

Fusion in first few minutes after Big Bang form lightest elements

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

* Lanthanide series

** Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
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Stars build the rest of the elements up to Iron (Fe) through fusion

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

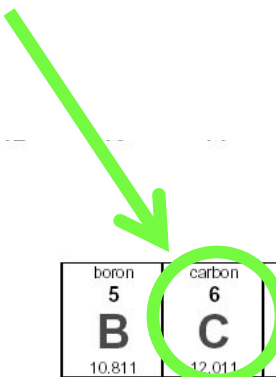
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** Actinide series

Example : How do we get Carbon ?



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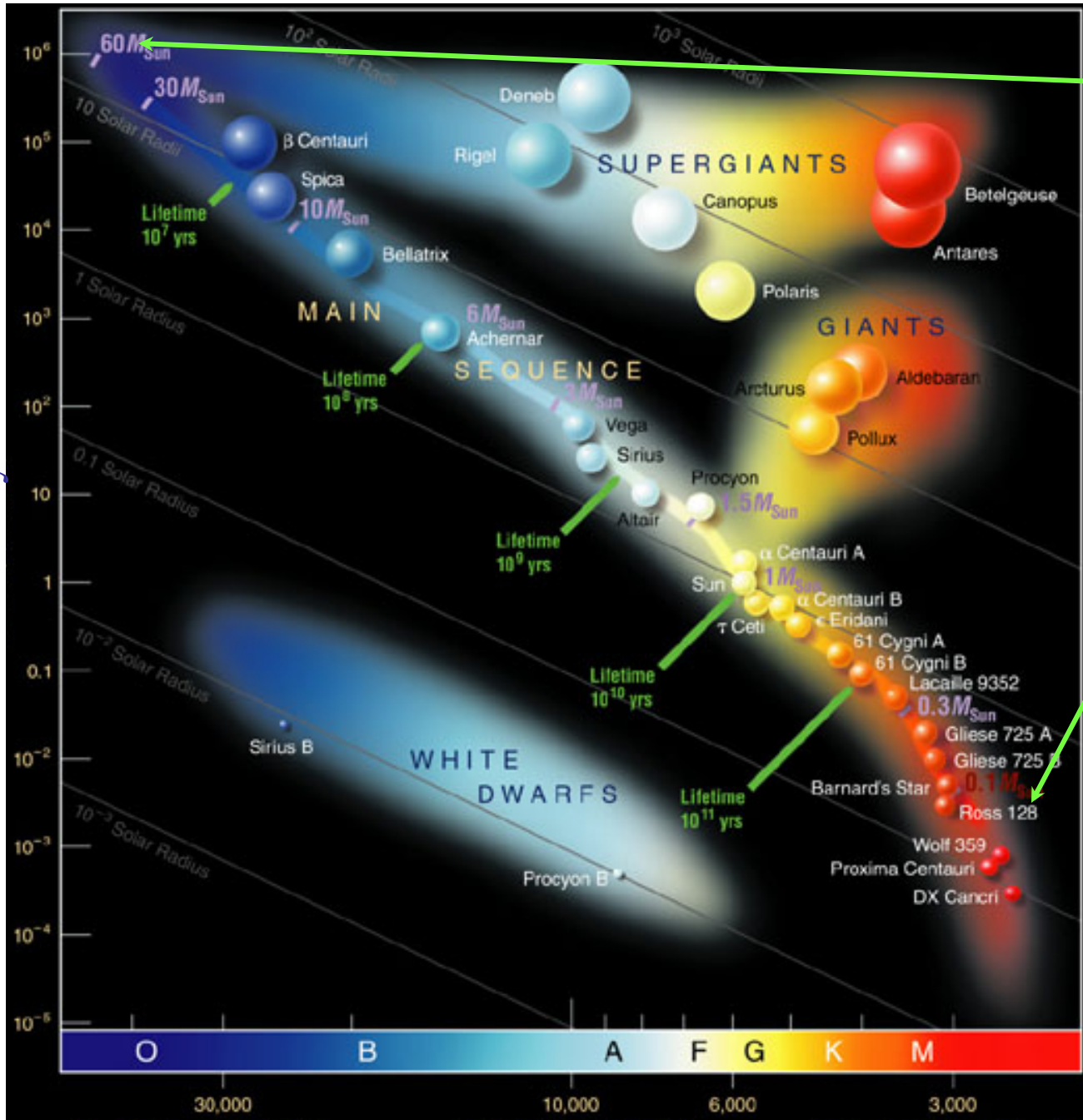
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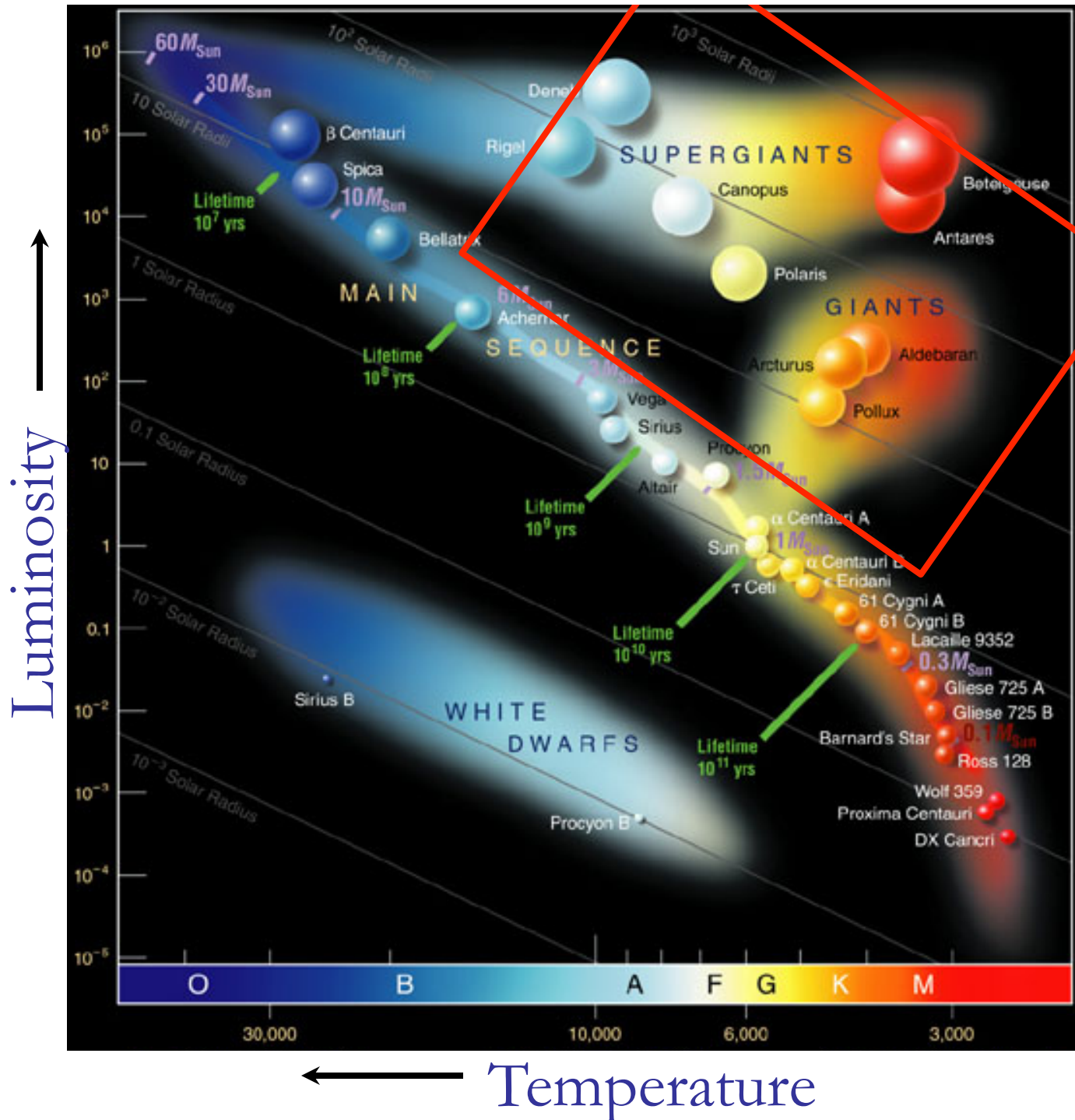
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Luminosity



Temperature

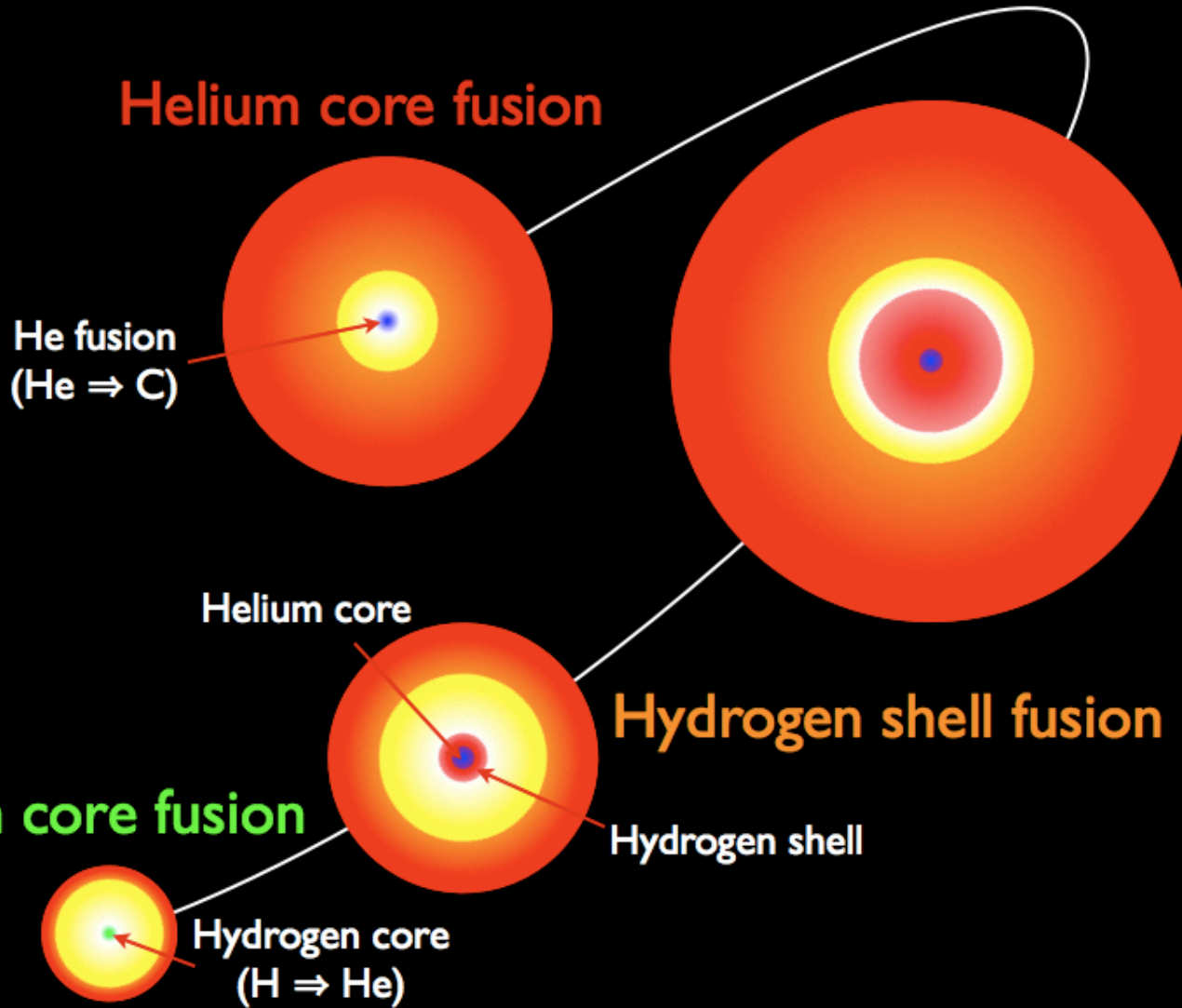
Stars along the main sequence are stably burning H to form He



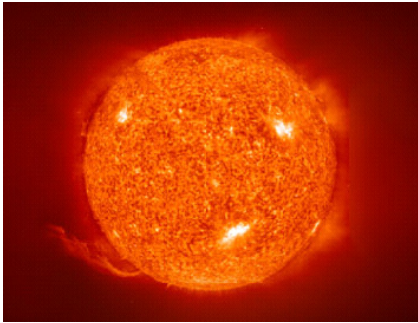
After stars run out of H in their core, they evolve to the red giant phase and, depending on their mass, can burn He, C, O, Si, etc. up to Fe.

Evolution off Main Sequence (Red Giant Phase)

(sizes not to scale!)

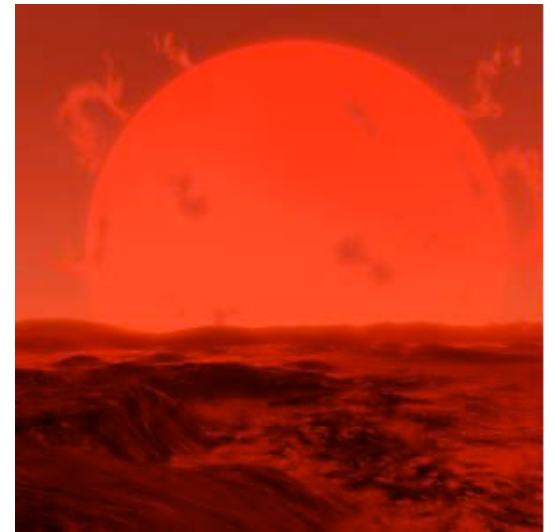


Review: Where does Carbon Come From ?



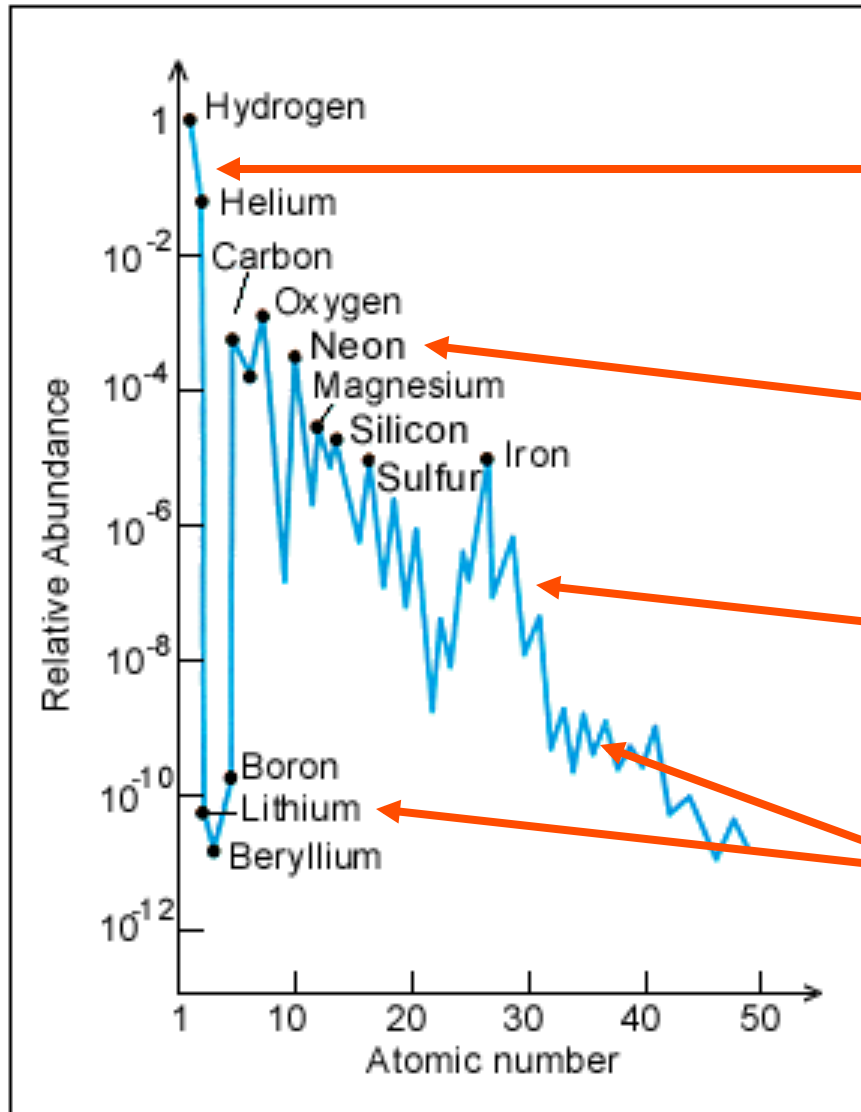
Hydrogen is fused to Helium in a star on the *main sequence*.

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

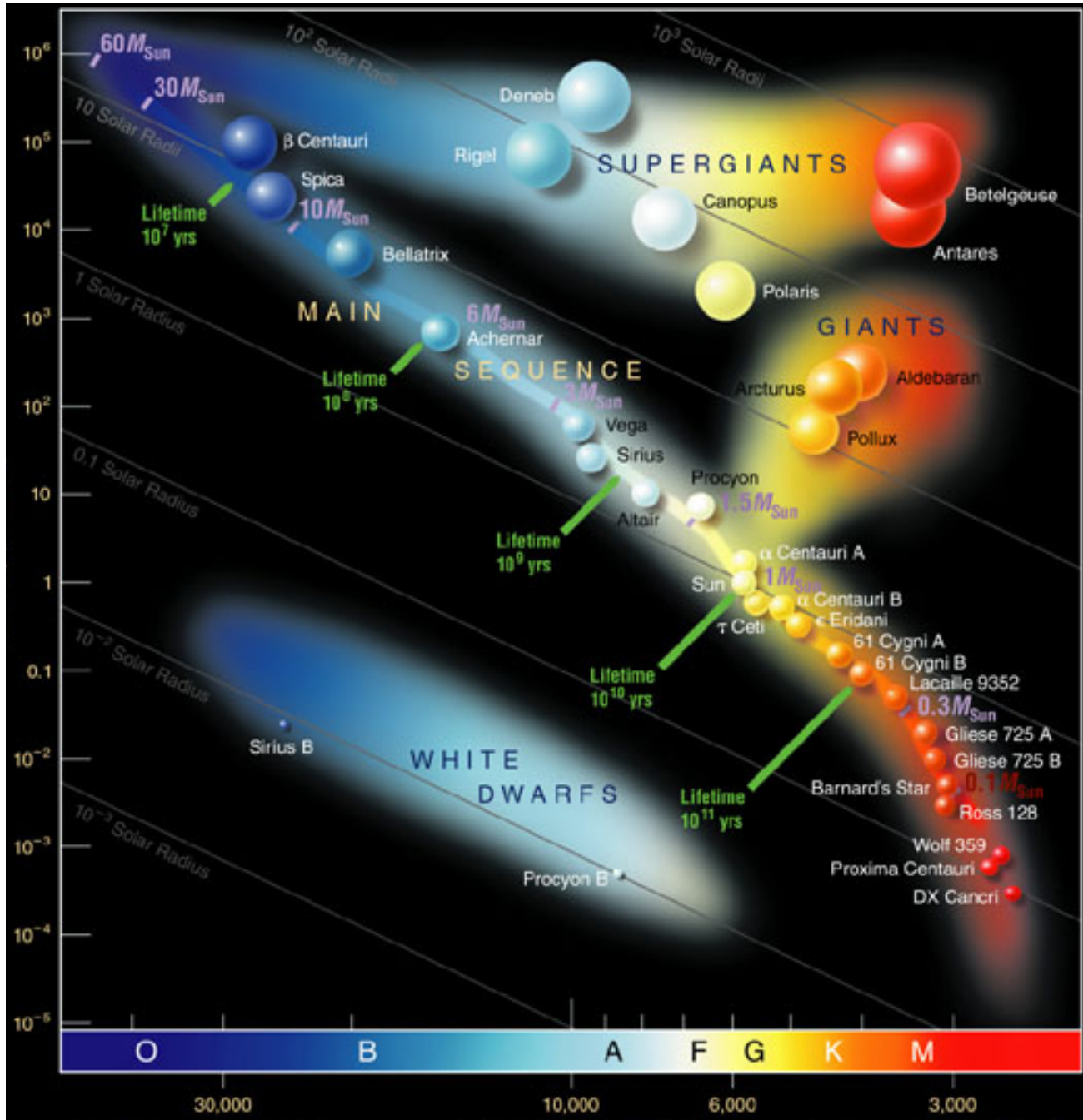
Temperature: from color and spectral type

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

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

0.08 M_{Sun} - 100 M_{Sun}

Luminosity



Temperature

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

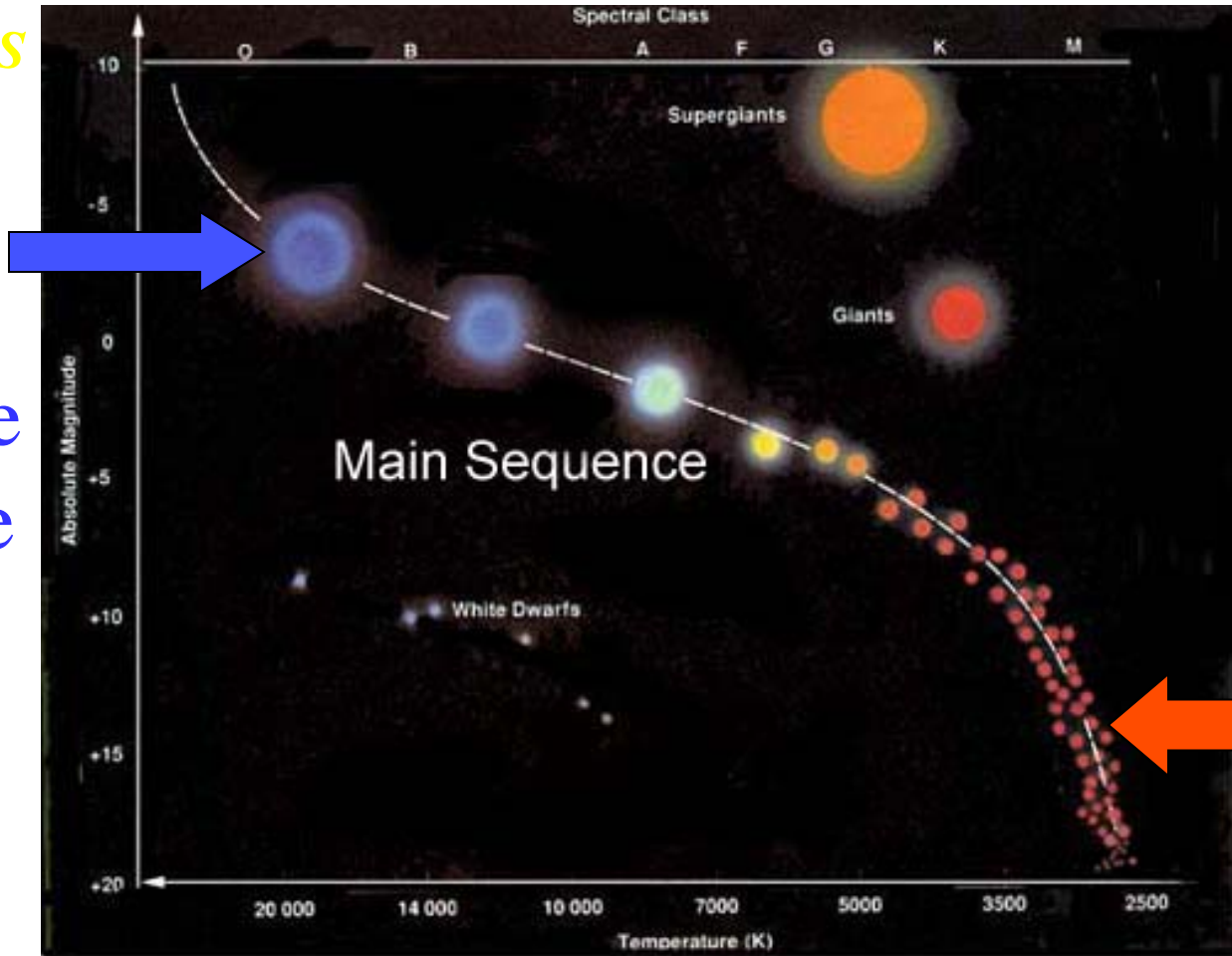
How Fast Do Different Stars Evolve?

HOT

COOL

LUMINOUS

Blue
MS
stars are
massive



DIMMER

Red MS
stars are
low
mass

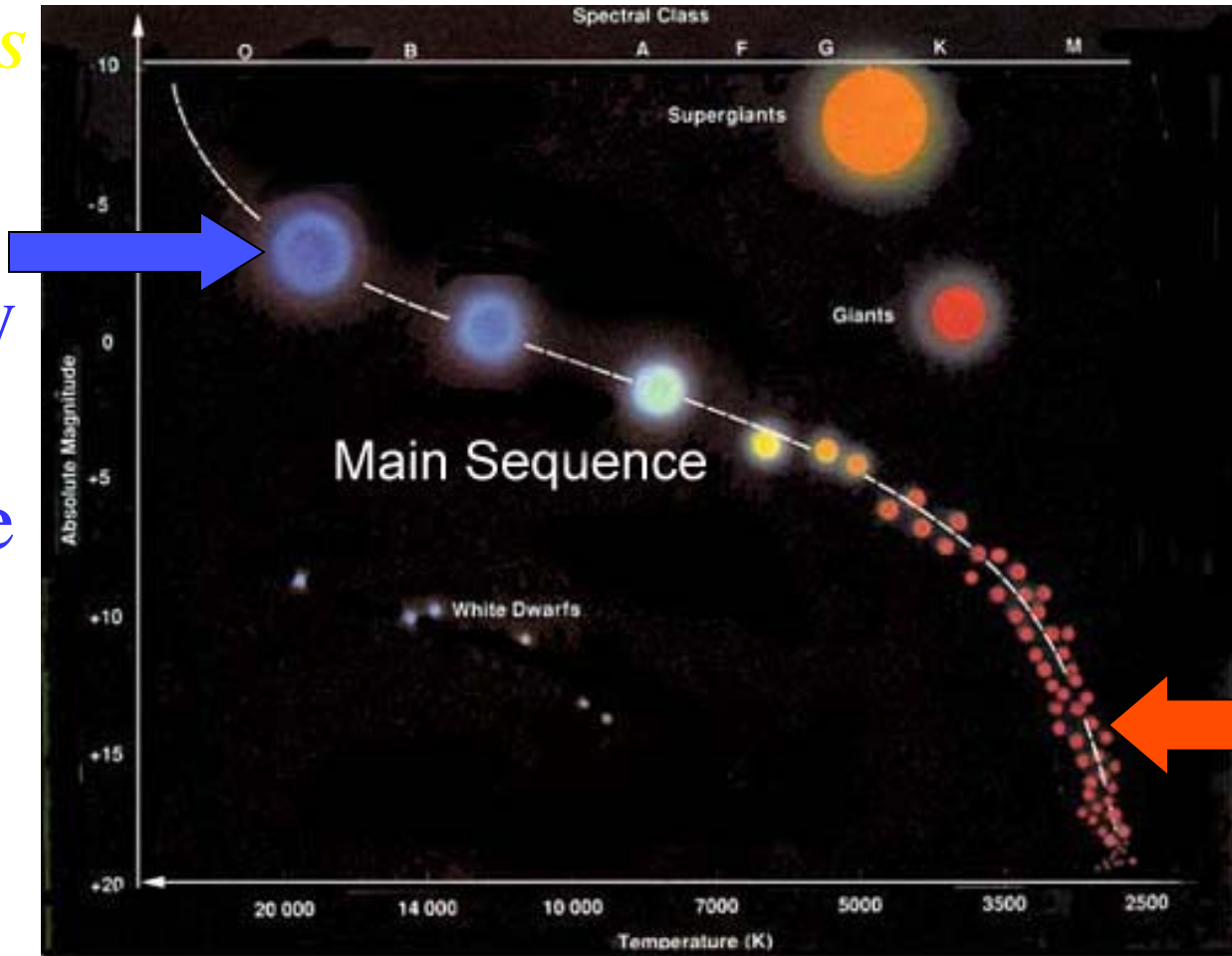
Most stars are low mass and relatively cool.

HOT

COOL

LUMINOUS

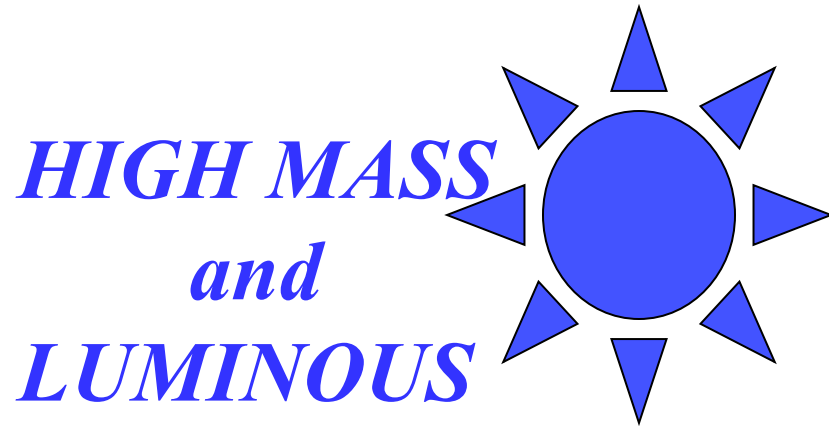
There are very few massive MS stars



DIMMER

There are a lot of low mass MS stars

Massive stars have the shortest lives.



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

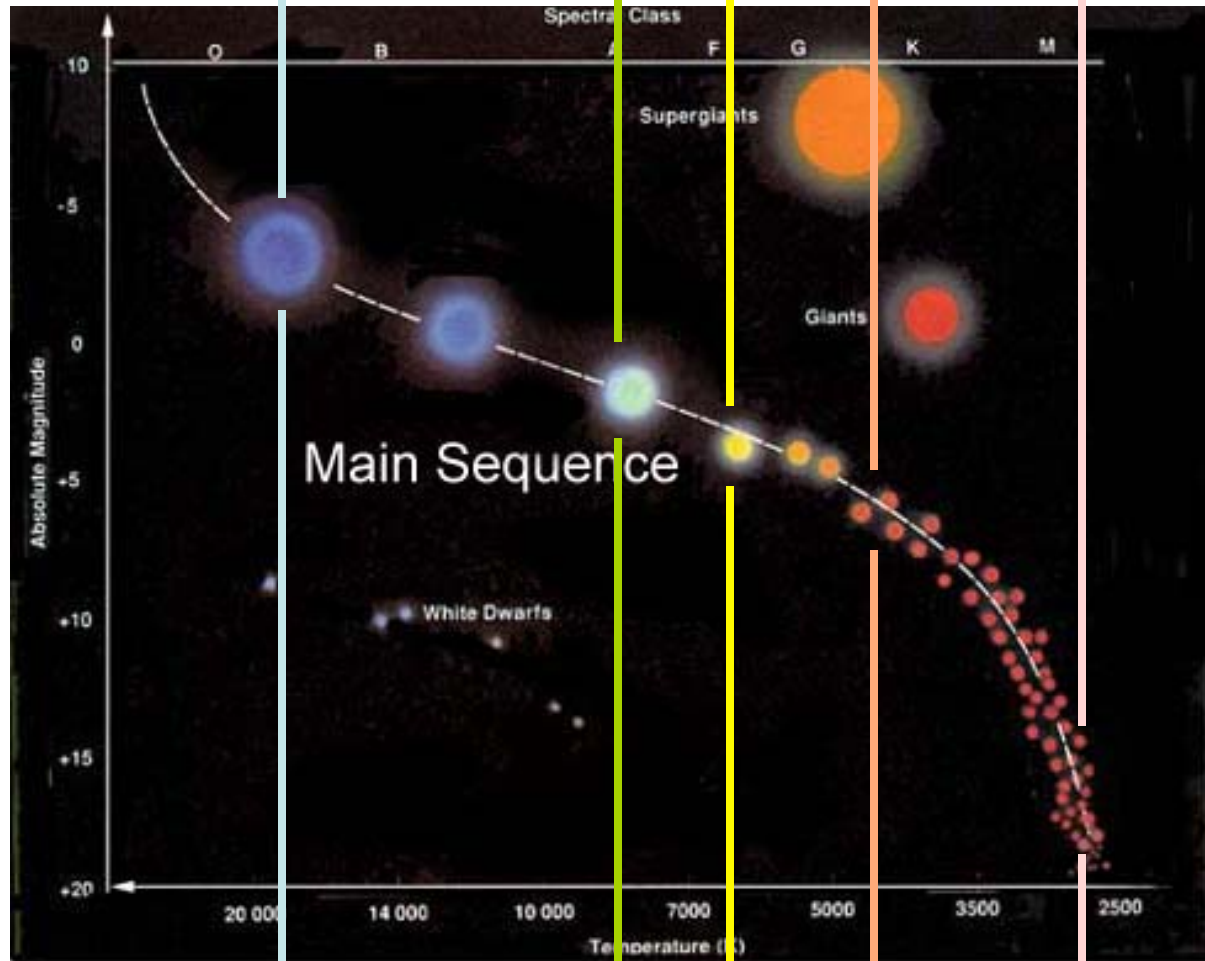
100 billion years \sim 10 billion years \times $0.1 / 0.01$

times the mass of the Sun

MASS:

10 2 1 0.5 0.1

LUMINOUS



DIMMER

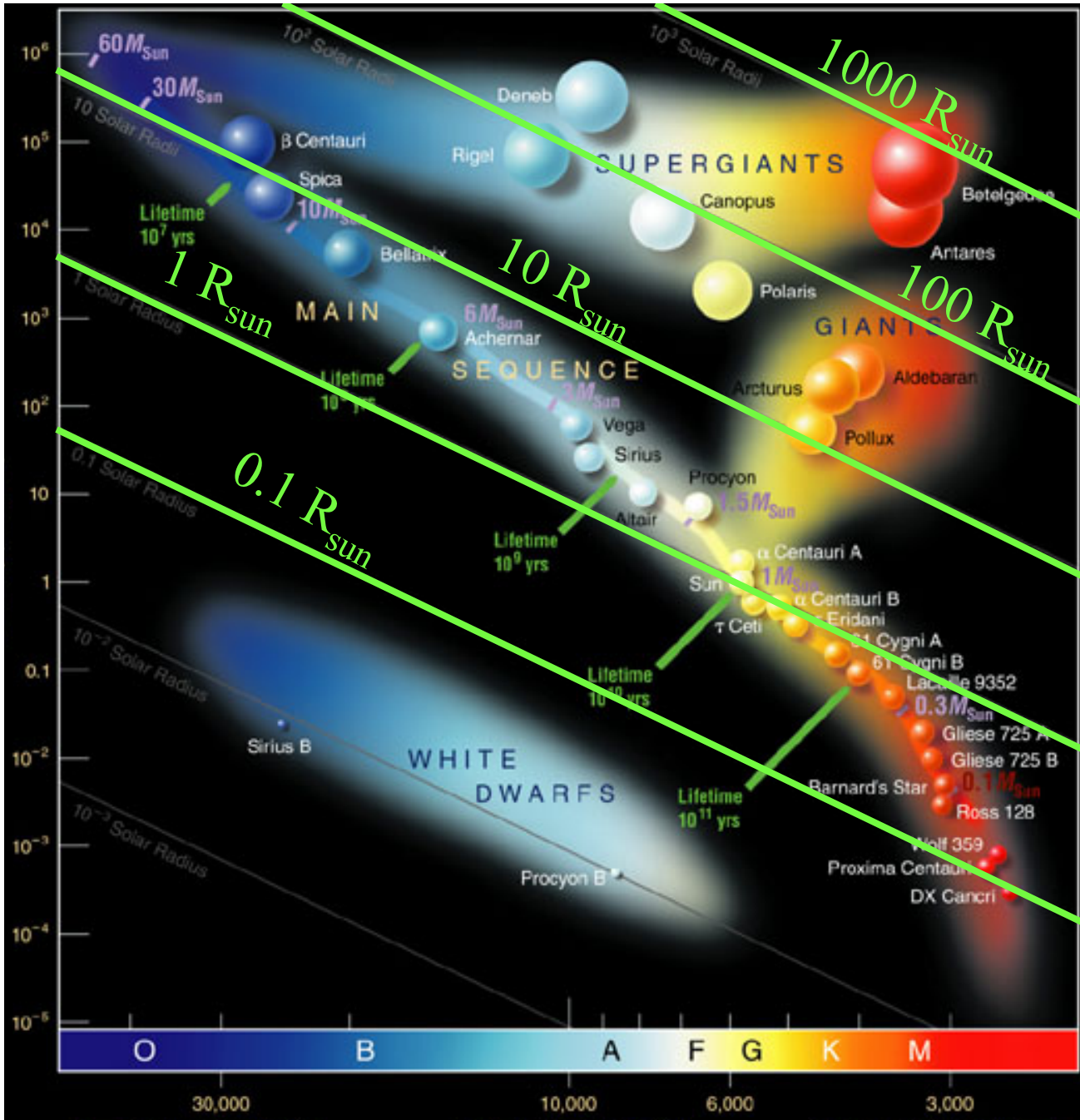
LIFETIME:

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

in years

Luminosity

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



Temperature

Star Comparison

High Mass:

High Luminosity

Short-Lived

Large Radius

Blue

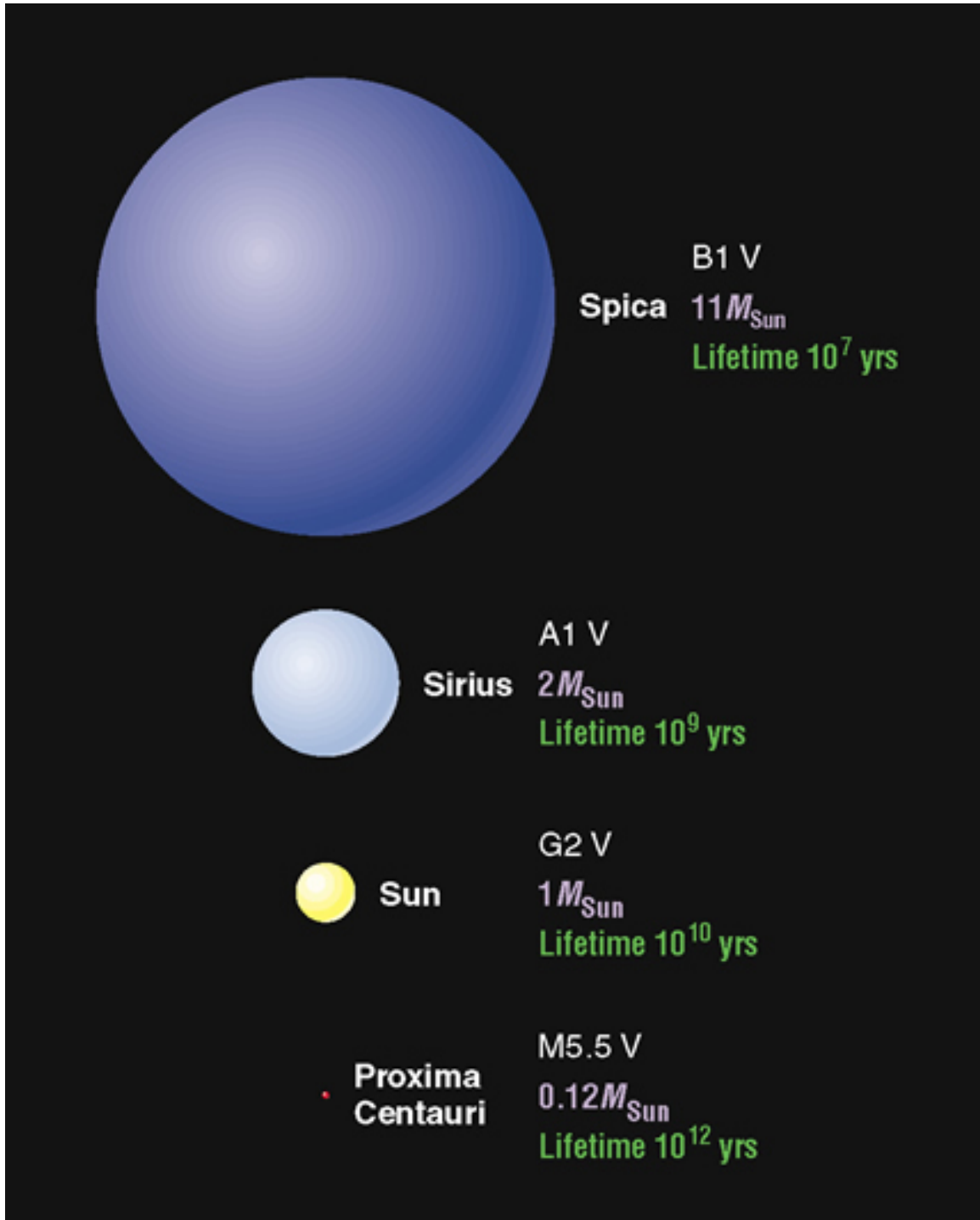
Low Mass:

Low Luminosity

Long-Lived

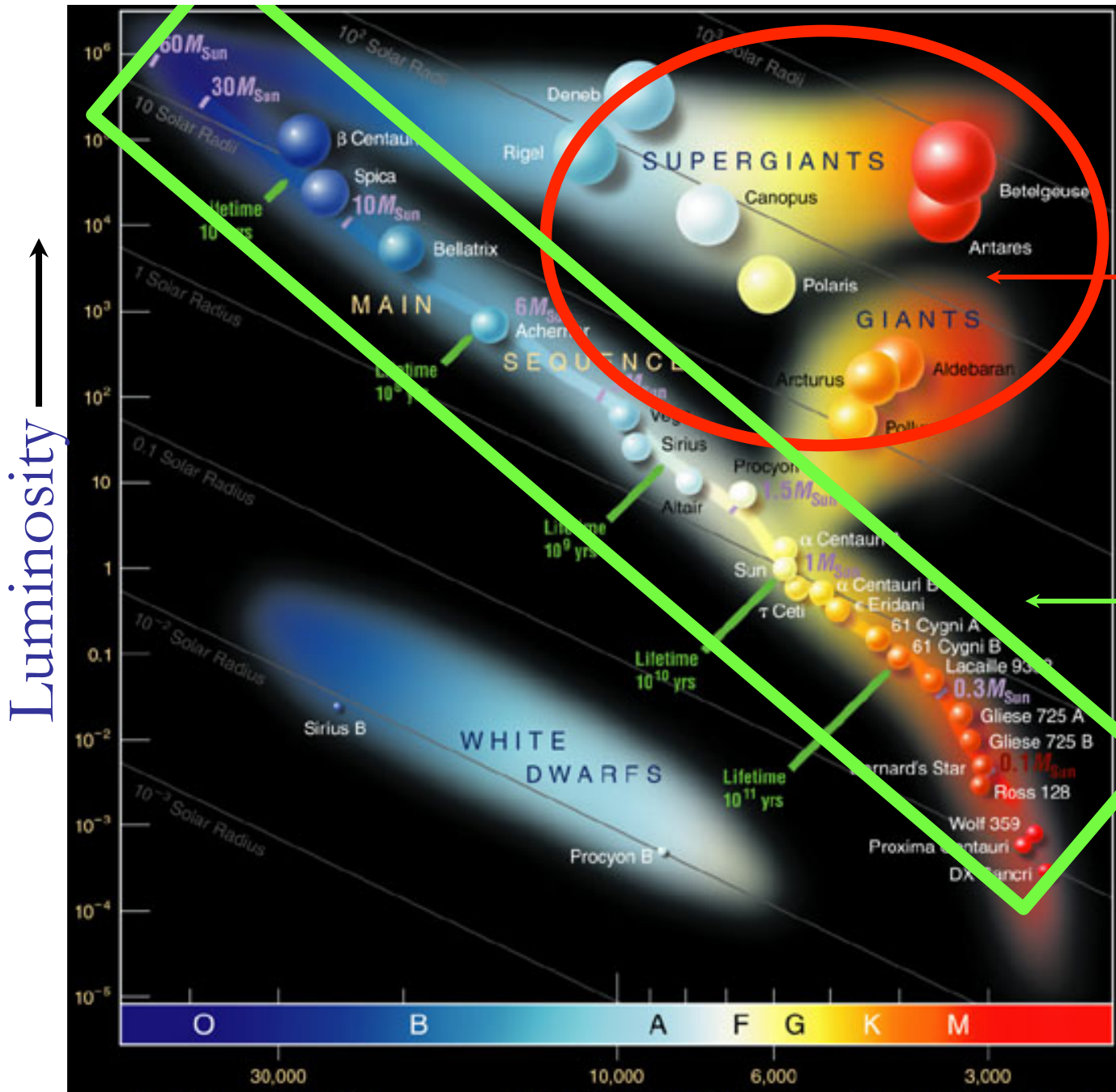
Small Radius

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.

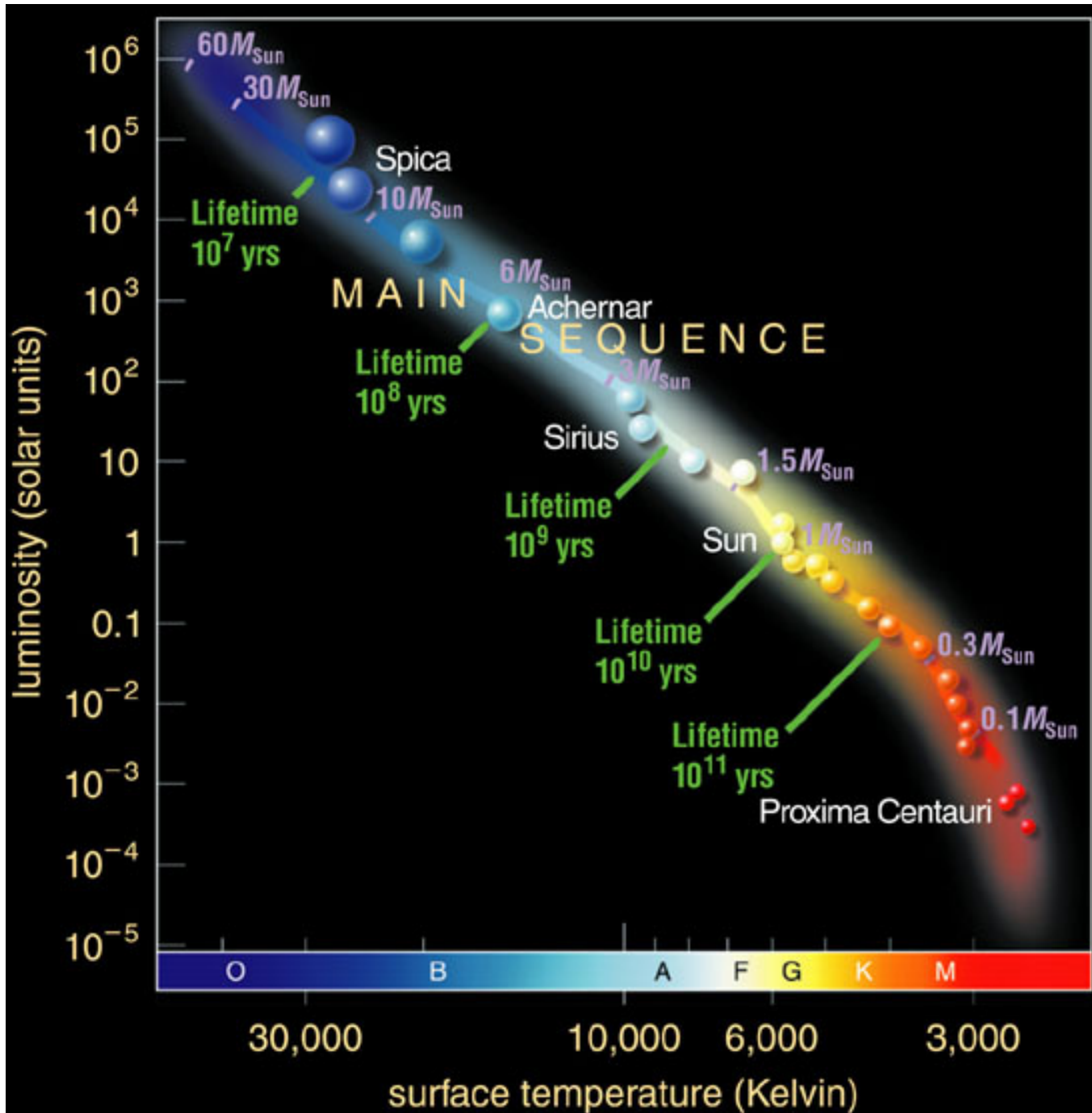


Stars off the main sequence have short remaining life!

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

Luminosity

Temperature



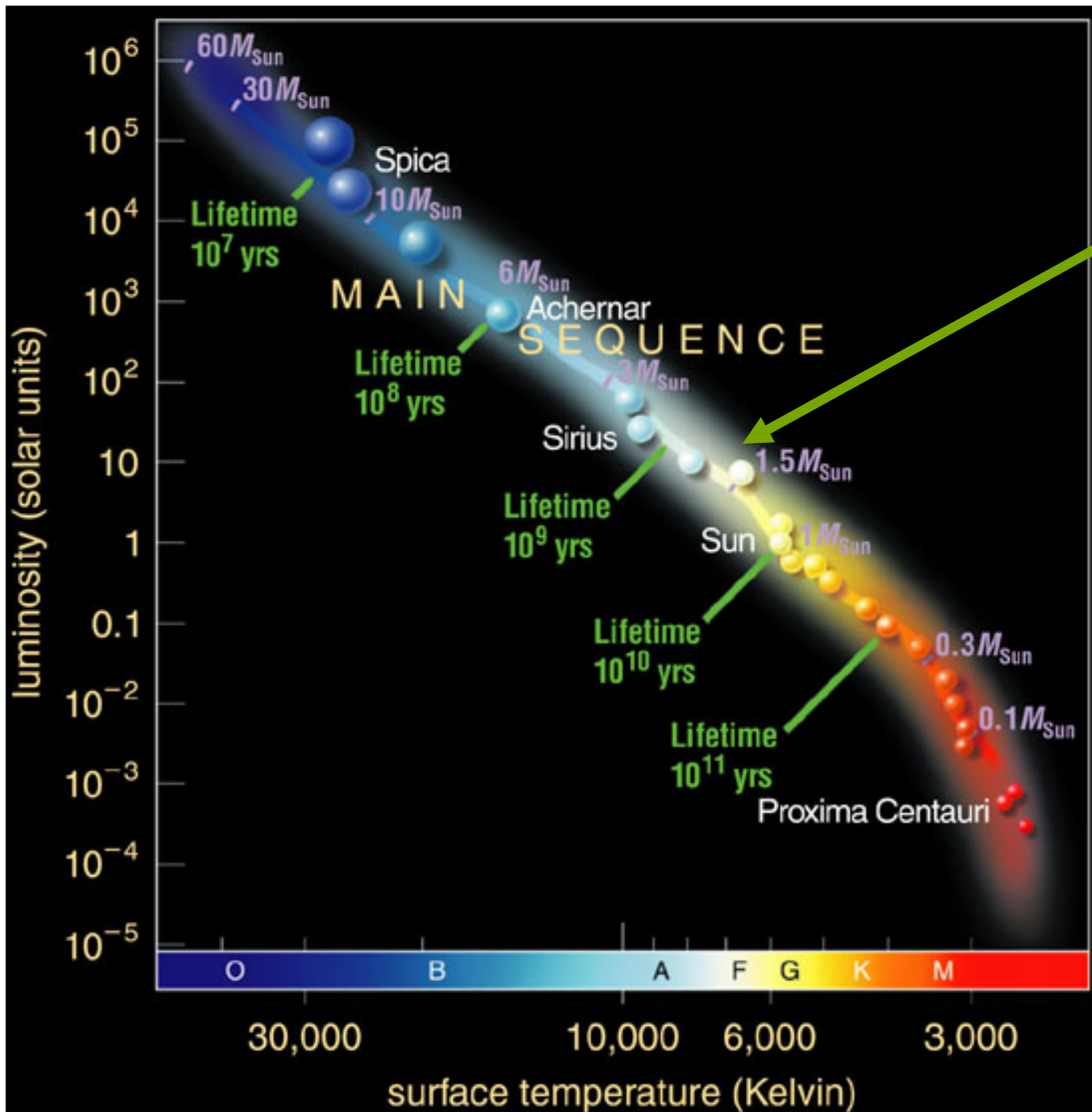
In terms of their suitability to host life, massive stars:

Are rare: **bad**

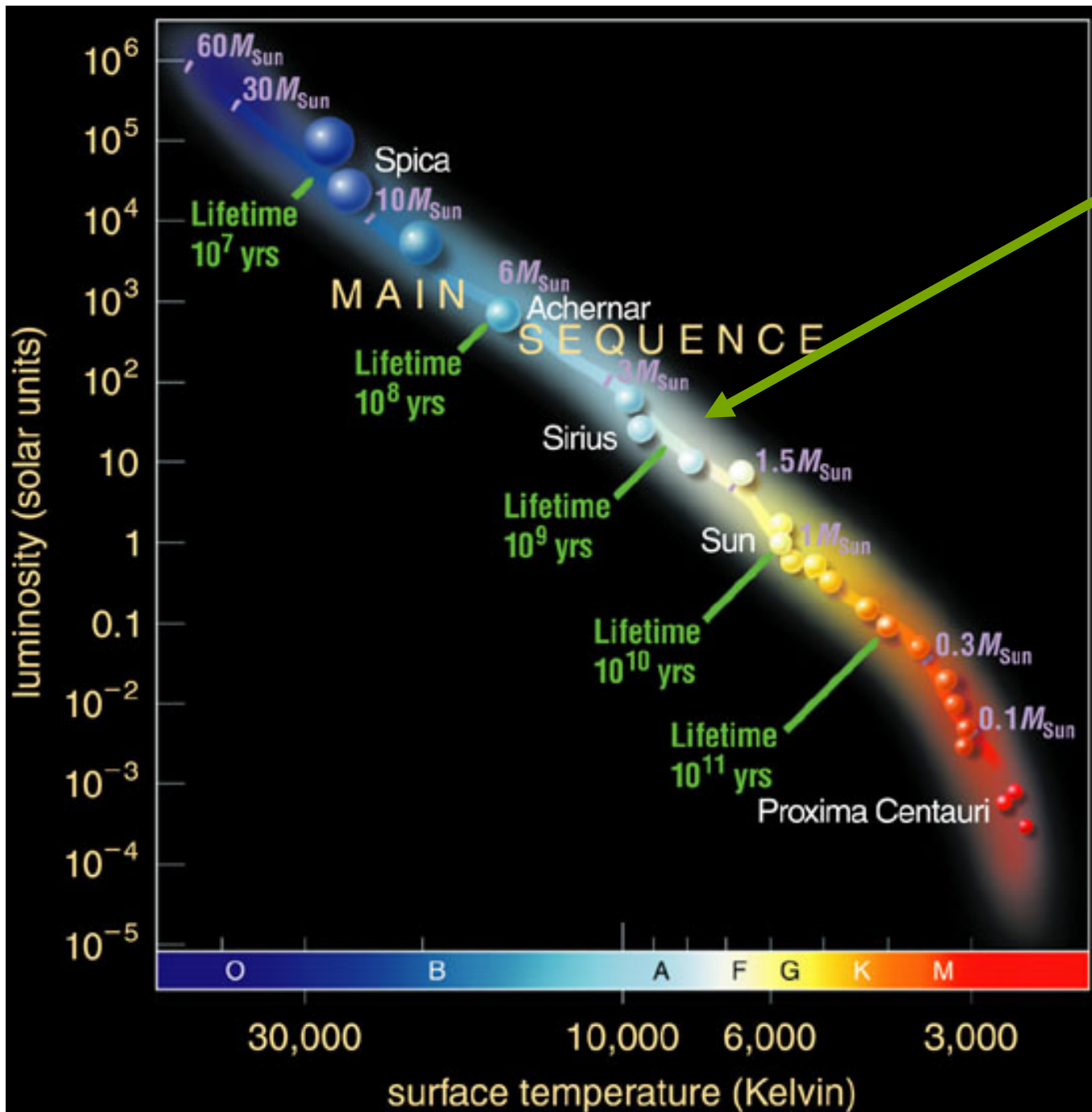
Emit a lot of energy: **good**

Have short lives: **bad**

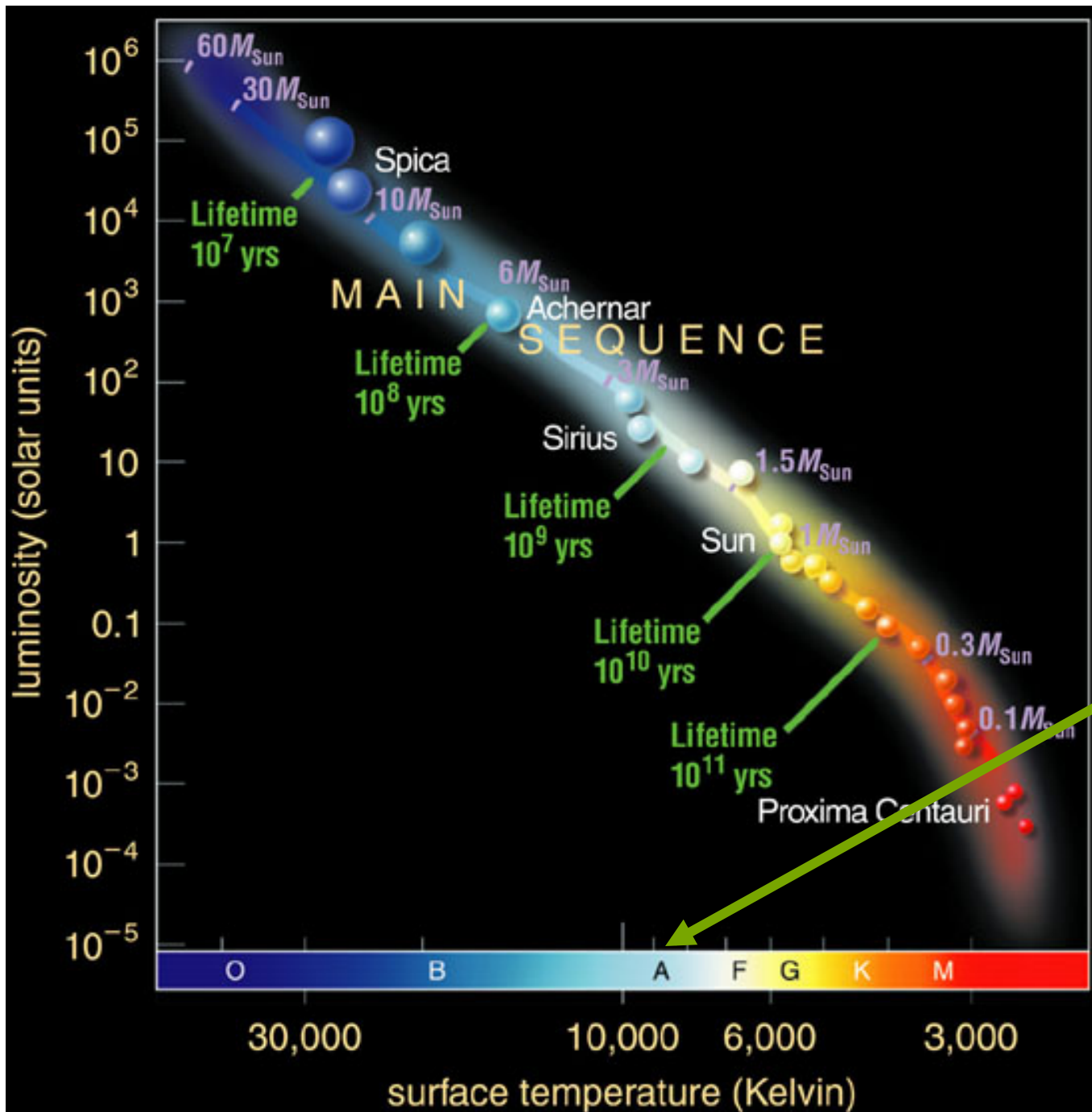
Give off lots of UV: **bad**



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.

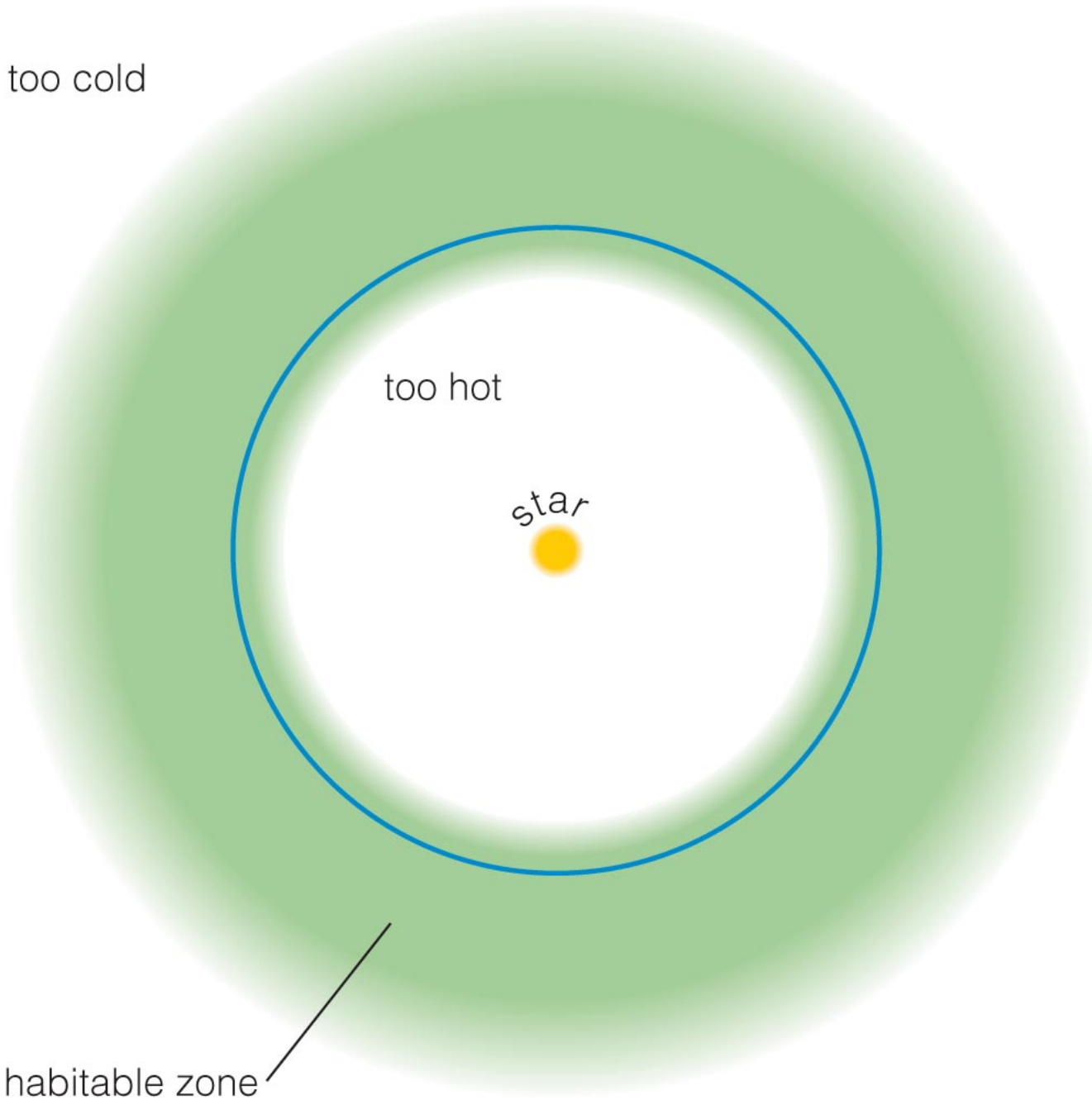
too cold

too hot

star

habitable zone

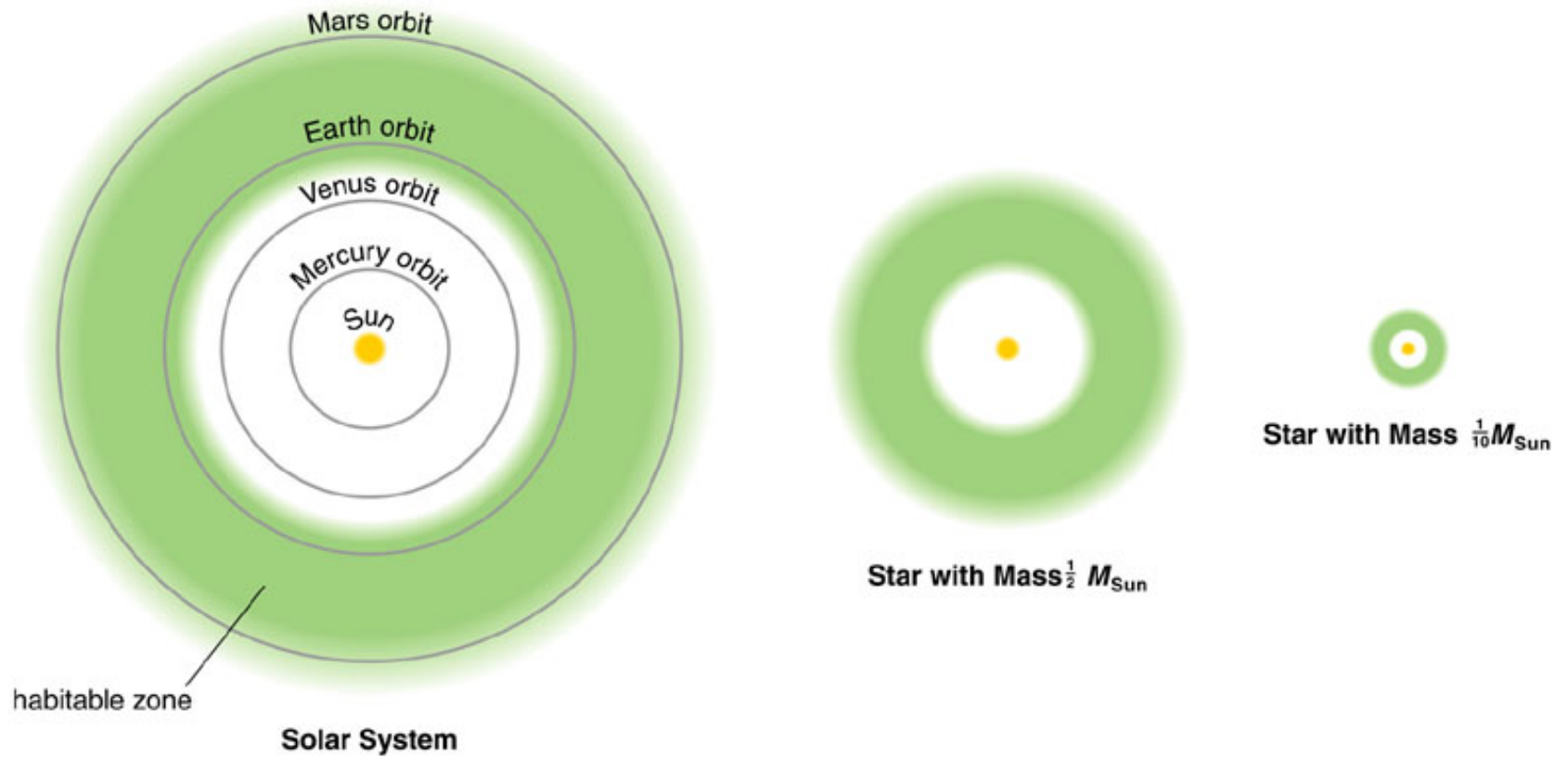
The Goldilocks premise: for a planet to be habitable, it must be within the range of distances from a star where the temperature allows water to be liquid on its surface.



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

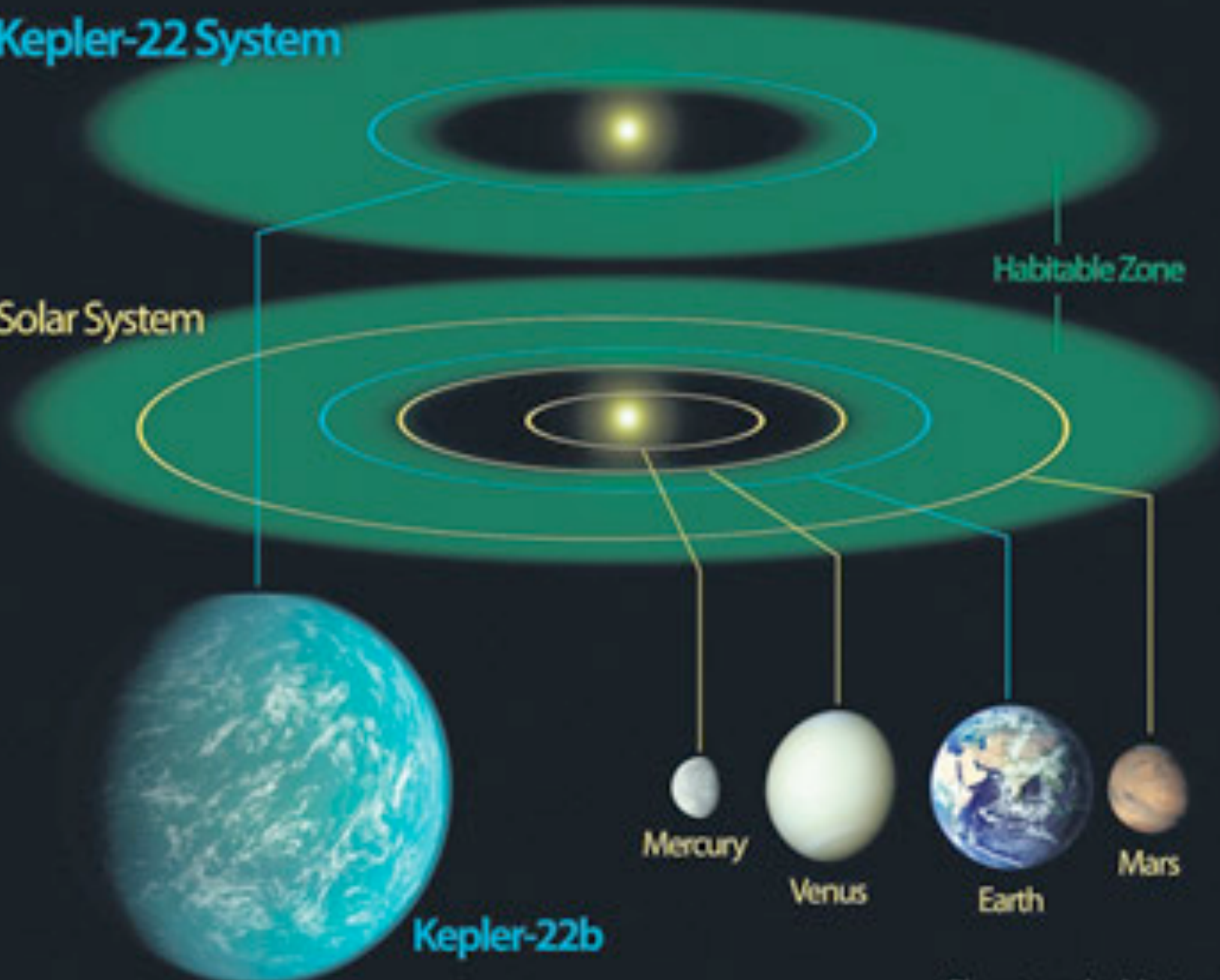


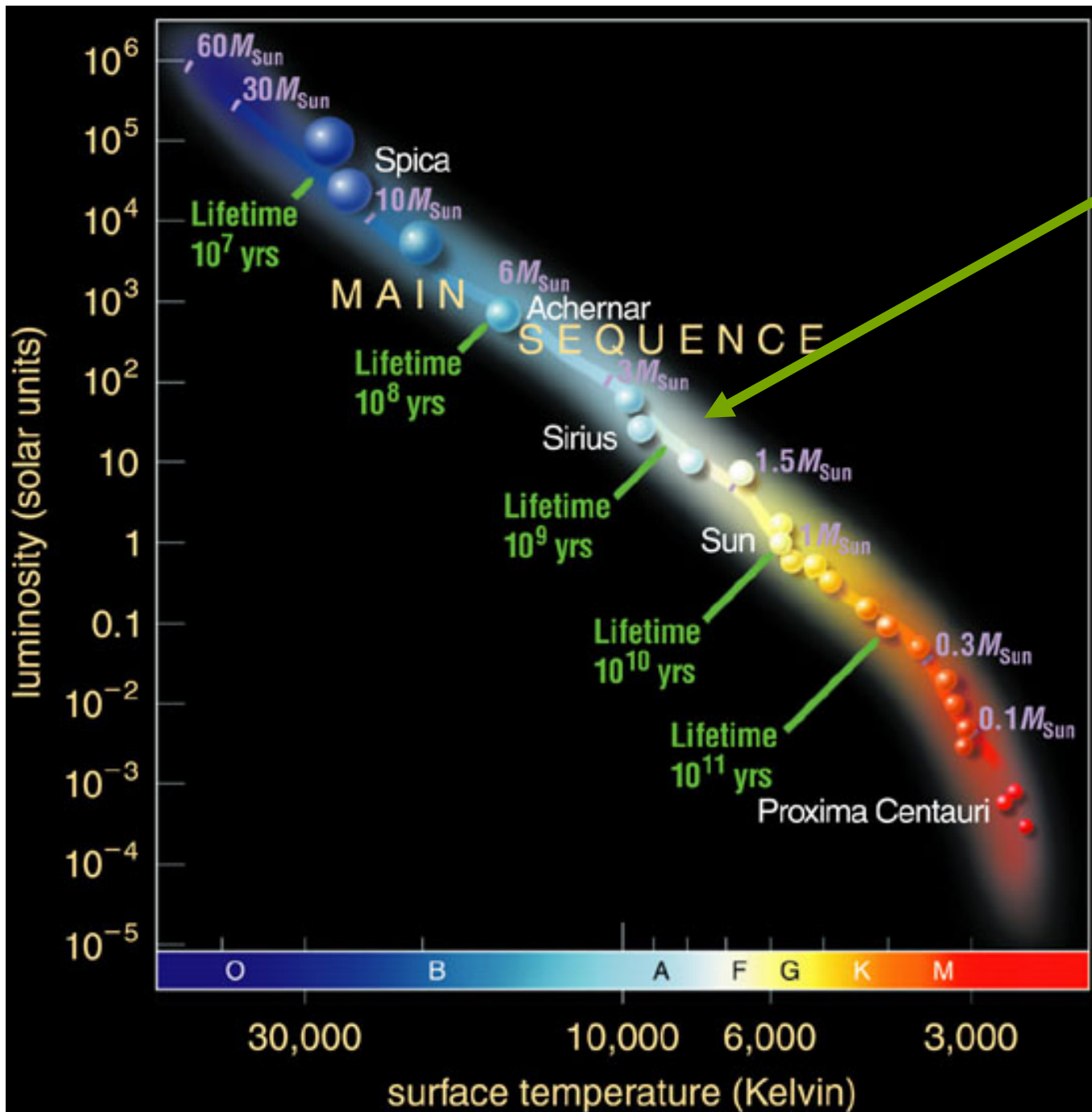
Earth



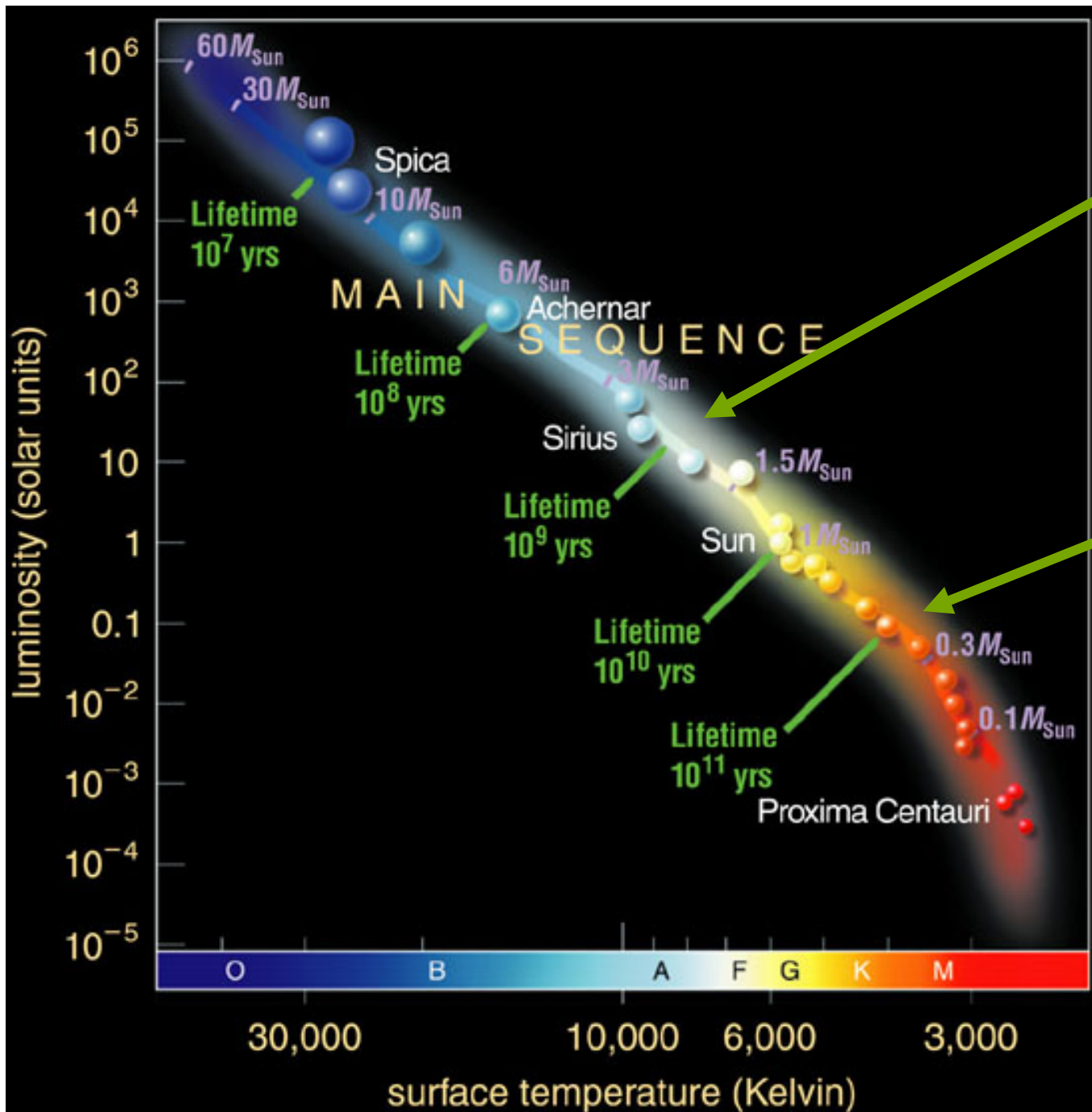
Mars

Planets and orbits to scale

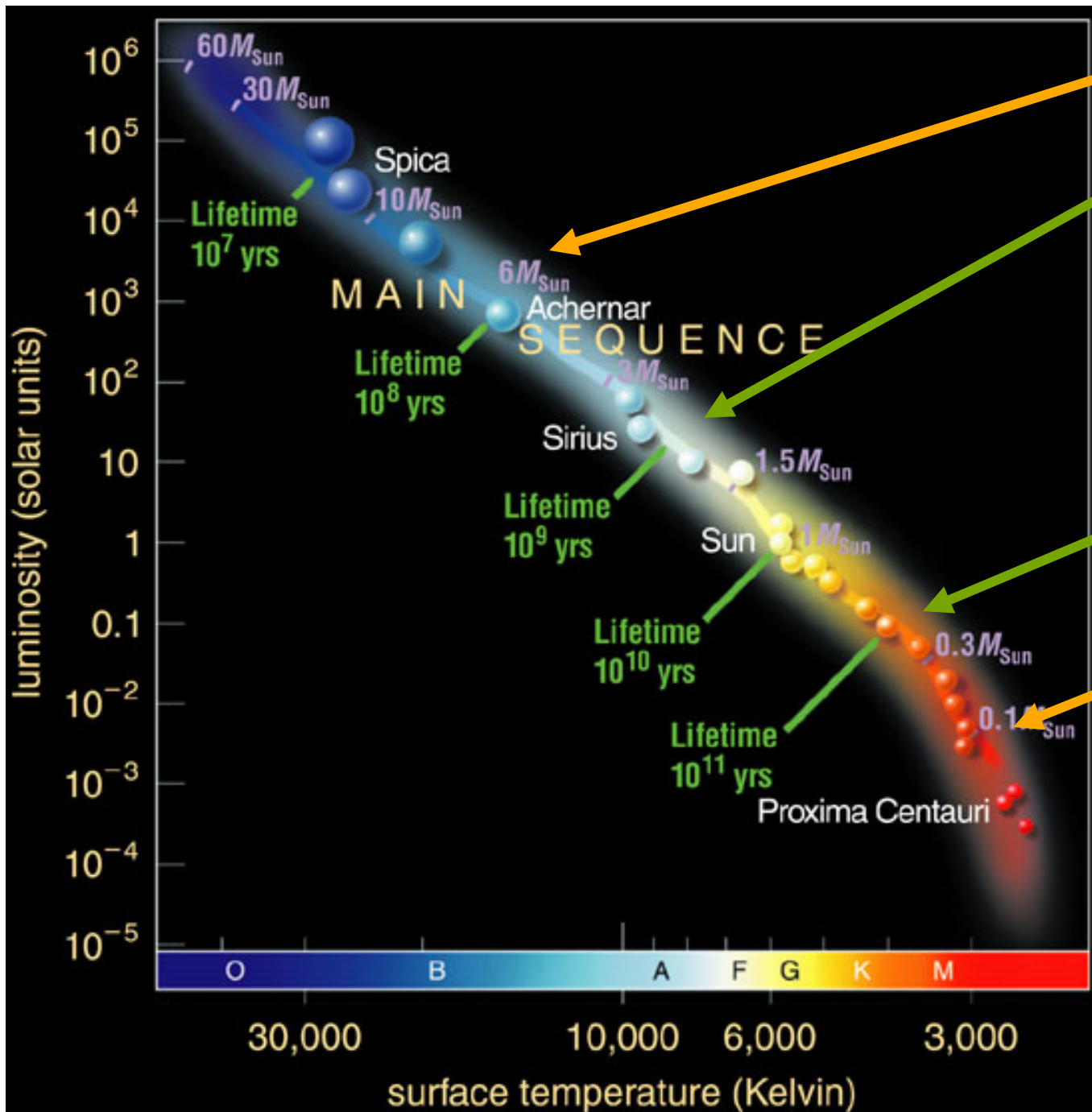




High mass limit of 2 times solar mass for lifetime to be at least 1 billion years for development of life.



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.