Habitable Planets

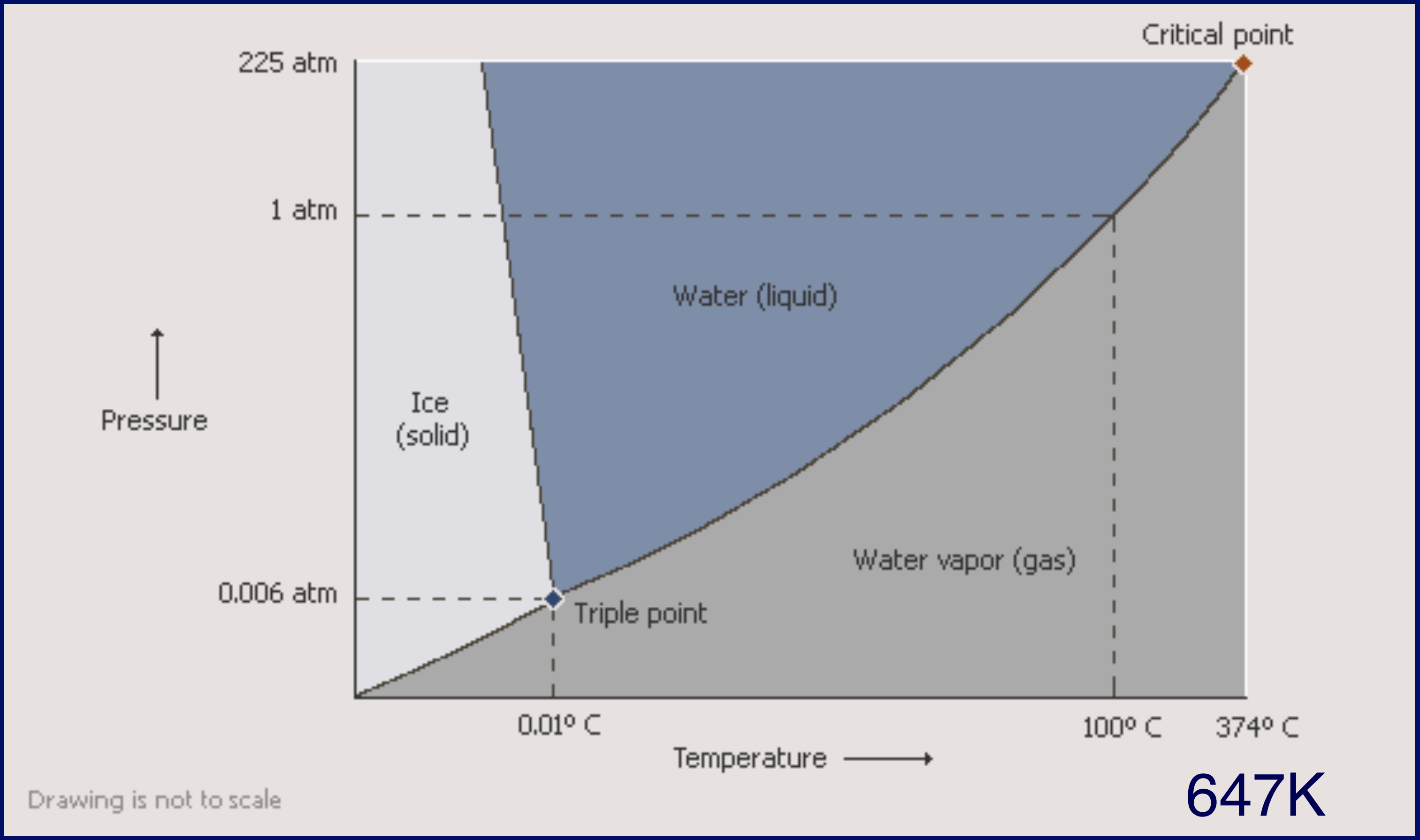
General Considerations

- Number of planets, per planetary system, suitable for life (n_e)
- Useful to break into 2 factors
  - $n_e = n_p \times f_s$
- $n_p = n_e$ for stars like Sun
- f_s is fraction of stars that are suitable
- $f_s \leq 1$, but n_e, n_p can be > 1

Key Requirement: a Liquid

- Need a liquid for a solvent
- Liquid phase needs particular range of temperature, pressure
  - Pressure depends on gravity, hence mass
  - Water (H_2O) 273-373 K at Earth pressure
    - Up to 647 K at higher pressure
  - Methane (CH_4) 91-109 K at Earth pressure
  - Ammonia (NH_3) 195-240 K at Earth Pressure

Water Phase Diagram

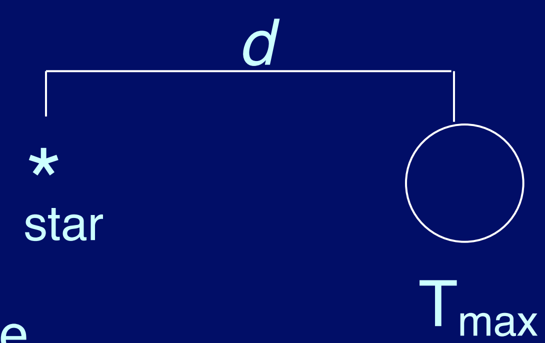


What Sets the Temperature?

- For solid objects in space
  - – Absorption and emission of light
  - – Heats and cools the object
  - – For a “blackbody”
    - Absorption $\propto L/d^2$
    - Emission $\propto T^4$
    - Radiative Balance
      - – Energy absorbed = Energy emitted

Planet Temperatures

1st approximation: A blackbody at a distance *d* from a star of luminosity L



Maximum temperature

$T = 394\ K\ (L / d^2)^{1/4}$

$T \propto L^{1/4}\ d^{-0.5}$

L in $L_{\odot}$

d in AU

Question

Question: Planet 1 has a temperature of 300 K. There is an identical second planet 4 times as far from the star as planet 1. What will be the temperature of planet 2?

2nd approximation: A fraction of the light is reflected (not absorbed)

Call this fraction the albedo (A)

$$T = 394\ K \left[\frac{(1\text{-}A)\ L}{d^2} \right]^{1/4}$$

e.g. Moon $A = 0.07$, $L = 1\ L_{\odot}$ — $T_{max} = 387$, correct to few %

But Earth : $A = 0.39 \Rightarrow T_{max} = 342$ K predicted

$T_{max} \leq 313$ K

3rd approximation:

Account for rapid rotation - T_{max} less

T_{min} more

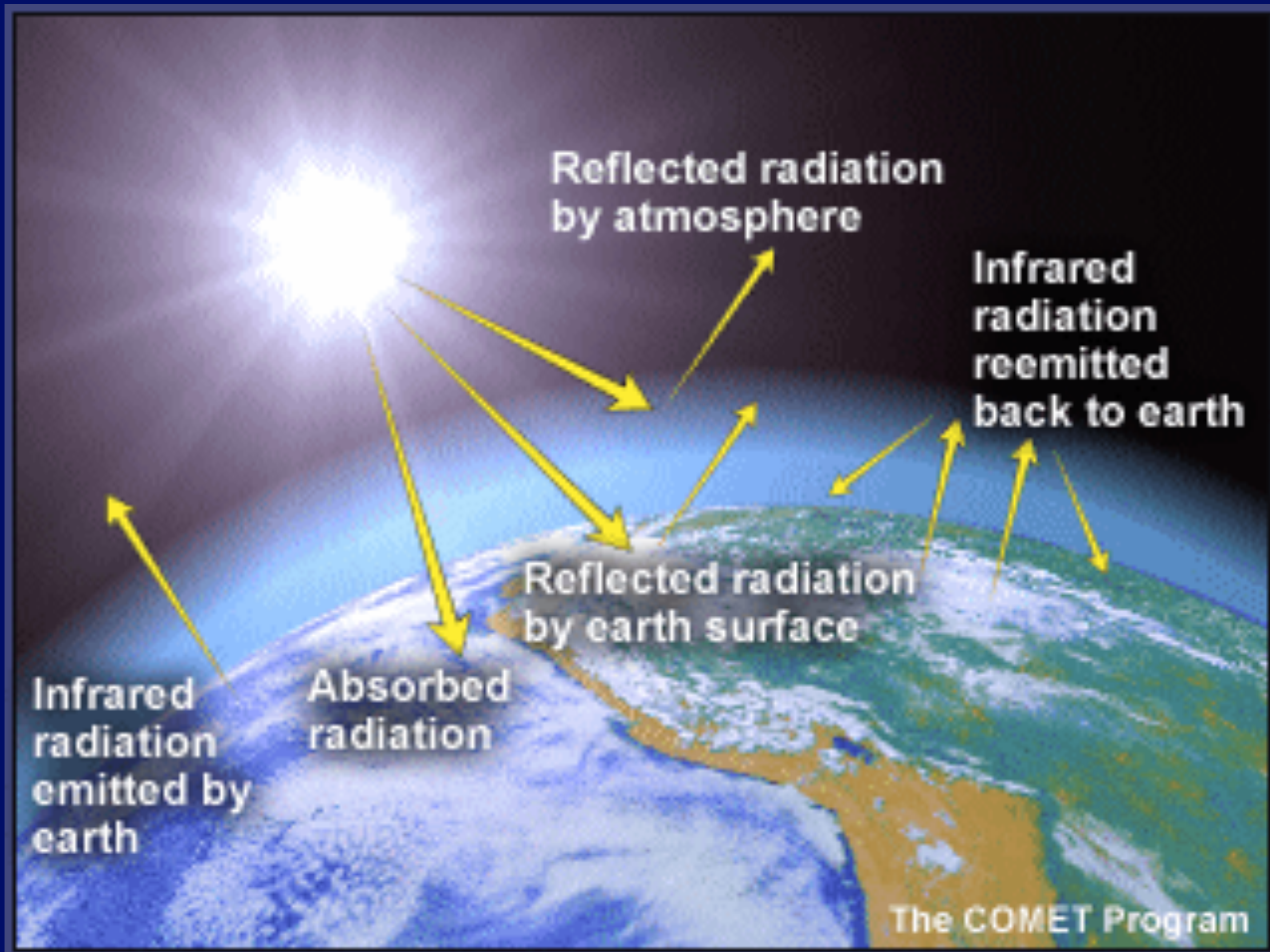
close to T_{avg}

$$T_{avg} = 279 \text{ K} \left[\frac{(1-A)\,L}{d^2} \right]^{1/4}$$

Earth: $A = 0.39 \Rightarrow T_{avg} = 246K$

Actual $T_{avg} = 288K$

4th approximation: Greenhouse effect



Consequences of Greenhouse Effect:

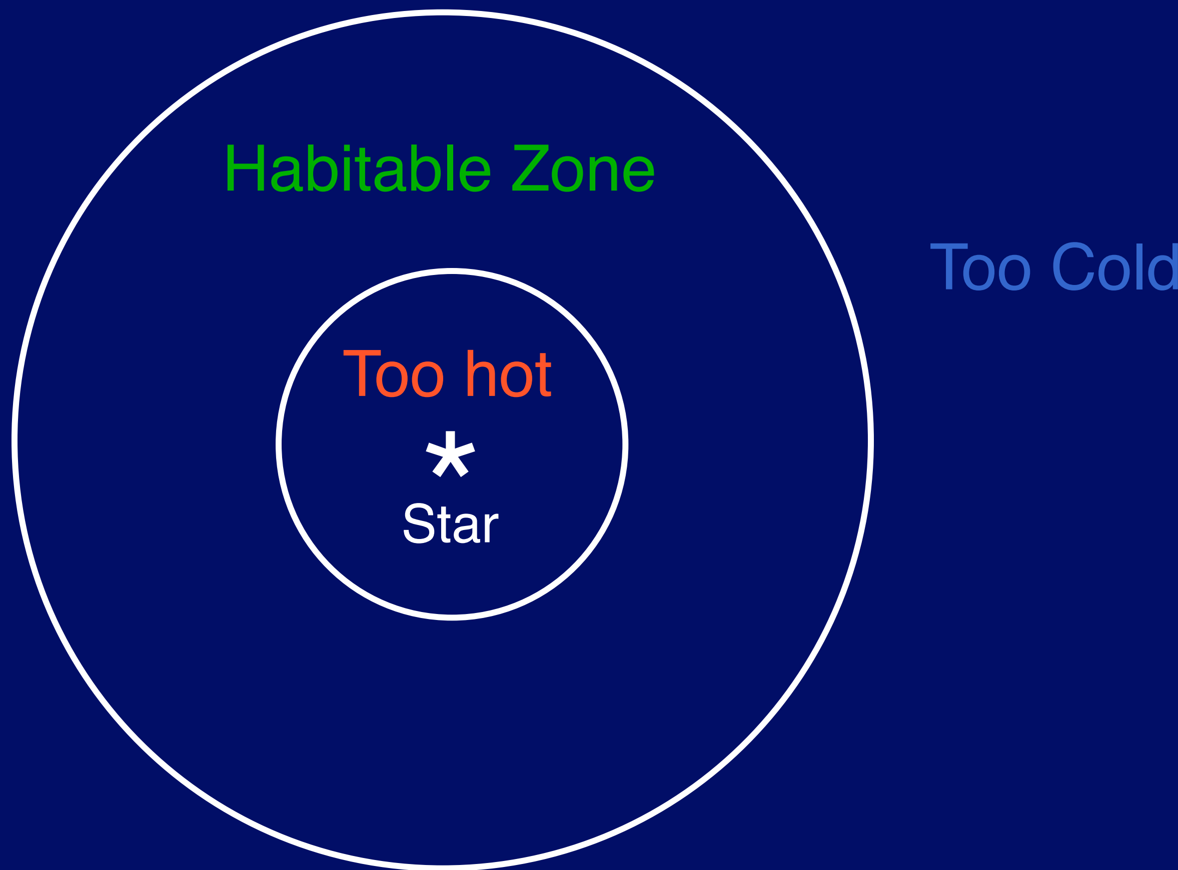
Raises T_{avg} (Earth) by about 40K

Otherwise $T_{avg} < T_{freeze}$

$\Rightarrow$ Frozen Planet

The Habitable Zone

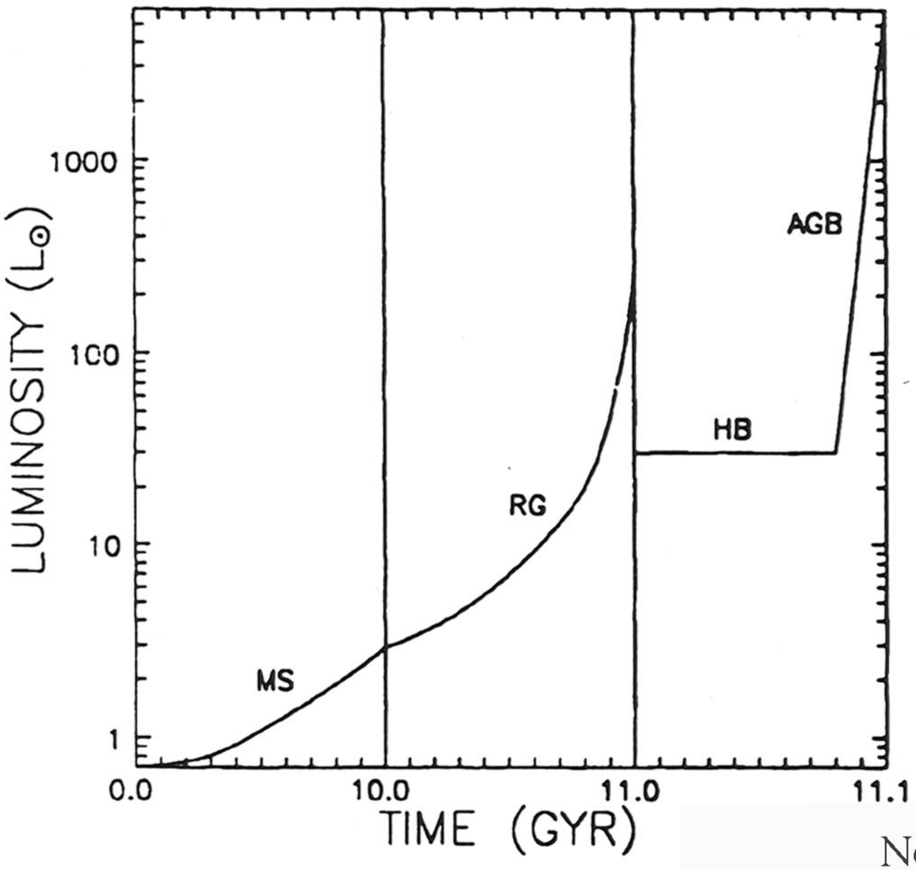
- For fixed stellar luminosity, greenhouse effect
- A required temperature range
  - For example, liquid water
- Translates to required range of distances from the star



But Greenhouse Effect could have a big impact on the size and location of HZ

Continuously Habitable Zone

- Nearly 5×10^9 yrs for intelligent life on Earth
- CHZ is habitable for 5×10^9 yr
- Stars increase L during main sequence
  - HZ moves out, CHZ is smaller than HZ at any given time
  - For example, current Earth would have been frozen over when Sun was young
  - Greenhouse effect must have been larger then



Note Changing Scale

FIG. 1. *Luminosity evolution of a 1 $M_\odot$ star of solar composition. Note that the scale is broken at 10 and 11 Gyr. The discontinuity at 11 Gyr is real and is due to the helium flash. The phases are: MS = main sequence, RG = red giant, HB = horizontal branch, and AGB = asymptotic giant branch. The final white dwarf phase is not illustrated. Details of the evolution during the HB and AGB phases are omitted.*

$$r_2 = \sqrt{\frac{L(t)}{S_2(T)}}$$

Pessimist

Computer Models

Hart CHZ 0.95 - 1.01 AU

$\Rightarrow \quad n_p \lesssim 0.1$

Middle of the Road

Negative feedback → thermostat

T ↗ Rainfall ↗ rock weathering ↗

⊖

T ↘ ← CO_2 ↘

Whitmire et al. CHZ 0.95 - 1.5 AU

$\Rightarrow \quad n_p \sim 1$

The Carbon Cycle without Life

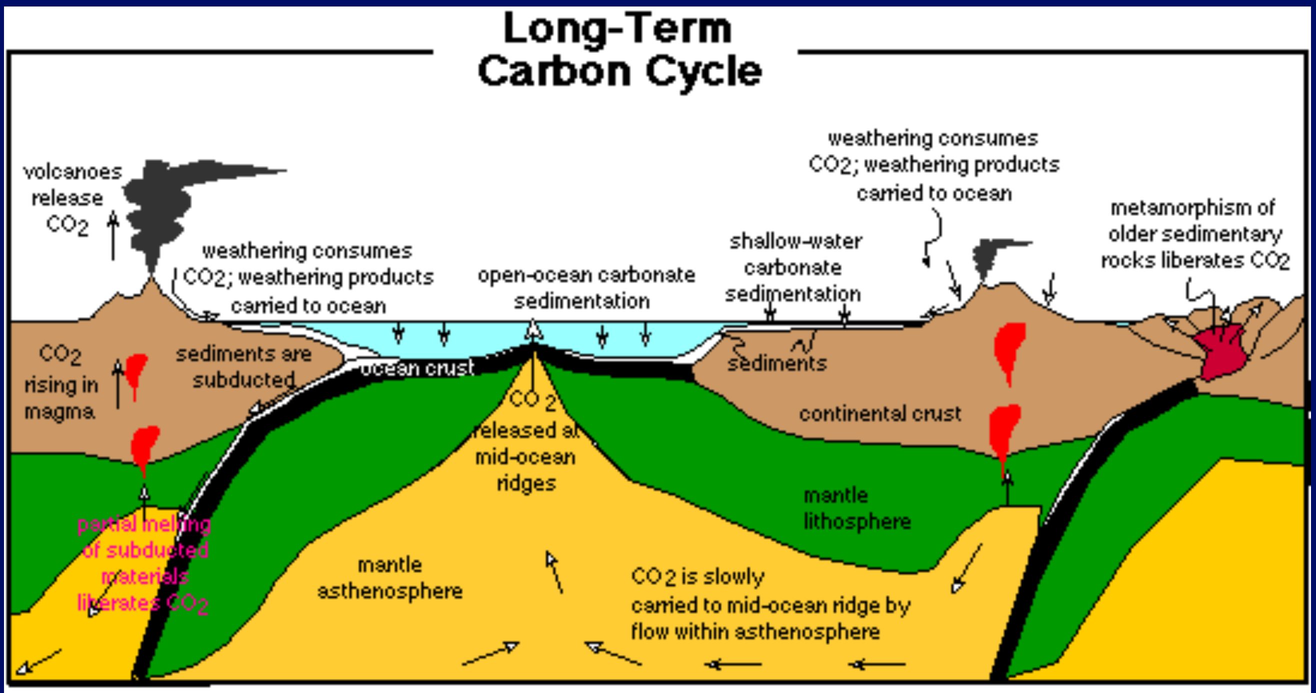
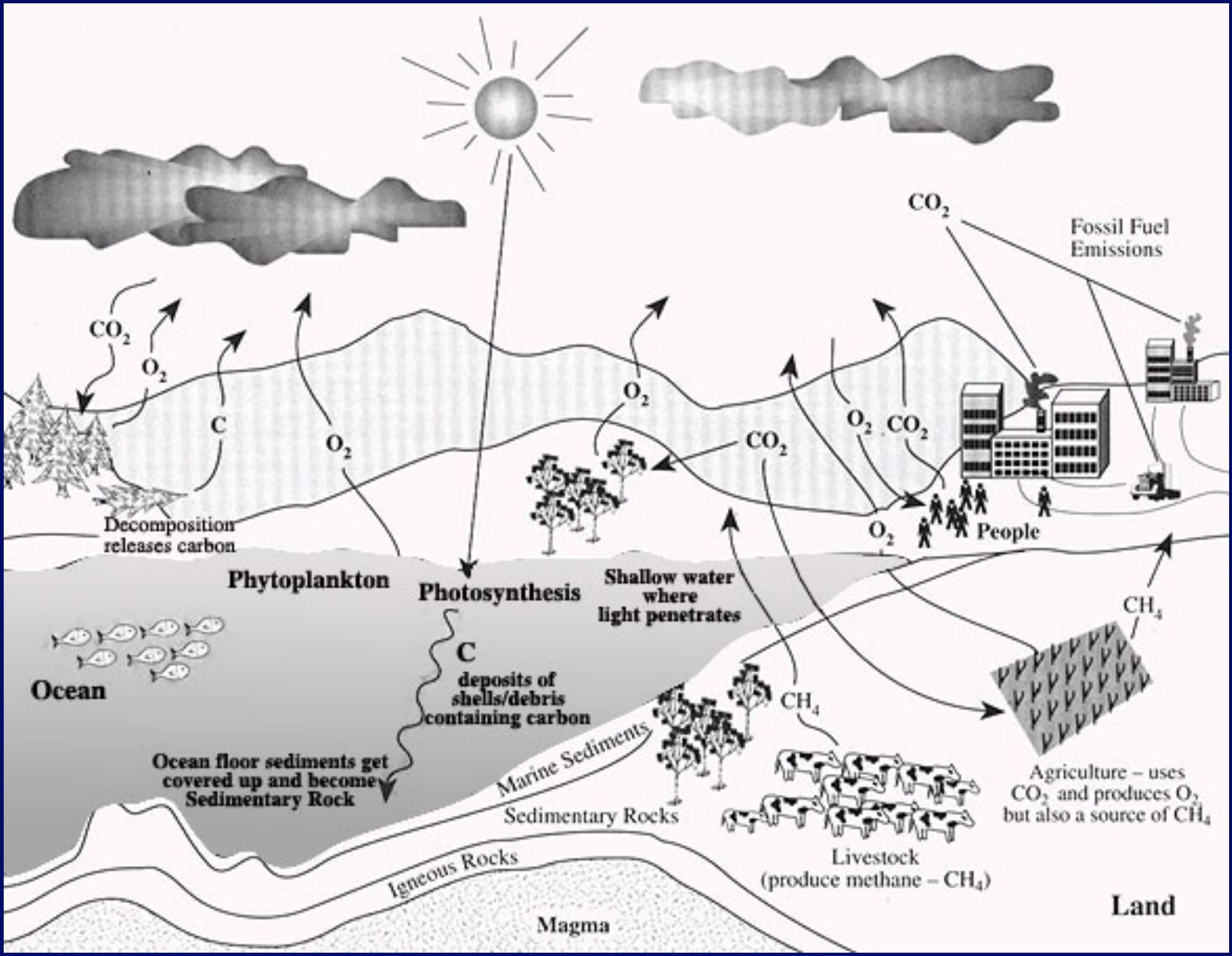


Figure 7.3. Schematic representation of the long-term global carbon cycle showing the flows (hollow arrows) of carbon that are important on timescales of more than 100 Kyr. Carbon is added to the atmosphere through metamorphic degassing and volcanic activity on land and at mid-ocean ridges. Atmospheric carbon is used in the weathering of silicate minerals in a temperature-sensitive dissolution process; the products of this weathering are carried by rivers to the oceans. Carbonate sedimentation exracts carbon from the oceans and ties it up in the form of limestones. Pelagic limestones deposited in the deep ocean can be subducted and melted. Limestones deposited on continental crust are recycled much more slowly — if they are exposed and weathered, their remains may end up as pelagic carbonates; if they get caught up in a continental collision, they can be metamorphosed, liberating their CO_2.

The Carbon Cycle on Earth Now



Cold Starts?

- As Habitable Zone moves out
  - Can you unfreeze a frozen planet?
  - Will it become suitable for life?
  - If not, HZ will shrink
  - CHZ is smaller

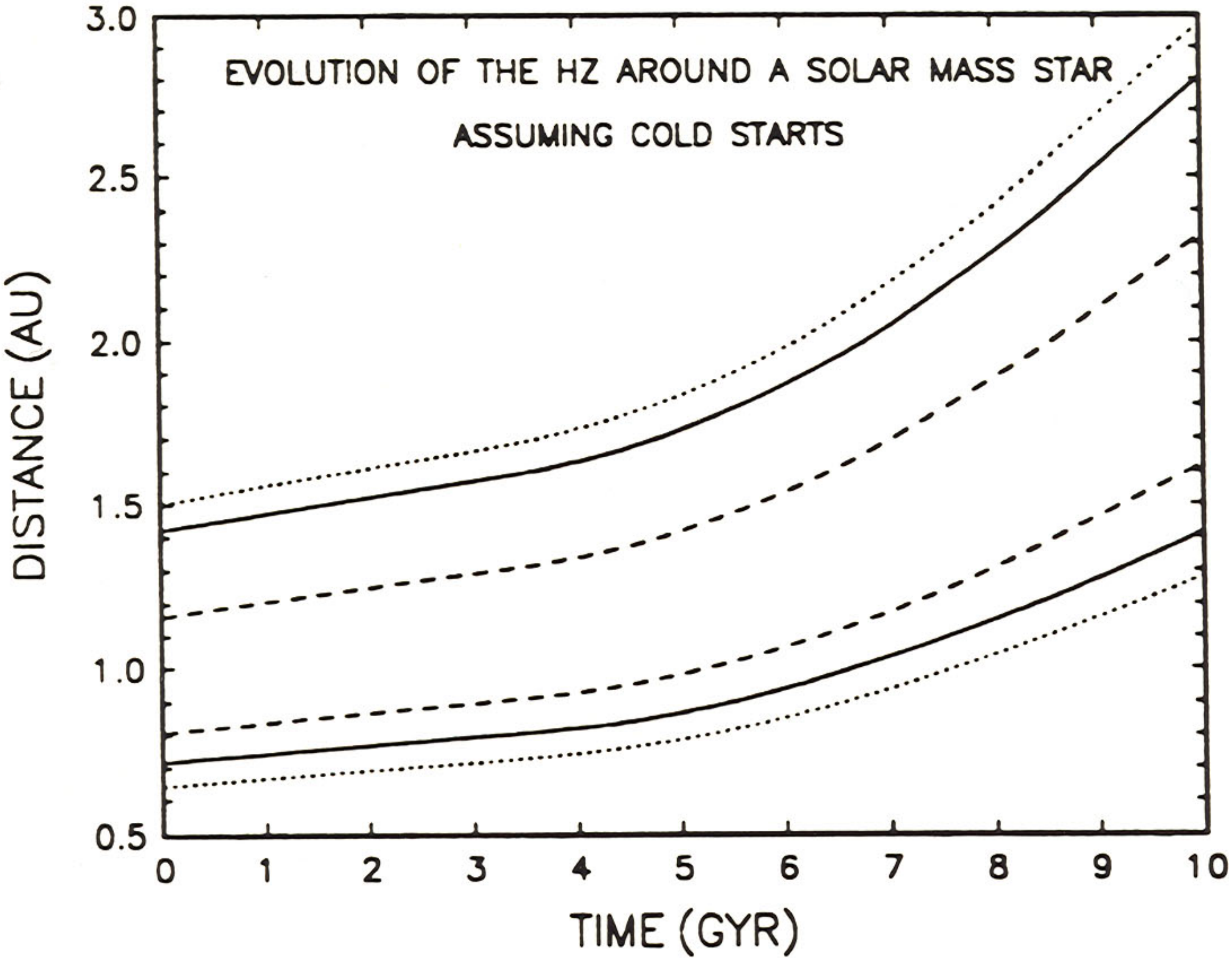


FIG. 2. *Evolution of the HZ around a 1 $M_{\odot}$ star assuming that an ice covered planet that was initially beyond the outer HZ boundary can be cold started. The three cases shown are discussed in the text and correspond to the most conservative Case 1 (long dashes), the intermediate Case 2 (solid curves), and the least conservative Case 3 (short dashes).*

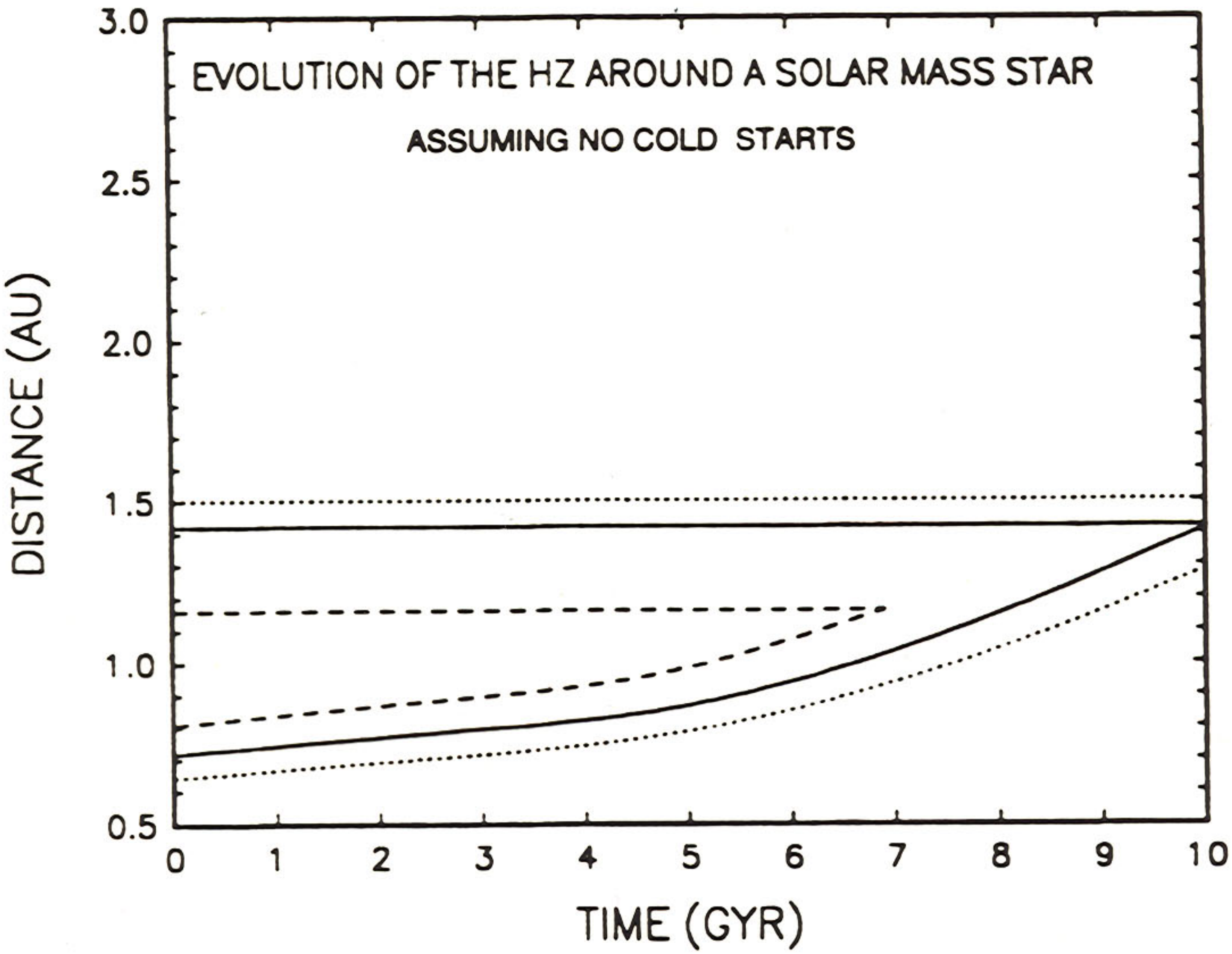


FIG. 3. *Evolution of the HZ around a 1 $M_\odot$ star assuming that an ice covered planet that was initially beyond the outer HZ boundary cannot be cold started until the stellar flux is greater than the critical greenhouse value. The three cases shown are discussed in the text and correspond to the most conservative Case 1 (long dashes), the intermediate Case 2 (solid curves), and the least conservative Case 3 (short dashes).*

Snowball Earth

Increasing evidence that Earth nearly froze over twice

2.4 billion years ago & 650-800 Myr ago

Climate can have dramatic changes

Apparently - these were ended by volcanic eruptions that put much more CO_2 in atmosphere

What Else Do We Need?

- So far, we considered liquid water sufficient
- What else?
  - Temperature range
  - Pressure
  - Salt concentration
  - Acidity/alkalinity

Lower Limit to Temperature?

Some microbes survive for long periods in Antarctic ice

e.g. Lake Vostok - 2.5 miles below glacial ice in Antarctica

Sample has been obtained, will be analyzed (2012)

Freeze-dried for ~ 10^6 yrs?

Revive when exposed to liquid

Lower limit is probably about -20° C (253 K)

Upper Limit?

We have learned that some microbes can survive in pressurized water at T up to 400 K (120° C)!

Such microbes have special adaptations to protect their heat-sensitive molecules

For complex life, upper limit seems to be ~ 325K

~52° C or 126° F

But is this limit just an accident of evolution on Earth?

Other Habitable Zones

Microbial Habitable Zone (MHZ)

Fixed by Range of T microbes can withstand

"Animal" Habitable Zone (AHZ)

"Animal" = complex, differentiated, multicellular life

Ward + Brownlee in *Rare Earth* note AHZ much smaller than MHZ

They also argue that parts of our Galaxy unsuitable for animal life

We will consider this last point under f_i

On the Optimistic Side

1. Sub-surface Water?

   If you don't need photosynthesis, no need to be on surface

   T increases with depth into Earth

   ⇒ liquid water under "ground"

   e.g. Mars? Europa (Moon of Jupiter)

   HZ ⟶ 1.5 AU 5 AU

   n_p ~ 2 ~ 3

2. Other Solvents

e.g. Titan (moon of Saturn) has some liquid methane (CH_4)

HZ $\longrightarrow$ 10 AU

n_p $\longrightarrow$ $\sim$ 4

3. Other planetary systems

Jupiter-like planets $\sim$ 1 AU (in HZ)

Life on Moons?

Other requirements?

Pressure?

Bacteria on deep sea floor withstand up to 1000 atmospheres

But not "animal" life

Not too salty? - halophilic bacteria

up to 33% salt solution

pH? –LOG [H ions]

pH 1	7	pH 14
acid	normal	alkali
	H_2O	

Almost all cells regulate pH to 7.7

1 ← microbes → 13

Again, microbes have adapted to just about any environment of Earth

Importance of Heavy Elements

Planetary systems found so far are found more commonly around stars with more heavy elements

Does this apply to systems more like ours?

Still under study, but seems less important for lower mass planets.

Updated slide

The Importance of the Moon

The Moon makes the tides bigger than if only the Sun caused tides

May be important in the origin of life

The Moon stabilizes the Earth's obliquity

Varies regularly from 22.1 to 24.5 over 41,000 yrs.

Without the Moon, tugs from other planets could make it vary chaotically

Large obliquity could cause snowball Earth

Ward & Brownlee

Only if a large supercontinent at the poles

Williams, Kasting, Caldeira

Stellar Requirements

- We assume that our planet needs to orbit a star
  - Leaves out planets around brown dwarfs
  - Leaves out “nomad planets” (may be many)
  - About 6% of stars are white dwarfs (after all red giant phases). May be OK

Stellar Requirements (f_s)

1. Sufficient Heavy Elements

Terrestrial planets, bioelements

1st generation - ruled out

Population II - ruled out

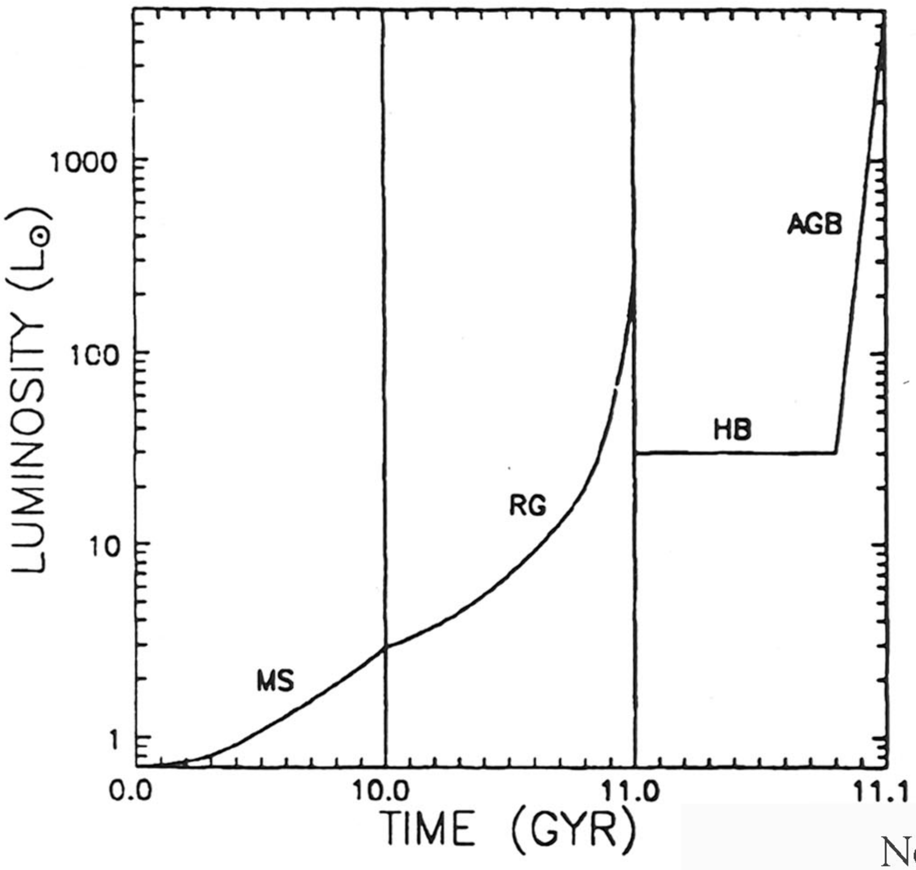
No significant loss

2. Main Sequence
(Stable L $\Rightarrow$ Stable T possible)

e.g. Sun will increase L by 10^3
5×10^9 yr from now

Red Giants - ruled out

0.99 OK (0.94 if leave out white dwarfs)



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$$r_2 = \sqrt{\frac{L(t)}{S_2(T)}}$$

3. Stellar Mass Not Too High
(Main sequence Life $\geq 5 \times 10^9$ yr)

Roughly, $L \propto M^4$ Fuel $\propto M$

$$\text{Lifetime} \propto \frac{\text{Fuel}}{L} \quad \text{or} \quad \frac{1}{M^3}$$

Stellar Lifetimes

$M\ (M_\odot)$	Lifetime (yrs)
30	2×10^{6}
10	3×10^{7}
3	6×10^{8}
1	1×10^{10}
1/3	2×10^{11}
1/10	3×10^{12}

If $t > 5 \times 10^9$ yrs

$M < 1.25\ M_\odot$

$M > 1.25\ M_\odot$ - ruled out if we require 5×10^9 yr for intelligent life to evolve

Most stars are low mass, so 0.90 OK

White dwarfs OK once they cool below 6000K, then planet orbiting at 0.01 AU would be in CHZ for 8×10^9 years.

4. Stellar Mass Not Too Low

a) Do terrestrial planets form?

"Jupiters" should form closer to low mass star

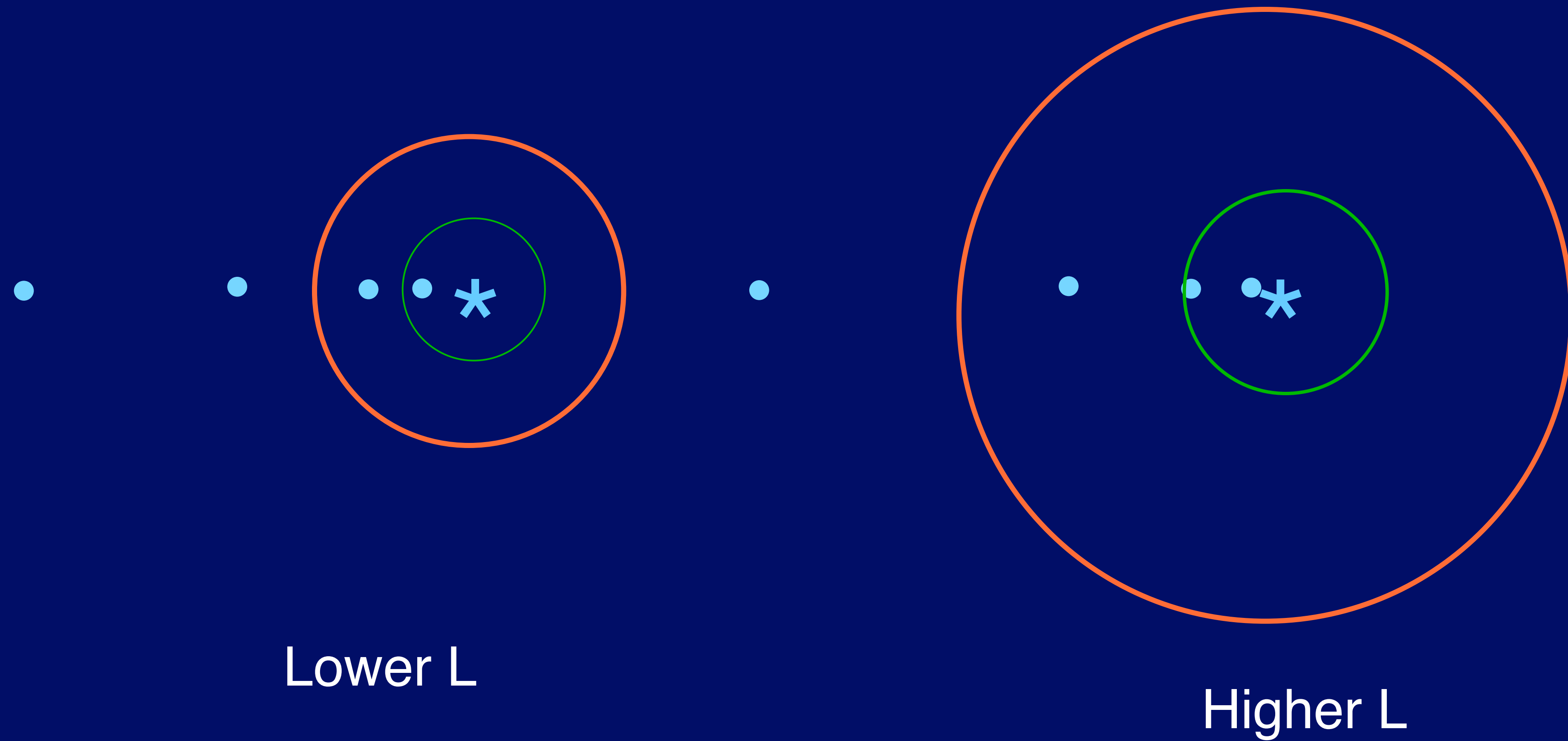
Prevent formation of terrestrial planets?

Probably not a problem from recent surveys.

b) Chance of having terrestrial planet in CHZ?

CHZ smaller for Low L

For Logarithmic Spacing, n_p independent of size



But if planet spacing as in Solar System
and
CHZ not smaller than innermost planet orbit

Chances are the same

c) Low mass stars have strong flares

High energy particles?

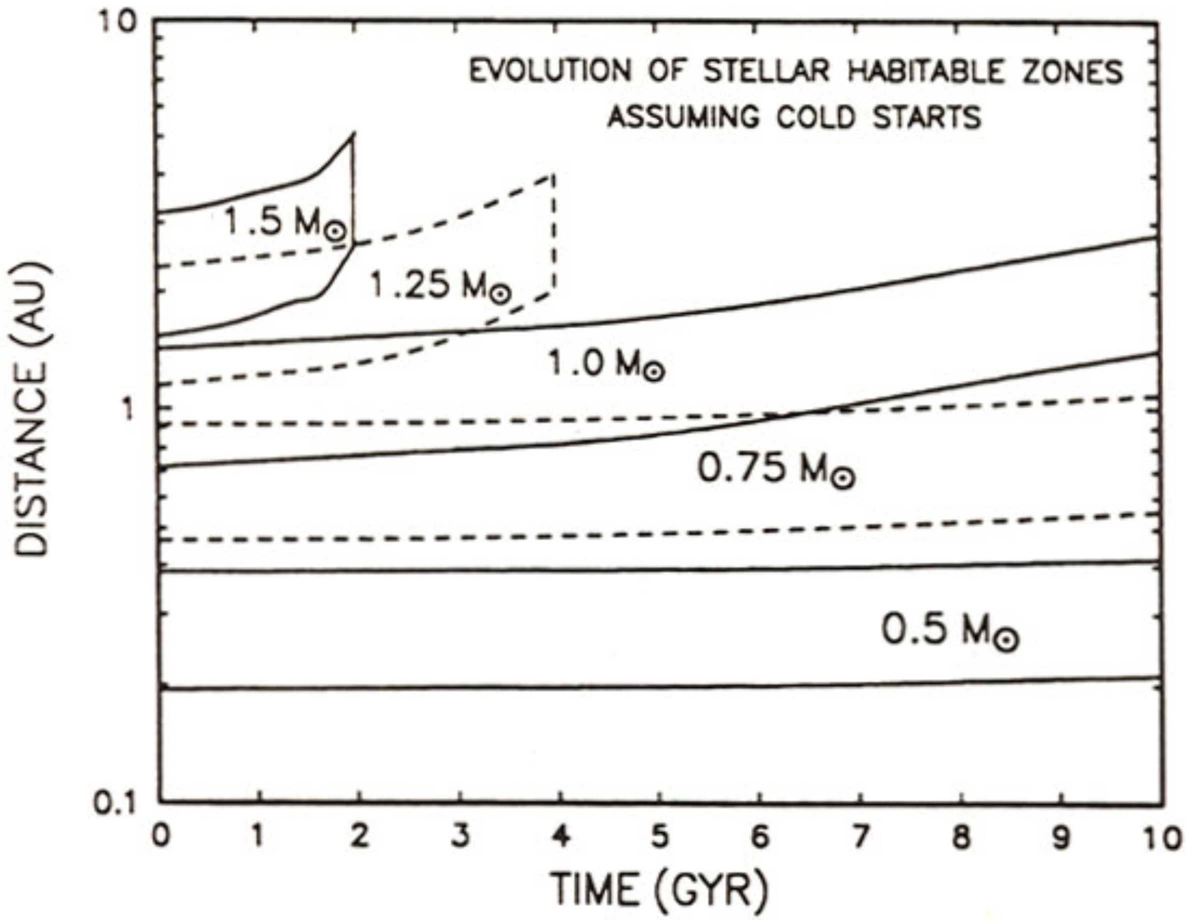


Fig. 5. *Evolution of the H around stars of different masses assuming that co starts are possible. Case critical fluxes were usec and the evolution was truncated at the end of tl main sequence phase.*

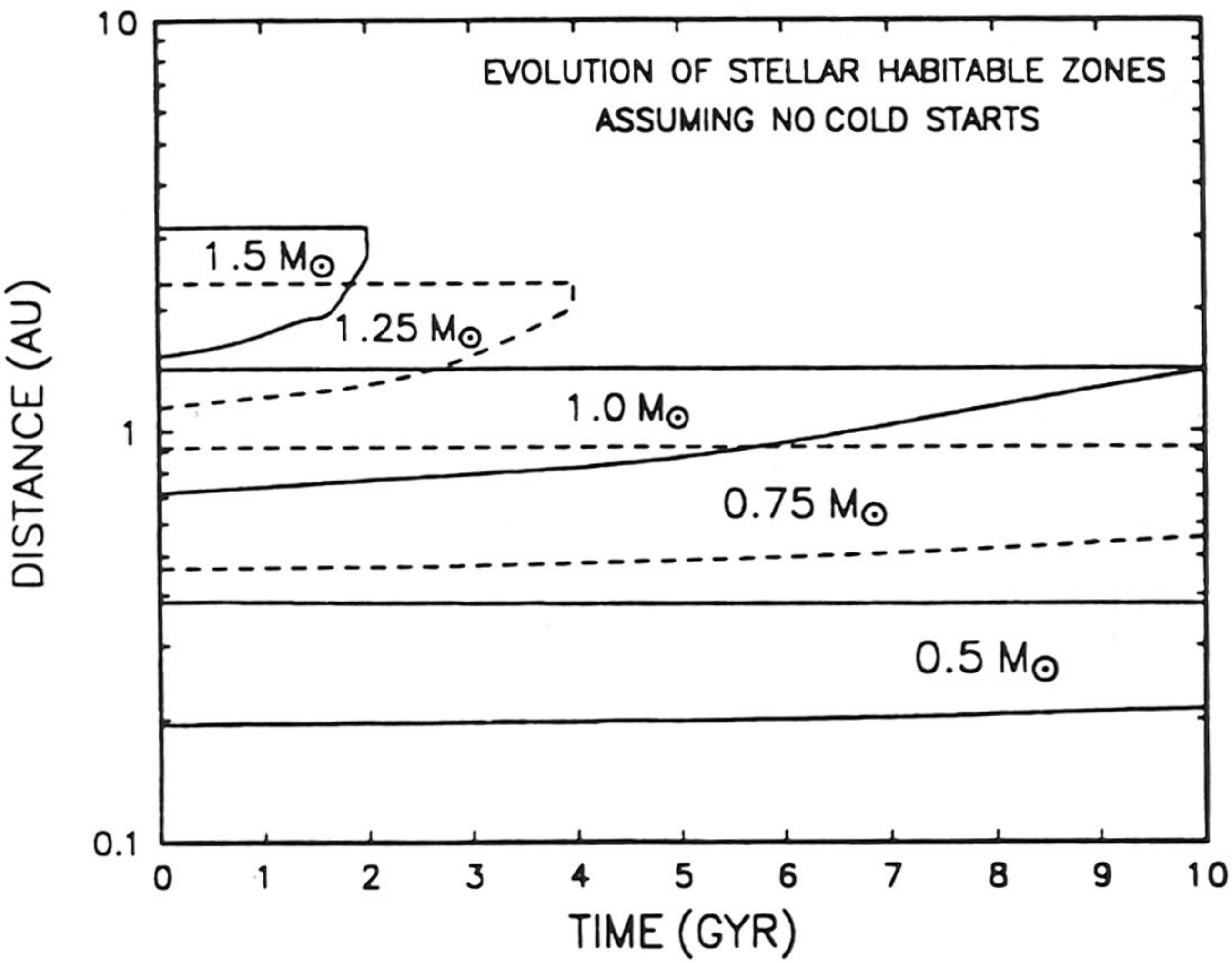


FIG. 6. *Evolution of the HZ around stars of different masses assuming that cold starts are not possible. Case 2 critical fluxes were used and the evolution was truncated at the end of the main sequence phase.*

d) Synchronous Rotation (Same side always faces star)

$$T \propto \left(\frac{L}{D^2}\right)^{1/4} \propto \frac{L^{1/4}}{D^{1/2}} \qquad \text{Tidal Forces} \propto \frac{1}{D^3}$$

$\Rightarrow$ As D decreases, Tidal forces become much more important

Cause synchronous rotation

Gravity greatest on side closest

$\Rightarrow$ Bulge

\+ Rotation = Tides

If Rotation $\neq$ orbital period, friction

$\longrightarrow$ tends toward synchronous rotation

(but effect of other planets may prevent this)

$\Rightarrow$ Atmosphere freeze-out?

May not happen if atmosphere thick enough

(0.1 Earth pressure)

$M > 0.5\ M_\odot \Rightarrow 0.25$ OK

$M < 0.5\ M_\odot$ - may be bad choices, but not sure

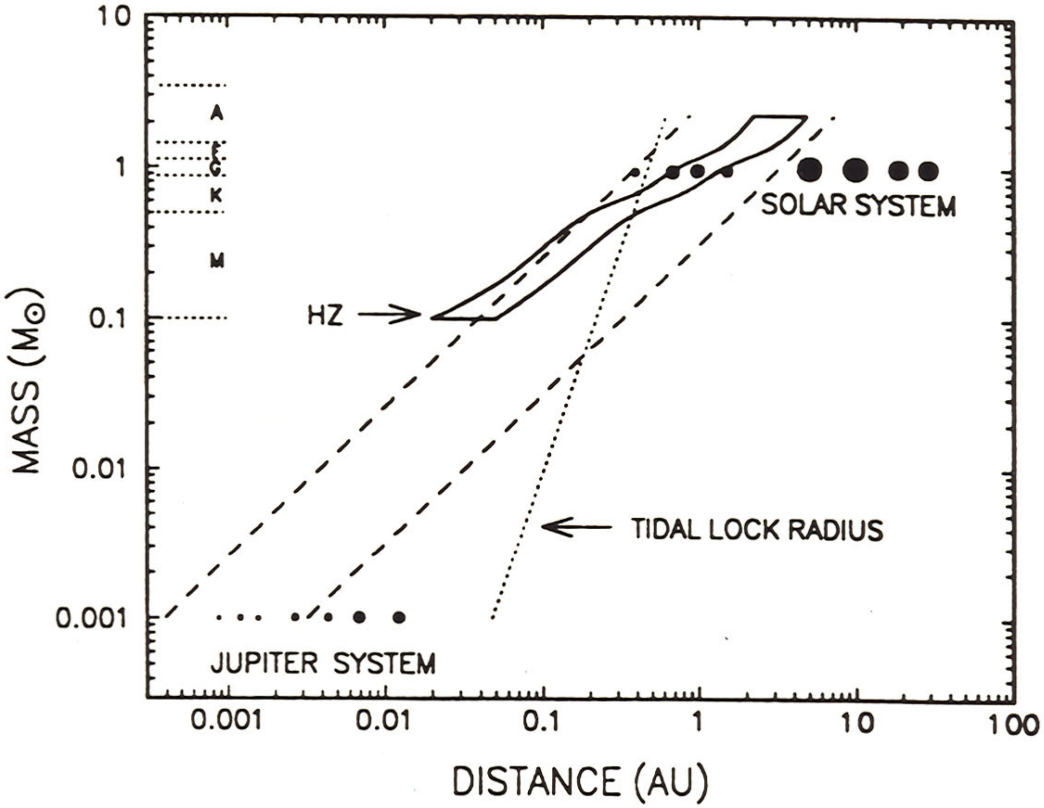


FIG. 8. *The ZAMS HZ (dark solid curve) as a function of stellar mass for Case 2 fluxes. The long-dash lines delineate the most probable terrestrial planet formation zone. The short-dash line is the radius for which an Earthlike planet in a circular orbit would be synchronously or slowly rotating as a result of tidal damping. Note that all such planets in the HZ around M stars are within this radius.*

5. Binary Stars

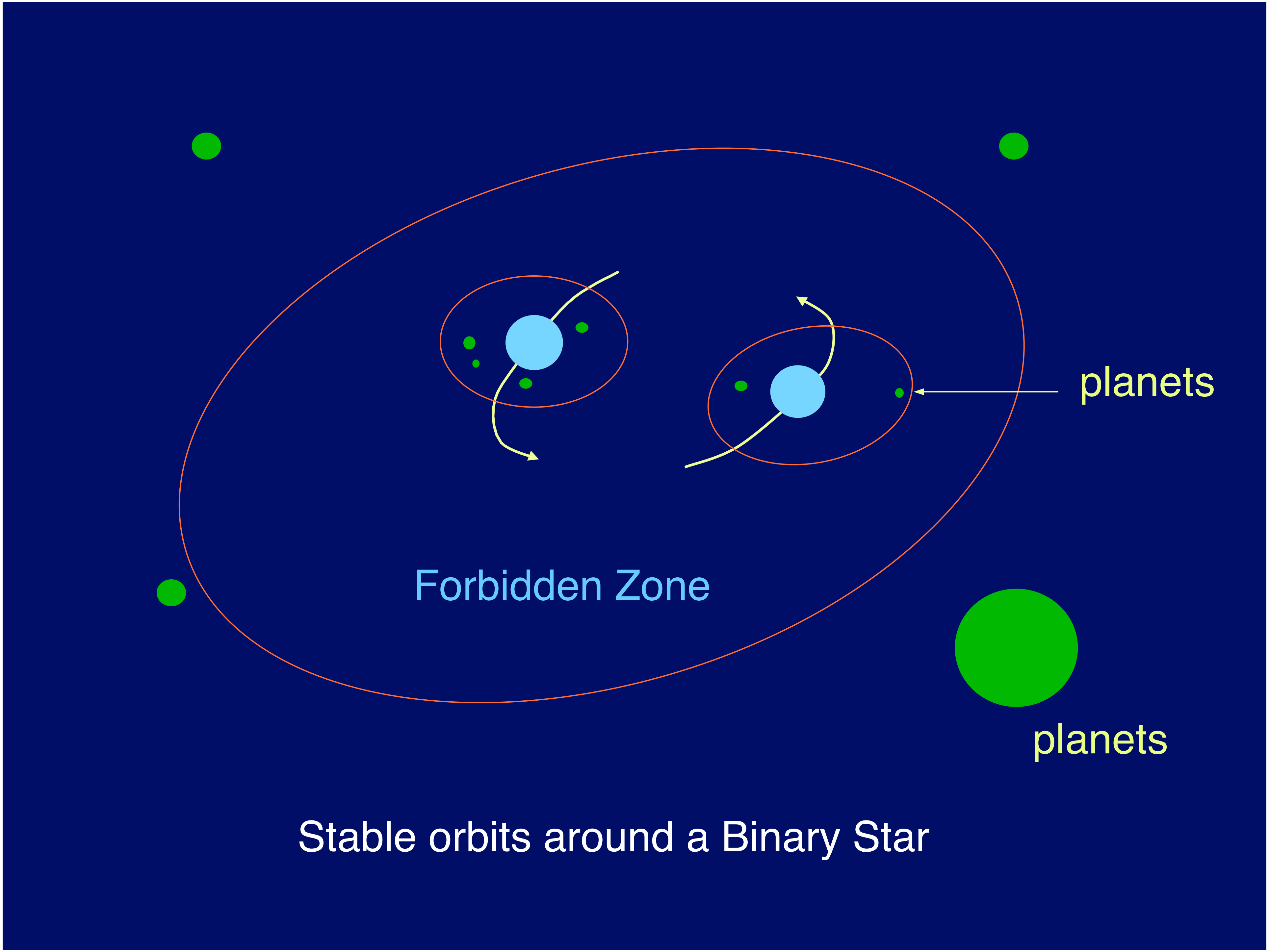
a) Unstable orbits

Unless two stars widely separated
or very close

Need $\frac{\text{Distance to Second Star}}{\text{Distance to Planet}} > \frac{7}{1}$ or $< \frac{1}{7}$

or

(more likely)


planets
Forbidden Zone
planets
Stable orbits around a Binary Star

b) Varying temperature in orbit
also need $\sim 7:1$

c) Both stars on main sequence,
$M < 1.25\ M_\odot$, …

2/3 of all stars are binaries
2/3 $\sim$ "wide enough"

Binaries ruled out? $f_s < 1/3$ (if you kept them for f_p)
Not > 7 : 1 ruled out? $f_s < 1/2$

Summary

Stellar Requirement	**Mass limit**	**Fraction OK**	**Cumulative Fraction**
Heavy Elements	…	1.0	1.0
Possibly Stable Temperature	…	0.99 0.94 w/o WDs	0.99 0.94 w/o WDs
Main Sequence Lifetime	$(M<1.25\ M_\odot)$	0.90	0.89 0.85 w/o WDs
Not Synchronous Rotation	$(M>0.5\ M_\odot)$	0.25	0.22 0.21 w/o WDs
Not a binary	…	0.30	0.07 0.06 w/o WDs
Wide separation binary	…	0.50	0.11 0.11 w/o WDs

Bottom Line

- Points 1 to 3 are pretty clear
  - But don't matter much…
- Points 4 and 5 are less established
  - And could matter a lot…
- Room for different estimates for f_s
  - Range 0.07 to 0.89 OK
- Then final step:
  - $n_e = n_p f_s$

Hope for Better Data

- As more and more low mass planets are seen in larger orbits
- Extrapolation of current data:
  - 23% of Sun-like stars should have masses of 0.5 to 2 M_{earth} in orbits near 1 AU
    - Howard et al. 2010, in Science, 330, 653
- Time will tell…
  - The Kepler mission will provide real numbers

Kepler as of Feb. 2011…

- Based on statistics of candidates so far
  - For planets in close orbits (<0.5 AU) that are currently well constrained
  - Correcting for bias and sensitivity
  - Probability of "earth size" ($r<1.25\ R_{earth}$) planet is 6%
  - Probability of "super-earth" ($1.25\ R_{earth} < r < 2R_{earth}$) planet is 7%
  - Probability of "Neptune-size" ($2\ R_{earth} < r < 6\ R_{earth}$) planet is 17%
  - More low mass planets in close orbits than predicted

Update: August 2012

- Down to about 2 R_{earth} , periods 50-100 days:
  - 12-17% of stars have super-Earths
  - Number of planets increasing as sizes get smaller; suggests Earth size should be common
  - Also increasing with period; suggests Earth-like orbits will also be common

New slide

Other Predictions

- Results from spectroscopic search of low-mass stars (Mar. 2012)
- 9 super-earths (1-10 M_{earth}) toward 102 “red dwarfs”
- Two were in HZ
- Extrapolate: 0.3–0.9 of such stars have planets in HZ
- 10^{10} super-earths around such low mass stars
- This is a big extrapolation!
- Other issues with low mass stars still unclear