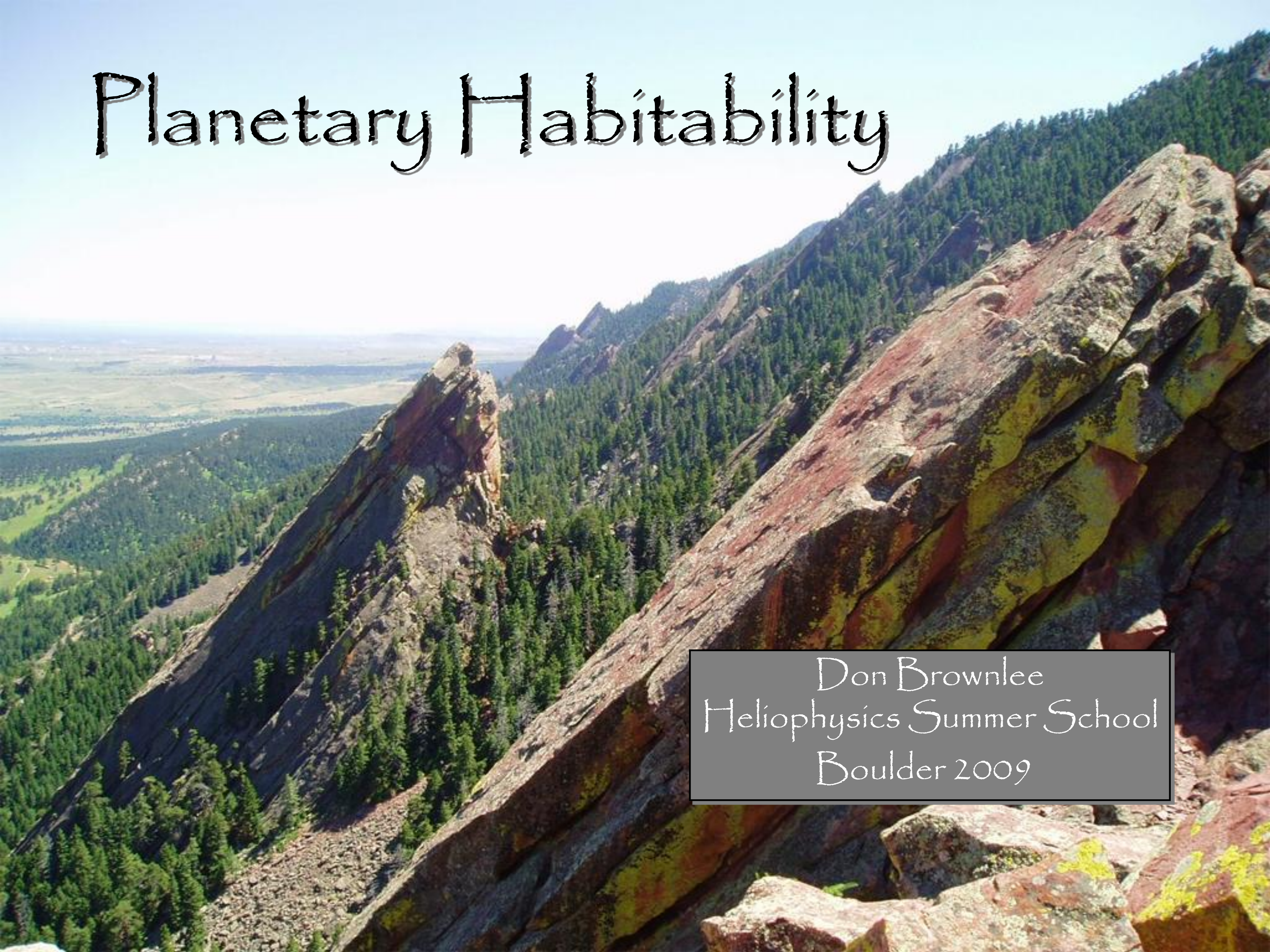
Planetary Habitability



Don Brownlee
Heliophysics Summer School
Boulder 2009

What are the limits of “habitability”

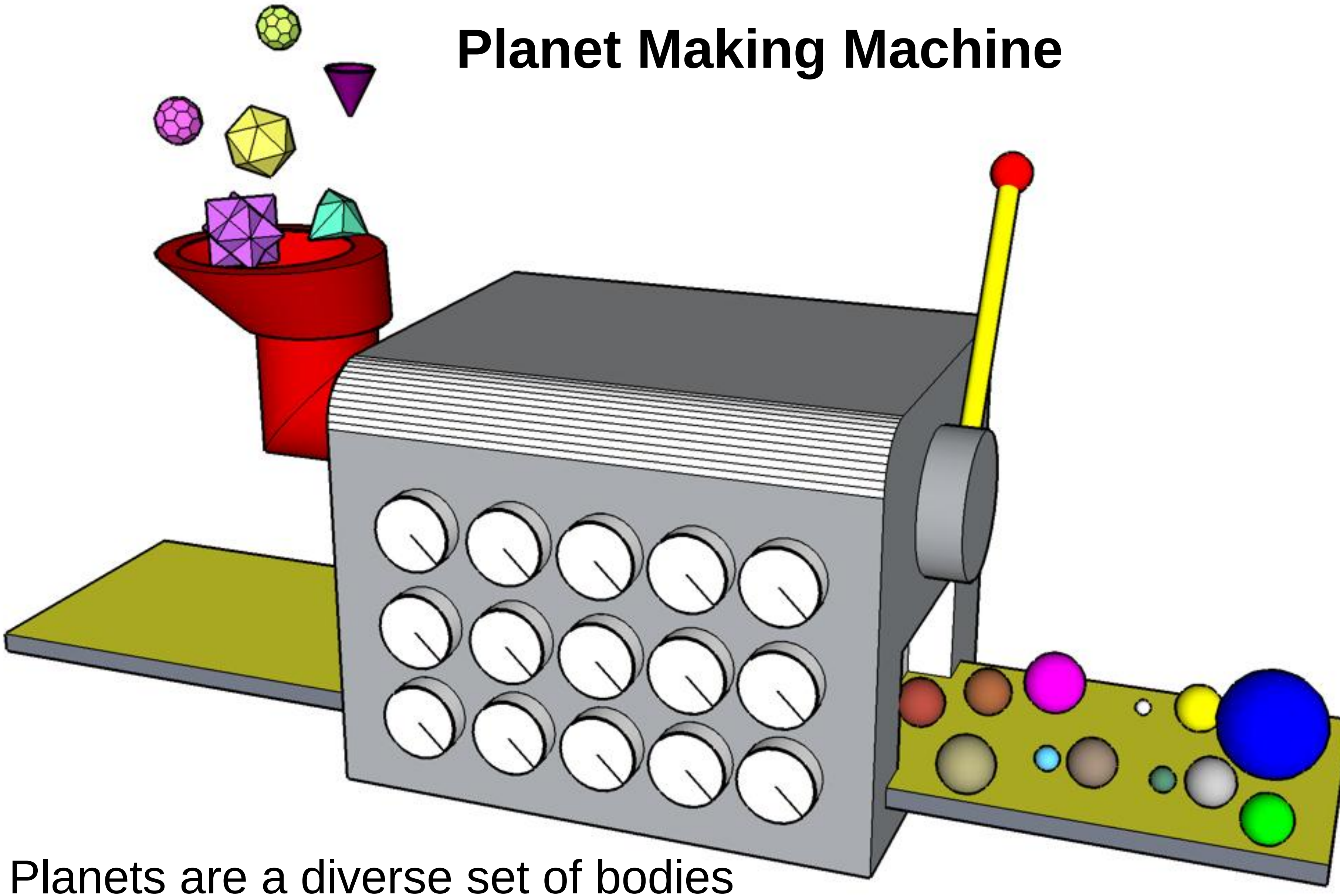
The actual limits of habitability in the Universe are unknown

And surely unknowable

Unless et-life visits or sends messages:
we will never know about life outside our local stellar neighborhood

Future knowledge about life
is probably limited to life around
the nearest few thousand stars

Planet Making Machine



Planets are a diverse set of bodies
that have complex evolutionary processes

Habitability - best estimates

Necessarily based on Earth-life

Habitability issues usually focus on environmental requirements that

that plausibly might support life that is analogous to Earth life

Standard habitability needs

Animals (multi-cellular air-breathing)

- Restricted environmental needs

  $0<T<50$ ºC

- Not well adapted to change
- Species short-lived - easy to extinct
- Need oxygen
- Took 2.2 by to have O_2 in atmosphere
- Took ~ 4 billion years for animals to become abundant in the fossil record
- Difficult to evolve?

Standard habitability needs

Microbial organisms

- Less restricted environmental needs

  -15ºC<T<122 ºC (probably much higher)

- Specific organisms adapted to extreme environments
- Very difficult to extinct, species may last billions of years
- Microscopic, numerous, can remain dormant for long times
- Appear early in Earth history >3.5 AE, easy to evolve?
- Most common life on Earth
- Probably the most common life in the Universe

Habitability of planets involves many potential factors

- Planet mass
- Planet C, H_20 & K content
- Continent/ocean ratio
- Salinity
- Solar, stellar activity
- Planet history
- Magnetic field
- Orbital stability and eccentricity
- Spin rate, obliquity

Water

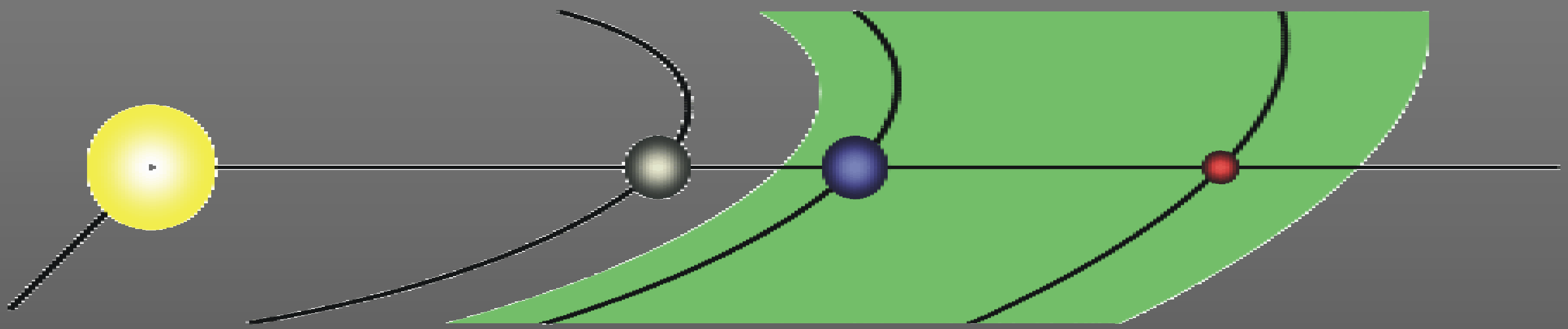
a fundamental need for life (as we know it)

- Surface water - sets restricted environmental limits

- Sub-surface water- wide range of occurrences probably in Pluto, certainly in Europa, apparently in 500 km Enceladus, in many asteroids for millions of years. Interiors warmed by accretional heat, radiogenic and tidal heat.

Habitable Zone Concept

An increasingly used & increasingly loosely used concept



The range of distances around a central star at which Earth-like planets maintain conditions sufficient for the existence of life at the surface.

First publications:

Huang (1959, 1960), Dole (1964), Shklovski & Sagan (1966)

Most Common Habitable Zone Concept

The range of distances from a star where an Earth-like planet can have surface water (oceans!)

Too close to star - oceans lost to space (~.95AU for Sun)

Too far from star - oceans freeze

(~when CO_2 ice clouds

Planet surface temperatures

$$T_{eq} = \left(\frac{S(1-A)}{f\sigma} \right)^{\frac{1}{4}}$$

A-albedo

S-energy flux

f-redistribution factor

uniform $f = 4$ (rapid spinner)

starlite side only $f = 2$ (slow spinner)

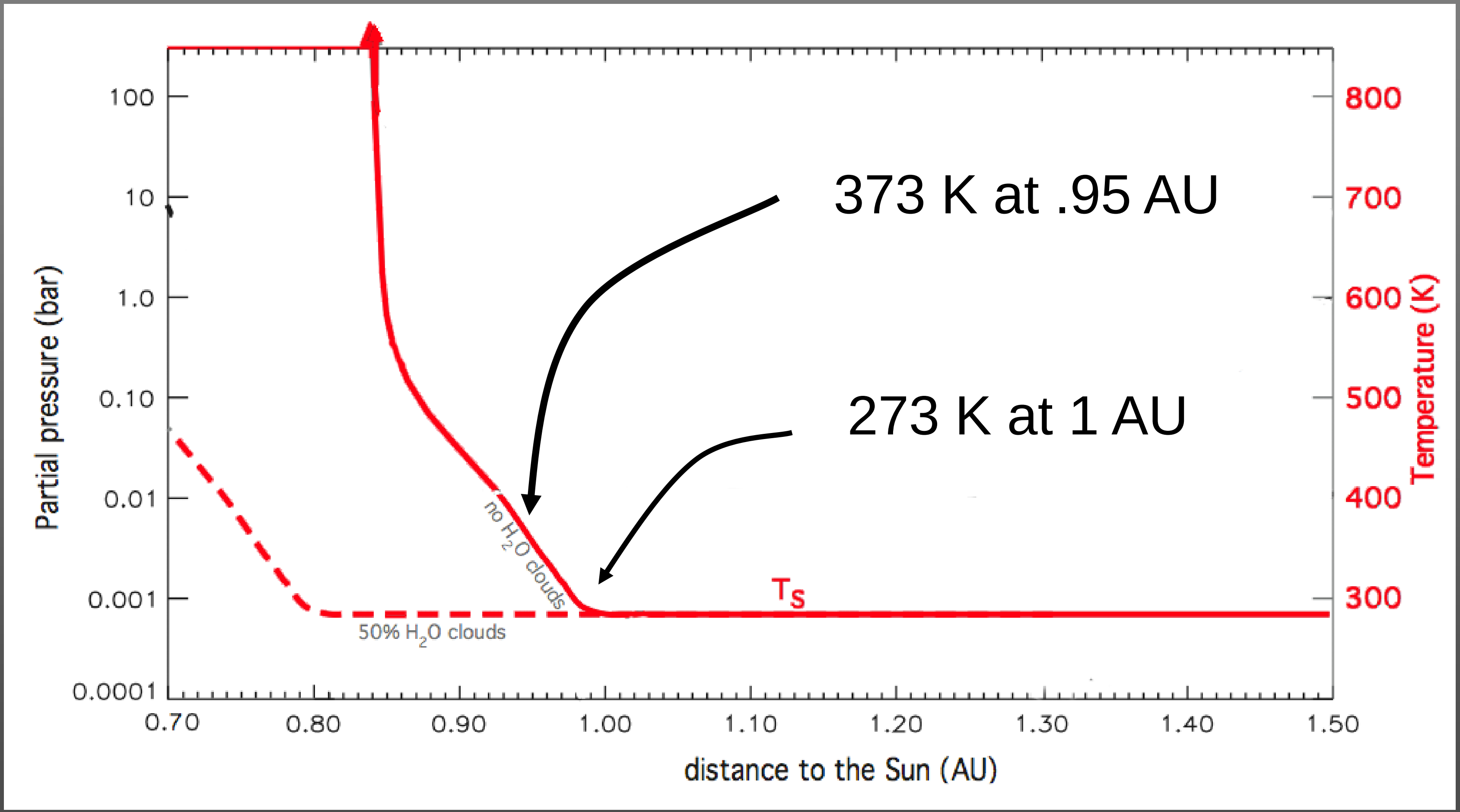
local equilibrium temp $f = 1/\cos\theta$ (lunar noon)

$T_s \neq T_{eq}$

Due to greenhouse warming

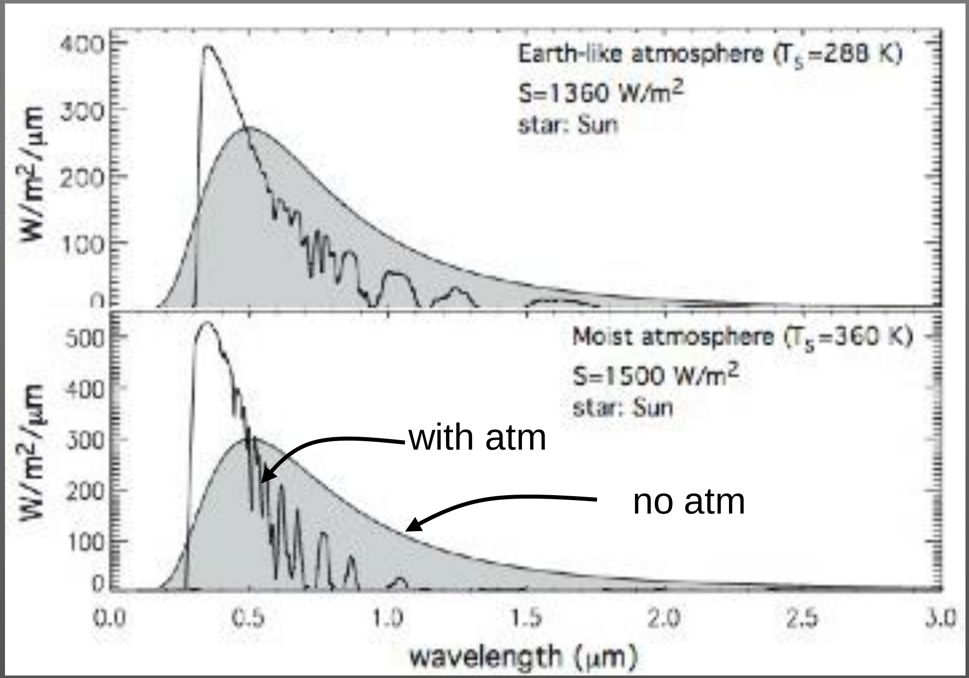
	Venus	Earth	Mars
albedo	.75	.29	.22
T_{eq} (f=4)	231K	255 K	213K
T_s mean	737 K	288K	218 K

Inner edge of HZ - steep rise in T_s



(CO_2 free atmosphere) Selsis et al. 2007

The rapid rise of surface temperature Is due to increased water vapor



Increased water vapor- more greenhouse

more Raleigh backscatter

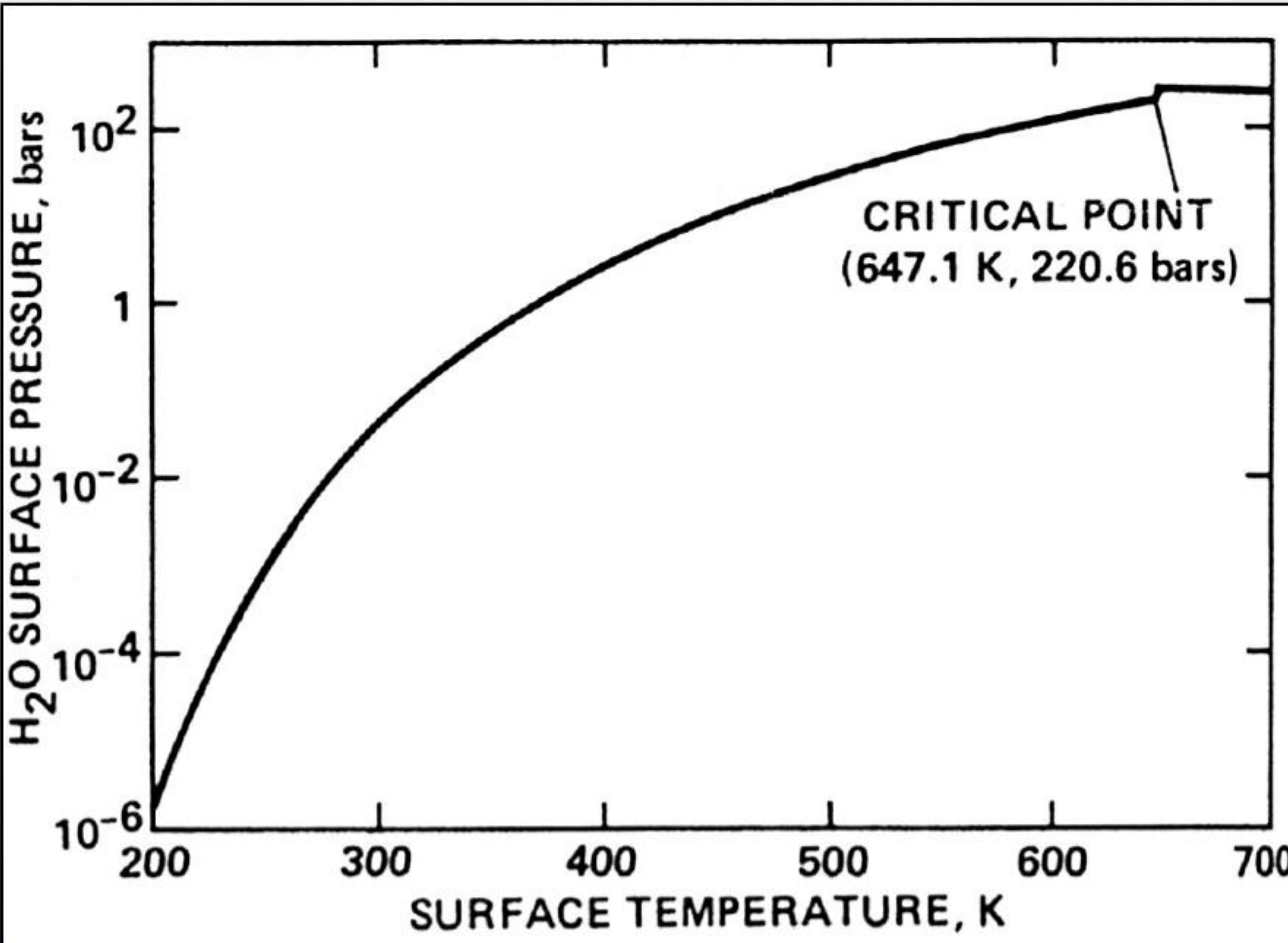
Inner edge of the HZ

Extreme inner edge

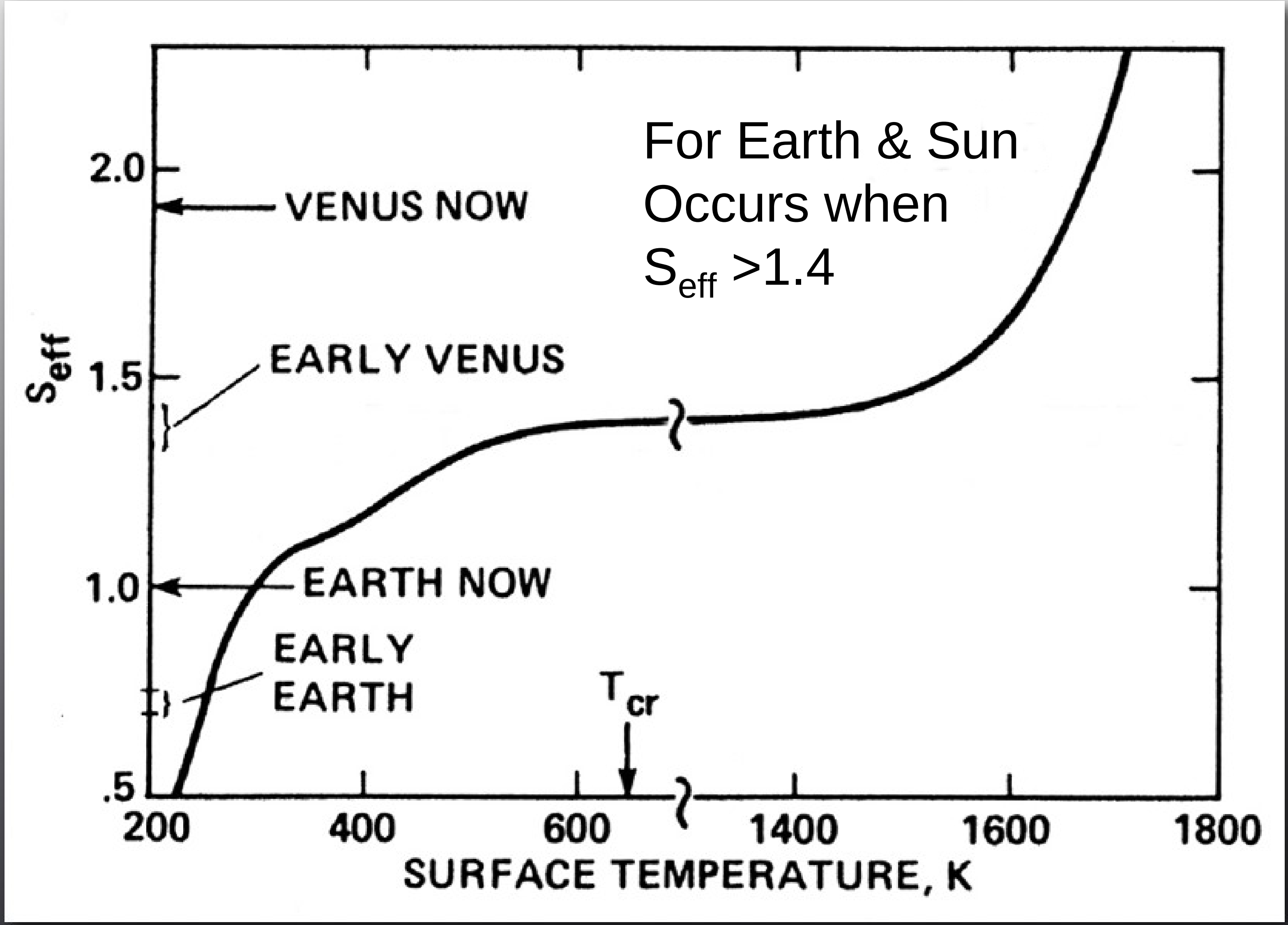
Runaway greenhouse (4π) emission threshold ~300 Wm^{-2}

(“solar constant” = 1360 wm^{-2})

In a runaway -- positive feedback due to water vapor
Greenhouse drives the surface temperature
> the critical point of water


CRITICAL POINT
(647.1 K, 220.6 bars)
H_2O SURFACE PRESSURE, bars
10^2
1
10^{-2}
10^{-4}
10^{-6}
200
300
400
500
600
700
SURFACE TEMPERATURE, K

Runaway Greenhouse



Kasting et al.

A lesson from Venus

High D/H (100X Earth)- consistent with ocean loss

Loss occurred >1by ago when Sun was >8% fainter

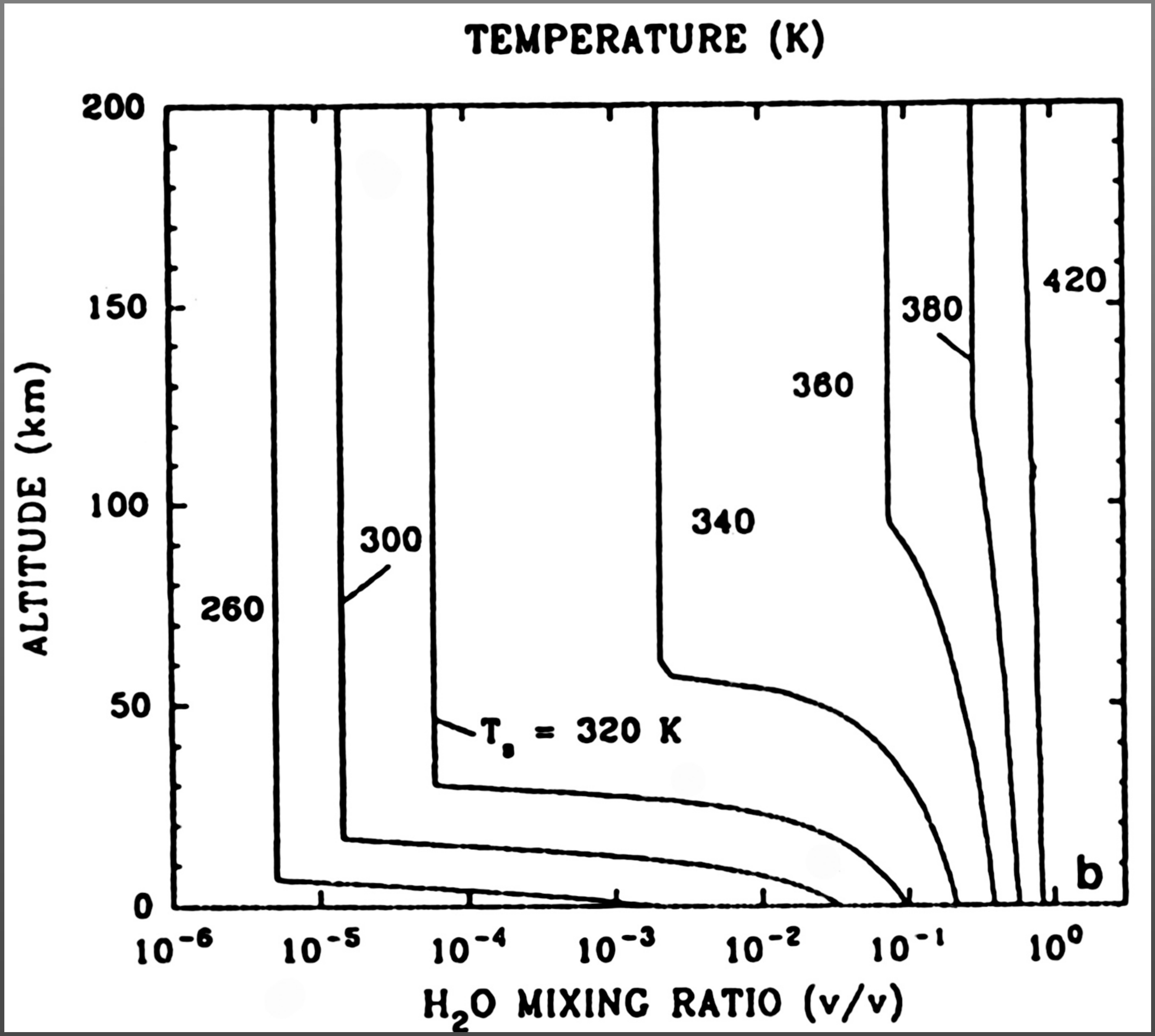
This implies an evidence-based estimate of the HZ inner edge of 0.75AU


TWO FATES OF THE OCEANS
MOIST greenhouse
RUNAWAY greenhouse
Starts in ~ 1 By
Ocean lost to space
LIFE SAVER
Starts in ~ 3.5 By
Melts surface of Earth!
KILLS EVERYTHING

Moist Greenhouse

- Begins ~ 0.95 AU, T_s ~ 340K
- Hi water vapor abundance >20%
- Tropopause lifts
- Stratospheric P_{H2O} increases
- Tropopause “cold- trap” ceases to limit water loss
- H_2O photolyzed- H is lost to space
- Depletes ocean $<10^9$ yrs

Water mixing into the upper atmosphere & space



Kasting et al


L_α Geocorona
Apollo 16

Earth's ocean-free future

Outer edge of the HZ

Formation of CO_2 clouds leads to “Snowball Earth”

Ts > 273 K to prevent ice-albedo positive feedback
(when ice cap reaches a critical latitude
increased albedo causes global freeze-over)

Estimates

1.37 AU for CO_2 cloud formation
1.67 AU max greenhouse for cloud-free Earth
2.4 AU optimized warming by CO_2 clouds

A detailed HZ estimation for planets around Gliese 581
Three super-Earth mass planets around $0.4M_{Sun}$ M star

Habitable zone

QuickTime™ and a
decompressor
are needed to see this picture.

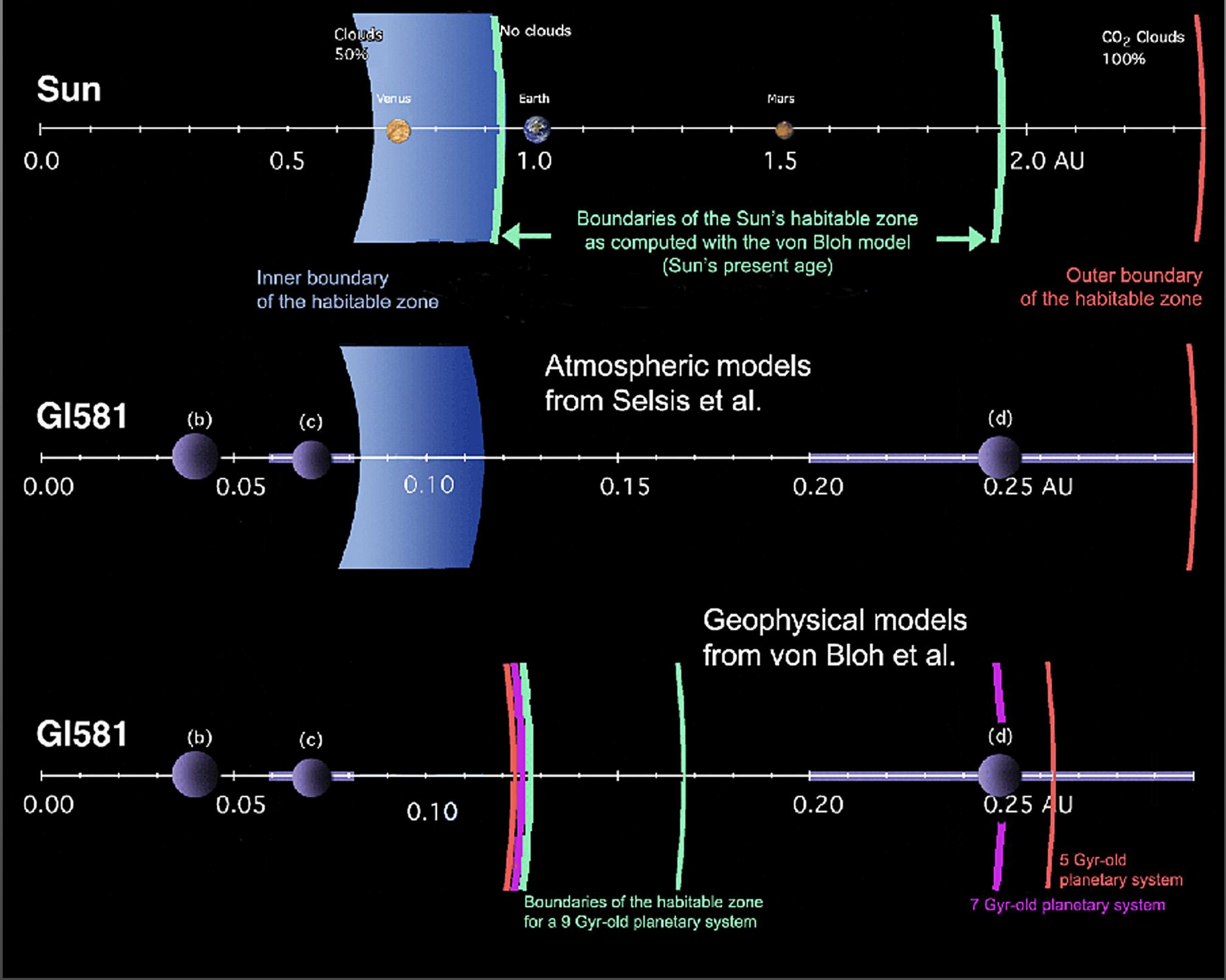
	L	T_{eff}(k)
Sun	1	5600
Gl581	.01	3200

Selsis et al. 2007

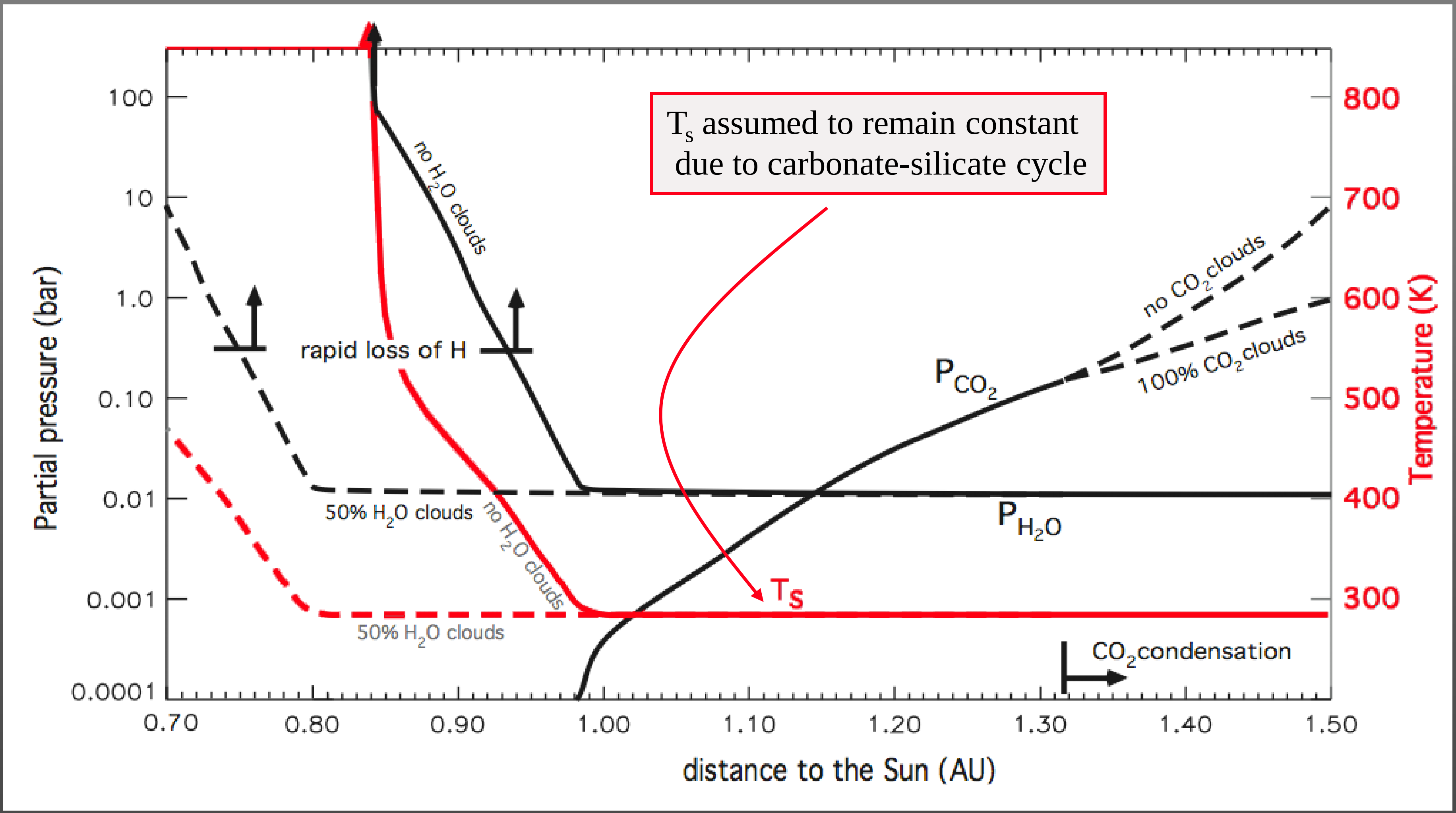
HZ complexities for different types of stars

QuickTime™ and a
decompressor
are needed to see this picture.

Effects of central star temperature



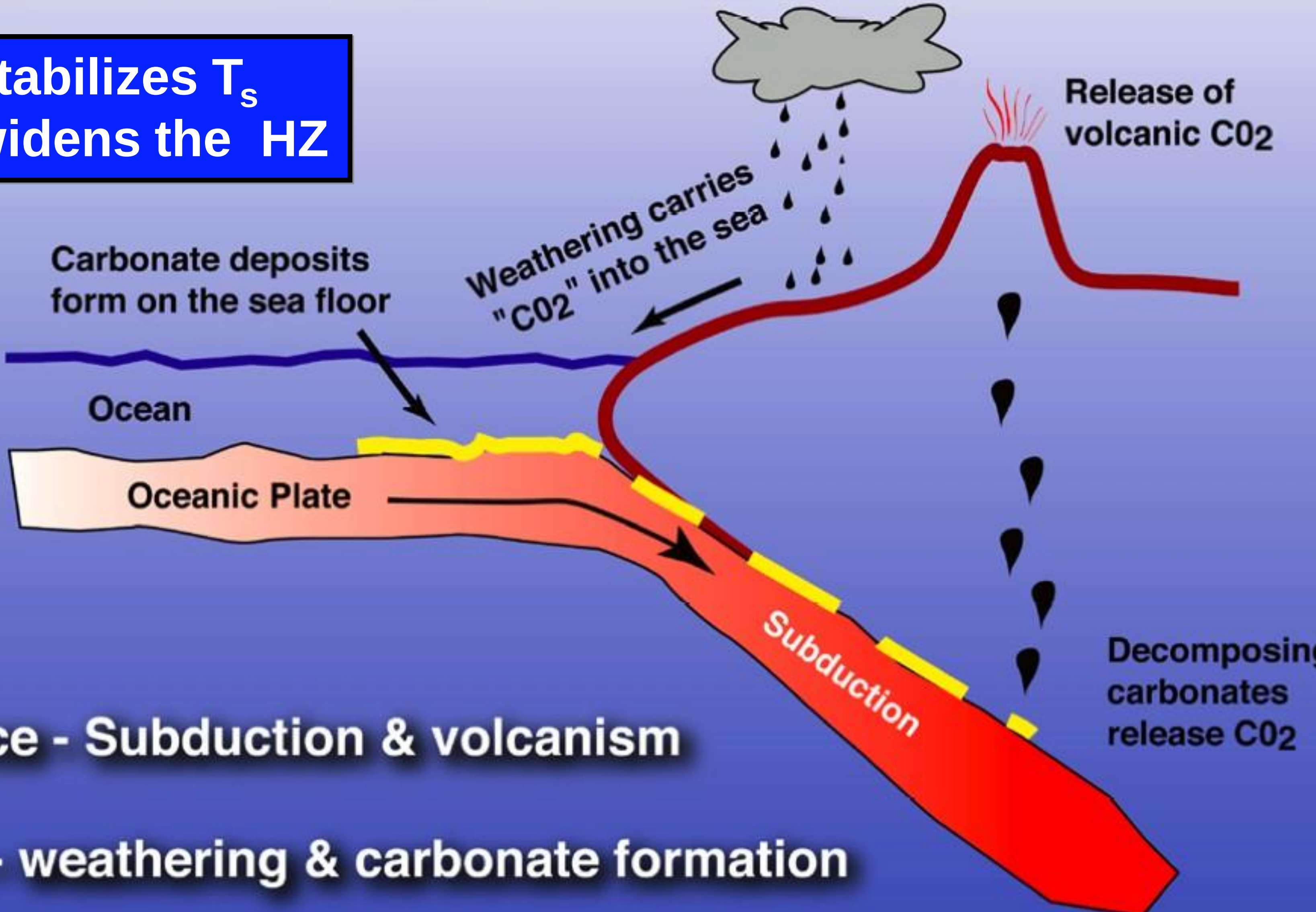
Sun
Clouds
50%
No clouds
CO_2 Clouds
100%
Venus
Earth
Mars
0.0
0.5
1.0
1.5
2.0 AU
Boundaries of the Sun's habitable zone
as computed with the von Bloh model
(Sun's present age)
Inner boundary
of the habitable zone
Outer boundary
of the habitable zone
Gl581
(b)
(c)
(d)
Atmospheric models
from Selsis et al.
0.00
0.05
0.10
0.15
0.20
0.25 AU
Geophysical models
from von Bloh et al.
Gl581
(b)
(c)
(d)
0.00
0.05
0.10
0.20
0.25 AU
Boundaries of the habitable zone
for a 9 Gyr-old planetary system
5 Gyr-old
planetary system
7 Gyr-old planetary system



Ts assumed to remain constant due to carbonate-silicate cycle
no H2O clouds
rapid loss of H
50% H2O clouds
no H2O clouds
50% H2O clouds
Ts
PCO2
PH2O
no CO2 clouds
100% CO2 clouds
CO2 condensation
Partial pressure (bar)
100
10
1.0
0.10
0.01
0.001
0.0001
Temperature (K)
800
700
600
500
400
300
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
distance to the Sun (AU)

THE $C0_2$ - ROCK WEATHERING CYCLE

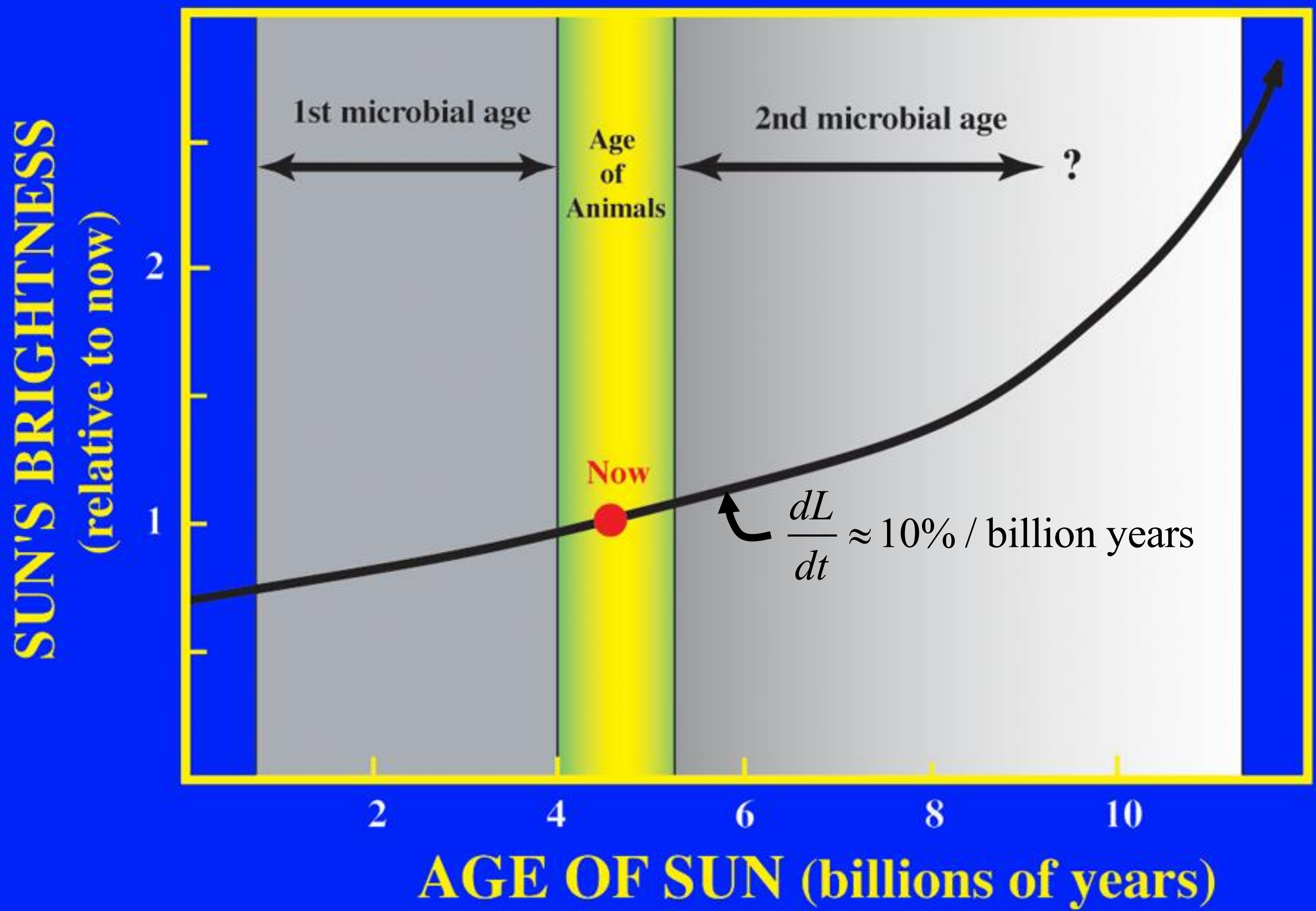
stabilizes T_s
widens the HZ



Source - Subduction & volcanism

Sink - weathering & carbonate formation

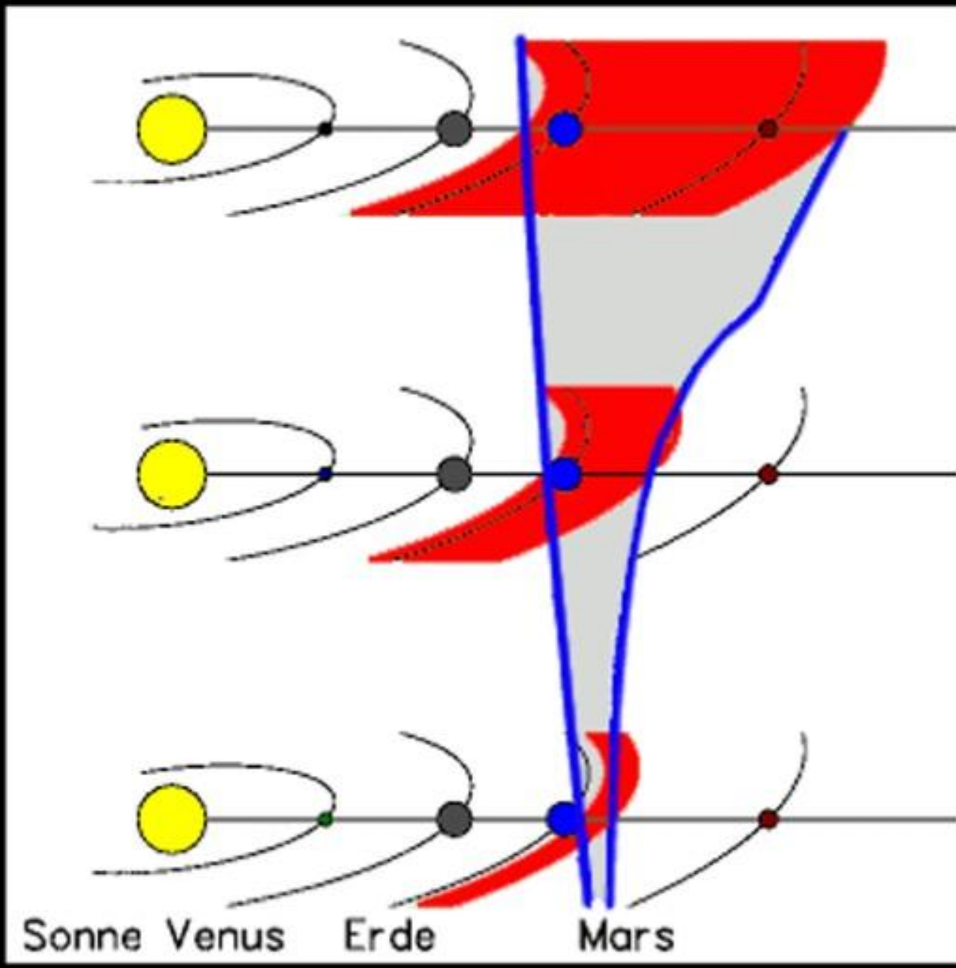
Long-term effects due to the slow brightening



The loss of CO_2 ends the age of planets and animals

Earth's Clock of Life
(billions of years)

The Photosynthetic "Habitable Zone" (pHZ)



1 Billion years ago

Now

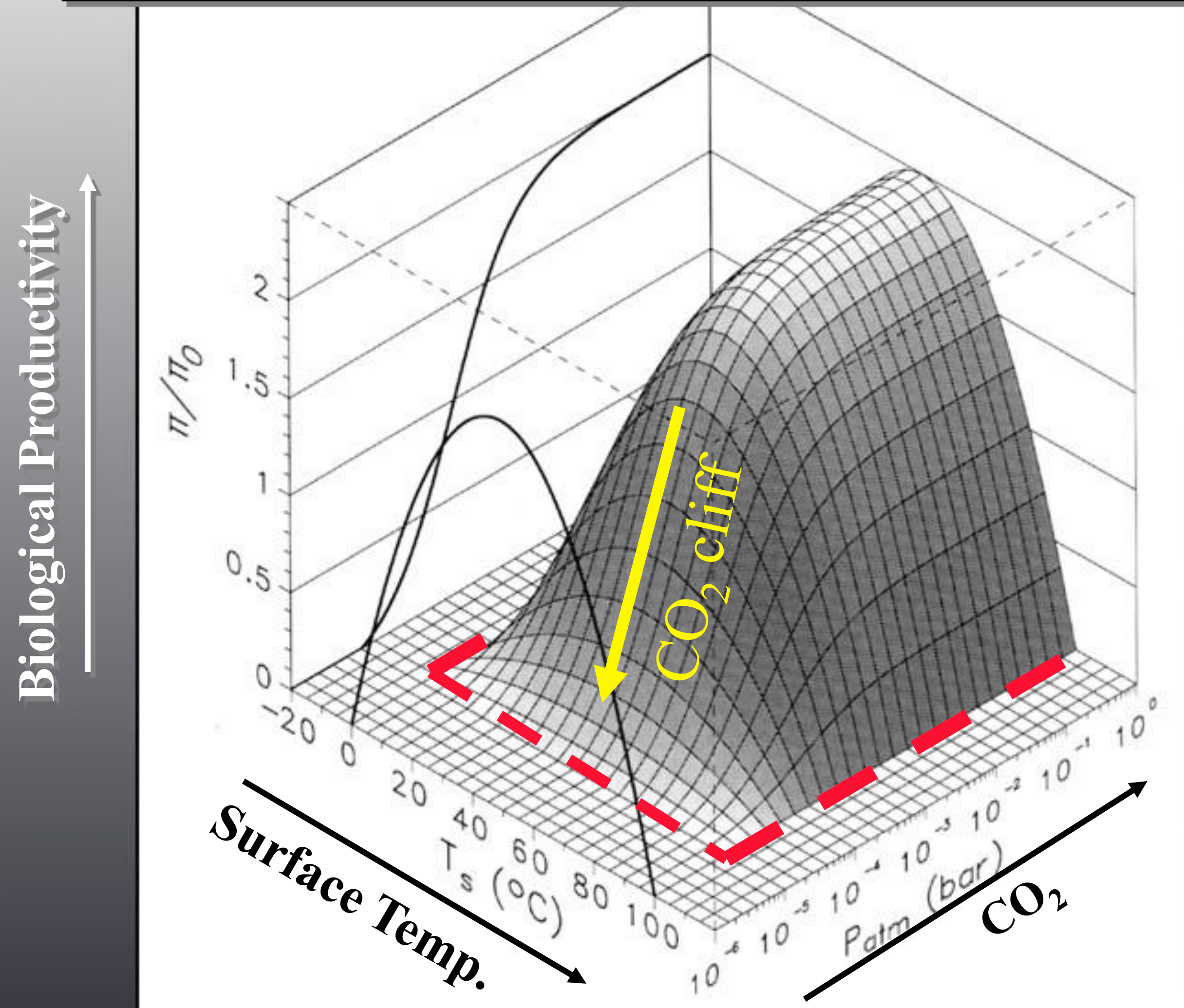
1 Billion years from now

pHZ definition
H_20 on surface
CO_2 in the air

Franck et al 2001

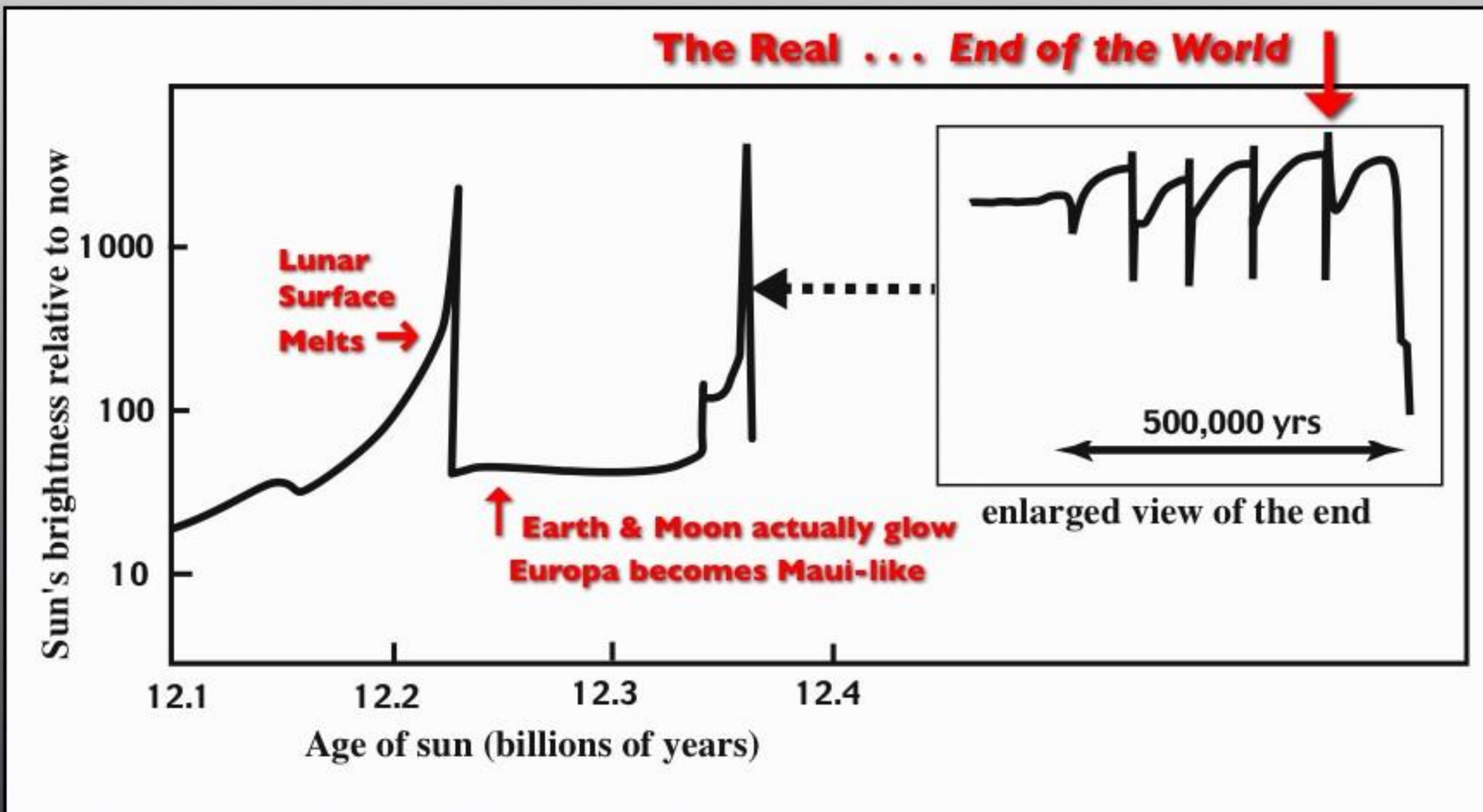
□Biological Productivity

a function of surface temperature & CO_2 partial pressure



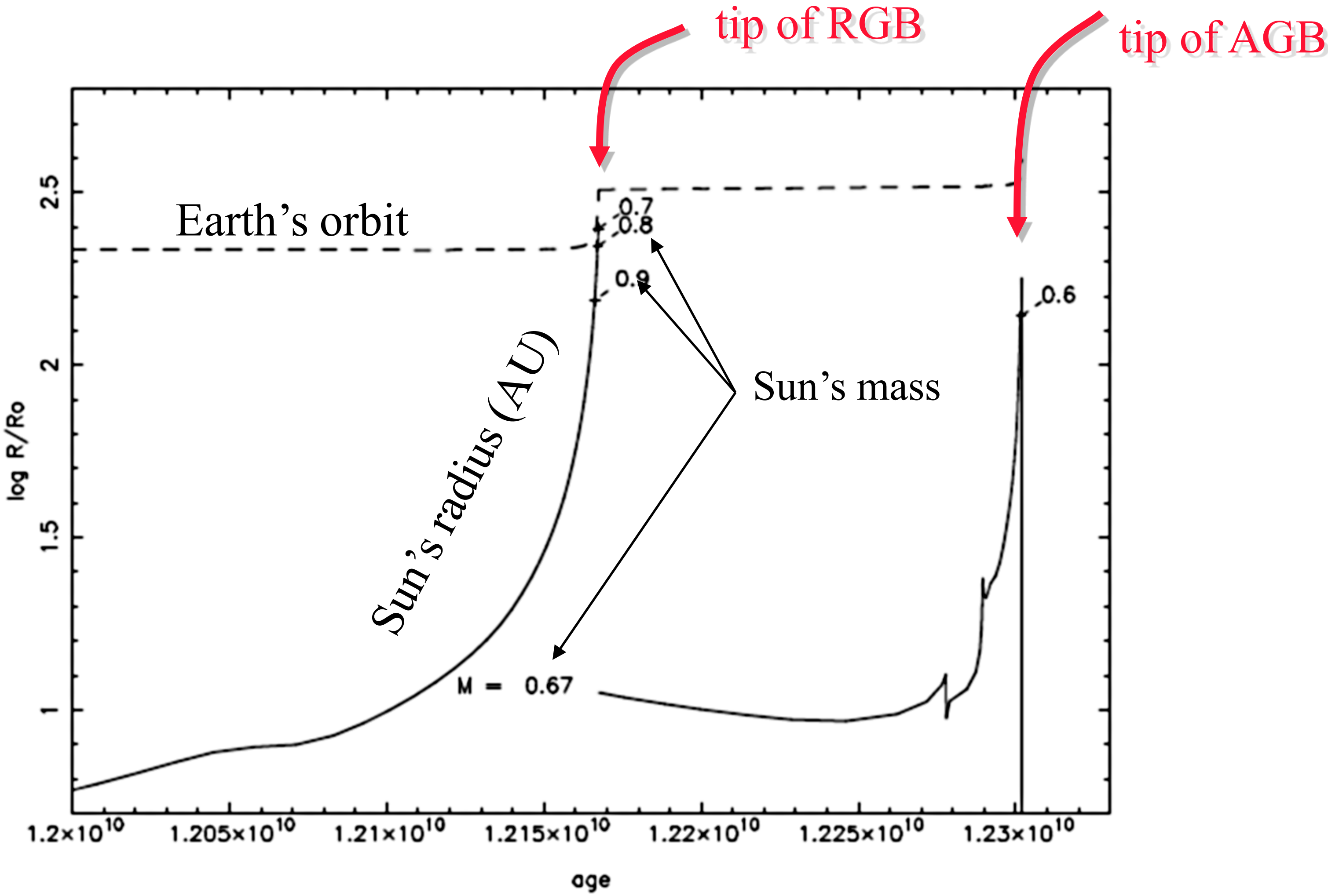
Franck et al. 2001

Red Giant Sun
(Earth's final 250my)



Due to tidal effects - Earth is assimilated into the red giant Sun
Rybicki & Denis 2001

The Sun's last 300 million years

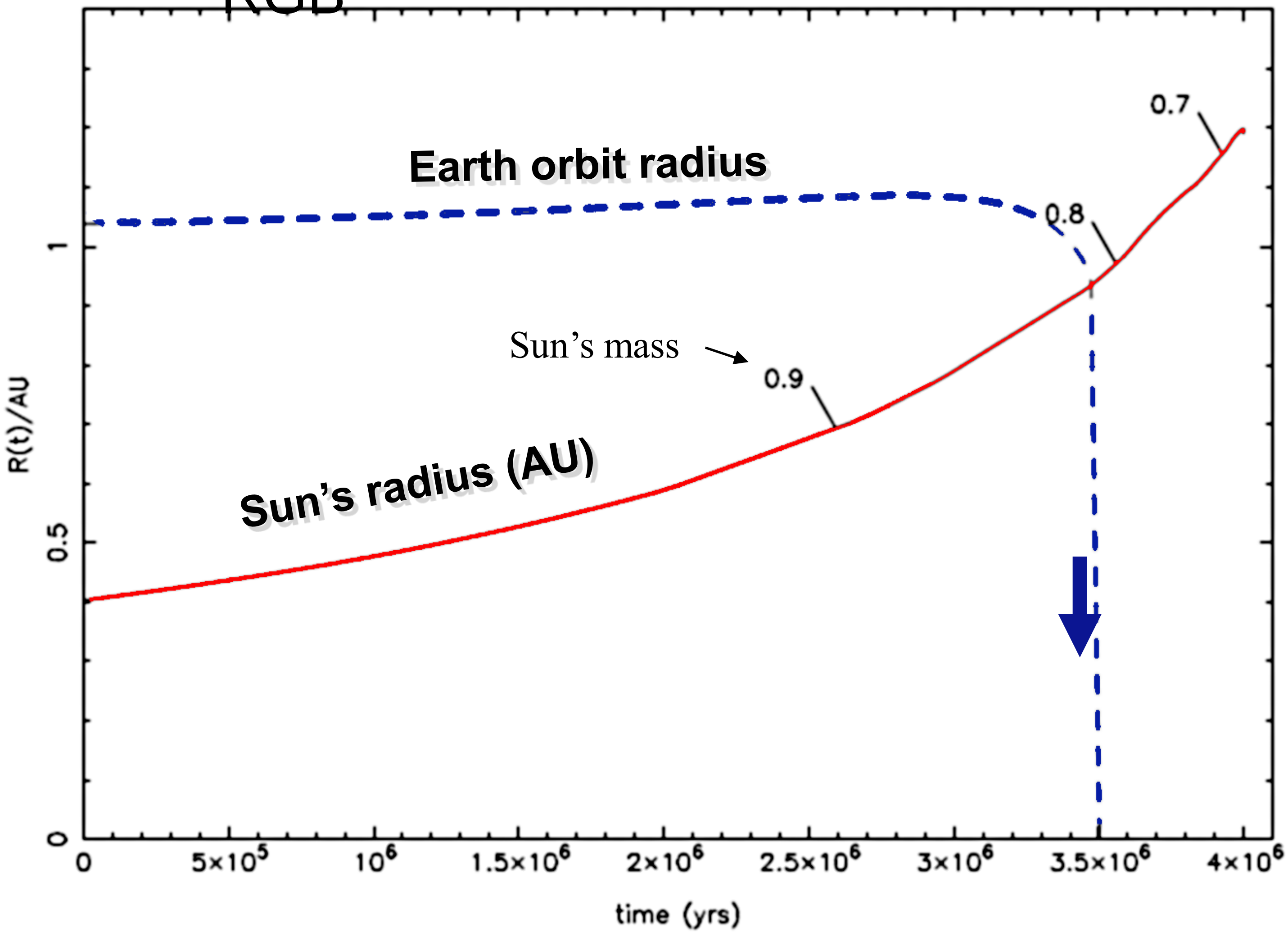


Schroder & Smith 2008

Schroder & Cuntz 2007

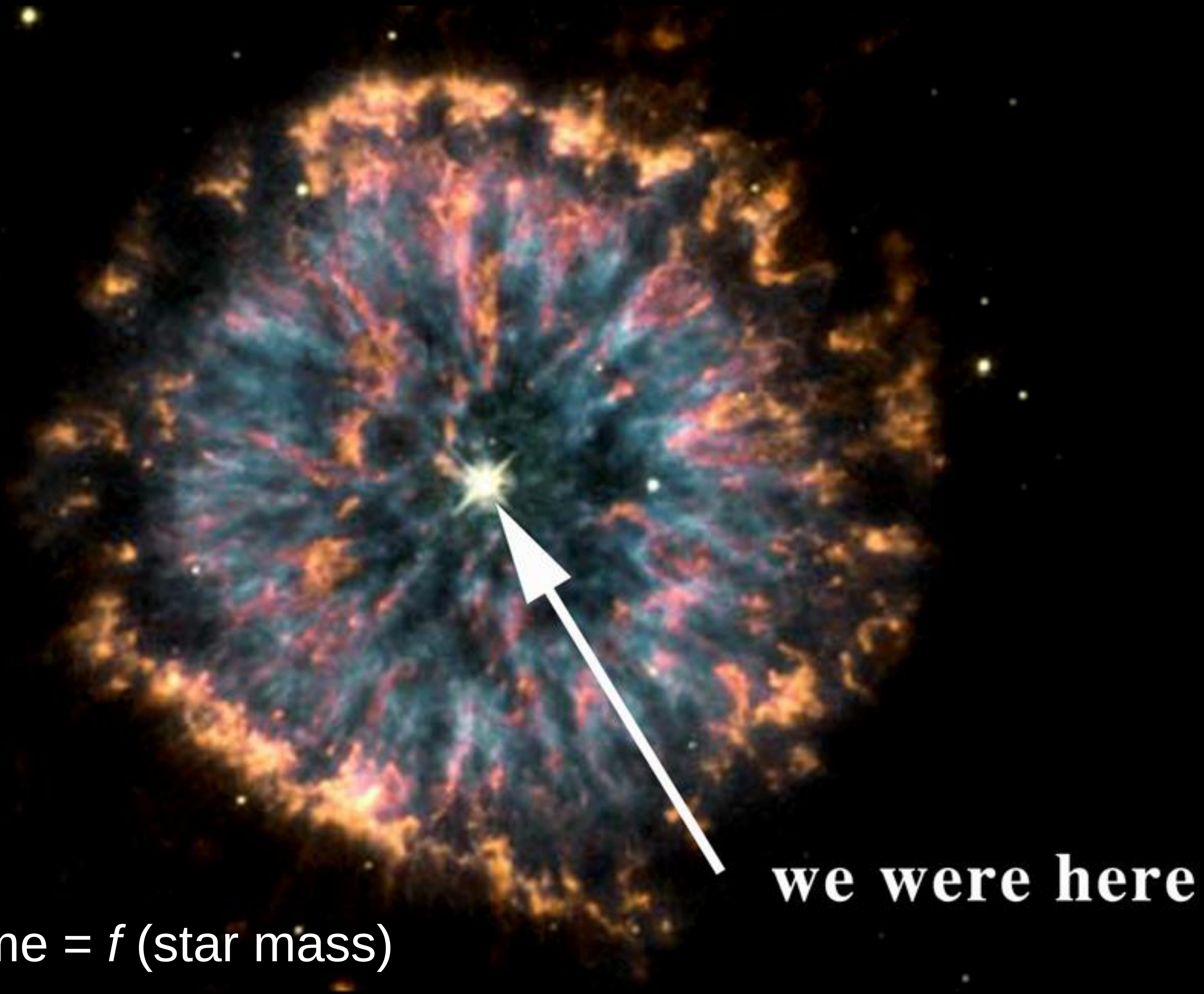
Earth's last 3 million years

Doomsday just before the tip of the RGB



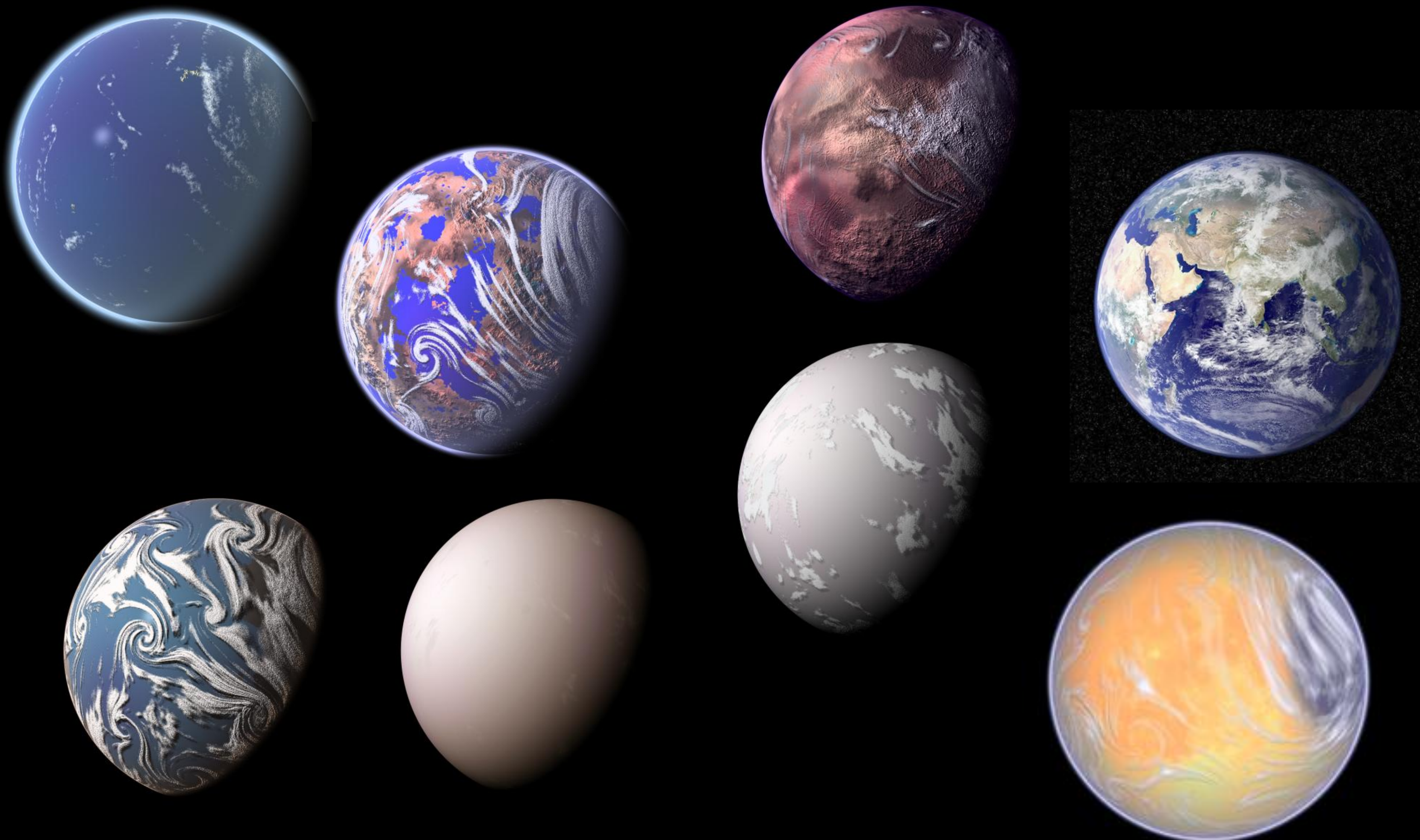
Schroder & Smith 2008, Schroder & Cuntz 2007

The ultimate fate of all stars with planets



Lifetime = f (star mass)

What is an earth-like planet ?



Other habitability issues

Stellar activity - “burning off” atmospheres

QuickTime™ and a
decompressor
are needed to see this picture.

Probably most important for low mass planets - like Mars

Earth may also have lost appreciable early water & volatiles
^{129}I ($t_{1/2}$ - 17my) decay product lost, ^{40}K decay product retained

HZ is “descreened when solar wind bow shock pushed to HZ
Allows GCRs + IS dust and gas to impact HZ planets

QuickTime™ and a
decompressor
are needed to see this picture.

Happens every 1-10Gy for Solar like stars   Smith & Scalo 2009
Injected H reacts with O_2 to form H_2O depleting ozone layer

Rare Earth Factors

RIGHT DISTANCE FROM STAR

Habitat for complex life
Liquid water near surface
Far enough to avoid tidal lock

JUPITER-LIKE NEIGHBOR

Clear out comets and asteroids
Not too close not too far

OCEAN

Not too much
Not too little

PLATE TECTONICS

CO_2-silicate thermostat
Build up land mass
Enhance biotic diversity
Enable magnetic field

LARGE MOON

Right distance

Stabilizes tilt

A MARS ?

Small neighbor as possible life source to seed Earth-like planet, if needed

RIGHT PLANETARY MASS

Retain atmosphere and ocean

Enough heat for plate tectonics

Solid/molten core

THE RIGHT TILT

Seasons not too severe

GIANT IMPACTS

Few giant impacts.

No global sterilizing impacts after an initial period

THE RIGHT AMOUNT OF CARBON

Enough for life

Not too much

RIGHT STAR MASS

Long enough lifetime

Not too much ultraviolet

STABLE PLANETARY ORBITS

Giant planets do not create orbital chaos

ATMOSPHERIC PROPERTIES

Maintenance of adequate temperature, composition and pressure for plants and animals

BIOLOGICAL

Evolution to complex organisms

Invention of photosynthesis

Evolution of oxygen- right time

RIGHT KIND OF GALAXY

Enough heavy elements

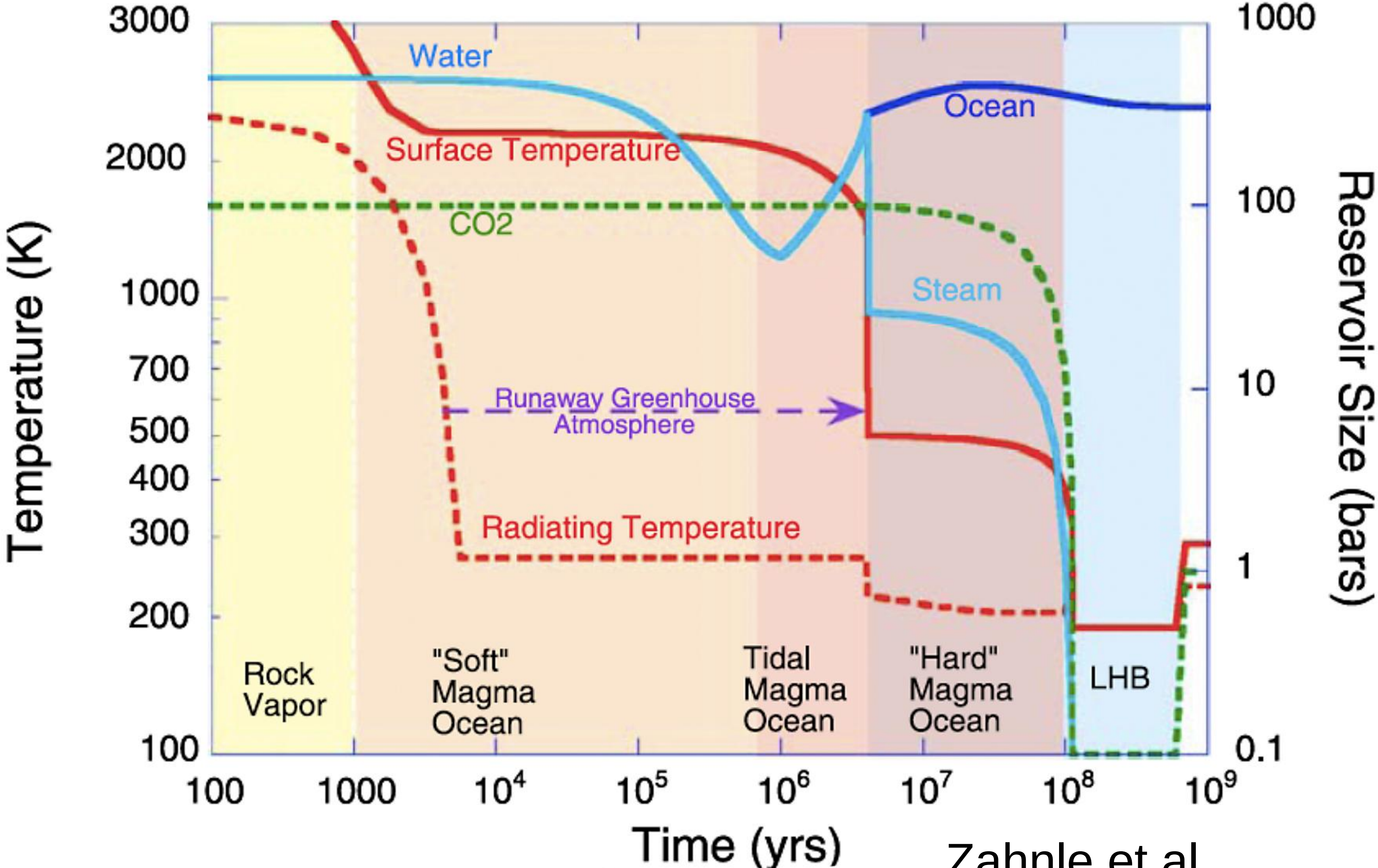
RIGHT POSITION IN GALAXY

Not in center, edge or halo

WILD CARDS

Snowball Earth

Cambrian explosion



3000
2000
1000
700
500
400
300
200
100
Temperature (K)
1000
100
10
1
0.1
Reservoir Size (bars)
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
Time (yrs)
Water
Ocean
Surface Temperature
CO2
Steam
Runaway Greenhouse Atmosphere
Radiating Temperature
Rock Vapor
"Soft" Magma Ocean
Tidal Magma Ocean
"Hard" Magma Ocean
LHB

Zahnle et al.

THE CONTINENTAL GROWTH MODEL

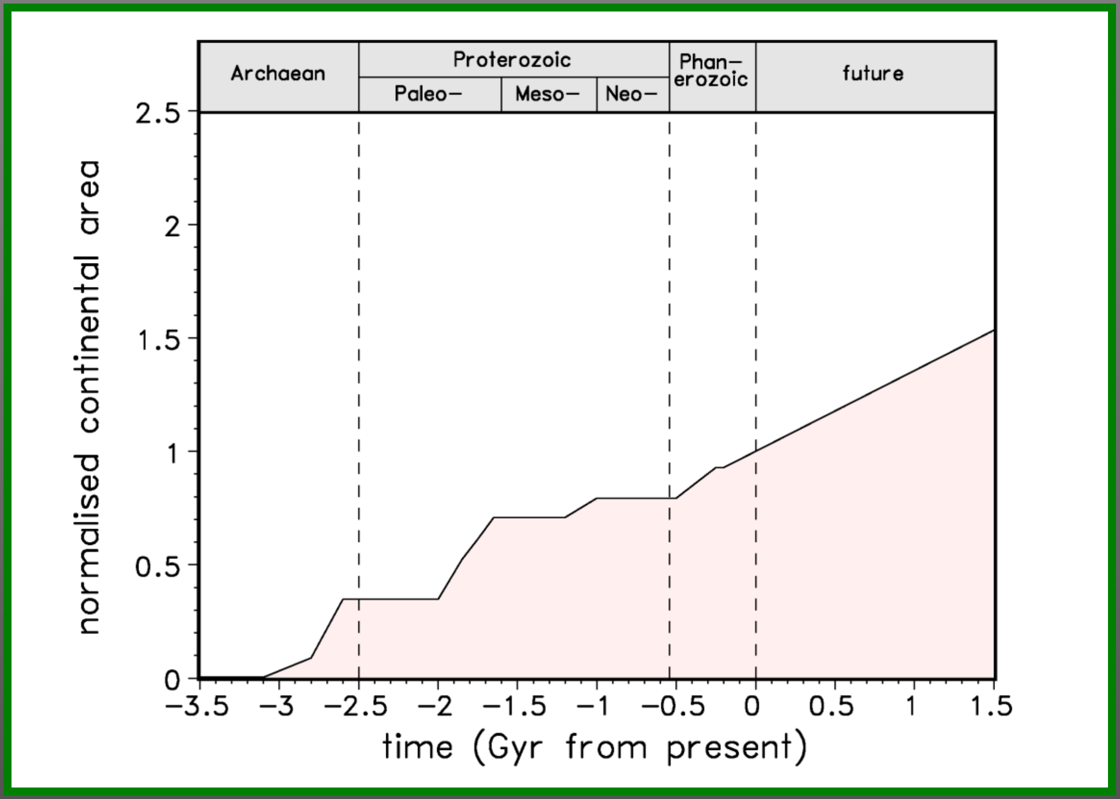
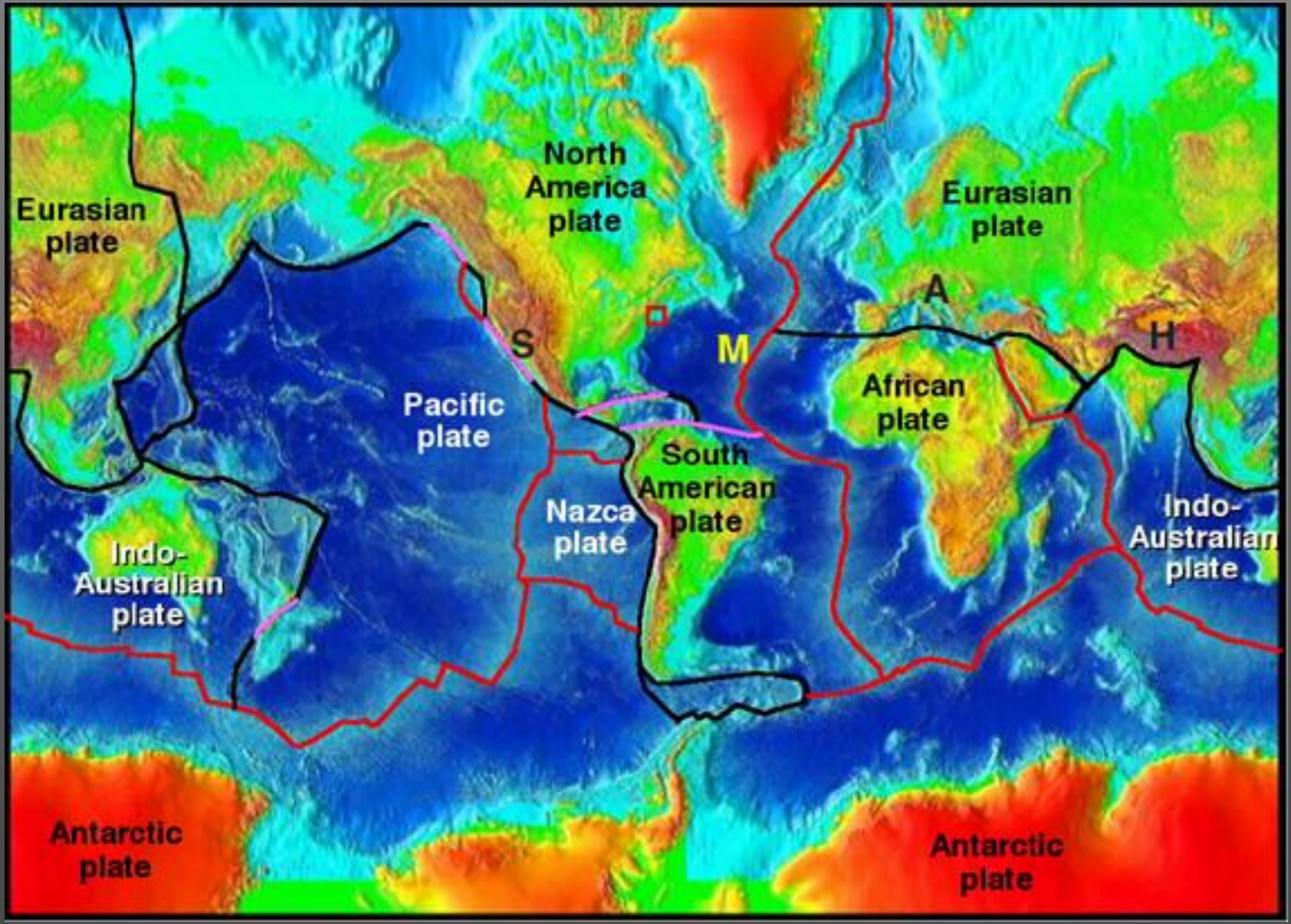


Plate Tectonics (unique to Earth)

CO_2 to atmosphere - stabilizes atmosphere - source of land



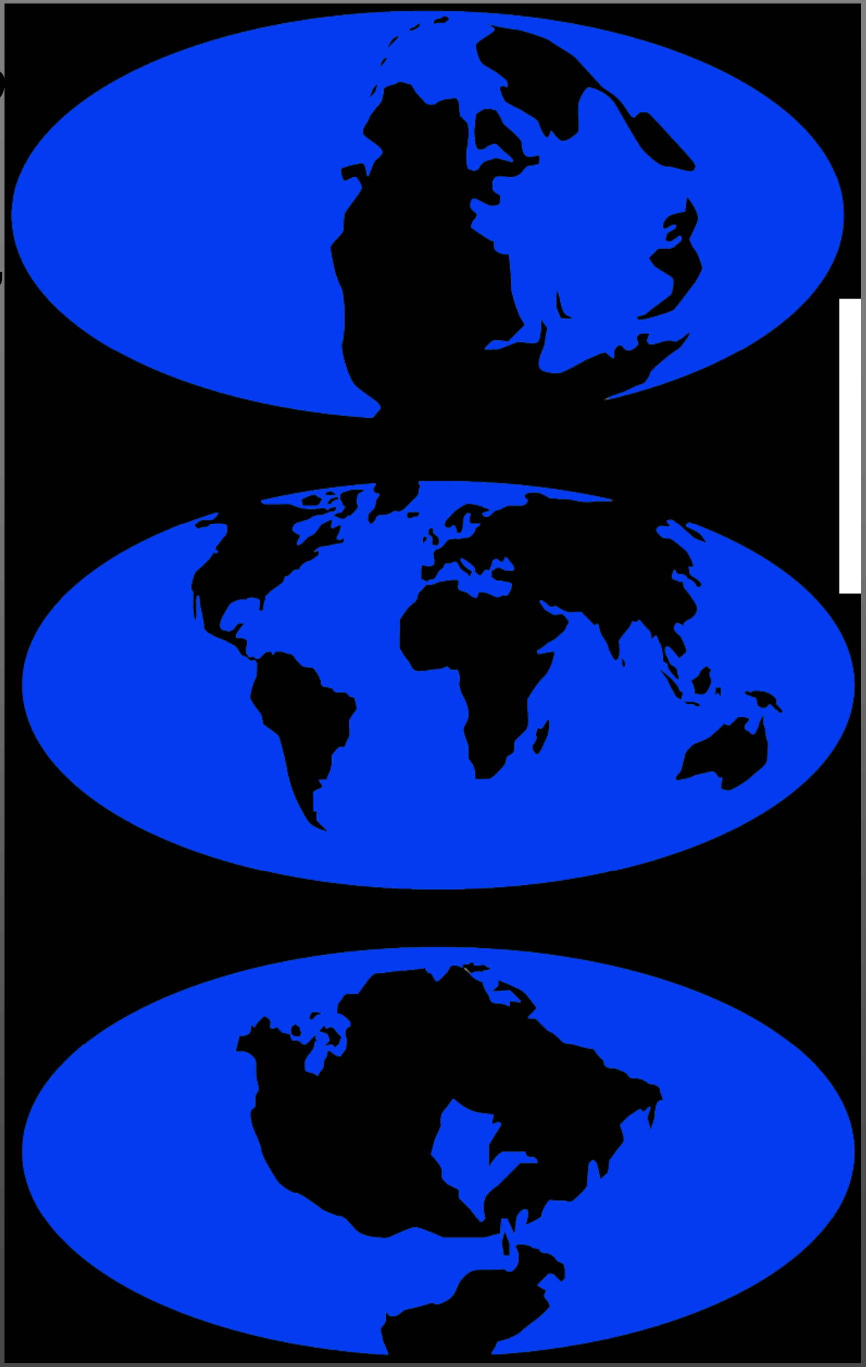
250 my ago

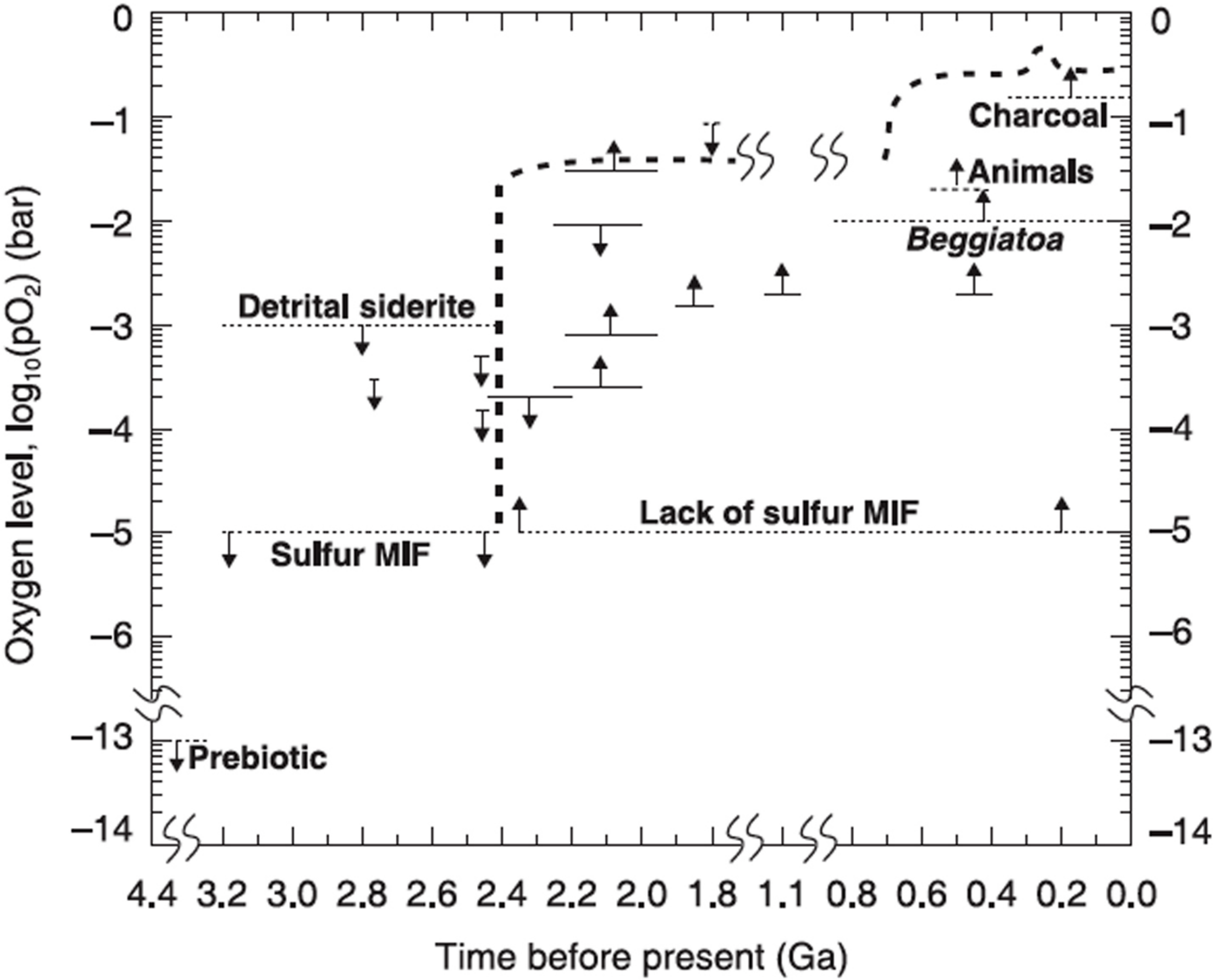
Permo-Triassic Extinction

"The Great Dying"

Today

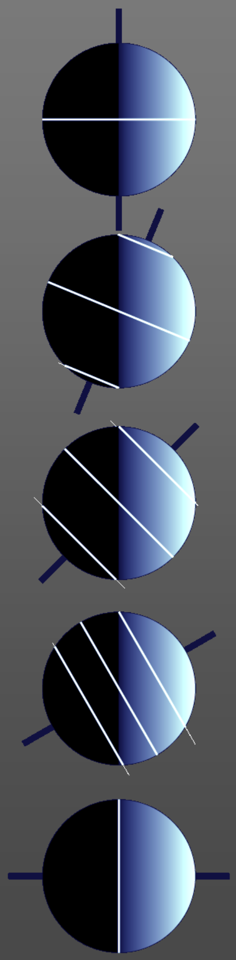
250 my from now





Oxygen level, $\log_{10}(pO_2)$ (bar)
Time before present (Ga)
0
−1
−2
−3
−4
−5
−6
−13
−14
4.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.1
0.8
0.6
0.4
0.2
0.0
Charcoal
Animals
Beggiatoa
Detrital siderite
Lack of sulfur MIF
Sulfur MIF
Prebiotic

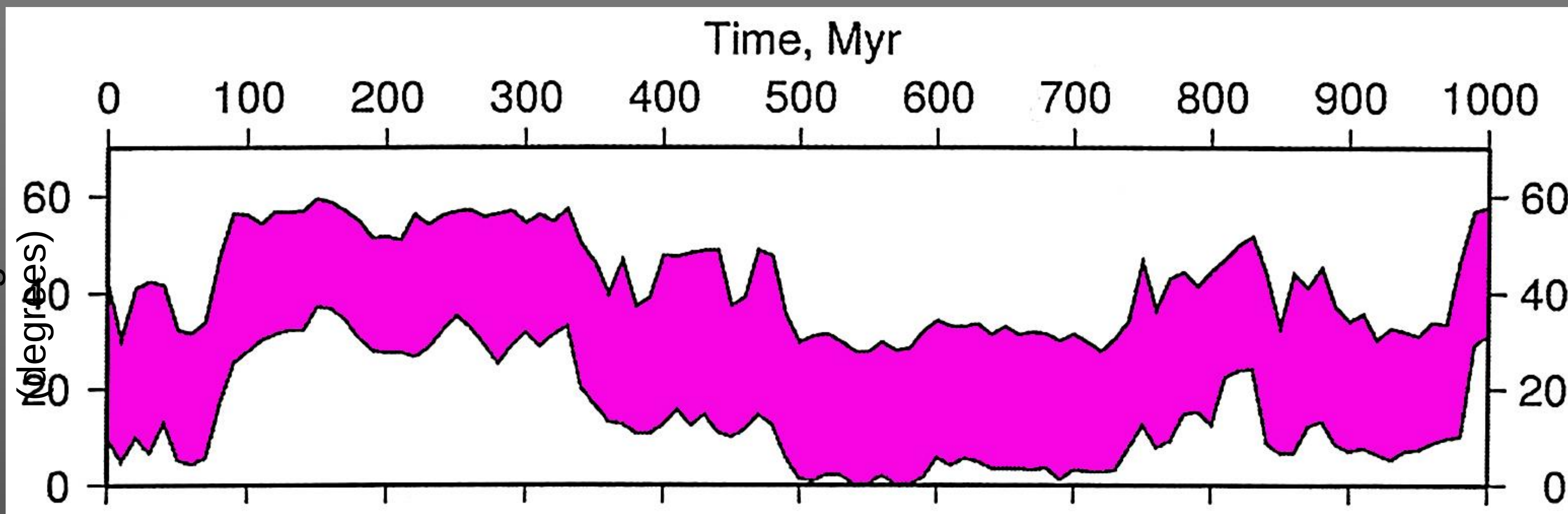
The remarkable effects of tilt (obliquity)



tilt angle	energy at pole / energy at equator
0°	0
22.5°	.4
45°	.9
60°	1.1
90°	1.6

Mars tilt angle (obliquity) over time

Mars is highly unstable



Tilt angle (degrees)

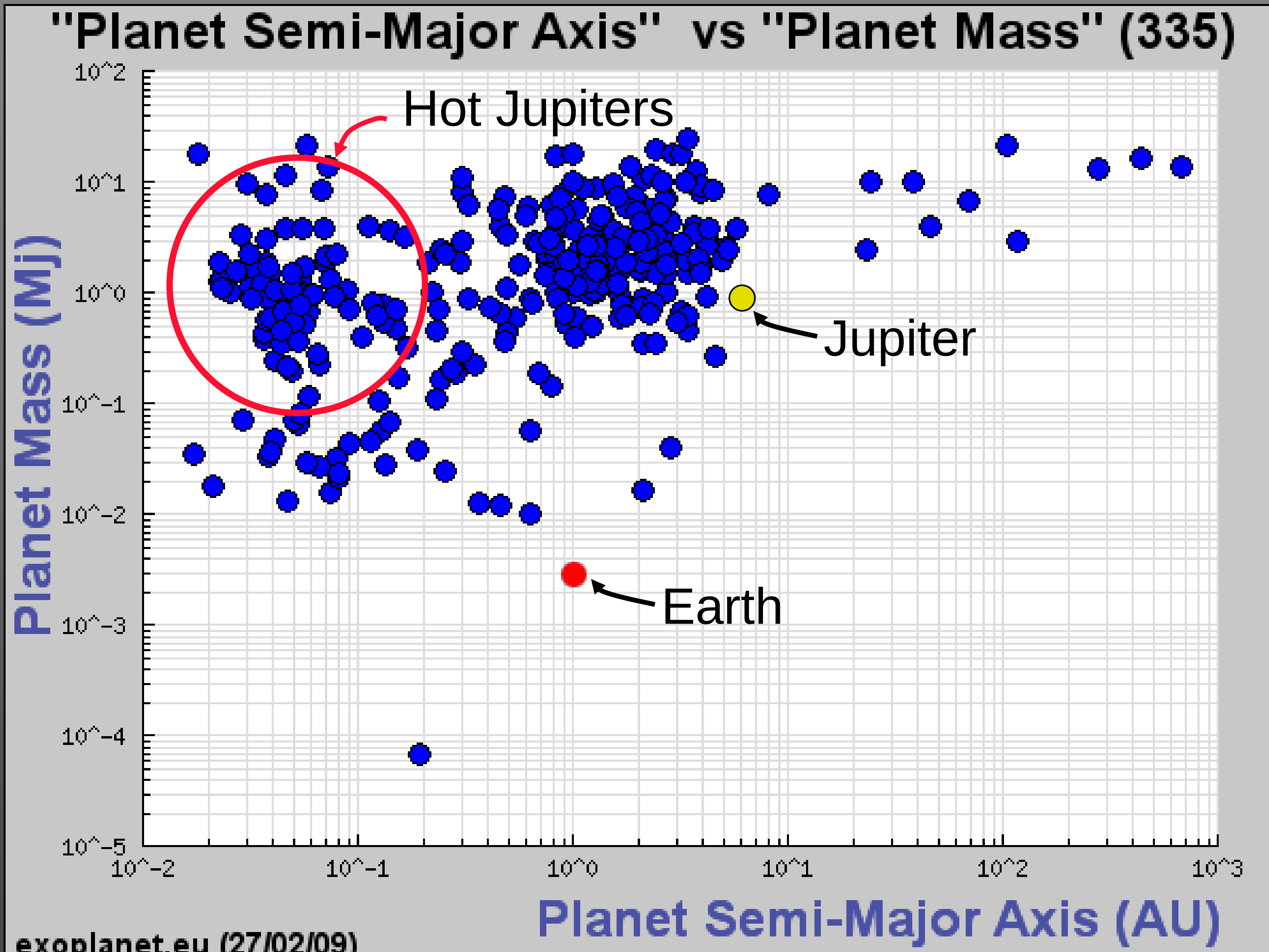
numerical simulations
Armstrong et al. 2003

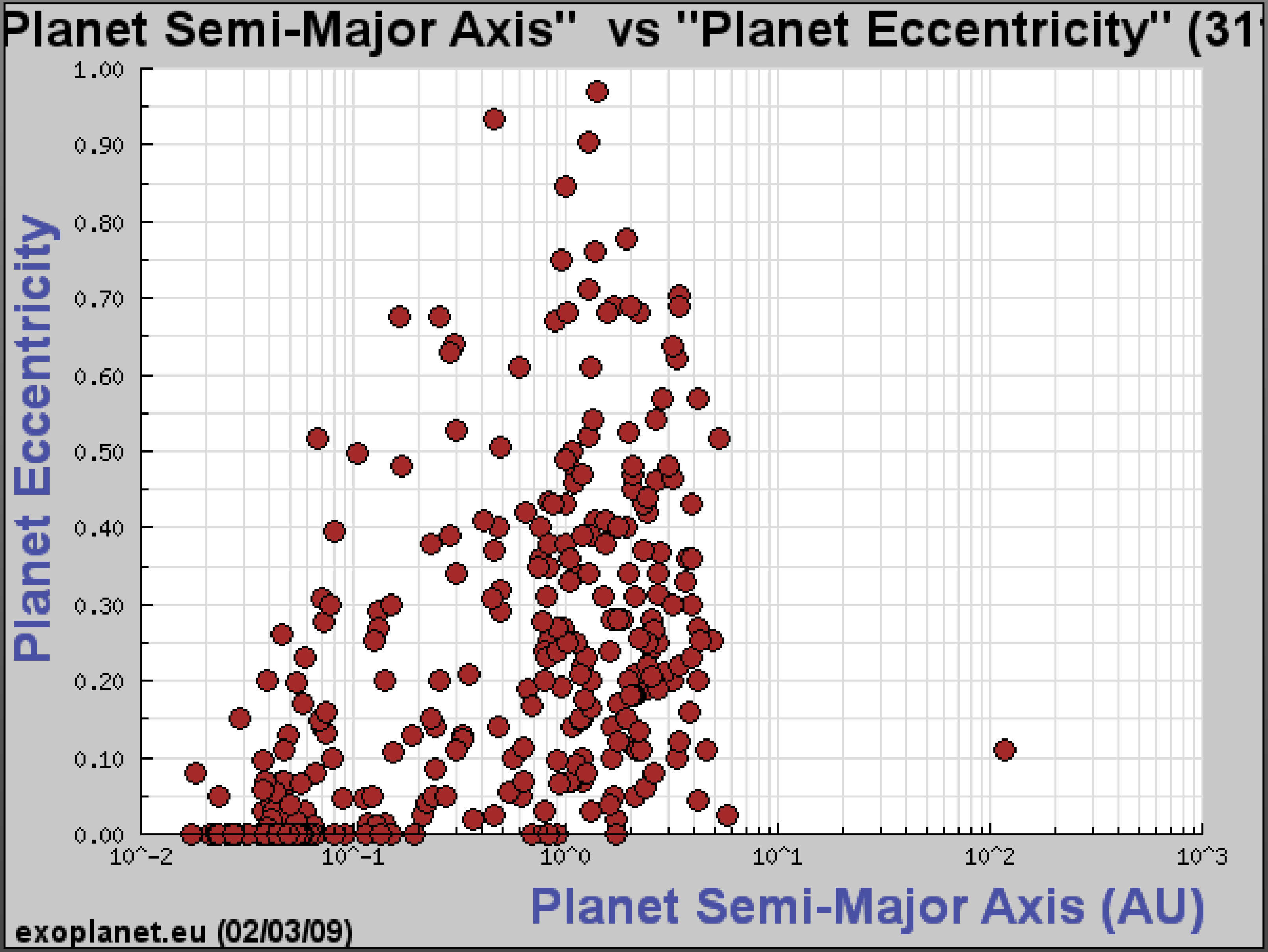
Earth's tilt angle is very stable

Stabilized by our large

QuickTime™ and a
decompressor
are needed to see this picture.

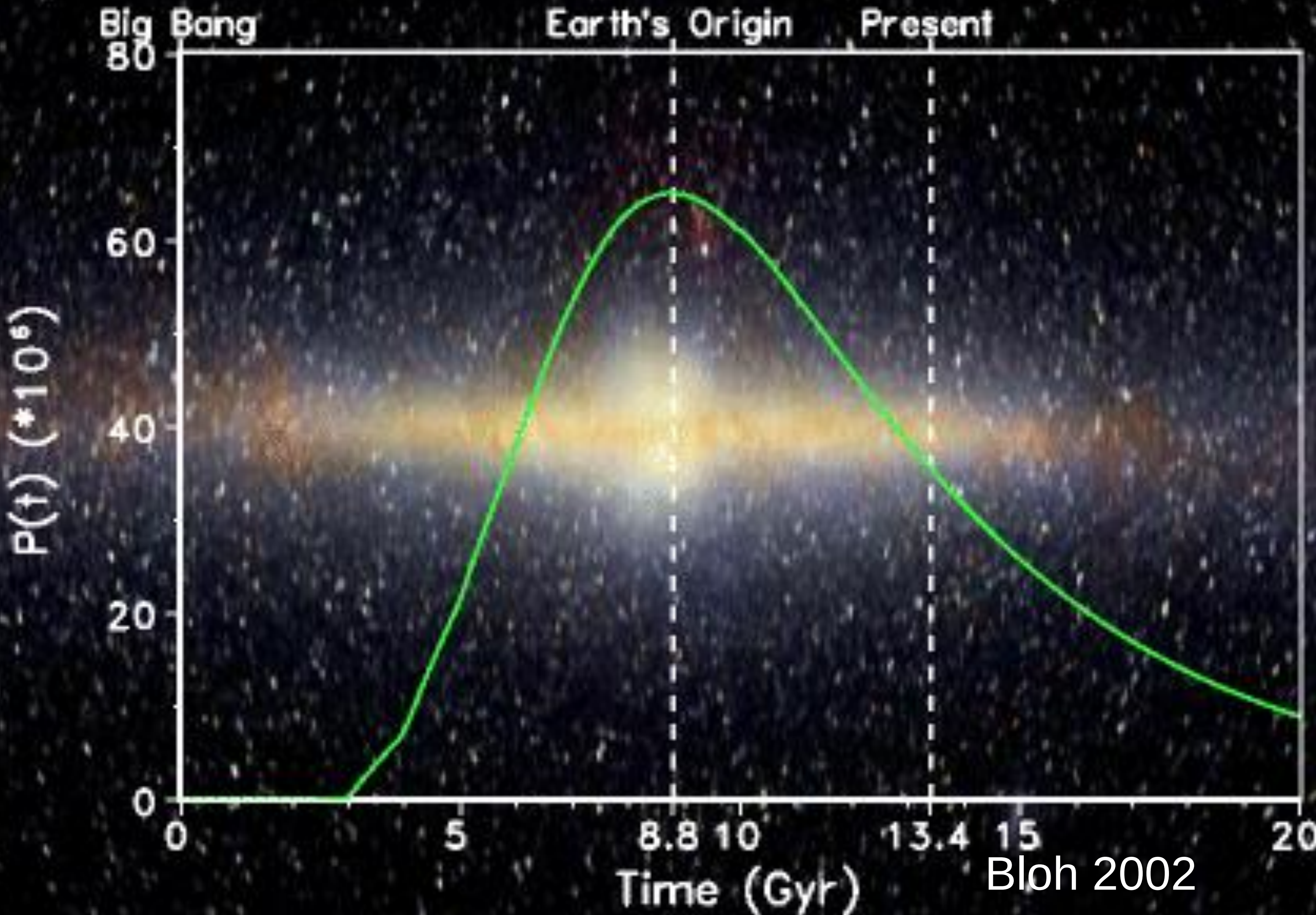
Earth mass


"Planet Semi-Major Axis" vs "Planet Mass" (335)
Hot Jupiters
Jupiter
Earth
Planet Mass (Mj)
Planet Semi-Major Axis (AU)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-2
10^-1
10^0
10^1
10^2
10^3
exoplanet.eu (27/02/09)



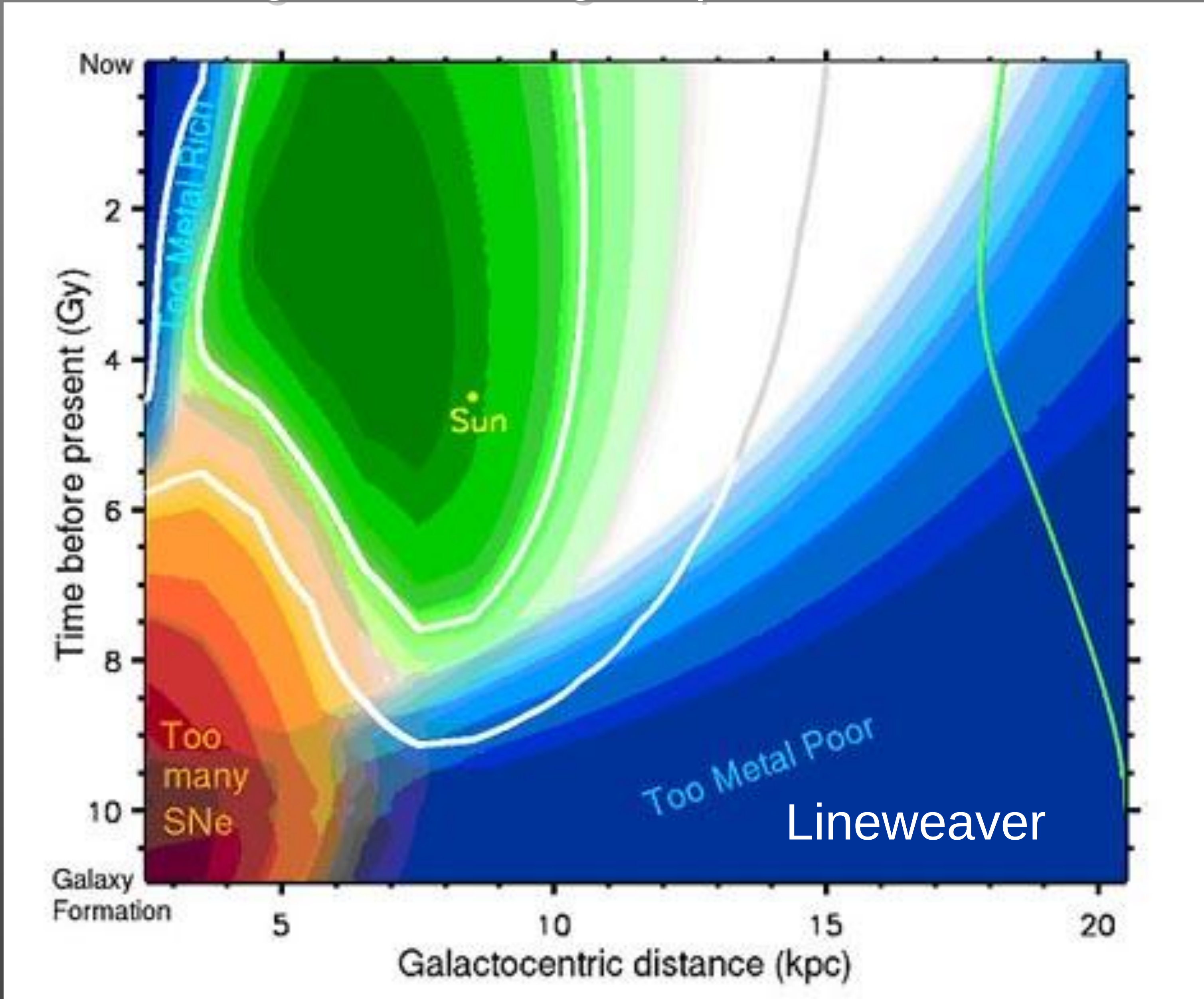
Planet Semi-Major Axis" vs "Planet Eccentricity" (31
Planet Eccentricity
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
10^-2
10^-1
10^0
10^1
10^2
10^3
Planet Semi-Major Axis (AU)
exoplanet.eu (02/03/09)

Number of habitable planets vs time for Milky Way

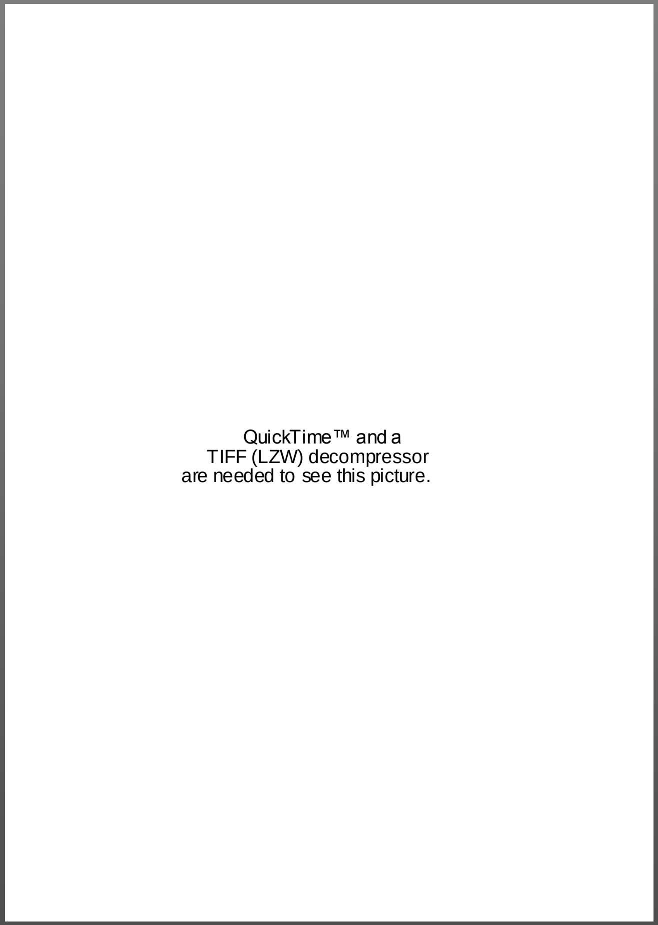


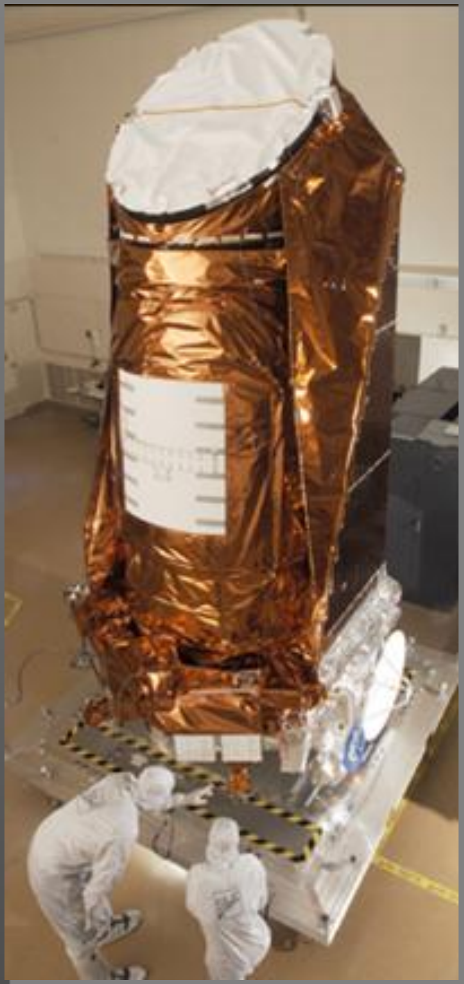
Bloh 2002

Galactic Habitable Zone
good stars in good places & times



Kepler - Planet Transit Telescope





Determine the frequency of terrestrial and larger planets in or near the habitable zone of a wide variety of spectral types of stars