The Cosmos

Planets & Life
PHYS 214

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Please start all class related emails with "214:"

Today's Lecture

- Evolution and lifetimes of stars

- Suggestions for additional reading (not compulsory!)
- Prof. Richard Pogge's Astronomy 162 notes:
  - http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit2/structure.html

Formation & evolution of stars

- Last time we considered the stellar properties in detail: including **structure**, what we know about it, and how **nuclear fusion** powers stars

- Let’s now look at the formation of stars and their evolution and death

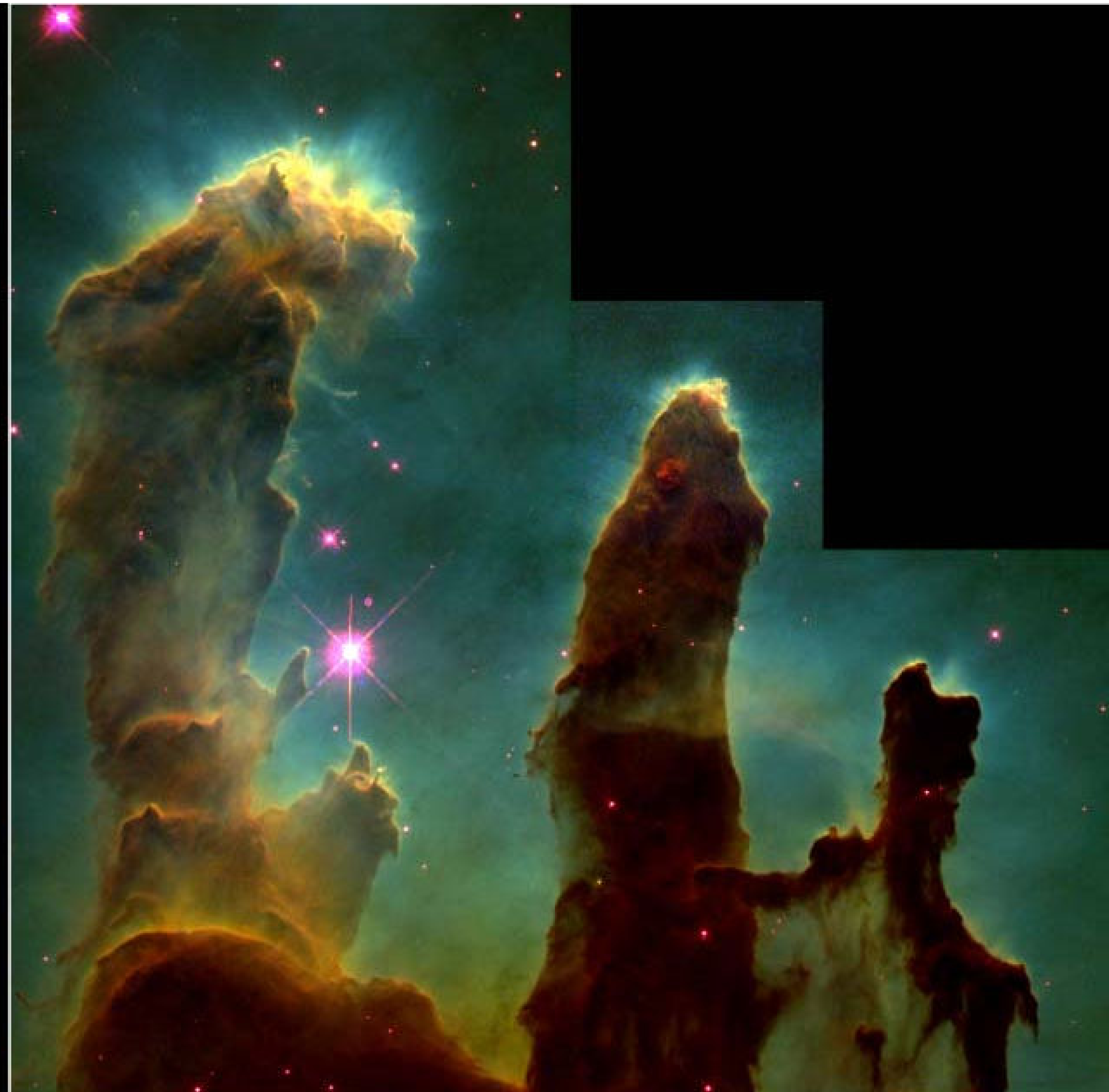
- Our goal is to see which kinds of stars will be most suitable for having (intelligent) life, and also to see how star deaths **create elements** that are used to make **new stars and planets** ...

The Interstellar Medium

- The space between stars is filled by extremely low density gas called the Interstellar Medium (ISM)
  - Density still varies by many orders of magnitude, but a rough average is about 1×10^{-24} g cm^{-3}!
  - This is about 1/10000th of the very best laboratory vacuum ever achieved on Earth!
- The distribution is quite non-uniform and they are regions (clouds) of higher density embedded within the ISM
- The higher density regions begin contraction under gravitational collapse and are the sites of star formation
- We see these areas as nebulae

Formation of stars

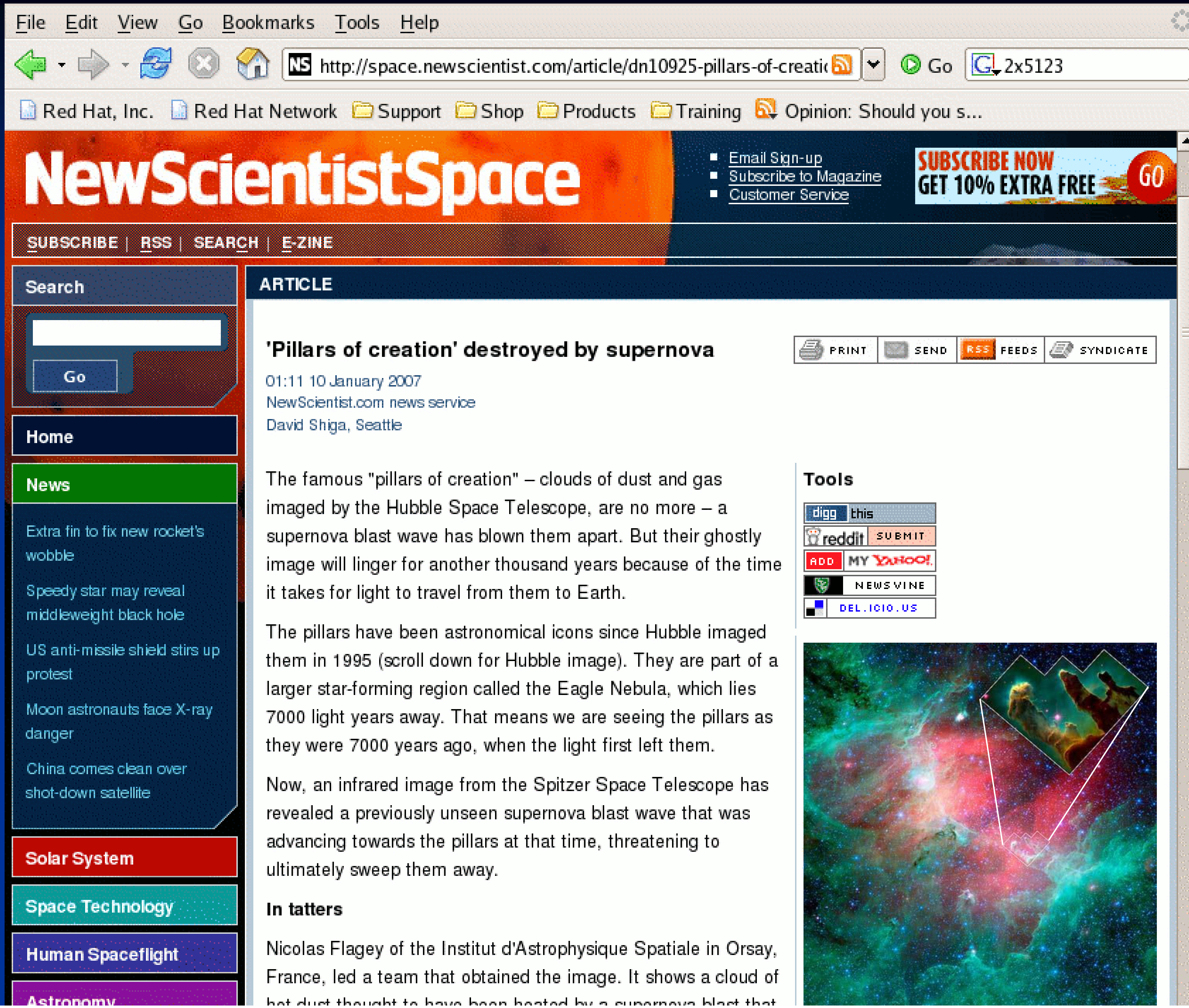
- Stars form through a gravitational collapse process similar to galaxies, but on a much smaller in scale
- Many of the tiny "fingers" of gas projecting out harbour forming stars
- Stars also usually ***form in groups*** within the nebulae



Gaseous Pillars · M16 HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995

J. Hester and P. Scowen (AZ State Univ.), NASA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Speedy star may reveal middleweight black hole
US anti-missile shield stirs up protest
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'Pillars of creation' destroyed by supernova
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01:11 10 January 2007
NewScientist.com news service
David Shiga, Seattle
The famous "pillars of creation" – clouds of dust and gas imaged by the Hubble Space Telescope, are no more – a supernova blast wave has blown them apart. But their ghostly image will linger for another thousand years because of the time it takes for light to travel from them to Earth.
The pillars have been astronomical icons since Hubble imaged them in 1995 (scroll down for Hubble image). They are part of a larger star-forming region called the Eagle Nebula, which lies 7000 light years away. That means we are seeing the pillars as they were 7000 years ago, when the light first left them.
Now, an infrared image from the Spitzer Space Telescope has revealed a previously unseen supernova blast wave that was advancing towards the pillars at that time, threatening to ultimately sweep them away.
In tatters
Nicolas Flagey of the Institut d'Astrophysique Spatiale in Orsay, France, led a team that obtained the image. It shows a cloud of
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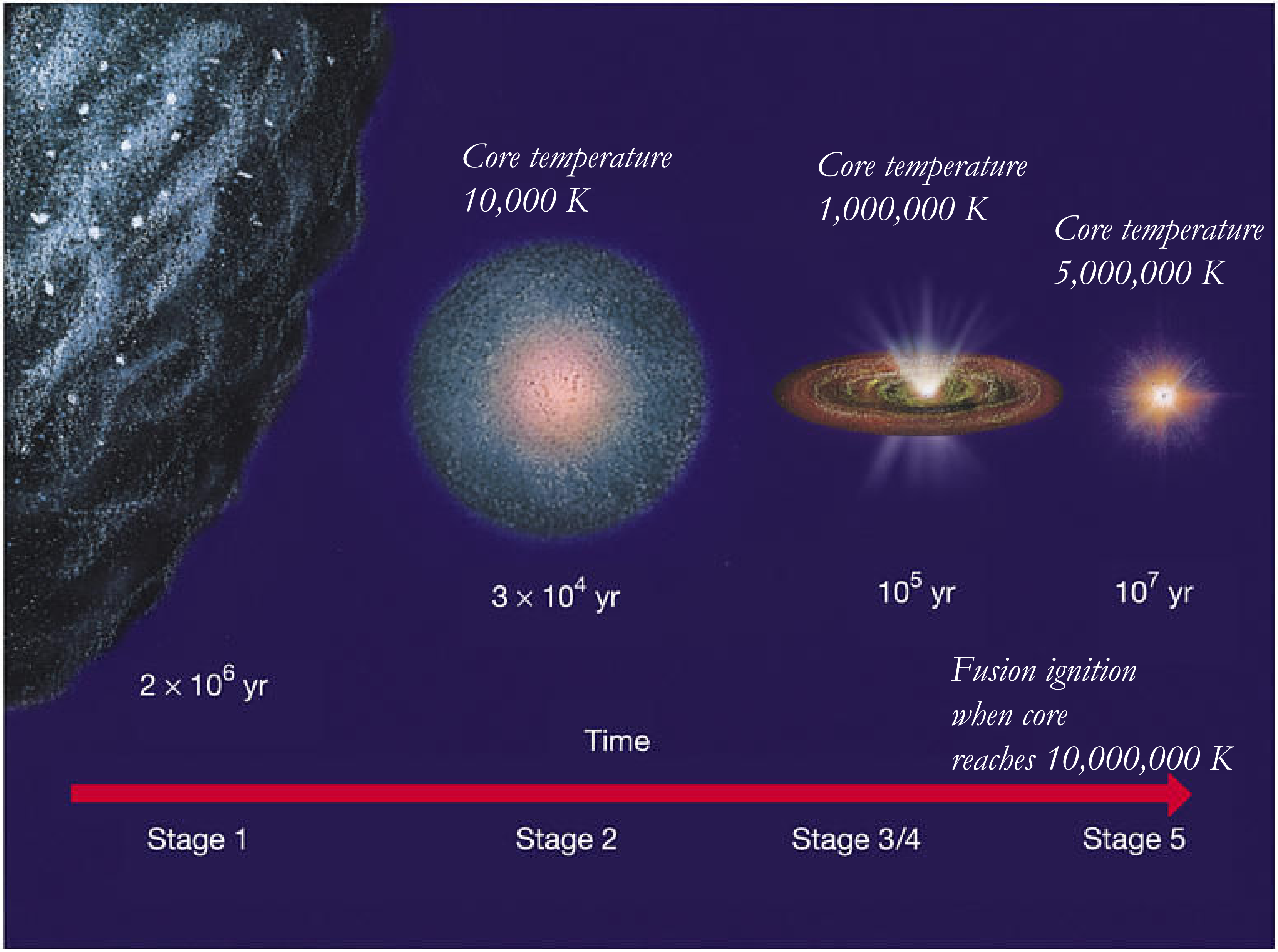
Stellar Birth



Stellar lifetimes

- All stars of same mass and luminosity have about same **lifetime**
  - “Lifetime” refers to time spent burning H to He which is ~90% of a star's life

- But what about stars of ***different mass***?

- The **lifetime** of a star, *t*, is proportional to Mass/Luminosity,

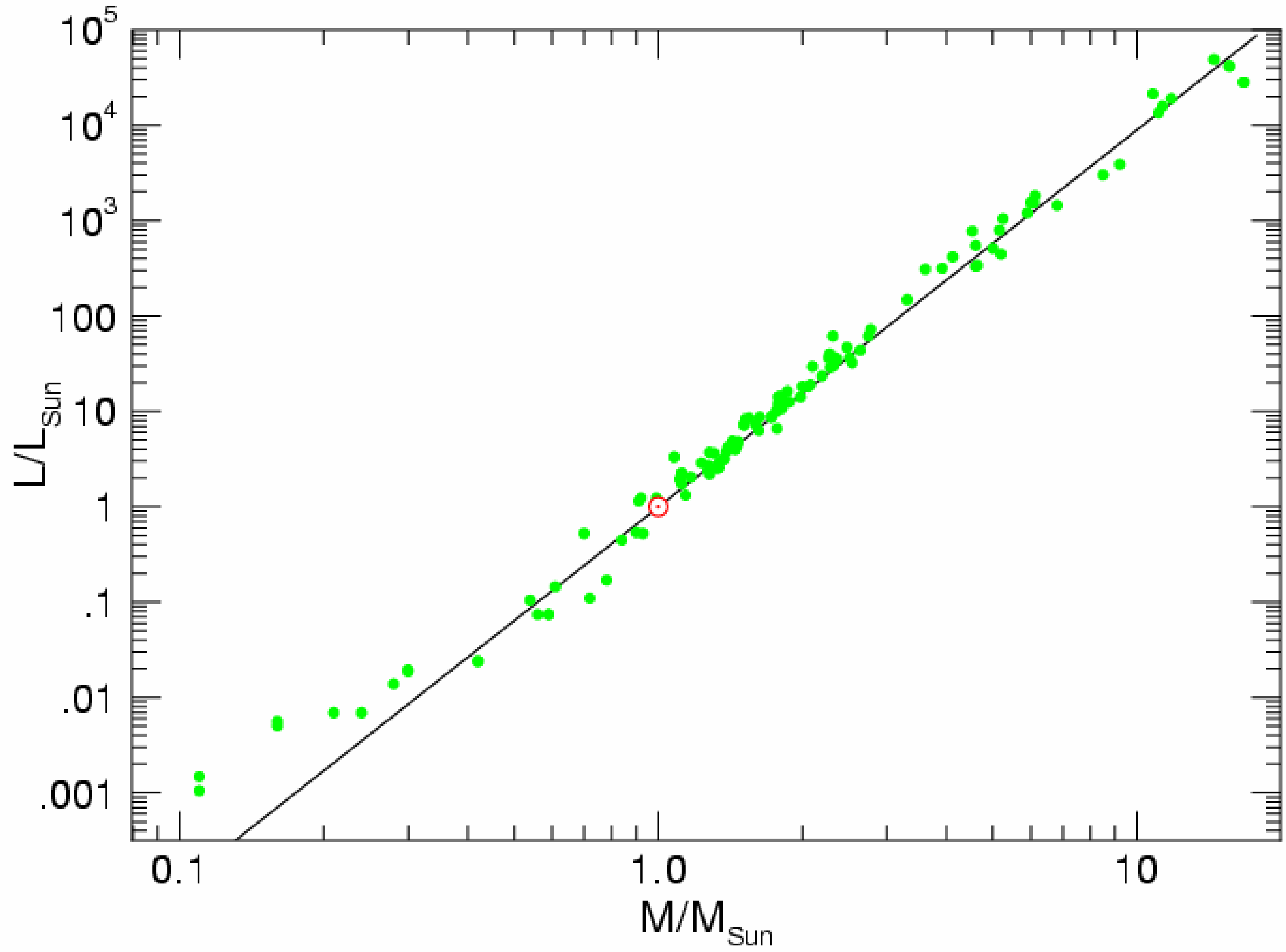
$$t \propto M/L$$

  - Remember mass corresponds to energy, so if luminosity is the energy consumption per unit time (power) then M/L has units of time

- **Luminosity** depends on ***core temperature*** (hotter stars fuse H faster). Core temp. in turn is set by **hydrostatic equilibrium:** *more massive stars have to have* ***higher temperatures*** to create more pressure to support their greater mass against gravity

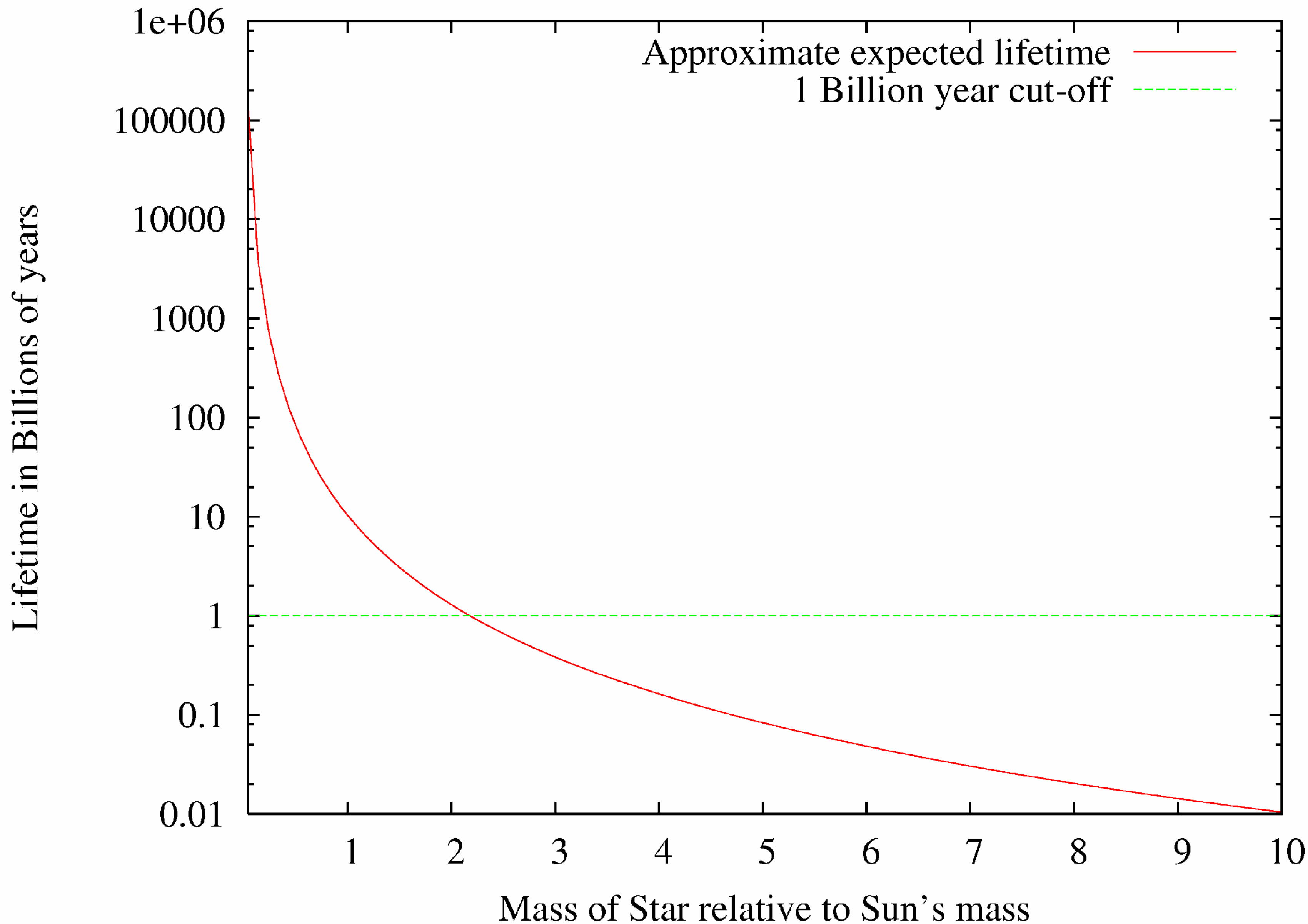
Mass-Luminosity relationship

$L \propto M^n$, where n = 3.5 - 4



Stellar lifetimes as a function of mass

- **Lifetime** $\propto \dfrac{M}{L} = \dfrac{M}{M^4} = M^{-3}$ so lifetime goes as the inverse cube of mass
- ***More massive stars have much shorter lifetimes***
  - A star twice as massive as the Sun will only live 1/8th as long (~1.3 billion years)
- Some good news for life though: there are many more low-mass stars than high-mass stars
- If we assume (very optimistically) that intelligent life needs a billion years to evolve from the formation of a planet then we need to look for stars that live longer than this
  - *Thus focus on stars no more than 1.5-2 times the mass of the Sun, to allow enough time to evolve intelligent life*
- Another question to ponder: *Is there a minimum stellar mass needed to support life?*



Approximate expected lifetime
1 Billion year cut-off
Lifetime in Billions of years
1e+06
100000
10000
1000
100
10
1
0.1
0.01
1
2
3
4
5
6
7
8
9
10
Mass of Star relative to Sun’s mass

Understanding stellar evolution

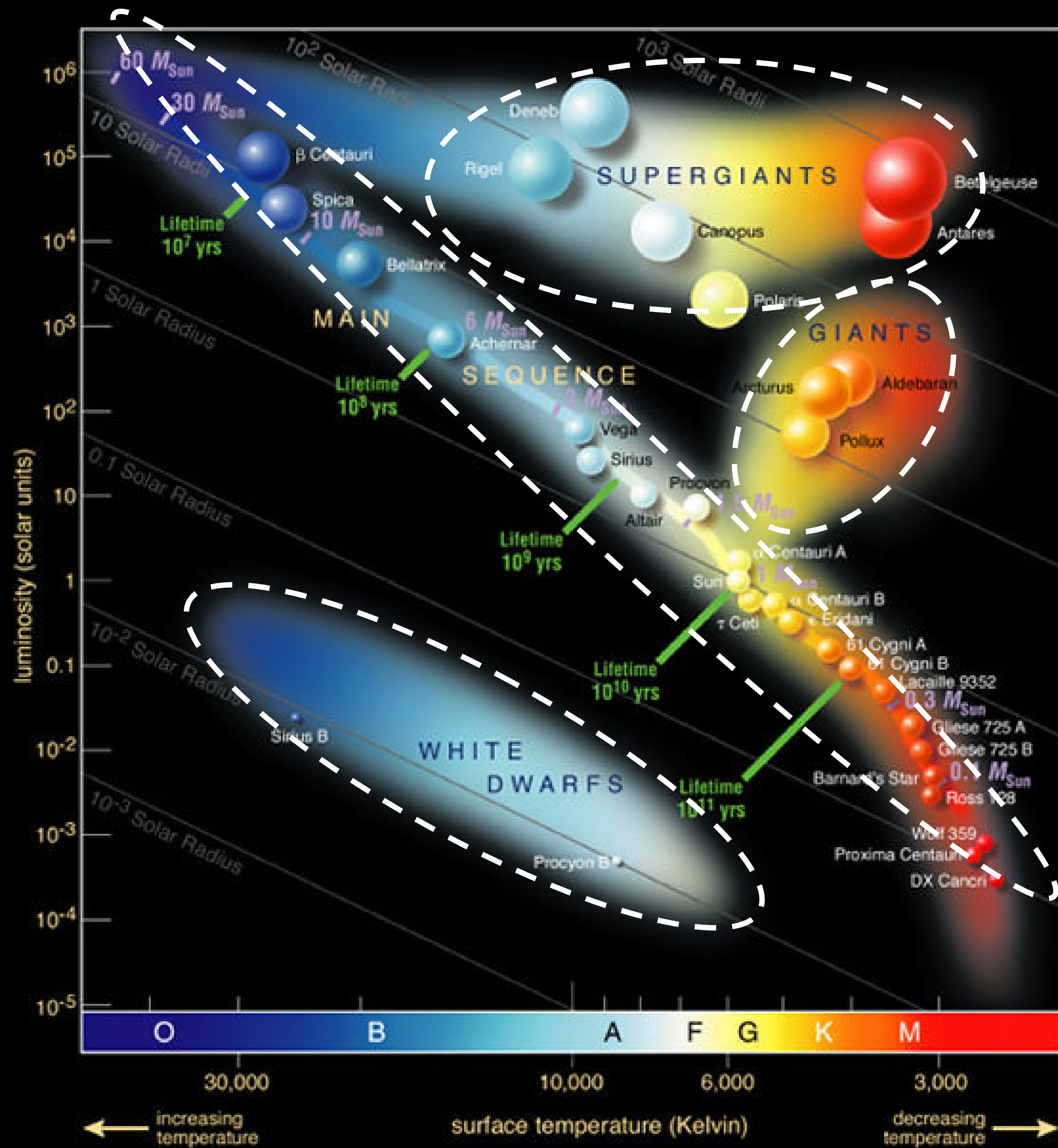
- The Stefan-Boltzman law tells us that
  - $E=\sigma T^4$, where E is the luminosity *per square meter*, T is the temperature in K, σ is the Stefan-Boltzman constant=5.67×10^{-8} Watts m^{-2} K^{-4}
- To get the total luminosity of the star, L, we need to multiply E by the surface area ($4\pi R^2$) of a star of radius R:

$$L=4\pi R^2\sigma T^4$$

- What happens if we plot temperature vs luminosity for many different types of stars?

The Hertzsprung-Russell Diagram

- Log L versus Log T
- Note if $L=4\pi R^2\sigma T^4$ then lines of constant R have a slope of -4
- A single star will move through different points on the HR diagram during it's lifetime "an evolutionary track"

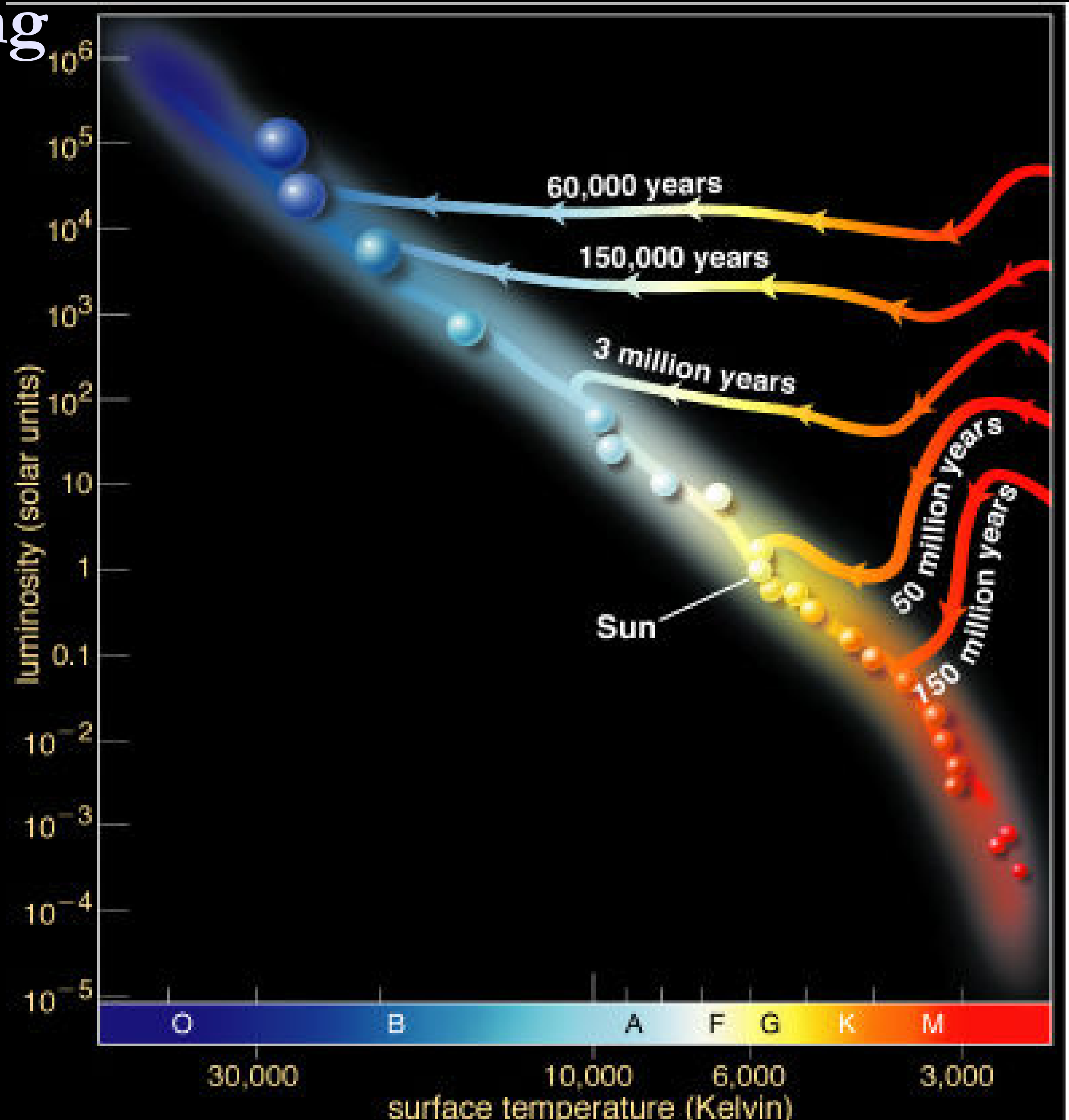


The Main Sequence

- **Most stars** are found on this diagonal swath – the star's mass determines where it sits on this "line"
- This is where stars spend most of their lives (~90%), burning H to He via nuclear fusion
- While stars are forming they are contracting and heating up (T rises, luminosity depends upon a number of issues)
  - Track moves from the right of the main sequence on to it
- When stars die they will move off the main sequence

Protostars entering the main sequence

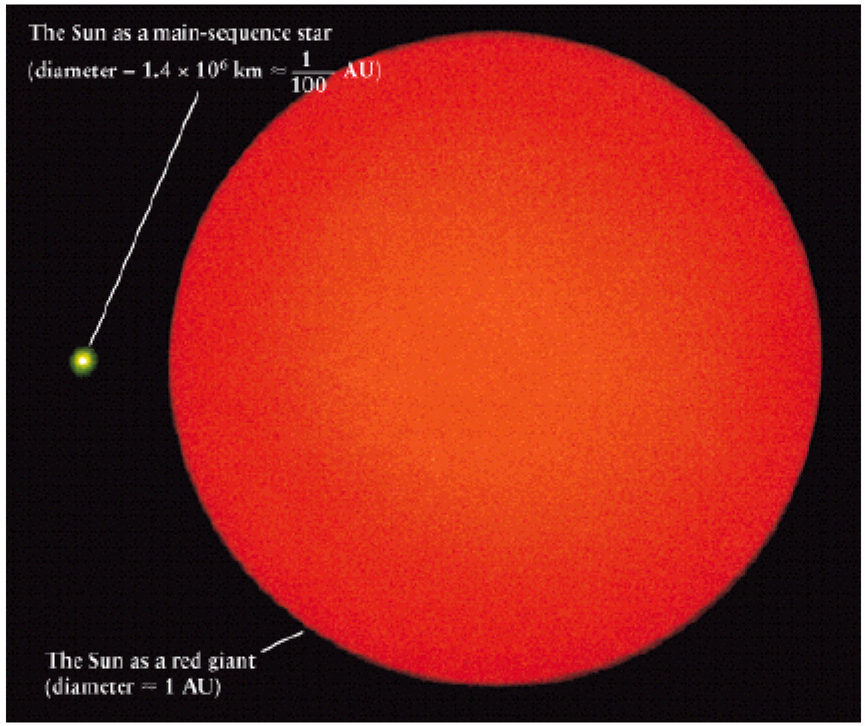
- Times give an indication of how long it takes the star to form



Giants and Supergiants

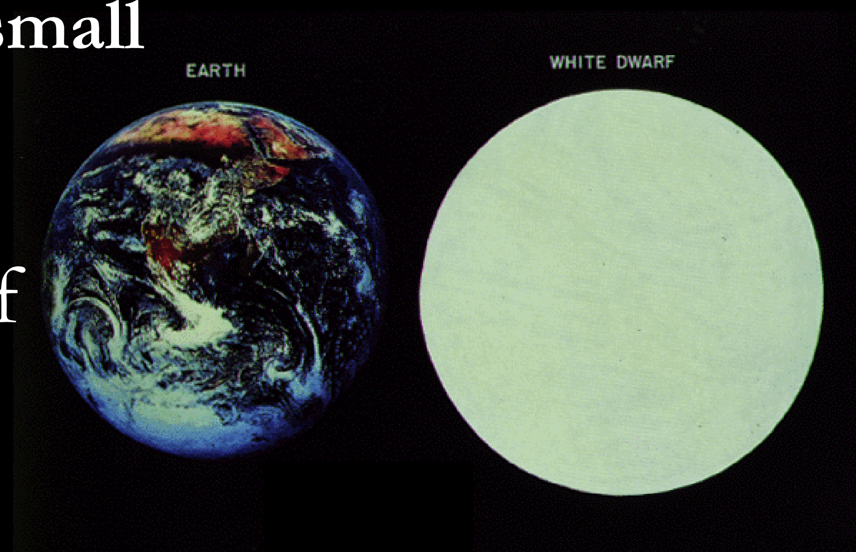
- These are found **above** the main-sequence
- Many stars (depends on their mass) end up here after they leave the main-sequence
- Their temperatures are not that high (2000—6000K) but they are very **luminous**
  - by Stefan-Boltzmann law they must be **very large** (big surface area)
  - Outer parts of the Sun’s atmosphere will engulf Earth and Mars when it becomes a red supergiant!

Sun Today and at Red Giant Phase



White Dwarfs

- These are found **below** the main sequence & are the end point of stellar evolution for many stars
- They have relatively **high** temperatures but **low** luminosity
  - Thus, they must be **very small**
- After going through its supergiant phase the Sun will become a white dwarf
  - with a size similar to the Earth
  - They are very dense, one teaspoon has a mass of 5 tons!



Evolution of stars on the main sequence

- Stars spend ~90% of their lives on the main-sequence, fusing H to He. **What happens when most of the H is used up?**

- **Subgiant Phase:** **temperature not high enough** to fuse He (yet), so energy generation falls. Fusion of H continues in a **shell** at the edge of the core, where temp is high enough

- **Red Giant Phase:** core cools and pressure drops, and thus contracts under gravity and heats up. H-burning shell **increases in luminosity** and expands. **Expansion** causes the surface temperature to **decrease,** while **luminosity has increased**.

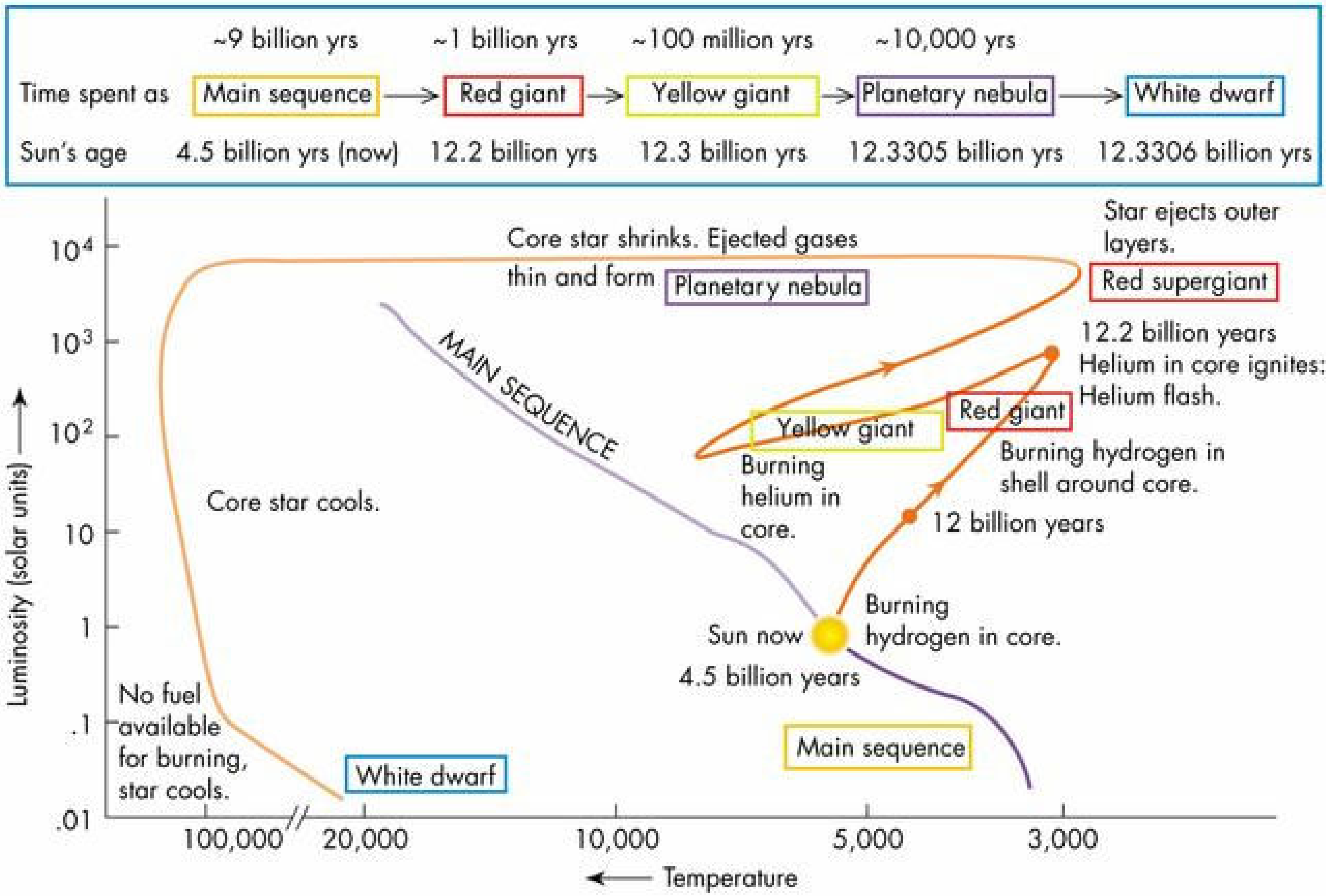
Evolution of the Sun

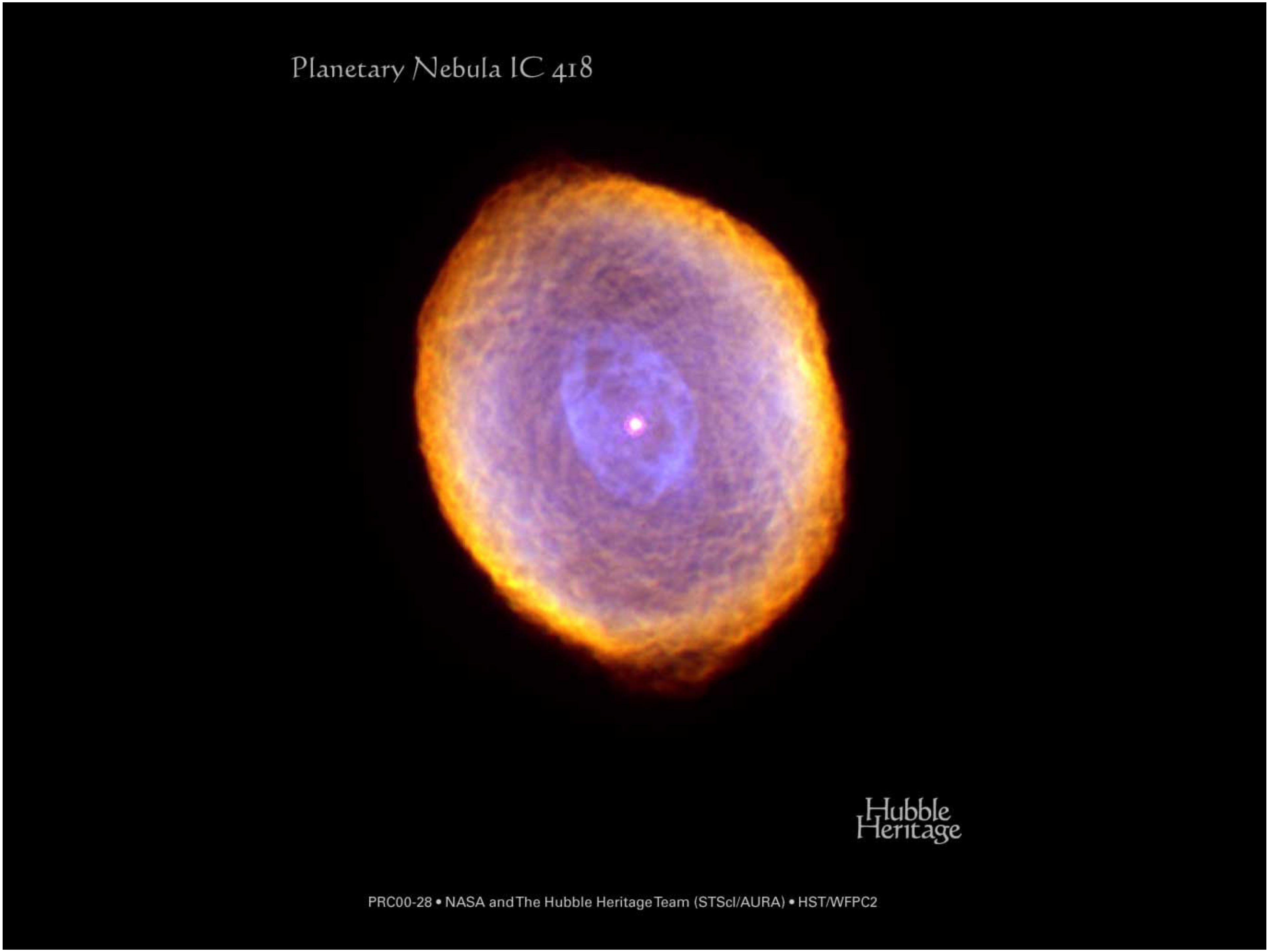
- **Helium Flash:** eventually core temperature is high enough for He to fuse (~100 million degrees) via the **triple-alpha process**: 3 He nuclei fuse to form Carbon 12. This is the **helium flash.**

- **Horizontal Branch:** more energy from He burning in core, so core re-expands and cools, thus luminosity goes down, but surface temperature **increases**.

- **Asymptotic Giant Branch:** eventually He supply dwindles. What happens next depends on how massive the star is. **For star < 1.4 solar masses**, will not get **hot enough** to fuse Carbon: so they have run out of fuel. Similar to when star ran out of H: get He shell burning, star **increases luminosity and expands** until it is a **Red Supergiant.**

Evolution on the HR diagram




Planetary Nebula IC 418
Hubble Heritage
PRC00-28 • NASA and The Hubble Heritage Team (STScI/AURA) • HST/WFPC2

Evolution of more massive stars

- Stars **more massive than 4-5 times the Sun**
- Similar to Sun-like stars until the AGB phase (when He supply runs out)
- At that point, more massive stars will be hot enough in their cores to fuse Carbon + He to form Oxygen, and Carbon with Carbon to make Magnesium.
- Similar reactions take place to make even heavier elements, but these reactions generate **less and less energy**, so star runs out of energy more quickly in each phase and lifetime is shorter

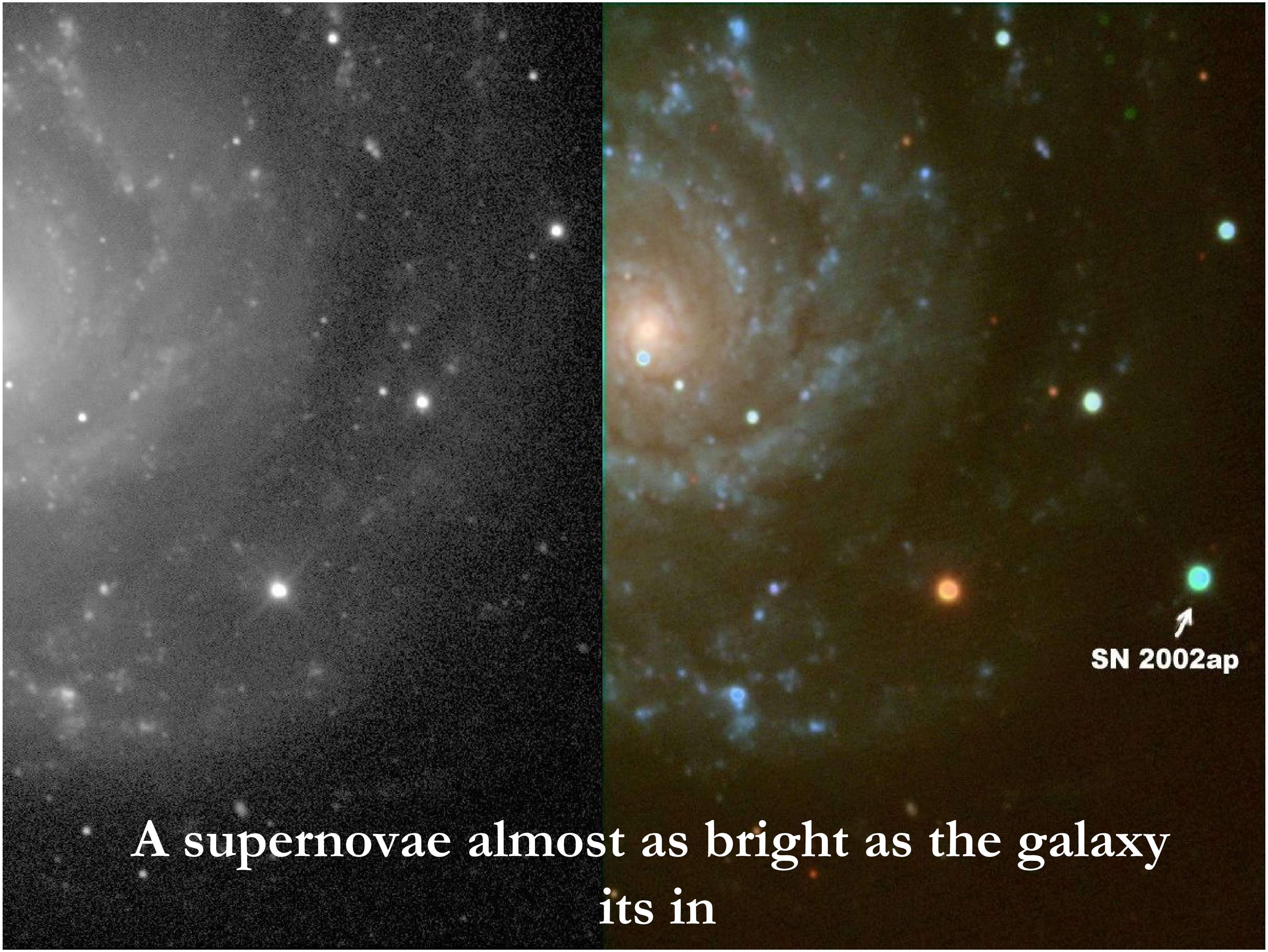
Supernovae

- The fusion cycle **ends** once Iron is produced in the core. You can't get energy by fusing iron, in fact it **takes energy** to do this.
- Star suddenly has ***no source of energy*** ... and can't support itself against **gravity**
- It collapses **very quickly** (less than one sec!), but the energy gained from the collapse fuses heavier and heavier elements, but consumes more and more energy
- At the very highest densities protons and electrons combine to form **neutrons** and **neutrinos**. Core quickly becomes a very stiff ***neutron star*** (about the size of a small town!)
- The core then **rebounds** (bounces) outwards and it may be destroyed (depends on mass)

One teaspoon of neutron star has a mass of 10 million tons

Fate of the core

- The neutron star that is left (if it isn't destroyed in the supernovae) will be spinning
  - The spinning produces regular pulses of radiowaves we can detect – ***a pulsar***
- If the neutron star has a mass greater than 3.2 solar masses it will continue to collapse and form a ***black hole***


SN 2002ap
A supernovae almost as bright as the galaxy its in

Stars & Life: Pros

- Planets associated with stars may **evolve life.** Stars also provide **energy for life.**
- Supernovae provide
  - **enrichment of the ISM**
  - emit **cosmic rays** -- mutation source.
- **Neutron stars** (pulsars) may serve as galactic lighthouses, i.e. cosmic reference points in the context of the SETI.

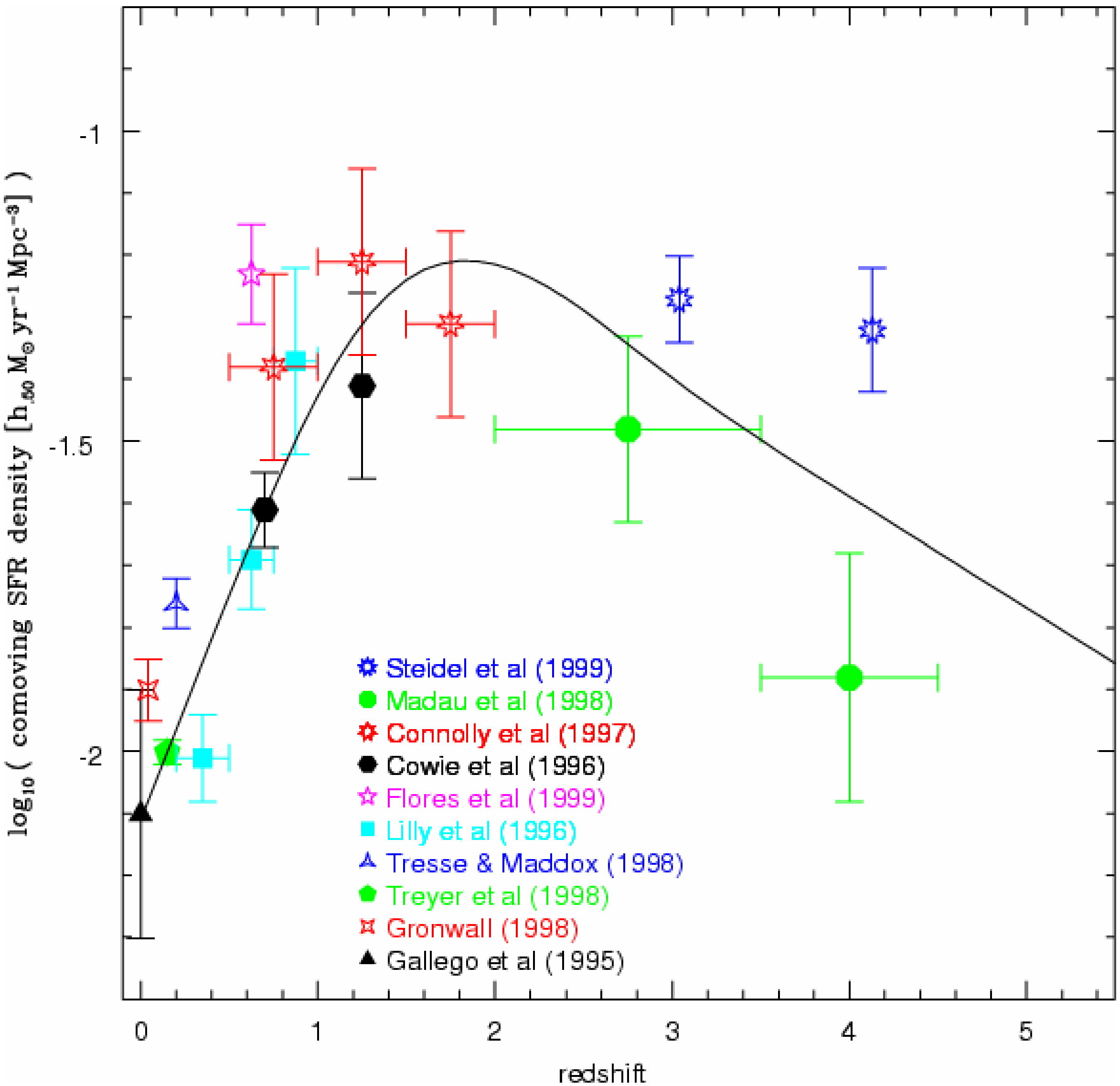
Stars & life: Cons

- **Multiple star systems** (e.g. binaries) are common, and it may be hard to evolve life in these systems
- **All** stars will evolve and become **unstable**. Even stars like the Sun will become red giants, engulfing inner planets, and generally making life **"difficult"** throughout the solar system
- **Supernovae** also destroy life on nearby planets

R – rate of formation of stars

- We can measure this number in a variety of ways, but all of them look for atomic emission associated with new stars
  - Depending upon the flux of the emission we associate either a higher or lower star formation rate
- We can then average the emission over an entire galaxy to calculate the average star formation rate
- Estimates suggest for the Milky Way (now) $R \sim 2$ to 4 solar masses per year, or around seven stars on average
- However, it was much higher in the past, and a reasonable average estimate is probably close to 20 solar masses per year

Evolution of cosmic star formation



- R was much higher in the past than it is now

Summary of lecture 9

- The HR diagram allows us to define the evolution of stars in terms of tracks on a luminosity/temperature diagram’
- Stars heavier than 2 solar masses don’t live long enough for intelligent life to evolve
- Even stars like the Sun are destined to expand through a supergiant phase which will eventually make the Earth uninhabitable
- Supernovae are responsible for the generation of elements heavier than iron and enrich the interstellar medium making the formation of terrestrial planets, and life, possible

Next lecture

- Habitable zones (p 44-48)