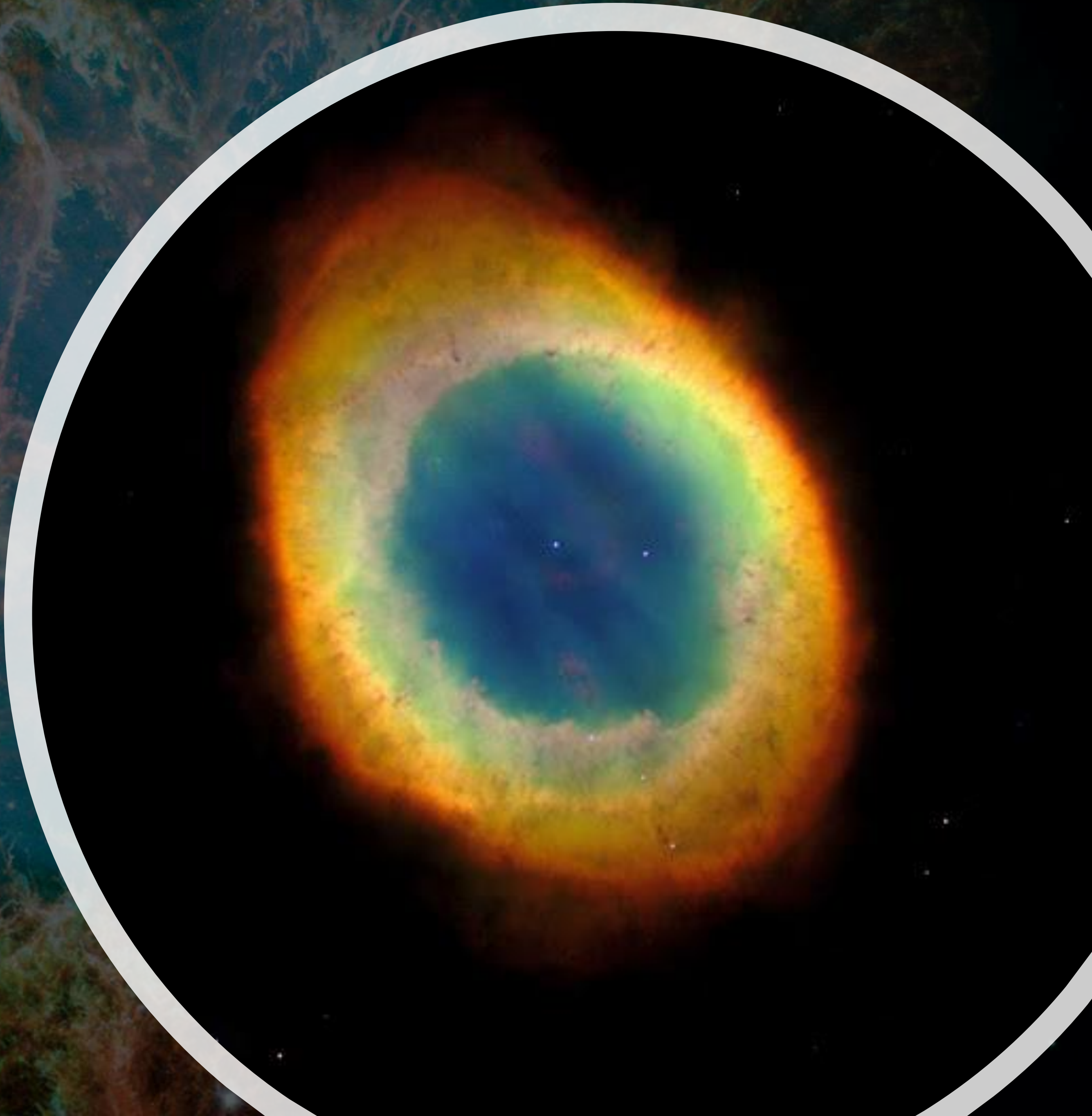
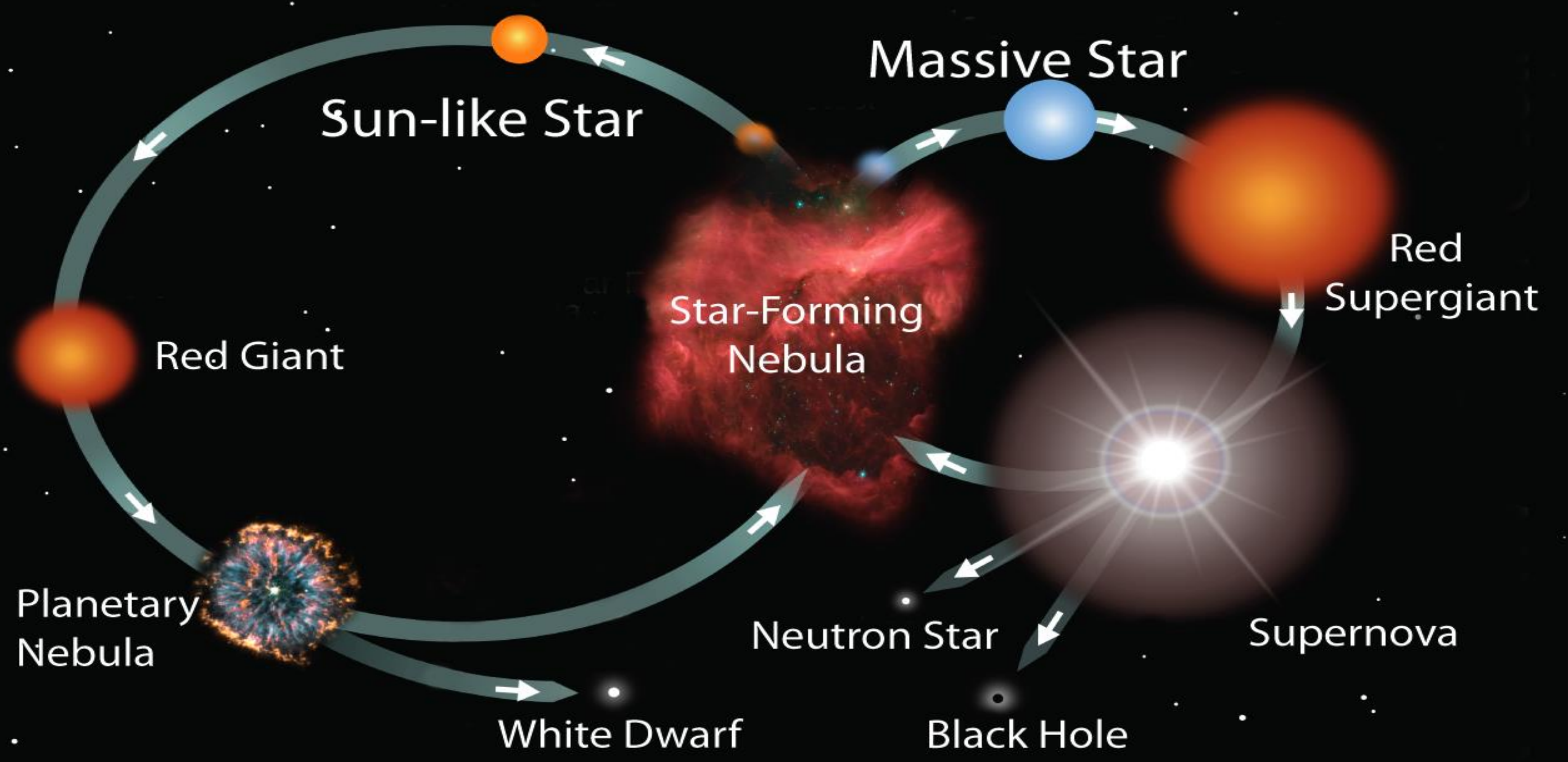
The Life-Cycle of Stars



Friday, March 14, 2025

Chanan Greenberg

THE LIFE CYCLE OF STARS



Agenda

- Key concepts of how stars work
- Star Formation
- Life on the Main Sequence
- When the Fuel runs out…
  - Low Mass Stars
  - High Mass stars
- Death of Stars and Stellar Remnants
  - White Dwarfs
  - Neutron Stars
  - Black Holes

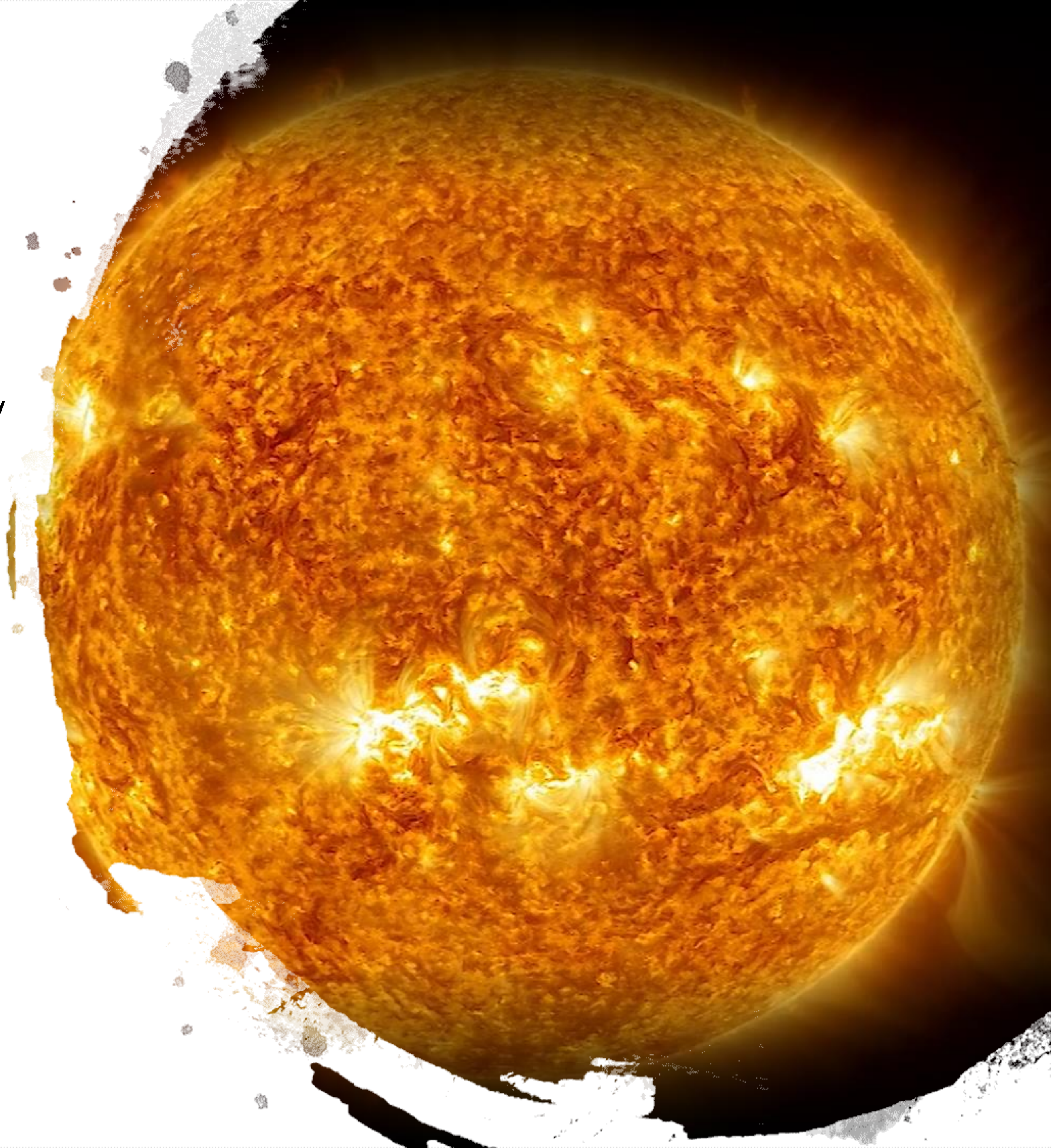
Key concepts of how stars work

- Kelvin – Helmholtz mechanism: the sun is a ball of gas held by the balance of two forces, **gravity** crushing down and **pressure** pressing up. In order to be a stable star these forces must be balanced – hydrostatic equilibrium

- Nuclear fusion in the heart of the star fuses lighter elements into heavier elements. The total mass input is greater than the output (4 atoms of Hydrogen weigh more than one atom of Helium), the delta is converted into energy which is lost in the form of photons and neutrinos that leave the star

- This means a stable star is in both **hydrostatic** and **thermal** equilibrium

- The bigger a star is, the more luminous it is, the more energy it needs to produce in its core to stay luminous.



Star Formation

- Stars form from giant molecular clouds of gas (H_2) and dust

- There are two phases for star formation: Raw materials that create a protostar and the ignition of nuclear fusion in the core

Star Formation

- Giant molecular clouds are typically 30-40 light years across and contain the mass of about 100,000 suns

- They are cold (10-30 Kelvin), and they are dense 100,000 atoms per cm^3

- There is a very delicate balance between gravity and pressure

- A collapse can be triggered by colliding with another cloud, passing through the spiral arm of a galaxy, a supernova shockwave

Star Formation

- The trigger causes the gas to clump which creates a gravitational pull-on surrounding material that starts falling in

- As more material builds up, pressure and heat increase, initially light and heat can escape but as the ball of gas becomes denser it becomes opaque, trapping in heat which builds up more pressure

- When the core achieves hydrostatic balance, internal pressure equals the force of gravity, more material falls on increasing gravity and heat and pressure inside also increase – a protostar is born

- Solar wind pushes away the accretion disk which can form planets

- Time scale depending on mass: 10,000 for a star 30 times heavier than our sun to 1B years for a star that is 0.5 the mass of our sun

Star Formation

- The protostar is still not in thermal equilibrium, as it shines it loses energy and has no mechanism to compensate. So it contracts under gravity, builds more pressure in the core and is balanced again

- When the core temperature reaches 10M Kelvin the core is hot enough and dense enough to start fusing Hydrogen into Helium producing enough energy to compensate for the loss of energy through luminosity

- Now we have **hydrostatic** and **thermal** balance – a Star is born!

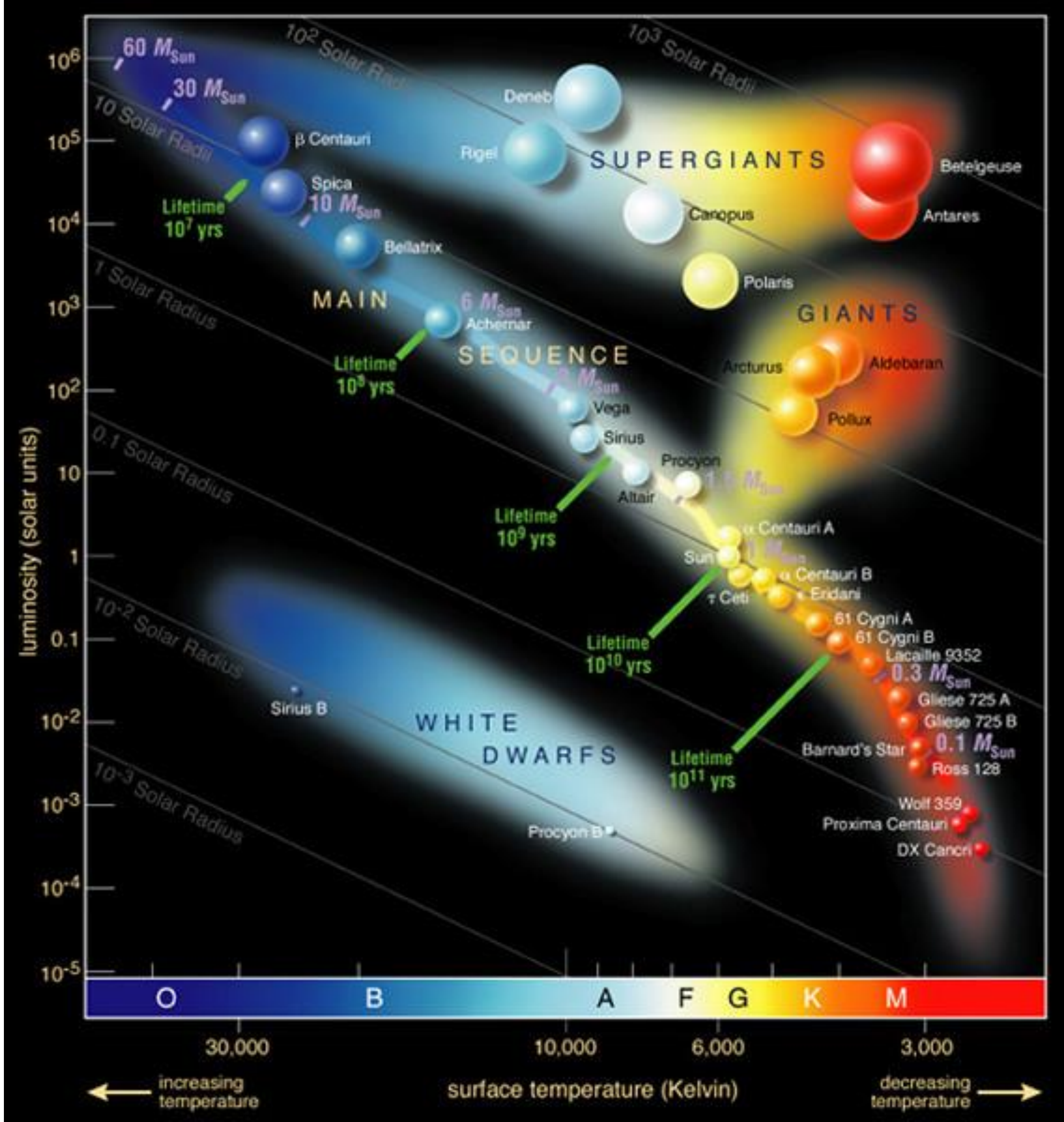
- The smallest star possible is about 8% the mass of the sun and the largest star possible is about 100-150 solar masses

Life on the Main Sequence

- The HR Diagram is a diagnostic tool. Based on spectral analysis of the light of a star we can discern its luminosity & temperature

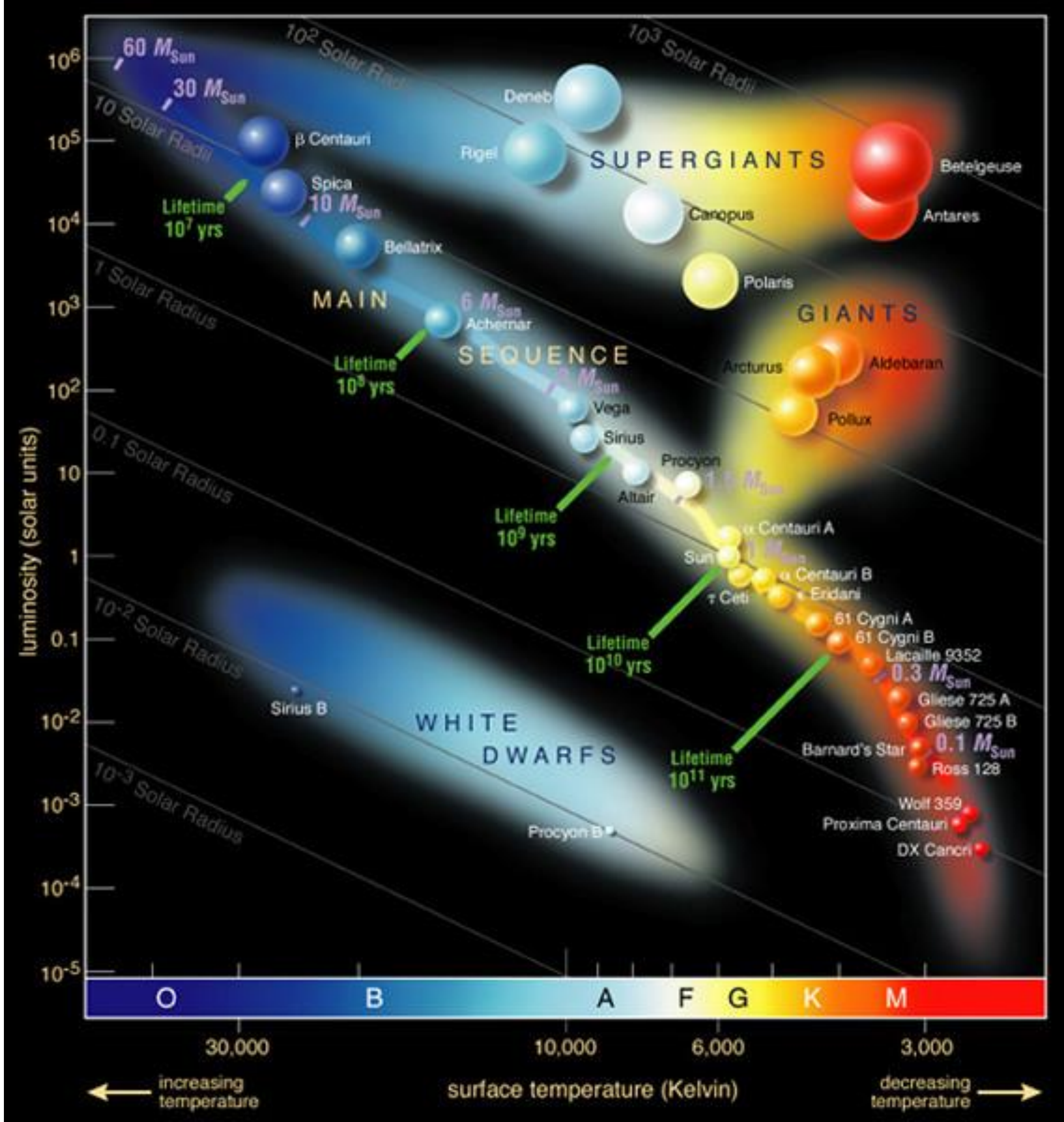
- To be a Main Sequence star, 3 conditions must be met:
    - Hydrostatic Equilibrium
    - Thermal Equilibrium
    - Fusing H into H_e in the core

- If any of these conditions change, the star's temperature and luminosity will change, and it will no longer be a main sequence star



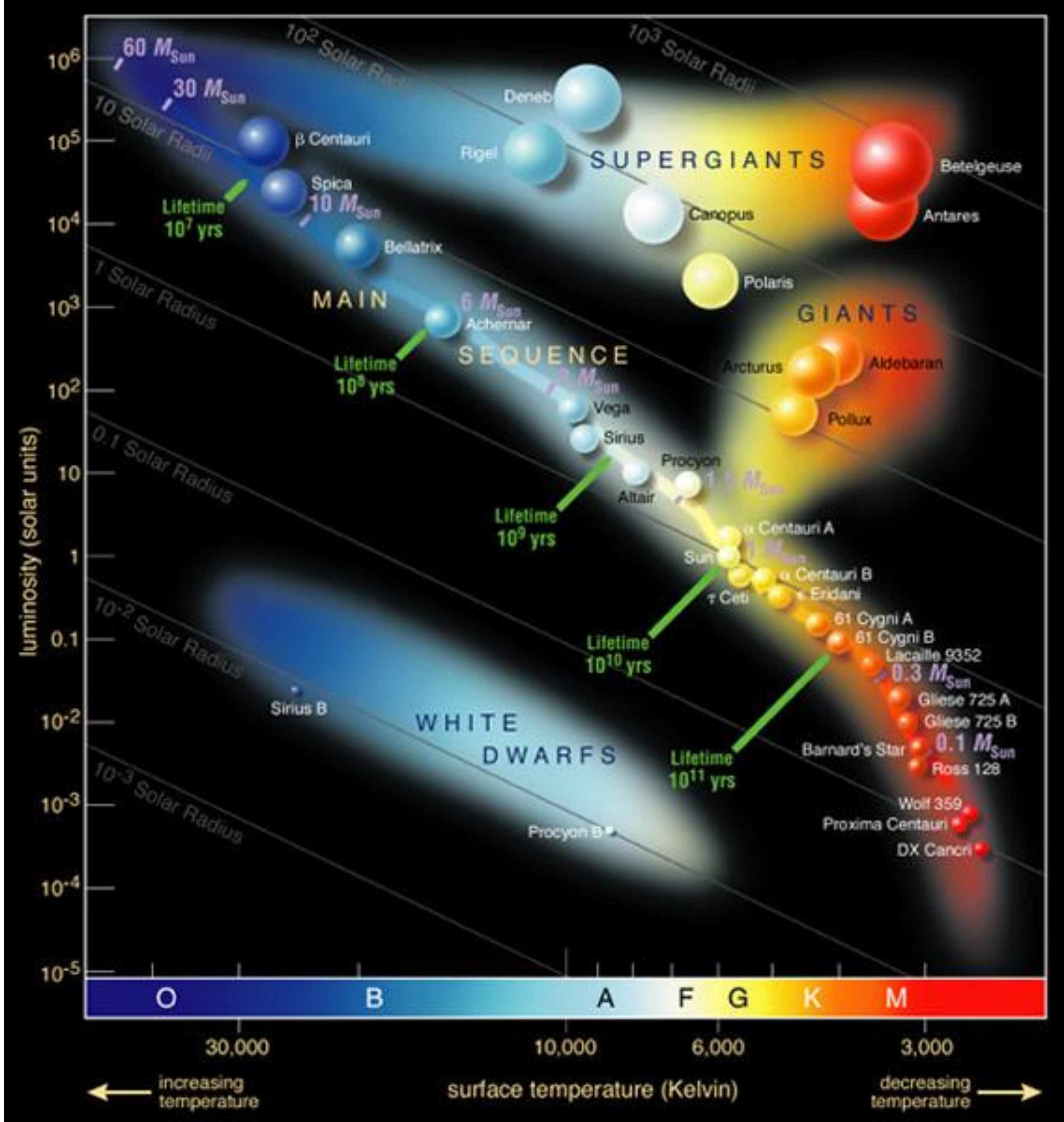
Life on the Main Sequence

- The lifetime of a star is inversely proportional to its mass cubed
- Our sun spent 30M years as a protostar and will spend 10B years on the main sequence
- A star with 10 solar masses will only spend 10M years on the main sequence
- Small stars are less luminous and consume less energy. Luminosity is proportional to mass to the power of 4. So a star that has 10 times the mass of our sun will be 10,000 times more luminous and will burn through its fuel much faster



Life on the Main Sequence

- In stars up to 1.2 solar masses – proton-proton chain reaction is the main source of energy
- In stars that are bigger than 1.2 solar masses the CNO cycle is the main source of energy production
- Nuclear fusion is VERY sensitive to temperature
  - In P-P a 10% increase in temperature will cause a 40% increase in fusion and energy generation
  - In CNO a 10% increase in temperature will cause a 180% increase in fusion and energy generation
- Pressure is a function of density and temperature. As fusion reduces the number of particles density drops, so temperature must go up. Fusion levels go up, producing more energy than the star can shine away, this expands the star and makes it more luminous

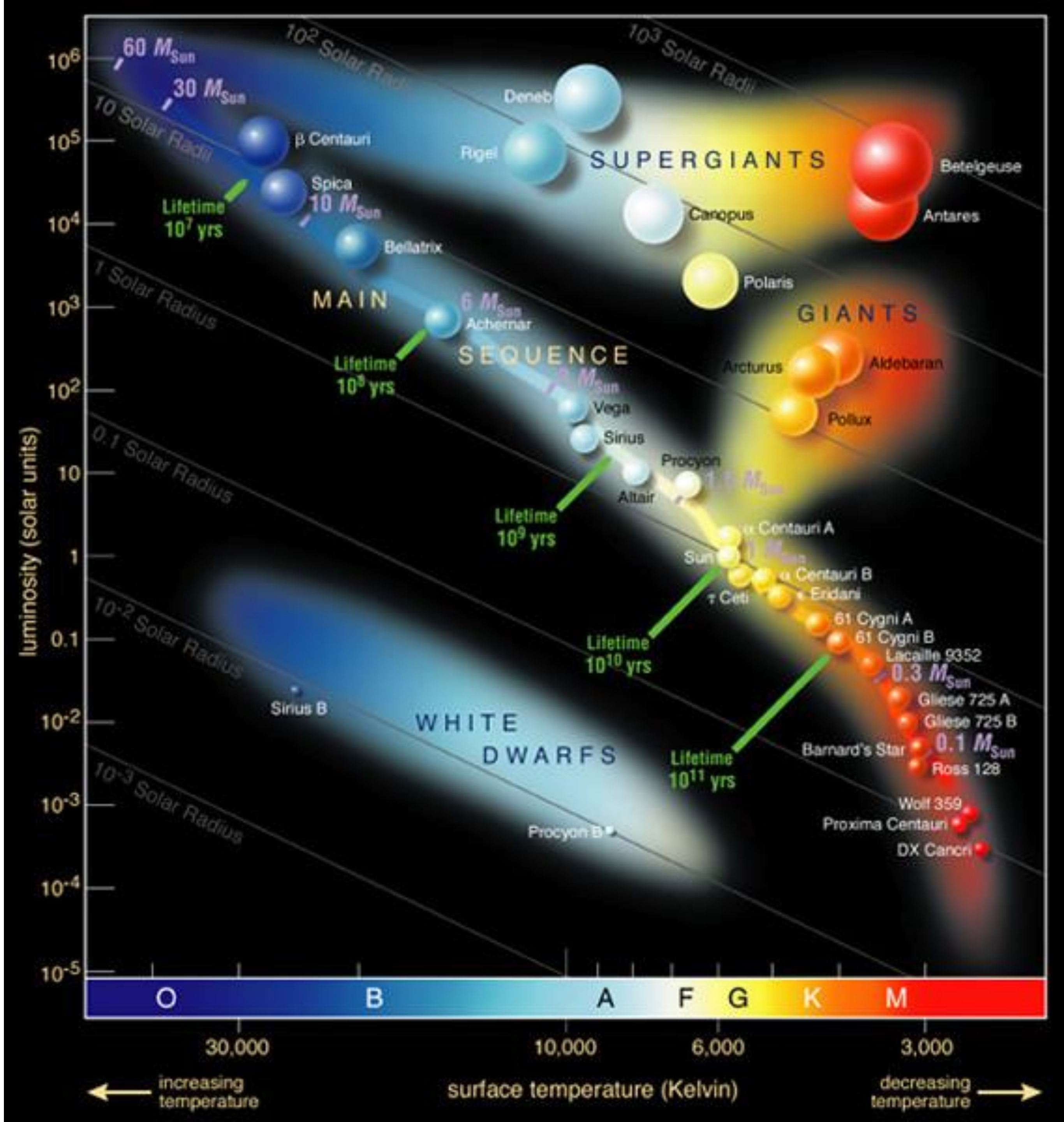


Life on the Main Sequence

- Star structure is impacted as well
  - In stars up to 1.2 solar masses – there is radiative core and a convective envelope
  - In stars that are bigger than 1.2 solar masses there is a convective core and a radiative envelope
  - Low mass 25% of the sun to 8% - both the core and envelope are convective

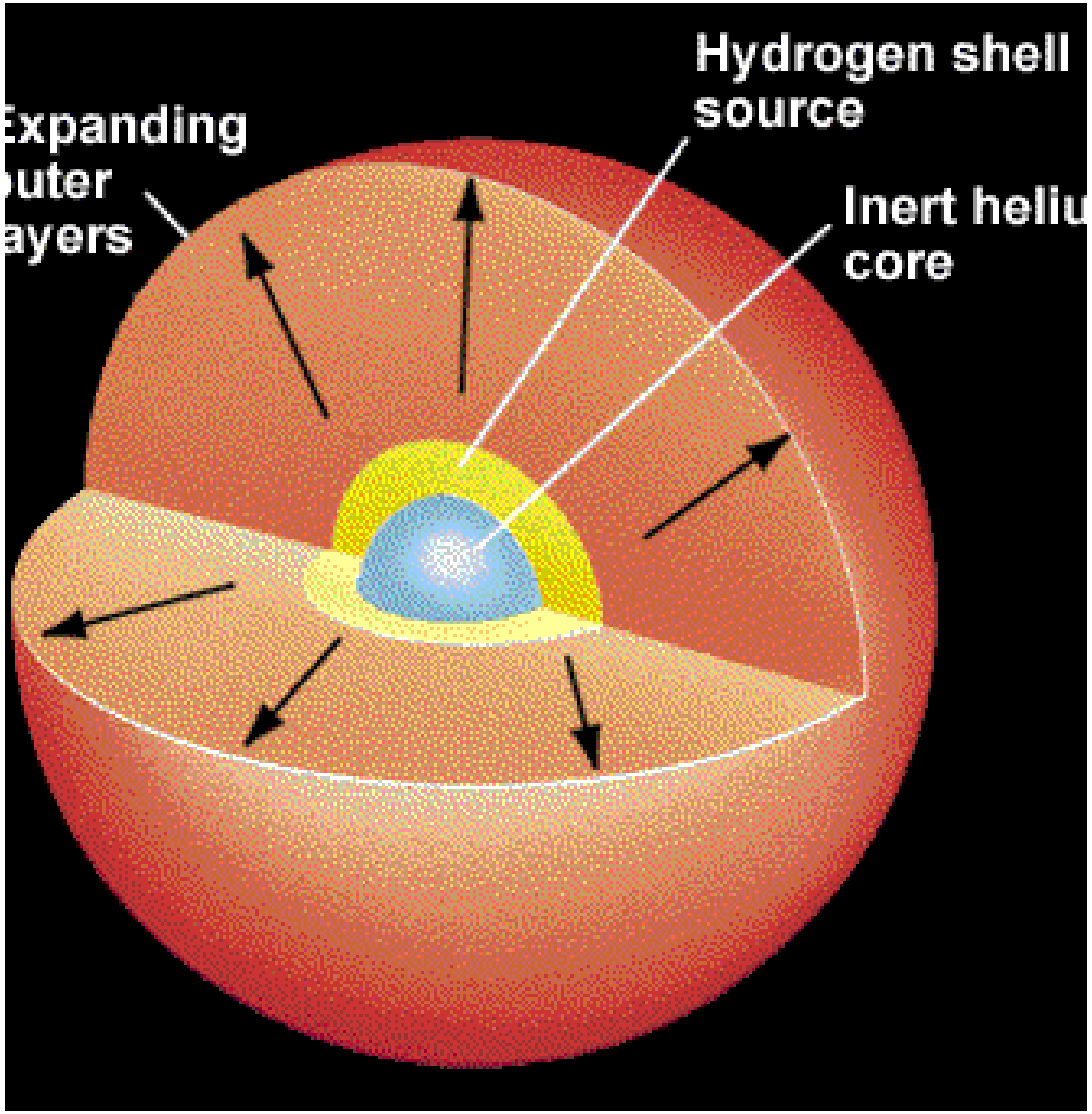
- Lifetime on the Main Sequence:
  - 10 solar masses – 10M years
  - 1 Solar mass – 10B years
  - 0.1 Solar masses (Red Dwarfs) – 10 Trillion tears

- Big bright blue stars (O and B) – are all young because they cannot last longer than a few million years



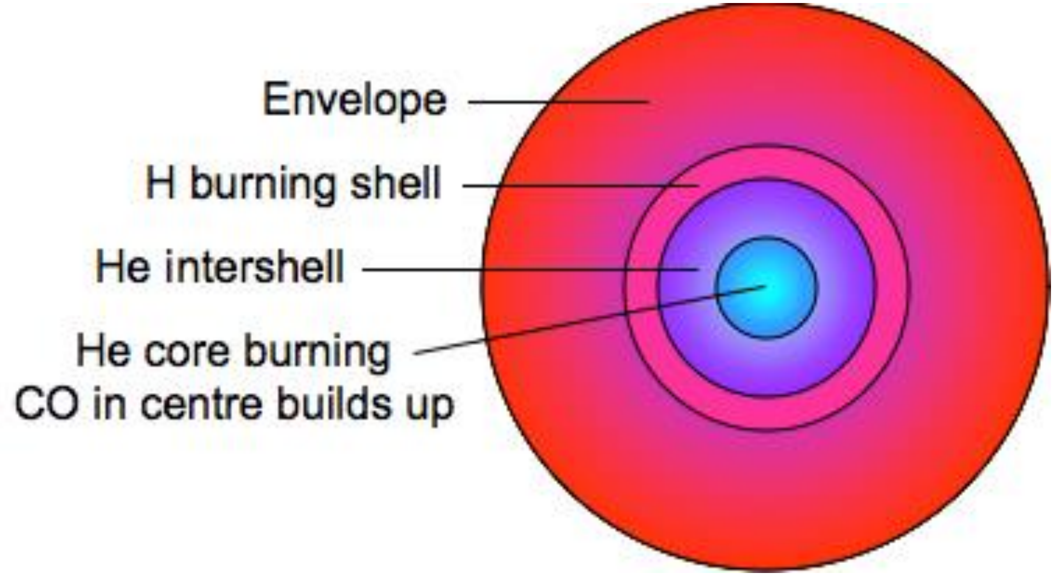
Low Mass Stars

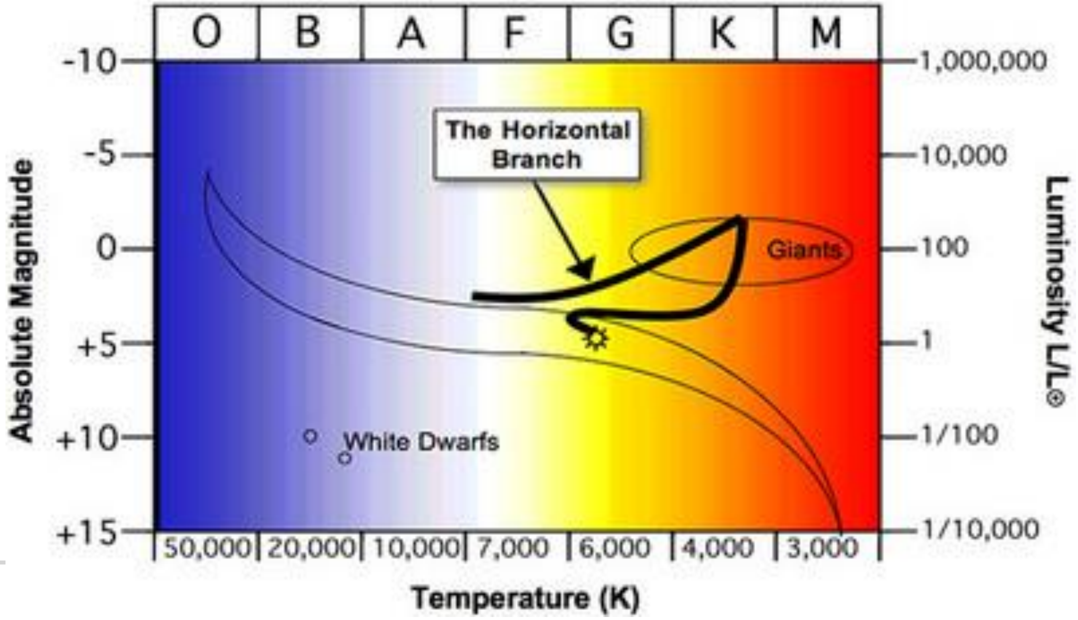
- Stars with 4 solar masses or less, will fuse hydrogen to helium for billions of years (4 Hydrogens become one Helium atom)
- The helium that is generated basically falls to the center as an inert core of helium and the hydrogen fusing is pushed out into a shell around the core
- As the number of particles goes down, to maintain pressure, temperature goes up accelerating nuclear reactions
- This creates more energy than the star can shine away, converting into energy that pushes the outer layers out
- The star's surface expands, its luminosity goes up, it gets a bit cooler and turns red – we now have a Red Giant



Low Mass Stars

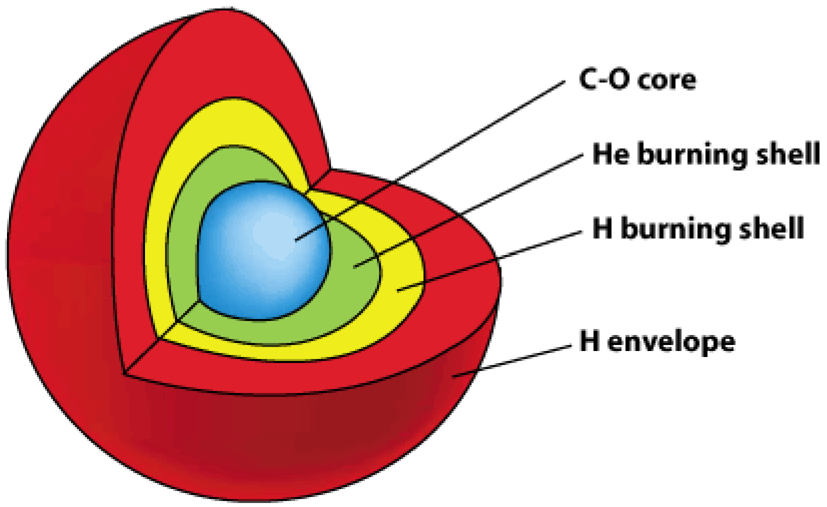
- After 1B years, the core contracts enough to drive core temperature to 100M Kelvin which ignites Helium fusion
- H_e fusion produces Carbon. Unique attributes of the isotope C_{12} allows it to undergo some fusion as well producing some Oxygen
- The star now is building up a core of Carbon and Oxygen, with a shell of Helium and a shell of Hydrogen fusing, it regains hydrostatic and thermal equilibrium
- The star contracts, becomes less luminous and its temperature goes up, becomes a bit blue – it is now a Horizontal Branch Star

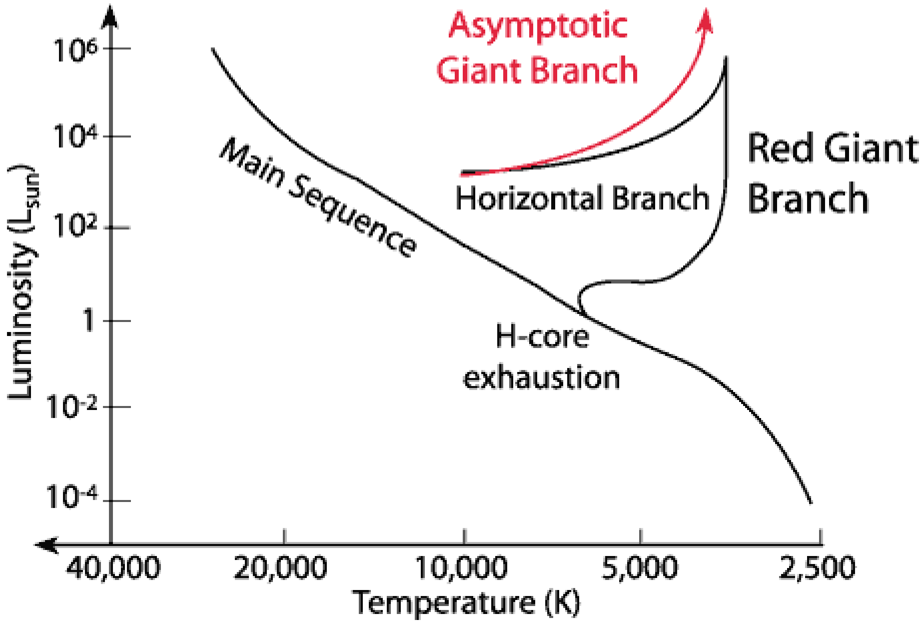




Low Mass Stars

- Helium fusion is only 1% as efficient as hydrogen fusion. To keep up with its luminosity needs, the star will burn through its helium core in 100M year
- A Carbon-Oxygen core builds up, it is 100-150M Kelvin but not close to 600M Kelvin required to for carbon fusion
- The core contracts getting hotter, driving fusion into overdrive. The star is producing more energy than it can shine away, and it expands again, gets brighter getting a bit cooler – it is now an Asymptotic Giant (10M years)
- Minor fluctuations in temperature drive helium fusion way up. 1% temperature increase causes a 40% increase in fusion. These helium flashes start to push away the envelope in a process that can take 100,000 years





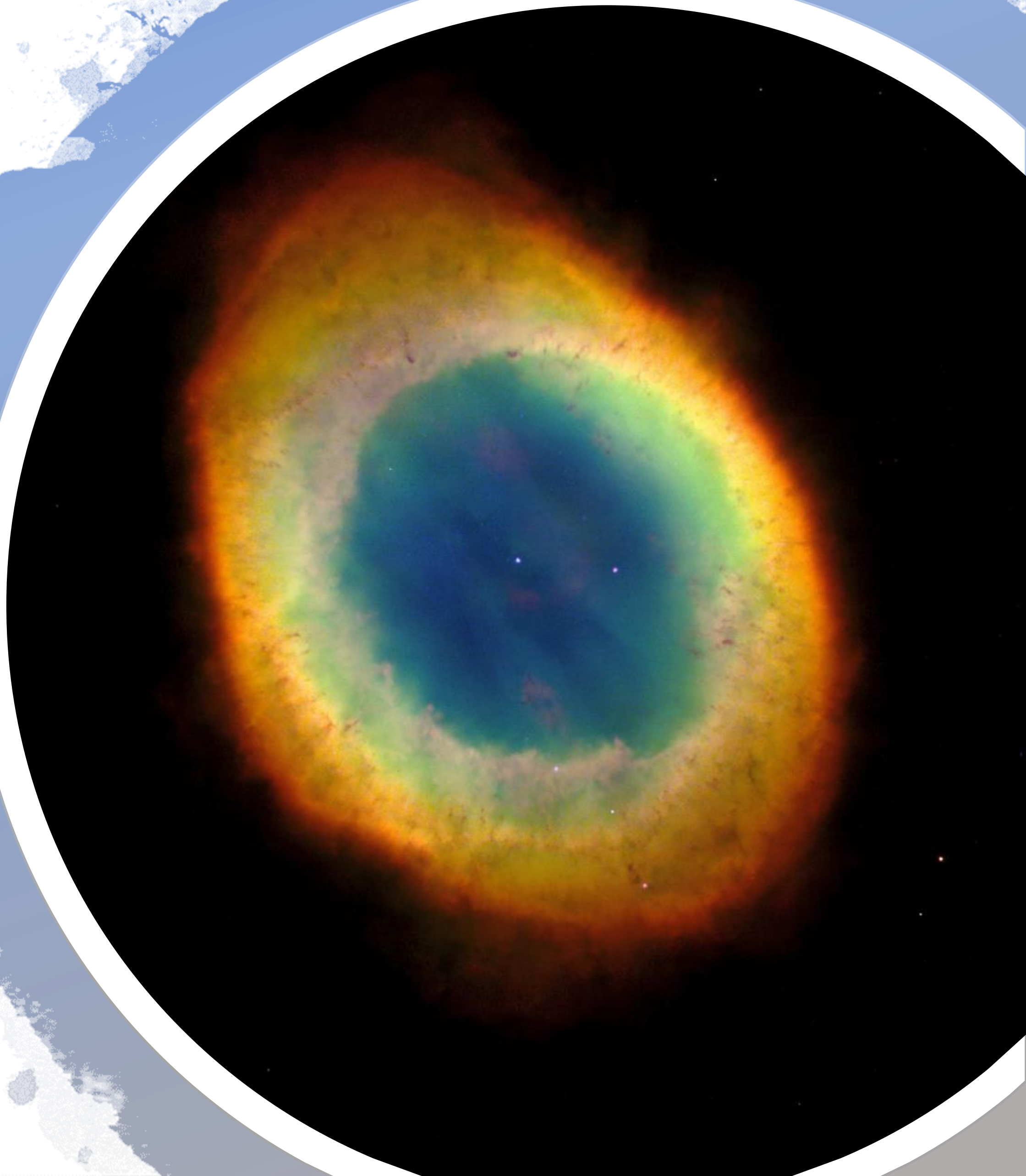
Low Mass Stars

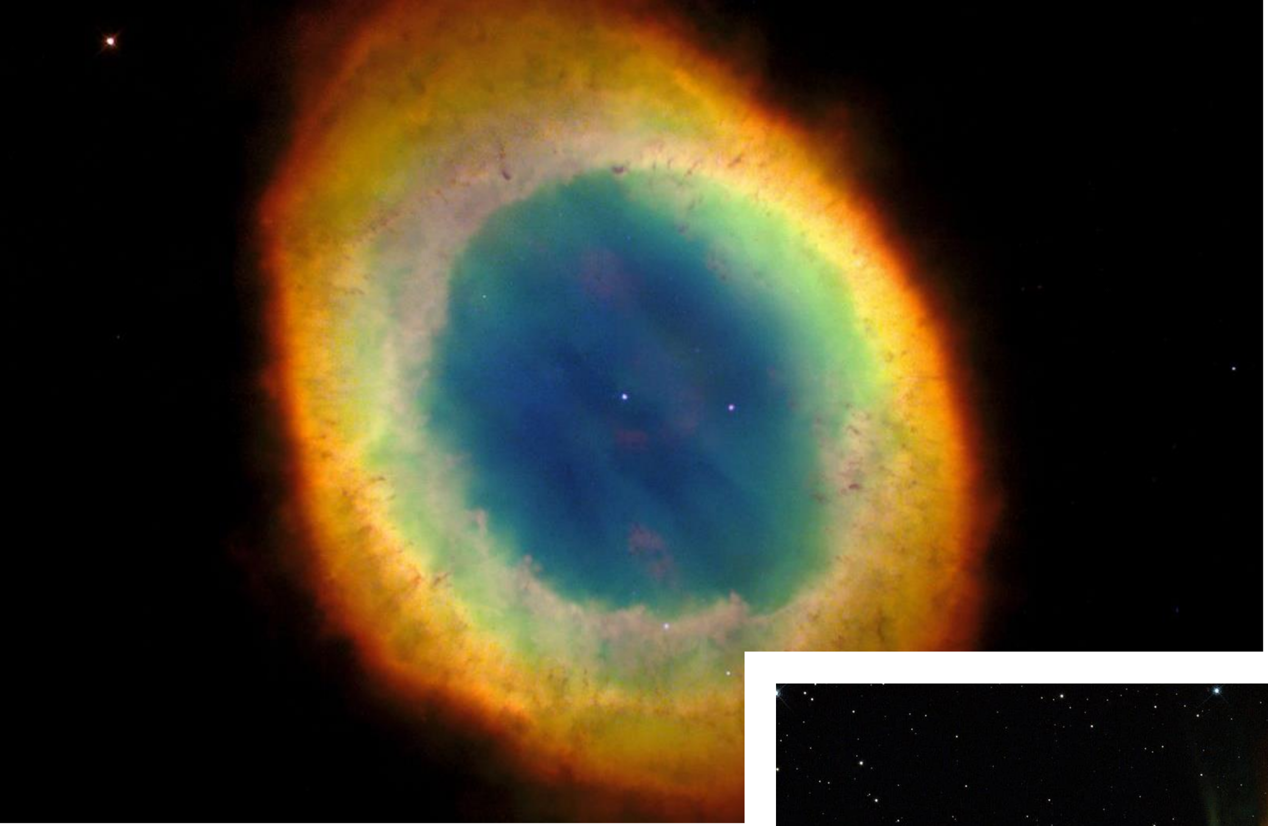
- As the envelope drifts away, the core is still extremely hot. Its heat and ultraviolet radiation ionize the gasses of the envelop to create one of the most beautiful objects in the universe – a Planetary Nebula

- The different colors reflect the chemical composition of the gasses that made up the star

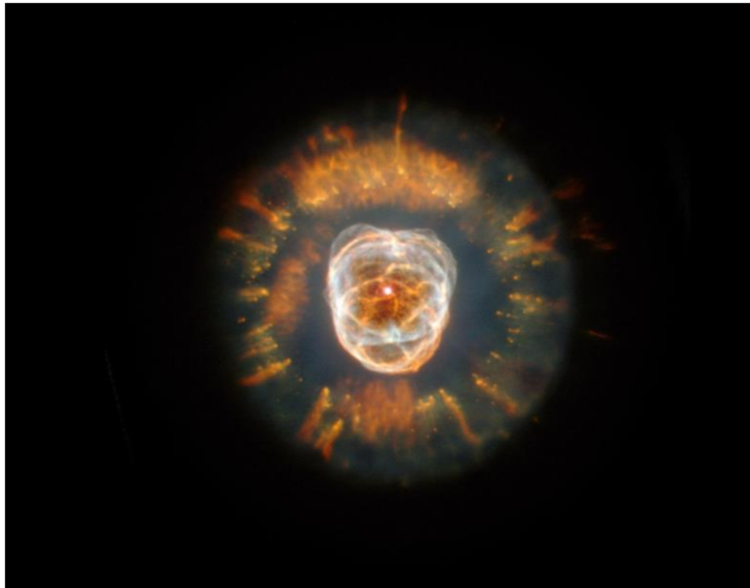
- Over 10-15 thousand years, these gasses will cool off and will not be visible

- All that remains is a dense inert core we call a White Dwarf









Low Mass Stars

- The core of a White Dwarf is typically between 0.6 to 0.8 solar masses and about the size of the Earth
- It is no longer fusing elements. It finds a new way to achieve balance against gravity
- The atomic structure is pressed so much that a new state of degenerate matter and pressure balances off gravity – this pressure is created by electron degeneracy repulsion
- This pressure is independent of temperature. The white dwarf shines because it is hot. When it loses all its heat to space it will become a Black Dwarf. That process will take 10 trillion years

Low Mass Stars – Lifecycle Summary

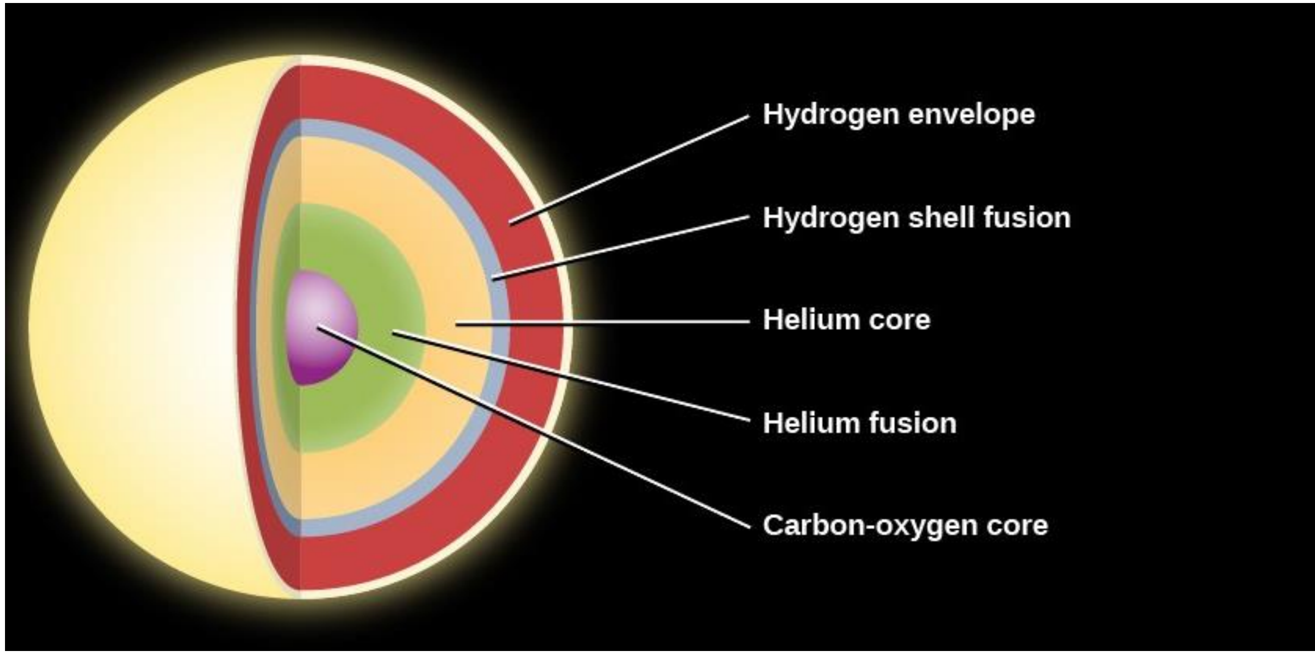
Formation	Protostar	Main Sequence	Red Giant	Horizontal Branch	Asymptotic Giant	Planetary Nebula	White Dwarf
100,000 Years	30M Years	10B Years	1B Years	100M Years	10M Years	100K Years	10 Trillion Years

Low Mass Stars

- If more material is added to a white dwarf pushing its mass above the 1.4 solar masses Chandrasekhar limit gravity will take over again
- The increasing density causes fusion to ignite again. C and O star fusing generating heat.
- Because this is degenerate matter, pressure does not go up, the collapse continues accelerating fusion releasing more heat driving more fusion until the whole star detonates in a thermal nuclear explosion
- Supernova Type 1a are useful “standard candles”

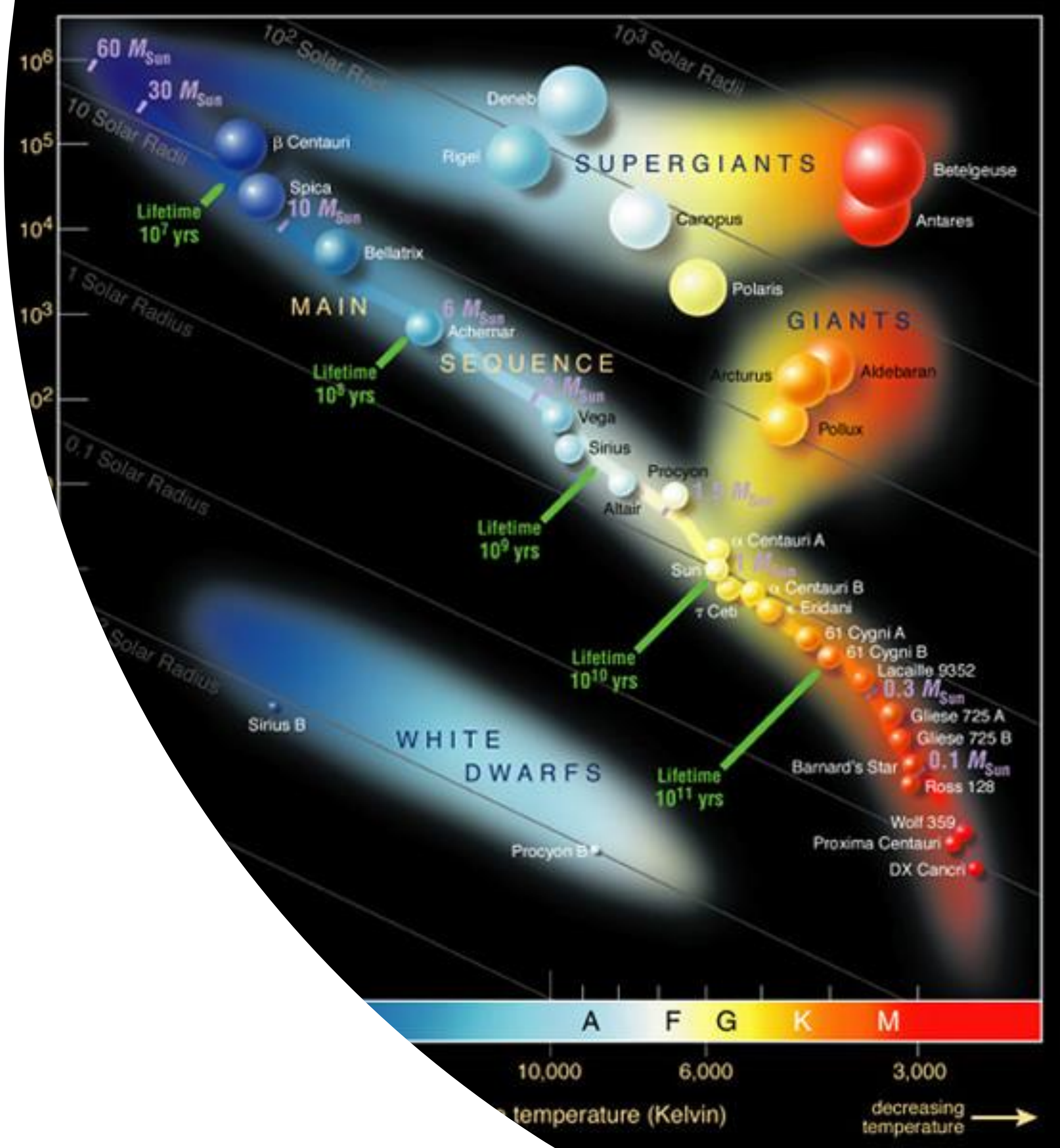
High Mass Stars

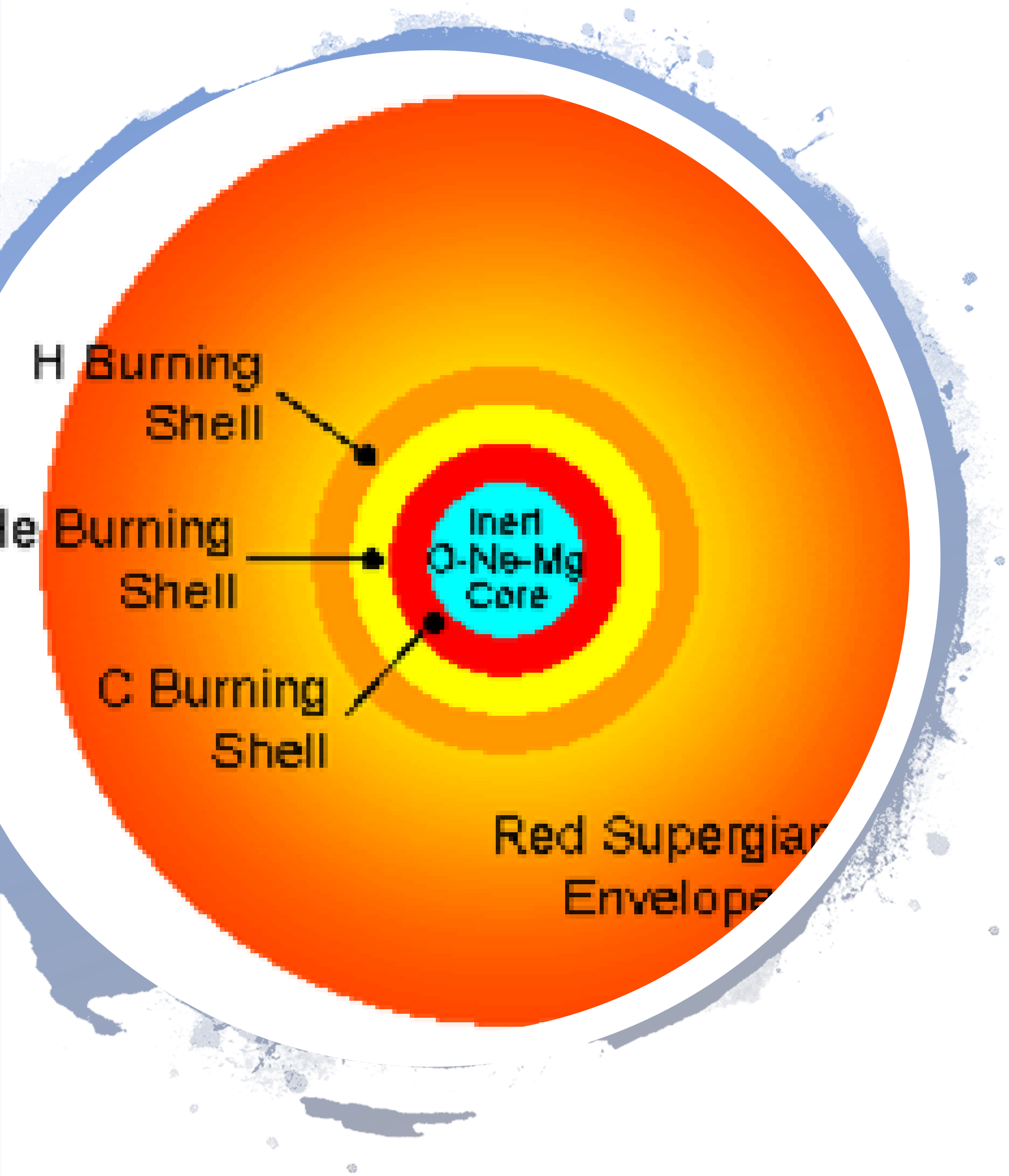
- Stars with more than 4 solar masses evolve beyond a carbon-oxygen core
- Stars with 4-8 solar masses will climb up the red giant branch scale within 1M years (compared to 1B years for low mass stars)
- They will balloon to a size of 5 AU and their helium core can be the size of the sun
- When the core reaches 100M Kelvin, helium fusion starts. The star restores hydrostatic and thermal balance, it becomes hotter and they become a Blue Supergiant



High Mass Stars

- The size and rate of luminosity of a Blue Supergiant requires a ferocious rate of fusion which lasts about 1M years
- As Carbon & Oxygen builds up in the core, the helium and hydrogen get pushed out into a fusing shell, the star loses hydrostatic balance and contracts to a Super Red Giant
- When the core density reaches 155,000 grams per CM^3 and temperatures rise to 600M Kelvin, Carbon fusion begins.
- This time the star will never be able to restore its balance again



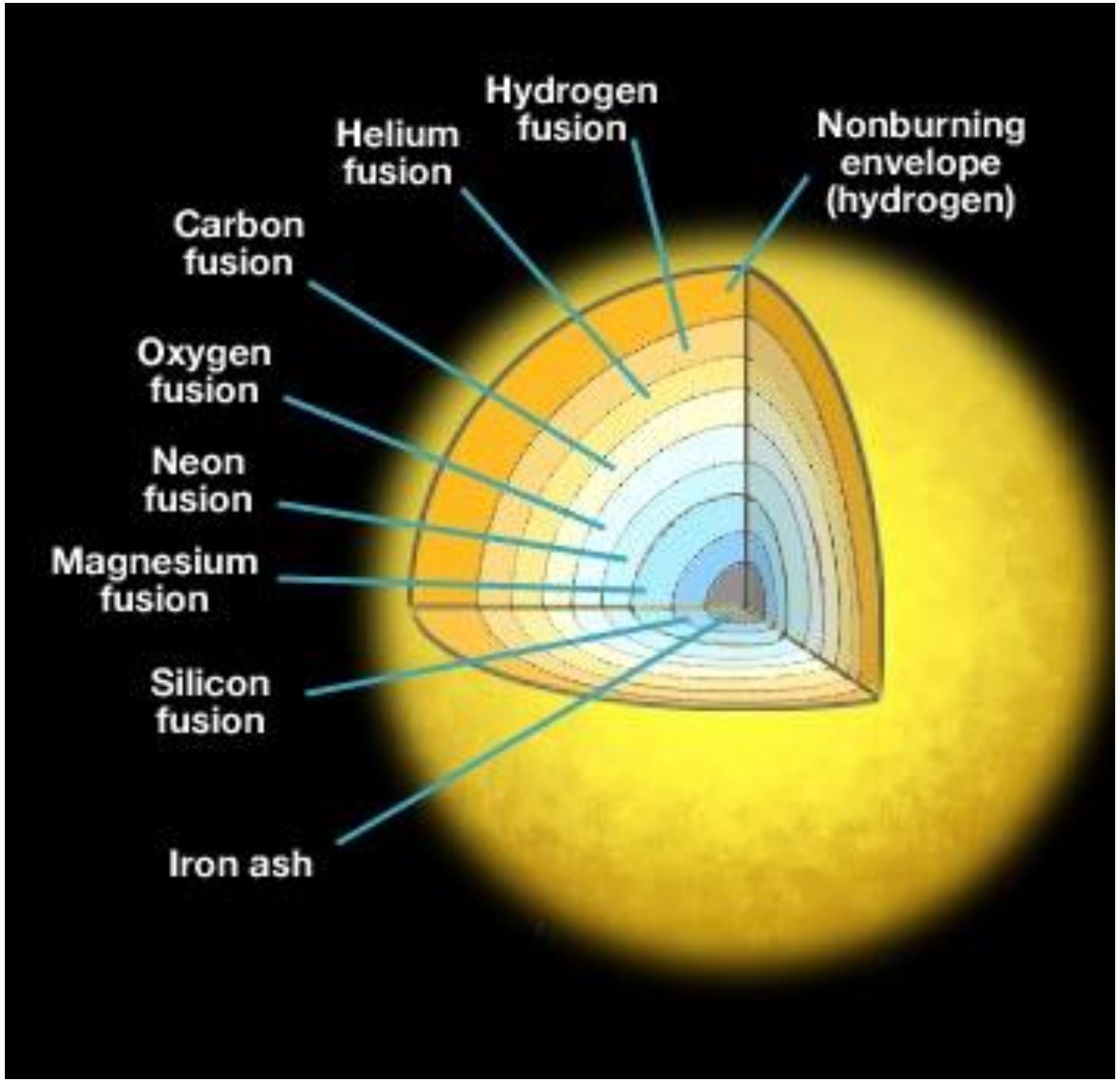


High Mass Stars

- The rate of fusion is so fast, and the energy production is so inefficient the star can no longer compensate for its energy loss.
- The byproducts of Carbon fusion are Oxygen, Neon and Magnesium. The star is losing energy by shining and by the massive outpour of neutrinos coming out of the fusion process
- This process lasts about 1,000 years
- 4-8 solar mass stars will have a core of O-Ne-Mg which will contract, producing more heat accelerating the fusion process in the shells, sending flashes of energy pushing the envelope away from the core. They can create massive planetary nebulae, but sometimes the process is so fast, there is not rime for a planetary nebula to evolve
- The remaining core is a 1 solar mass white dwarf

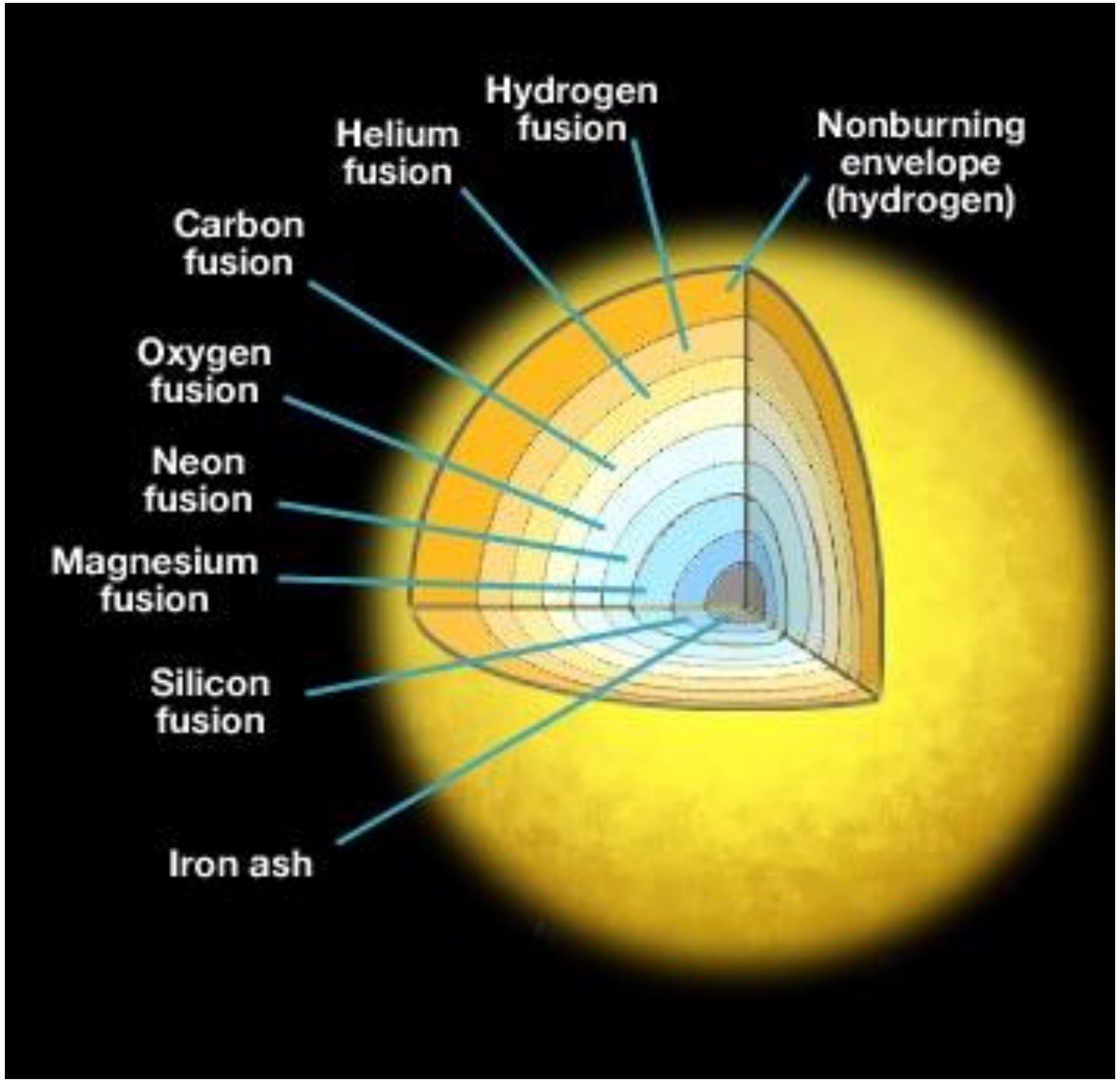
High Mass Stars

- In stars with more than 8 solar masses the O-Ne-Mg core continues to contract. When it reaches 1.5B Kelvin and a density of 1M gr/ cm^3 Neon starts fusing
- It is a very inefficient process; the star shines brighter in neutrinos than it does in photons
- This process will last less than a decade



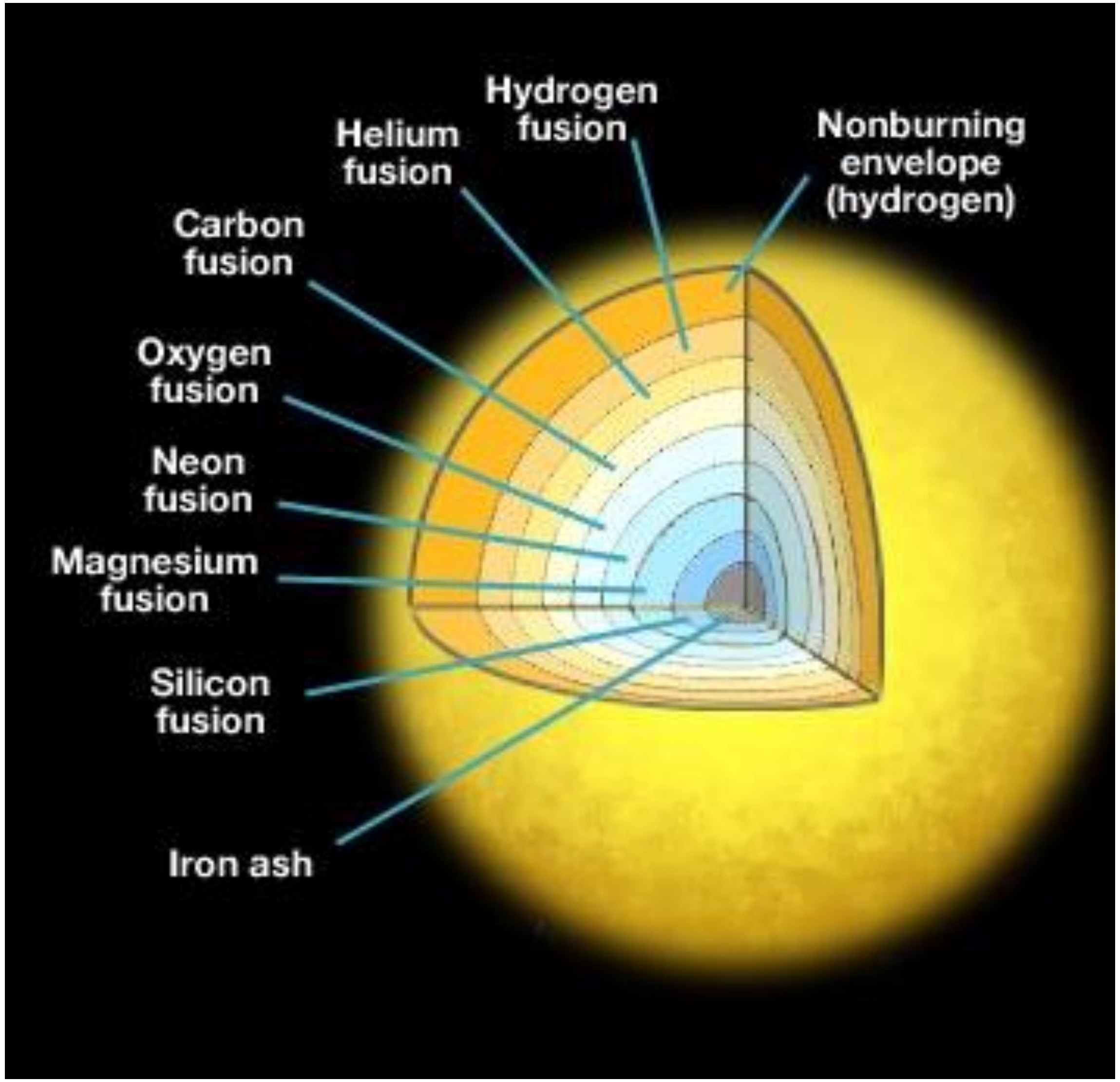
High Mass Stars

- The core is compressed, we have burning shells of Ne, C, He and H
- When the core reaches 2.1B Kelvin Oxygen starts fusing
- Energy loss is huge, for every 1 photon generated, the star loses 100,000 neutrinos
- Within 1 year a core of silicon is created



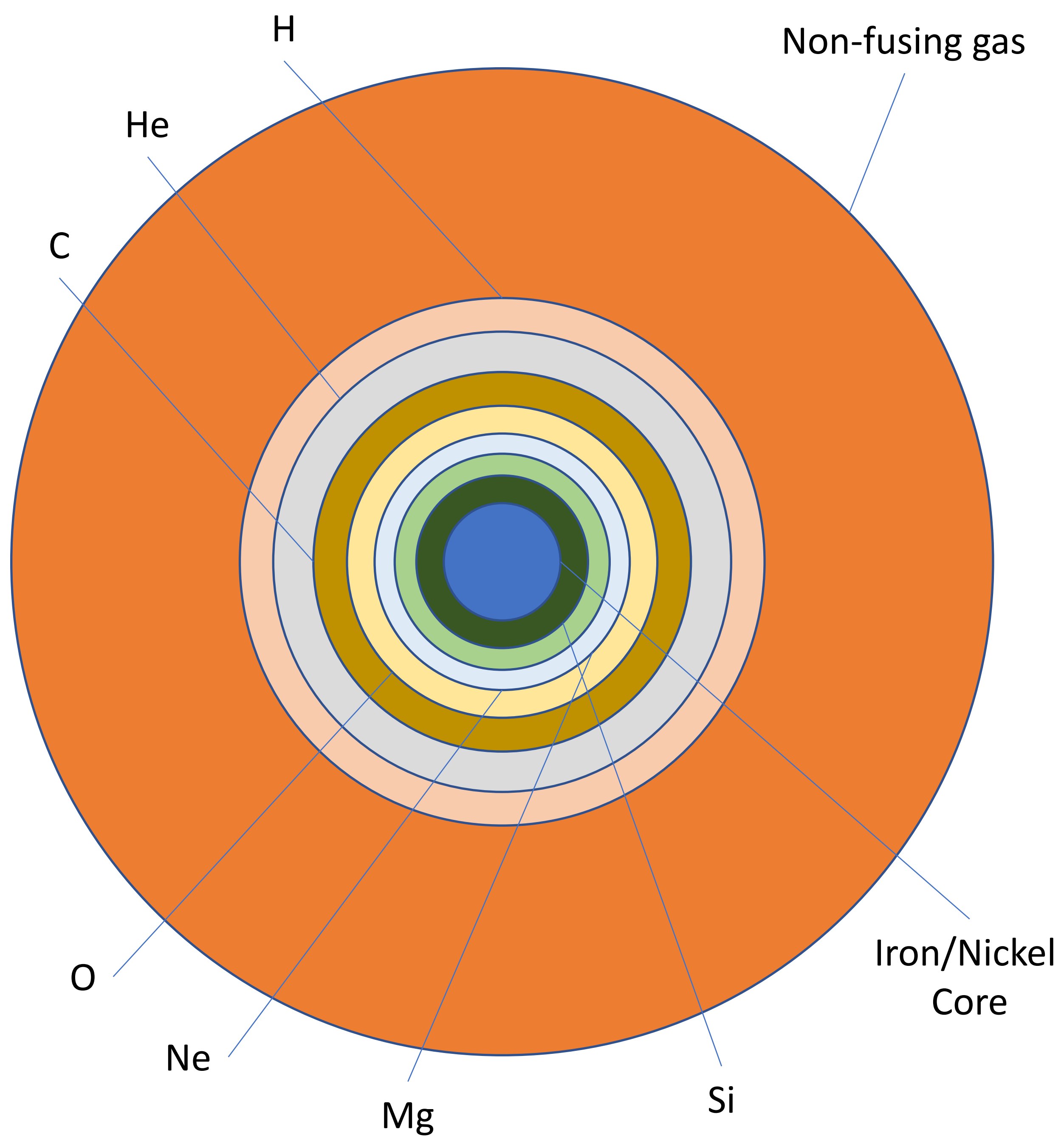
High Mass Stars

- The core contracts and reaches 3.5B Kelvin, density is in tens of millions of grams per cm^3 the fusion process produces many elements including: Potassium, Sulfur, Chlorine, Phosphorus, Calcium, Chromium, Cobalt and finally Iron and Nickel
- The rate of fusion is out of control, a 1 solar mass of Si will be fused into Iron and Nickel in ONE DAY
- The process stop. Fusing iron requires investing more energy than it produces, the total mass required to produce new elements is greater than the output – and so this process comes to an instant stop
- The core is 1-1.2 solar masses of Iron and Nickel, there is no fusion, there is no balance, it contracts, temperature builds up to around 4B Kelvin – but no new fusion will happen this time it will end – Death via Supernova



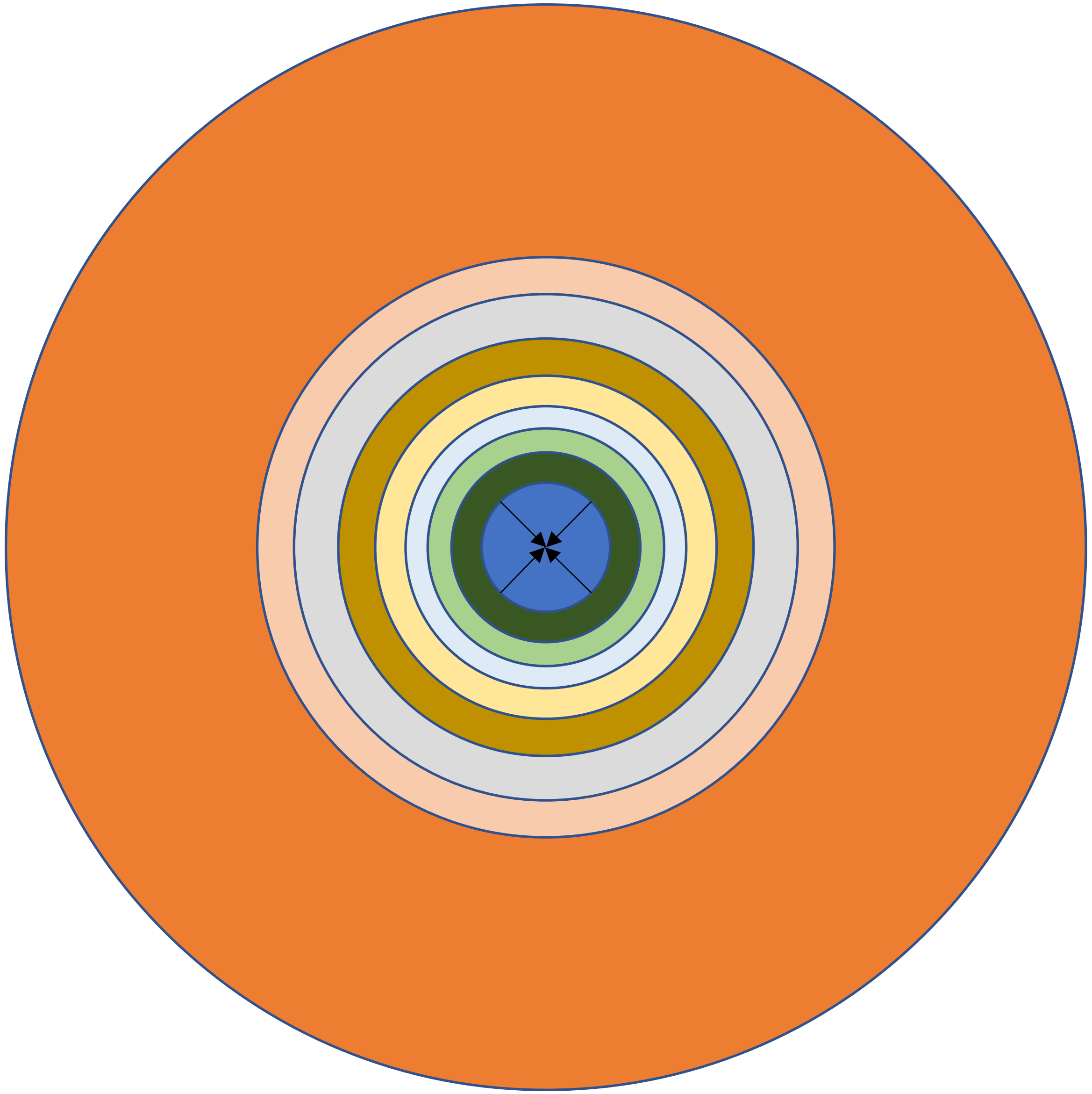
Into the heart of a Supernova

- This high mass star spent 10,000 years as a protostar, 10M years on the main sequence, 1M years as a super giant, 1,000 years burning Neon in its core, a decade burning Oxygen and 1 year building up a Si core and now, in one day it builds up an iron / nickel core
- We have a star with an Iron / Nickel core at 3.5B Kelvin, with an onion layers of Si, Mg, Ne, O, C, He and H fusing – barely making up enough energy to compensate for the loss of energy to luminosity and the neutrinos pouring out of the star
- What happens next is measured in seconds and milliseconds



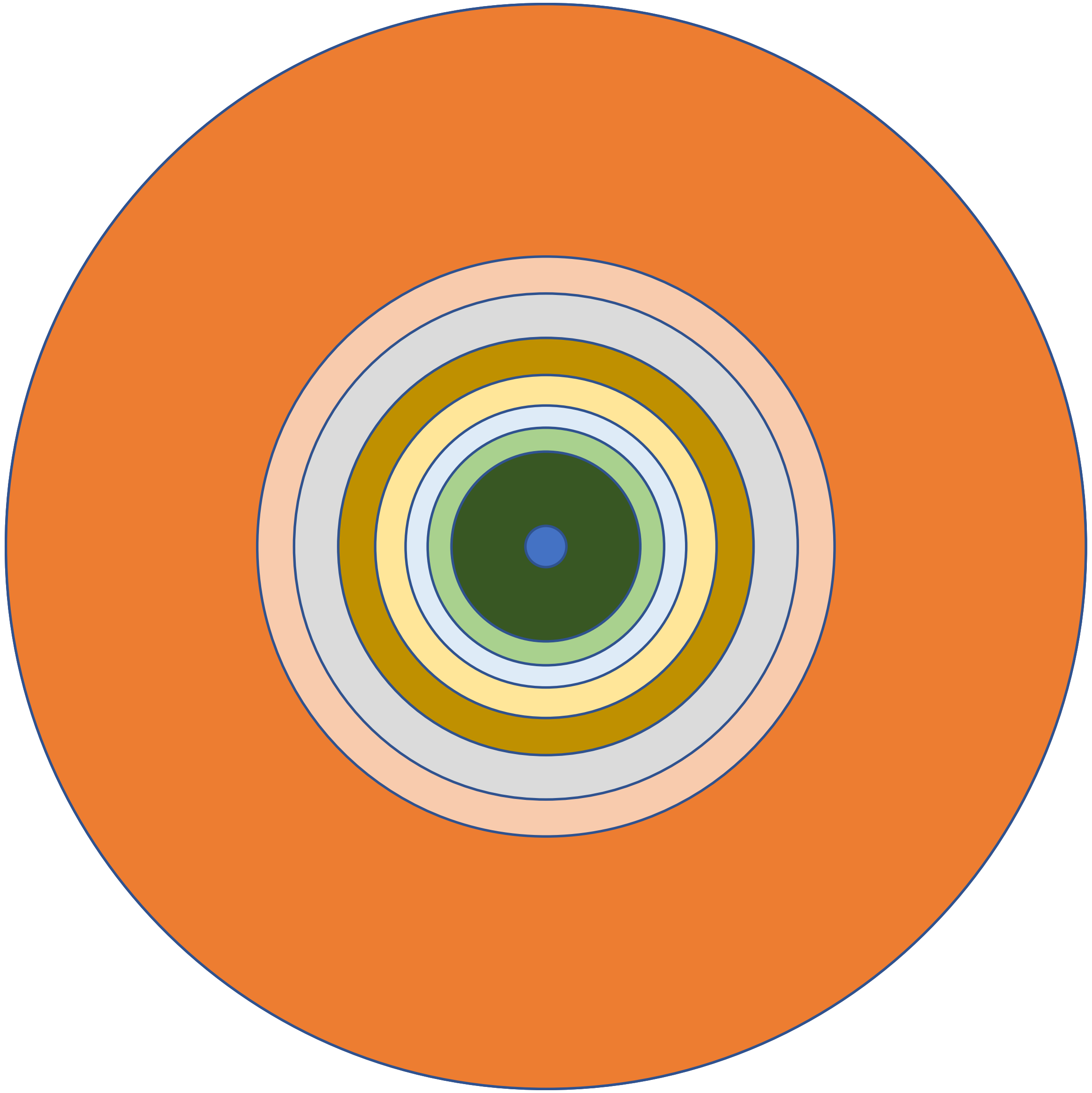
Into the heart of a Supernova

- The core is not fusing, nothing is pushing back on gravity and the core starts collapsing driving heat up
- When the core reaches 10B Kelvin and a density of 10B grams per cm^3 atomic nuclei start melting
- The core starts to photo disintegrate into lighter elements. Last few seconds, protons start to combine with electrons into Neutrons releasing a sea of neutrinos carrying more energy out of the star



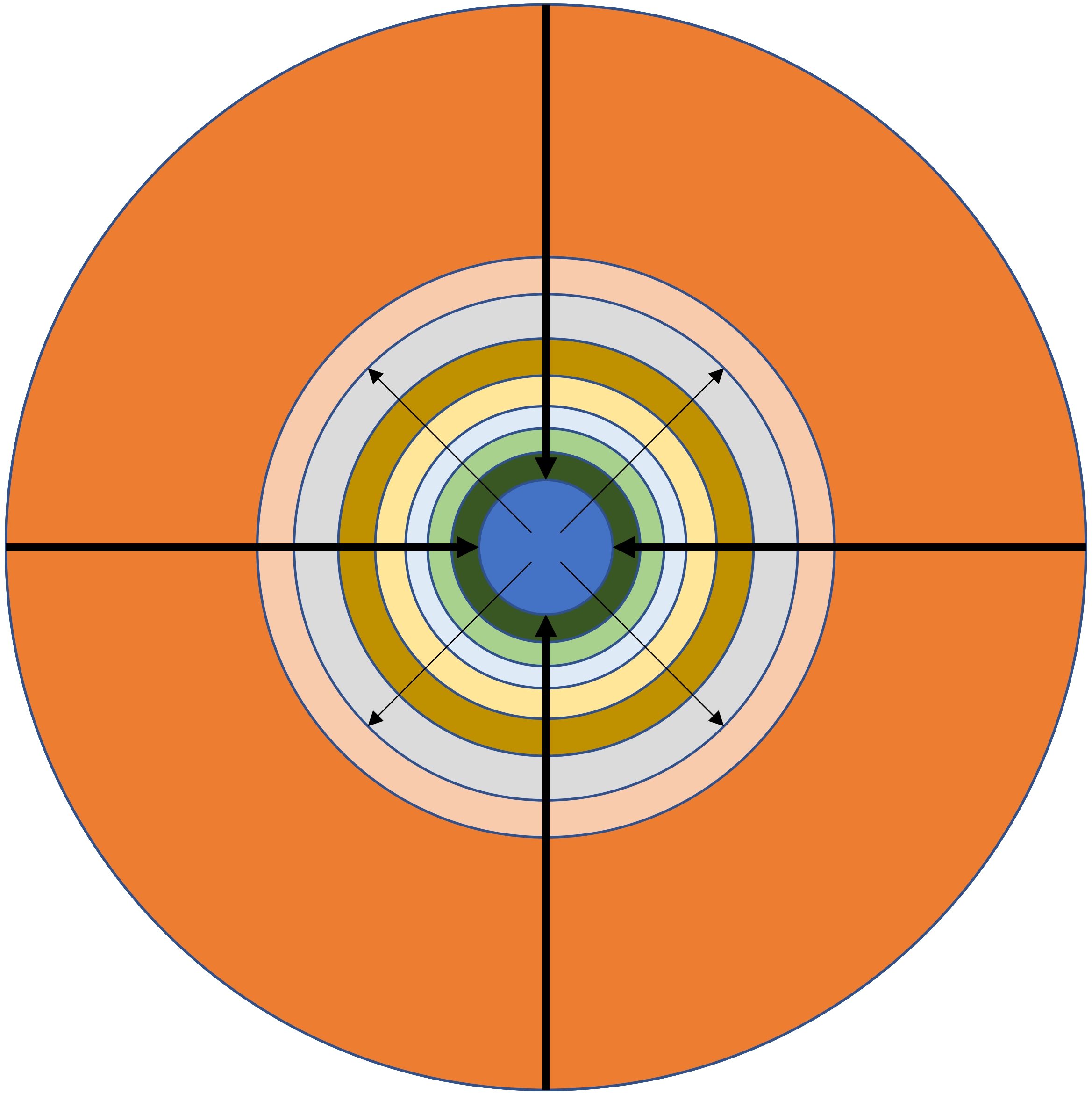
Into the heart of a Supernova

- This is a catastrophic process
- Energy is dropping, pressure is dropping, and gravity takes over
- When this process starts the core is the size of the Earth with a density of 100M gr/ cm^3.
- One second later the core is the size of a city (50km) and a density of 100B gr / cm^3 .



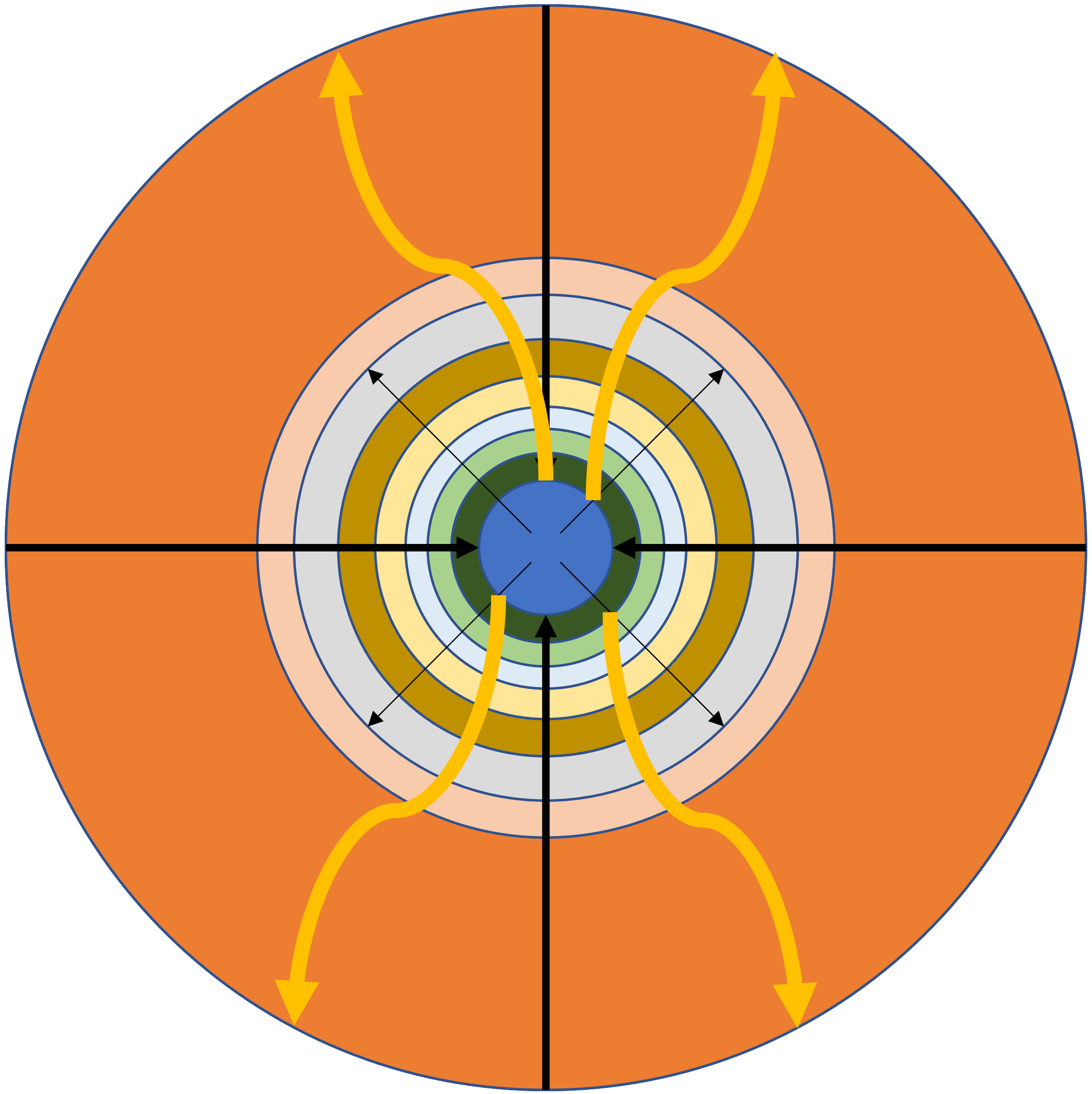
Into the heart of a Supernova

- Core collapse is so fast, its outer edge is falling at 25% the speed of light
- When the core density reaches the same density as atomic nuclei a different force takes over, the Strong Nuclear force which pushes back causing the core to bounce back at a speed of 50% the speed of light
- The rest of the star is falling at 25% the speed of light towards this solid wall of nuclear material moving at 50% the speed of light



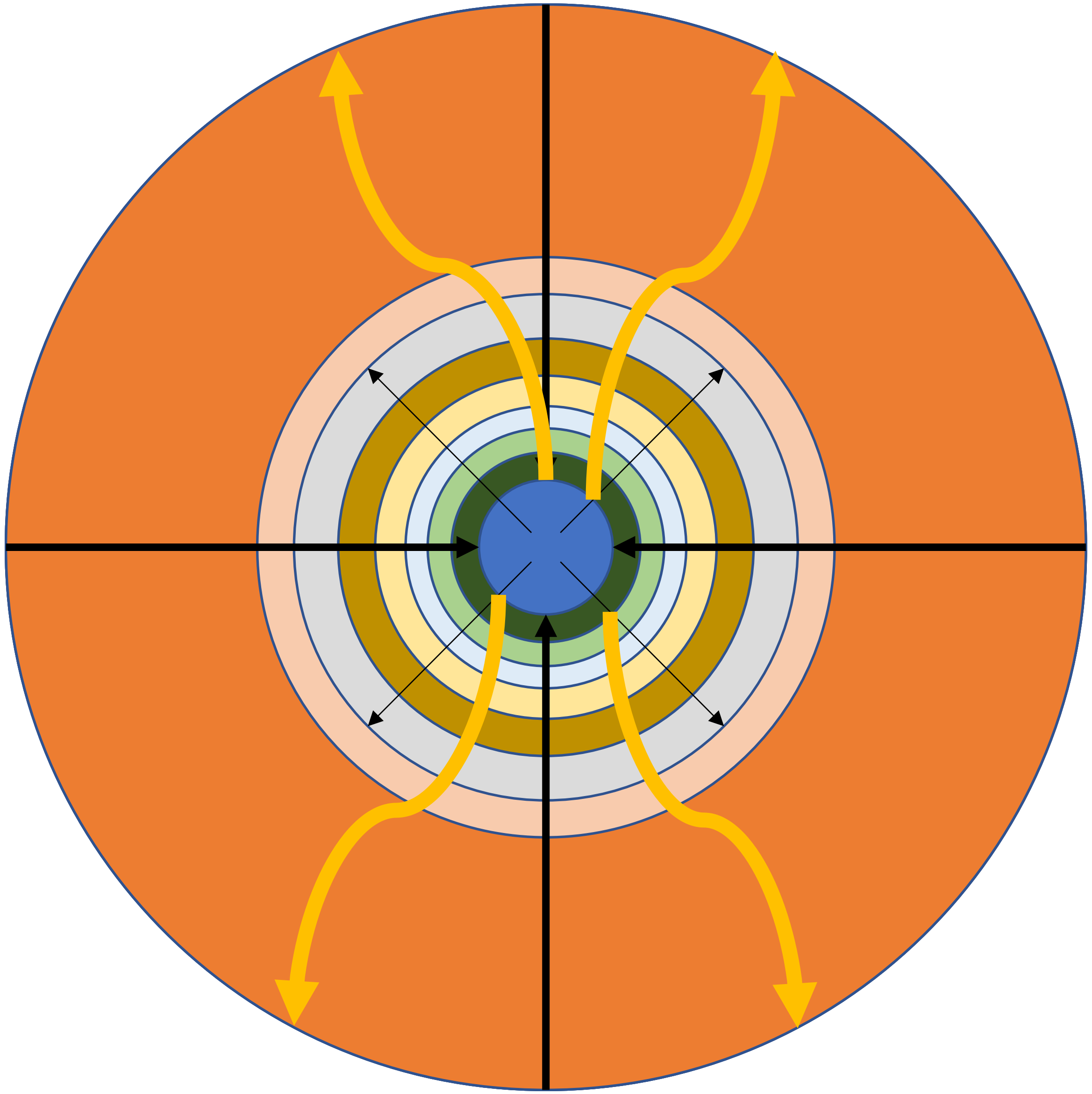
Into the heart of a Supernova

- The core rebound sends shockwaves through the material falling towards it creating a “traffic jam”
- Neutrinos from the core are ramming into this dense material which is millions of times denser than lead
- It creates enough pressure to push the envelope explosively away in milliseconds
- Enough energy is released to cause explosive nuclear synthesis in the envelope



Into the heart of a Supernova

- So much energy is released, that it no longer matters that iron fusion is an endothermic process
- Neutrons fuse with Iron creating new elements like Gold and Platinum
- While this process takes sub seconds, the star is so large (5 AU) that it can take hours before the explosive process reaches the outer layers of the star making it one of the brightest objects in the universe with a luminosity of 10B suns



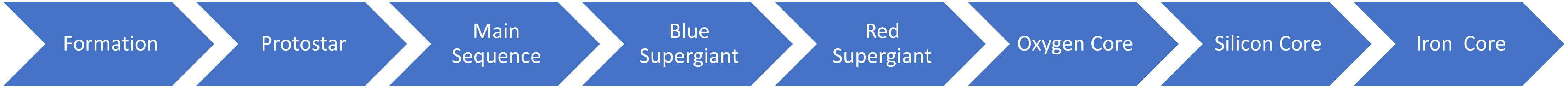
Into the heart of a Supernova

- If the iron core was less than 2 solar masses, it will leave behind a Neutron star – an object that is so dense it has 1.5 solar masses in an object the size of about 20 Km

- If the core was bigger than 2 to 3 solar masses, it will continue to collapse into a black hole

- To have an iron core of at least 2-3 solar masses, requires a progenitor star of at least 18 solar masses

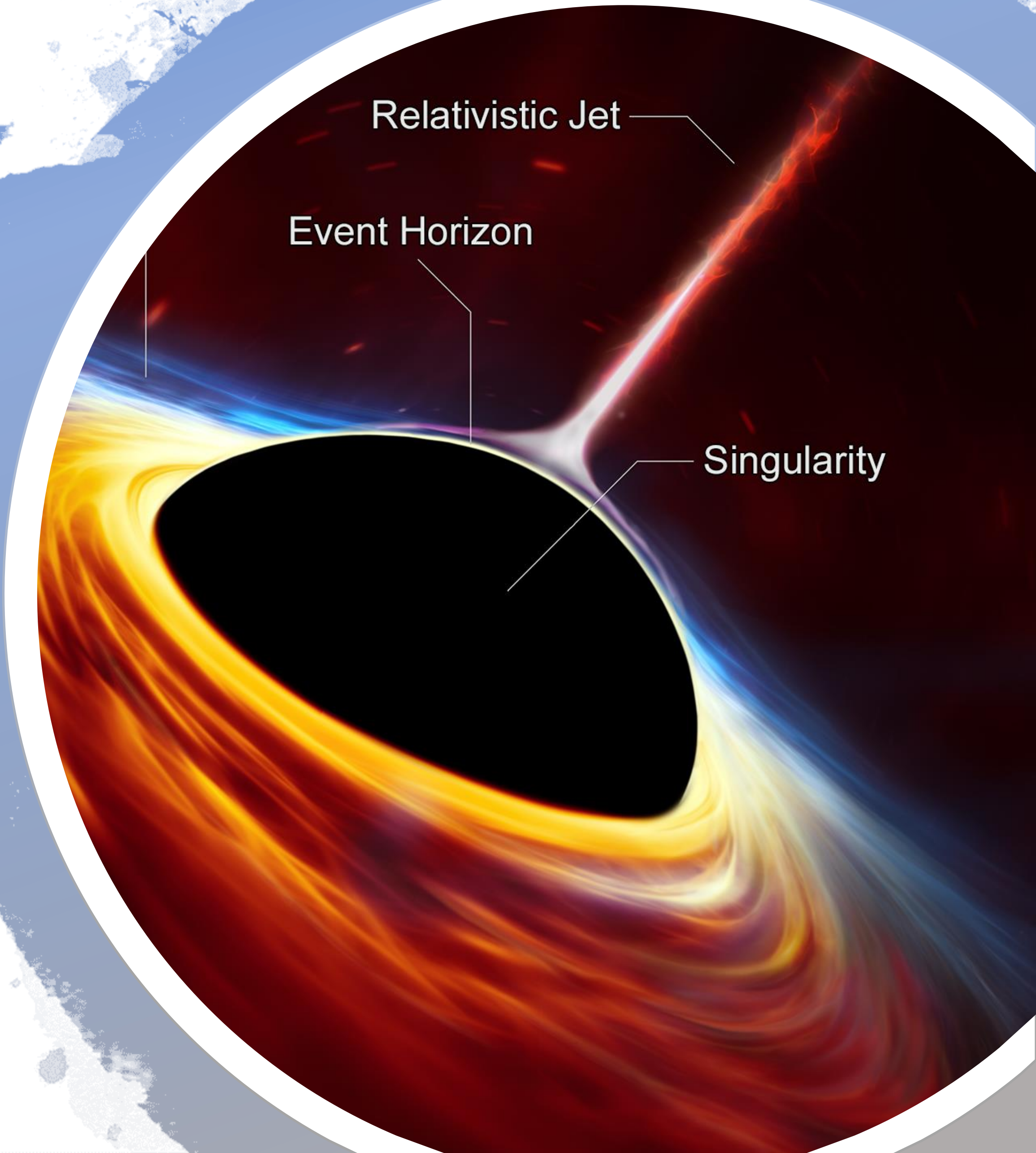
High Mass Stars – Lifecycle Summary



10,000 Years 10,000 Years 10M Years 1M Years 1M Years 1,000 Years 10 Years 1 Day

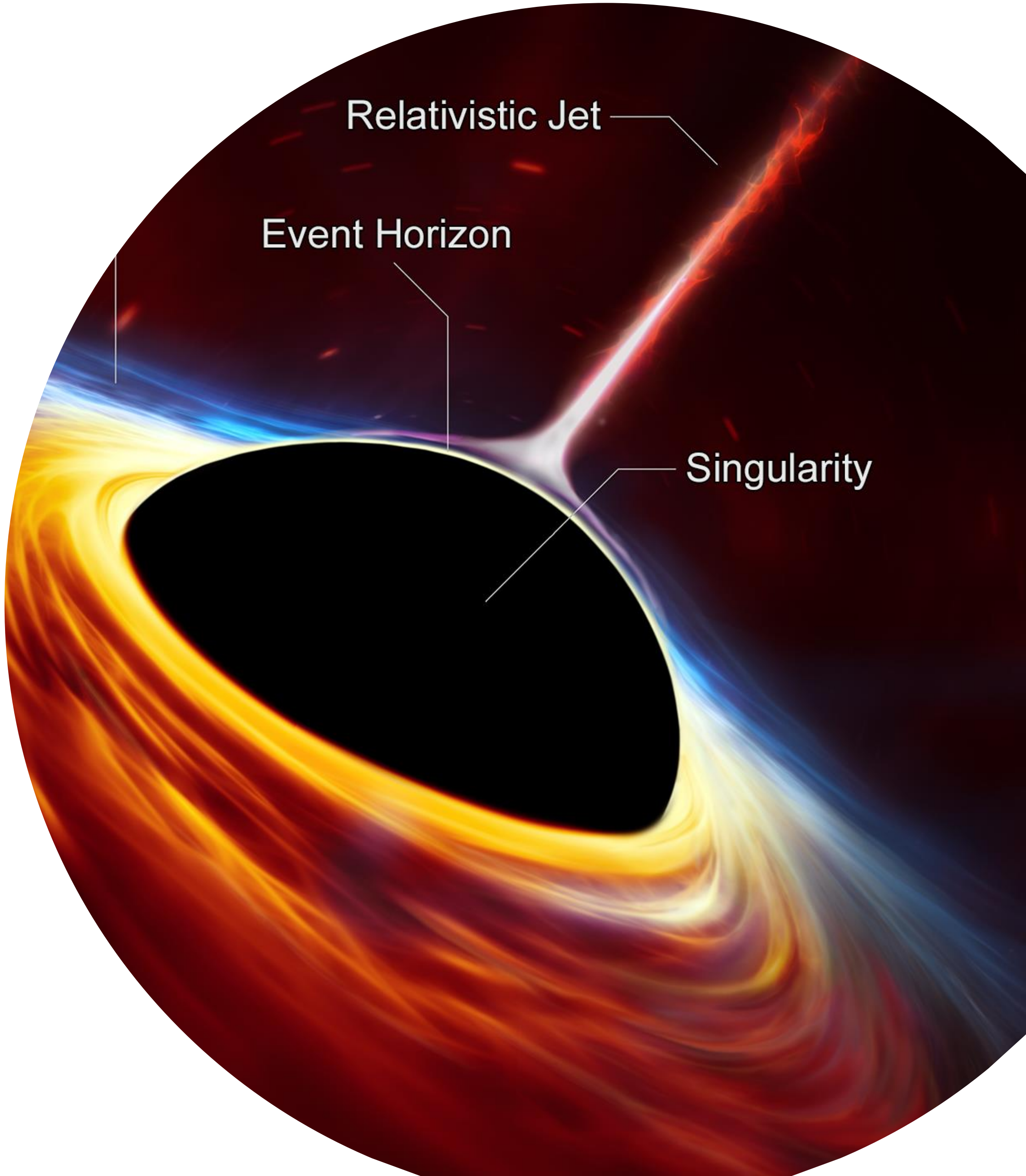
Black Holes

- If the core was bigger than 2 to 3 solar masses, Neutron degeneracy cannot push back on gravity and the core continues to collapse on itself
- It creates an object with almost infinite density and almost zero size which we call a singularity
- It twists and wraps spacetime around itself
- Escape velocity is greater than the speed of light, so nothing, not even light can escape out of a black hole



Black Holes

- A black hole has no surface
- We call them black holes, because once something goes in it cannot come out and we cannot see them hence they are black
- There is a radius from the singularity below which nothing can escape (Schwartzwald Radius), using this radius we depict them as balls
- This radius represents the point beyond which no more information, not even light can be returned, this is called the Event Horizon – beyond this point we get no information we can detect and measure



Black Holes

- While we cannot see black holes directly, we can see and measure their impact on their surroundings
- Stars in a binary system will have orbits that are affected by the black hole, and in some cases maybe losing material on to the blackhole creating an accretion disk
- Black holes do emit Hawking's Radiation and over time evaporate into nothing (a long time, 10^{73} years)

Testing Stellar Evolution

- How can we talk about process that take millions and billions of years when modern astrophysics is just over one century old?

- If we wanted to study the life of an Oak tree, we would face the same problem – Oak trees can live 400-600 years

- Studying a single tree will be difficult

Testing Stellar Evolution

- One afternoon in a forest of Oak trees can show us acorns, saplings, middle aged trees, old trees and dead trees

- That is how we learn about stars, we do not study a single star but a group of stars, star clusters

Testing Stellar Evolution

- One afternoon in a forest of Oak trees can show us acorns, saplings, middle aged trees, old trees and dead trees
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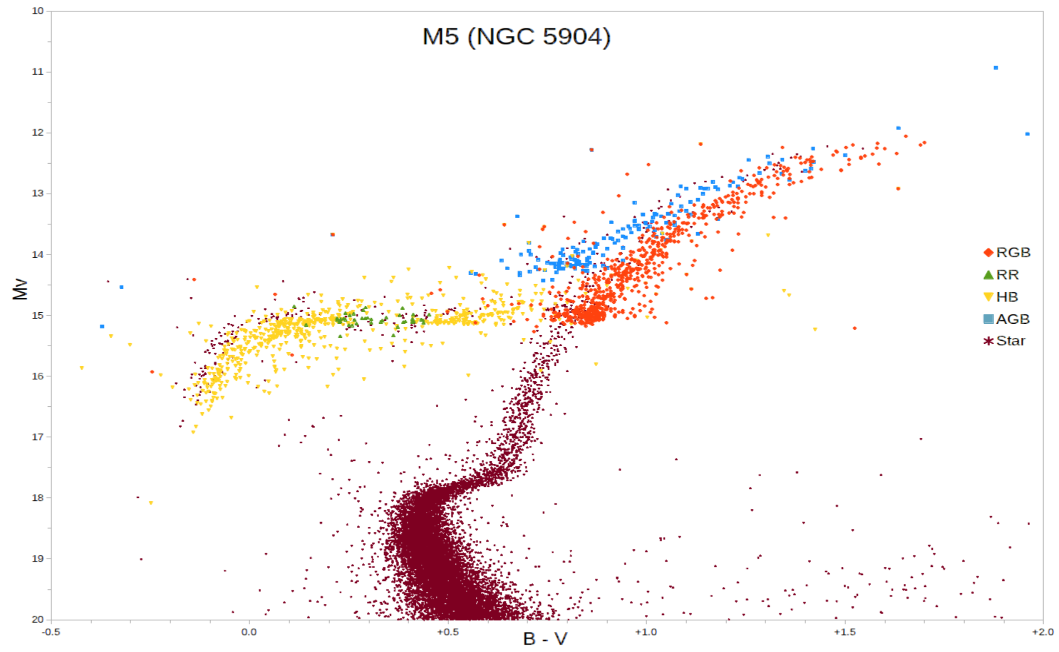
Testing Stellar Evolution

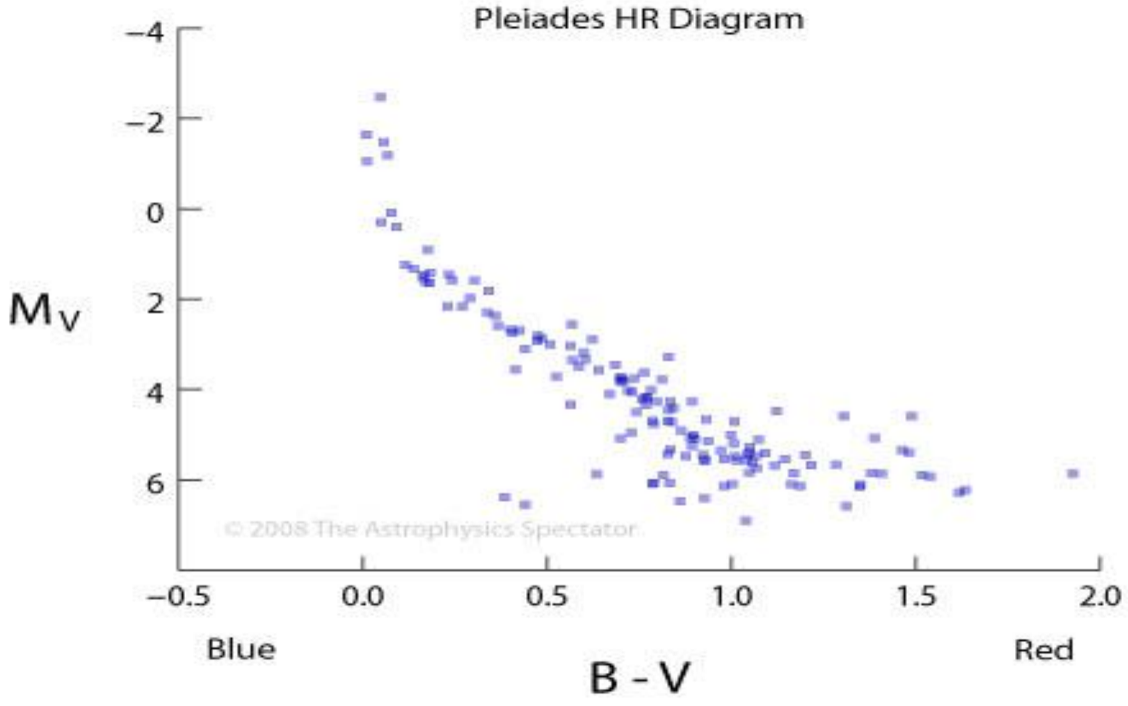
- The stars in a cluster where born from the same nebula, they share the same chemical composition, the move together and they are roughly the same distance from us, and we can measure that

- Differences in their luminosity are intrinsic

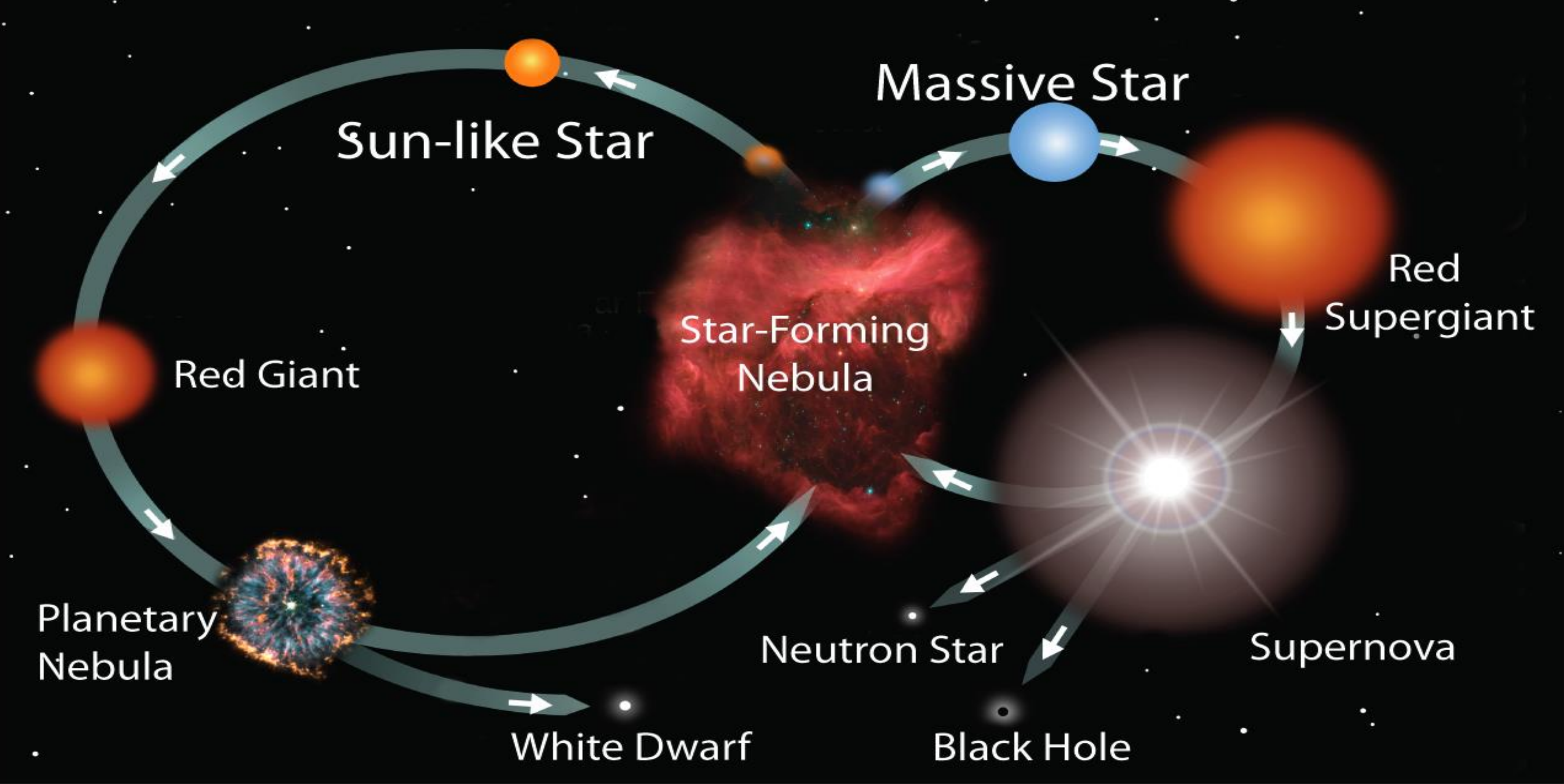
Testing Stellar Evolution

- The shape of the HR diagram tells you a lot about the age of the stars
- Old clusters will not have O stars or very few because they live fast and die young
- In addition to HR diagram diagnostics, there is a ton of observational evidence for protostars, planetary nebulae, supernovae, pulsars and black holes





THE LIFE CYCLE OF STARS




"We are all made of stardust",