

# Fusion in first few minutes after Big Bang form lightest elements

hydrogen 1 <b>H</b> 1.0079	beryllium 4 <b>Be</b> 9.0122											boron 5 <b>B</b> 10.811	carbon 6 <b>C</b> 12.011	nitrogen 7 <b>N</b> 14.007	oxygen 8 <b>O</b> 15.999	fluorine 9 <b>F</b> 18.998	helium 2 <b>He</b> 4.0026																																														
lithium 3 <b>Li</b> 6.941	sodium 11 <b>Na</b> 22.990	potassium 19 <b>K</b> 39.098	rubidium 37 <b>Rb</b> 85.468	caesium 55 <b>Cs</b> 132.91	francium 87 <b>Fr</b> [223]	calcium 20 <b>Ca</b> 40.078	strontium 38 <b>Sr</b> 87.62	barium 56 <b>Ba</b> 137.33	radium 88 <b>Ra</b> [226]	scandium 21 <b>Sc</b> 44.956	yttrium 39 <b>Y</b> 88.906	lanthanum 57 <b>La</b> 138.91	titanium 22 <b>Ti</b> 47.867	zirconium 40 <b>Zr</b> 91.224	hafnium 72 <b>Hf</b> 178.49	rutherfordium 104 <b>Rf</b> [261]	vanadium 23 <b>V</b> 50.942	niobium 41 <b>Nb</b> 92.906	tantalum 73 <b>Ta</b> 180.95	dubnium 105 <b>Db</b> [262]	chromium 24 <b>Cr</b> 51.996	molybdenum 42 <b>Mo</b> 95.94	tungsten 74 <b>W</b> 183.84	seaborgium 106 <b>Sg</b> [266]	manganese 25 <b>Mn</b> 54.938	technetium 43 <b>Tc</b> [98]	rhenium 75 <b>Re</b> 186.21	bohrium 107 <b>Bh</b> [264]	iron 26 <b>Fe</b> 55.845	ruthenium 44 <b>Ru</b> 101.07	osmium 76 <b>Os</b> 190.23	hassium 108 <b>Hs</b> [269]	cobalt 27 <b>Co</b> 58.933	rhodium 45 <b>Rh</b> 102.91	iridium 77 <b>Ir</b> 192.22	meitnerium 109 <b>Mt</b> [268]	nickel 28 <b>Ni</b> 58.693	palladium 46 <b>Pd</b> 106.42	platinum 78 <b>Pt</b> 195.08	unnilium 110 <b>Uun</b> [271]	copper 29 <b>Cu</b> 63.546	silver 47 <b>Ag</b> 107.87	gold 79 <b>Au</b> 196.97	ununium 111 <b>Uuu</b> [272]	zinc 30 <b>Zn</b> 65.39	cadmium 48 <b>Cd</b> 112.41	mercury 80 <b>Hg</b> 200.59	ununium 112 <b>Uub</b> [277]	gallium 31 <b>Ga</b> 69.723	tin 50 <b>Sn</b> 118.71	ununquadium 114 <b>Uuq</b> [289]	germanium 32 <b>Ge</b> 72.61	antimony 51 <b>Sb</b> 121.76	lead 82 <b>Pb</b> 207.2	arsenic 33 <b>As</b> 74.922	tellurium 52 <b>Te</b> 127.60	polonium 84 <b>Po</b> [209]	bromine 35 <b>Br</b> 79.904	iodine 53 <b>I</b> 126.90	astatine 85 <b>At</b> [210]	krypton 36 <b>Kr</b> 83.80	xenon 54 <b>Xe</b> 131.29	radon 86 <b>Rn</b> [222]

\* Lanthanide series

\*\* Actinide series

lanthanum 57 <b>La</b> 138.91	cerium 58 <b>Ce</b> 140.12	praseodymium 59 <b>Pr</b> 140.91	neodymium 60 <b>Nd</b> 144.24	promethium 61 <b>Pm</b> [145]	samarium 62 <b>Sm</b> 150.36	europium 63 <b>Eu</b> 151.96	gadolinium 64 <b>Gd</b> 157.25	terbium 65 <b>Tb</b> 158.93	dysprosium 66 <b>Dy</b> 162.50	holmium 67 <b>Ho</b> 164.93	erbium 68 <b>Er</b> 167.26	thulium 69 <b>Tm</b> 168.93	ytterbium 70 <b>Yb</b> 173.04
actinium 89 <b>Ac</b> [227]	thorium 90 <b>Th</b> 232.04	protactinium 91 <b>Pa</b> 231.04	uranium 92 <b>U</b> 238.03	neptunium 93 <b>Np</b> [237]	plutonium 94 <b>Pu</b> [244]	americium 95 <b>Am</b> [243]	curium 96 <b>Cm</b> [247]	berkelium 97 <b>Bk</b> [247]	californium 98 <b>Cf</b> [251]	einsteinium 99 <b>Es</b> [252]	fermium 100 <b>Fm</b> [257]	mendelevium 101 <b>Md</b> [258]	nobelium 102 <b>No</b> [259]

# Stars build the rest of the elements up to Iron (Fe) through fusion

hydrogen 1 <b>H</b> 1.0079																	helium 2 <b>He</b> 4.0026						
lithium 3 <b>Li</b> 6.941	beryllium 4 <b>Be</b> 9.0122																	boron 5 <b>B</b> 10.811	carbon 6 <b>C</b> 12.011	nitrogen 7 <b>N</b> 14.007	oxygen 8 <b>O</b> 15.999	fluorine 9 <b>F</b> 18.998	neon 10 <b>Ne</b> 20.180
sodium 11 <b>Na</b> 22.990	magnesium 12 <b>Mg</b> 24.305																	aluminum 13 <b>Al</b> 26.982	silicon 14 <b>Si</b> 28.086	phosphorus 15 <b>P</b> 30.974	sulfur 16 <b>S</b> 32.065	chlorine 17 <b>Cl</b> 35.453	argon 18 <b>Ar</b> 39.948
potassium 19 <b>K</b> 39.098	calcium 20 <b>Ca</b> 40.078	scandium 21 <b>Sc</b> 44.956	titanium 22 <b>Ti</b> 47.867	vanadium 23 <b>V</b> 50.942	chromium 24 <b>Cr</b> 51.996	manganese 25 <b>Mn</b> 54.938	<b>Fe</b> 26 55.845	cobalt 27 <b>Co</b> 58.933	nickel 28 <b>Ni</b> 58.693	copper 29 <b>Cu</b> 63.546	zinc 30 <b>Zn</b> 65.39	gallium 31 <b>Ga</b> 69.723	germanium 32 <b>Ge</b> 72.61	arsenic 33 <b>As</b> 74.922	selenium 34 <b>Se</b> 78.96	bromine 35 <b>Br</b> 79.904	krypton 36 <b>Kr</b> 83.80						
rubidium 37 <b>Rb</b> 85.468	strontium 38 <b>Sr</b> 87.62	yttrium 39 <b>Y</b> 88.906	zirconium 40 <b>Zr</b> 91.224	niobium 41 <b>Nb</b> 92.906	molybdenum 42 <b>Mo</b> 95.94	technetium 43 <b>Tc</b> [98]	ruthenium 44 <b>Ru</b> 101.07	rhodium 45 <b>Rh</b> 102.91	palladium 46 <b>Pd</b> 106.42	silver 47 <b>Ag</b> 107.87	cadmium 48 <b>Cd</b> 112.41	indium 49 <b>In</b> 114.82	tin 50 <b>Sn</b> 118.71	antimony 51 <b>Sb</b> 121.76	tellurium 52 <b>Te</b> 127.60	iodine 53 <b>I</b> 126.90	xenon 54 <b>Xe</b> 131.29						
caesium 55 <b>Cs</b> 132.91	barium 56 <b>Ba</b> 137.33	lanthanum 57-70 *	lutetium 71 <b>Lu</b> 174.97	hafnium 72 <b>Hf</b> 178.49	tantalum 73 <b>Ta</b> 180.95	tungsten 74 <b>W</b> 183.84	rhennium 75 <b>Re</b> 186.21	osmium 76 <b>Os</b> 190.23	iridium 77 <b>Ir</b> 192.22	platinum 78 <b>Pt</b> 195.08	gold 79 <b>Au</b> 196.97	mercury 80 <b>Hg</b> 200.59	thallium 81 <b>Tl</b> 204.38	lead 82 <b>Pb</b> 207.2	bismuth 83 <b>Bi</b> 208.98	polonium 84 <b>Po</b> [209]	astatine 85 <b>At</b> [210]	radon 86 <b>Rn</b> [222]					
francium 87 <b>Fr</b> [223]	radium 88 <b>Ra</b> [226]	actinide series 89-102 **	lawrencium 103 <b>Lr</b> [262]	rutherfordium 104 <b>Rf</b> [261]	dubnium 105 <b>Db</b> [262]	seaborgium 106 <b>Sg</b> [266]	bohrium 107 <b>Bh</b> [264]	hassium 108 <b>Hs</b> [269]	meitnerium 109 <b>Mt</b> [268]	ununnium 110 <b>Uun</b> [271]	ununium 111 <b>Uuu</b> [272]	unubium 112 <b>Uub</b> [277]	ununquadium 114 <b>Uuq</b> [289]										

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\*\* Actinide series

The rest of the elements beyond Iron (Fe) are produced in the dying stages of a stars life.

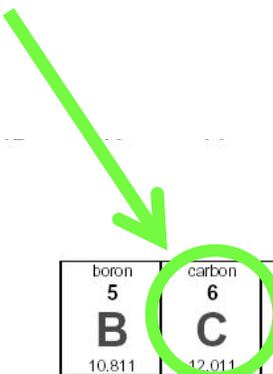
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potassium 19 <b>K</b> 39.098	calcium 20 <b>Ca</b> 40.078	scandium 21 <b>Sc</b> 44.956	titanium 22 <b>Ti</b> 47.867	vanadium 23 <b>V</b> 50.942	chromium 24 <b>Cr</b> 51.996	manganese 25 <b>Mn</b> 54.938	iron 26 <b>Fe</b> 55.845	cobalt 27 <b>Co</b> 58.933	nickel 28 <b>Ni</b> 58.693	copper 29 <b>Cu</b> 63.546	zinc 30 <b>Zn</b> 65.39	gallium 31 <b>Ga</b> 69.723	germanium 32 <b>Ge</b> 72.61	arsenic 33 <b>As</b> 74.922	selenium 34 <b>Se</b> 78.96	bromine 35 <b>Br</b> 79.904	krypton 36 <b>Kr</b> 83.80	
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\*\* Actinide series

# Example : How do we get Carbon ?



hydrogen 1 <b>H</b> 1.0079																	helium 2 <b>He</b> 4.0026	
lithium 3 <b>Li</b> 6.941	beryllium 4 <b>Be</b> 9.0122											boron 5 <b>B</b> 10.811	carbon 6 <b>C</b> 12.011	nitrogen 7 <b>N</b> 14.007	oxygen 8 <b>O</b> 15.999	fluorine 9 <b>F</b> 18.998	neon 10 <b>Ne</b> 20.180	
sodium 11 <b>Na</b> 22.990	magnesium 12 <b>Mg</b> 24.305											aluminium 13 <b>Al</b> 26.982	silicon 14 <b>Si</b> 28.086	phosphorus 15 <b>P</b> 30.974	sulfur 16 <b>S</b> 32.065	chlorine 17 <b>Cl</b> 35.453	argon 18 <b>Ar</b> 39.948	
potassium 19 <b>K</b> 39.098	calcium 20 <b>Ca</b> 40.078	scandium 21 <b>Sc</b> 44.956	titanium 22 <b>Ti</b> 47.867	vanadium 23 <b>V</b> 50.942	chromium 24 <b>Cr</b> 51.996	manganese 25 <b>Mn</b> 54.938	iron 26 <b>Fe</b> 55.845	cobalt 27 <b>Co</b> 58.933	nickel 28 <b>Ni</b> 58.693	copper 29 <b>Cu</b> 63.546	zinc 30 <b>Zn</b> 65.39	gallium 31 <b>Ga</b> 69.723	germanium 32 <b>Ge</b> 72.61	arsenic 33 <b>As</b> 74.922	selenium 34 <b>Se</b> 78.96	bromine 35 <b>Br</b> 79.904	krypton 36 <b>Kr</b> 83.80	
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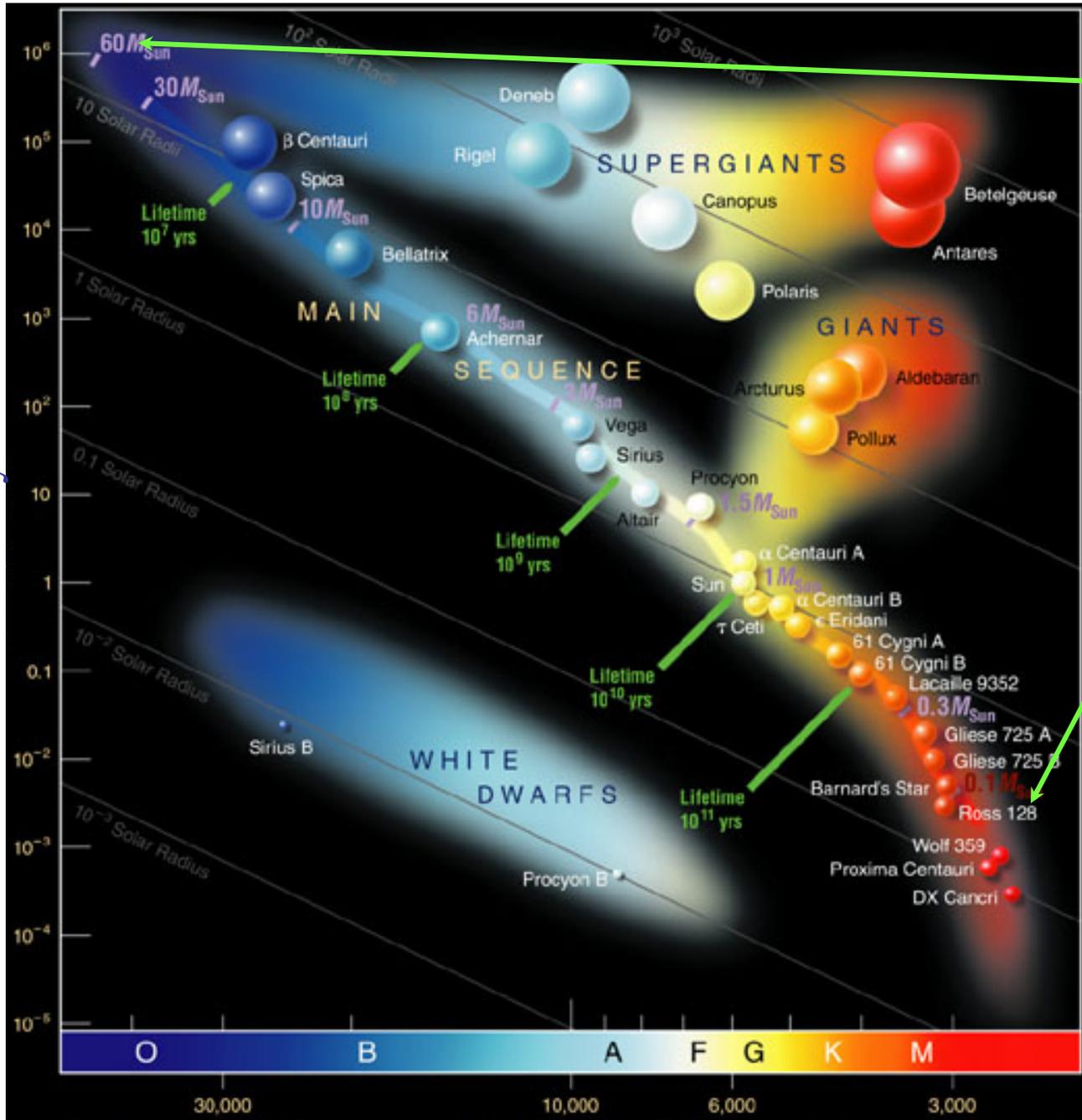
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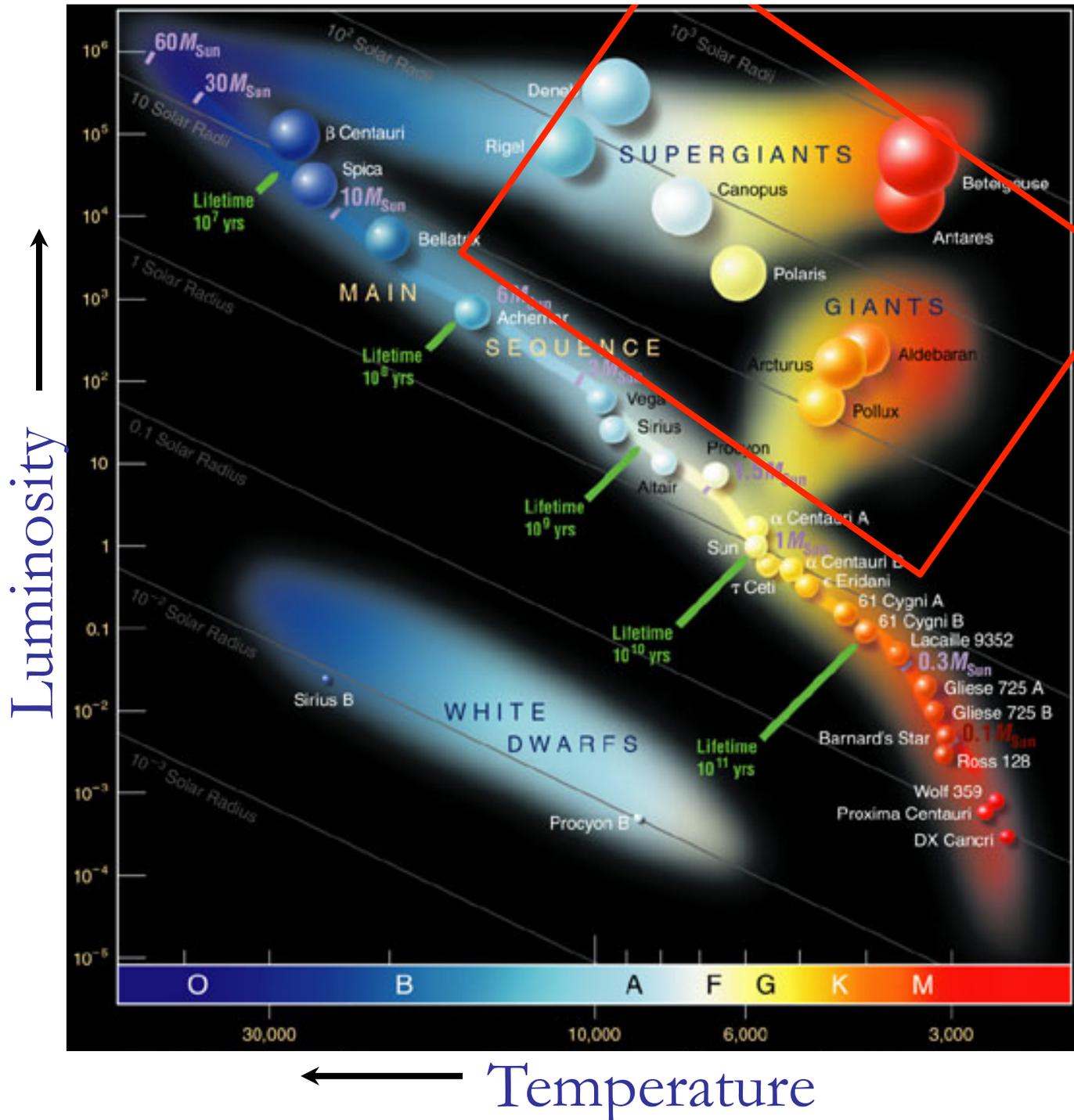
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Luminosity



Temperature

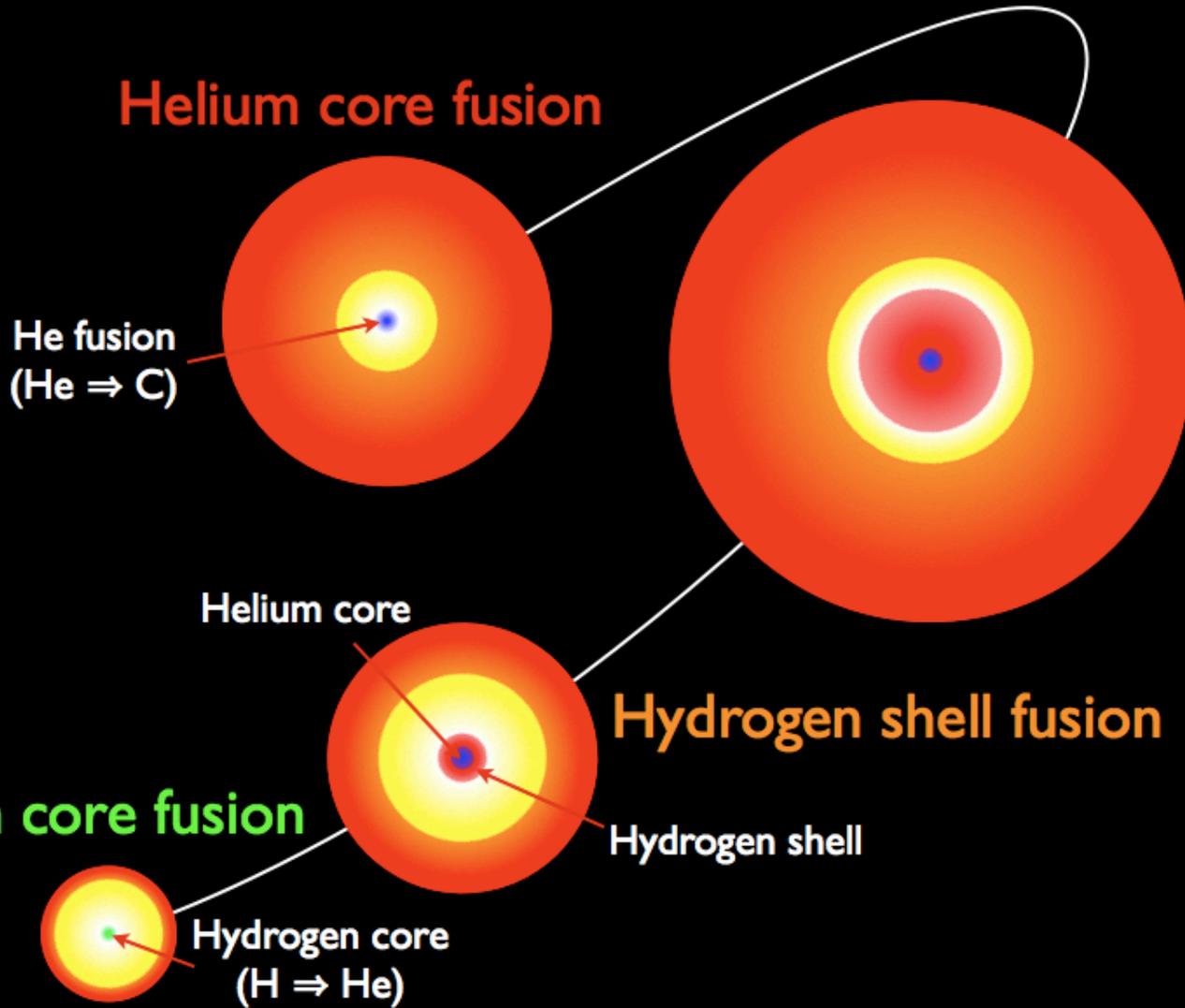
Stars along the main sequence are stably burning H to form He



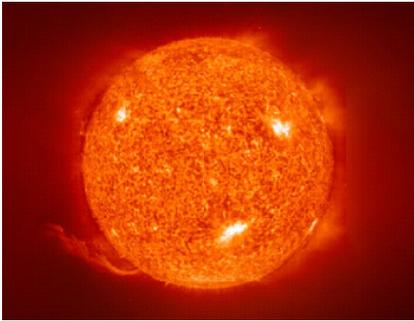
After stars run out of H in their core, they evolve to the red giant phase and, depending on their mass, can burn He, C, O, Si, etc. up to Fe.

# Evolution off Main Sequence (Red Giant Phase)

( sizes not to scale! )



## *Review: Where does Carbon Come From ?*



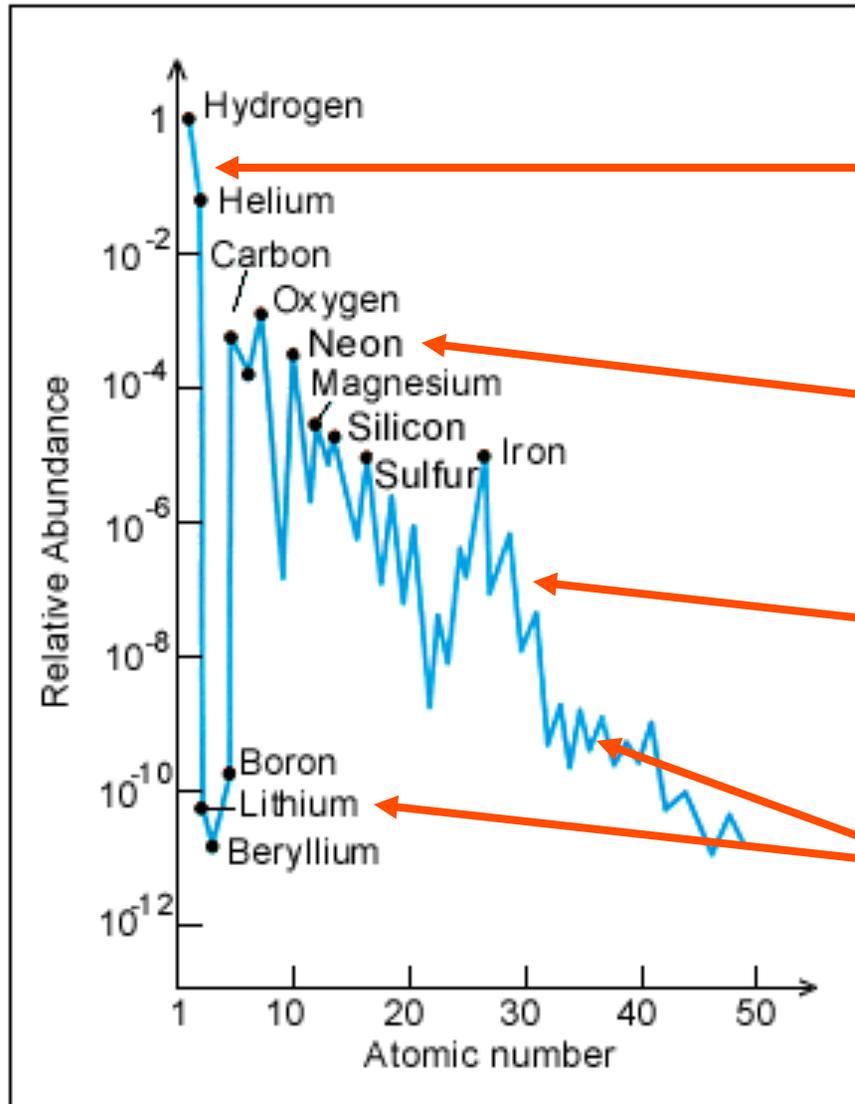
Hydrogen is fused to Helium in a star on the *main sequence*.

Late in the stars life, it runs out of Hydrogen, contracts and becomes hot enough to burn Helium to form Carbon (Red Giant Phase)



Carbon is ejected into space in the planetary nebula phase at the end of the star's life.

# Cosmic Element Abundance



Cosmic chemistry:

H is fundamental and the He is fused in the early hot big bang

Elements from C to Fe fused in moderately massive stars

Elements beyond Fe are mostly fused in supernova blast waves

Sawtooth is He nucleus added, trough due to unstable atoms

***Stars are chemical factories.  
The universe is built for life!***

# *Stellar Properties Summary*

***Luminosity:*** from brightness and distance

**(0.08  $M_{\text{Sun}}$ )**  $10^{-4} L_{\text{Sun}}$  -  $10^6 L_{\text{Sun}}$  **(100  $M_{\text{Sun}}$ )**

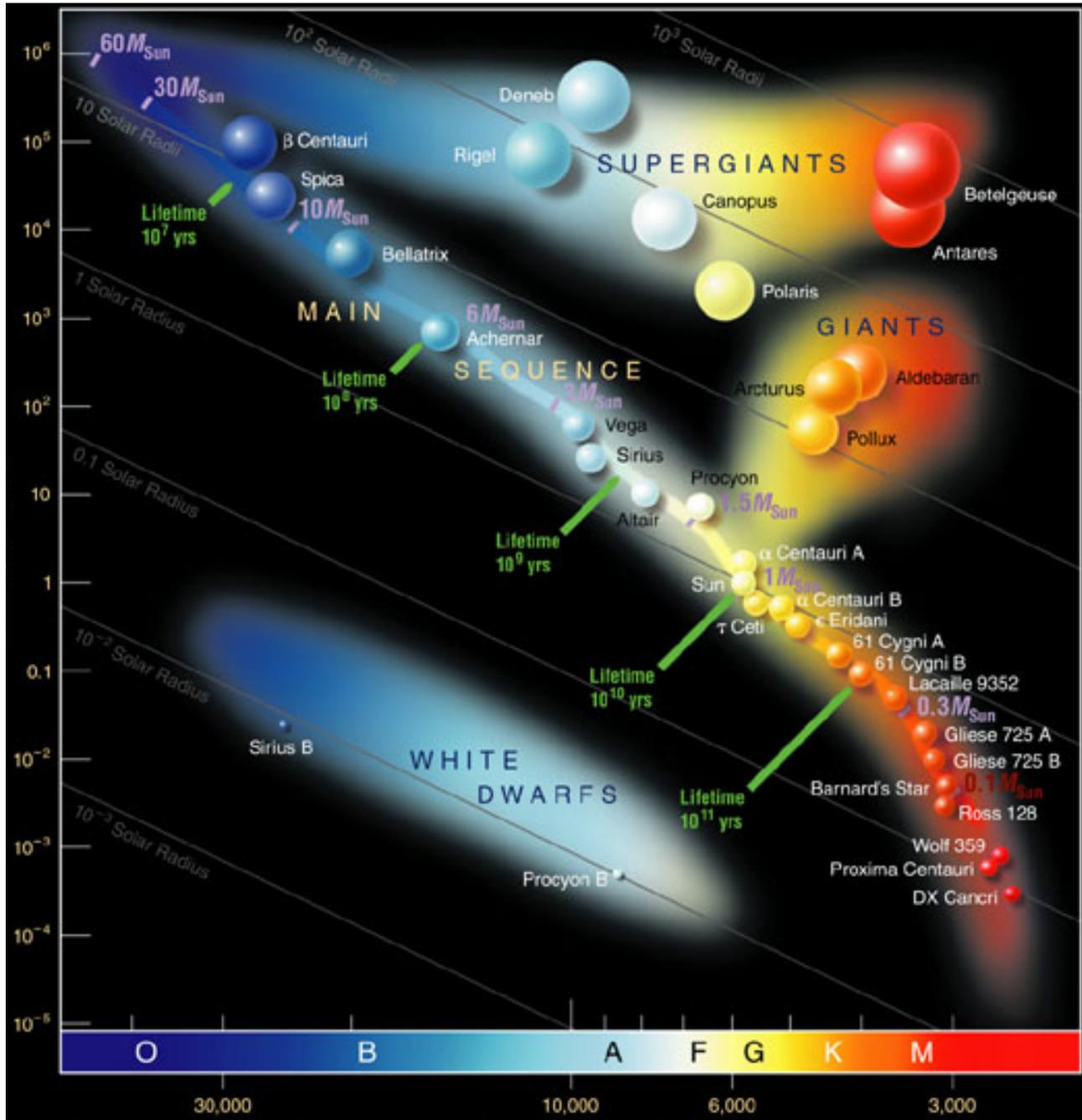
***Temperature:*** from color and spectral type

**(0.08  $M_{\text{Sun}}$ )** 3,000 K - 50,000 K **(100  $M_{\text{Sun}}$ )**

***Mass:*** calculated from period (p) and average separation (a) of a binary-star orbit

0.08  $M_{\text{Sun}}$  - 100  $M_{\text{Sun}}$

Luminosity



Temperature

The H-R diagram is the fundamental plot used to describe how a star evolves. It plots luminosity vs. temperature

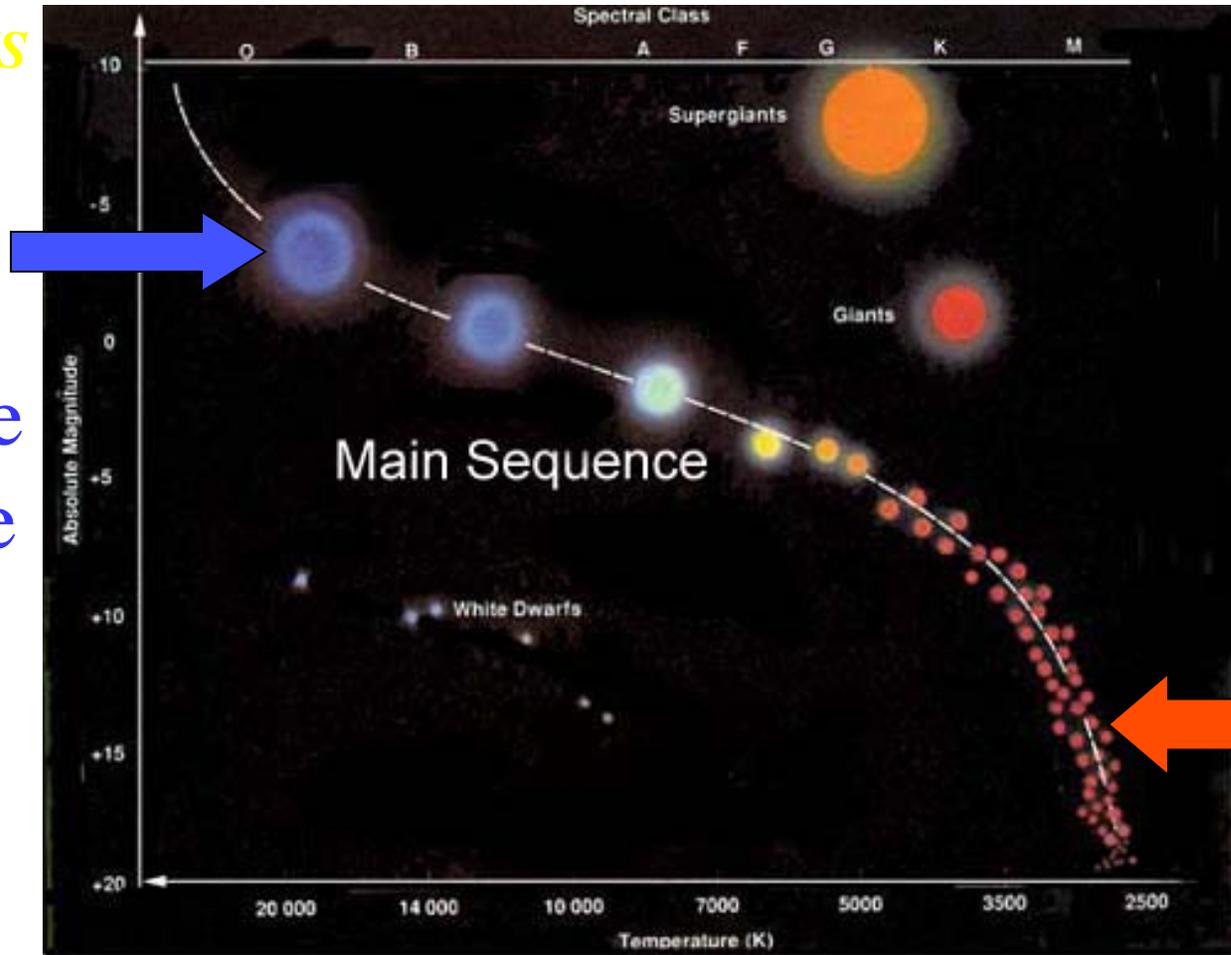
# How Fast Do Different Stars Evolve?

*HOT*

*COOL*

*LUMINOUS*

Blue  
MS  
stars are  
massive



*DIMMER*

Red MS  
stars are  
low  
mass

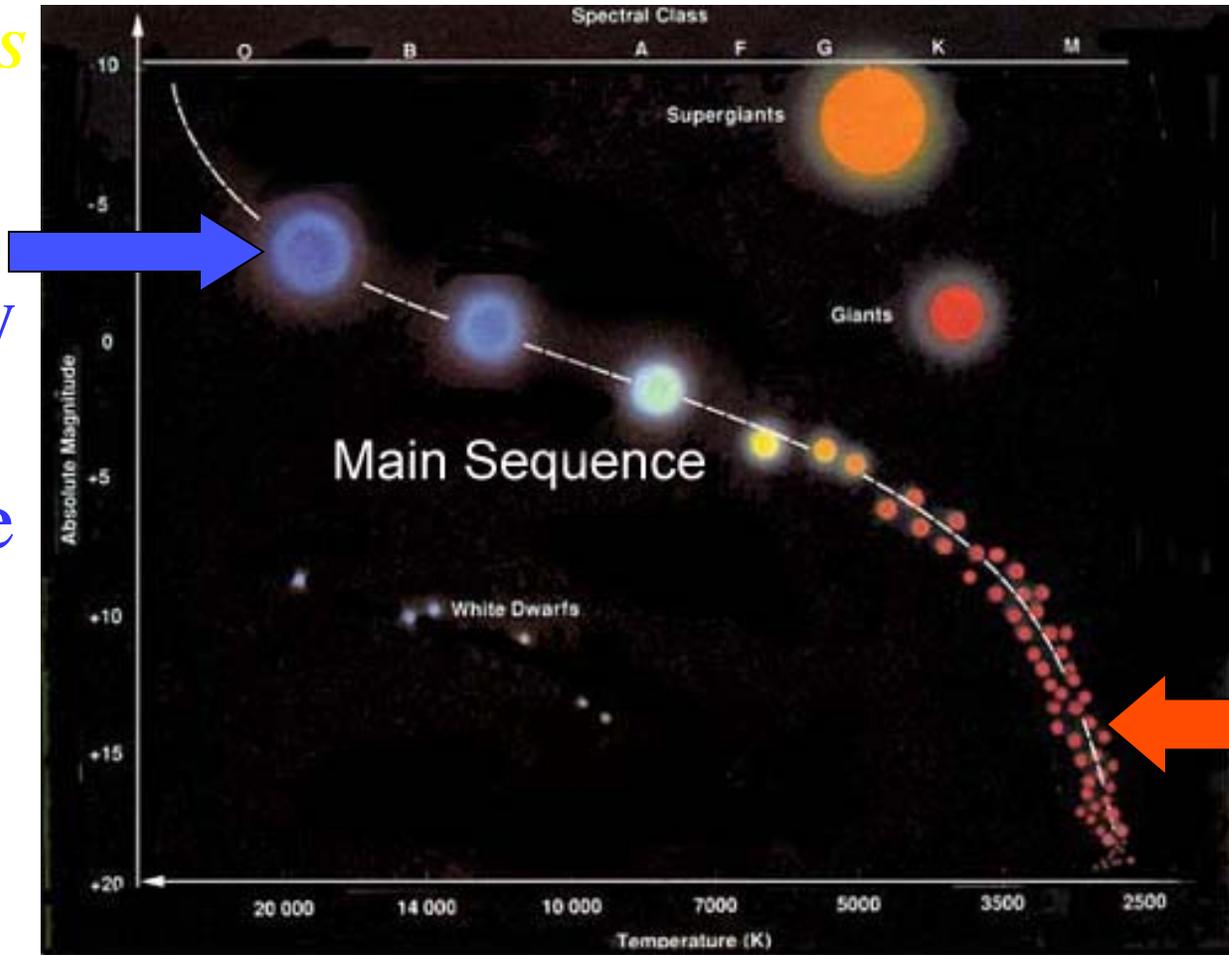
*Most stars are low mass and relatively cool.*

**HOT**

**COOL**

**LUMINOUS**

There are very few massive MS stars

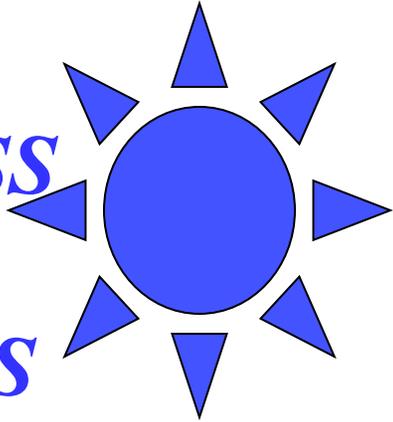


**DIMMER**

There are a lot of low mass MS stars

*Massive stars have the shortest lives.*

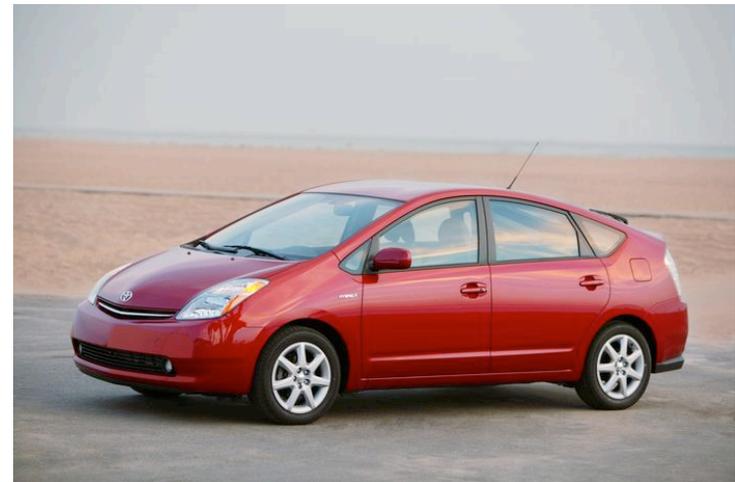
*HIGH MASS  
and  
LUMINOUS*



*LOW MASS  
and  
DIM*



**Like a gas-guzzling car, big fuel tank but burns fuel fast, so the tank of gas does not last long.**



**Like a fuel-efficient car, small fuel tank but burns fuel slowly, so the tank lasts a long time.**

# *Mass & Lifetime*

*Sun's life expectancy:* 10 billion years

Until core hydrogen  
(10% of total) is  
used up

*Life expectancy of  $10 M_{Sun}$  star:*

10 times as much fuel, uses it  $10^4$  times as fast

10 million years  $\sim$  10 billion years  $\times$   $10 / 10^4$

*Life expectancy of  $0.1 M_{Sun}$  star:*

0.1 times as much fuel, uses it 0.01 times as fast

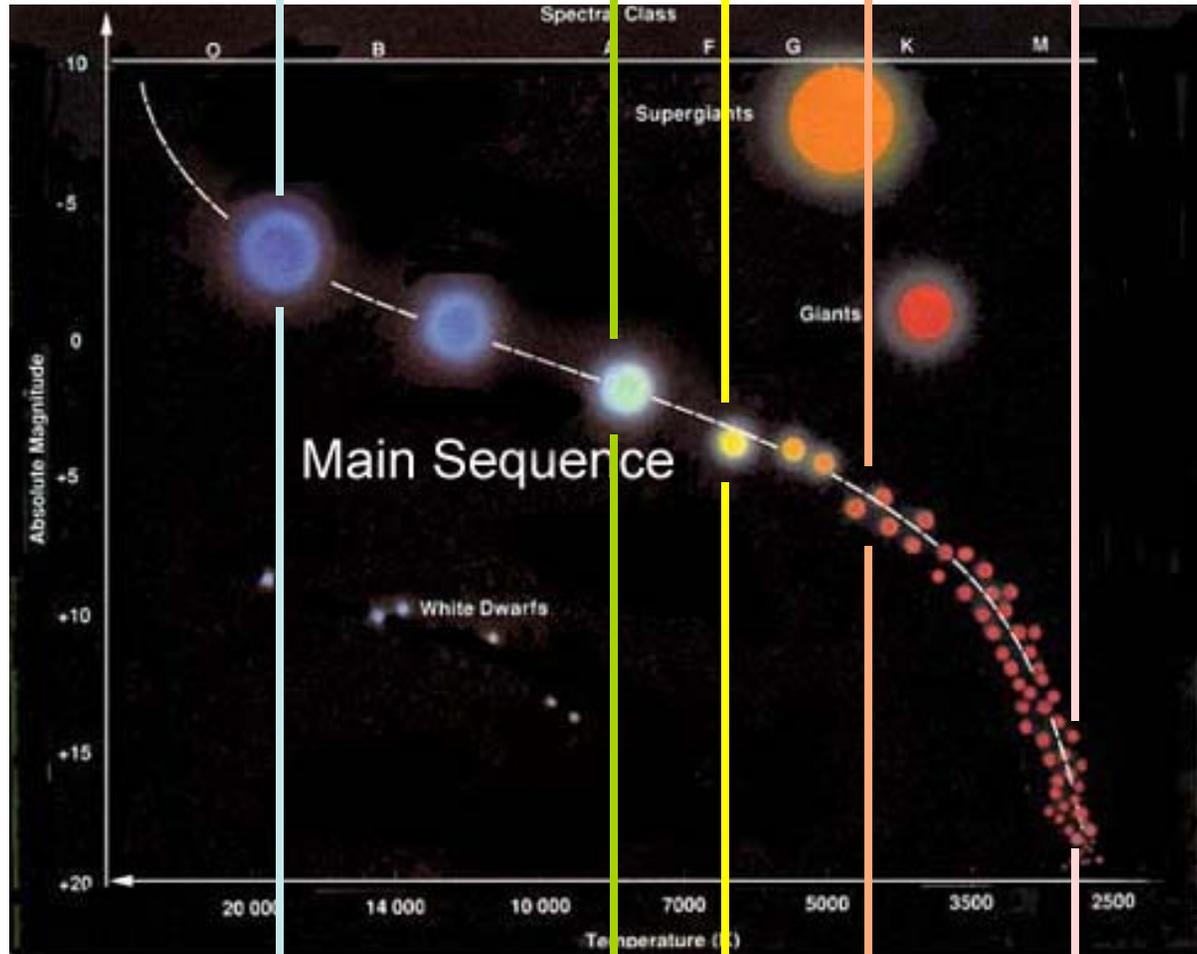
100 billion years  $\sim$  10 billion years  $\times$   $0.1 / 0.01$

*times the mass of the Sun*

**MASS:**

10      2      1      0.5      0.1

**LUMINOUS**



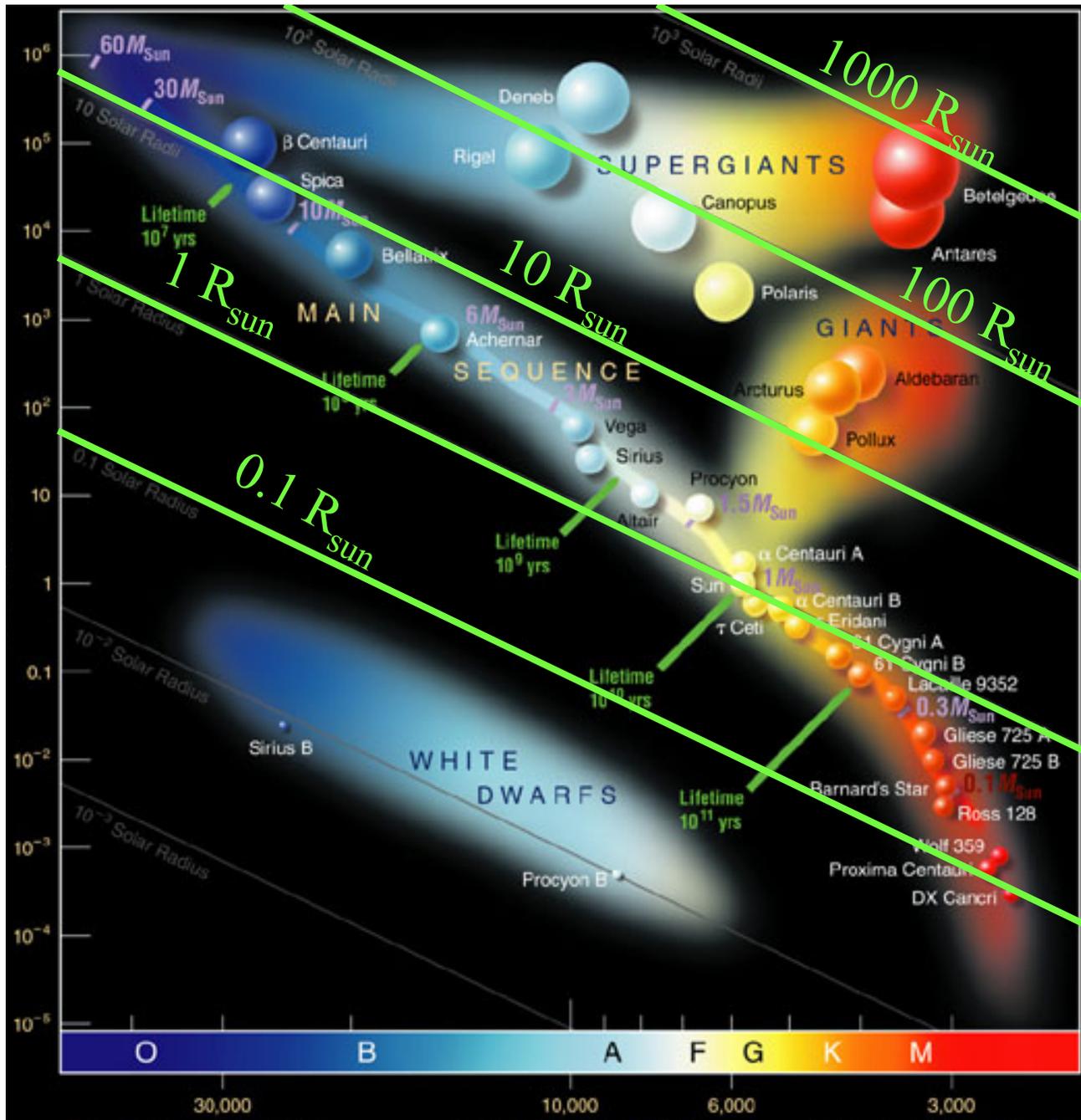
**DIMMER**

**LIFETIME:**

$10^7$        $10^9$        $10^{10}$        $10^{11}$        $10^{12}$

*in years*

Luminosity



Temperature

Stars in the upper right are bigger than stars in the lower left of the diagram

# Star Comparison

High Mass:

High Luminosity

Short-Lived

Large Radius

Blue

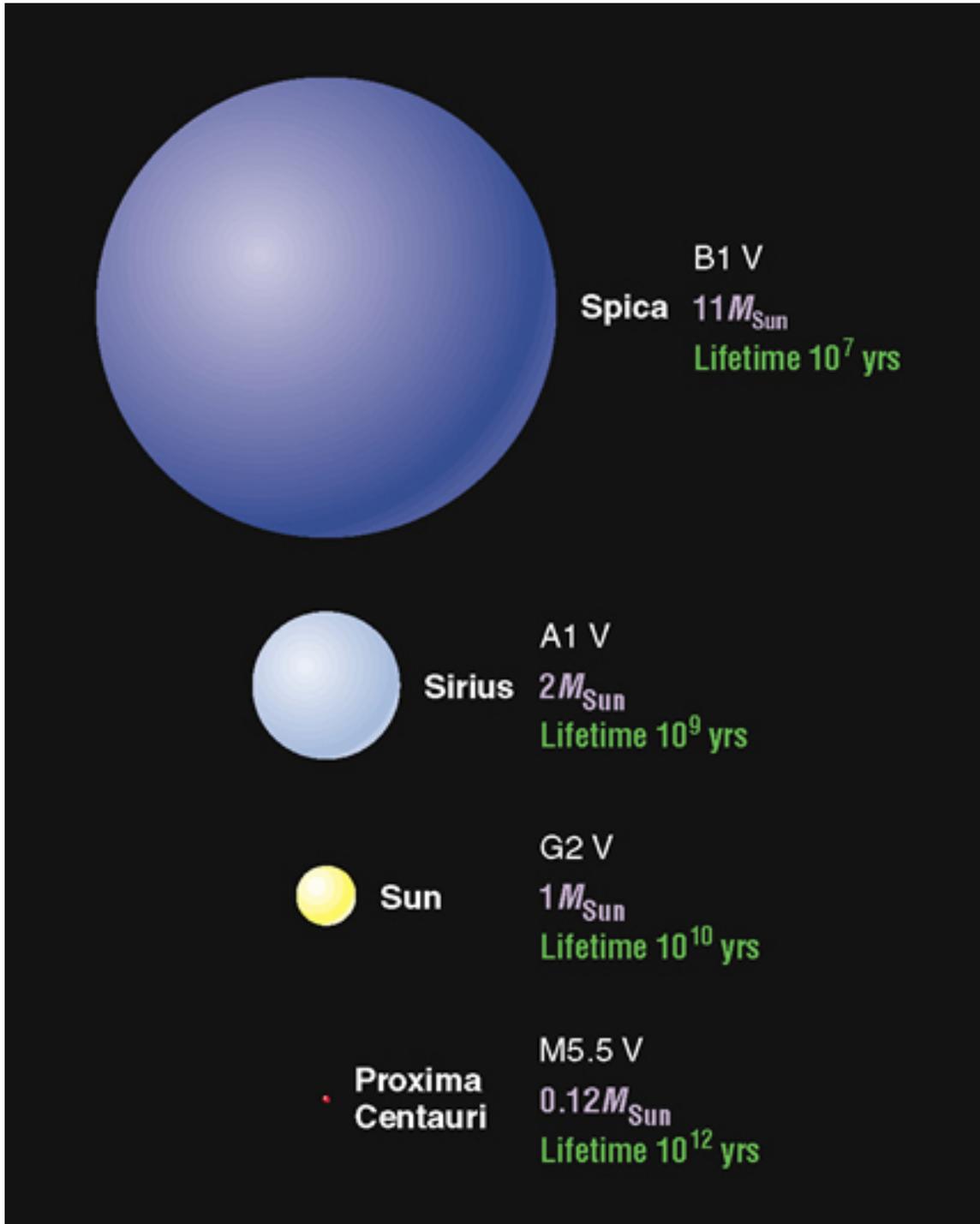
Low Mass:

Low Luminosity

Long-Lived

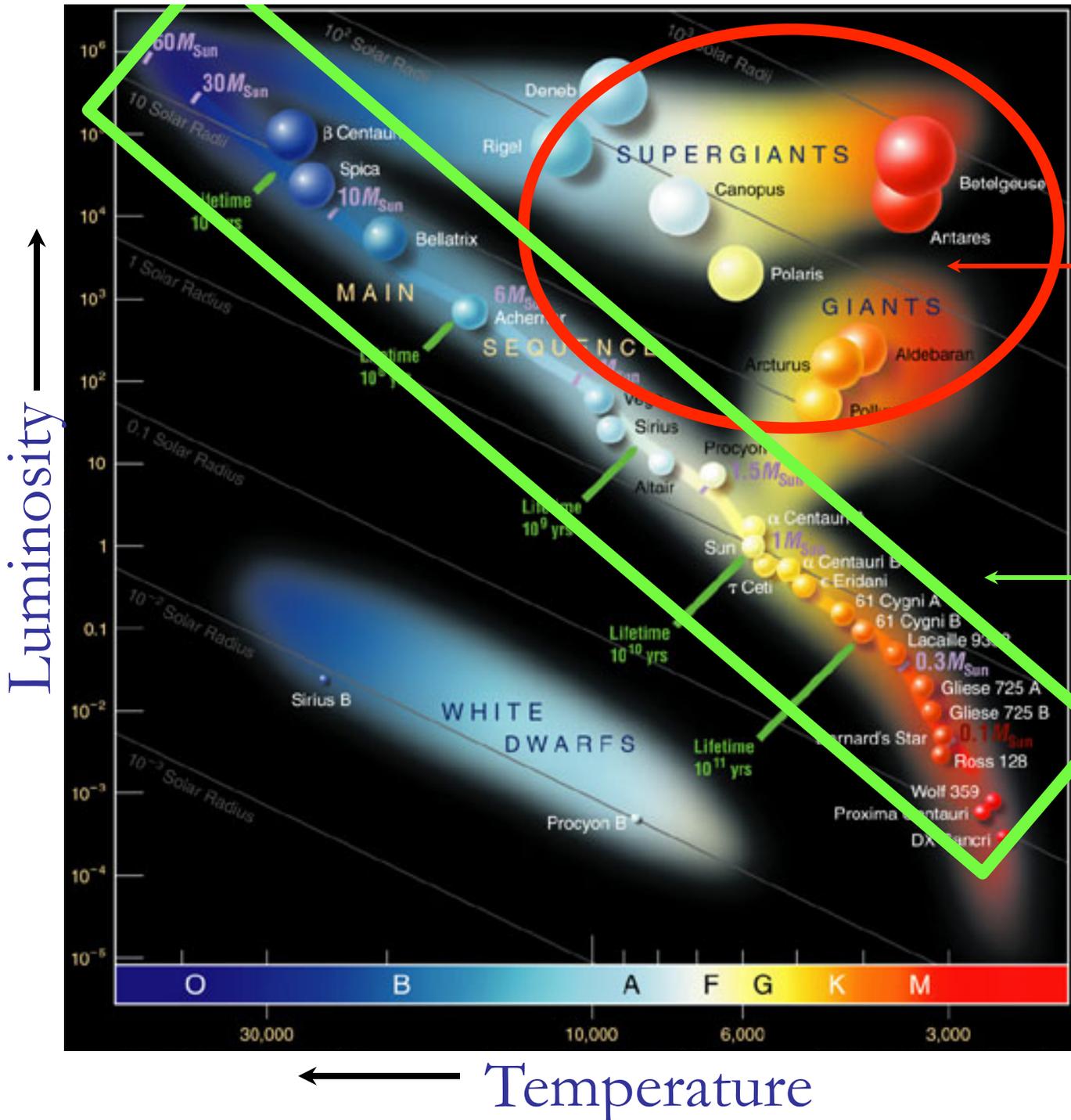
Small Radius

Red



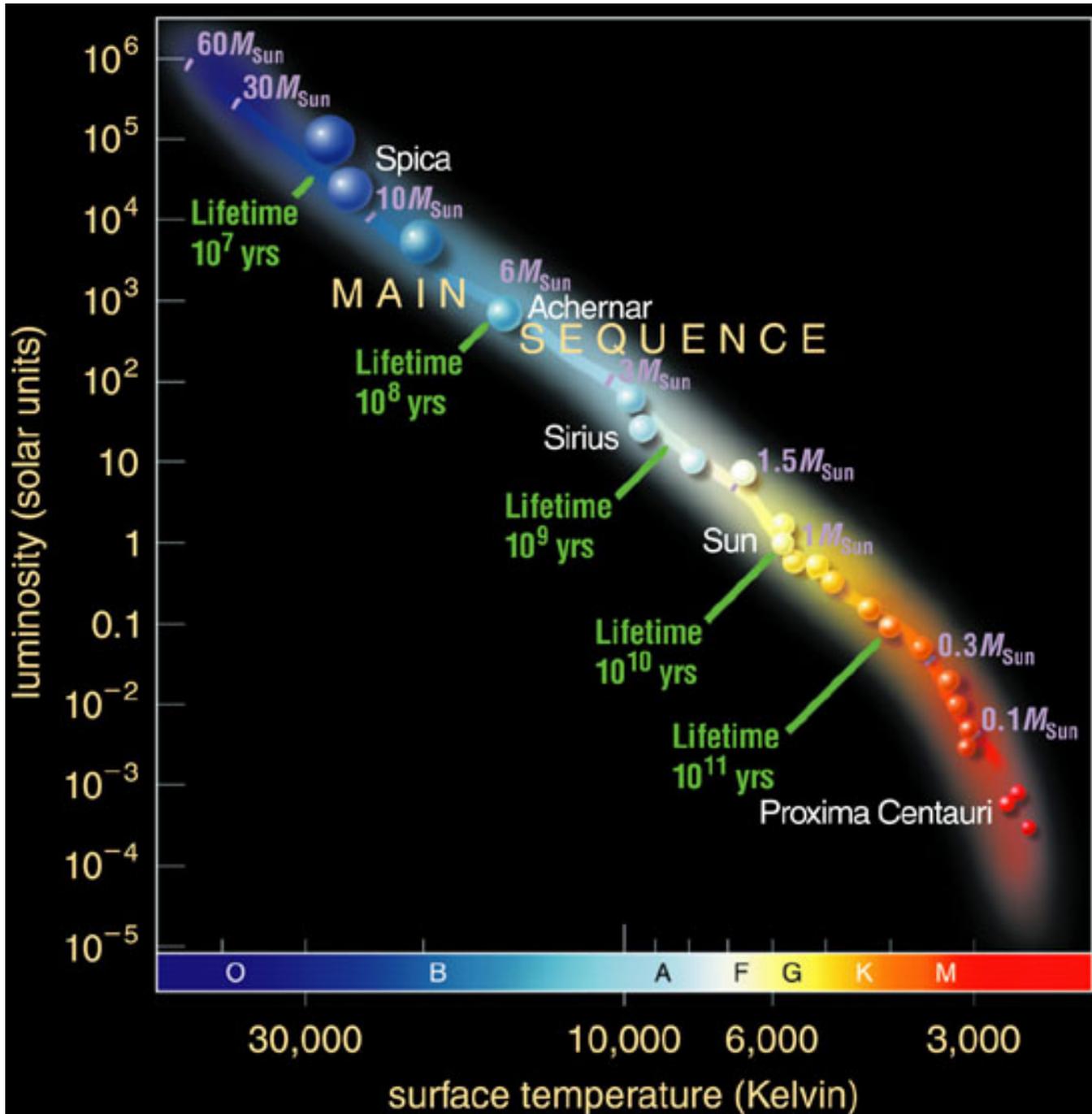
# Defining Habitability

- Are habitable planets likely?
- Are Earth-like planets rare or common?
- Habitability depends on luminosity of the star
- Habitability depends on the longevity of the star
- Both are governed by the mass of the star
- There may be a “sweet spot” in mass for habitability.



Stars off the main sequence have short remaining life!

So, let's focus on the main sequence where stars burn H the longest.



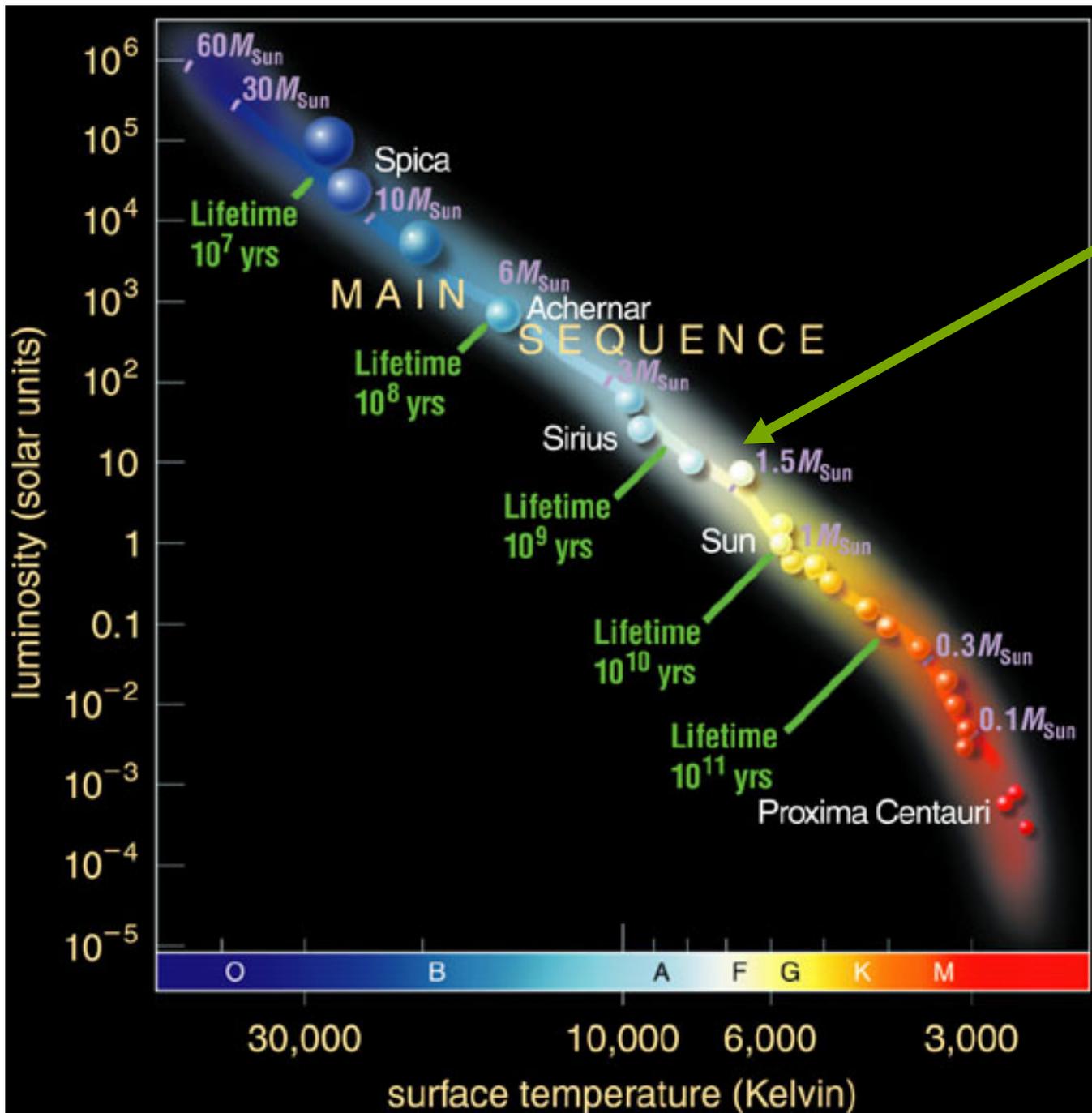
In terms of their suitability to host life, massive stars:

Are rare: **bad**

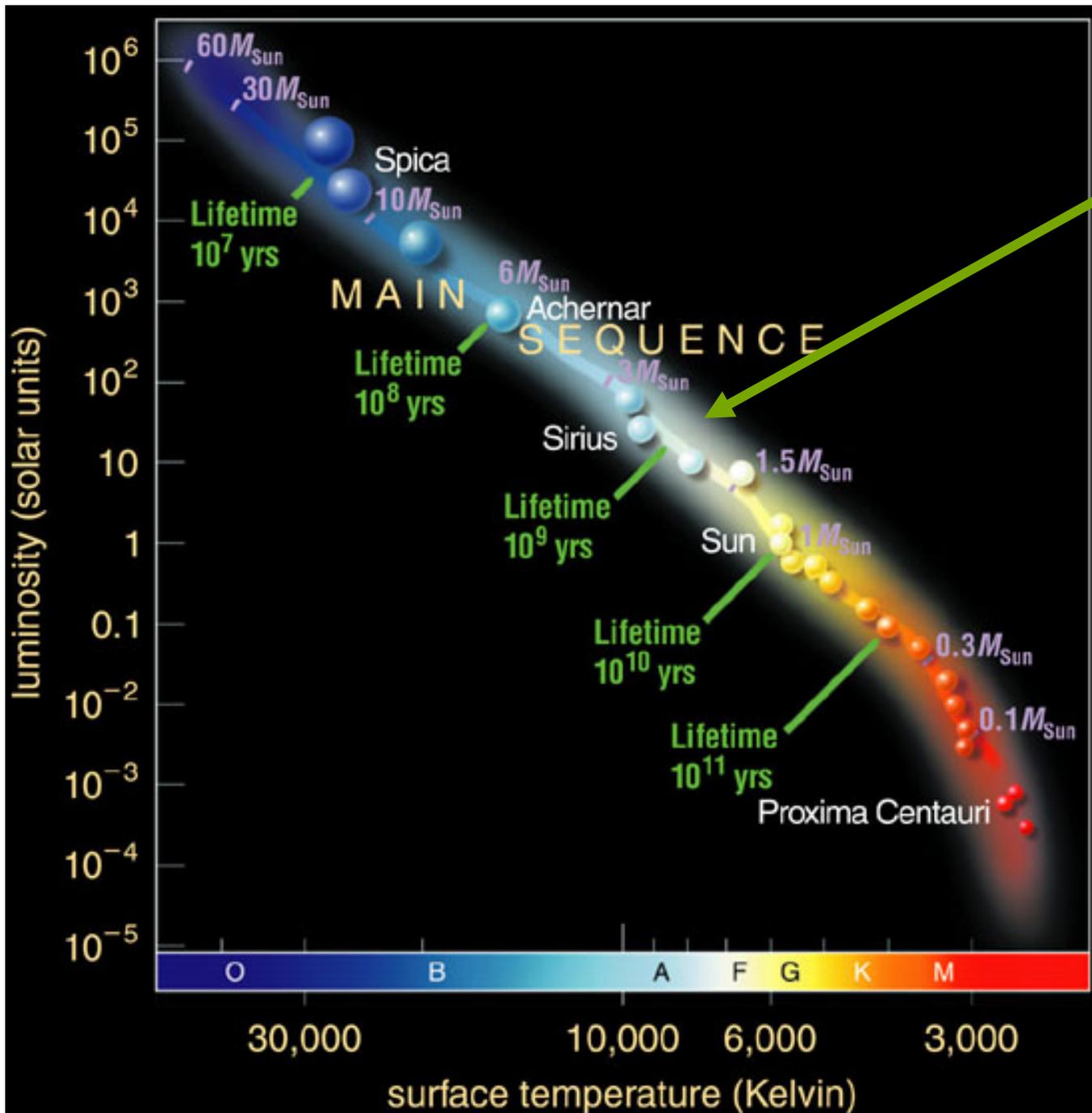
Emit a lot of energy: **good**

Have short lives: **bad**

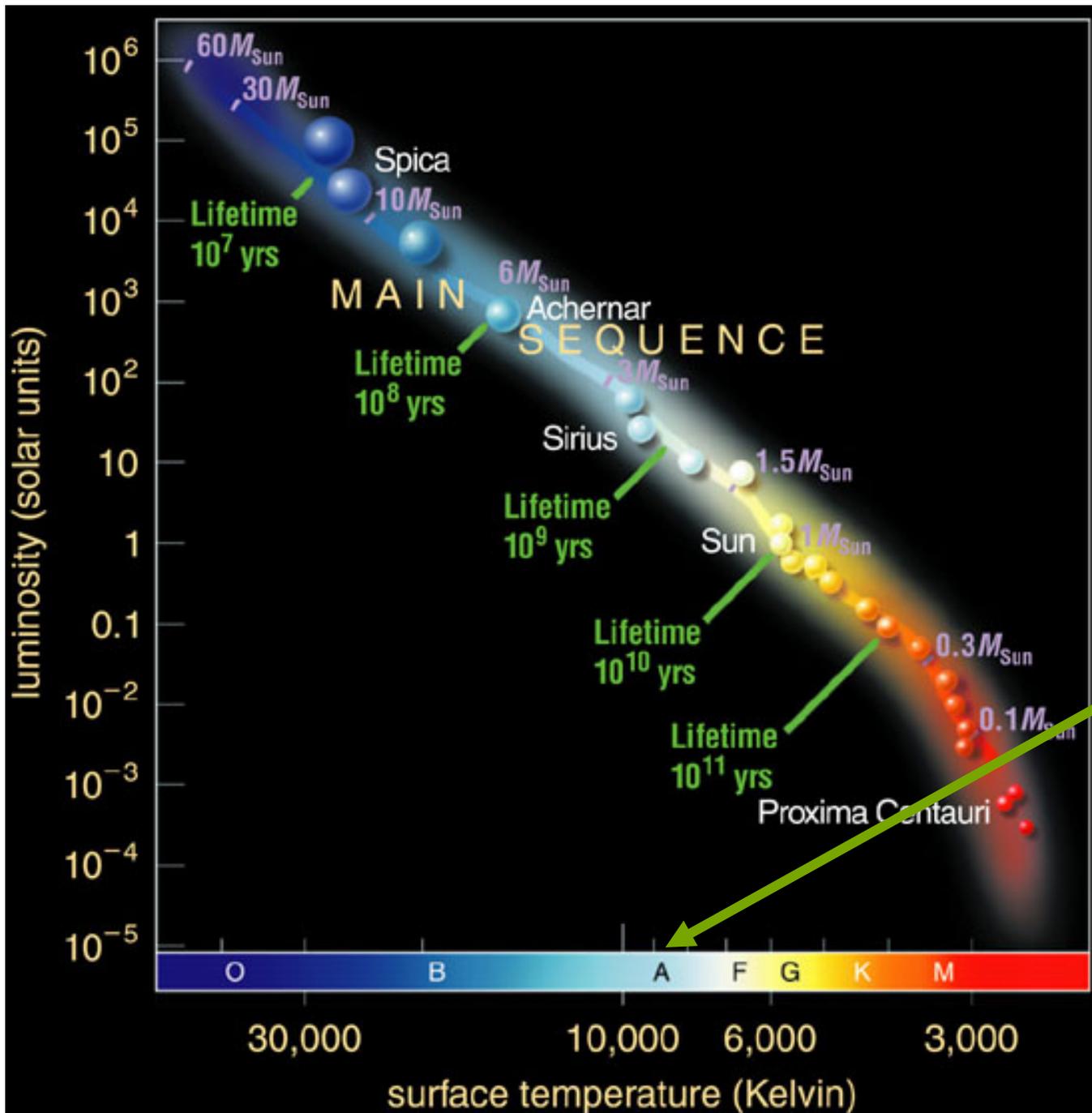
Give off lots of UV: **bad**



High mass limit of **1.5** times solar mass for lifetime to be at least **4** billion years for development of complex life.



High mass limit of **2** times solar mass for lifetime to be at least **1** billion years for development of life.



High mass stars also put most of their energy out in damaging **UV** radiation — life may not be able to tolerate this.

# Are habitable planets likely?

Definition:

A **habitable** world contains the necessities for life as we know it: liquid water, a source of energy, and organic (carbon-rich) material.

- It does *not* necessarily have life.

Caveat: Telescopically, we can search only for planets with habitable *surfaces* — not for worlds with Europa-like subsurface oceans.

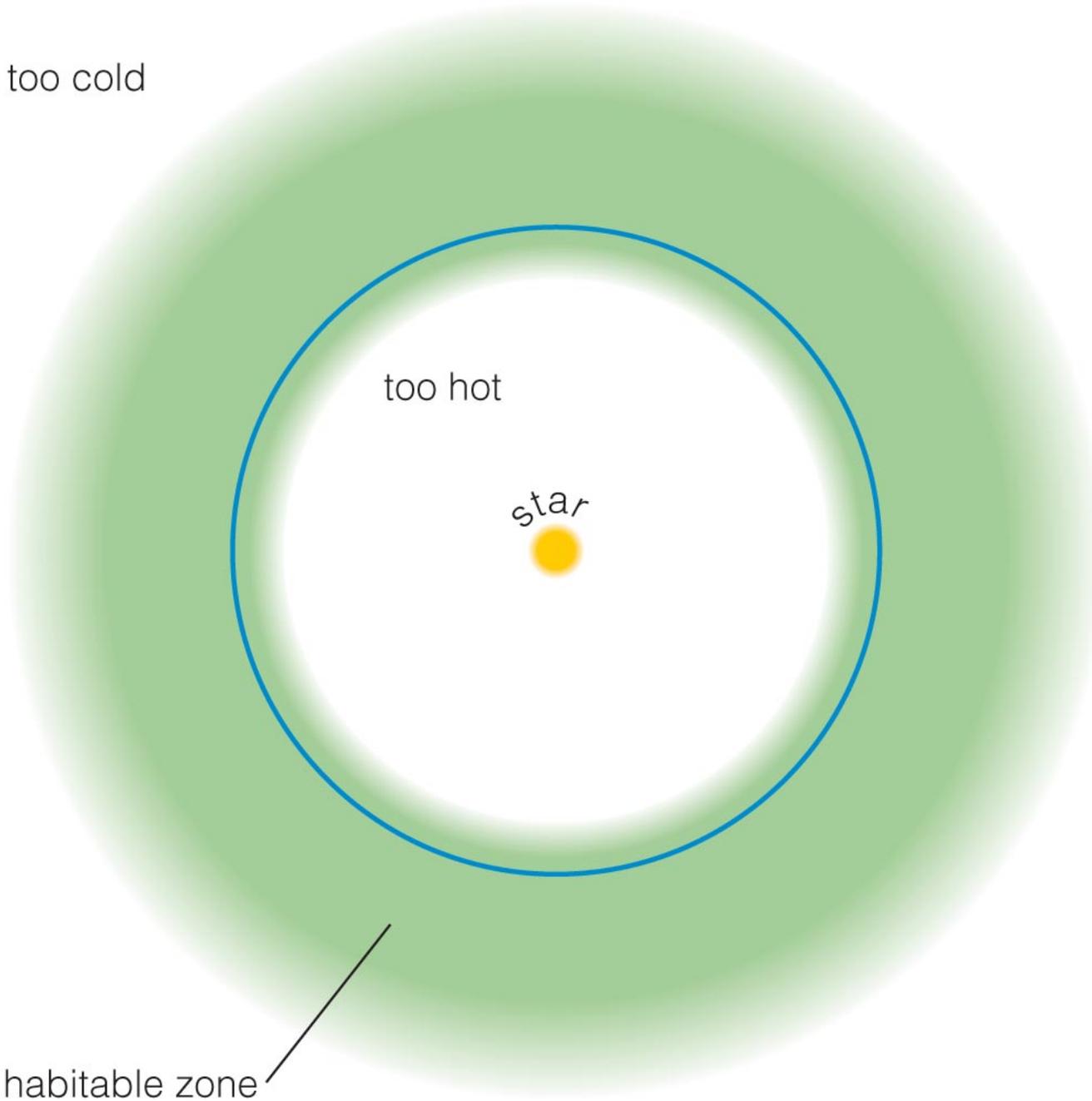
too cold

too hot

star

habitable zone

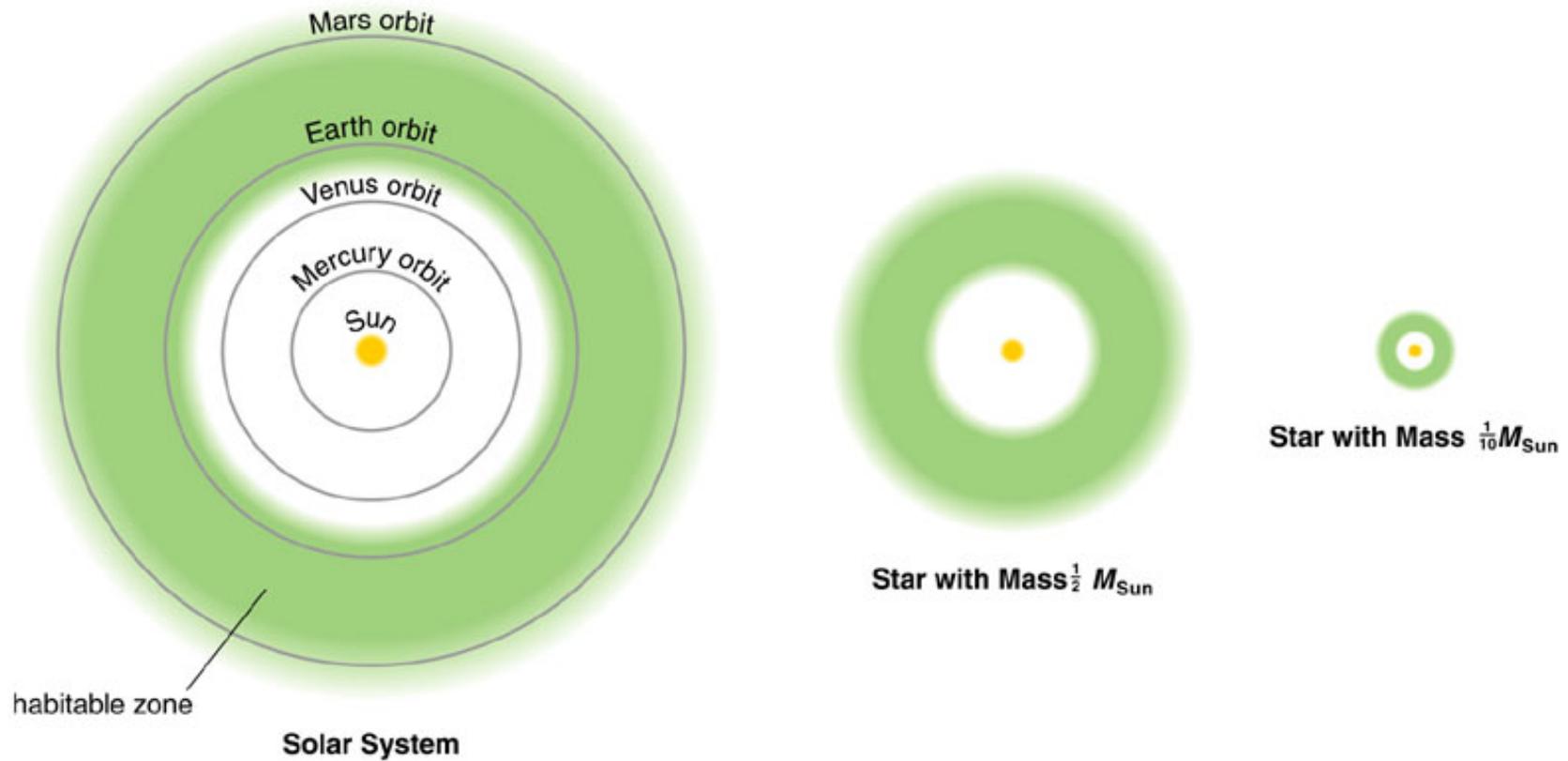
The Goldilocks premise: for a planet to be habitable, it must be within the range of distances from a star where the temperature allows water to be liquid on its surface.



## Constraints on star systems:

- 1) Old enough to allow time for evolution (rules out high-mass stars – only a few %)
- 2) Need to have stable orbits (this *might* rule out binary/multiple star systems – 50%)
- 3) Size of the “habitable zone”: region in which a planet of the *right size* could have liquid water on its surface (this is probably overly stringent)

Even so... the billions of stars in the Milky Way seem to offer the prospect of many habitable worlds.



The less massive the star is, the smaller the habitable zone — lower probability of a planet in this zone.

Kepler-22 System

Solar System

Habitable Zone



Kepler-22b

Mercury



Venus

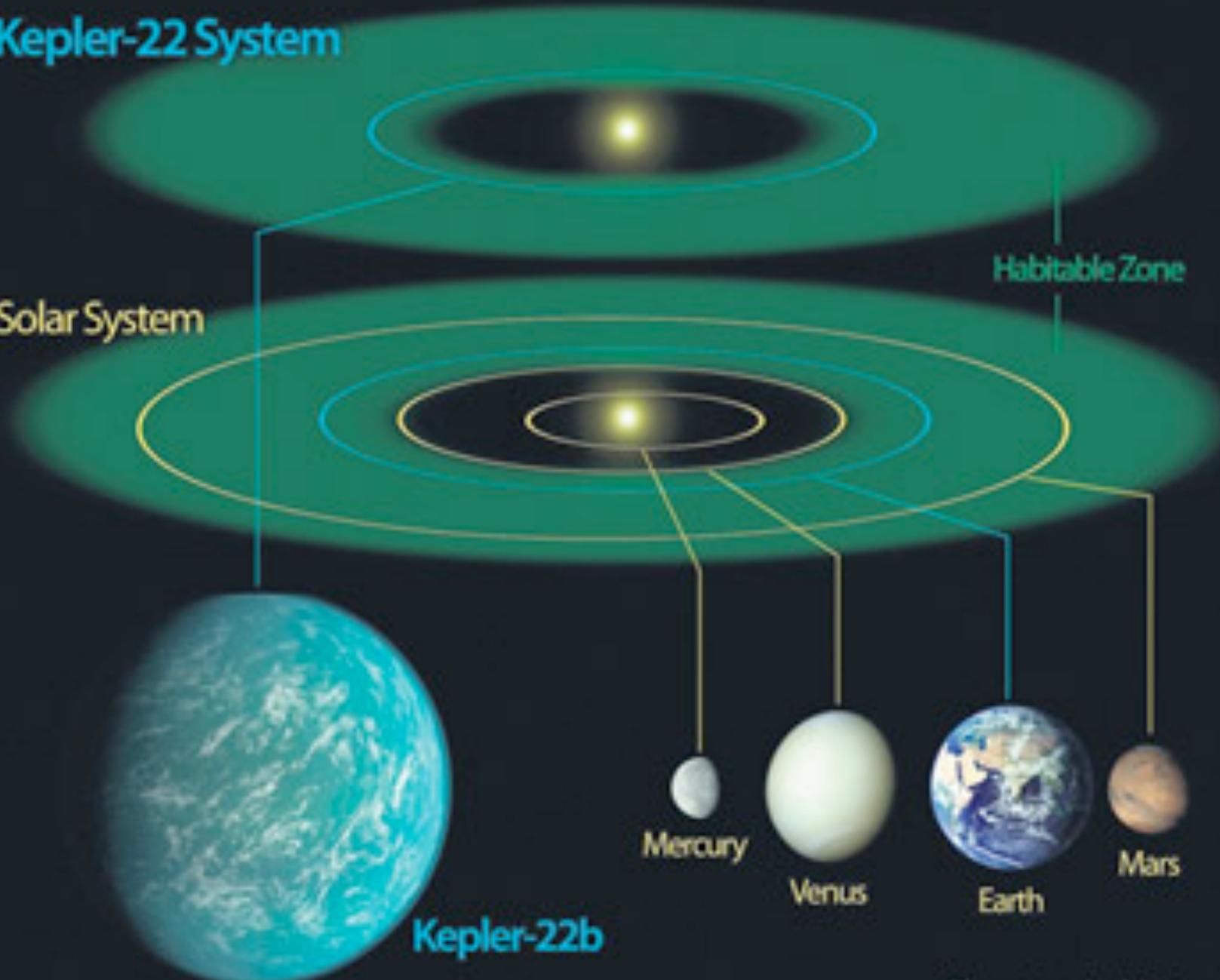


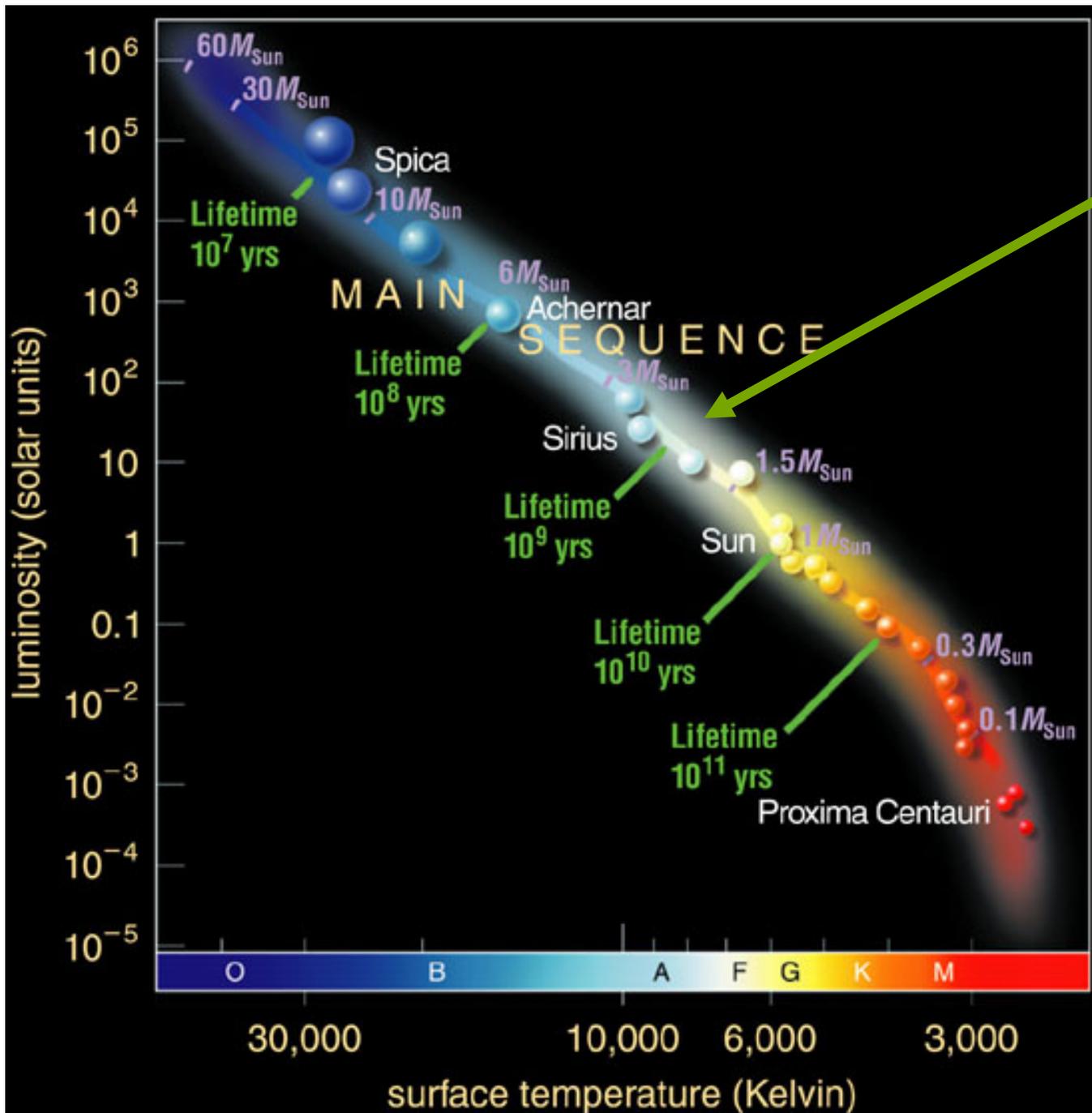
Earth



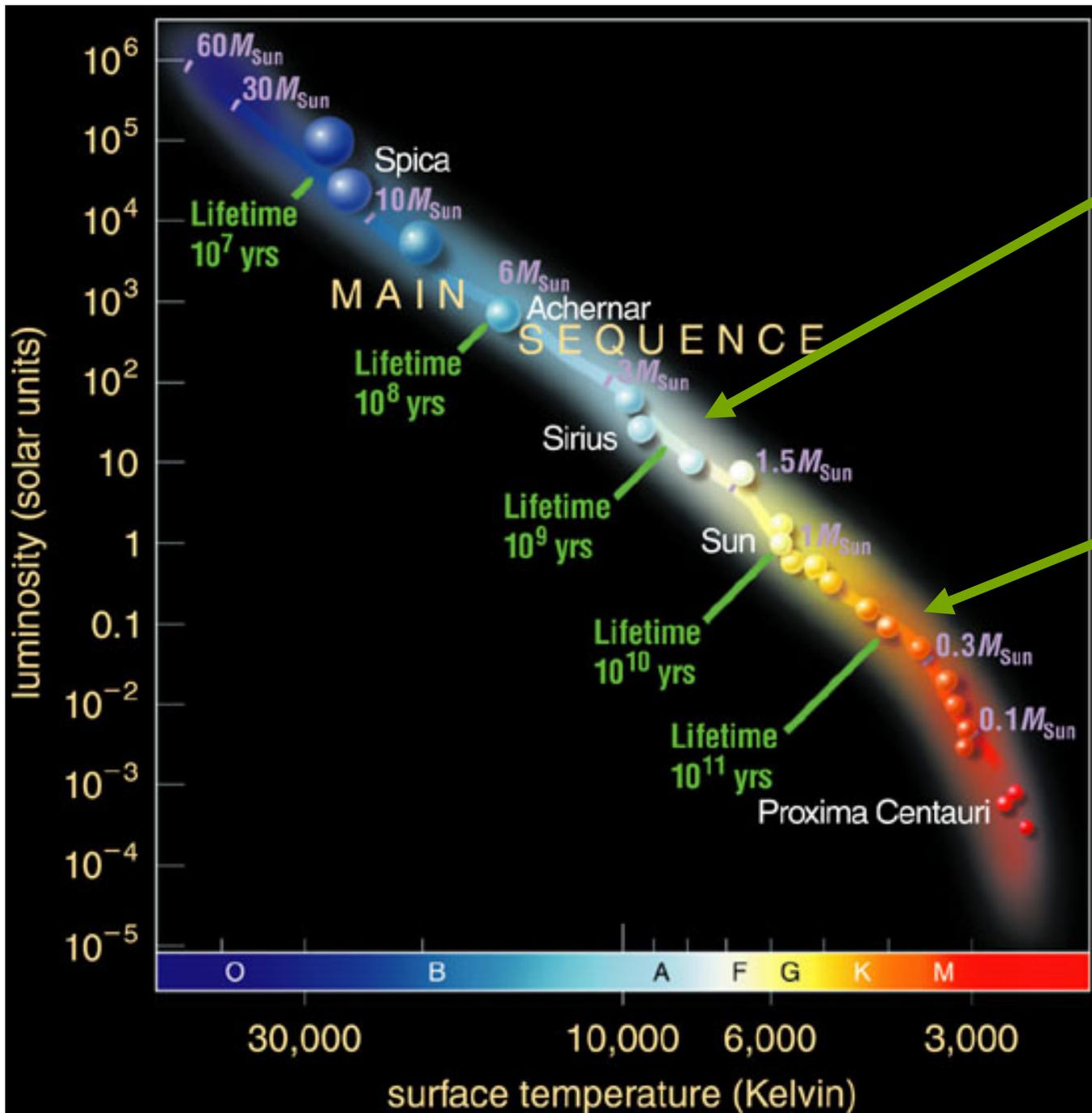
Mars

Planets and orbits to scale

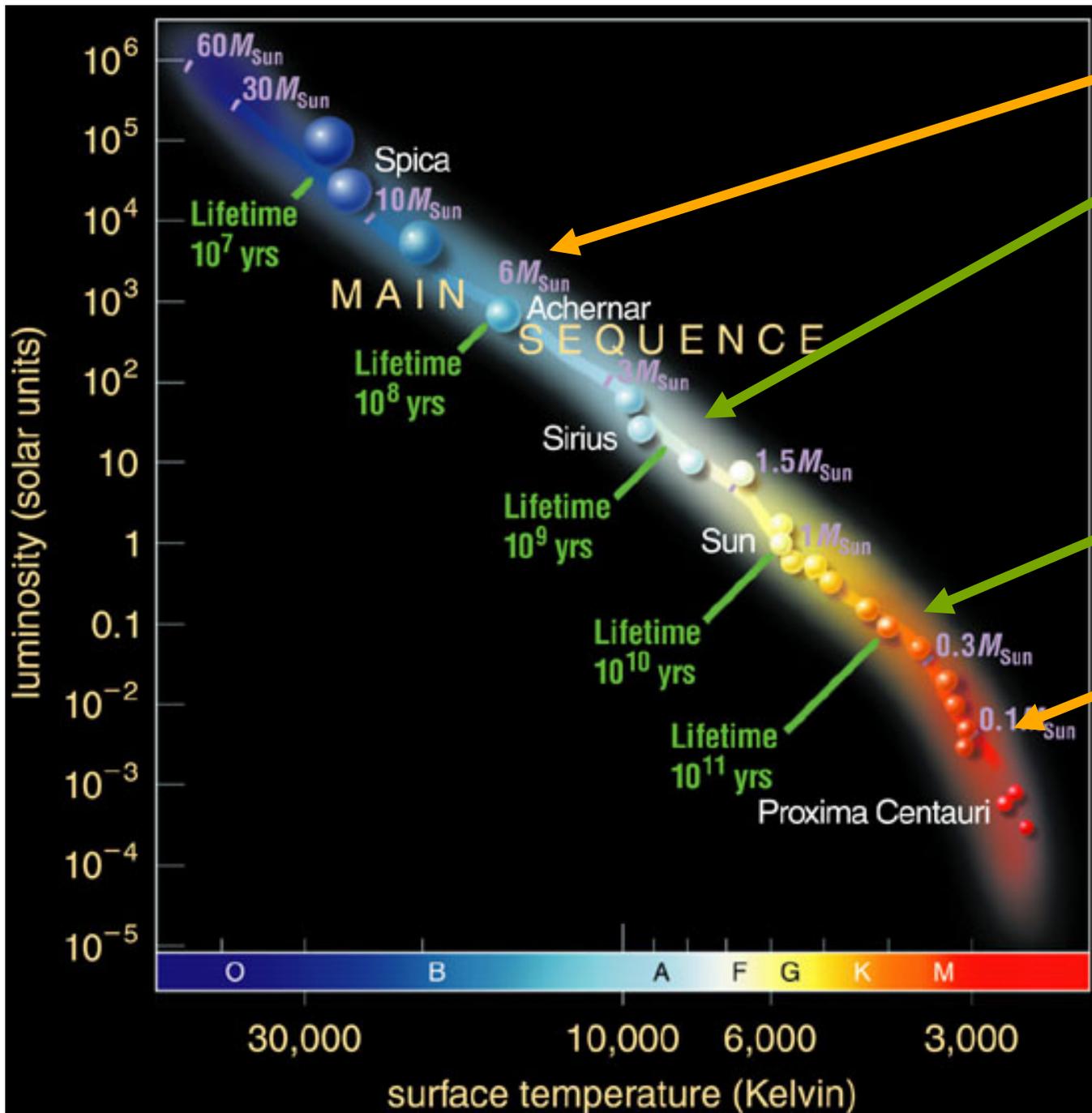




High mass limit of 2 times solar mass for lifetime to be at least 1 billion years for development of life.



Conservative  
 Low mass limit  
 of 30% of solar  
 mass to have a  
 habitable zone  
 spanning region  
 of the terrestrial  
 planets in our  
 Solar System.



The “sweet spot” for microbial life may be much wider and include many more stars

i.e. planets around short lived stars, and planets or moons that use internal energy for life support

## *How Many Stars fit these criteria?*

- A conservative estimate of the habitable zone gives ~**100 million** potential stars for (possibly advanced) life in the Milky Way.
- A generous estimate based on extremophile properties and a flexible definition of what habitable means gives several billion stars.
- Remember, there are **60 billion** galaxies in the universe beyond the Milky Way.