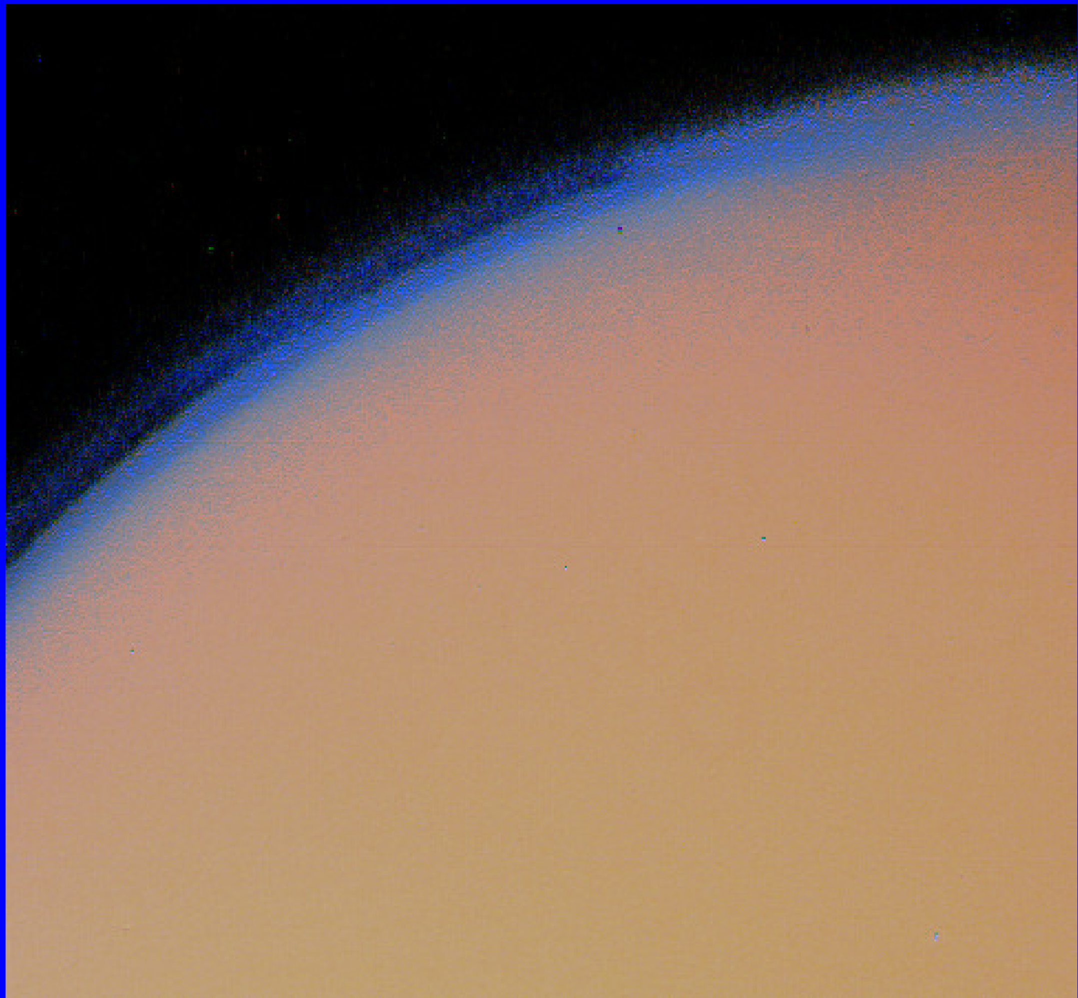
Today's CO_2 level (3×10^{-4} atm)

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

- Thesis of Rodanelli (2009), adviser Richard Linzen (MIT)
- Stratospheric clouds in nitrogen/methane atmosphere can produce sufficient greenhouse shielding to obtain high temperatures (albedo effect minor)
- Does not work once atmosphere becomes oxygen rich/methane poor (~ - 2.5 Gyr)

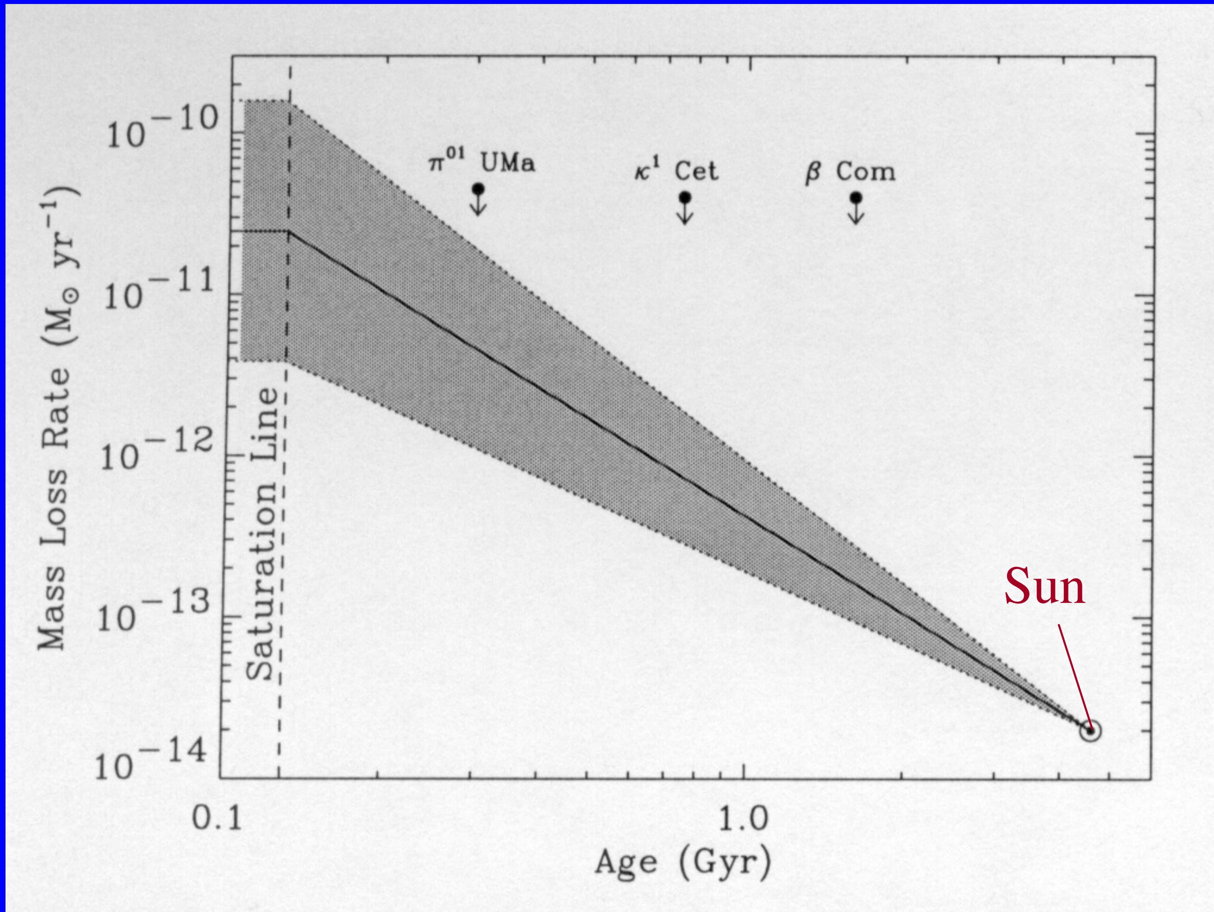
Albedo Effects?

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)

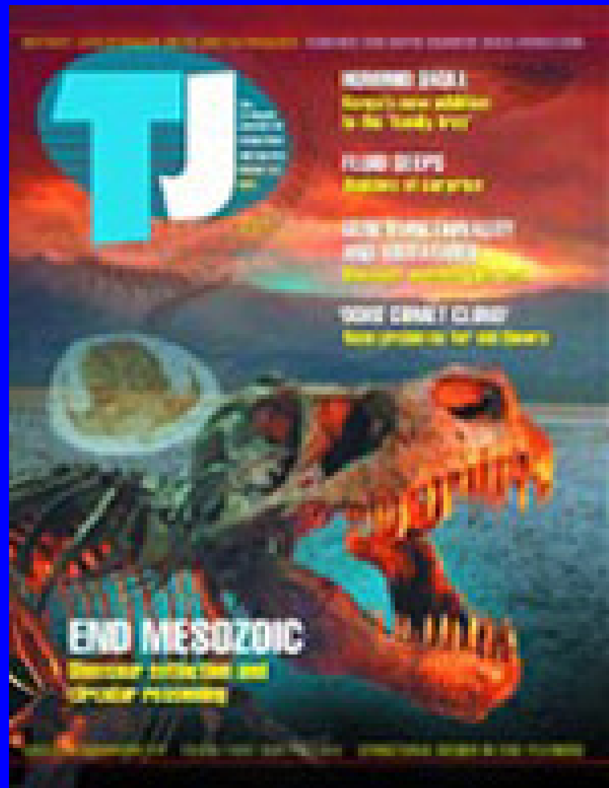
Summary

- 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 been devised yet to reconcile these results

Why Does Anyone Care?

- It’s fascinating
- It poses as fundamental

question. Quote from the Journal Of Creation: “*So, the early faint Sun paradox is evidence that the Sun, and therefore the solar system, is young and consistent with the 6,000-year age of the solar system as recorded by Biblical chronology*’.



Faint Young Sun problem requires a truly interdisciplinary approach

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

This so much fun!

The Faint Young Sun Paradox Collaborators

Jim Kasting (Penn State) – Atmospheric Chemistry

Richard Linzen (MIT) – Climate Science

John Priscu (MSU) – Origins of Life Biology

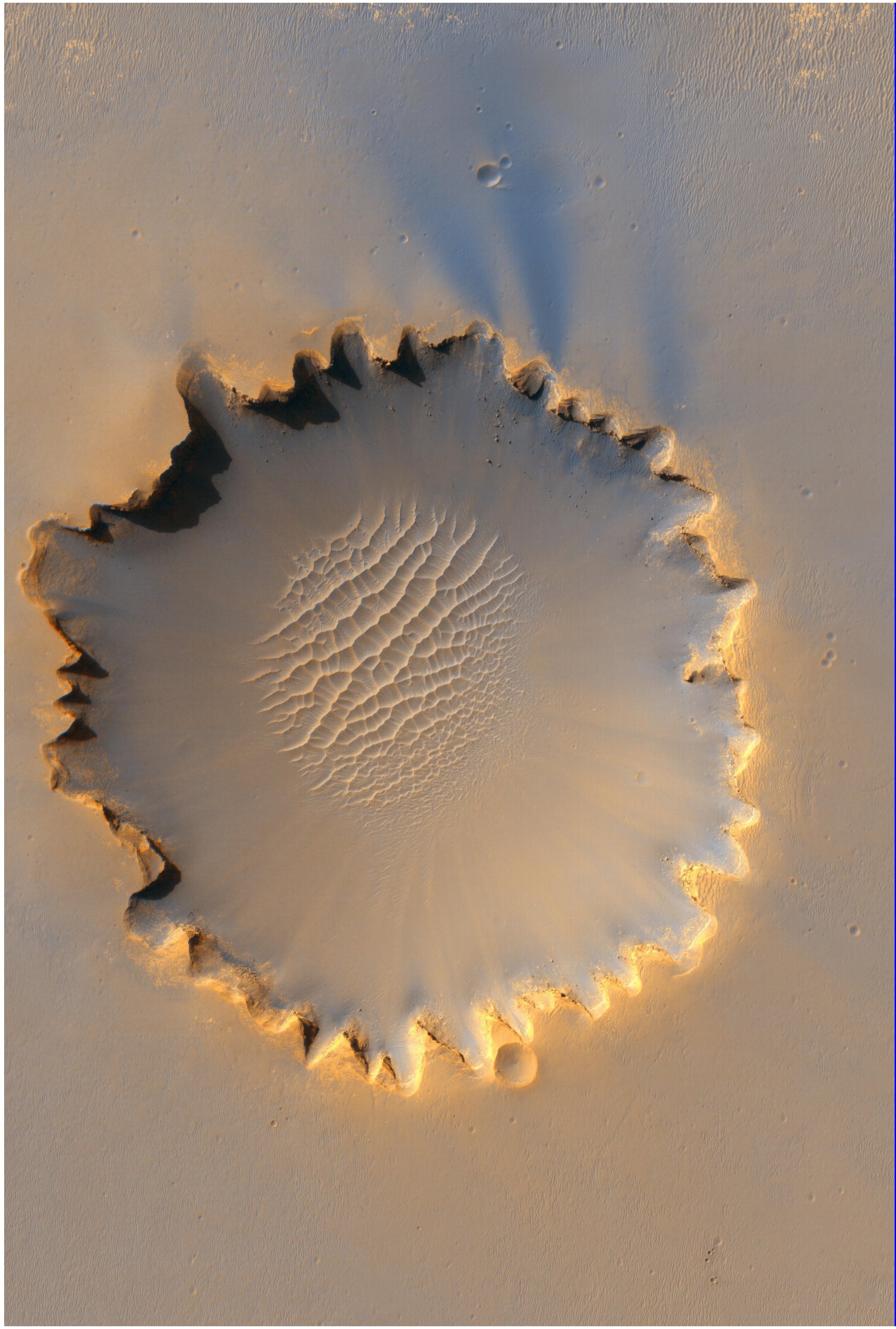
Ed Guinan (Villanova) and Steve Saar (CfA) – Solar Stellar Connection

Jeremy Drake (CfA) – CME Mass Loss

Liquid Water on Young Mars: Confirmed by NASA Rovers

NASA Press release, May 2009: "NASA Rover Sees Variable Environmental History at Martian Crater" …..."The data show water repeatedly came and left billions of years ago".

Squyres et al. (Nature, May 2009): "…alteration may have required several hundreds of millions of years of water exposure".



Victoria impact crater on Mars, explored for eight months by Mars Rover Opportunity

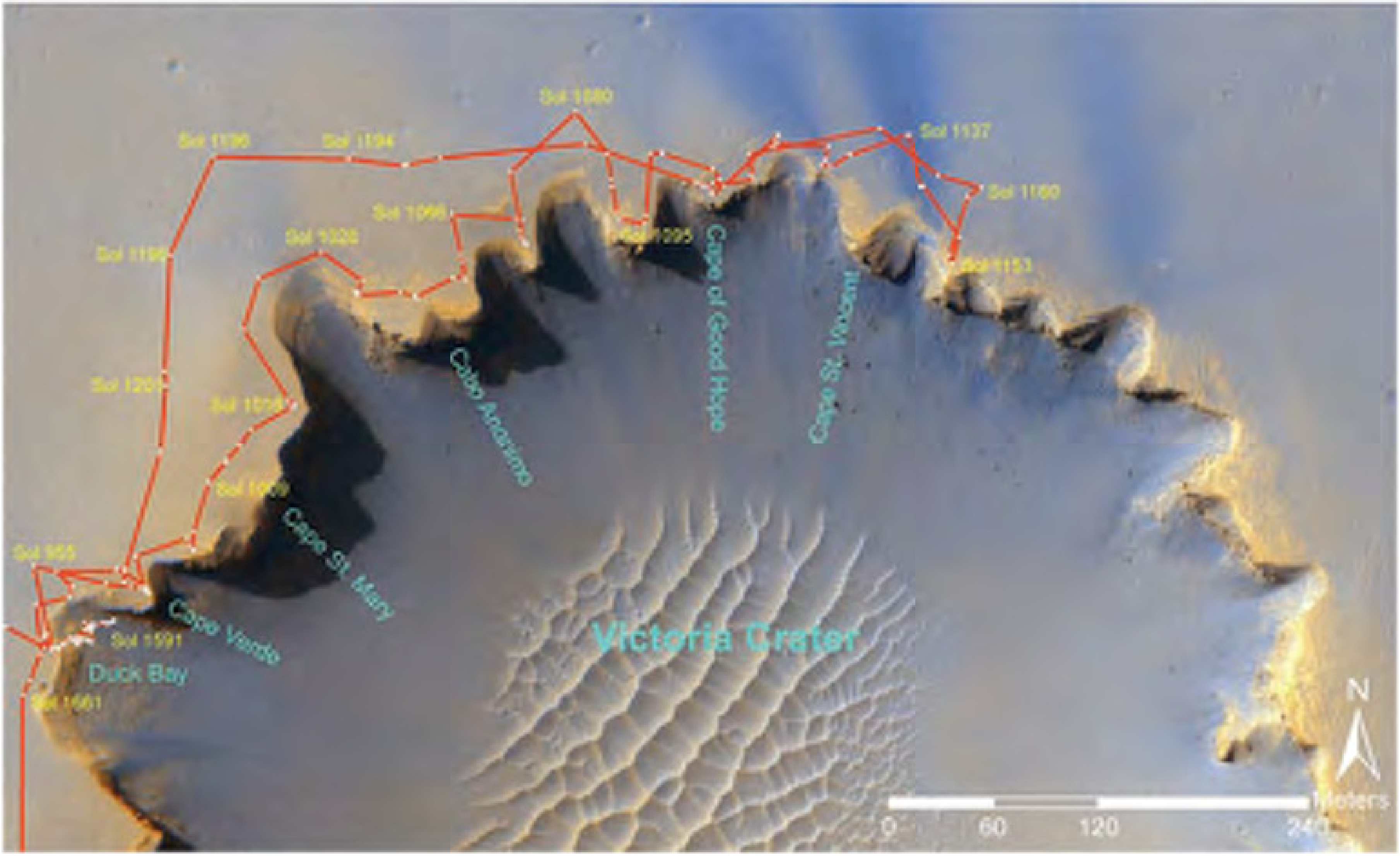
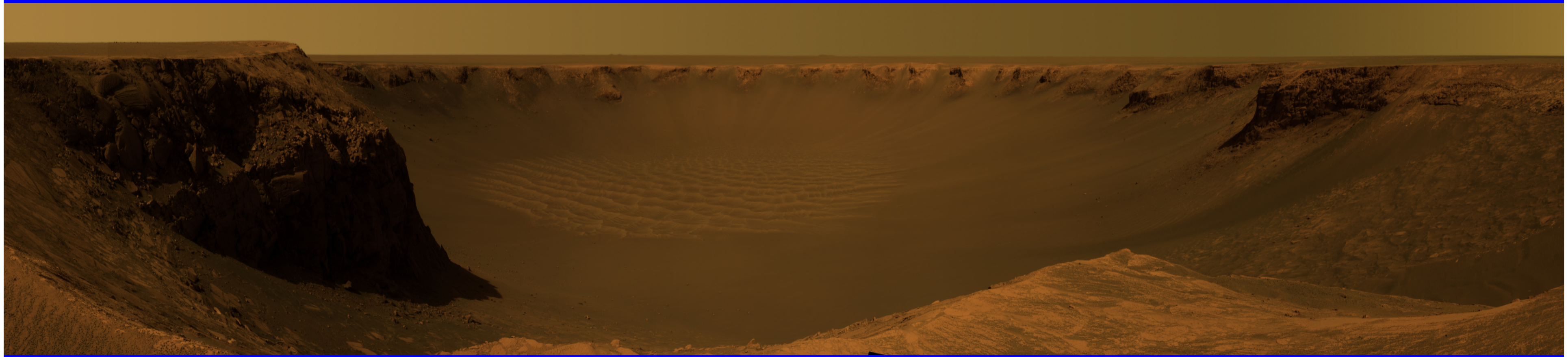


Fig. 1. Opportunity's traverse at Victoria crater. Image acquired by the Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment camera.

Panoramic View of the Crater Rim



If Mars has had surface liquid water for periods of hundreds of millions of years throughout the last two or three billion years, it's atmosphere must have been MUCH warmer than what a "faint young Sun" would sustain

More Recent Sign of Water on Mars: Curiosity

If

Occam's "Razor": Some Background

Occam's Razor (father William of Occam, 1285-1349): "*one should not increase, beyond what is necessary, the number of entities required to explain anything*". (Quote is dubious)

One of the basic principles of modern scientific reasoning – but often ignored.

Occam's Razor Applied

If both the Earth and Mars throughout their history have had liquid surface water then it is reasonable to look for a common cause, i.e. a considerably brighter Sun than stellar evolution simulations predict.

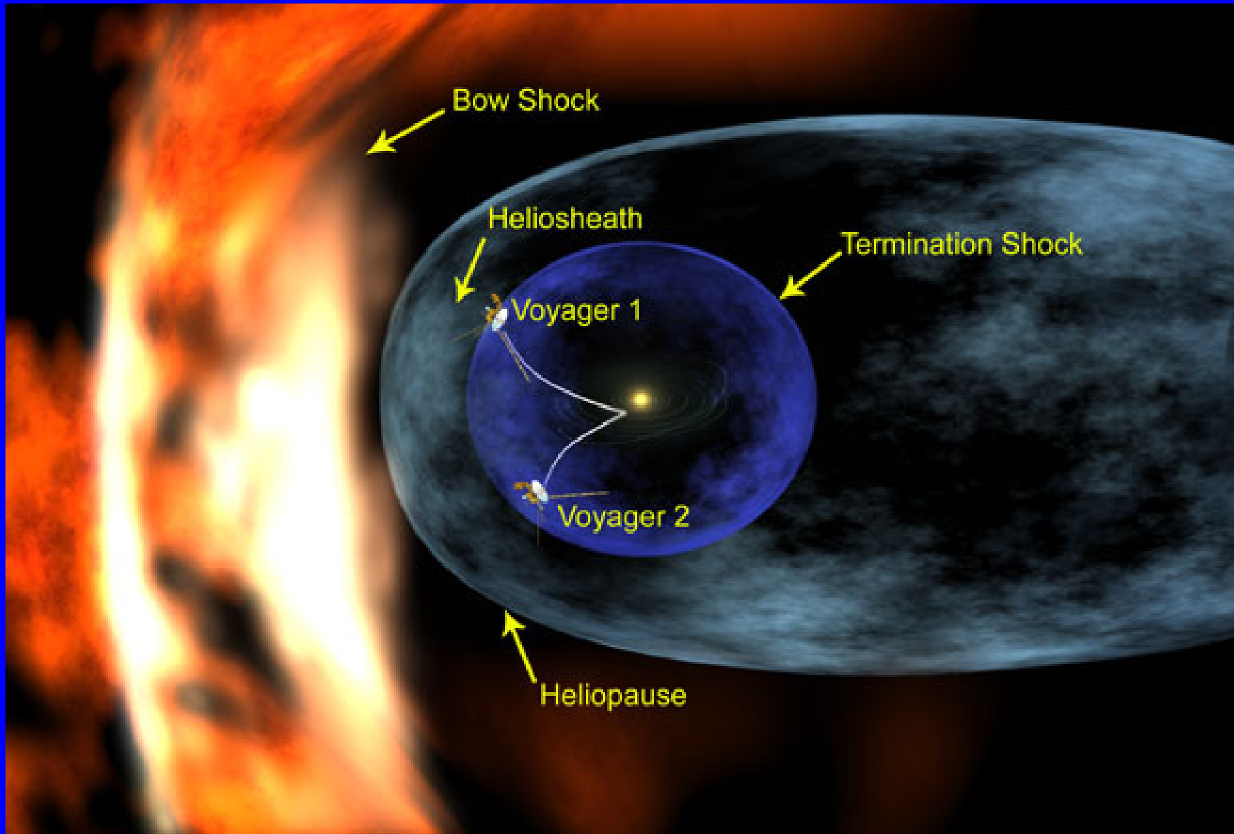
Mass Loss of a Younger Sun

- Solar flux to the planets goes as

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

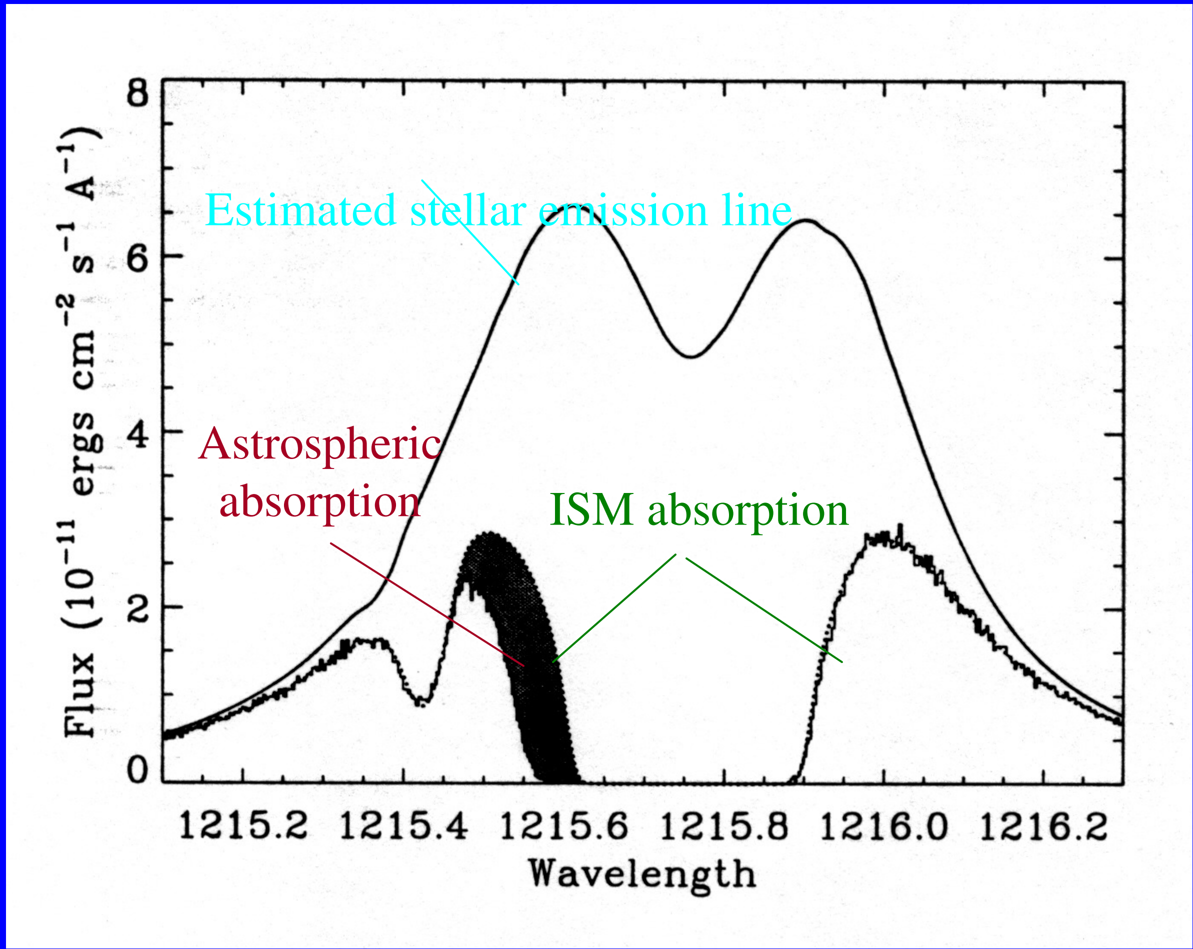
- So an early Sun that was ~5% more massive would yield 30% more irradiance, needed to have warm planetary atmospheres
- Hence, required solar mass loss is ~1% per billion years, i.e. $\dot{M}_{sun} = 10^{-11} M_{sun} / yr$
- Current (observed) mass loss $\dot{M}_{sun} = 3x10^{-14} M_{sun} / yr$
- Factor 300 off!

Observations of Mass Loss of Sun-like Stars



Mass loss of solar type stars is very hard to detect because it is so small. How is it done?

Ly-α Spectrum of ε-Eridani (HST)



B. Wood et al., *Ap. J.* **574**, 412 (2002)

Some Observational Results

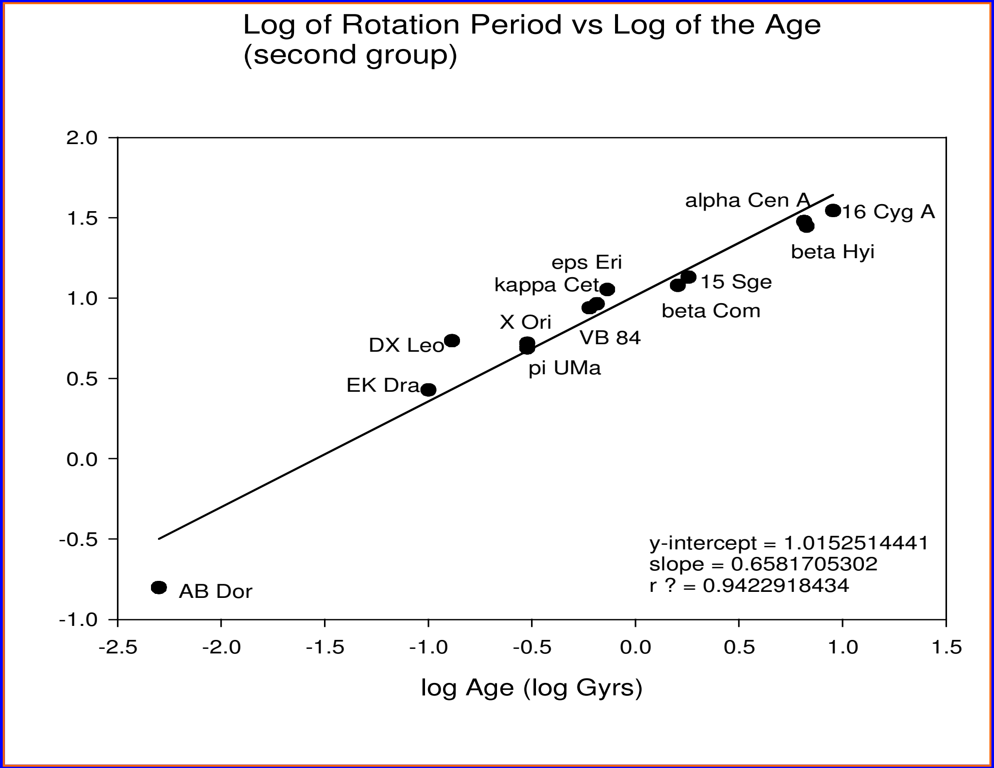
70 Ophiuchi, mass ~ 0.92 M_{sun}, age ~ 0.8 billion years, mass loss ~ 3×10^{-12} M_{sun}/yr

E-Eridani, mass ~ 0.85 M_{sun}, age ~ 0.5-1.0 billion years, mass loss ~ 10^{-12} M_{sun}/yr

Conclusion: the handful of young solar type stars that have been observed tend to have a much higher mass loss.

Spin-down Analysis

Much more is known about the spin-down of solar-type stars over their evolution. The spin-down can be related to mass-loss

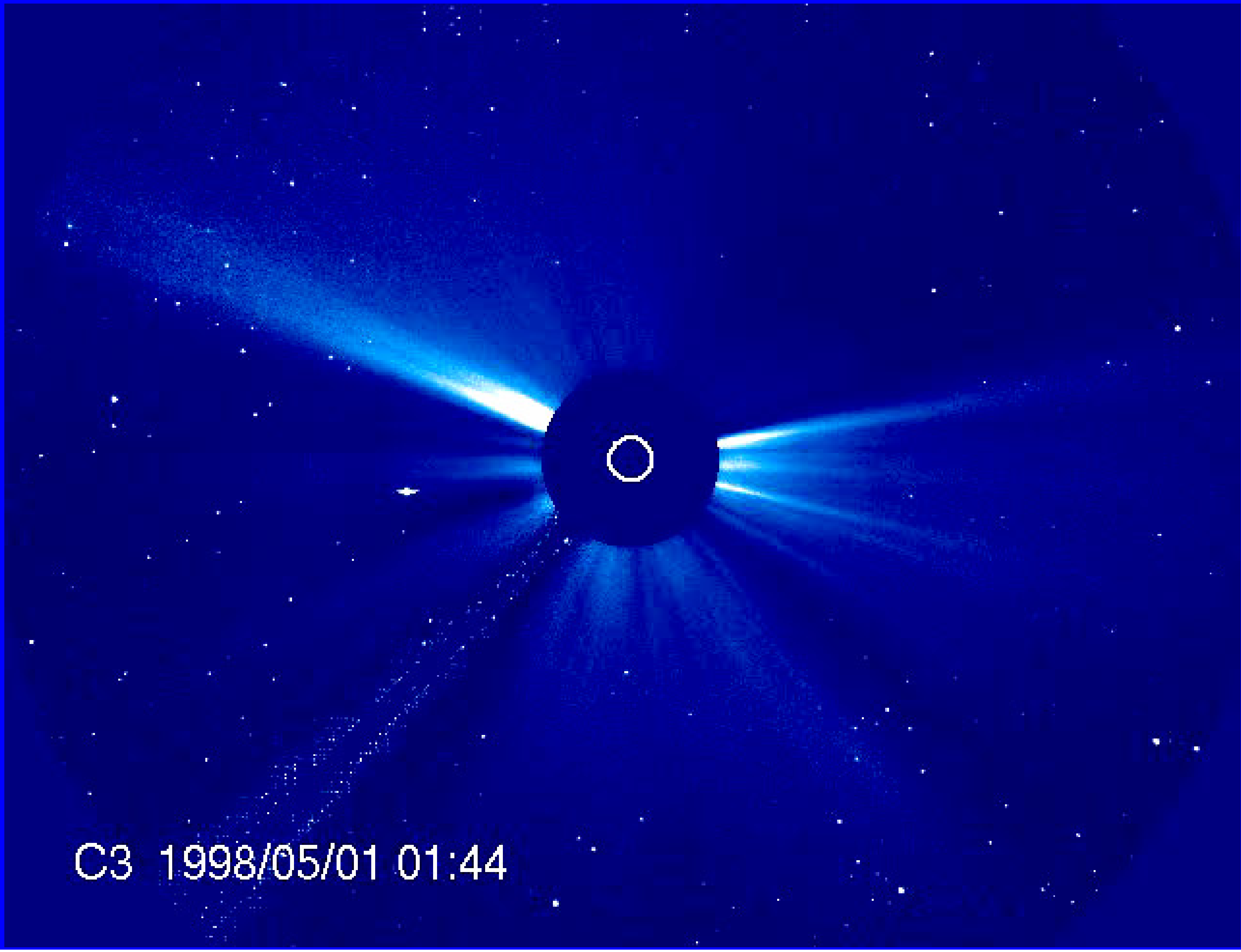


From Nandy and Martens 2007

$$P_{rot} \sim \tau^{-2/3}$$

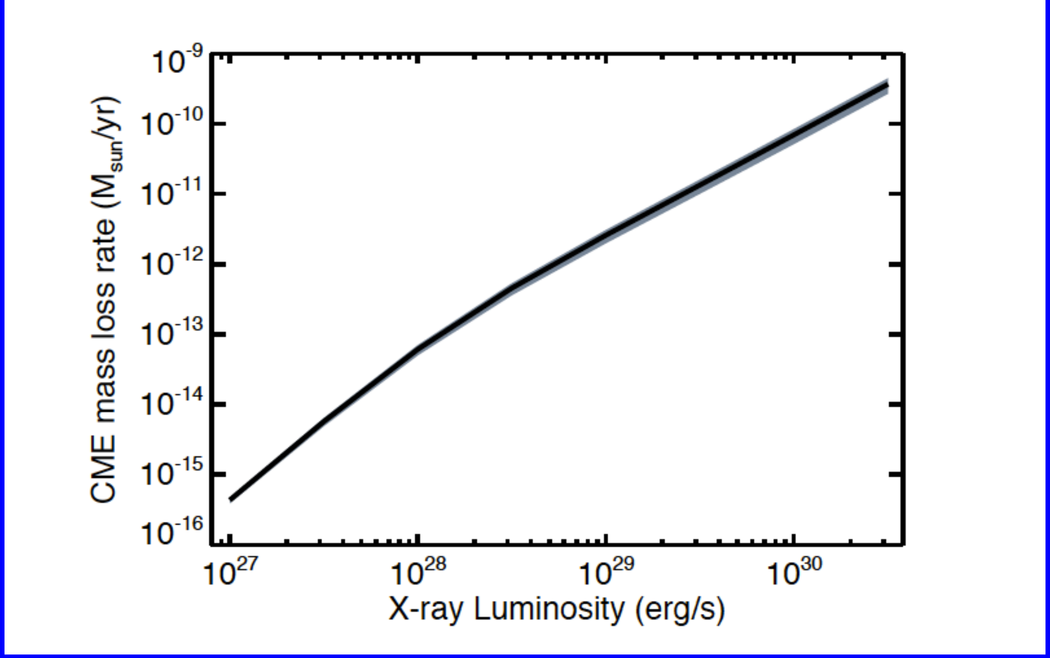
$$\tau_{spin-down} \sim 2 \text{ billion years}$$

What is Solar Wind Anyway?



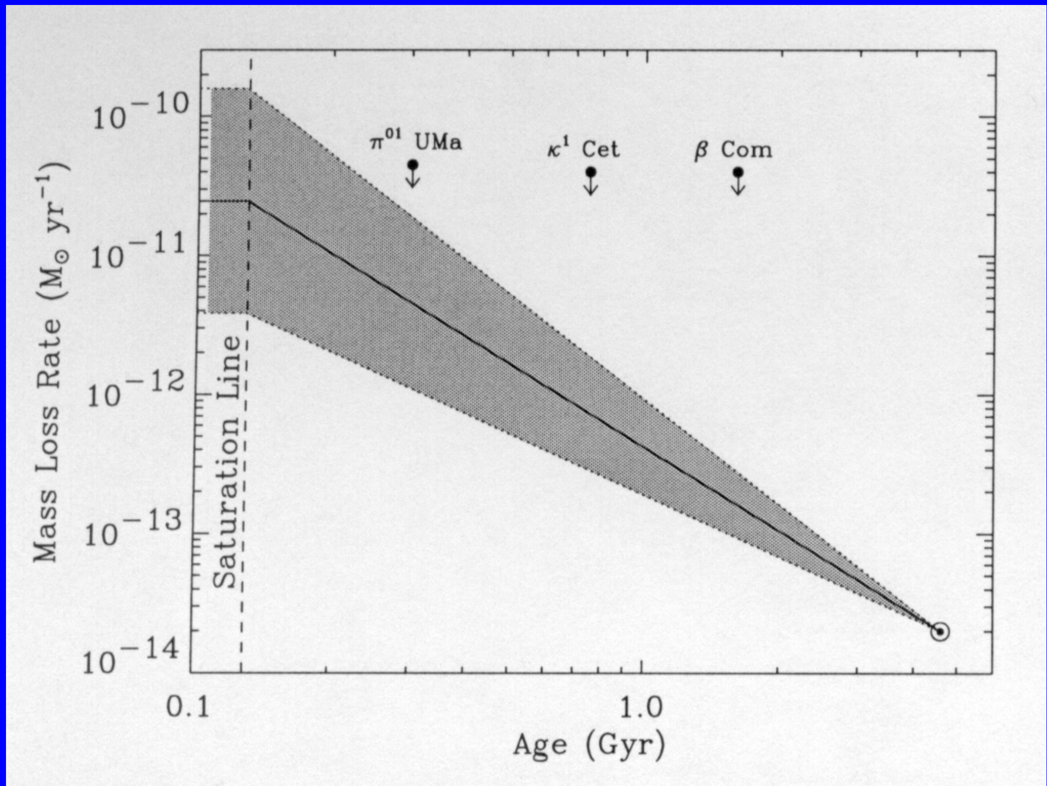
Mass-Loss and X-Ray Luminosity

Key Result: Mass-loss rate via CME's scales with X-ray luminosity to the power 3/2 (Jeremy Drake et al. 2012). Yields good results for current Sun and for very young Suns (~ 3×10^{-12} M_{sun}/yr). Mass-loss may not be sustainable by stellar dynamo in upper range.



Hypothesis

What if the early large mass loss of the Sun – observed in analogs – was sustained until fairly recently, and then suddenly switched off?

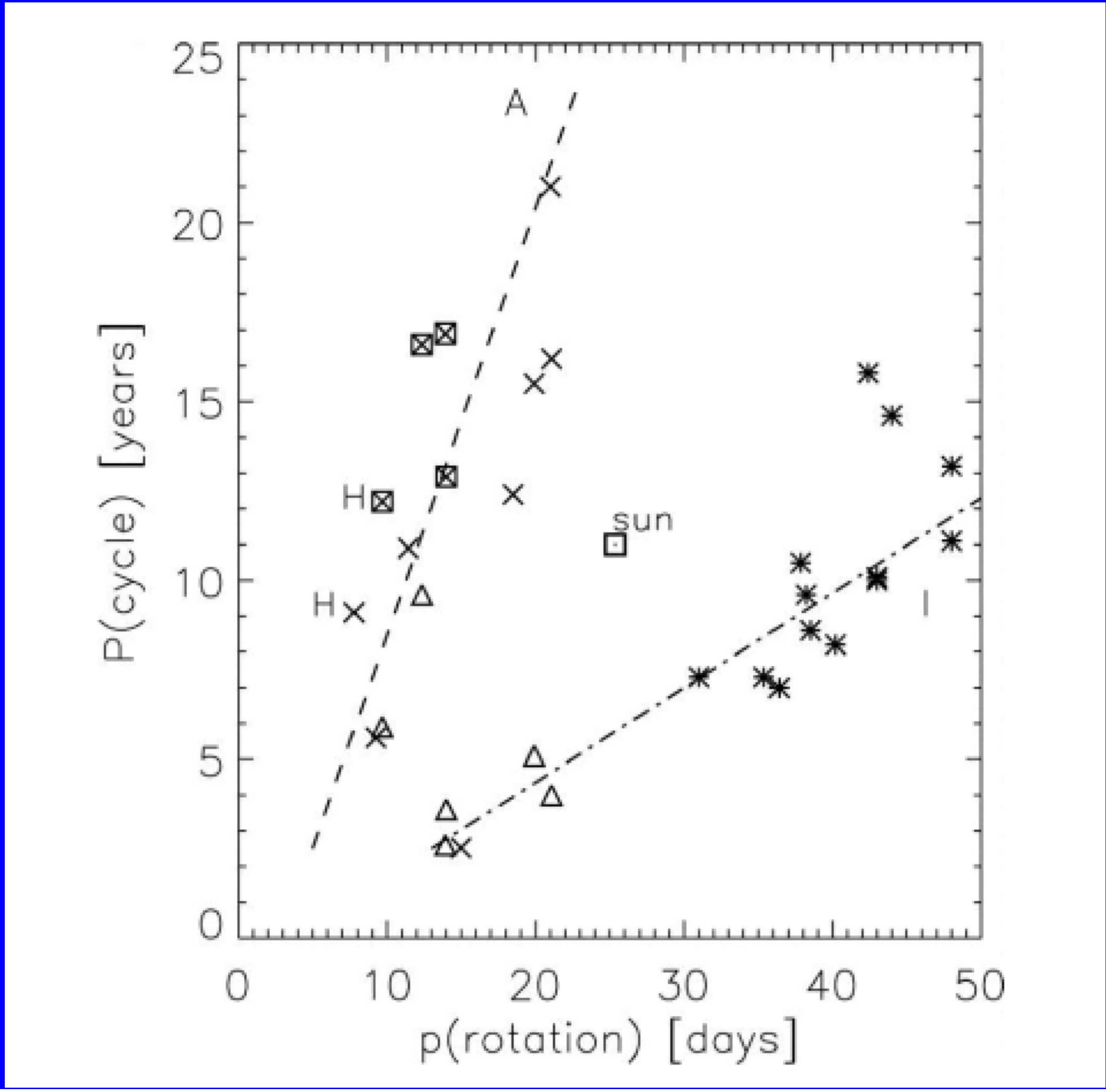


Supporting Evidence: Dynamo Modes

From Böhm-Vitense (2007), based on CA II S index data from Mt Wilson and Lowell.

Note the two dynamo branches, with the Sun in transition

Active Branch:
P(cycle) ~ 400 P(rot)
Inactive Branch:
P(cycle) ~ 90 P(rot)



Supporting Evidence: Dynamo Modes

From Nandy & Martens (2007)

Again, note the two dynamo branches, with the Sun in transition. This time the branches are not that evident, but they can be recognized.

Active Branch: P(cycle) ~ 400 P(rot)

Inactive Branch: P(cycle) ~ 90 P(rot)

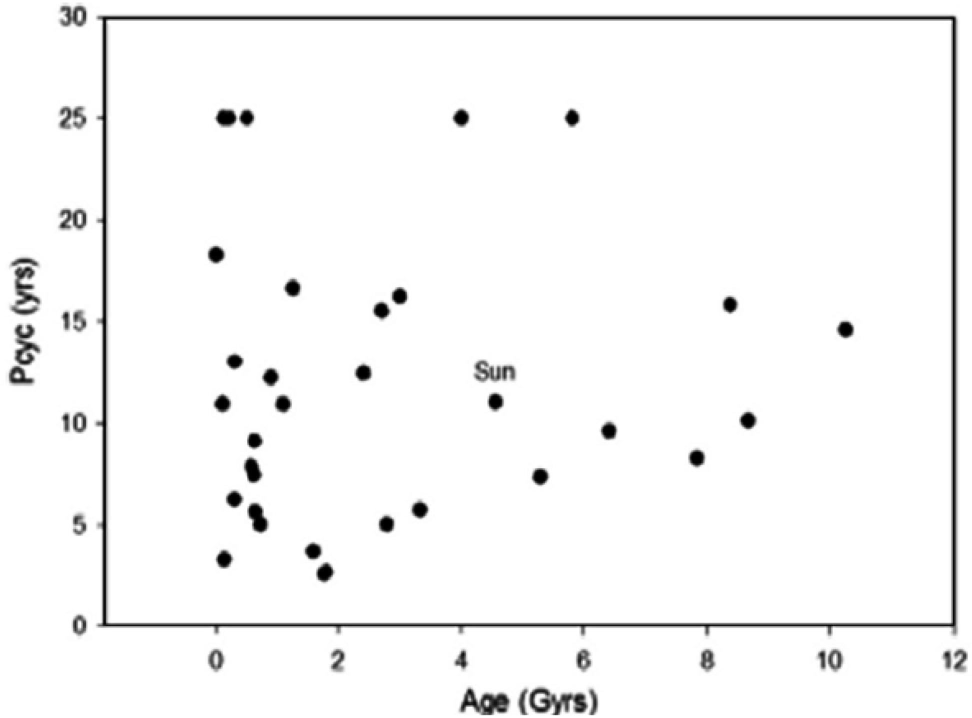
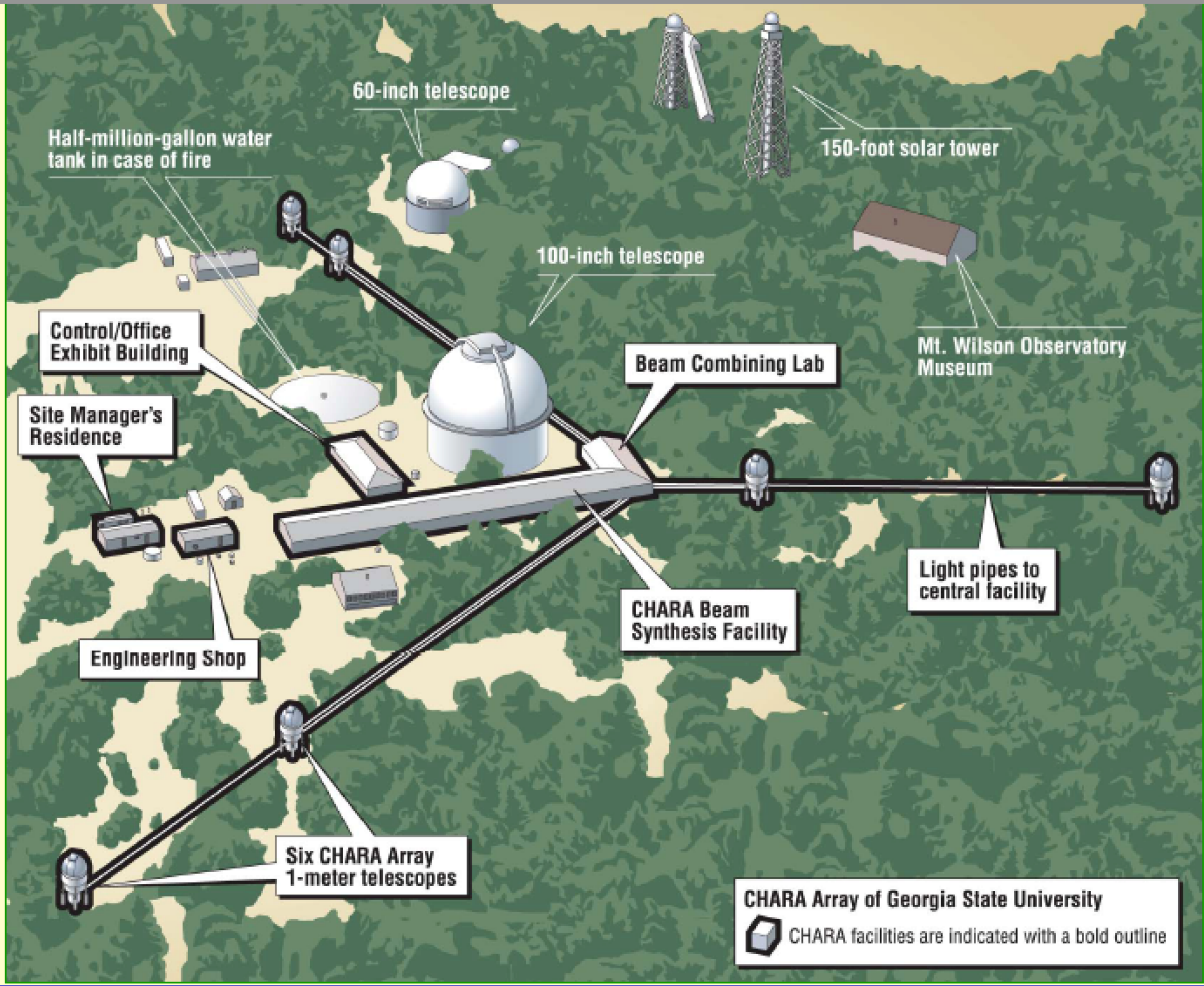


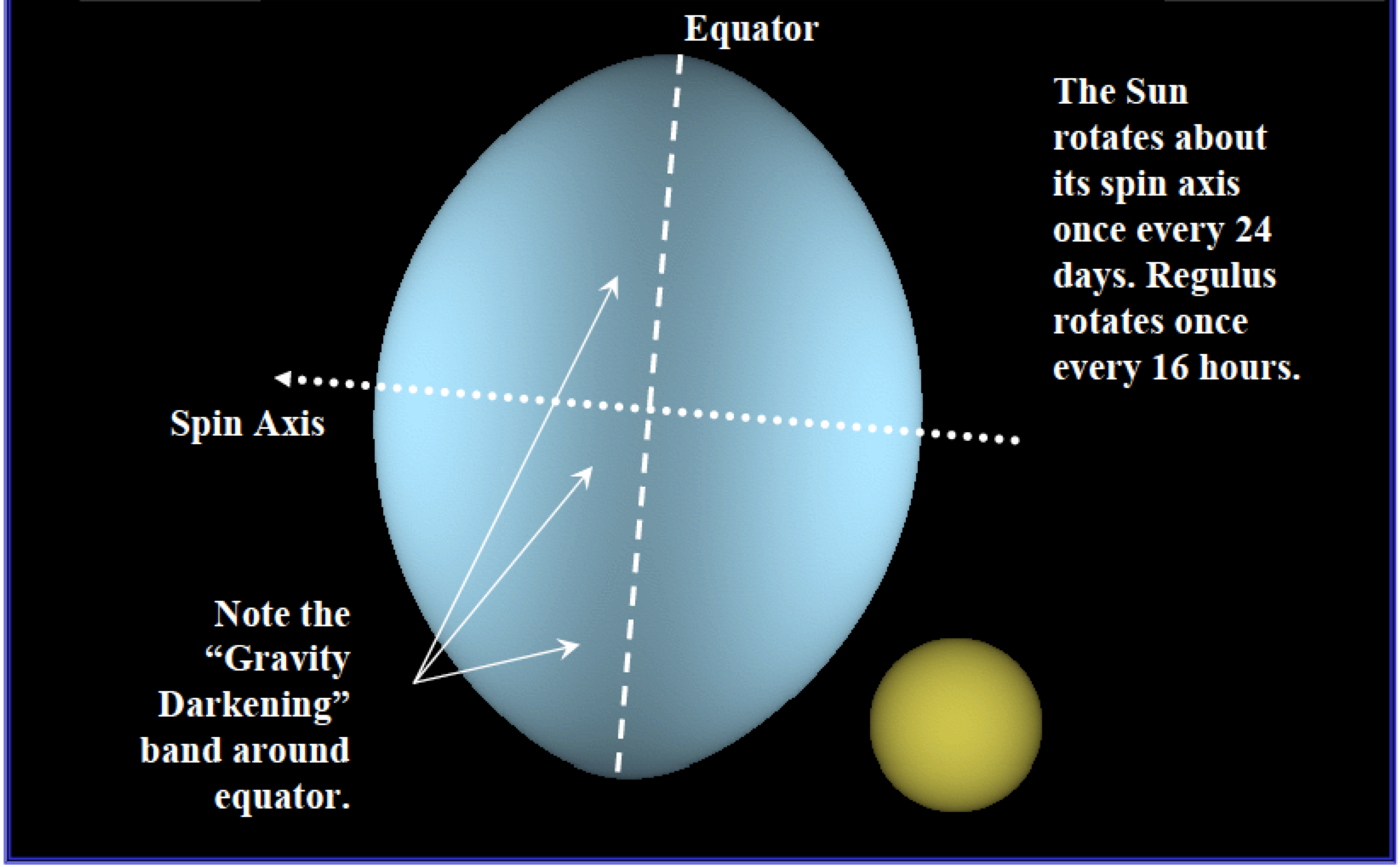
Fig. 6. The magnetic activity period (y-axis; in years) versus age (x-axis; in Gyrs) relationship in a subset of our stellar sample for which period measurements exist. No statistically significant trend is recovered in this sample.

Layout of the CHARA Array



Regulus & the Sun

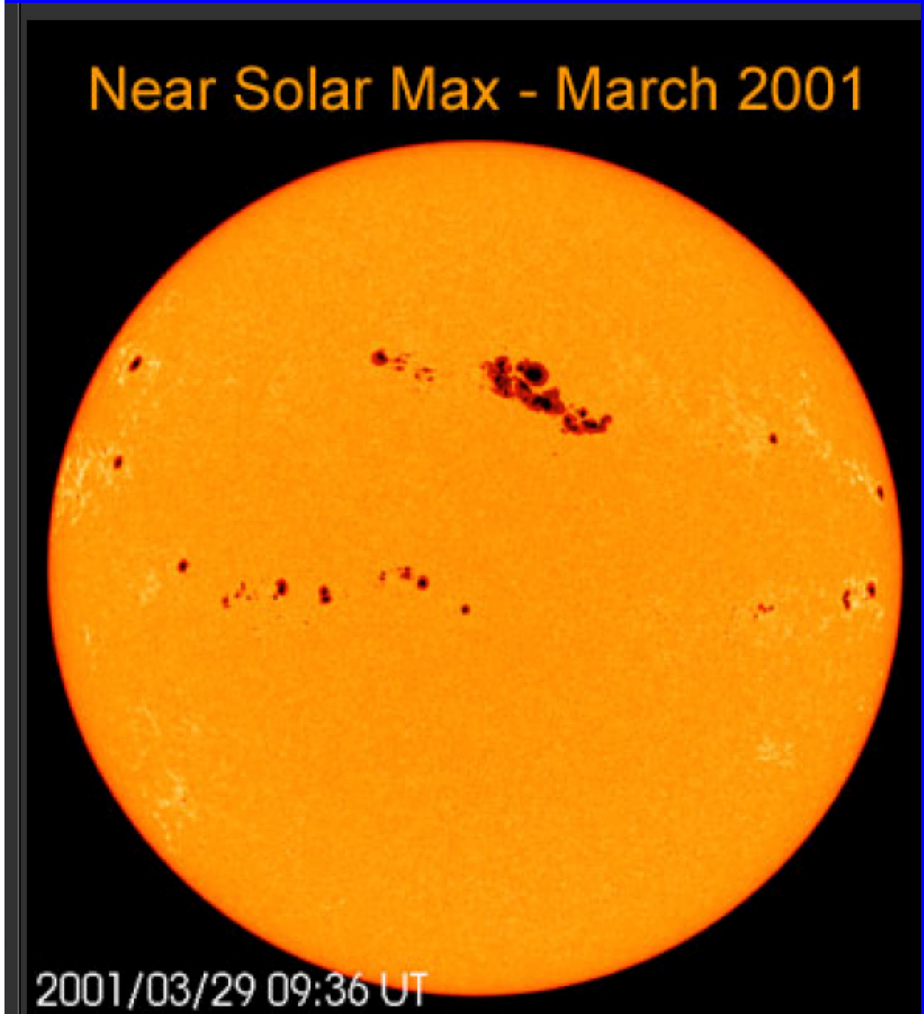
CHARA's First Science Paper – Detailed Modeling by Wenjin Huang

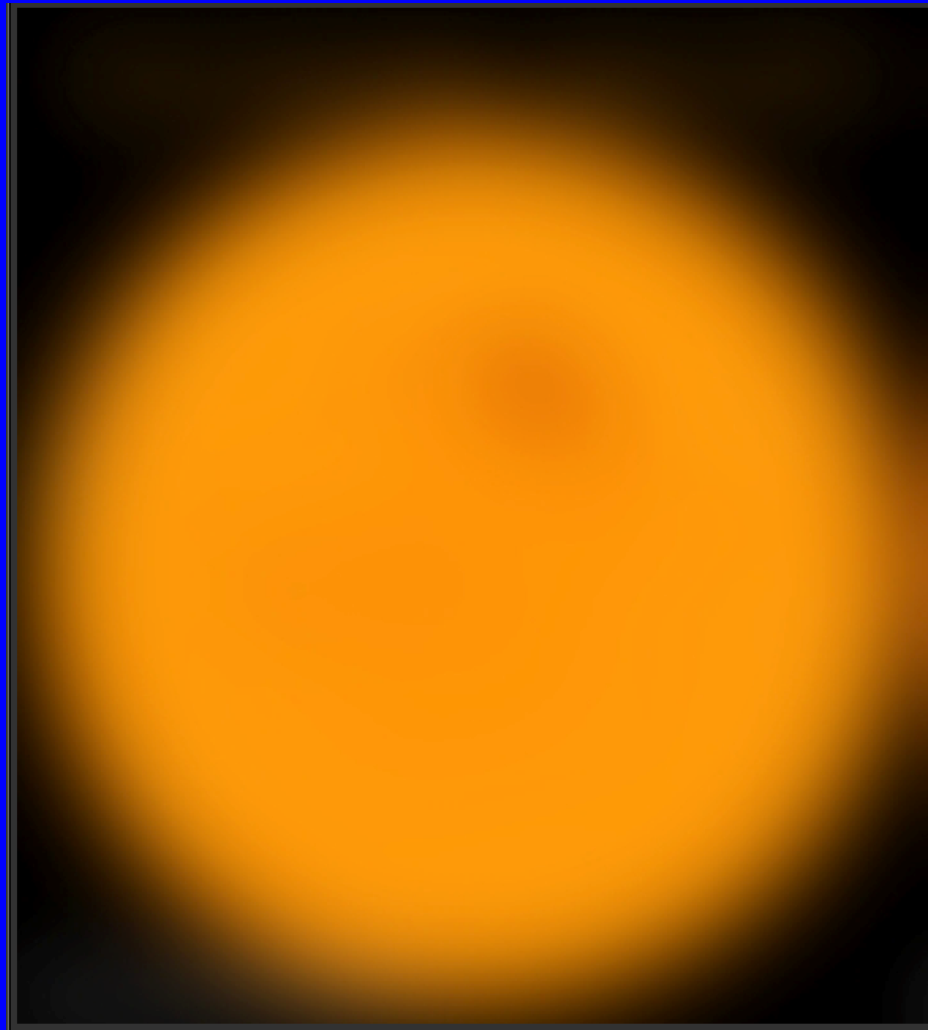


What can CHARA do for me?

- CHARA can observe nearby solar analogs (F 8 V to K 2 V), e.g. ε Eridani (10.5 ly), and τ Ceti (11.9 ly). Radius of τ Ceti ~ 0.001 arcsec.
- The spot activity on these stars is a probably direct indicator of the dynamo mode they are in, related to the mass loss mode
- This also is a key observation for solar/stellar dynamo theory

CHARA Observing the Sun at 11.9 ly, distance of τ Ceti





Conclusion: A Work in Progress

- The resolution of the "Faint Young Sun" paradox probably lies in that the young Sun was not faint
- Mass loss is a likely candidate because planetary insolation scales so efficiently with mass loss.
- Observations of mass loss from very young solar analogs show a sufficient mass loss rate.
- Hypothesis: the early mass loss rate could have been sustained for a long time and then switched off as the Sun transitions to a different dynamo mode.
- CHARA, Kepler, and Lowell data can help resolve this paradox.

This is very much a work in progress!