The Cosmos

Planets & Life
PHYS 214

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Please start all class related emails with “214:”

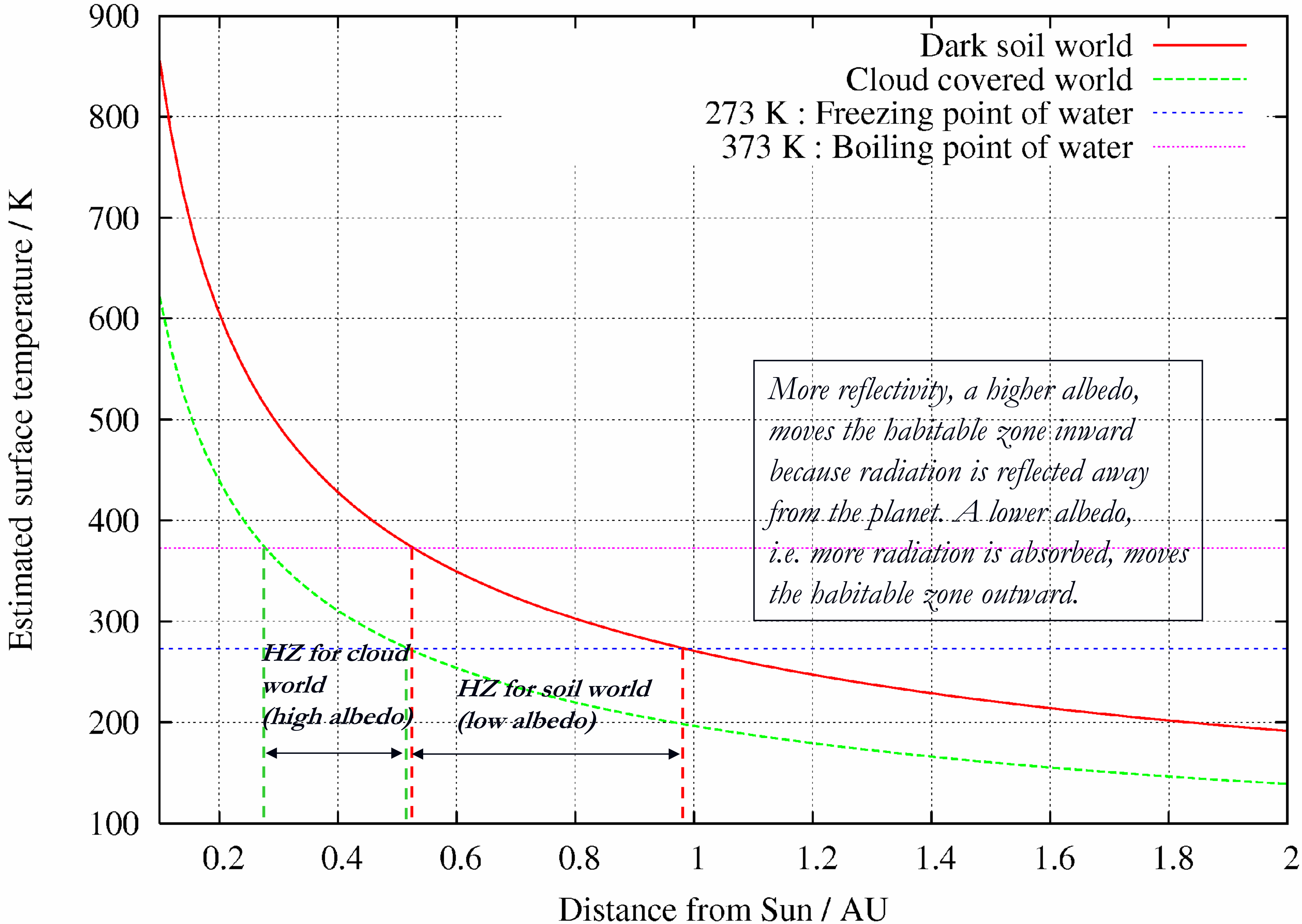
Today's Lecture

- More on Habitable zones
  - Changes in size
  - Impact of greenhouse effect
  - Galactic habitable zones

- Possibly(?) no lecture Friday Feb 9th, more information about this on Friday
- Monday 5th Feb, guest lecture: Dr Martin Duncan (Astronomy) on formation of the outer solar system

Impact of albedo on the HZ

- Because albedo can take such a wide variety of values it is interesting to study it's effects on the HZ
- Let's compare the average temperature of a planet with high cloud cover (a=0.75) with dark soil (a=0.1)

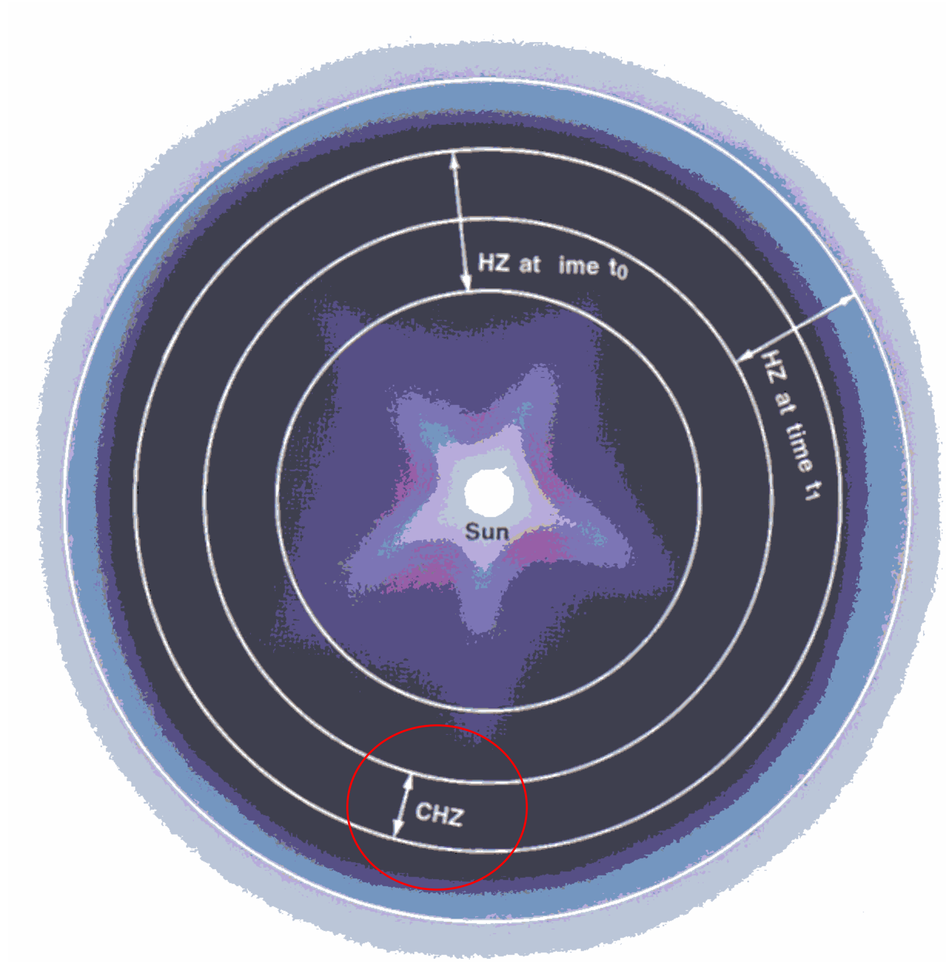

Dark soil world
Cloud covered world
273 K : Freezing point of water
373 K : Boiling point of water
More reflectivity, a higher albedo, moves the habitable zone inward because radiation is reflected away from the planet. A lower albedo, i.e. more radiation is absorbed, moves the habitable zone outward.
HZ for cloud world (high albedo)
HZ for soil world (low albedo)
Estimated surface temperature / K
Distance from Sun / AU
900
800
700
600
500
400
300
200
100
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Changes in stellar luminosity

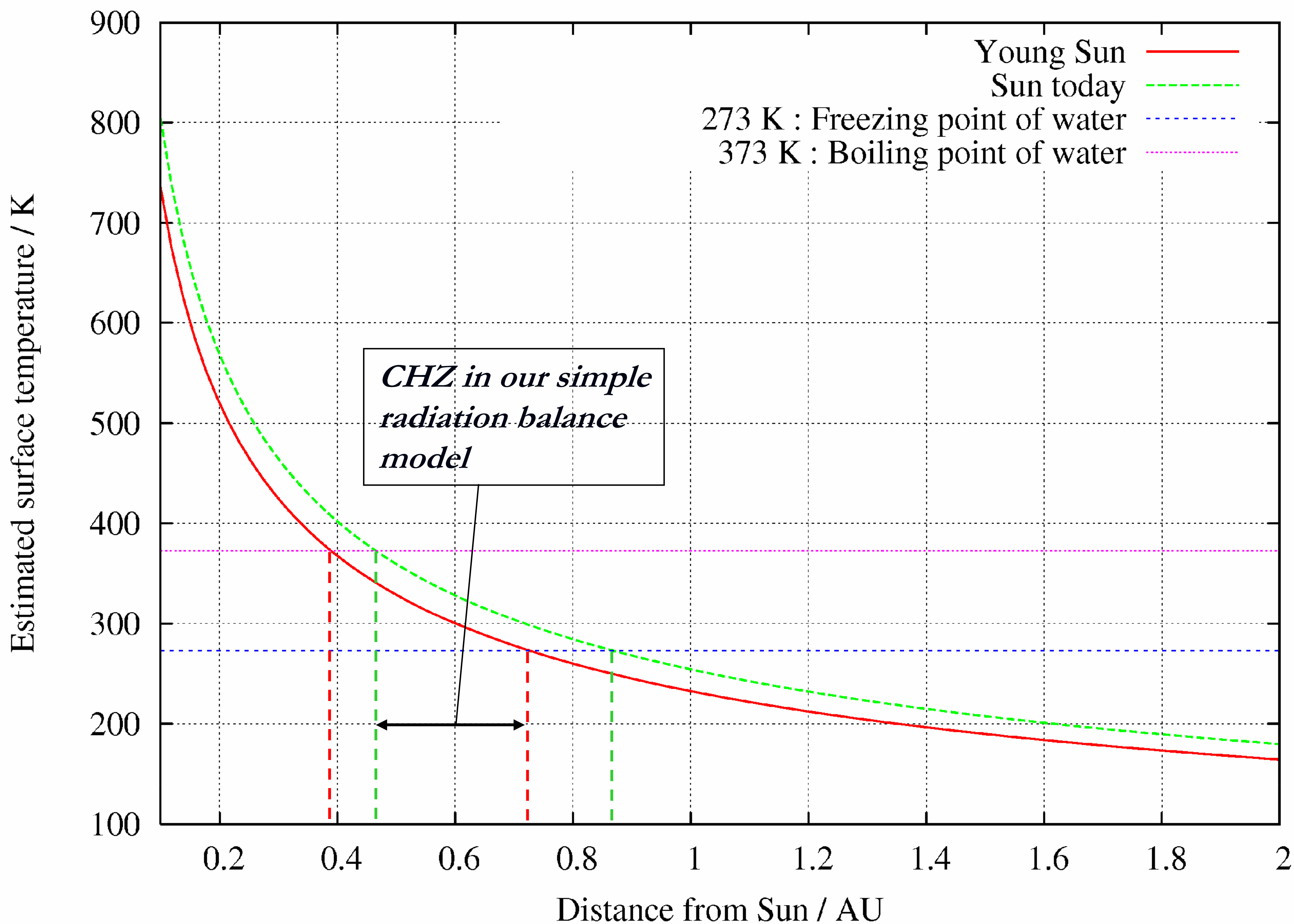
- 4 billion years ago the Sun’s luminosity was 70% of its current value
  - In fact all main sequence stars show this brightening over time
- What impact does it have on the habitable zone?
- HZ must move outward over time
- Planetary orbital radii are quite stable, so as the HZ moves over time a planet may find itself move in, or out of the HZ

Continuously Habitable Zone

- The region in which a planet may reside and maintain liquid water throughout most of a star's life, is called the ***continuous habitable zone*** (CHZ).



CHZ marks the middle region that remains habitable as the boundaries move outward.


Young Sun
Sun today
273 K : Freezing point of water
373 K : Boiling point of water
CHZ in our simple radiation balance model
Estimated surface temperature / K
Distance from Sun / AU
900
800
700
600
500
400
300
200
100
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Impact of the greenhouse effect

- All our preceding estimates have neglected the greenhouse effect
  - We have also assumed our planet to be a perfectly radiating black body – which is far from true
- As we have discussed, it is actually extremely important in assessing the extent of the CHZ
- Before discussing how we model its impact on the CHZ, we first review the concepts behind the greenhouse effect itself

A note about the greenhouse effect in the context of climate change

- As we’ve discussed already, the greenhouse effect is necessary for life on Earth
- When it is talked about in terms of climate change they really mean a more severe greenhouse effect due to anthropogenic CO_2 emissions
  - Believe it or not, we knew the temperature increase to within a factor of 2 in the early 1960s

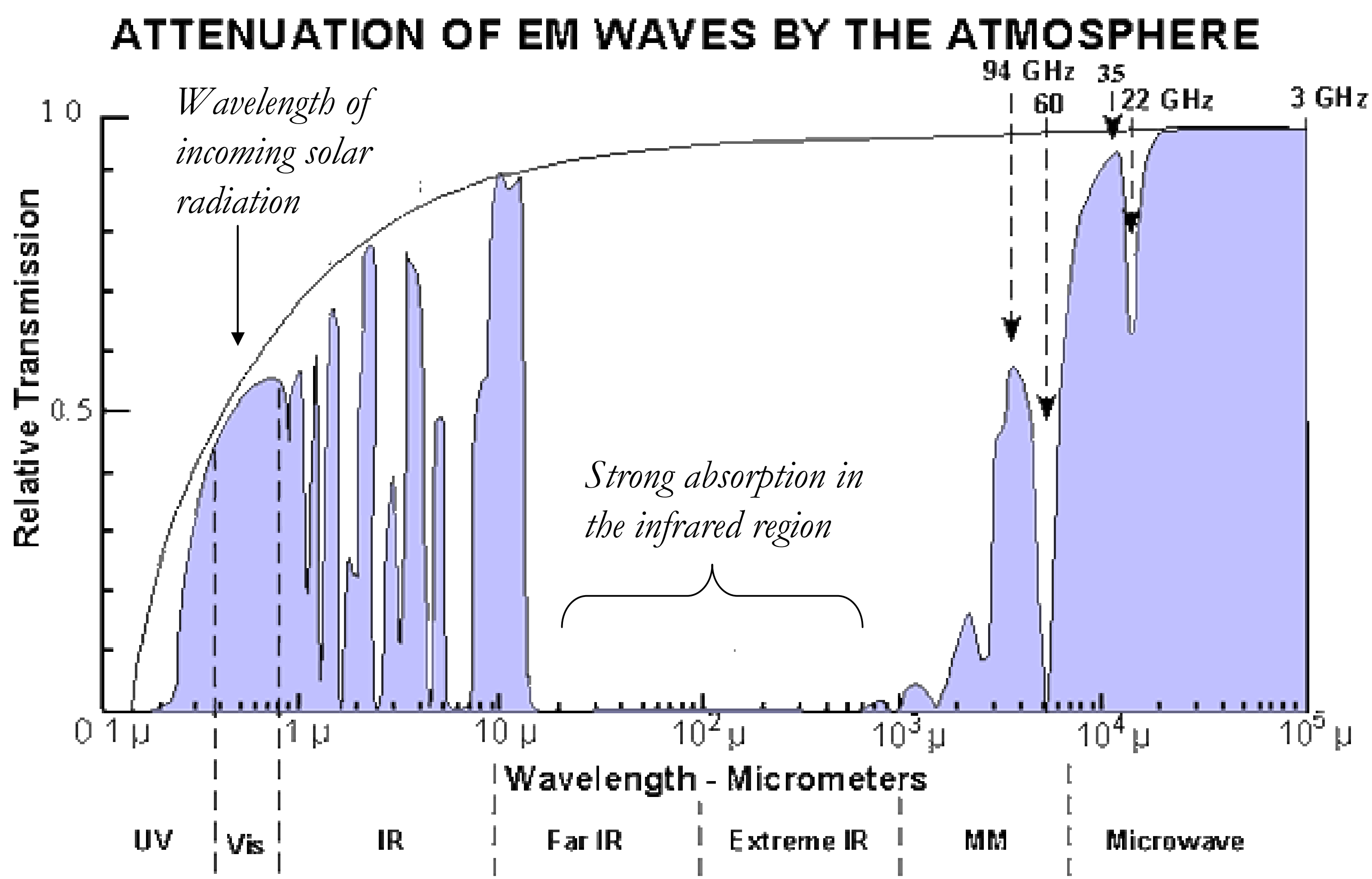
Jay Leno: “According to a survey in ths week’s Time Magazine, 85% of Americans think global warming is happening. The other 15% work for the White House.”

Greenhouse effect

- The greenhouse effect can be understood as arising from two facts

  (1) The Earth's atmosphere transmits visible light efficiently, but strongly absorbs infra-red light

  (2) The Earth's temperature is sufficiently low that incoming light energy from the Sun will be re-radiated at infra-red wavelengths (black-body-"ish")


ATTENUATION OF EM WAVES BY THE ATMOSPHERE
Relative Transmission
1.0
0.5
0
Wavelength of incoming solar radiation
Strong absorption in the infrared region
94 GHz
60
35
22 GHz
3 GHz
0.1 μ
1 μ
10 μ
10² μ
10³ μ
10⁴ μ
10⁵ μ
Wavelength - Micrometers
UV
Vis
IR
Far IR
Extreme IR
MM
Microwave

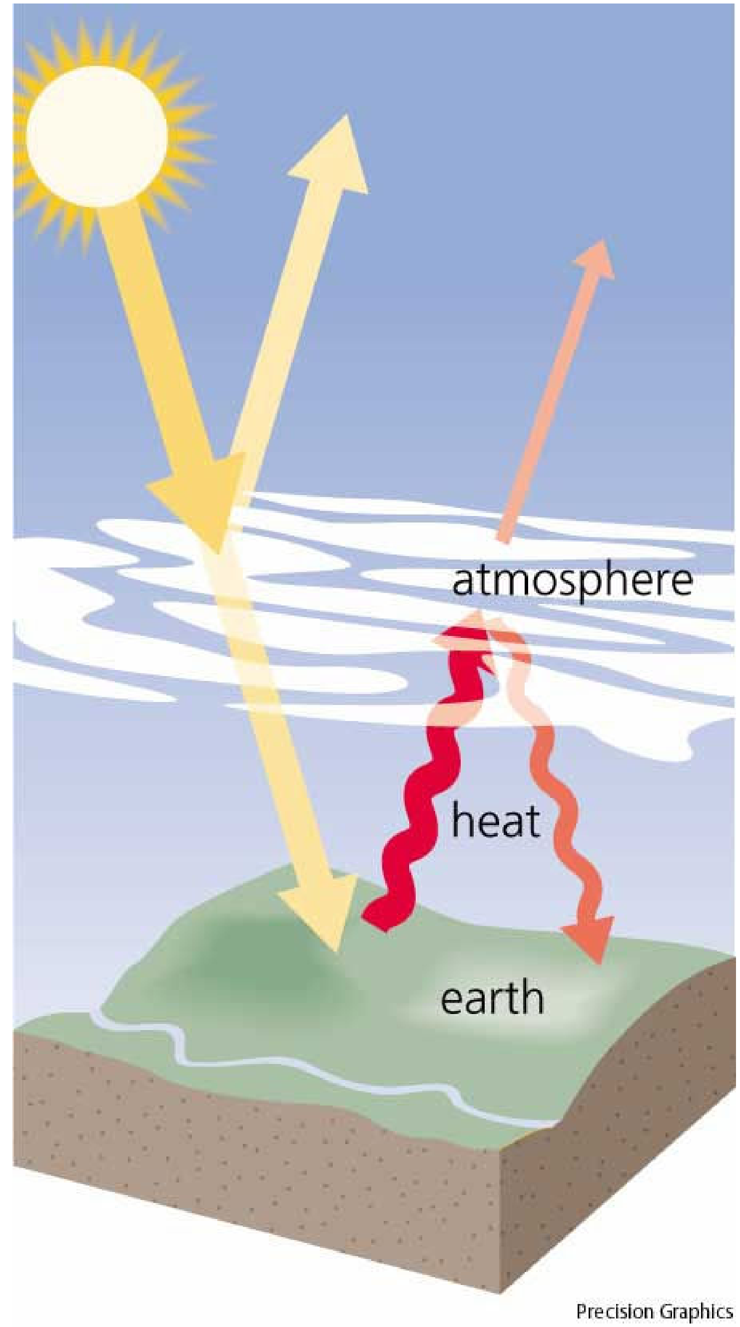
Greenhouse Gases

- H_2O (water vapour) and CO_2 are the two dominant greenhouse gases
  - Water vapour probably contributes more (by a factor of 2 perhaps) to the greenhouse effect than CO_2
  - Methane (CH_4) and ozone (O_3) also play a roll along with other organic molecules
- These molecules have molecular structures that absorb photons at infrared wavelength and incite vibrations in the molecule
- On a per molecule basis some man made CFC's are spectacularly more capable of absorbing infrared than CO_2, but fortunately the atmospheric concentrations are very low

Nitrogen, N_2, and oxygen, O_2, which make up the bulk of the atmosphere are not greenhouse gases.

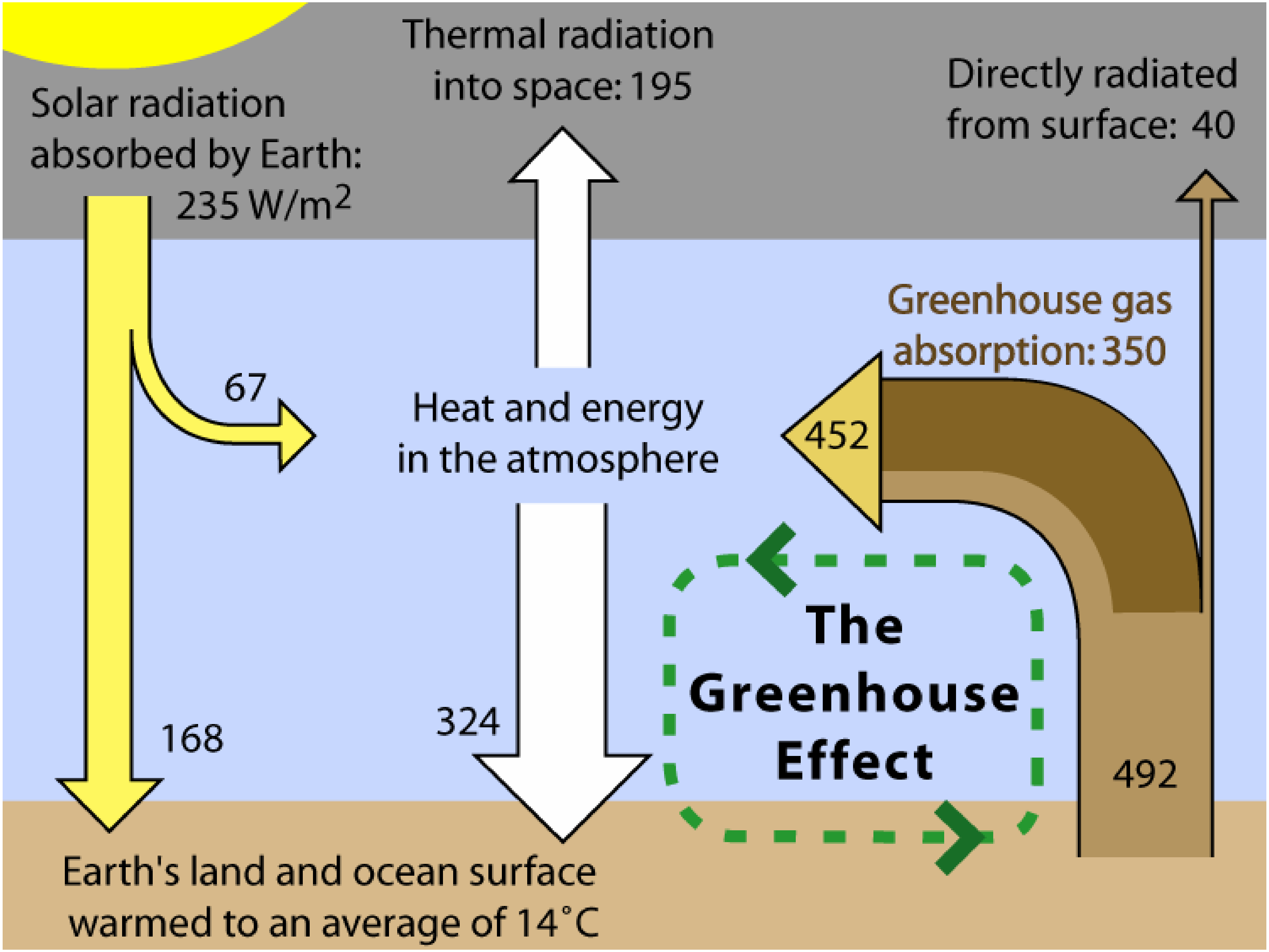
Greenhouse Effect

- Incoming radiation is at visible wavelengths
  - Some is reflected due to the albedo of the planet
- Most radiation is transmitted down to planet's surface
- Re-radiated at long (infra red) wavelengths from the planet's surface
  - A small fraction escapes out directly
- Atmospheric greenhouse gases absorb most of the infrared radiation and will re-emit too
- Most radiation is sent back down to the Earth



The Earth's Energy budget

- Once the greenhouse effect is established it will reach an equilibrium where the net radiation outward equals that coming in
- If you work out the amount of energy arriving from the Earth it is about 340 W m^{-2}
- Albedo serves to reduce the net radiation through the atmosphere to about 235 W m^{-2}
- Yet the Earth's average radiation output is about about 492 W m^{-2} – where is the excess energy going?



Solar radiation absorbed by Earth: 235 W/m2
Thermal radiation into space: 195
Directly radiated from surface: 40
67
Heat and energy in the atmosphere
Greenhouse gas absorption: 350
452
168
324
The Greenhouse Effect
492
Earth's land and ocean surface warmed to an average of 14°C

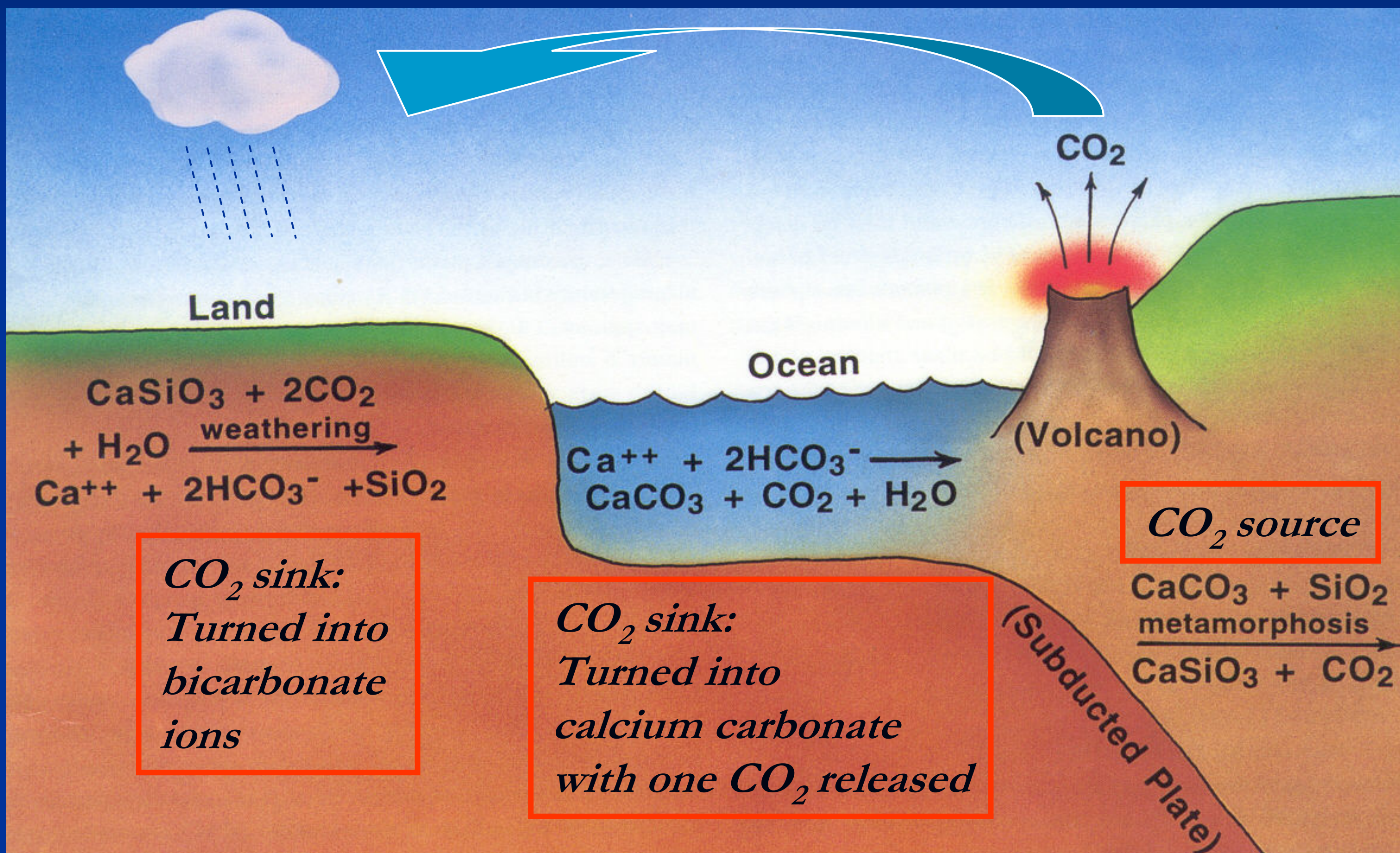
Kasting's models

- In the early 1990s Kasting and co-workers examined the effect of greenhouse gases on the Sun's habitable zone using computer models
  - CO_2, H_20, N_2 atmosphere
- They estimated the inner edge of the HZ on the basis of when water breaks down into oxygen and hydrogen due to UV radiation
  - Hydrogen then escapes the atmosphere and water is essentially "boiled" away from the planet
- They found the inner edge of the HZ to be 0.95 AU

What about the outer edge?

- How far out can CO_2 and H_2O still maintain a habitable planet?
- Obviously depends on atmospheric concentrations of greenhouse gases
- Model's showed that the existence of a "*CO_2 thermostat*" could extend the HZ
  - Atmospheric CO_2 rises as surface gets colder because weathering (a sink of CO_2) stops and volcanic activity (a source of CO_2) becomes more important

The carbonate-silicate cycle



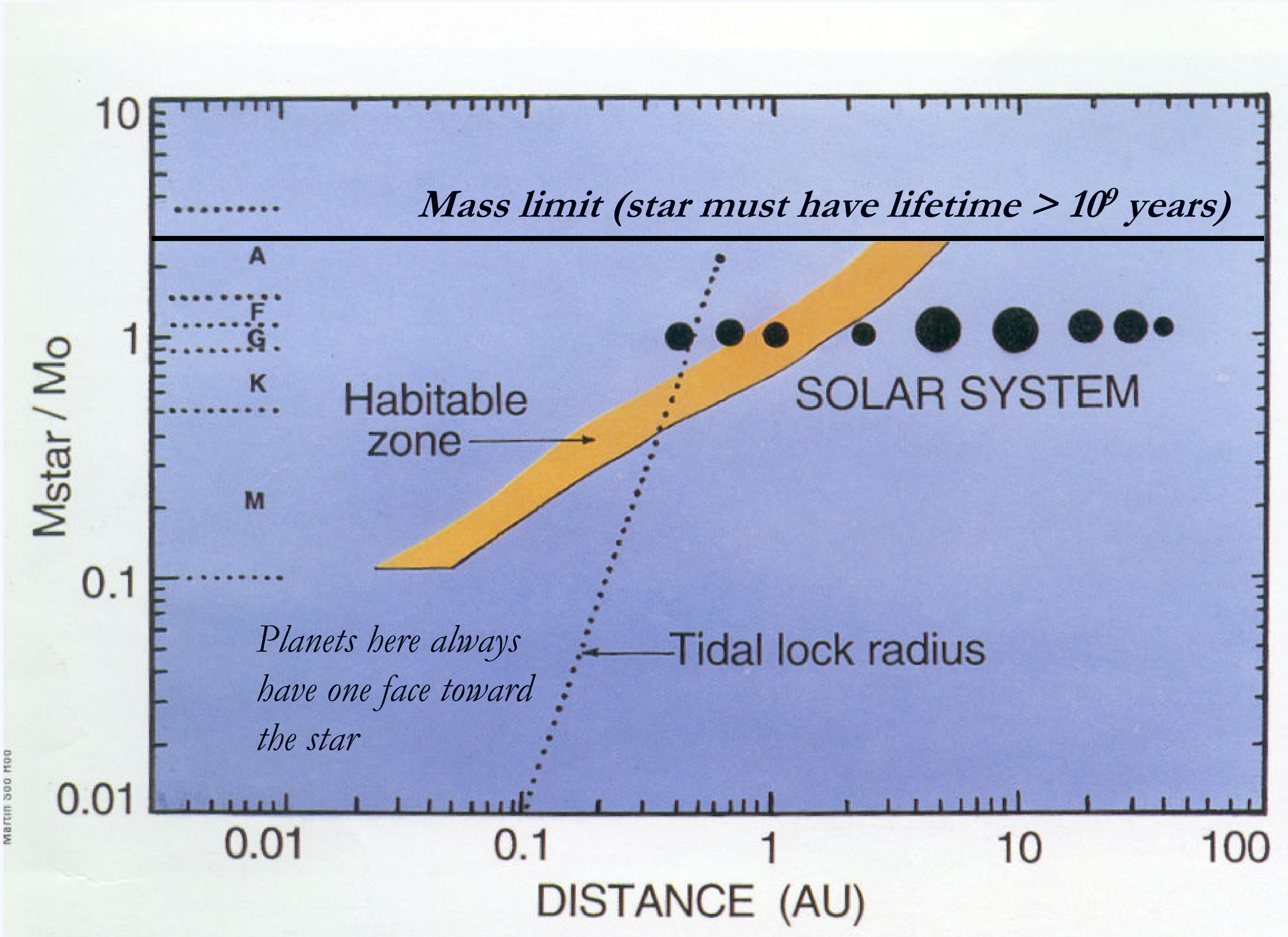
Outer edge of the HZ

- Kasting's work provided two estimates for the outer edge of the HZ
- The first estimate: 1.37 AU was based upon where CO_2 would start to condense out of the atmosphere
  - Without the CO_2 to drive the greenhouse effect, temperatures are expected to fall rapidly
- The second estimate: 1.67 AU was based upon establishing the maximum greenhouse effect that could operate and produce an average temperature of 273 K

Venus & Mars

- Venus, at 0.72 AU, is clearly well inward of the inner boundary
  - Runaway greenhouse there has lead to a temperature 500 K higher than you would estimate!
- Mars is at 1.52 AU, which is within the maximum limit but outside the CO_2 condensation limit
  - Average surface temperature very low (-55 C)
  - Thin atmosphere left
  - We'll look at Mars in more detail later

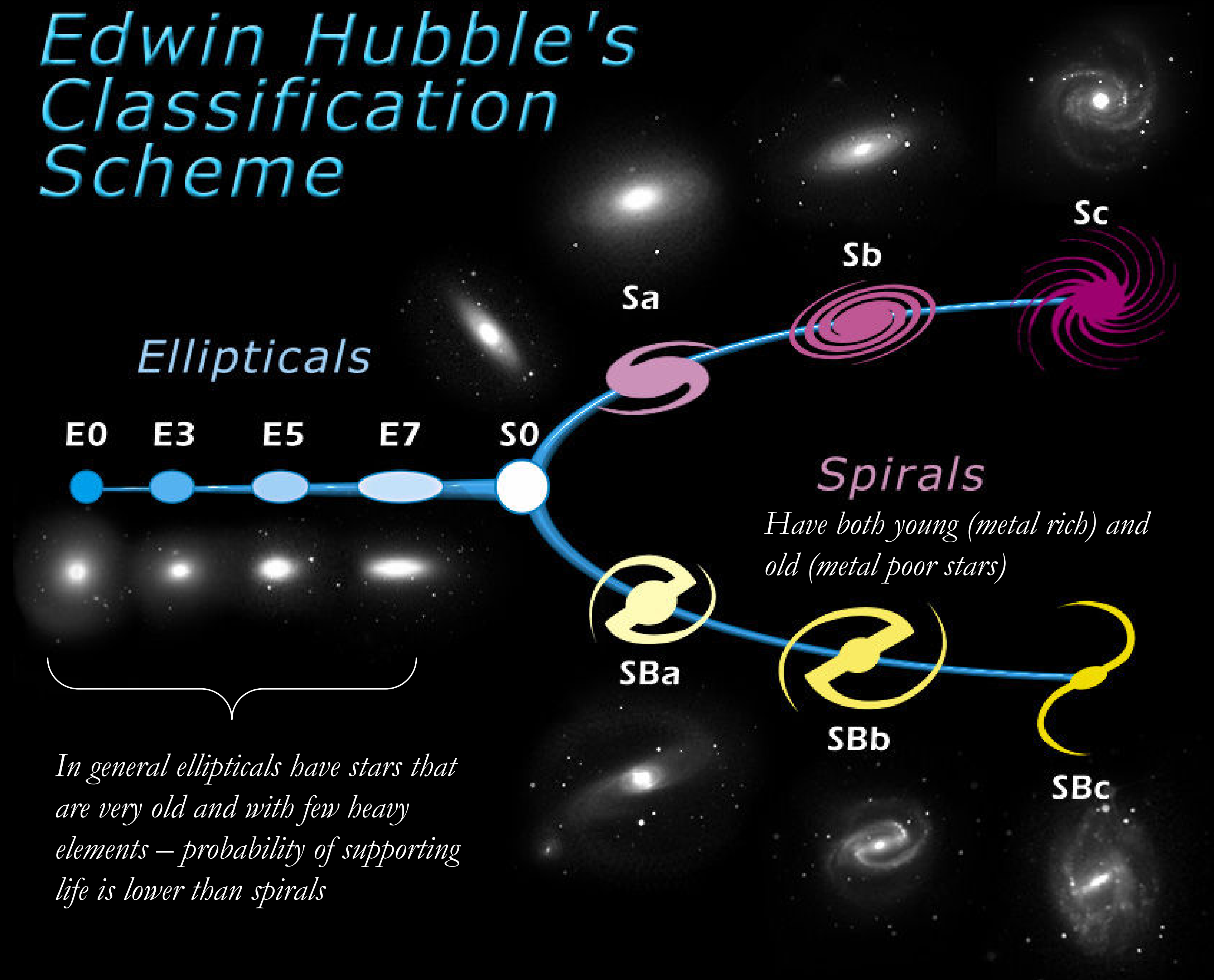
Habitable zones around other stars



Galactic Habitable Zones

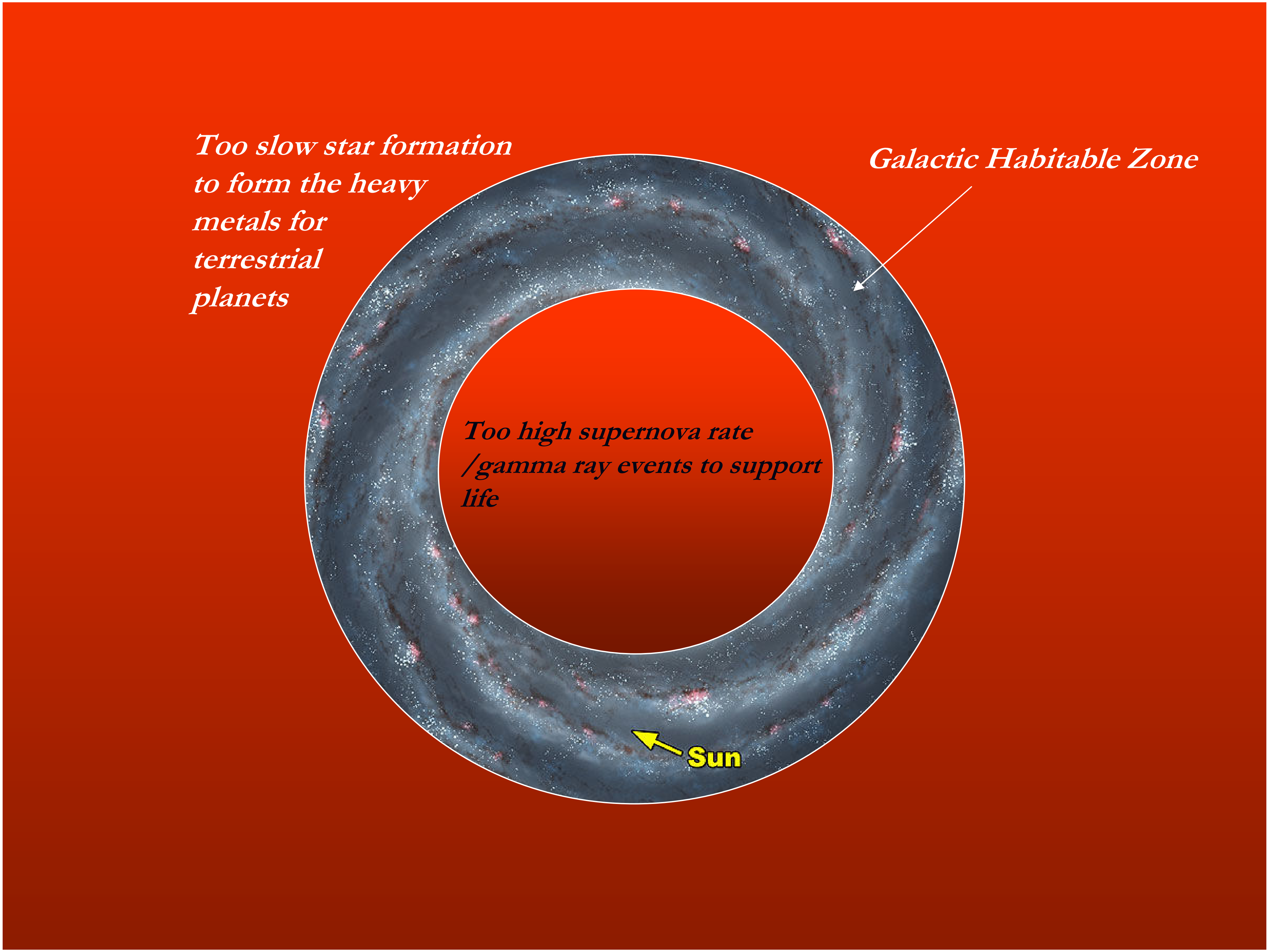
- Just as we can define regions of space in the solar system, we can extend this idea to the galaxy itself
- The main constraints are
  1. Have enough heavy elements to create terrestrial planets been created in a region of space? (this is largely a time constraint)
  2. Are there few enough supernova events so that life is not wiped up by a large burst of gamma-rays?

Edwin Hubble's Classification Scheme



Distribution of stars in the galaxy

- There is more matter in the centre of the galaxy than edges (especially at early times)
- This means there will be more supernovae & powerful radiation in the centre of the galaxy
  - life will have a very hard time evolving in this environment
  - There are also more exotic events to worry about "gamma-ray bursters"
- At the outer edges of the galaxy star formation proceeds more slowly because there is less gas
  - Creating heavy elements will take a very long time, so again at the present age of the Universe life is unlikely to have evolved out there


Too slow star formation to form the heavy metals for terrestrial planets
Galactic Habitable Zone
Too high supernova rate /gamma ray events to support life
Sun

When and where do life-supporting stars form?

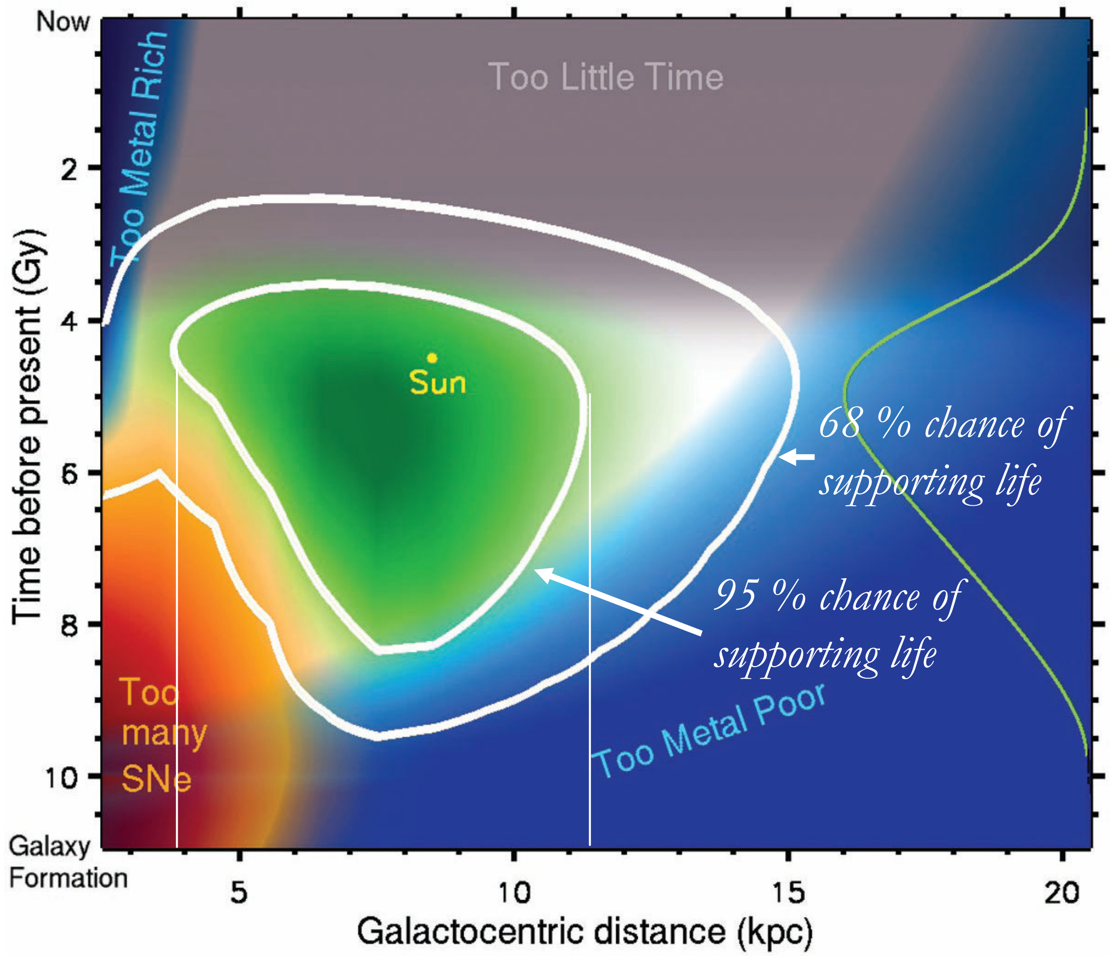
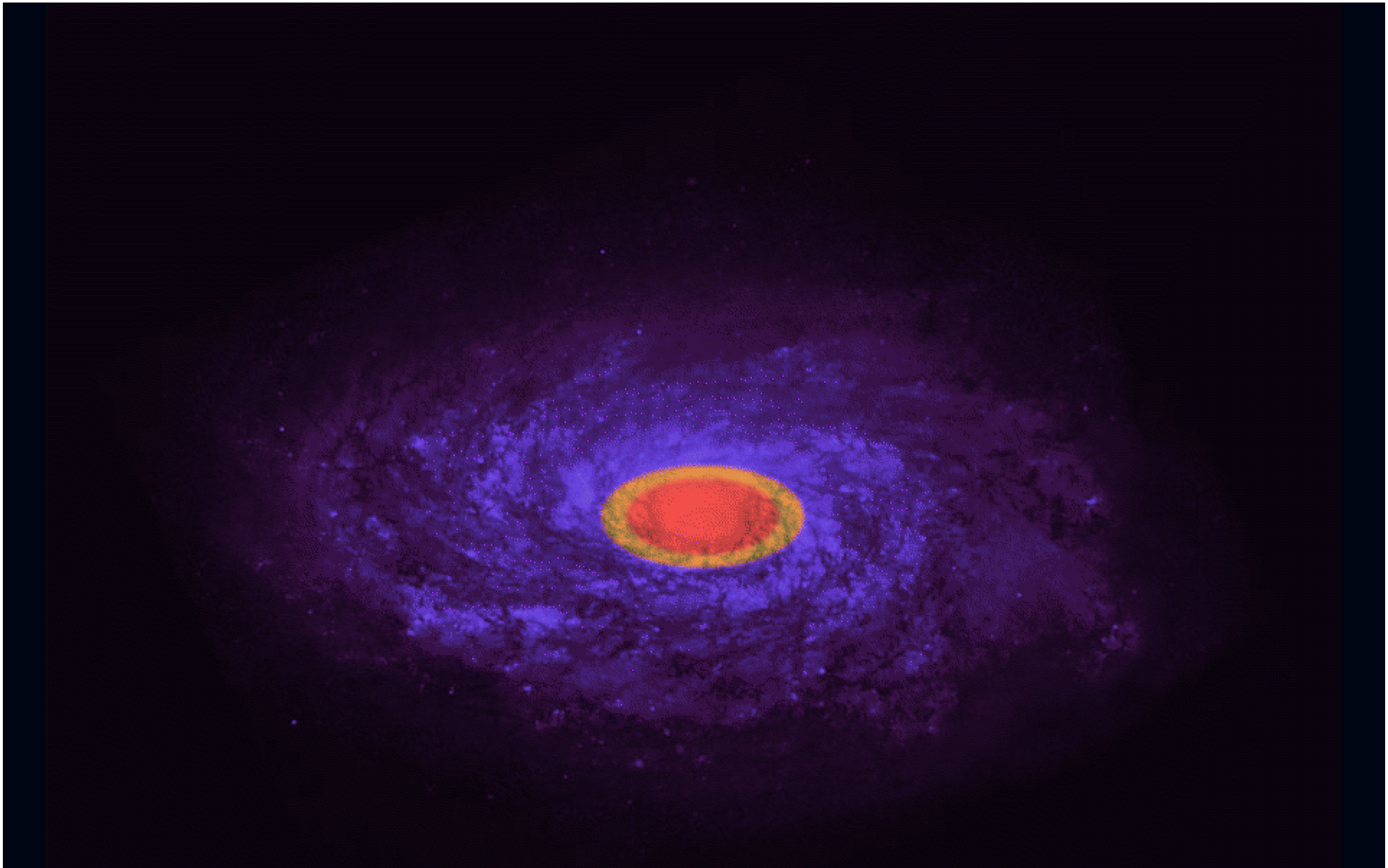


Fig.3. The GHZ in the disk of the Milky Way based on the star formation rate, metallicity (blue), sufficient time for evolution (gray), and freedom from life-extinguishing supernova explosions (red).

Green line is the expected age distribution of stars that support complex life (most are expected to be between 4-8 Gyrs)

C. H. Lineweaver, Y. Fenner, B. K. Gibson (2004): The Galactic Habitable Zone and the Age Distribution of Complex Life in the Milky Way, *Science* 302, 59-62.



Series of frames showing evolution of the Milky Way to the present day. Each frame is 600 million years of evolution. Red indicates regions too full of supernova activity to support Life, blue areas have too few heavy elements, green represents most favoured regions.

Much to be learnt in this field

- The concept of galactic habitable zones was first discussed in 1991 (Gonzalez, Brownlee & Ward)
  - The field is still very young
- There remains considerable controversy over assumptions about supernovae rates and the extinction efficiency of them
  - We'll improve our guesses in the future, but a true answer will be elusive

Summary of lecture 10

- Increasing albedo moves the HZ inward
- The luminosity of the Sun is growing over time and is moving the HZ outward
- The continously HZ (CHZ) defines a region of space that a planet can in habit while still maintaining liquid water
- The greenhouse effect strongly alters the CHZ allowing it to push outward, possibly beyond the orbit of Mars
- A galactic habitable zone analysis suggests there is a region in the galaxy that is suitable for life

Next lecture

- Formation of planets (p 245-246)