Crash Course in Stellar Evolution

Day 3, Python Bootcamp

Anna Rosen

Wednesday and Thursday Agenda

Wednesday:

1:30 - 2:30: Stellar Evolution Concepts and Data

2:30 - 2:45: Activity Description

2:45 - 3:00: Pair up and brainstorm - possible questions to investigate

3:00 - 3:10: Break

3:10 - 4:30: Begin investigations

Thursday:

1:30 - 3:00: Continued investigation and plotting

3:00 -3:10: Break

3:10 - 4:00: Continued investigation and plotting

4:00 - 4:30: Put together presentations

Friday:

1:30-2:00: Present your results and fabulous plots!

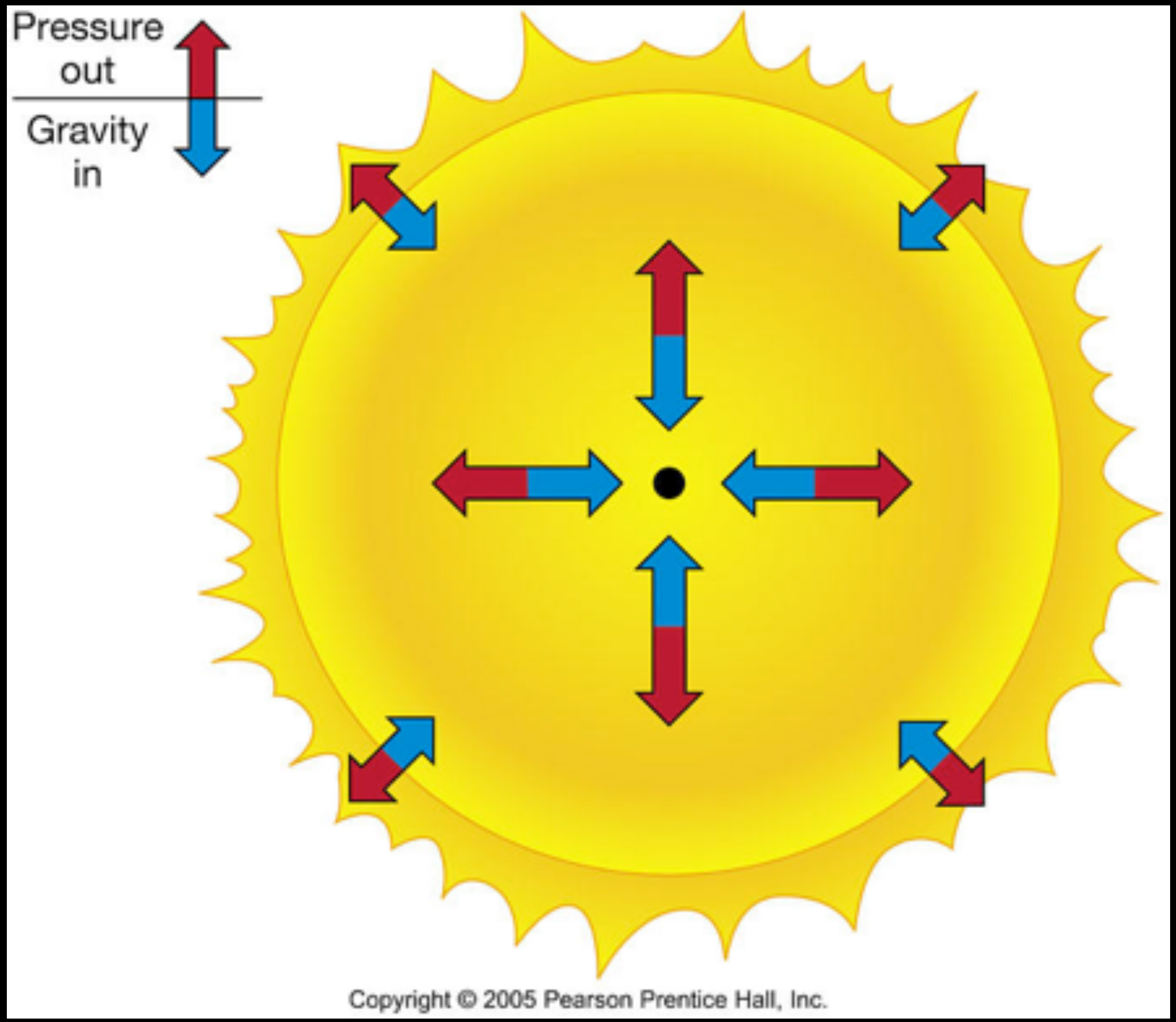
What is a star?

A star is a massive, luminous sphere of plasma held together by its own gravity.

Hydrostatic Equilibrium: Gravity holds a star together

A star is an object that is in hydrostatic equilibrium (HE).

HE occurs when the compression due to gravity is balanced by a pressure gradient force in the opposite direction.



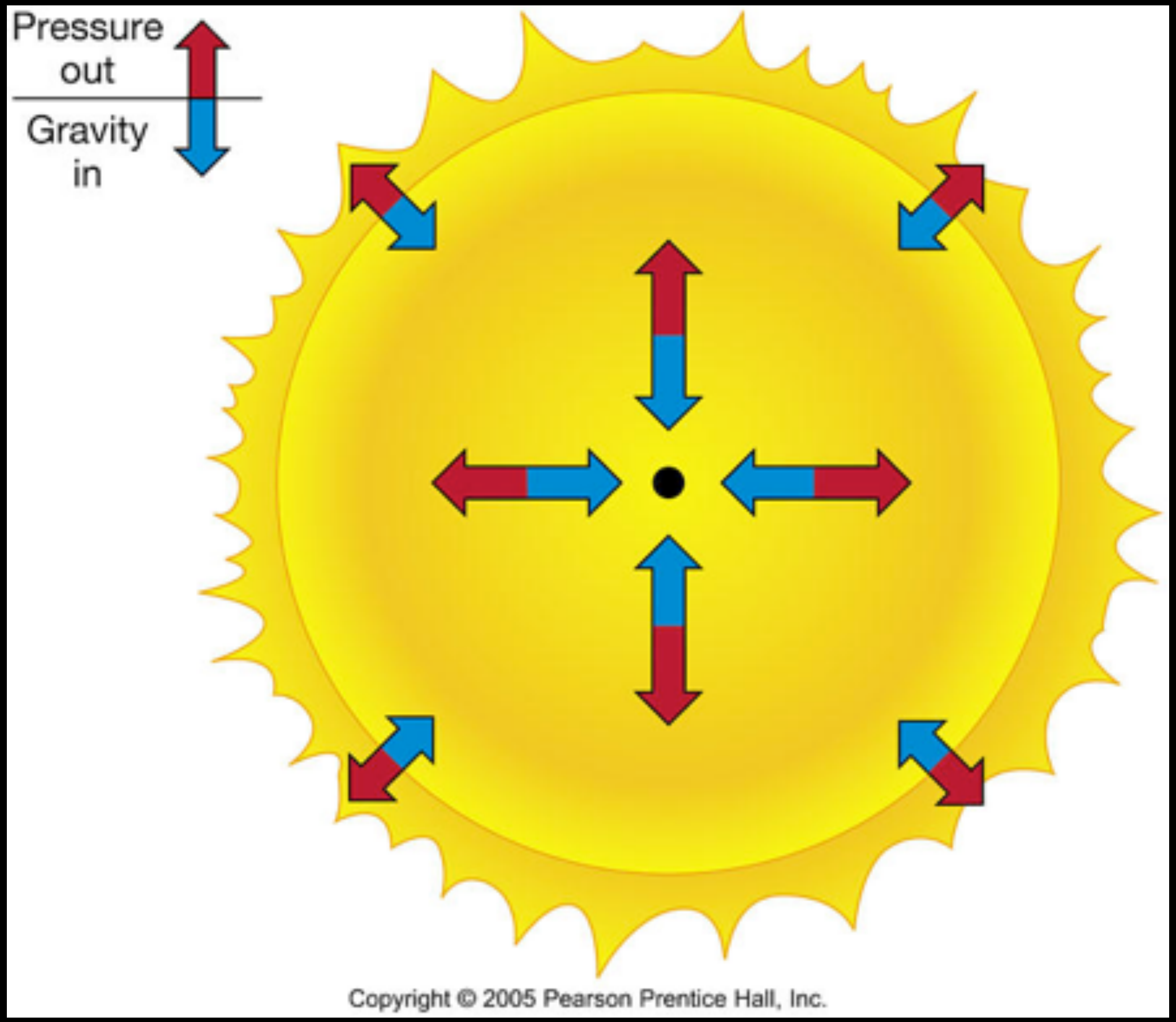
Deviations from hydrostatic equilibrium: What happens if…

|Pressure out| > |Gravity In|?

Expansion

|Pressure out| < |Gravity In|?

Contraction



Hydrostatic Equilibrium Examples

HE requires an internal pressure source.

In an ordinary star, thermal (gas) and radiation pressure (photons) prevents collapse.

Gas Pressure

$$P_{\mathrm{g}} = nkT$$

Radiation Pressure

$$P_{\mathrm{r}} = \frac{1}{3}aT^4$$

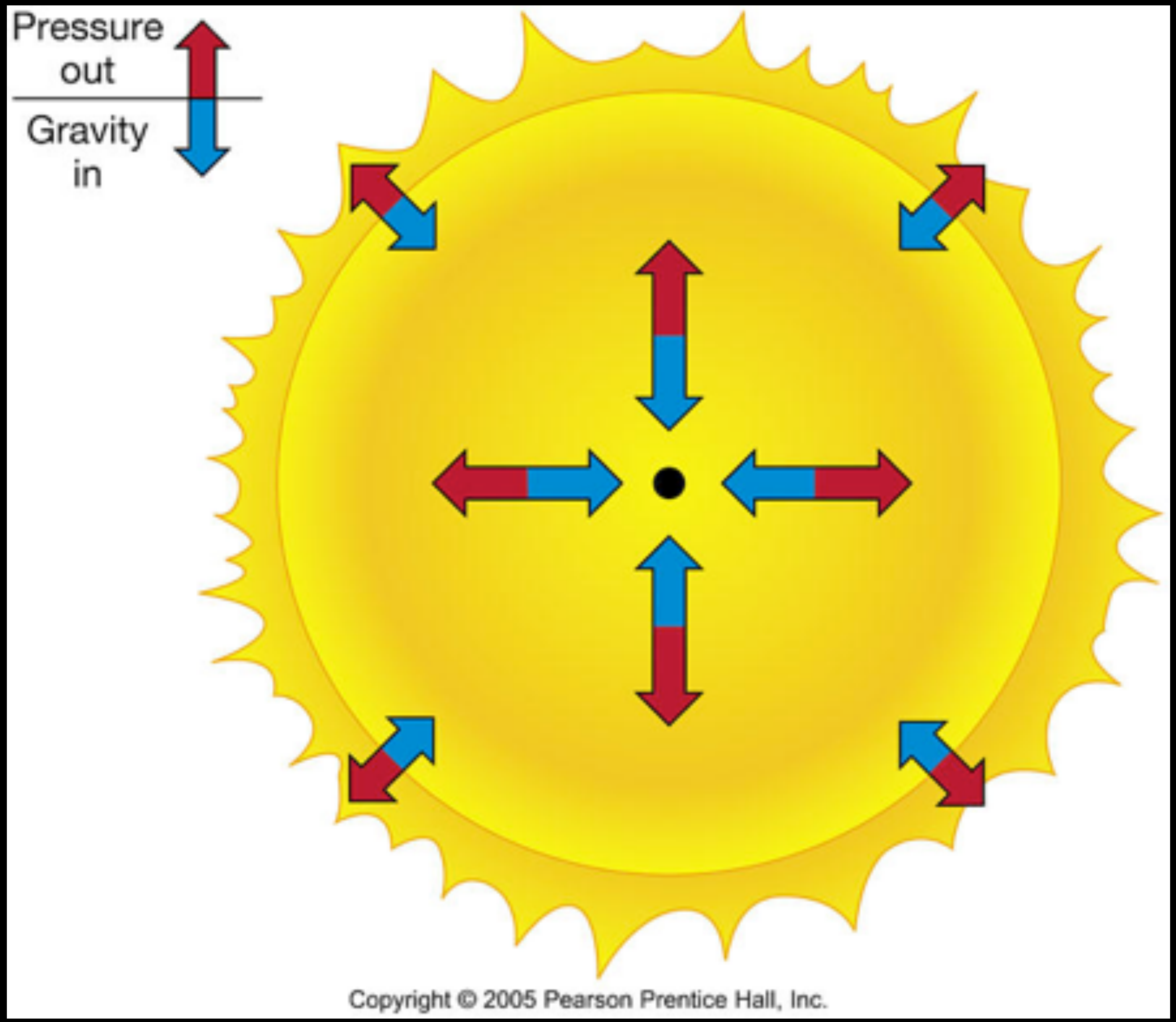
Hydrostatic Equilibrium (Revisited): What happens if…

|Pressure out| > |Gravity In|?

Expansion: Star will expand causing self-gravity to decrease,
T will decrease causing P_g and P_r to decrease

|Pressure out| < |Gravity In|?

Contraction: Star will contract causing self gravity to increase,
T will increase causing P_g and P_r to increase



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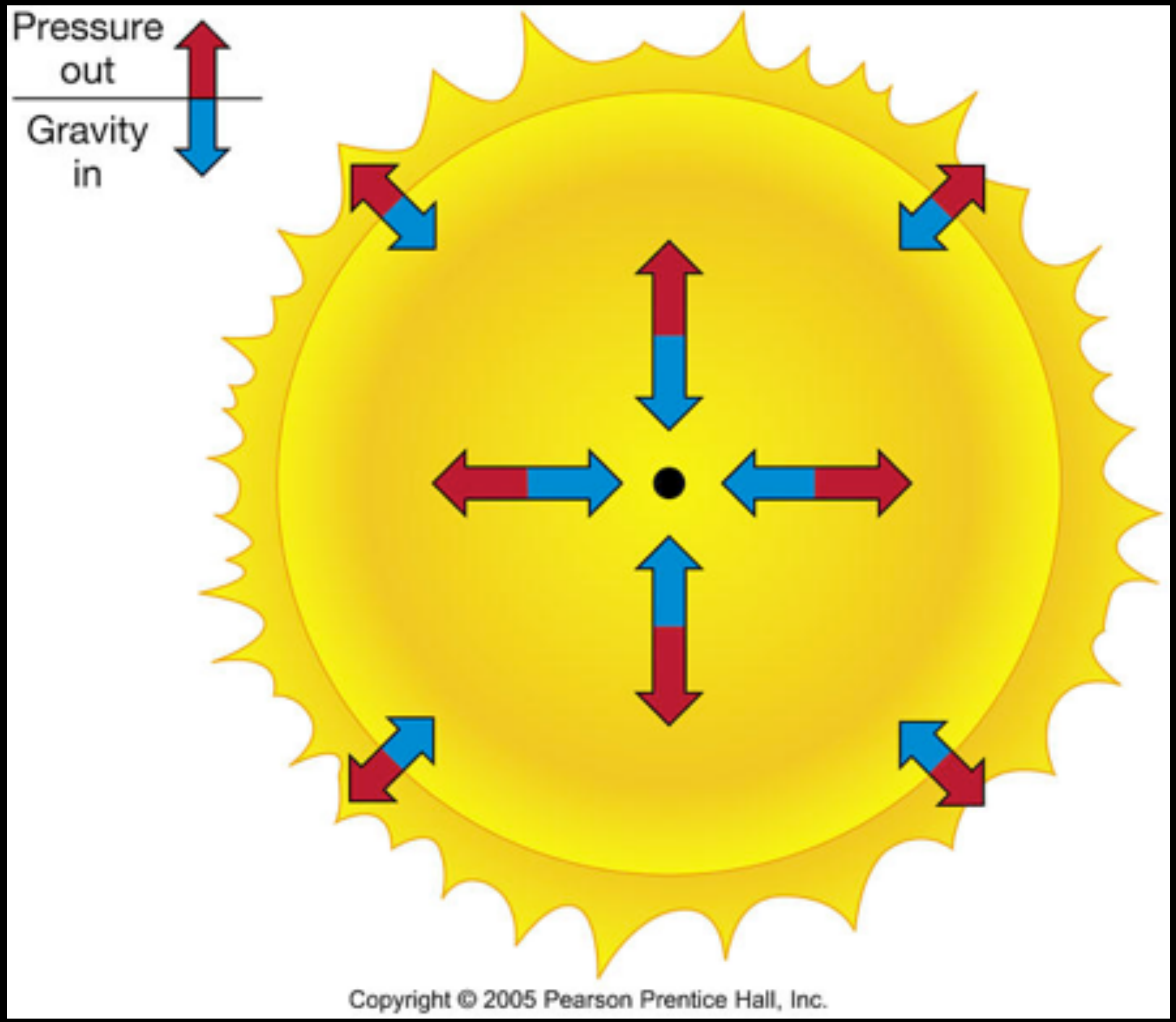
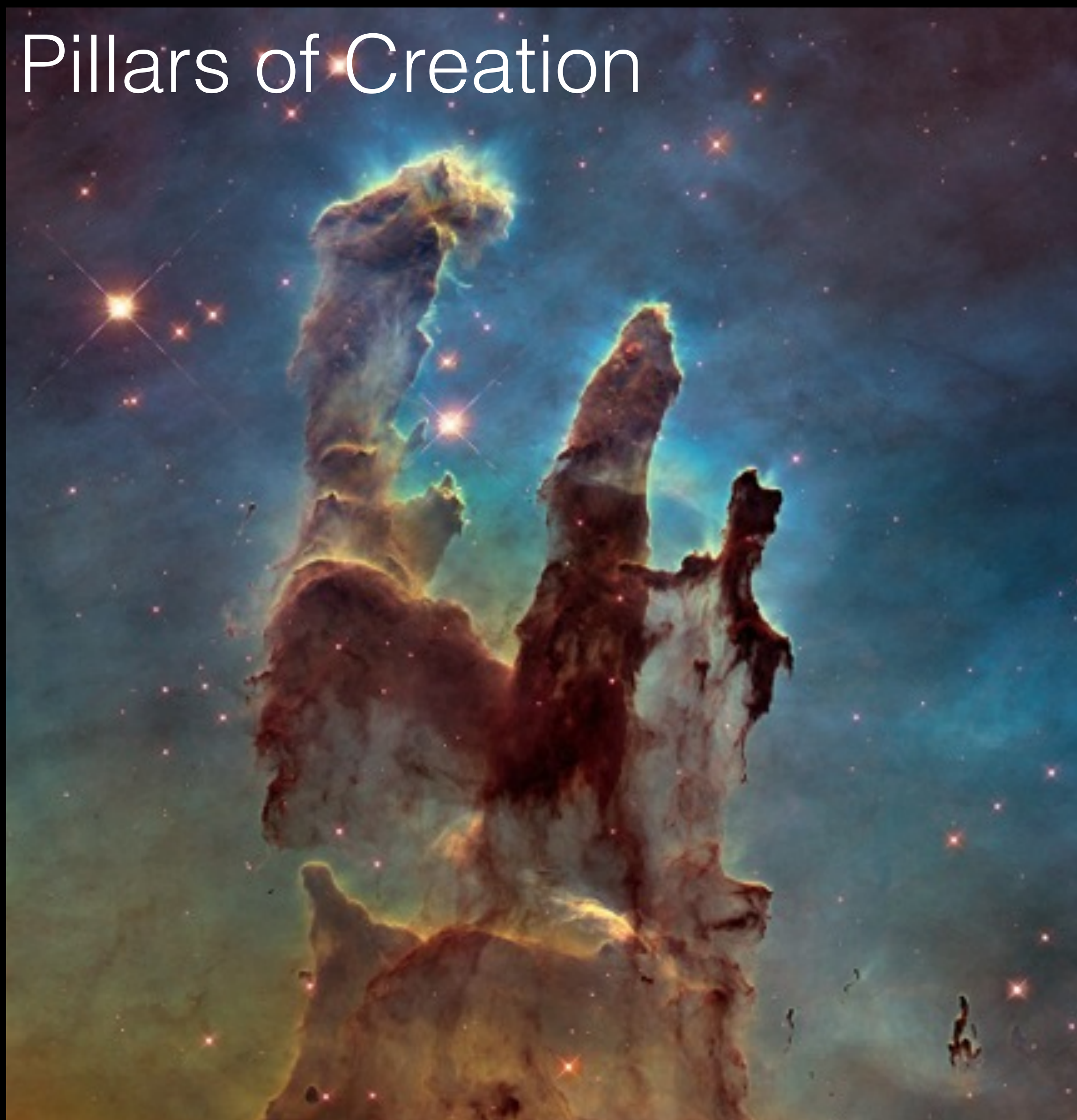


The star will always (try to) self-equilibrate!

How do stars form?

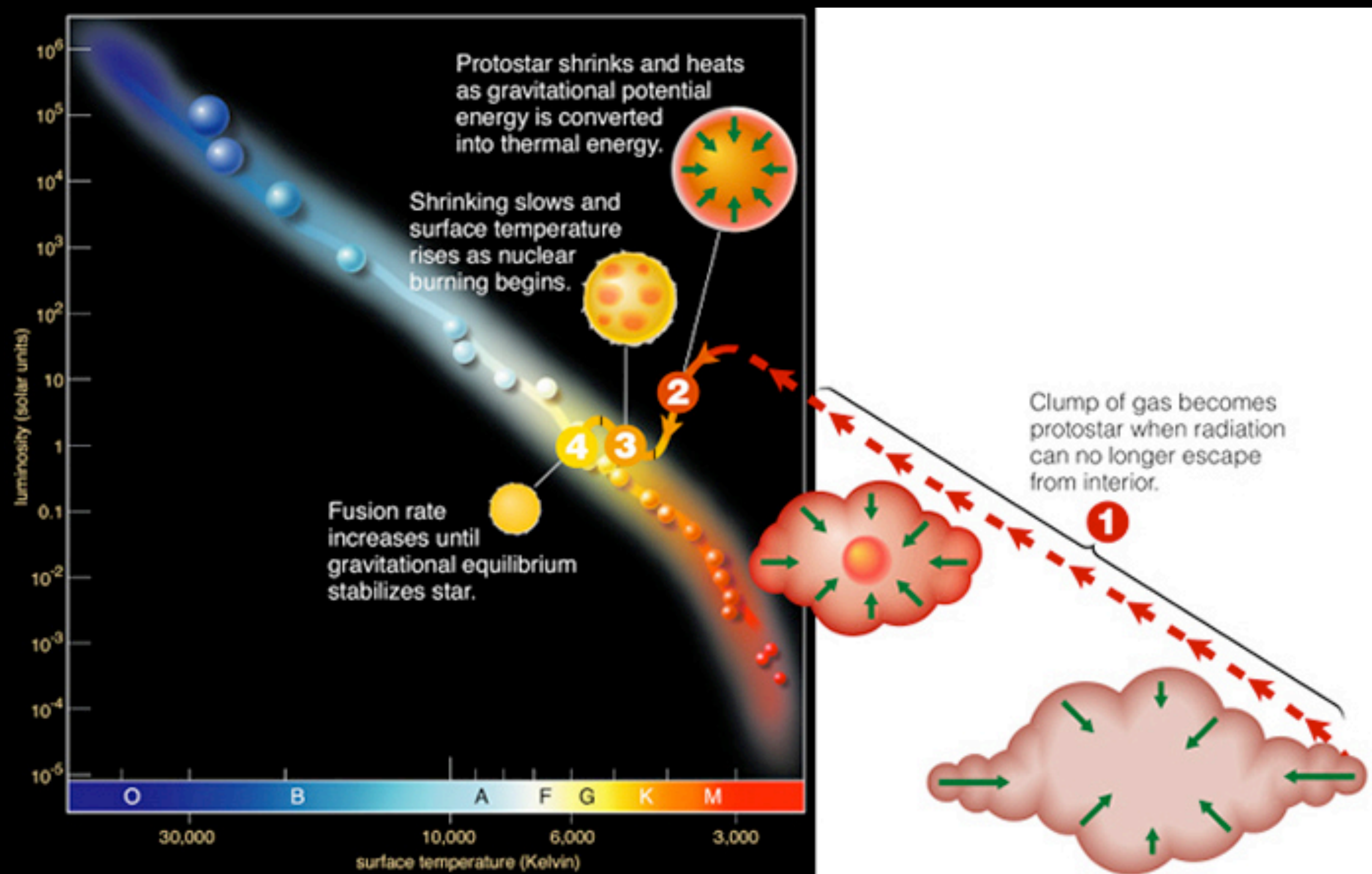
Stars form out of the densest, coolest gas in the universe



Visible (Hubble)

Near-Infrared (Hubble)

Star Formation 101



Gravitational Potential Energy

$$E_{\rm GR} \approx -\frac{GM^2}{R}$$

Thermal Kinetic Energy

$$E_{\rm KE} = \frac{3}{2} N k T_{\rm cl}$$

Collapse occurs when

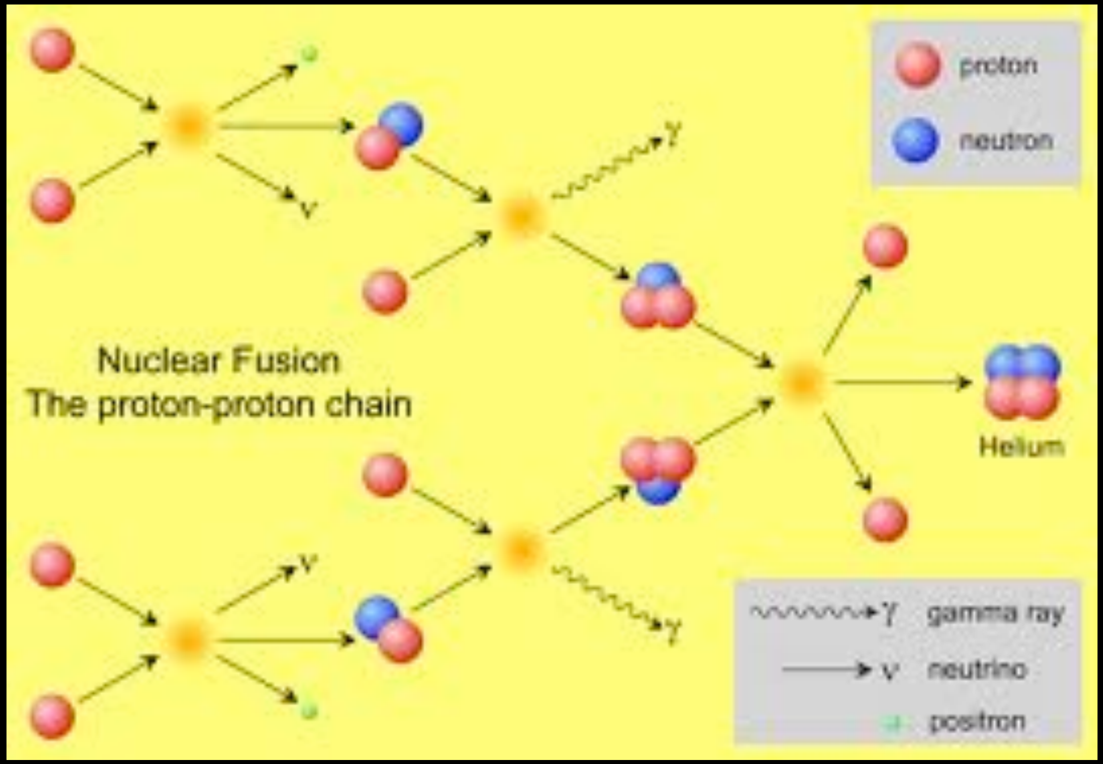
$$|E_{\rm GR}| > E_{\rm KE}$$

Nuclear Fusion acts as energy source to halt contraction

As the protostar contracts it will become hot and dense enough to start nuclear fusion…

A star is born!

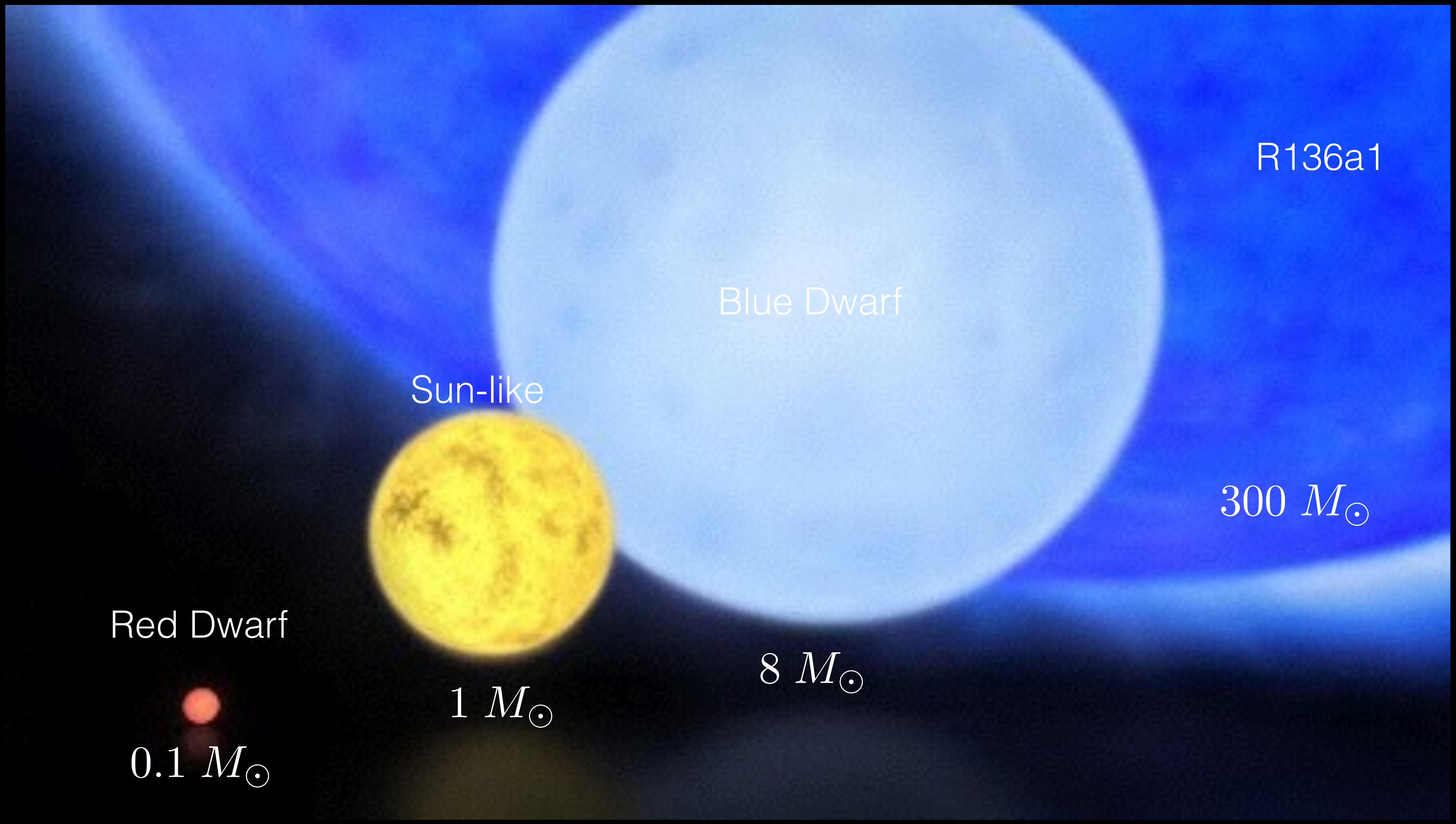
In the sun, energy is generated by fusing 4 H atoms into an He atom. The excess mass is converted to energy.



$$4\ {}^{1}H \rightarrow {}^{4}He + \text{Energy}$$

$$E = mc^2$$

Stars span a large mass range…



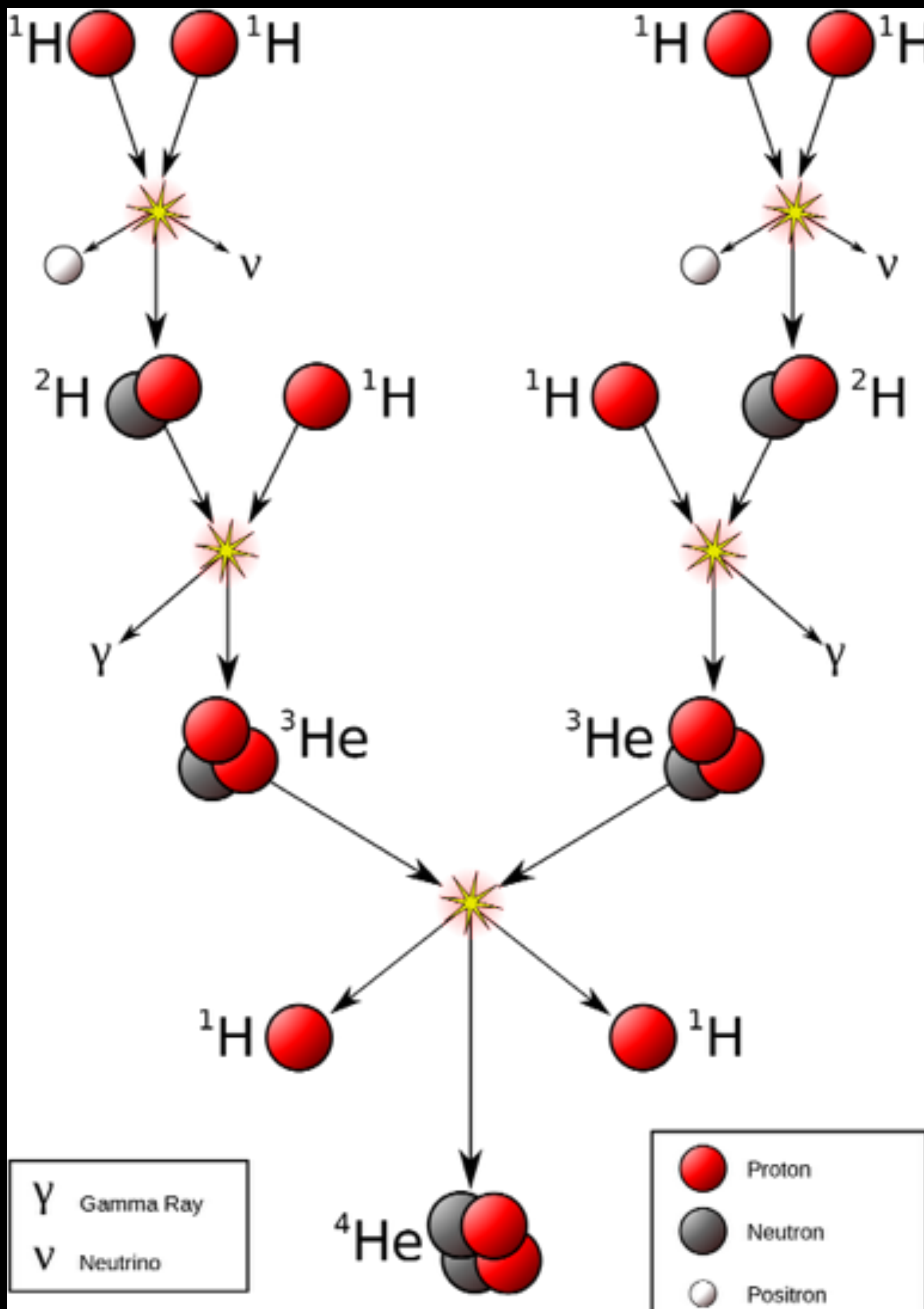
Star's birth mass controls its properties (luminosity, temperature, color, etc.) and evolution.

Sagittarius Star Cloud

Hubble Heritage

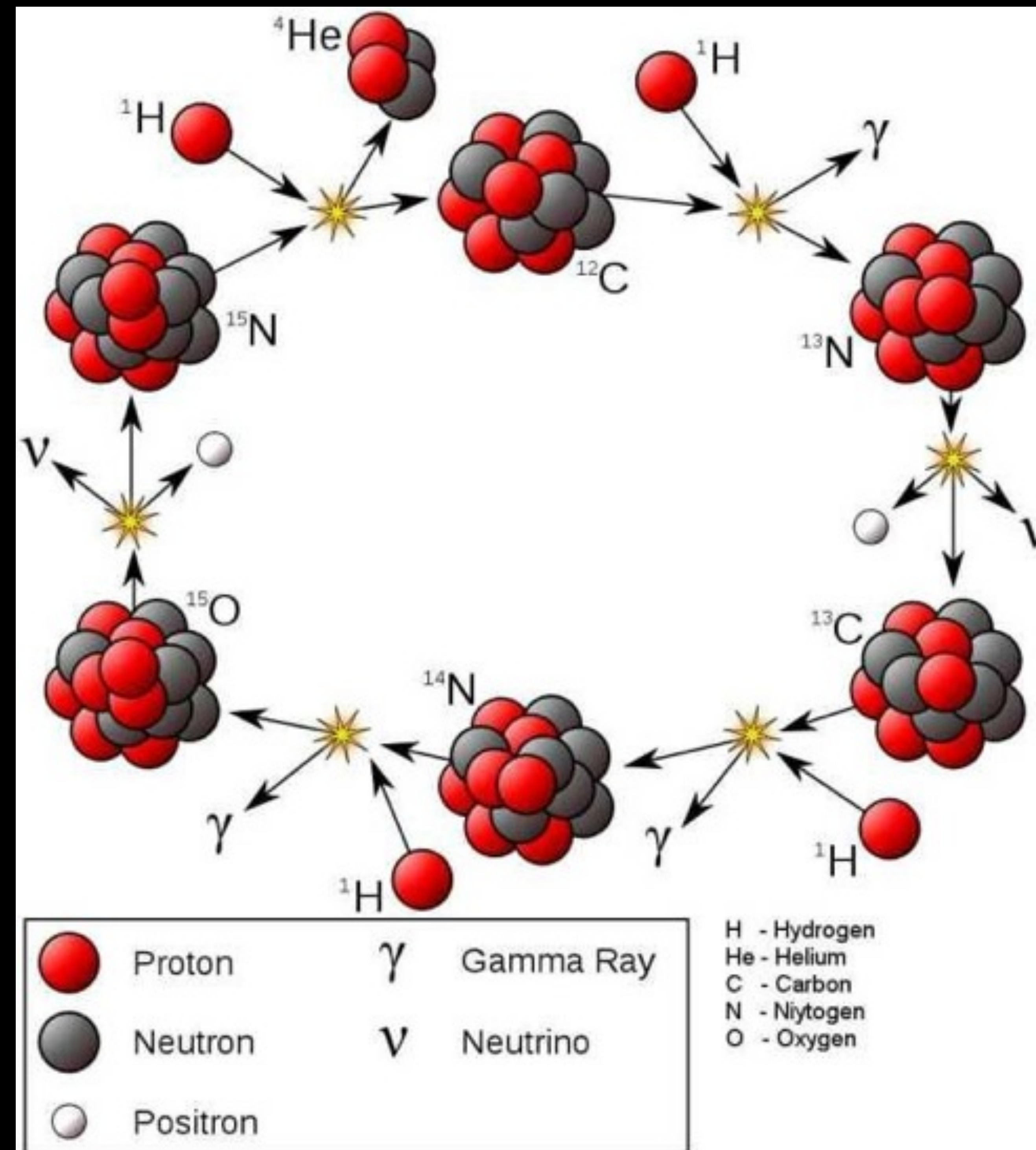
PRC98-30 • Space Telescope Science Institute • Hubble Heritage Team

Low-mass and high-mass stars undergo different fusion reactions



p-p chain in low-mass stars $M \lesssim 1 M_\odot$

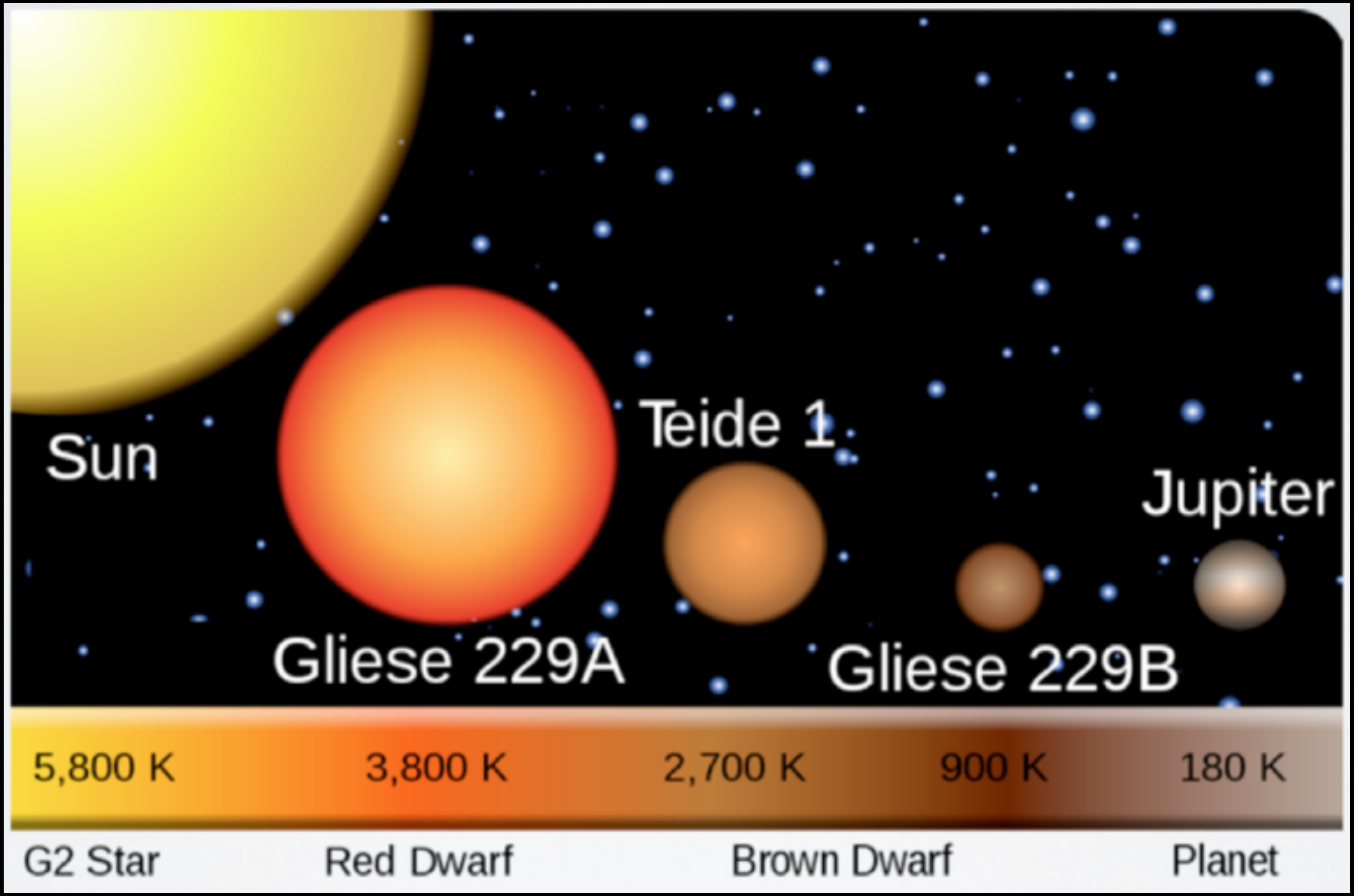
$$4\ ^1H \rightarrow ^4 He + \text{Energy}$$



CNO cycle in massive stars $M \gtrsim 1 M_\odot$

CNO acts as catalysts

Lower limits on stellar masses



Objects with masses less than ~0.075 $M_{\odot}$ (brown dwarfs) can not reach high enough temperatures to ignite hydrogen.

Upper limits on stellar masses

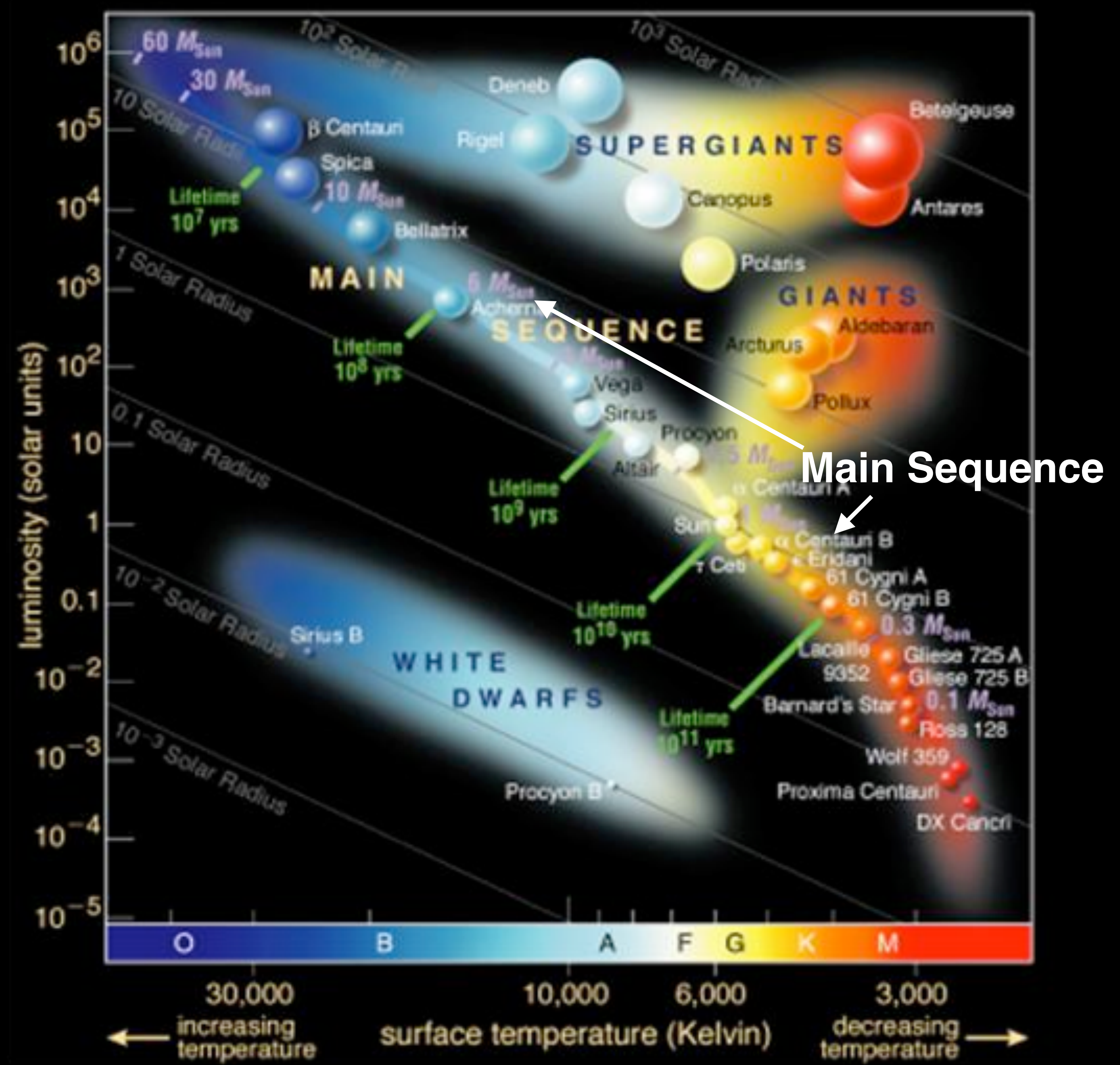
Upper mass limit: ~few 100 $M_\odot$
(Upper mass limit from observations - still debated)

Hydrogen Burning: Main-sequence stars

Stars undergoing hydrogen fusion live on the main sequence

After a star burns all of it’s available H it deviates from HE and the core contracts

Once core is hot enough due to contraction it will ignite He



Hertzsprung-Russell (HR) Diagram

Exercise: How long will the sun burn Hydrogen?

Luminosity of the sun (energy emitted/sec)

$$L_\odot = 3.84 \times 10^{33}\ \mathrm{ergs/s}$$

Hint: L ≈ (total energy emitted)/(time scale)

1 reaction releases (conversion of 4 H→He)

$$E_{\mathrm{rel}} = 4.28 \times 10^{-5}\ \mathrm{erg/reaction}$$

Assume core mass (amount of hydrogen burned)

$$M_{\mathrm{core}} \approx 0.1\ M_\odot = 1.99 \times 10^{32}\ \mathrm{g}$$

Mass burned during fusion reaction

$$m_{4\mathrm{H}} \approx 4 \times m_{\mathrm{p}} \approx 6.68 \times 10^{-24}\ \mathrm{g}$$

Solution: How long will the sun burn Hydrogen?

$$L \approx \frac{E_{\mathrm{tot}}}{t_{\mathrm{life}}} \longrightarrow t_{\mathrm{life}} \approx \frac{E_{\mathrm{tot}}}{L}$$

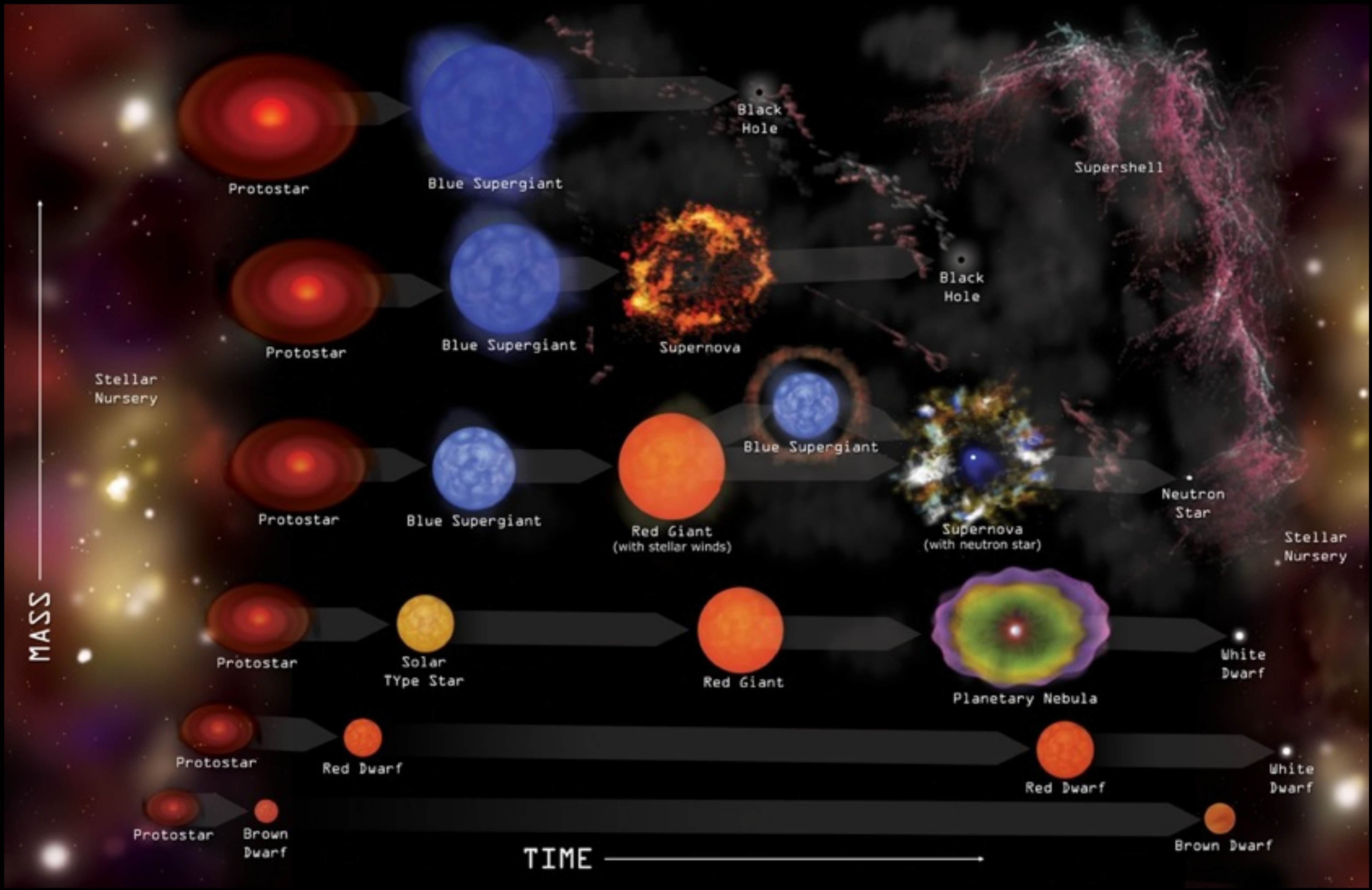
$$E_{\mathrm{tot}} \approx \frac{M_{\mathrm{core}}}{M_{4H}} \times E_{\mathrm{rel}}$$

Total number of reactions

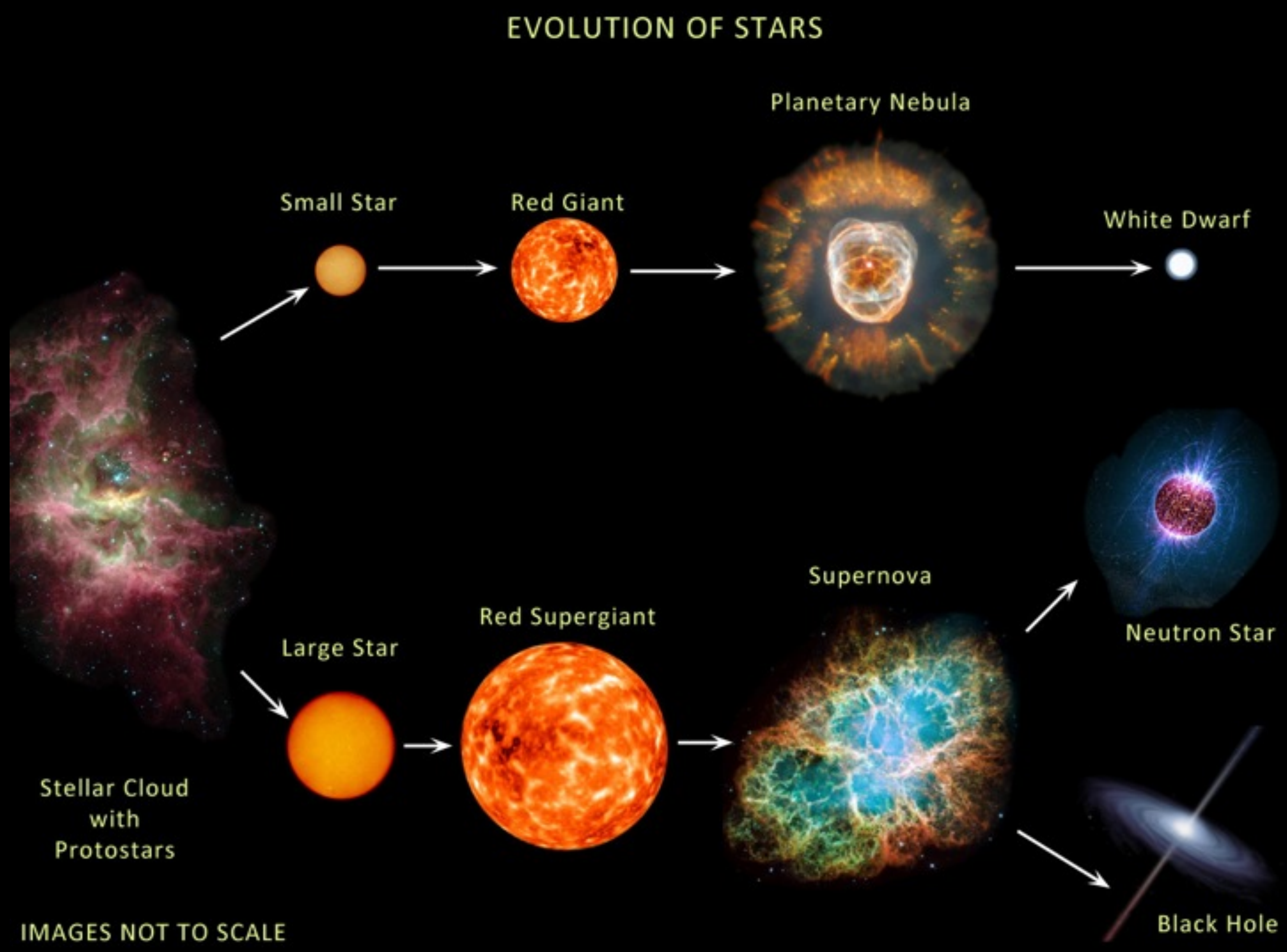
$$t_{\mathrm{life}} \approx \frac{\frac{M_{\mathrm{core}}}{M_{4H}} \times E_{\mathrm{rel}}}{L}$$

$$t_{\mathrm{life}} \approx 3.32 \times 10^{17}\ \mathrm{s} \approx 10.5\ \mathrm{Gyr}$$

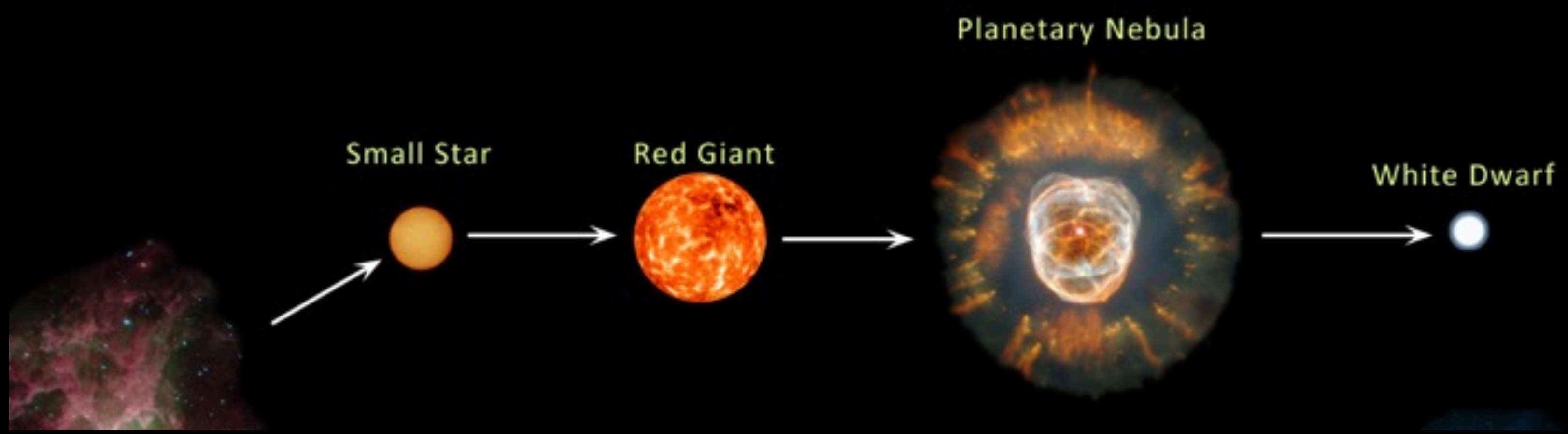
Initial stellar mass controls the star's evolution

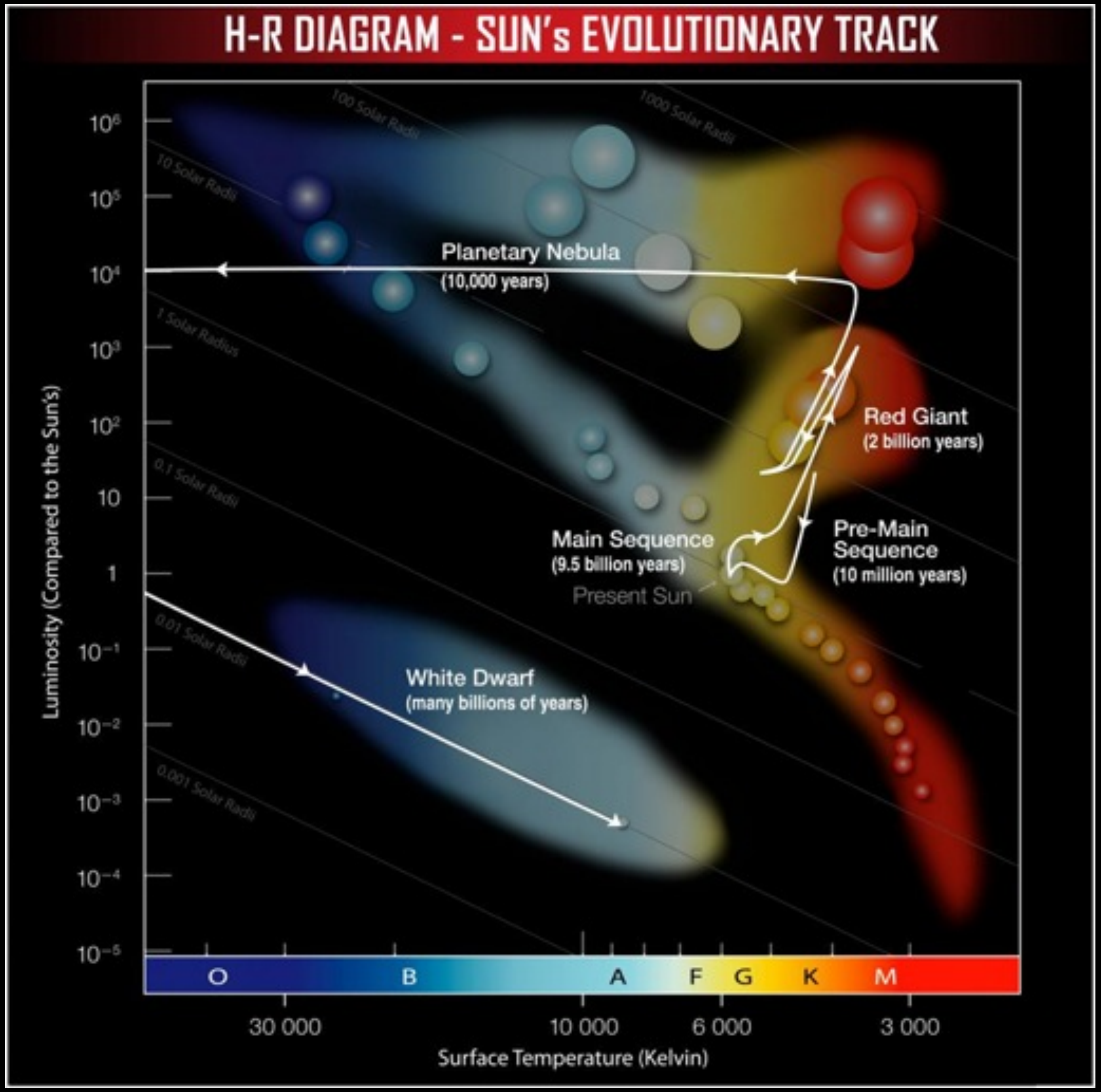


Let's focus on sun-like and 8-25 $M_\odot$ stars



Evolution of a sun-like star





Sits on the main-sequence for a few-several billion years

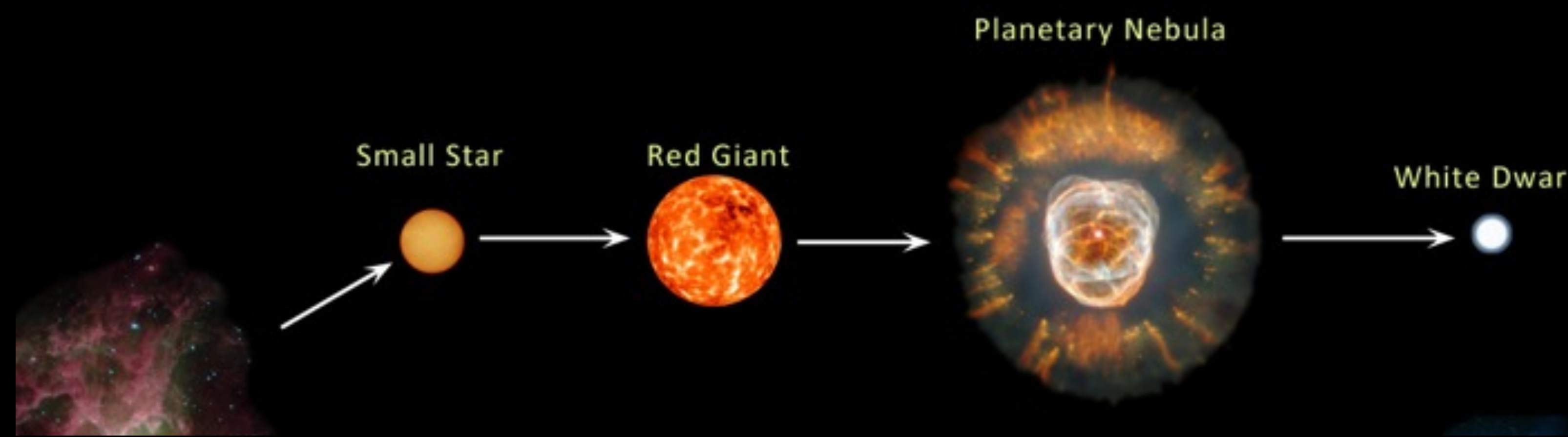
(H→He)

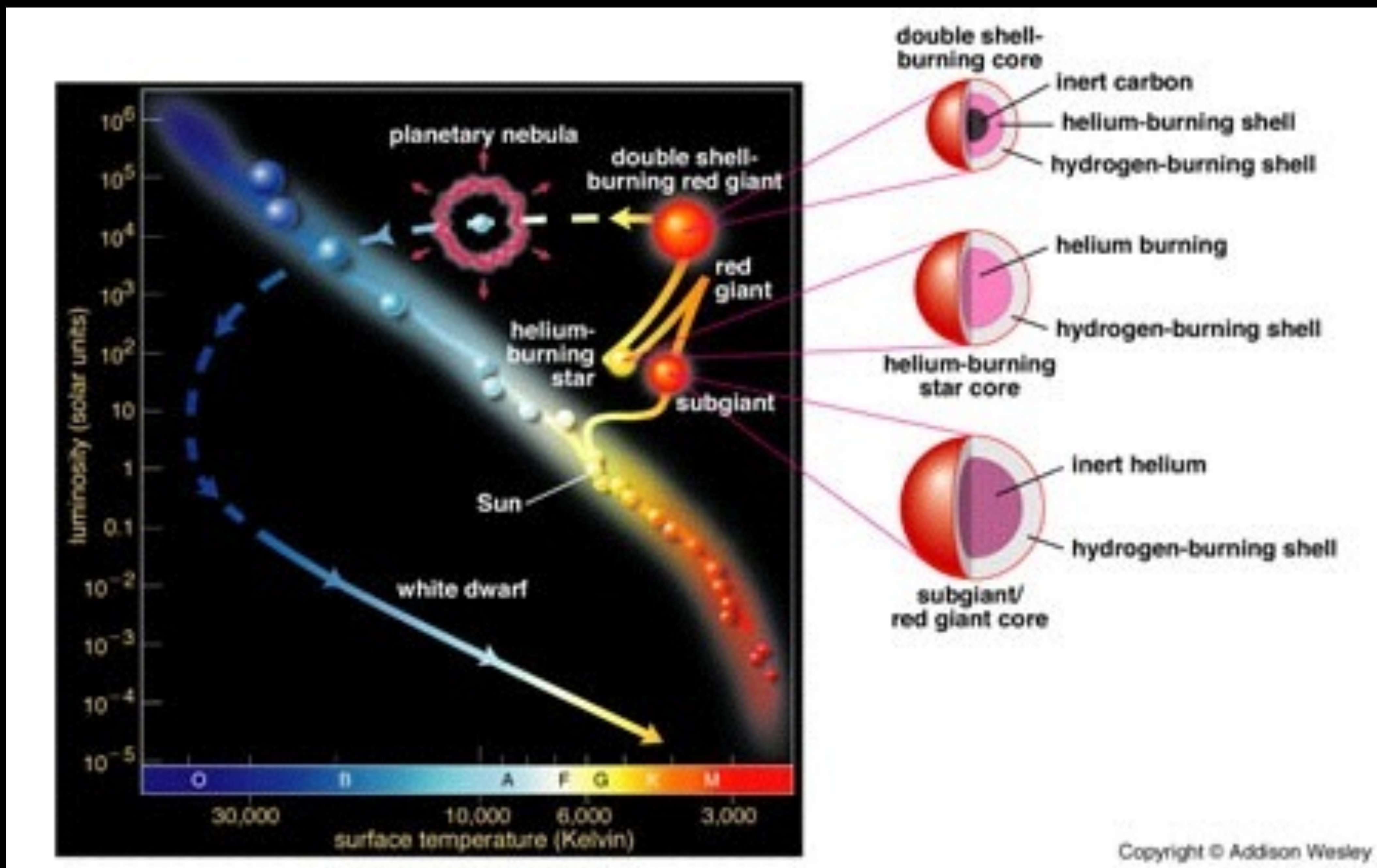
Eventually becomes a red giant

(He→C and O)

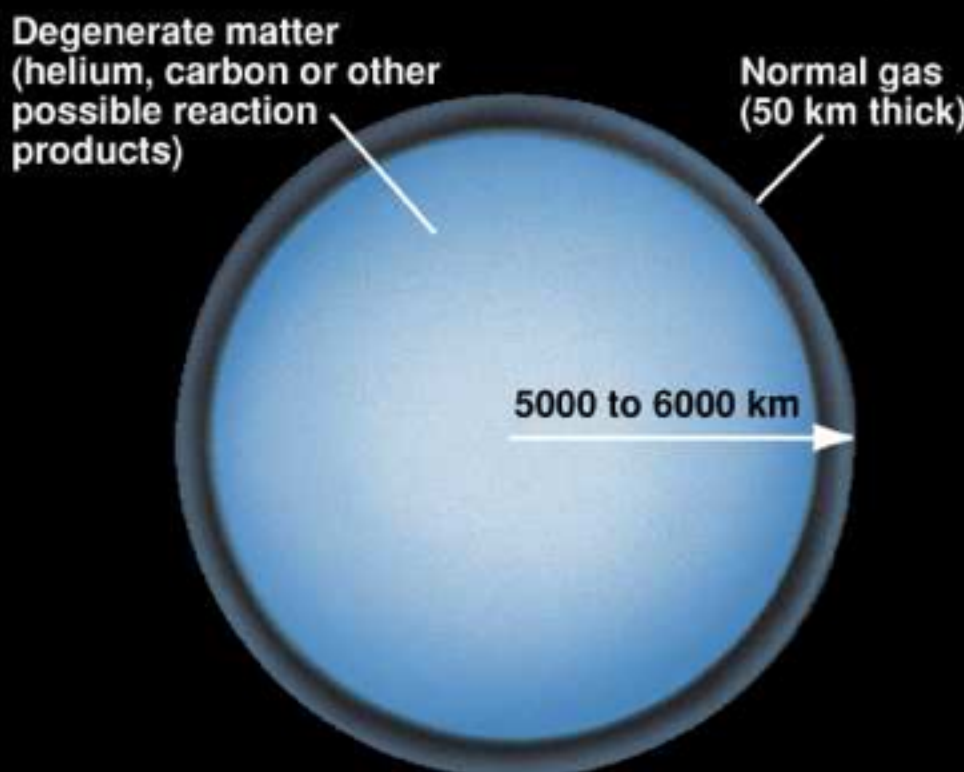
Ends as a white dwarf (supported by degeneracy pressure)

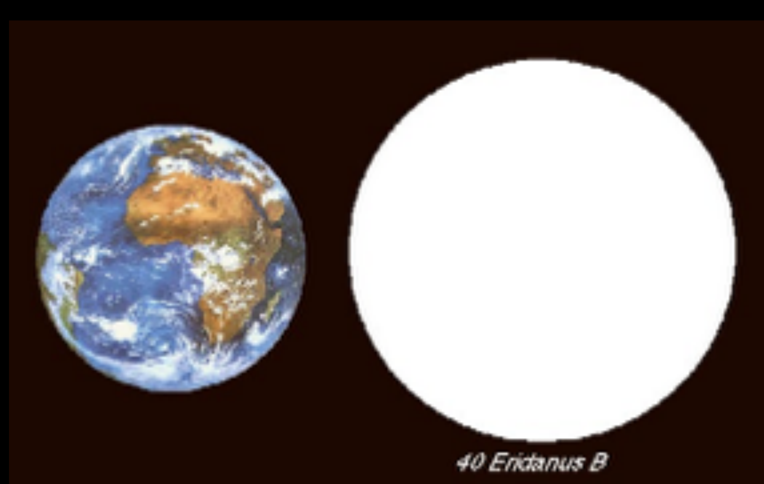
Evolution of a sun-like star





End product of a sun-like star: White Dwarfs





White dwarfs (WDs) are supported by electron degeneracy pressure

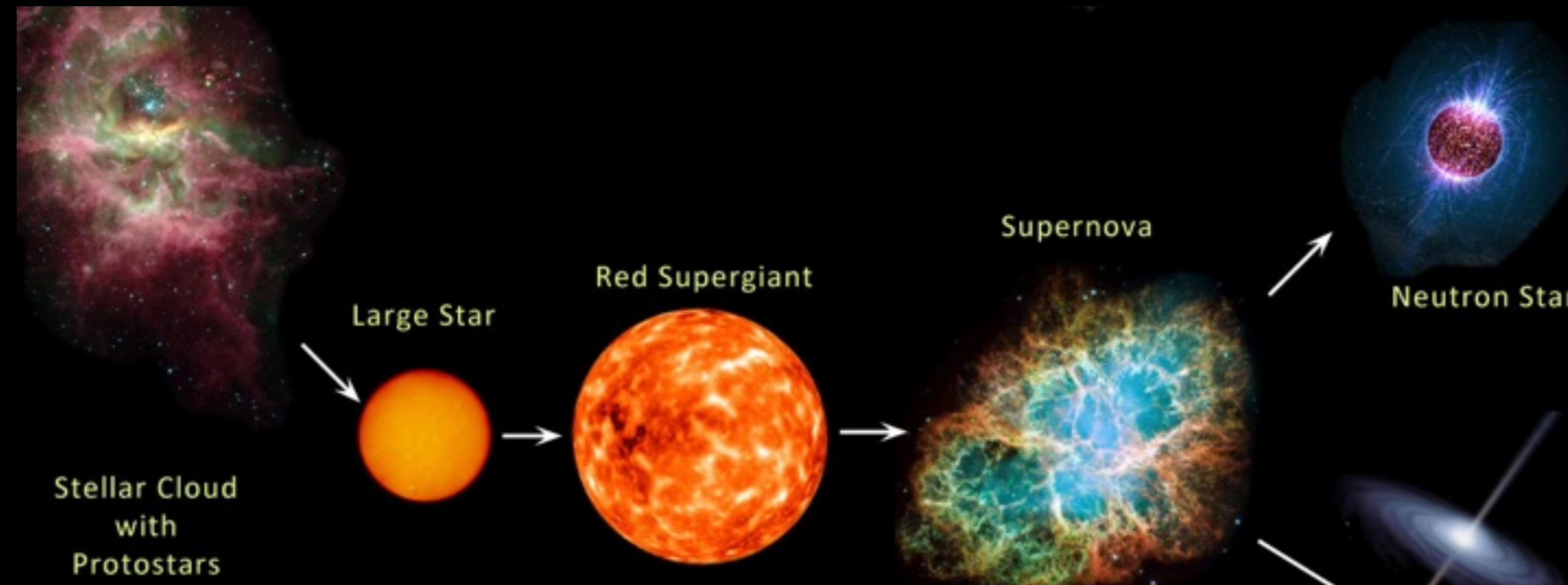
WDs are extremely dense and small.

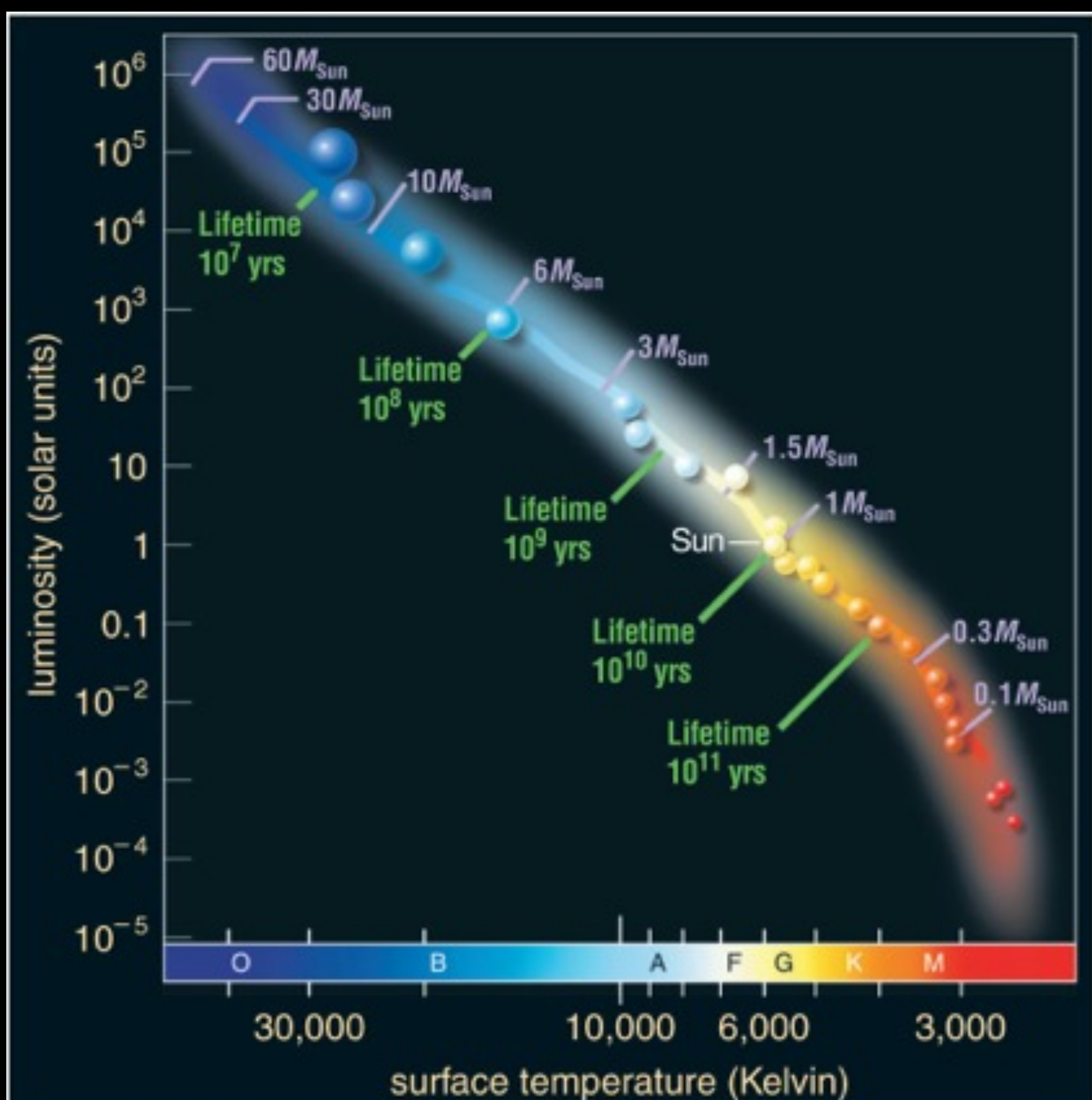
No more reactions! WD shines as nuclei lose energy.

Mass limit of WD ≈ 1.4 $M_\odot$

Massive stars live much more exciting lives
(in my opinion)

Evolution of 8-25 $M_\odot$ stars

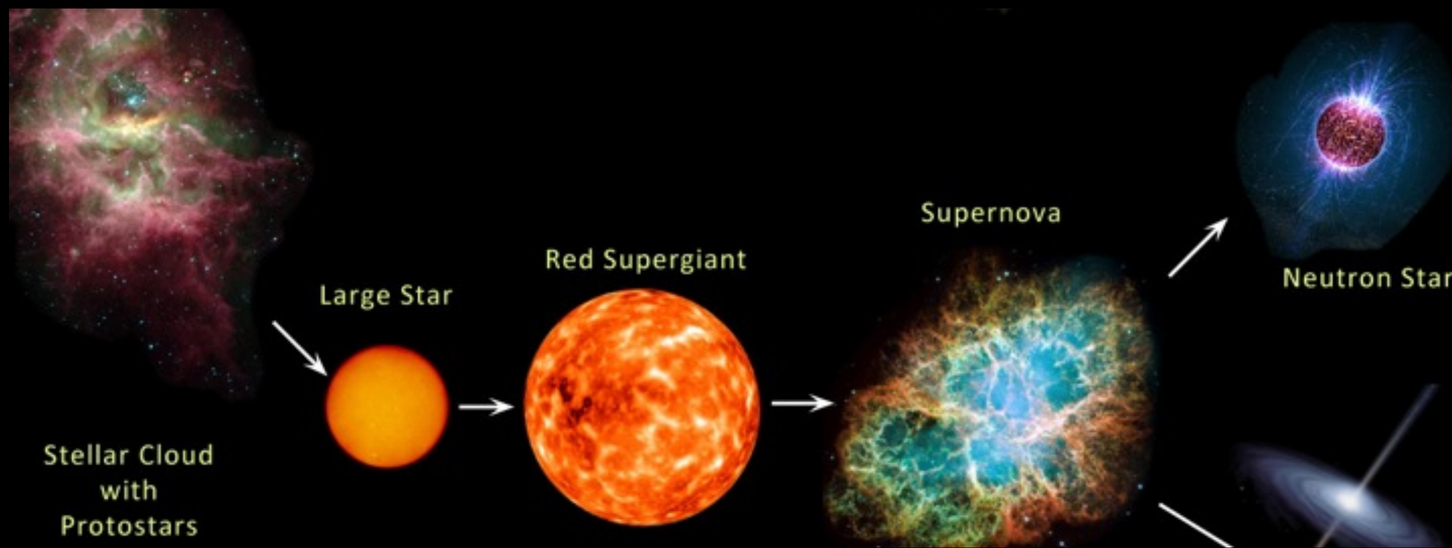


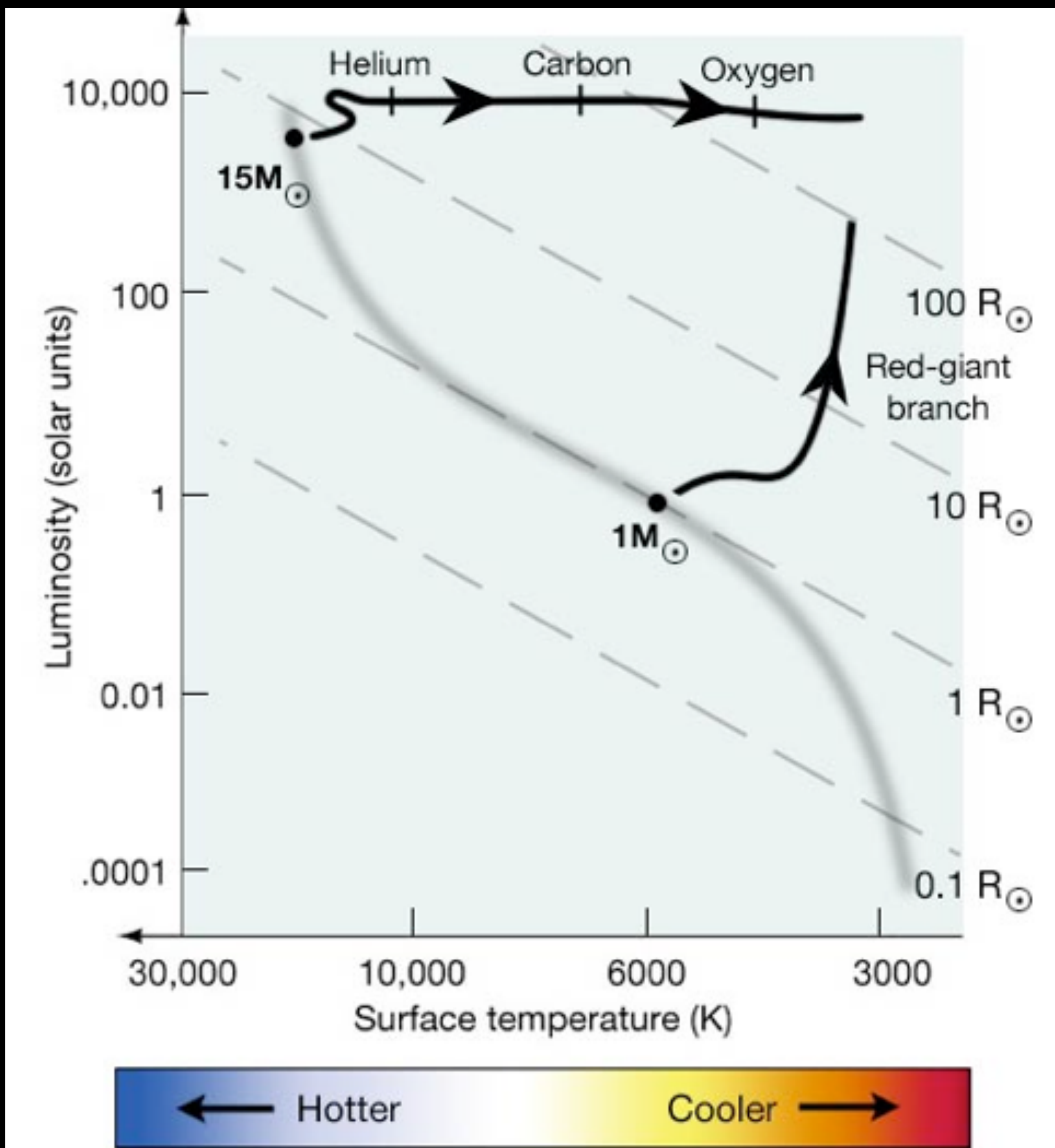


Massive stars have much higher luminosities so they burn through hydrogen faster

…they live fast and die young

Evolution of 8-25 $M_\odot$ stars

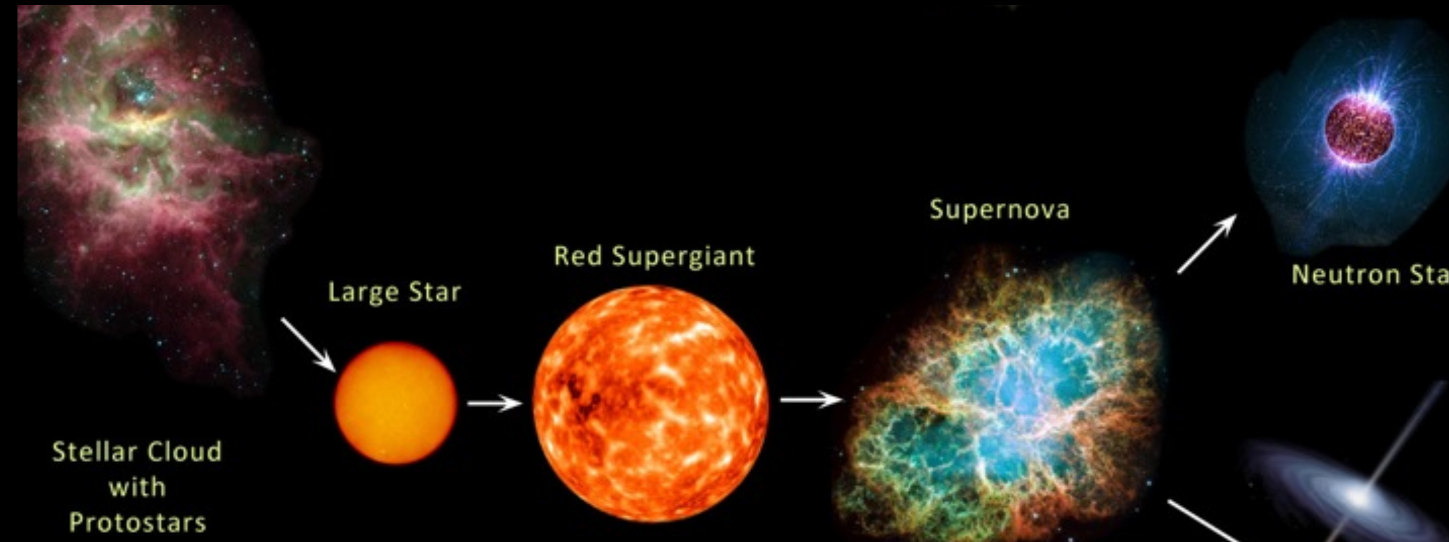




Massive stars burn heavier elements after they leave the main sequence

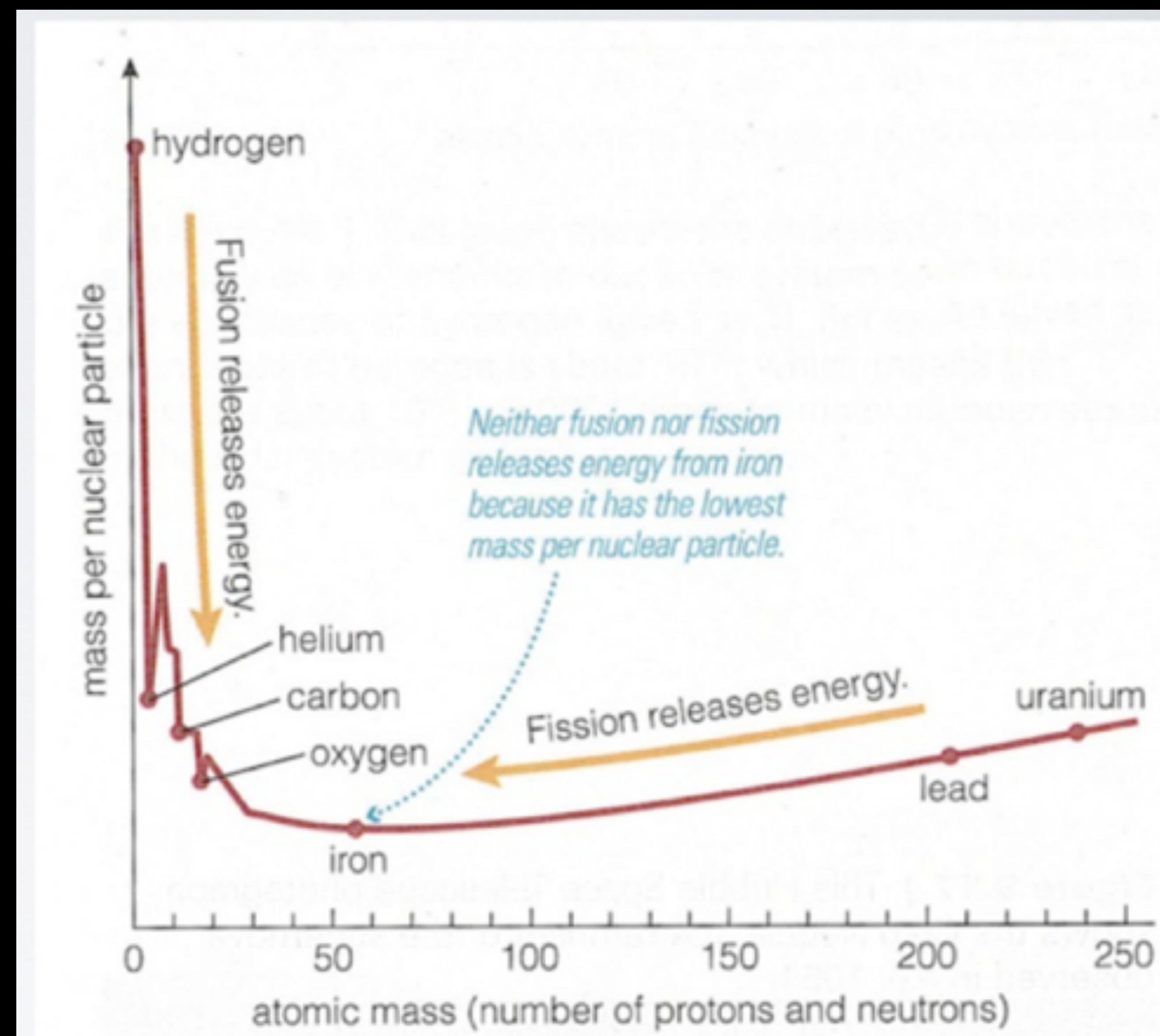
Each subsequent heavier element burning phase requires larger and larger core temperature.

Evolution of 8-25 $M_{\odot}$ stars

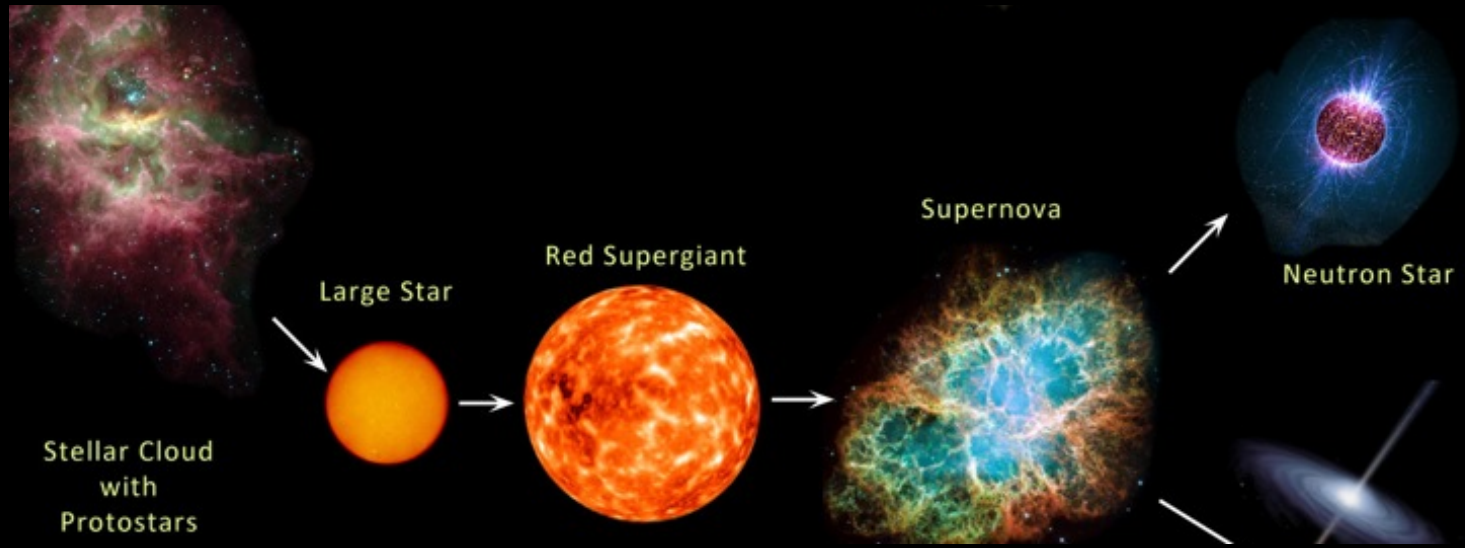


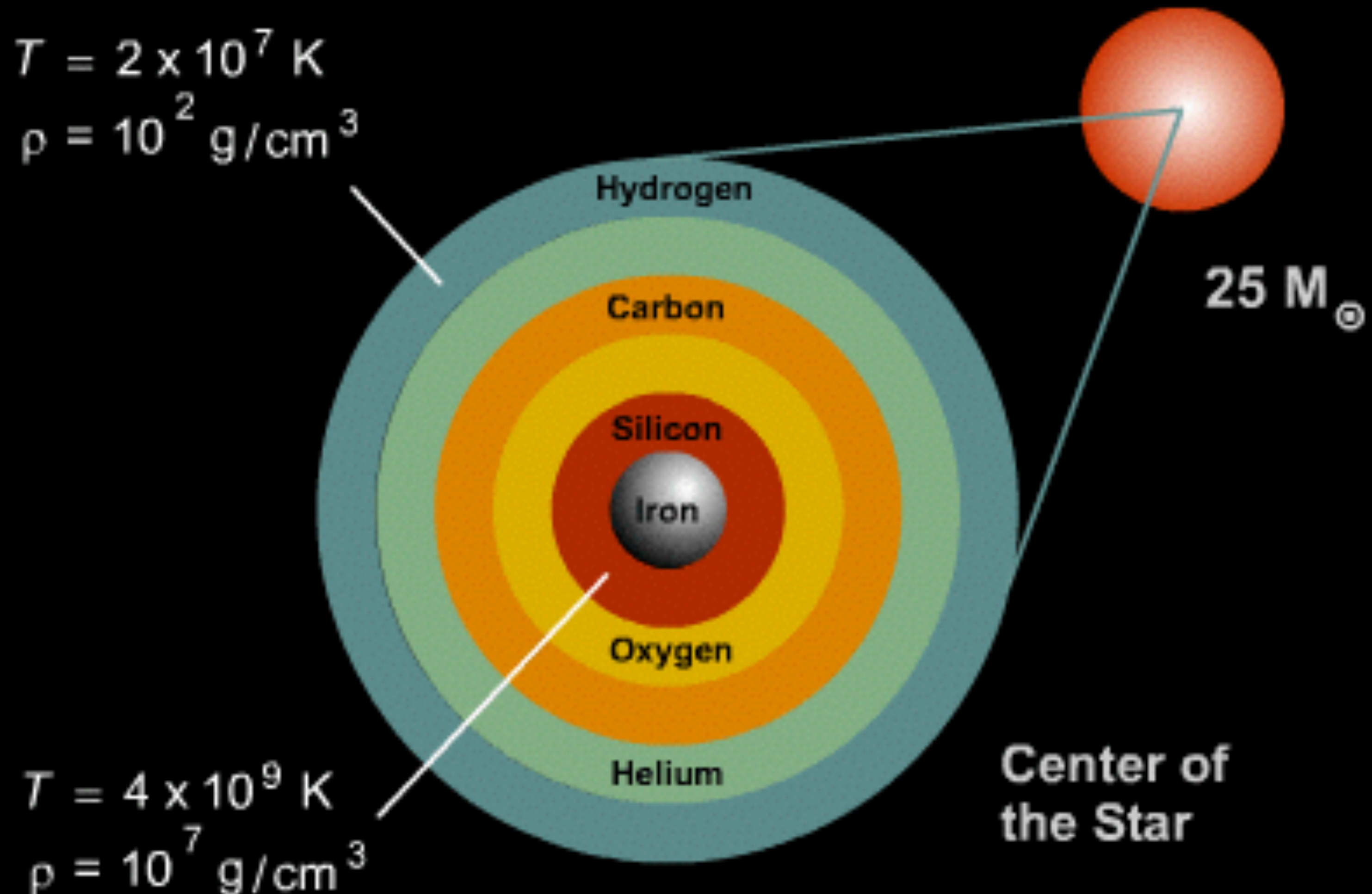
More massive elements require higher T to fuse.

Elements can fuse up to Iron in stars because Iron fusion is an endothermic reaction (requires energy input to fuse)



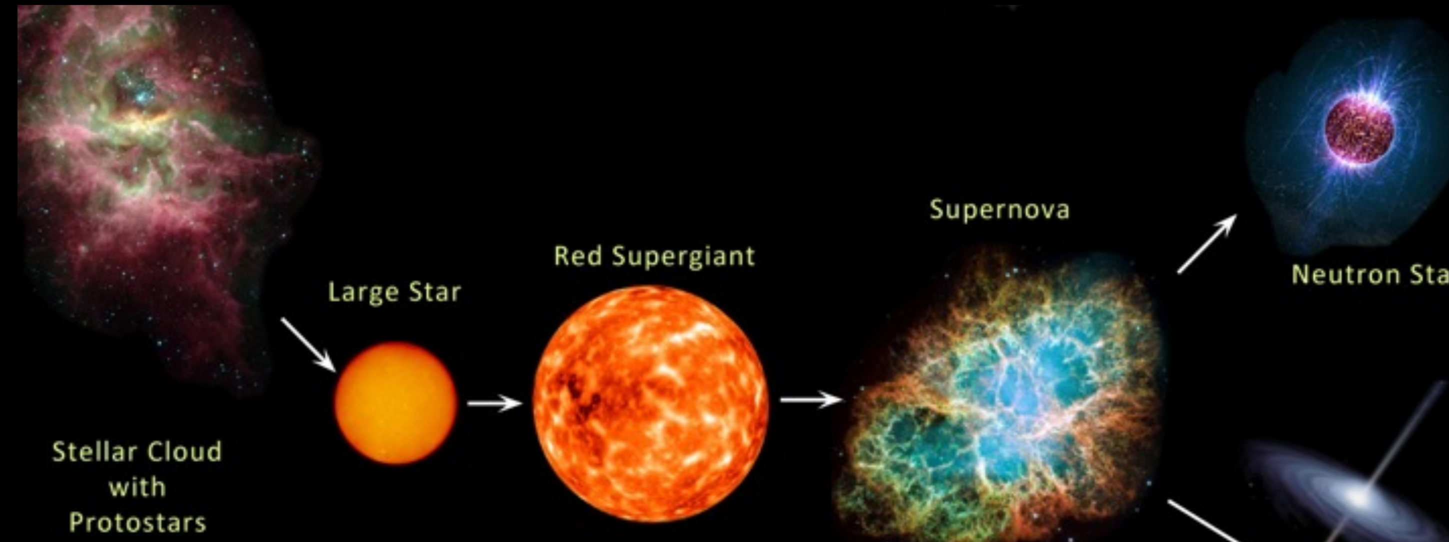
Evolution of 8-25 $M_\odot$ stars

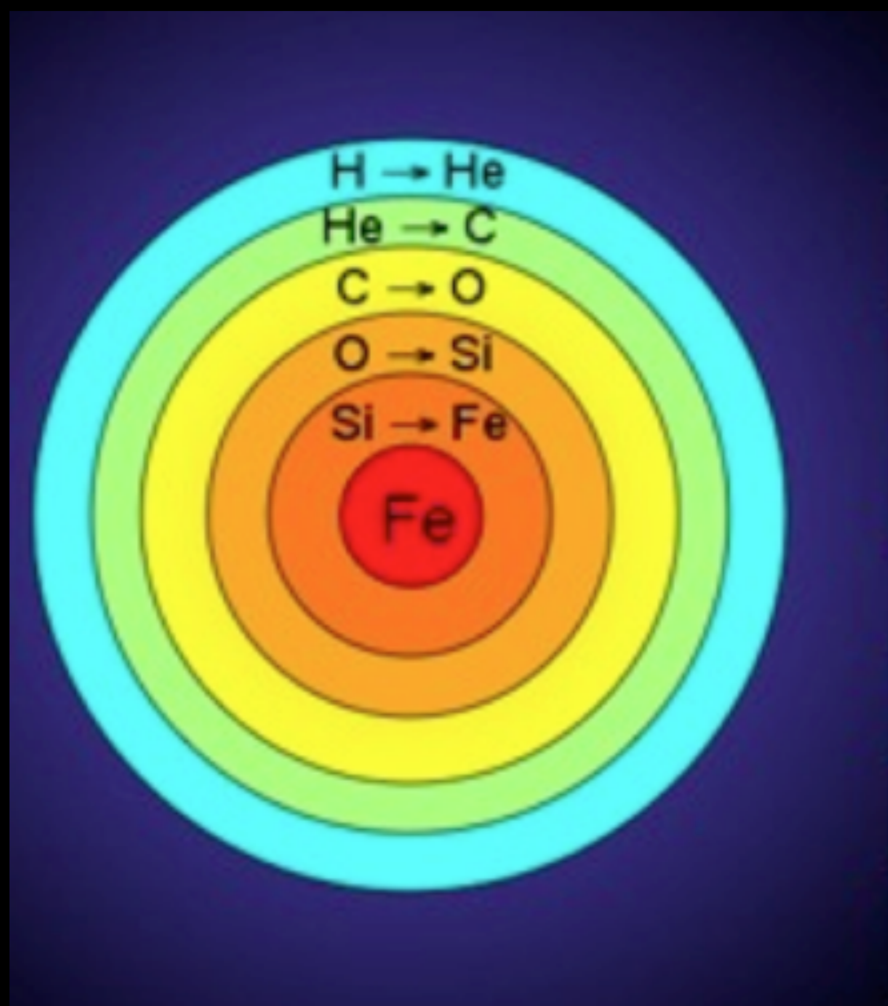




Because massive stars have much more gravity, several shell burning stages can occur.

Evolution of 8-25 $M_\odot$ stars





For a 25 solar mass star:

Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

Each subsequent burning phase takes less time to complete.

End stages of massive stars: Supernova Explosions

When the mass of the Iron core exceeds ~1.4 $M_{\odot}$ the core collapses.

Rapid gravitational collapse causes the star to explode in a supernova (SN) explosion.

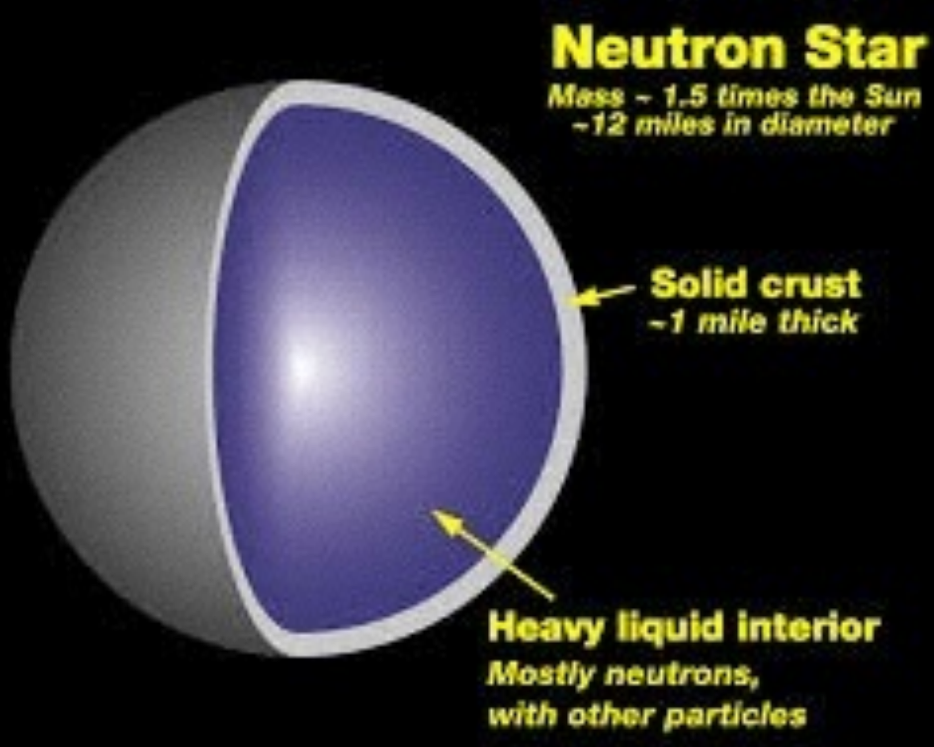
Typical energy output of a SN is ~10^{51} ergs and can outshine its host galaxy.

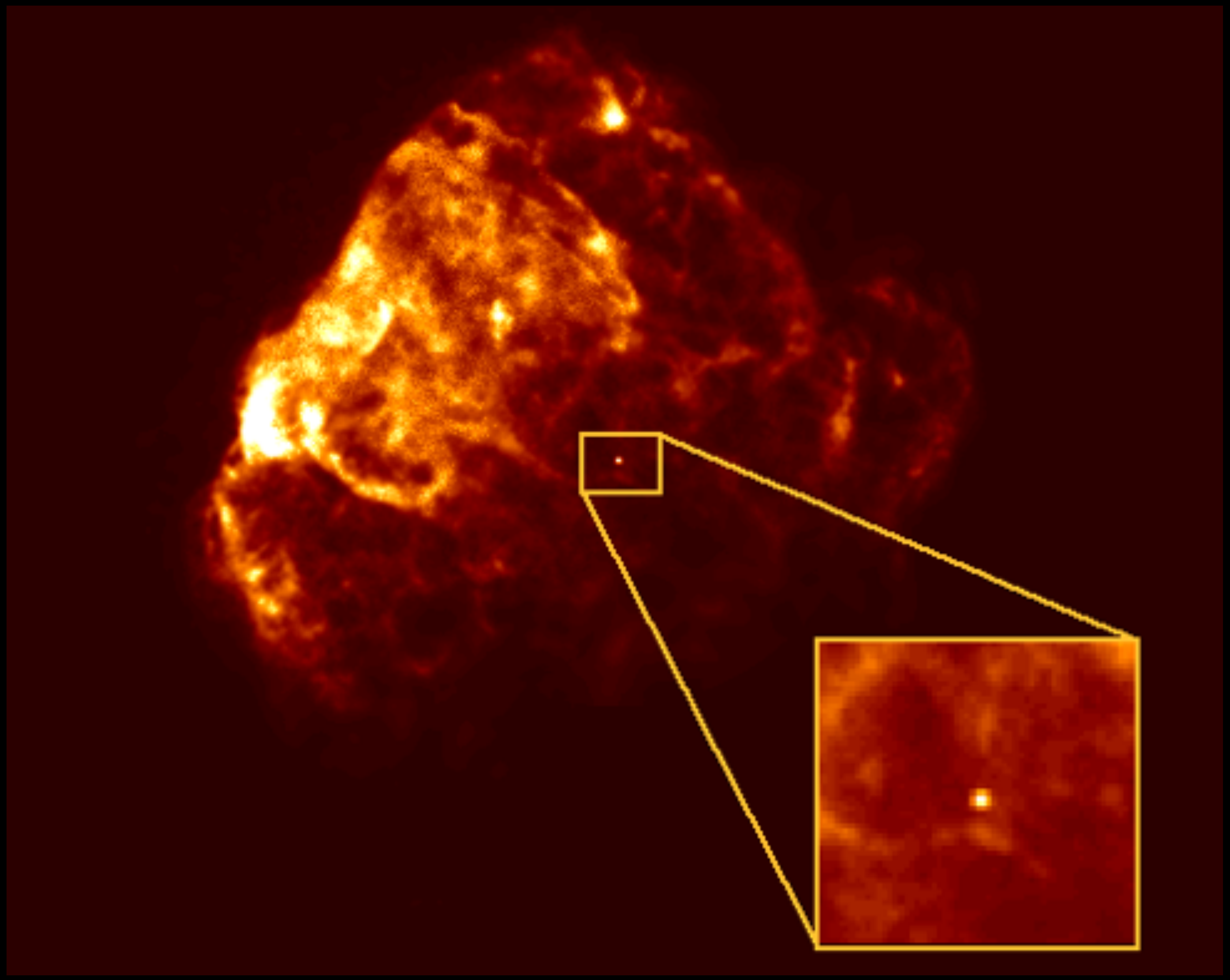
Elements heavier than Iron are made in this explosion

End stages of massive stars: Neutron Stars

High density core - protons capture electrons to form a neutron and a neutrino

$$p^{+} + e^{-} \rightarrow n + \nu$$





Neutron stars supported by neutron degeneracy pressure

End stages of massive stars: Black Holes

If the core becomes too massive that neutron degeneracy pressure can't support it then core will continue to collapse.

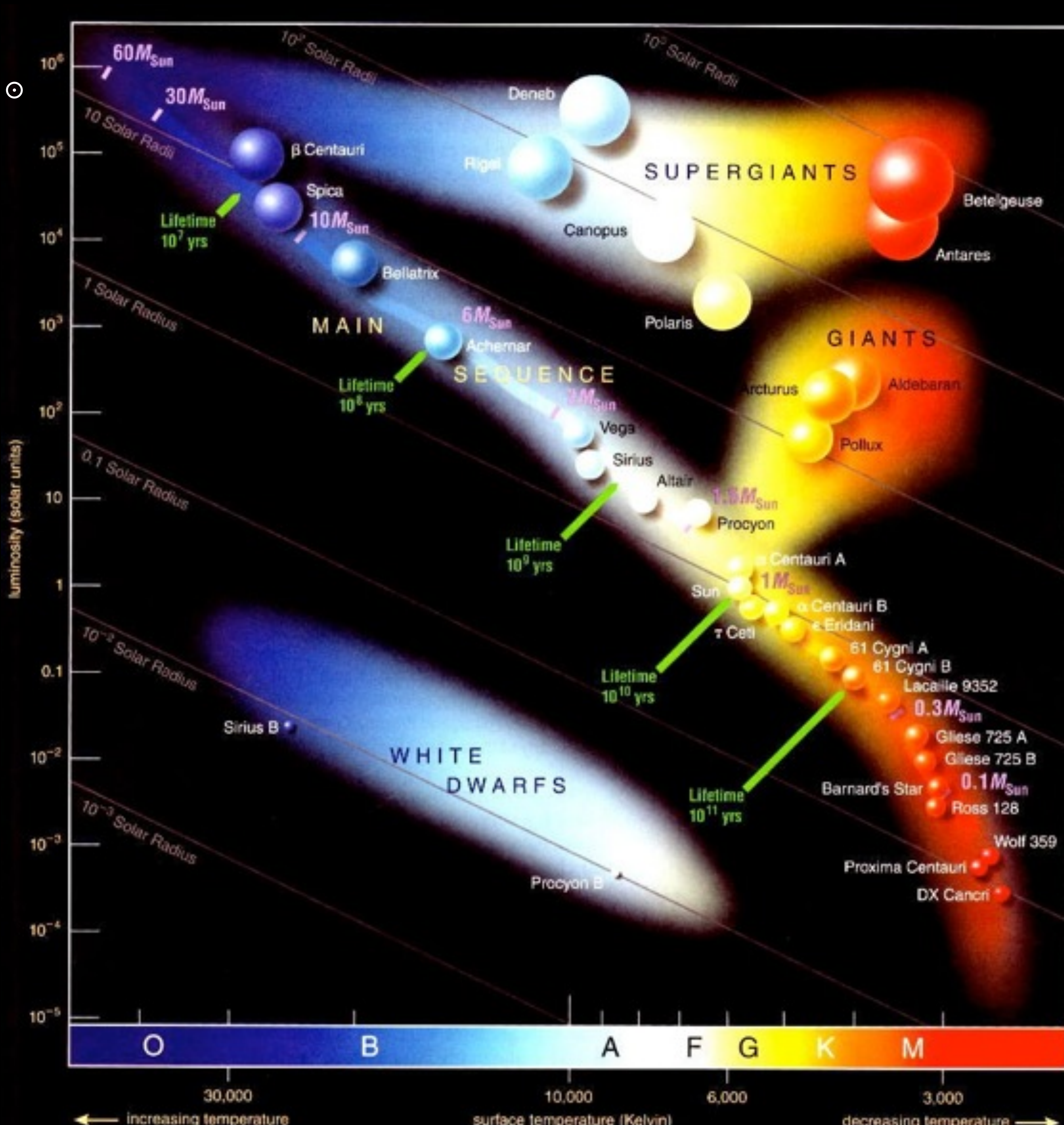
Nothing can stop it! The end result is a black hole.

Artist rendition of a black hole

End stages of massive stars: Black Holes

Hollywood rendition of a black hole with an accretion disk (credit: Interstellar)

Summarizing Stellar Evolution: The H-R Diagram



Luminosity=energy emitted per second

$10^6\ L_\odot$

$1\ L_\odot$

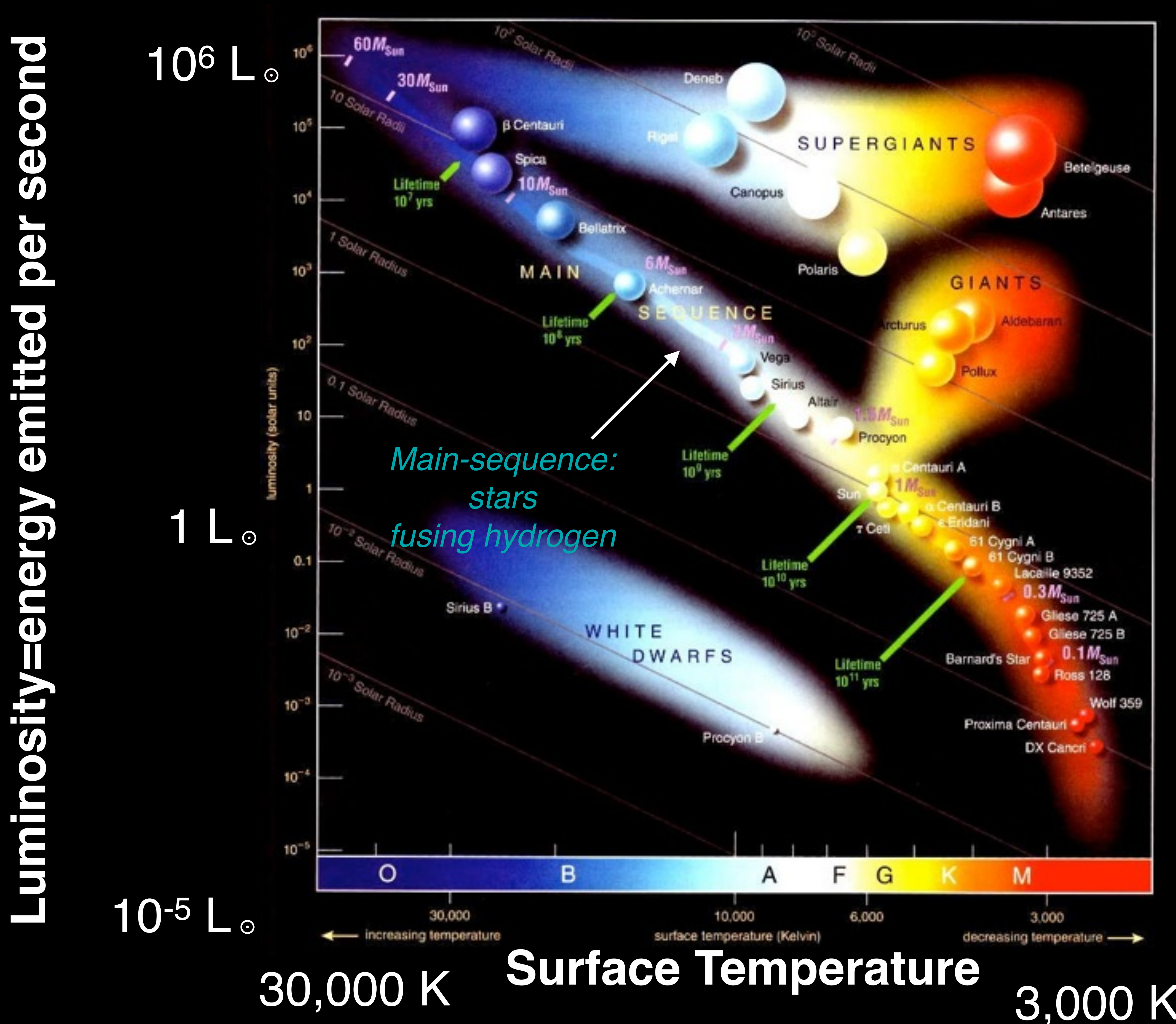
$10^{-5}\ L_\odot$

Surface Temperature

30,000 K

3,000 K

Summarizing Stellar Evolution: The H-R Diagram



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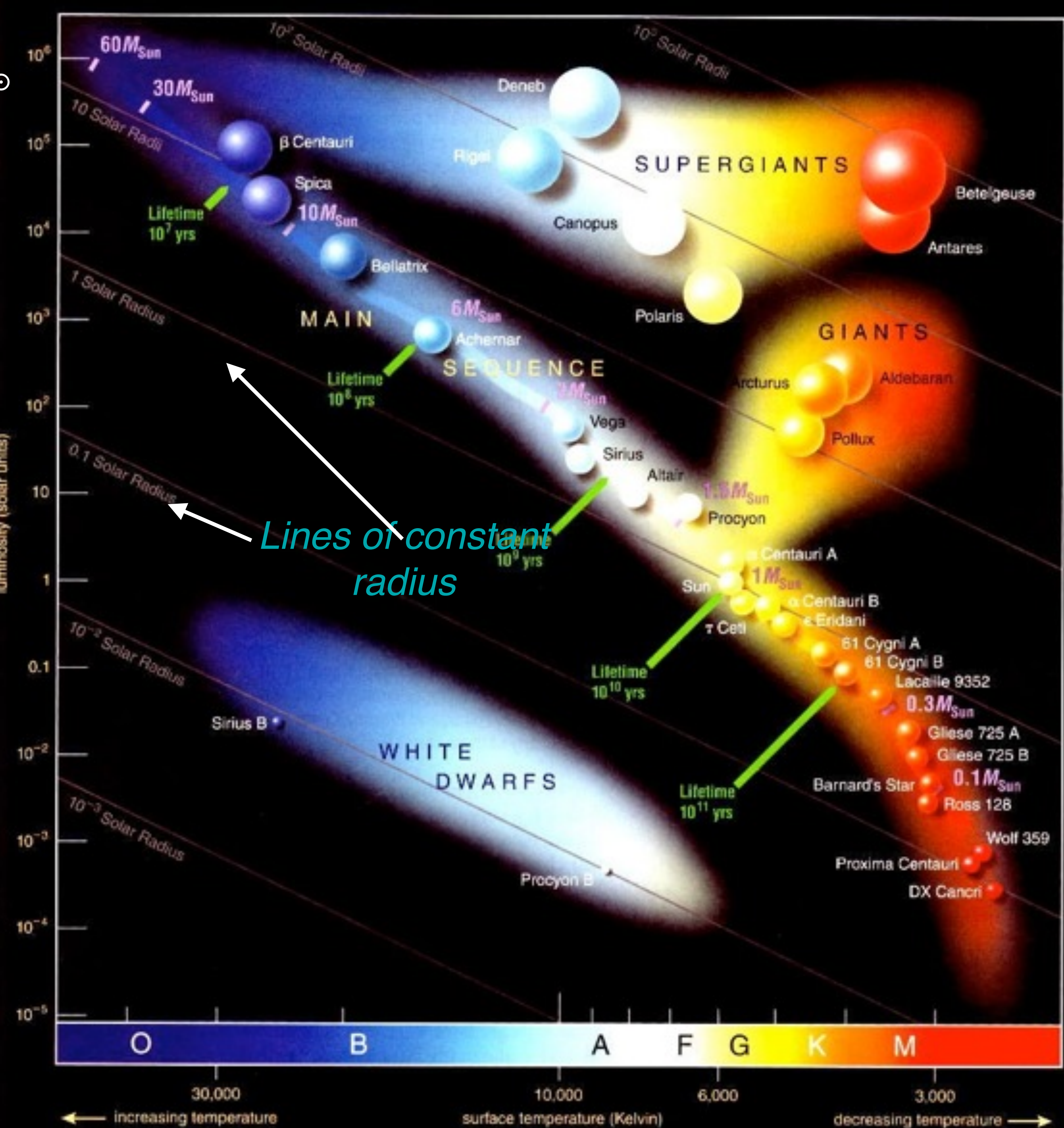

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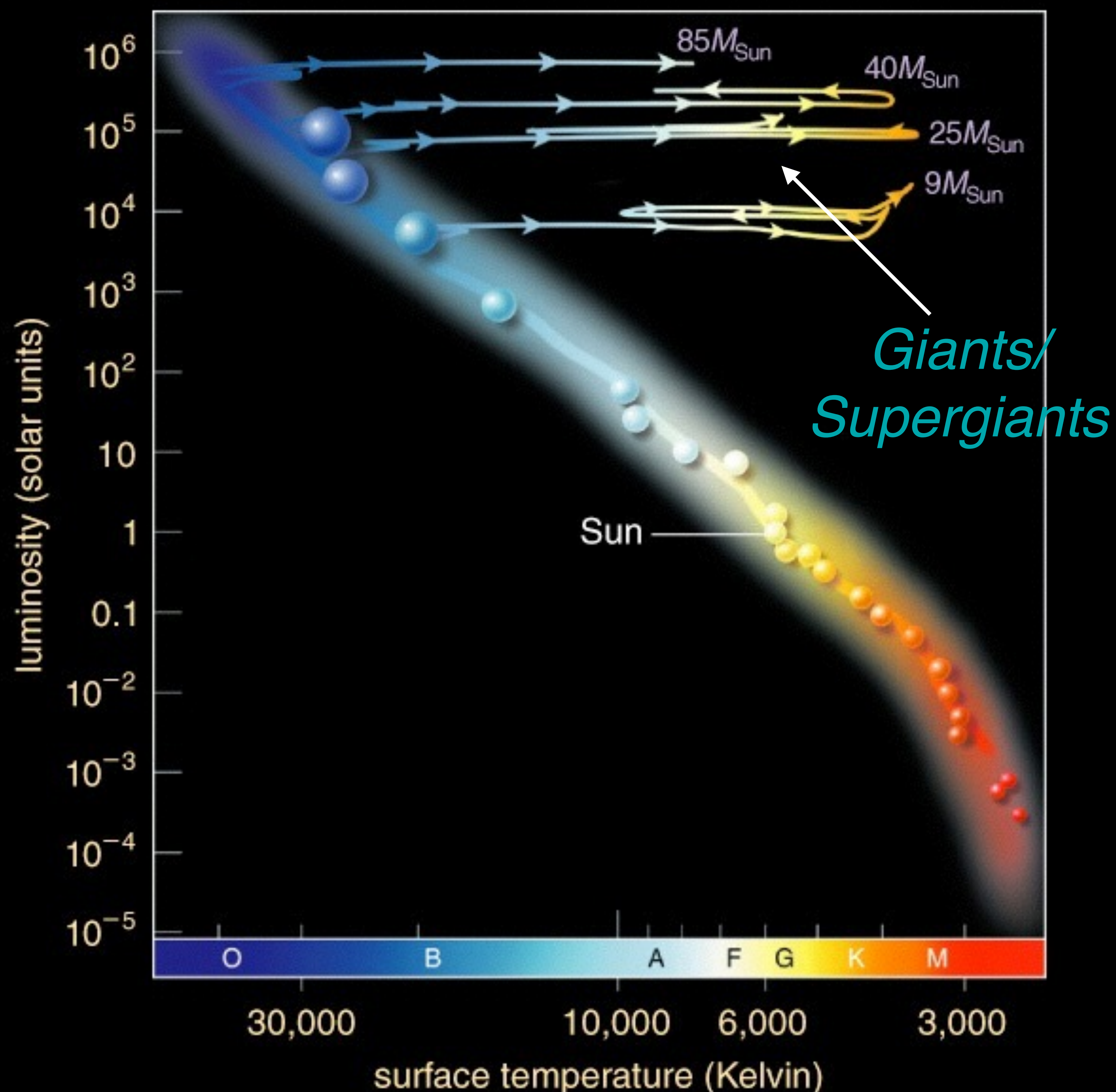

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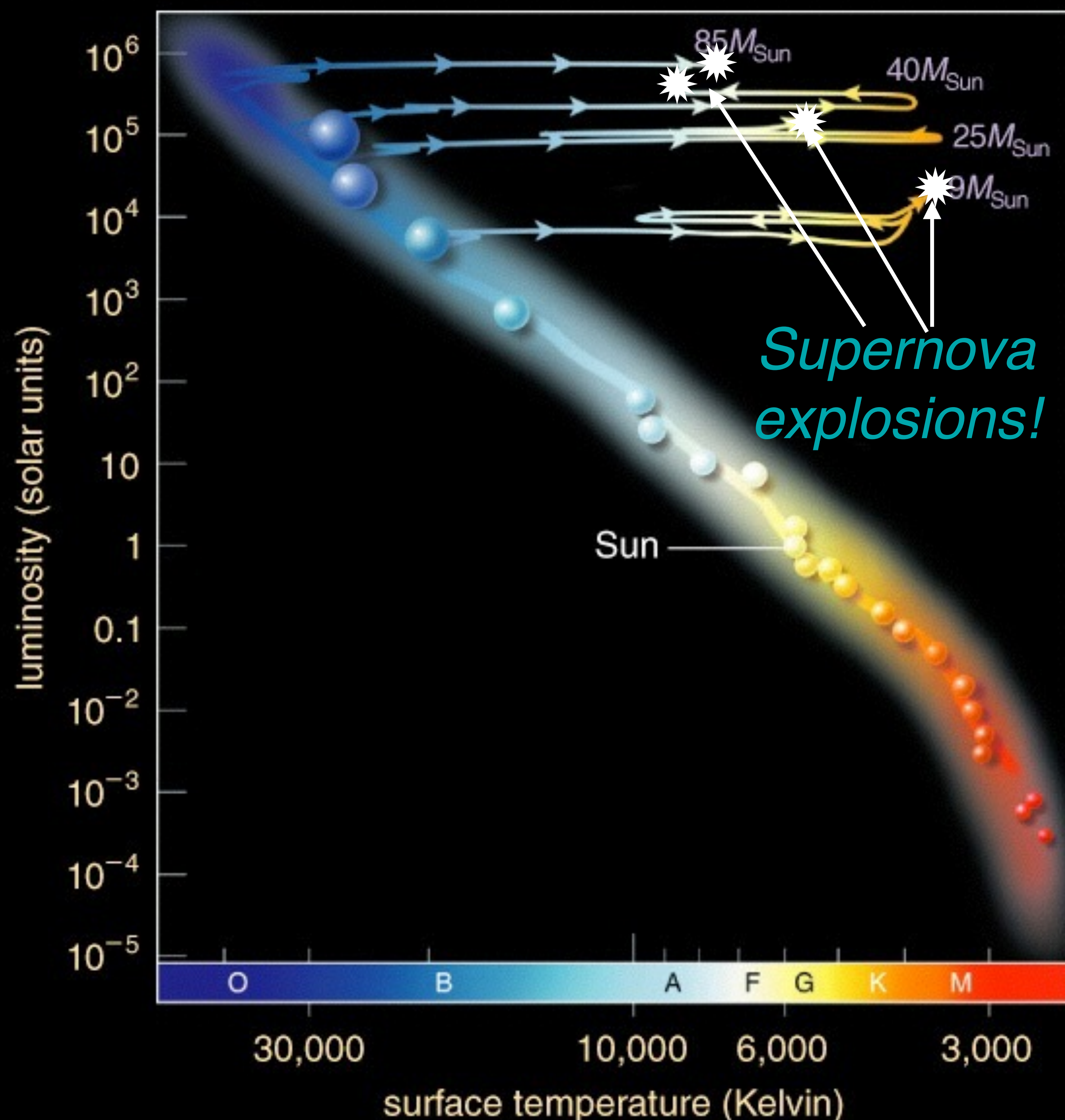

Now it’s your turn to explore some questions about stars and their exciting lives!

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Activity Description

1. You and a partner will use the MadStar EZ-Web tools to generate stellar models of stars.
2. You will pick your datasets to answer a specific question related to stellar evolution
3. You will use Python to read in your data files and plot your results.
4. You will have the rest of the class time and until 4 pm tomorrow to work with your data.
5. Afterwards, you will put your plots into a powerpoint presentation (from 4-4:30 tomorrow)
6. You and your partner will present your results to the class Friday at the beginning of class.

Using EZ-Web

http://www.astro.wisc.edu/~townsend/static.php?ref=ez-web#Using_EZ-Web

Using EZ-Web

To construct and evolve a model, enter parameters into the form below, and then submit the calculation request to the server. The parameters control what sort of star is evolved, for how long it is evolved, and what sort of output is produced. In order, they are

- the **initial mass** of the star, in solar units. This value must be between 0.1 and 100.
- the **metallicity** of the star, as a mass fraction.
  0.02 = Solar value, means “2% of this star is made of elements heavier than He”
- the **maximum age** to evolve the star up to, in years. If zero, the star will be evolved until the code can go no further.
- the **maximum number of steps** to evolve the star through. If zero, the star will be evolved until the code can go no further.
- whether to **create detailed structure files** describing the interior structure of the star.
  Detailed structure files contain data for each time step.
- whether to **use CGS units** in output files; if not, SI units are used.
- the **email address** to which a notification of calculation results should be sent.

Upon submission, the server will perform basic validation on the parameters, and then assign an identification number to the request. If you're submitting many requests in a row, it's a good idea to avoid confusion by noting down which id number corresponds to which calculation.

During a calculation, stellar properties (e.g., radius, core and surface temperature, luminosity) are written to a summary file at discrete time intervals ('steps'), extending up to the specified maximum age or maximum number of steps. If requested, detailed structure files are also written at each step, specifying state variables and associated data at each grid point in the stellar interior. The format of both types of file are discussed below.

After a calculation has completed (which may take a while, if the server is dealing with many requests at the same time), the output files are packaged into a zip file. Then, a notification email is sent to the specified address, containing a link which may be used to download the zip file from the server. Zip files that are not downloaded within a day of creation are automatically deleted.