ASTR 1P02

Brock University

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Lecture 14:
Star formation and evolution

We will learn about…

- Interstellar matter and nebulae.
- How stars are born.
- The evolution of stars over their lifetimes.

The star-forming region NGC 3324 in the Carina Nebula, captured in infrared.
Credits: NASA, ESA, CSA, STScI

The interstellar medium

- The interstellar medium (ISM) is the matter that exists in the space between the stars.
- Some interstellar matter is concentrated into giant clouds called nebulae.
    - Plural of nebula, pronounced “NEH-byoo-lee”.
- Nebulae often glow or reflect light, and can be seen from Earth.

The interstellar medium

- Interstellar clouds constantly shift, merge, grow, and disperse – much like clouds in Earth's atmosphere.
- A star is born when an interstellar cloud becomes dense and massive enough to collapse under its own gravity.
  - We will learn more about that later.
- When a star dies, it ejects some of its material into interstellar space, which can then form new clouds.

The interstellar medium

- ~99% of the mass of the interstellar medium is interstellar gas, mostly hydrogen and helium, but also heavier elements.
- The other ~1% are solid particles, called interstellar dust.
- A typical grain of interstellar dust has:
  - A core of silicates (rock-like material consisting of silicon and oxygen) or graphite (a form of carbon),
  - Surrounded by a mantle of ices (mostly water, methane, or ammonia).

The interstellar medium

- Interstellar gas has an extremely low density of ~ 1 atom/cm^3.
  - This is the average density, if we spread out all the gas in the galaxy smoothly.
- Compare this to air on Earth, which has a density of $\sim 10^{19}$ atoms/cm^3.
- Interstellar dust has an even lower density of $\sim 1{,}000$ grains/km^3. Each grain is typically less than ~ 0.1 µm (micrometer, a millionth of a meter) in diameter.

The interstellar medium

- Interstellar matter takes up much more volume than stars.
- For example:
  - The diameter of the Sun is ∼4.6 light-seconds.
  - In comparison, the distance from the Sun to the nearest star, Proxima Centauri, is ∼4.2 light-years, which is ∼29 million times larger.
- As a result, despite its extremely low density, the total mass of interstellar gas and dust in the Milky Way is ∼10 billion $M_\odot$.
- This is ∼15% of the total mass of stars in the galaxy.

Interstellar gas

- Interstellar gas can have temperature between a few degrees above absolute zero to millions of degrees, depending where it is located.
- Hot stars can heat nearby interstellar gas up to ~10,000 K.
- The UV light from the star also ionizes the hydrogen in the gas.
  - Remember: ionize = strip an electron from the atom.
- Regions of interstellar gas can be characterized based on whether the hydrogen is neutral (H I region) or ionized (H II region).
  - In astronomy, I means not ionized (neutral), II means singly-ionized (one electron stripped), III means doubly-ionized (two electrons stripped) and so on.

Interstellar gas

- In an H II region, the ionized atoms recapture electrons and they cascade down the energy levels until they reach the ground state.
- As usual, whenever the electron drops to a lower energy level, it emits a photon.
- The light that ionized the hydrogen atom was UV, but the light that is emitted is visible.
  - So H II regions "convert" UV light to visible light. This process is called fluorescence, and it also happens in e.g. fluorescent lamps.
- H II regions are a type of emission nebulae: interstellar clouds of ionized gas that emit their own light.

- The spectral lines corresponding to an electron dropping to energy level $n = 2$ in the hydrogen atom are called Balmer lines (or the Balmer series).
- The red line on the right, with wavelength ~656 nm, corresponds to a drop from $n = 3$ to $n = 2$. It is called the Hα (H alpha) line.
- This line is responsible for the characteristic red glow in some images of nebulae.

The Balmer series.
Credits: Jan Homann

The Orion Nebula in visible light. Note the red glow, indicating ionization due to hot stars nearby. The blue at the edges of some clouds is produced by dust that scatters the light of the stars.
Credits: NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team

Video

- This video simulates "flying through" the Orion Nebula in 3 dimensions, in both visible and infrared light.
- When watching the video, remember that the nebula is 24 light-years across!
- The video can be found at this URL:

https://youtu.be/fkWrjrdT3Zg

Interstellar gas

- The very hot stars required to produce H II regions are rare, and most interstellar matter is not close enough to them to be ionized.
- Therefore, most of the volume of the interstellar medium is filled with neutral hydrogen (H I).
- The Balmer lines are only emitted when an excited electron drops to a lower energy level.
- In the cold interstellar medium, away from stars, hydrogen atoms are all in the ground state, so they don’t produce the Balmer lines. Therefore, they cannot be seen in visible light.

Interstellar gas

- Neutral hydrogen in H I regions produces a strong line with a very long wavelength of ~21 cm.
- It is called the 21 cm line, the hydrogen line, or the H I line.
- In the electromagnetic spectrum, this line is found in the microwave or radio range.
- This wave has a frequency of ~1.4 GHz and an extremely small photon energy of ~5.9 μeV (micro electron volt, or millionths of electron volt).
- This is such a small energy that it cannot possibly come from electrons jumping between energy levels.

Interstellar gas

- Spin 1/2 particles like protons and electrons can be in two spin states: spin up and spin down.
- The energy of a hydrogen atom is slightly higher when the spins of the proton and the electron are parallel – both up or both down.
- An electron can flip its spin (from up to down or vice versa) so that the spins are no longer parallel. This is called a spin-flip transition.
- Since the atom now has a lower energy, the difference in energy (~5.9 μeV) is emitted as a photon.

Interstellar gas

- The electron did not change energy levels, it just flipped its spin within the same energy level.
- Either the atom started out with parallel spins, or a random collision with an atom or electron caused the spins to become parallel.
- The spin flip transition is extremely rare. It will take a hydrogen atom with parallel spins ~10 million years to undergo a spin flip.
- However, because there are so many hydrogen atoms in the universe, this happens all the time.
- Therefore, we detect the 21 cm line coming from all around us.


Parallel spins
(higher energy)
Anti-parallel spins
(lower energy)

Interstellar gas

- When a massive star dies, it explodes in a supernova. This happens once per ~100 years somewhere in our galaxy.
- This explosion is extremely energetic, launching gas into interstellar space at enormous speeds of up to 20,000 km/s.
- When this gas collides with interstellar gas, it can heat it to tens of millions of degrees.
- Gas at these temperatures emits very energetic light in the X-ray range.
- This is emitted, for example, by extremely ionized oxygen atoms stripped of 5 out of their 8 electrons (which takes a lot of energy)

A remnant of a supernova ~11,000 years ago in the constellation Vela. We can still see the filaments from the explosion. The edges are colliding with interstellar gas and heating it.
Credits: Digitized Sky Survey, ESA/ESO/NASA FITS Liberator

The Crab Nebula is a supernova remnant in the constellation Taurus.
Credits: NASA, ESA, J. Hester and A. Loll (Arizona State University)

Interstellar gas

- Molecular clouds are giant clouds, with mass up to 1 million $M_{\odot}$.
- They contain mostly molecular hydrogen (H_2), but also smaller quantities of molecules like water (H_2O), carbon monoxide (CO), and even more complex molecules like ethyl alcohol (C_2H_6O).
- These clouds can have densities of thousands of atoms per cm^3, much higher than average for interstellar gas.
- Although they account for a very small fraction of the volume of interstellar gas, they contain 20-30% of its mass.
- Due to their high density, molecular clouds block UV light, which heats interstellar gas, so they tend to be very cold, $\sim$10 K.

Interstellar dust

- Dense clouds of interstellar dust, or sometimes molecular clouds, can be seen because they block the light from stars behind them.
- Such a cloud is called a dark nebula (because it's dark) or absorption nebula (because it absorbs light).
- The largest dark nebulae are visible to the naked eye as dark patches across the Milky Way.

The dark nebula Barnard 68. It has a temperature of ~16 K, mass of 2 $M_{\odot}$, and diameter of ~1/2 light-year.
Credits: ESO

The Milky Way as seen by Gaia, with prominent dark features labeled in white, and prominent star clouds labeled in black.
Credits: Nsae Comp (Wikipedia)

Interstellar dust

- Dust clouds are dark because they are too cold to emit light in the visible spectrum.
- However, the small dust grains absorb visible and UV light very efficiently.
- This causes them to heat to temperatures of 10-500 K, and radiate this heat as infrared light.
- Therefore, they are typically dark in visible light but glow in infrared.

The Horsehead Nebula in the constellation Orion is an extension of a large dust cloud. It is dark in visible light (left) but bright in infrared (right).
Credits left: modification of work by ESO and Digitized Sky Survey, right: modification of work by NASA/JPL-Caltech)

Interstellar dust

- A reflection nebula is a dust cloud close to a luminous star, which becomes visible by reflecting (or scattering) light from the star.
- The small dust grains scatter blue light (short wavelength) more efficiently than red light (long wavelength).
- Therefore, they appear bluer than the illuminating star.
- This effect is similar to Rayleigh scattering (lecture 12), which is responsible for the sky being blue.

The Pleiades (PLY-a-deez) star cluster is surrounded by a reflection nebula, which scatters blue light from the stars in the cluster.
Credits: NASA, ESA, AURA/Caltech, Palomar Observatory

The reflection nebula NGC 1999 reflects the light of the variable star V380 Orionis.
Credits: NASA and The Hubble Heritage Team (STScI)

Interstellar dust

- When light is absorbed or scattered by dust, the stars behind the dust look dimmer. This is called interstellar extinction.
- Because dust scatters blue more than red, the stars will also appear more red than they really are. This is called interstellar reddening.
- Reddening also happens in other places. For example, if the Sun is lower in the sky, light travels a longer path through the atmosphere, so it undergoes more scattering, and appears redder.
- This means we can see through dust clouds if we observe in infrared, which has a longer wavelength and gets scattered less.

Scattering of blue and red light by a dust cloud.
Credits: OpenStax Astronomy

The dark nebula Barnard 68 in infrared. We can see that although visible light does not pass through due to extinction, infrared light, which has a longer wavelength, does pass through.
Credits: ESO

Cosmic rays

- Cosmic rays are charged particles traveling at very high speed.
  - Note: despite the name, they are not "rays" of light, they're matter particles.
- They can achieve speeds of up to ~90% of the speed of light!
- ~90% of cosmic rays are protons (hydrogen nuclei).
- Another ~9% are helium and heavier nuclei.
- The remaining ~1% are electrons or (in 10-20% of the cases) positrons (the antiparticles of electrons – see lecture 11).

Cosmic rays

- Cosmic rays reach Earth in substantial numbers, but it's hard to know where they came from.
- Light from stars travels in straight lines, so we can tell exactly where it comes from.
  - The exception is gravitational lensing, which we will learn about later.
- Cosmic rays are charged particles, so their path is affected by magnetic fields (unlike light).
- This includes magnetic fields in interstellar space as well as Earth's own magnetic field.

Cosmic rays

- However, we know that cosmic rays most likely come from supernova explosions.
- The material ejected by the explosion produces a shock wave (an abrupt, violent, and fast-moving wave) in the interstellar medium.
- Charged particles can become trapped by the shock wave, bouncing back and forth. Magnetic fields inside the shock wave accelerate the particles more and more.
- Eventually, they are traveling at close to the speed of light, and can escape from the shock to become cosmic rays.

The life cycle of interstellar matter

- The interstellar medium is not static. Interstellar gas moves in orbit through the Galaxy, and as it does so, it can change drastically.
- For example:
  - A specific cloud of gas may start out as neutral hydrogen.
  - Then it moves near a young, hot star, and becomes part of an H II region.
  - The star later explodes as a supernova, heating the nearby gas up to millions of degrees.
  - Over millions of years, the gas may cool down and become neutral again.
  - Later, it can collect into a dense region and be gathered into a giant molecular cloud by gravity.

The life cycle of interstellar matter

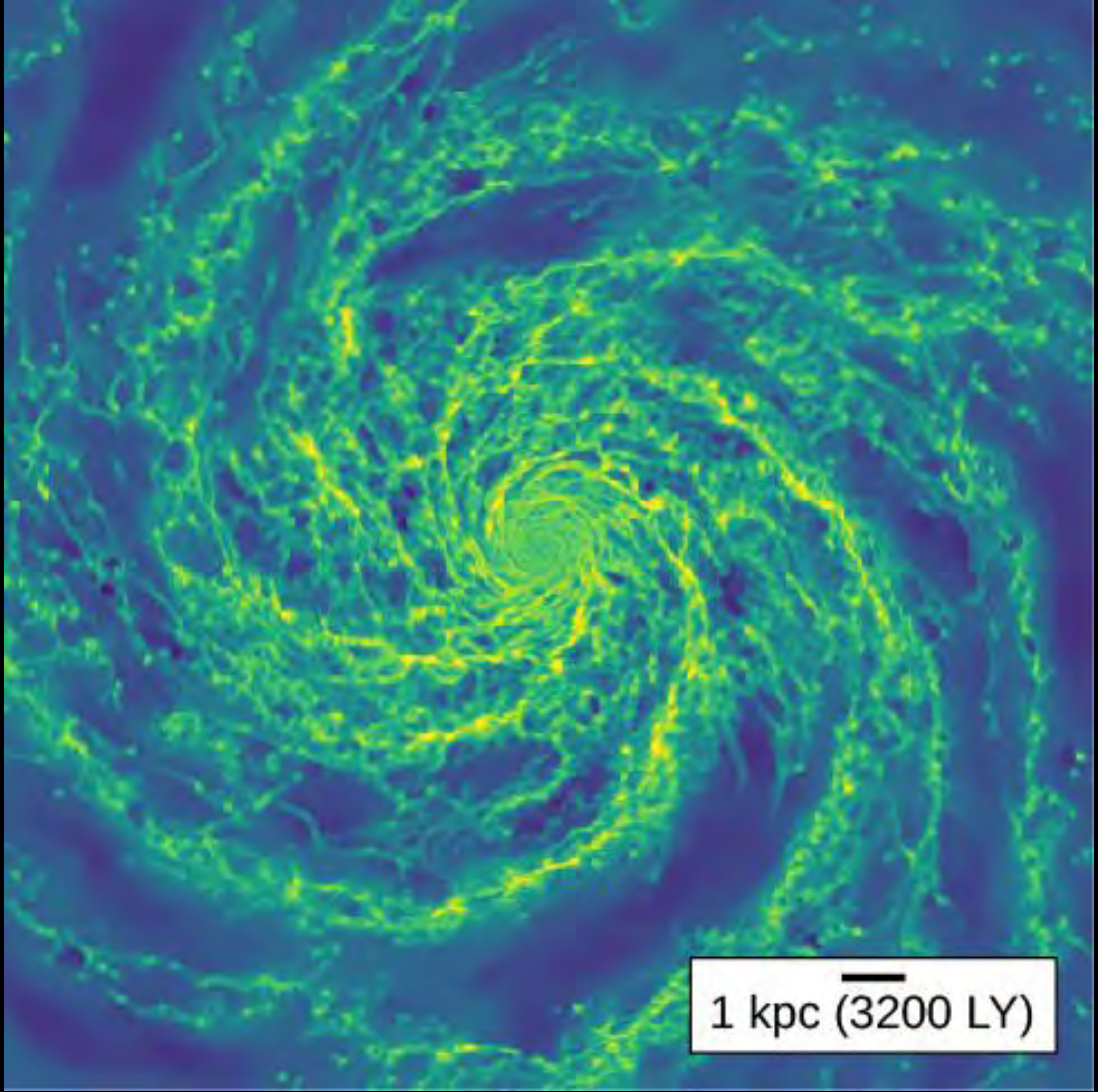
- In the Milky Way, most interstellar gas is atomic hydrogen.
- Molecular clouds occupy a tiny fraction of the volume but up to ~30% of the total mass of interstellar gas.
- The hot gas produced by supernova explosions contributes a negligible mass but occupies a significant volume.
- H II regions constitute only a very small fraction of either the mass or volume of interstellar material.

The life cycle of interstellar matter

- The interstellar medium is not a closed system; gas is constantly being added or removed.
- Gas from intergalactic space falls onto the Milky Way due to its gravity. This gas is added to the interstellar medium.
- Conversely, gas in giant molecular clouds can collapse to form new stars. This gas is removed from the interstellar medium.
- As the stars age, evolve, and die, ~1/3 of the matter in them goes back into interstellar space.
- Powerful supernova explosions can drive interstellar matter out of the Galaxy into intergalactic space (the space between galaxies).

The life cycle of interstellar matter

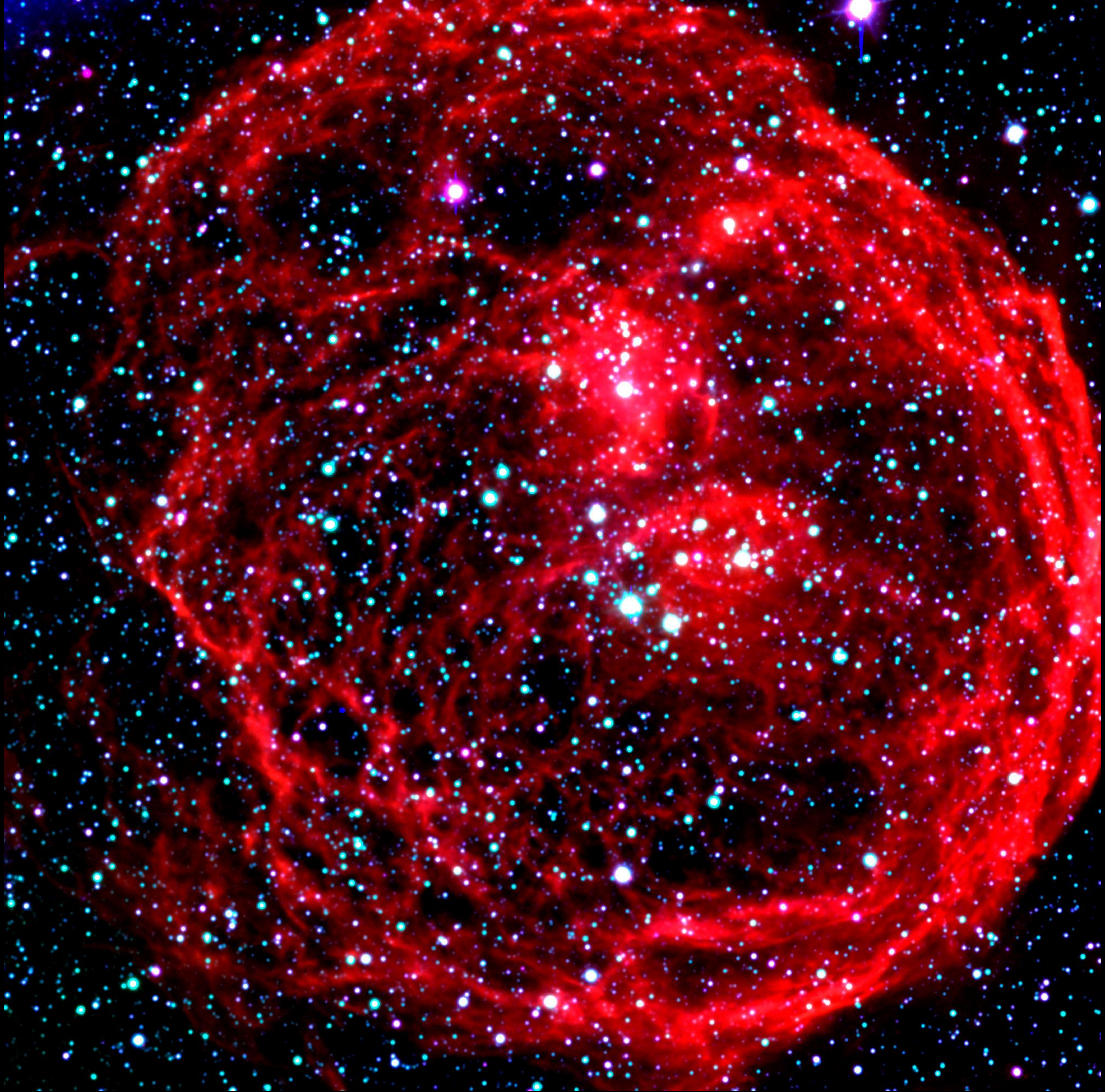
- The total amount of interstellar medium is determined by a competition between all these factors.
- This process is known as the baryon cycle.
  - A baryon is a composite subatomic particle with an odd number of quarks.
  - For example, protons (2 up, 1 down quark) and neutrons (1 up, 2 down quark) are types of baryons.
  - Electrons and neutrinos (not made of quarks) are classified as leptons.
  - So all the atoms in the universe are composed of baryons (protons and neutrons) inside the nuclei, along with leptons (electrons). But most of the mass is due to baryons, which is the origin of "baryon cycle".



In this computer simulation of the Milky Way's interstellar medium, we see neutral hydrogen in green, giant molecular clouds in yellow, and low-density "holes" due to supernovae in blue.
Credits: modification of work by Mark Krumholz

Superbubbles

- A superbubble is a "bubble" or "cavity" in the interstellar medium that is less dense, but very hot, with temperatures of ~1,000,000 K.
- Many superbubbles, hundreds of light-years across, are known in the Milky Way and nearby galaxies.
- They can be detected due to X-ray emission from the hot gas inside.
- Superbubbles are "carved out" by supernovae and stellar winds.
  - Stellar wind is a flow of gas ejected from a star (lecture 9).
- A dense shell of cold gas and dust usually surrounds the bubble.



The N70 Nebula is a superbubble in the Large Magellanic Cloud (a satellite galaxy to the Milky Way). This superbubble is ~300 light-years in diameter and located ~160,000 light-years away.
Credits: ESO

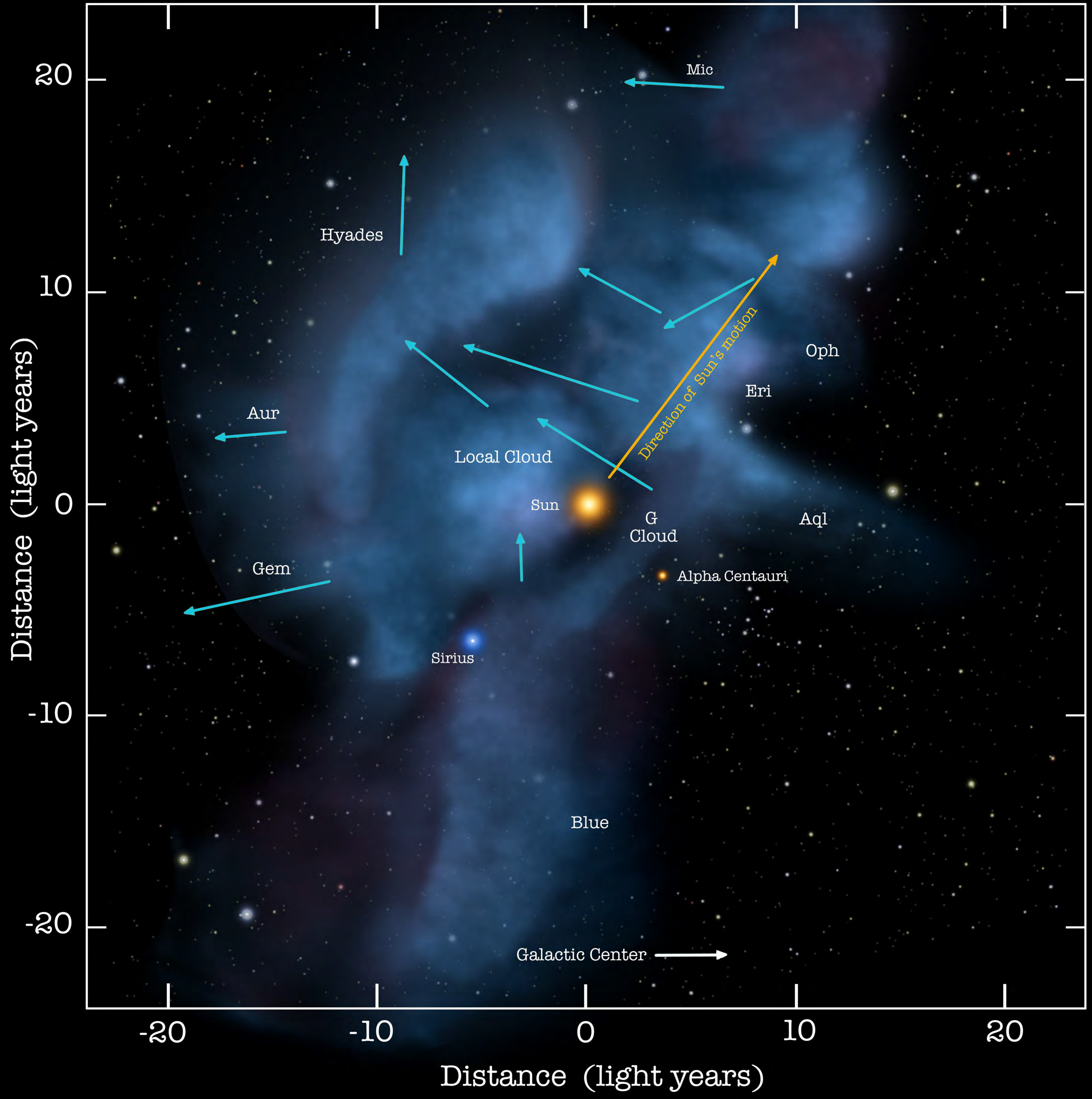
Superbubbles

- The solar system is inside a superbubble called the Local Bubble, ~1,000 light-years across, with a density of ~0.05 atoms/cm^3.
- It was created by a burst of supernovae which began ~14,000,000 years ago.
- As the bubble expanded over time, it swept up the interstellar medium into a shell, which later collapsed into molecular clouds.
- Since stars form in molecular clouds, this means that stars form on the shell of the Local Bubble, but not inside it.
- Our Sun entered the Local Bubble ~5,000,000 years ago.

Artist's illustration of the Local Bubble, with star formation occurring on the bubble's surface. The names indicate which constellation each star-forming region is located in.
Credits: Leah Hustak (STScI)

The Local Bubble

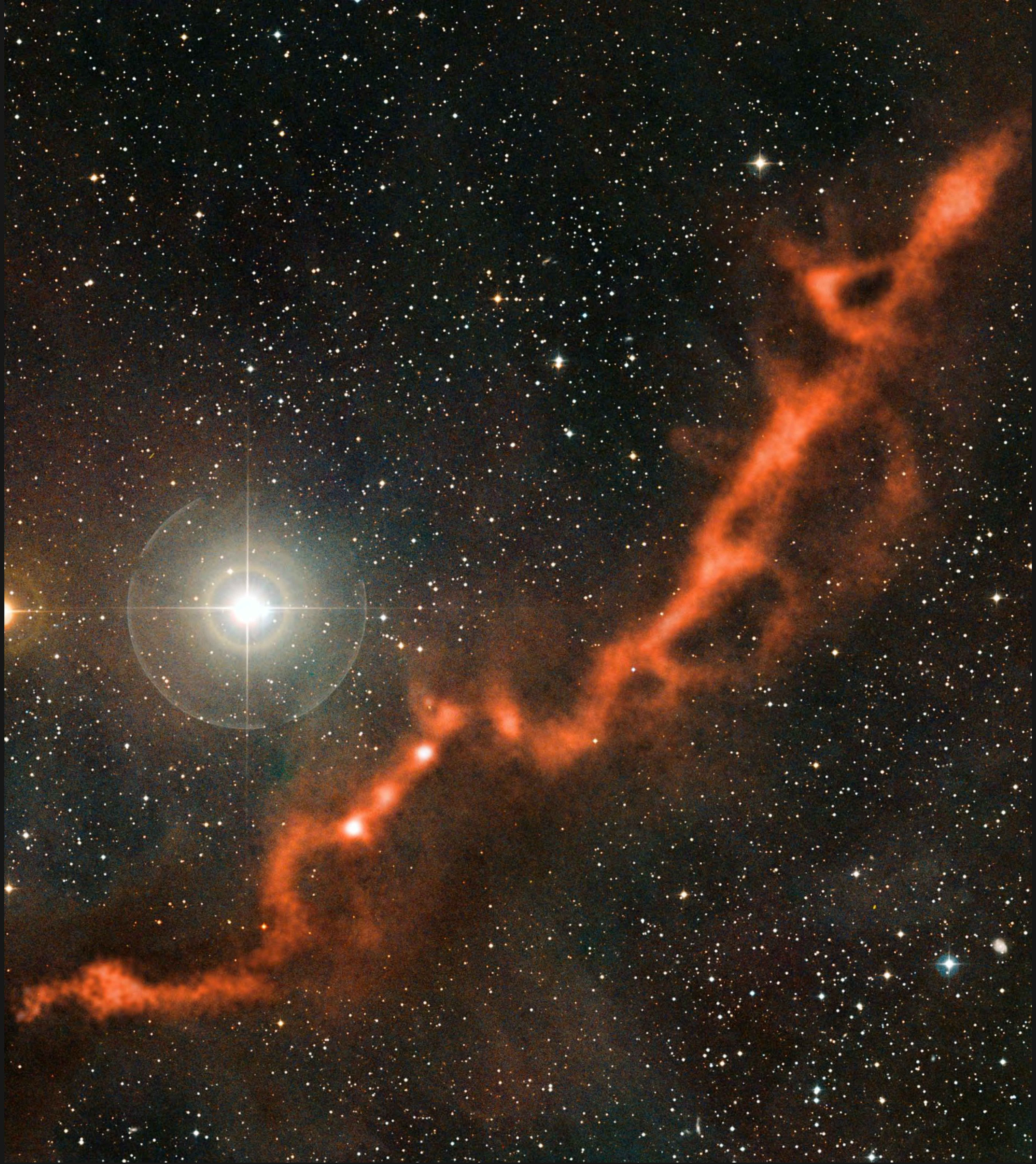
- There are a few clouds of interstellar matter within the Local Bubble.
- The Sun is inside a cloud called the Local Interstellar Cloud (LIC) or Local Fluff.
- The LIC is warm (~7000 K), has a density of ~0.3 atom/cm^3, and is ~30 light-years across.



The Local Interstellar Cloud, with arrows indicating cloud motion. The name next to each arrow indicates the constellation in the direction of the arrow.
Credits: NASA/Goddard/Adler/U. Chicago/Wesleyan

Star formation

- In the Milky Way galaxy, up to 7 new stars are formed every year.
- Stars are born within molecular clouds. When star formation is occurring within a molecular cloud, we call it a stellar nursery or a star-forming region.
- These clouds have a temperature of $\sim$10-20 K and a mass of $\sim$1,000-3,000,000 $M_{\odot}$.
- They have a complex structure of filaments, which can be up to $\sim$1000 light-years long.



A filament in the Taurus Molecular Cloud, more than 10 light-years long.
Credits: ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al./Digitized Sky Survey 2. Acknowledgment: Davide De Martin.

Star formation

- Within the molecular clouds are cold, dense regions with typical masses of $\sim$50-500 $M_{\odot}$ called clumps.
- Within these clumps are even denser, smaller regions called cores.
- The cores are the "embryos" of stars.
- In order to form a star, the core needs to shrink in radius and increase in density by a factor of $\sim 10^{20}$.

Star formation

- Two competing forces are involved in the birth and life of a star:
  - Gravity pulls matter inward and tries to make the star collapse.
  - Pressure pushes matter outward and tries to make the star expand.
- Atoms with higher temperature move faster and push on each other more. So low temperature means low pressure.
- More density means more mass and therefore more gravitational attraction. So high density means more gravity.
- Cores of molecular clouds have low temperature and high density, just the right conditions for gravity to “win” over pressure and collapse the matter into a star.

Star formation

- When gravity finally overwhelms pressure, the material undergoes a rapid collapse, and the density of the core increases greatly.
- While a core is contracting to become a star, but before nuclear fusion begins, we call the object a protostar.
- As the core contracts to a protostar, it spins faster and faster.
  - This is due to conservation of angular momentum (lecture 6). Angular momentum is the “total rotation” of an object.
  - There is always some initial non-zero angular momentum in the core. A large object rotating slowly has the same angular momentum as a small object rotating rapidly.

Star formation

- As the protostar rotates, the poles spin slower than the equator.
  - You can see this by watching a point on a spinning ball.
  - The closer the point is to the axis of rotation, the slower it rotates. If it's on the axis, it doesn't rotate at all.
- This means it is much easier for material to fall at the poles than the equator.
- Gas and dust falling in toward the protostar's equator are held back by the rotation, and form a disk around the equator.

Star formation

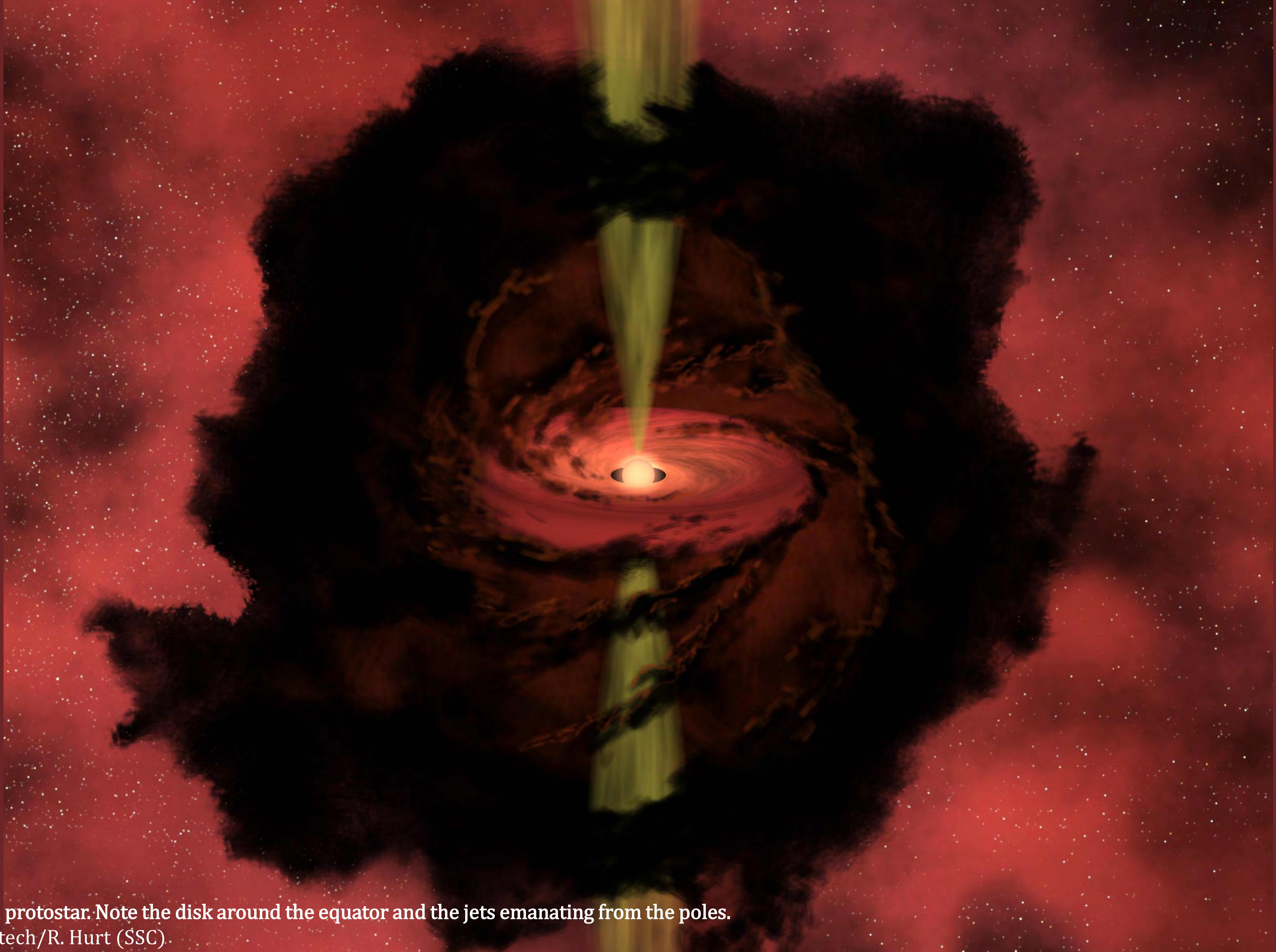
- The protostar and disk are embedded in an envelope of dust and gas from which material is still falling onto the protostar.
- This envelope blocks visible light, but infrared radiation can get through.
- As a result, in this phase of its evolution, the protostar is observable only in the infrared region of the spectrum.

Star formation

- Once almost all of the available material has been accreted and the protostar nearly reached its final mass, it is called a T Tauri star (pronounced TOR-eye).
  - These stars are named after the star T Tauri, in the constellation Taurus.
- Only stars with masses less than or similar to the mass of the Sun become T Tauri stars. Massive stars do not go through this stage.

Star formation

- Infrared images have revealed jets of material as well as stellar winds coming from some T Tauri stars.
- The stellar wind consists mainly of protons and electrons streaming away from the star at speeds of a few hundred km/s.
- When the wind first starts up, the disk of material around the star's equator blocks the wind in its direction.
- The wind particles escape most effectively in the direction of the star's poles, creating jets.
- These jets often indicate the location of a protostar even if it is hidden behind dust.



Artist's conception of a protostar. Note the disk around the equator and the jets emanating from the poles.
Credits: NASA/JPL-Caltech/R. Hurt (SSC)

Star formation

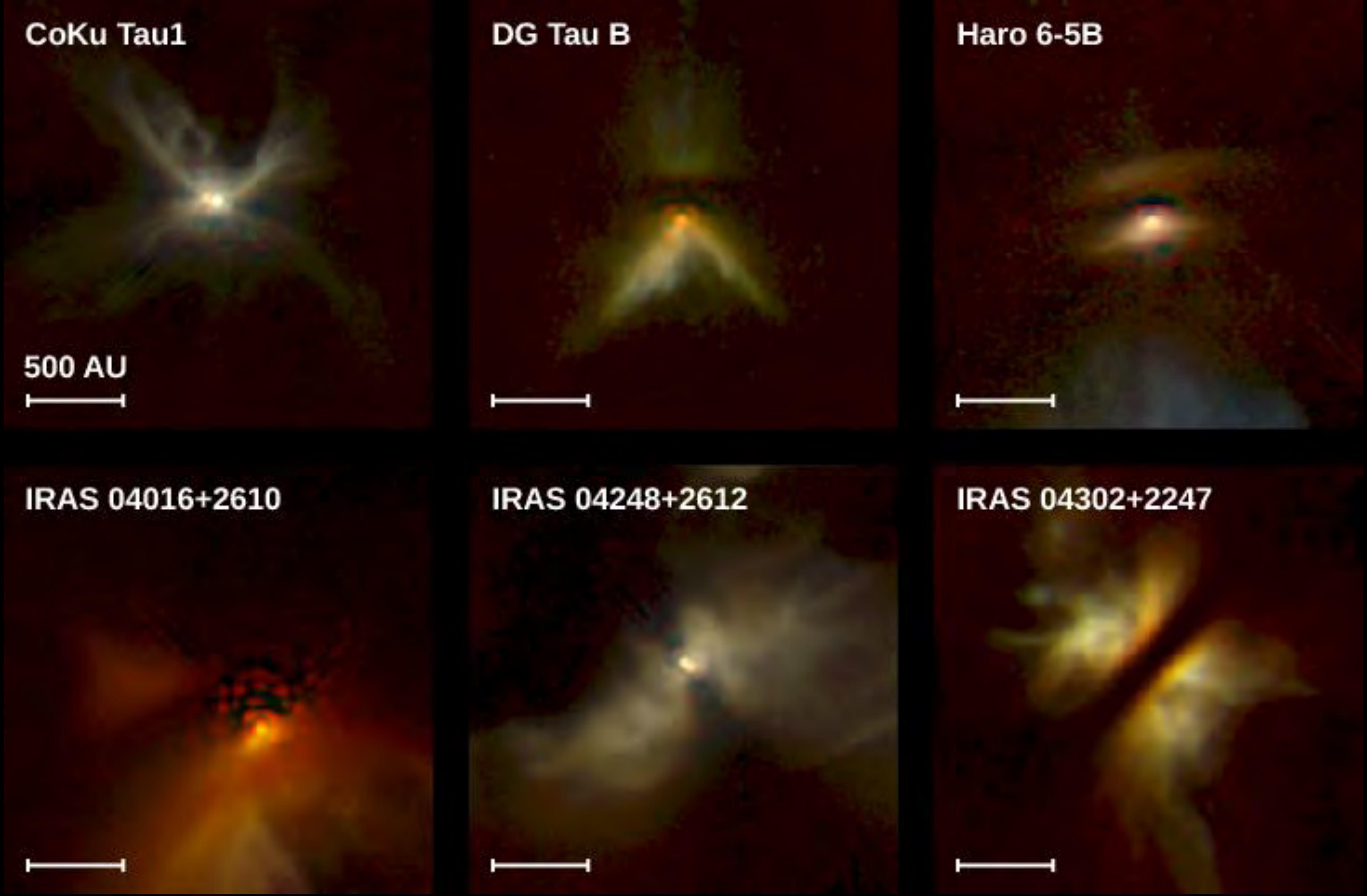
- Sometimes the jets collide with a denser lump of gas nearby, excite its atoms, and cause them to emit light.
- These glowing regions are known as Herbig-Haro (HH) objects.
- They allow us to trace the progress of the jet out to a distance of a light-year or more from the star that produced it.

Herbig-Haro objects HH 1 (upper right) and HH 2 (bottom left), created by a new star system hidden behind thick clouds of dust at the center, ~1,250 light-years from Earth.
Credits: NASA/ESA

This Hubble Space Telescope video shows material in Herbig-Haro object HH 47 moving away from the source star, hidden on the left, over a period of 14 years, from 1994 to 2008.
Credits: NASA, ESA, P. Hartigan (Rice University), G. Bacon (STScI), video available at https://youtu.be/Knc_2ip2uDw

Star formation

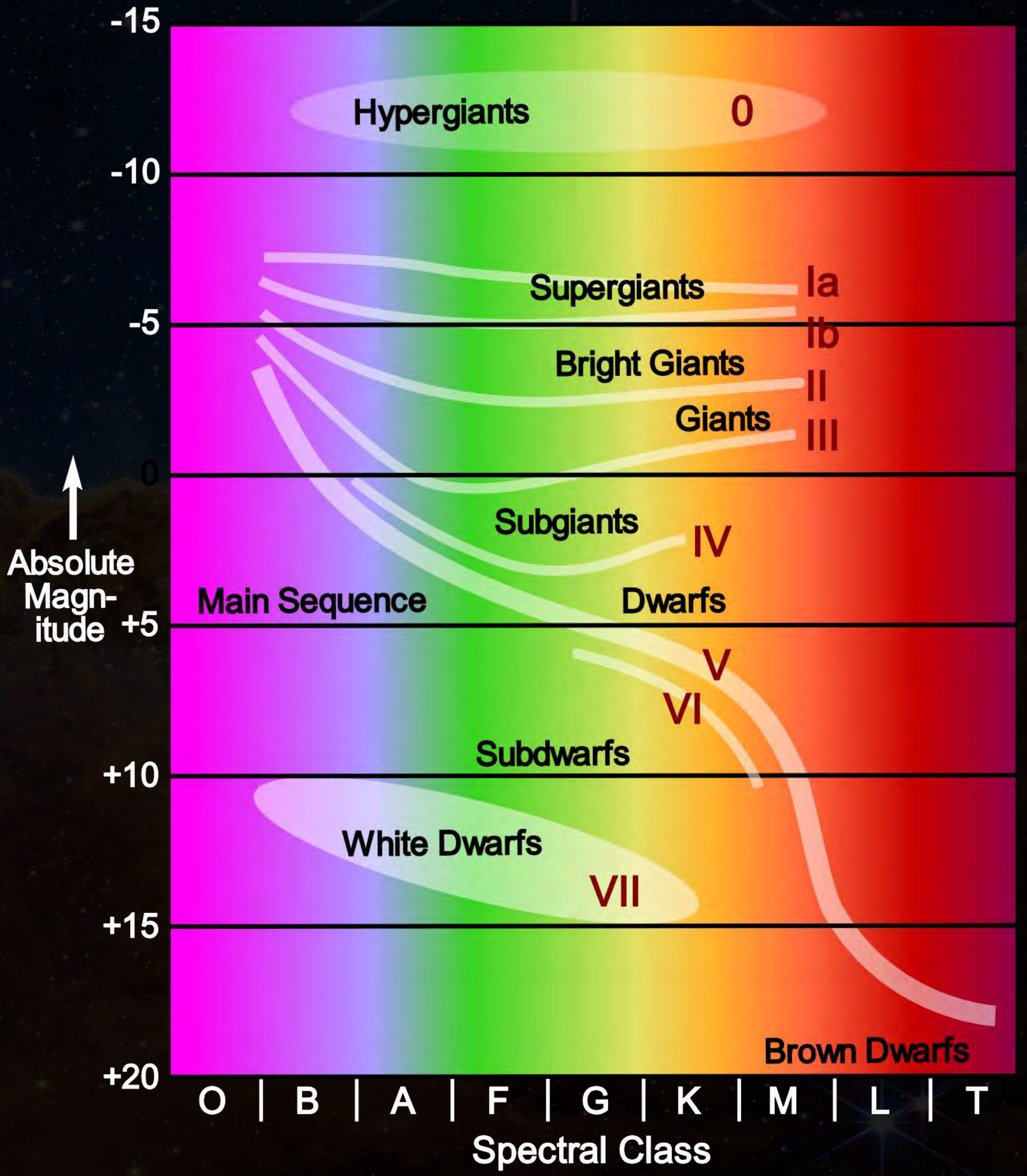
- The stellar wind will eventually sweep away the obscuring envelope of dust and gas, leaving behind the protostar and its disk, which can then be seen with visible light.
- At this point, the protostar itself is still contracting slowly and has not yet become a true star.
- The disk can be detected directly when observed at infrared wavelengths or when silhouetted against a bright background.
- Often, two or three stars will be born together. Each can have its own disk, or if they’re close enough, they may share a single disk.



Infrared images of disks around young stars in the constellation Taurus, ~450 light-years away. In some cases we can see the central star(s), but in other cases the dust disks are too thick.
Credits: modification of work by D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

Protostar evolution

- Remember that the Hertzsprung-Russell (H-R) diagram arranges stars according to two properties:
  - Temperature: hottest on the left, coldest on the right.
  - Luminosity: least luminous on the bottom, most luminous at the top.



Luminosity classes on the Hertzsprung–Russell diagram.
Credits: Rursus (Wikipedia)

Protostar evolution

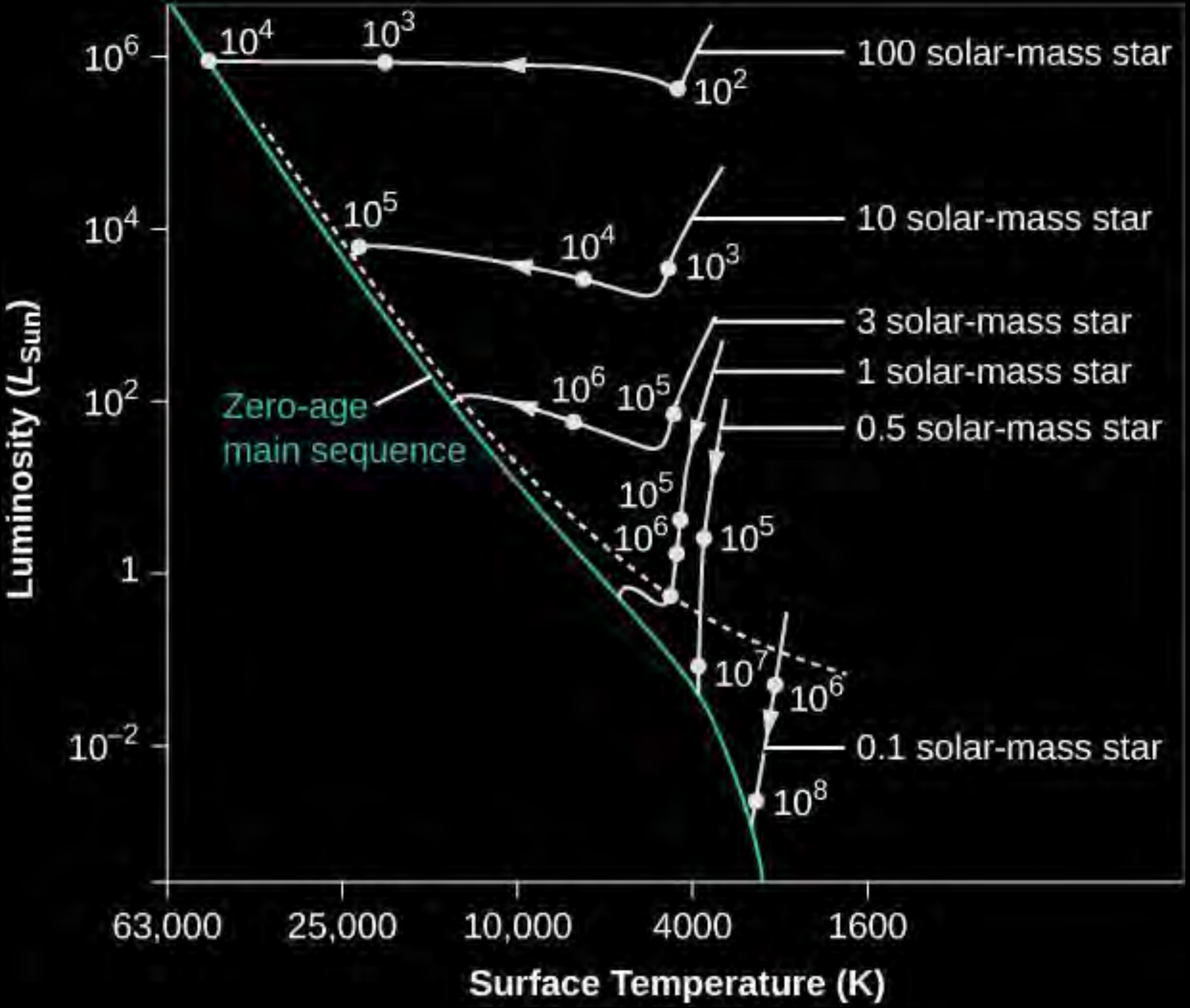
- As a star goes through the stages of its life, its luminosity and temperature change, so its position on the H-R diagram also changes.
- We say that a star "moves" or "traces out a path" on the diagram as it ages.
  - This has nothing to do with the star's motion through space. The path on the diagram only tells us how the temperature and luminosity change as the star evolves.
- The path that a star follows on the diagram is also called its evolutionary track, and depends on the mass of the star.

Protostar evolution

- The initial protostar does not produce energy by nuclear reactions, but it does produce some energy due to contraction, converting gravitational potential energy into heat.
- The protostar undergoes a rapid collapse. As it shrinks, its surface area gets smaller, so its total luminosity decreases.
- This can be seen on the H-R diagram as an initial line <u>pointing downward</u>, indicating a decrease in luminosity.
- The rapid contraction stops when the protostar becomes dense and opaque enough to trap the heat from gravitational energy.

Protostar evolution

- When the star begins to retain its heat, the contraction slows, and the luminosity stays roughly constant.
- The surface temperature starts to build up, and the star “moves” to the left in the H–R diagram.
- Stars first become visible only after the stellar wind clears away the surrounding dust and gas.
- This can happen during the rapid-contraction phase for low-mass stars, but high-mass stars remain shrouded until they finish contracting.



Stars above the dashed line are typically still surrounded by infalling material and hidden by it at this stage.

Evolutionary tracks for contracting protostars of different masses, indicating the protostar's age at each stage. Note that more massive stars evolve faster.
Credits: OpenStax Astronomy

Protostar evolution

- When the star's central temperature becomes high enough to fuse hydrogen into helium, about 12,000,000 K, we say that the star has reached the main sequence.
- Its rate of change then slows dramatically. Only the gradual depletion of hydrogen as it is transformed into helium in the core slowly changes the star's properties.
- The mass of a star determines where it falls on the main sequence:
  - Massive (high-mass) stars have high temperatures and high luminosities.
  - Low-mass stars have low temperatures and low luminosities.

Protostar evolution

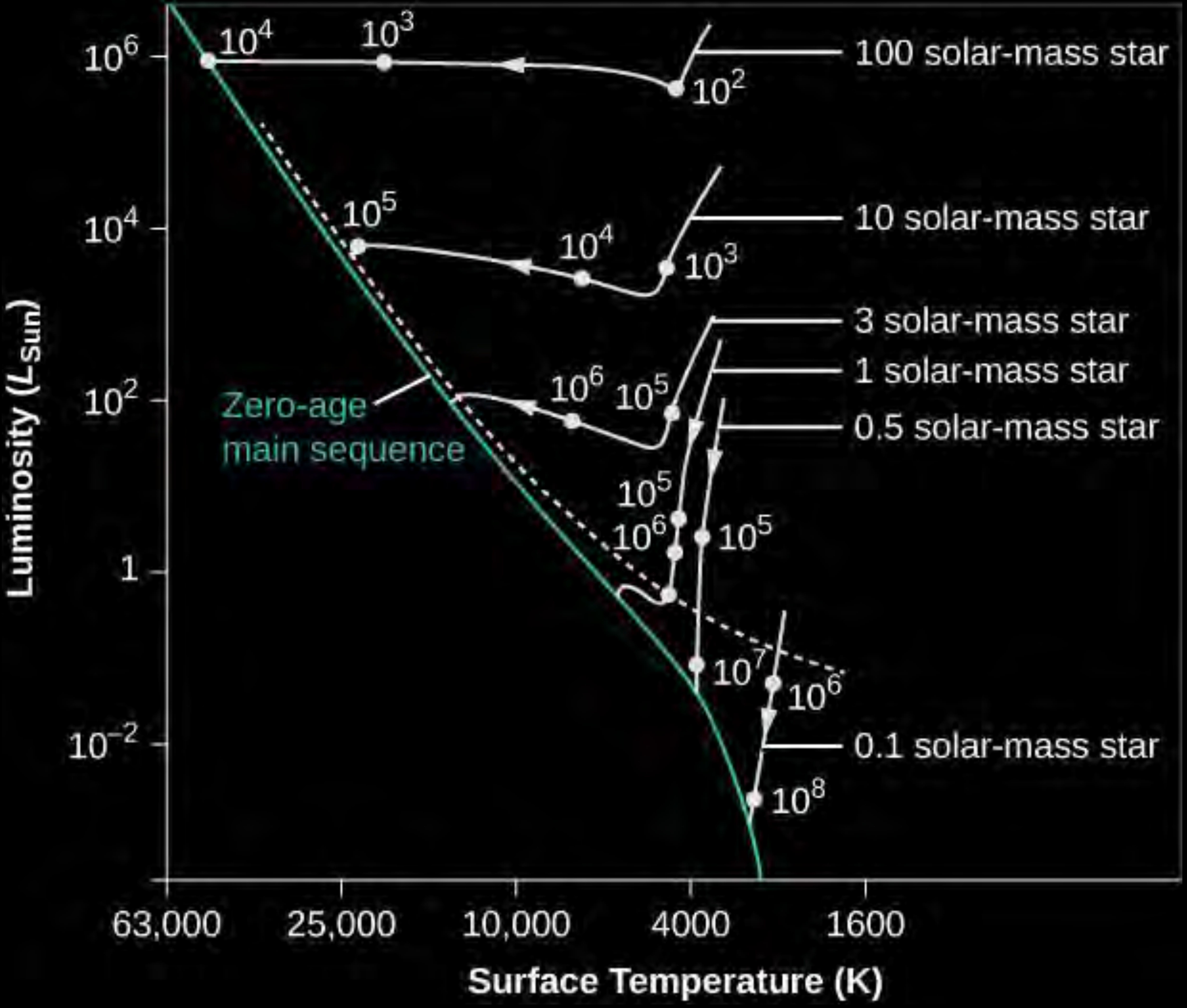
- The lower end of the main sequence ends with objects of extremely low mass, less than $\sim 0.075\ M_{\odot}$.
- These objects never achieve temperatures high enough to ignite nuclear reactions. They are either brown dwarfs or planets.
- The upper end of the main sequence terminates at the point where the energy radiated by the newly forming massive star becomes so great that it halts the accretion of additional matter.
- The upper limit of stellar mass is 100-200 $M_{\odot}$.

Main sequence evolution

- Once a star has reached the main-sequence stage, it derives its energy almost entirely from fusion of hydrogen to helium.
- At this point, the star is in equilibrium: neither expanding nor contracting, with the inward force of gravity being exactly balanced by the outward force of pressure.
- Since hydrogen is the most abundant element in stars, hydrogen fusion can maintain the star's equilibrium for a long time. This means all stars remain on the main sequence for most of their lives.

Main sequence evolution

- The left edge of the main-sequence band in the H-R diagram is called the zero-age main sequence.
- We use the term “zero-age” to mark the time when a star stops contracting, settles onto the main sequence, and begins to fuse hydrogen in its core.
- The zero-age main sequence shows where stars of different masses (but similar chemical composition) can be found when they begin to fuse hydrogen.



Evolutionary tracks for contracting protostars (same plot from before, just to review).

Credits: OpenStax Astronomy

Main sequence evolution

- Since only ~0.7% of the hydrogen mass is converted into energy of photons, fusion doesn't change the mass of the star significantly.
- However, fusion does change the chemical composition of the star. Hydrogen is fused into helium, so we have less hydrogen and more helium over time.
- This gradually changes the luminosity, temperature, size, and interior structure of the star.
- When a star's luminosity and temperature begin to change, it moves away from the zero-age main sequence.

Main sequence evolution

- The temperature and density in the inner region slowly increase as helium accumulates in the center of the star.
- As the temperature gets hotter, the protons move faster, so they're more likely to interact with other protons, and the rate of nuclear fusion increases.
- Since fusion generates light, this means that the luminosity of the star slowly rises over time.

Main sequence evolution

- The lifetime of a star in a particular stage of evolution depends on how much nuclear fuel it has and how quickly it uses up that fuel.
- More massive stars use up their fuel much more quickly than stars of low mass.
- The reason is that the more massive the star, the more pressure is needed to balance its gravity. Higher pressure requires higher temperatures, which means higher rate of fusion.
- Although more massive stars also have more fuel, they burn it so fast that their lifetimes are much shorter than low-mass stars.
- This is also why the most massive stars are the most luminous.

Lifetimes of main-sequence stars

Spectral Type	Surface Temperature (K)	Mass ($M_\odot$)	Lifetime on Main Sequence (years)
O5	54,000	40	1 million
B0	29,200	16	10 million
A0	9600	3.3	500 million
F0	7350	1.7	2.7 billion
G0	6050	1.1	9 billion
K0	5240	0.8	14 billion
M0	3750	0.4	200 billion

Main sequence evolution

- A quick digression:
  - It took ~4.5 billion years for intelligent life to evolve on Earth.
  - This means that intelligent life is less likely to evolve on planets orbiting very hot stars, since they don't remain stable long enough for intelligent life to evolve.
  - We will learn more about searching for extraterrestrial life later.

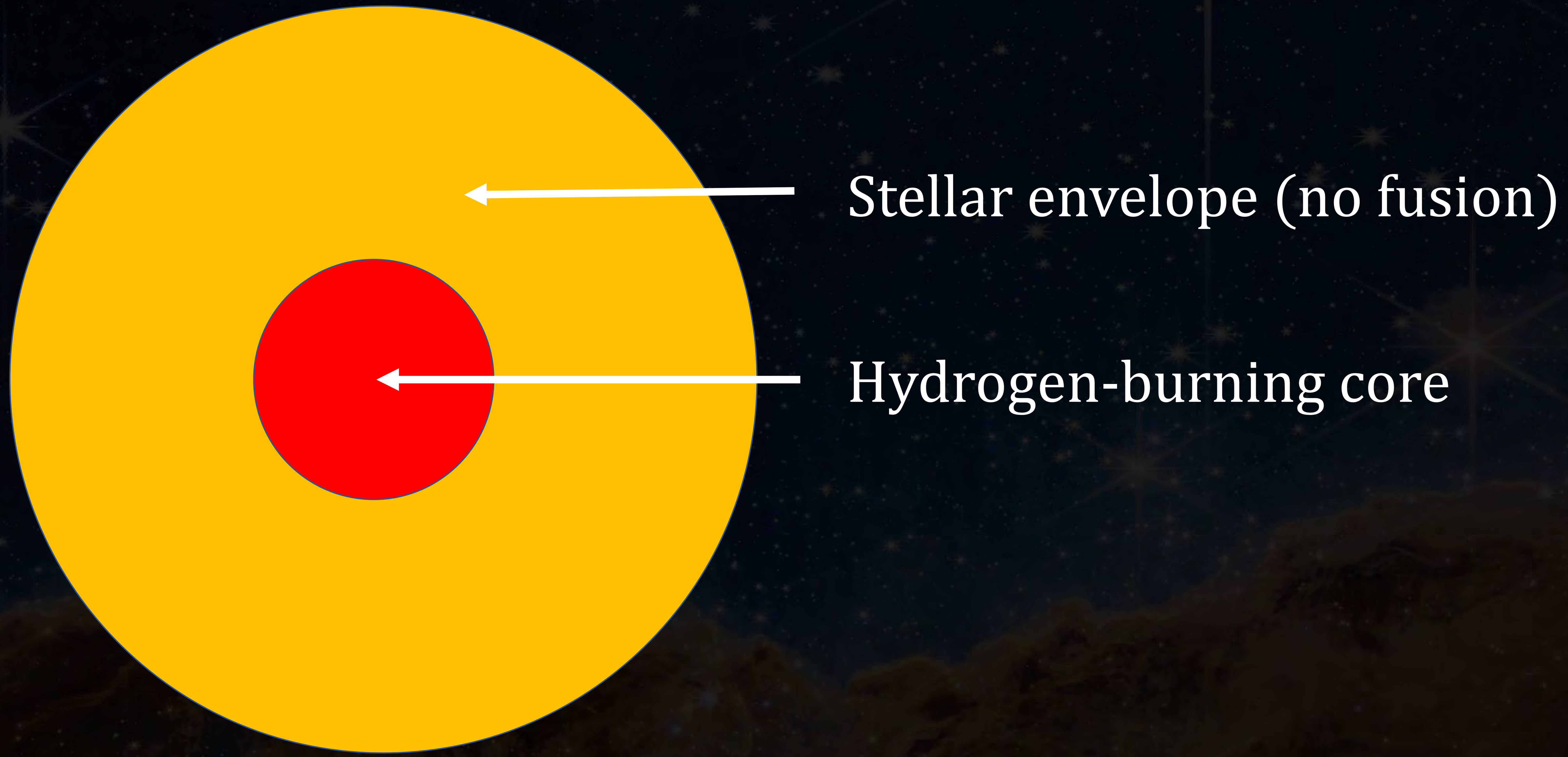
Evolution to giants

- Eventually, all the hydrogen in a star's core will be gone, since it has been fused into helium.
- At this point, hydrogen fusion is no longer possible, so the star can no longer be in equilibrium.
- The star's period of stability ends, gravity takes over, and the core begins to contract again, converting gravitational energy into heat.

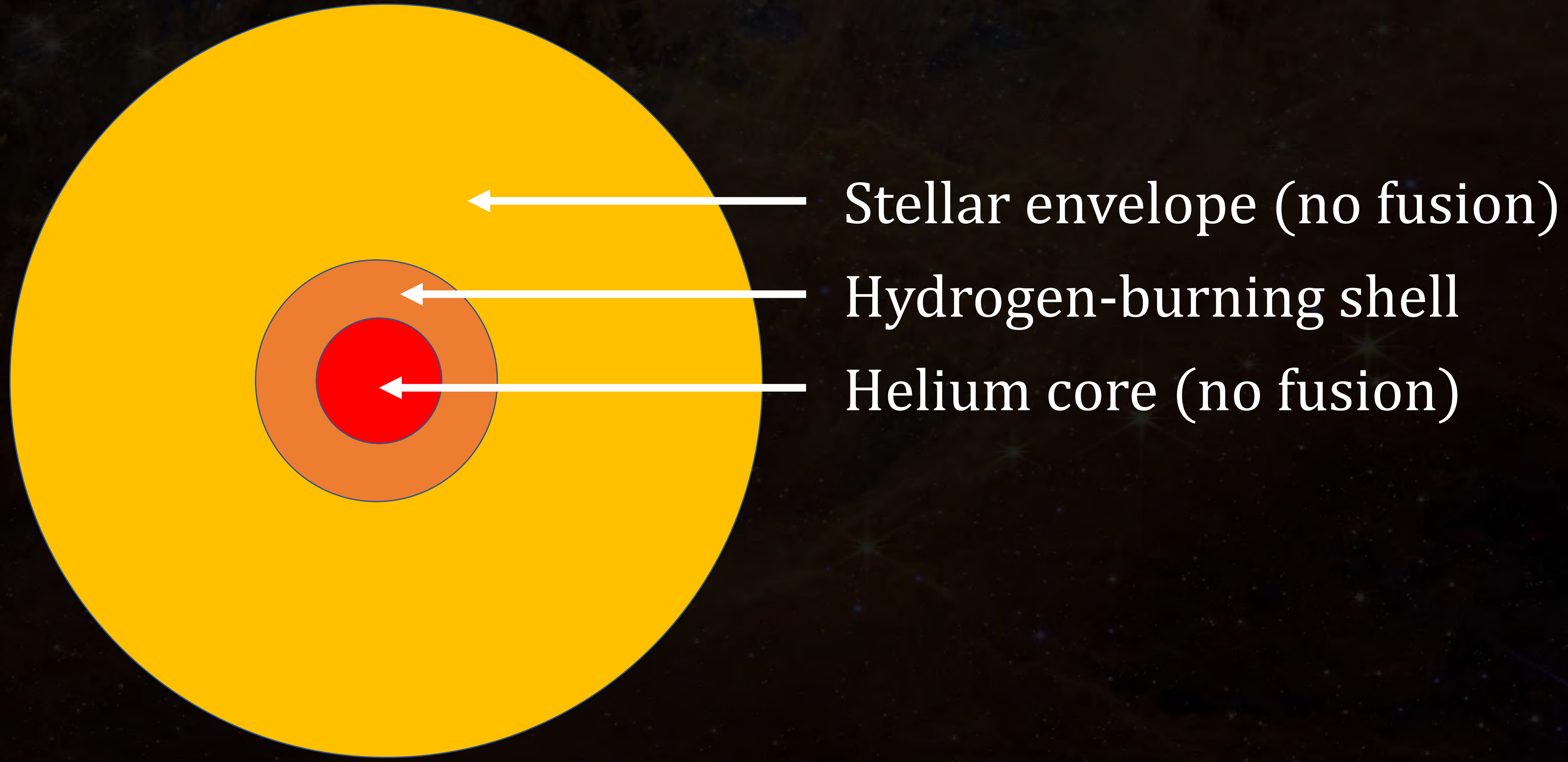
Evolution to giants

- Until now, hydrogen fusion only happened in the core, because the outer layers were too cold.
- But now, some outer layers have become hot enough to fuse the hydrogen that was “waiting” there.
- The layers between the core and atmosphere are called the stellar envelope.
- The layer immediately surrounding the helium core, where hydrogen fusion is now happening, is called a hydrogen-burning shell.

During the main sequence:



After hydrogen in the core is exhausted:



Evolution to giants

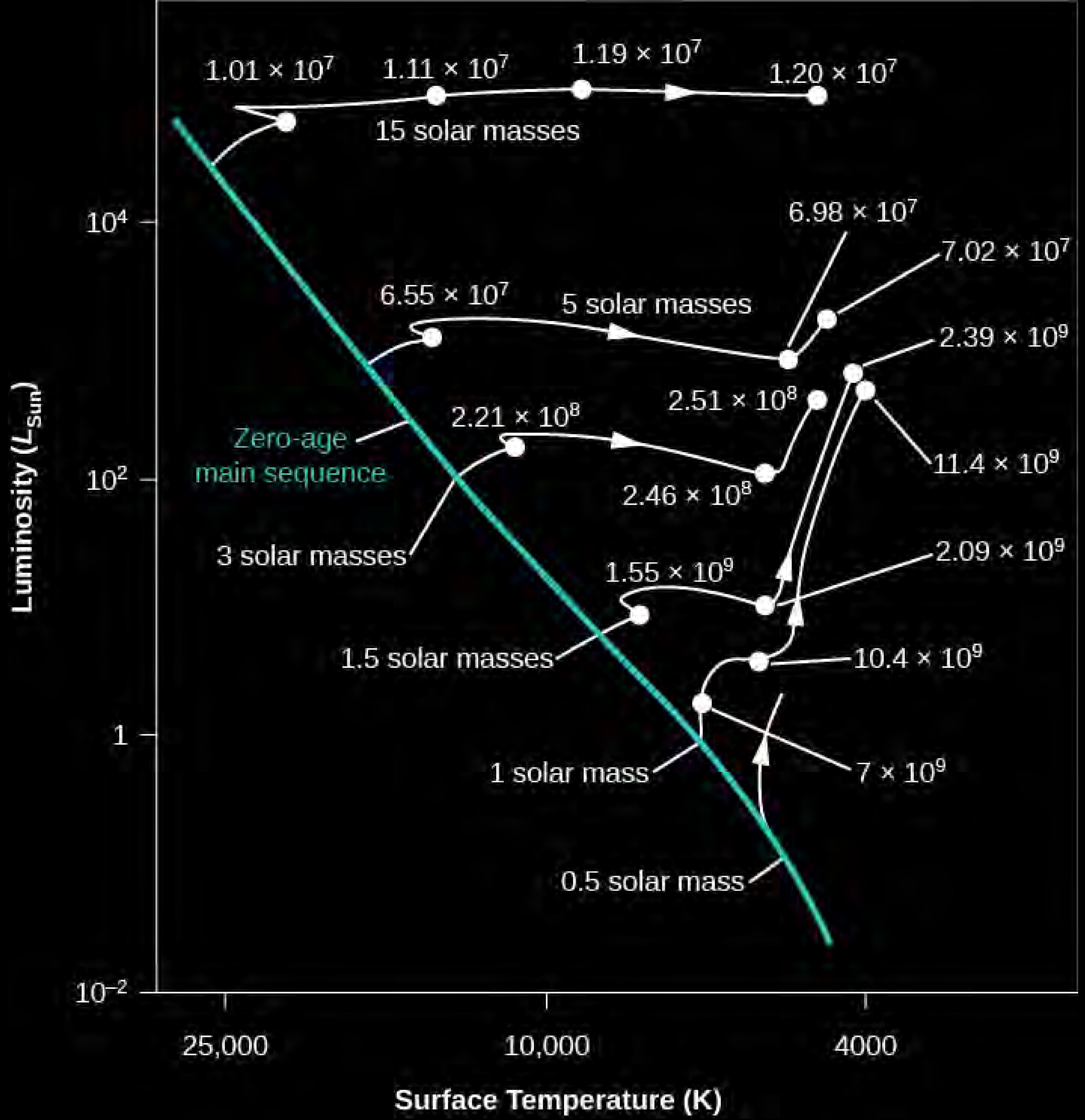
- Most stars generate more light from fusion in the hydrogen-burning shell than they did from fusion at the core, so they increase in luminosity.
- Because of the increased flow of energy outward, the outer layers of the star begin to expand, and the star grows in size.
- Due to this expansion, the surface of the star becomes cooler and therefore more red.
- On the H-R diagram, the star moves up (more luminosity) and to the right (colder temperature).

Evolution to giants

- Over time, massive stars become red supergiants, and lower-mass stars like the Sun become first subgiants and then red giants.
- As an example, the Sun (a G2 V star) has existed for ~4.6 billion years and is currently in the main-sequence stage.
- In ~5 billion years, the Sun will run out of hydrogen in its core, and lose equilibrium. It will become a subgiant, and later a red giant.
- As a red giant, the Sun will eventually engulf the orbit of Venus, with a radius of 110,000,000 km (compared to 695,000 km now), and it will have 1,000 times its current luminosity.

The life cycle of the Sun, from a protostar and disk (left) to a red giant (right). 18 Sco and HIP 102152 are stars similar to the Sun but currently at different life stages. Sizes not to scale.
Credits: ESO/M. Kornmesser

Size of the Sun as it is now compared to the size it will have as a red giant.
Credits: Oona Räisänen



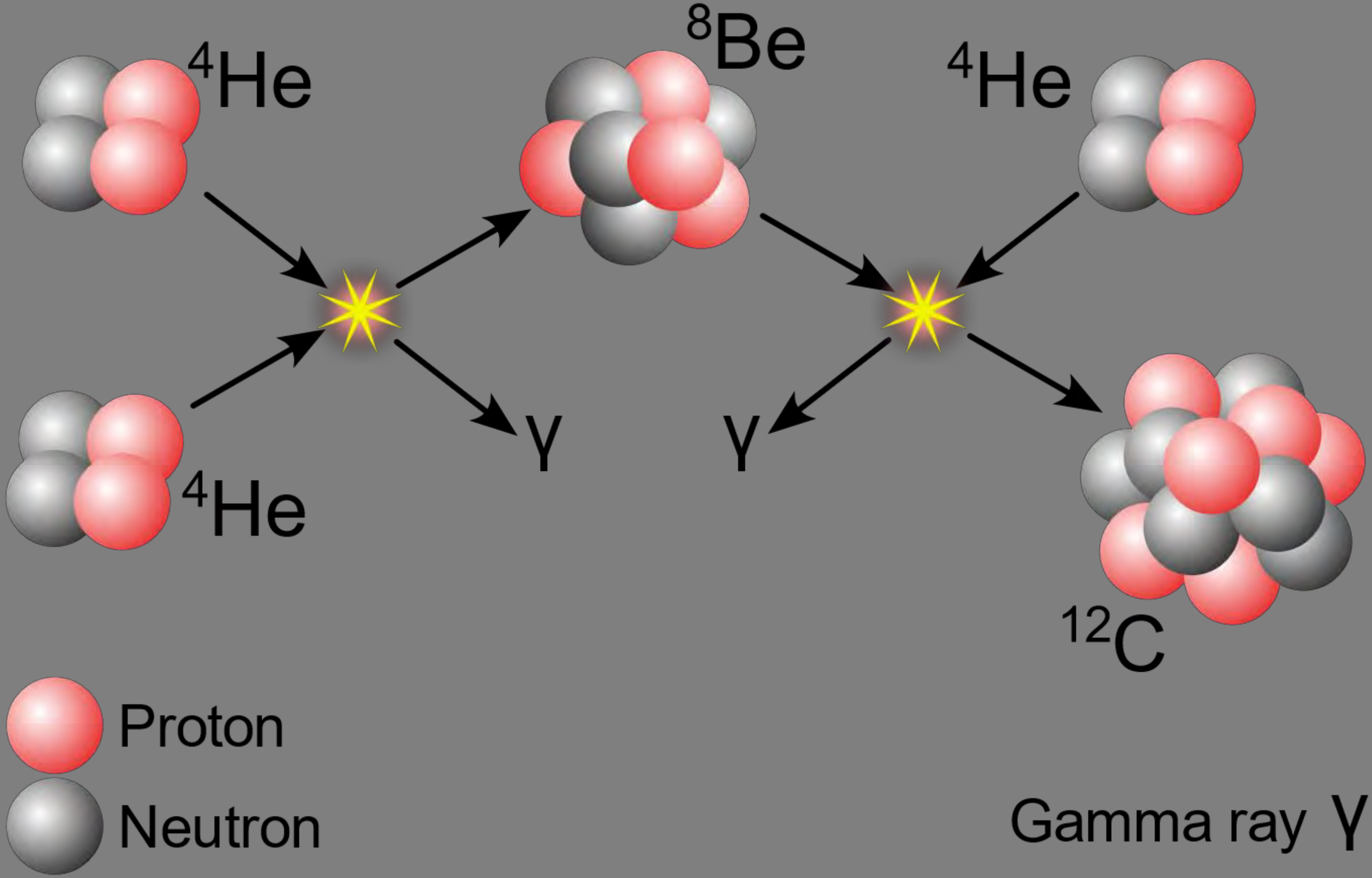
Evolutionary tracks for stars of different masses from main sequence to red giant/supergiant, indicating the star's age at each stage. Again, more massive stars evolve faster.
Credits: OpenStax Astronomy

Further evolution: low-mass stars

- What happens during the red giant phase? Let's first consider stars with initial masses less than 2 $M_{\odot}$, which are the most common.
  - Note: the mass of a star changes over its lifetime, here we're specifically talking about the <u>initial</u> mass.
- When the star becomes a red giant, the core is made of helium, with fusion only in the surrounding hydrogen shell.
- The core is not generating any energy, so it cannot oppose the gravitational force pulling the star inward.
- Therefore, the core shrinks and grows hotter.

Further evolution: low-mass stars

- Once the core reaches a temperature of ~100,000,000 K, helium fusion begins. The helium starts fusing into carbon.
- This is called the triple-alpha process, because the helium-4 nucleus is also called an alpha particle (for historical reasons).
- In this process: (this is a simplified description)
  - Two helium-4 nuclei (^{4}He, with 2 protons and 2 neutrons)
  - Fuse into beryllium-8 (^{8}Be, with 4 protons and 4 neutrons)
  - Which then fuses with another helium-4 to produce carbon-12 (^{12}C, with 6 protons and 6 neutrons)
  - This releases 2 photons (γ) with net energy ~7.275 MeV



In the triple-alpha process, 3 helium nuclei are fused into 1 carbon nucleus. We start and end with 6 protons and 6 neutrons, but in the end they are all fused into the same nucleus.
Credits: Borb (Wikipedia)

Further evolution: low-mass stars

- Carbon (6 protons) is a fundamental building block for all life on Earth, including humans.
- We are "made of star stuff" – the atoms making up our bodies were generated in the triple-alpha process inside red giants!
- Oxygen (8 protons) is another element that is important for life on Earth, and the most abundant element on Earth.
  - Also the 3rd most abundant in the universe, after hydrogen and helium.
- Carbon-12 produced in stars can further fuse with helium-4 into oxygen-16 (^{16}O). So the oxygen we breathe also comes from stars.

Further evolution: low-mass stars

- As soon as helium fusion starts, the extra energy is transmitted quickly through the entire core, producing very rapid heating.
- The heating speeds up the nuclear reactions, which provide more heating, and this accelerates the nuclear reactions even more.
- As a result, the entire helium core is ignited almost simultaneously in a helium flash.

Further evolution: low-mass stars

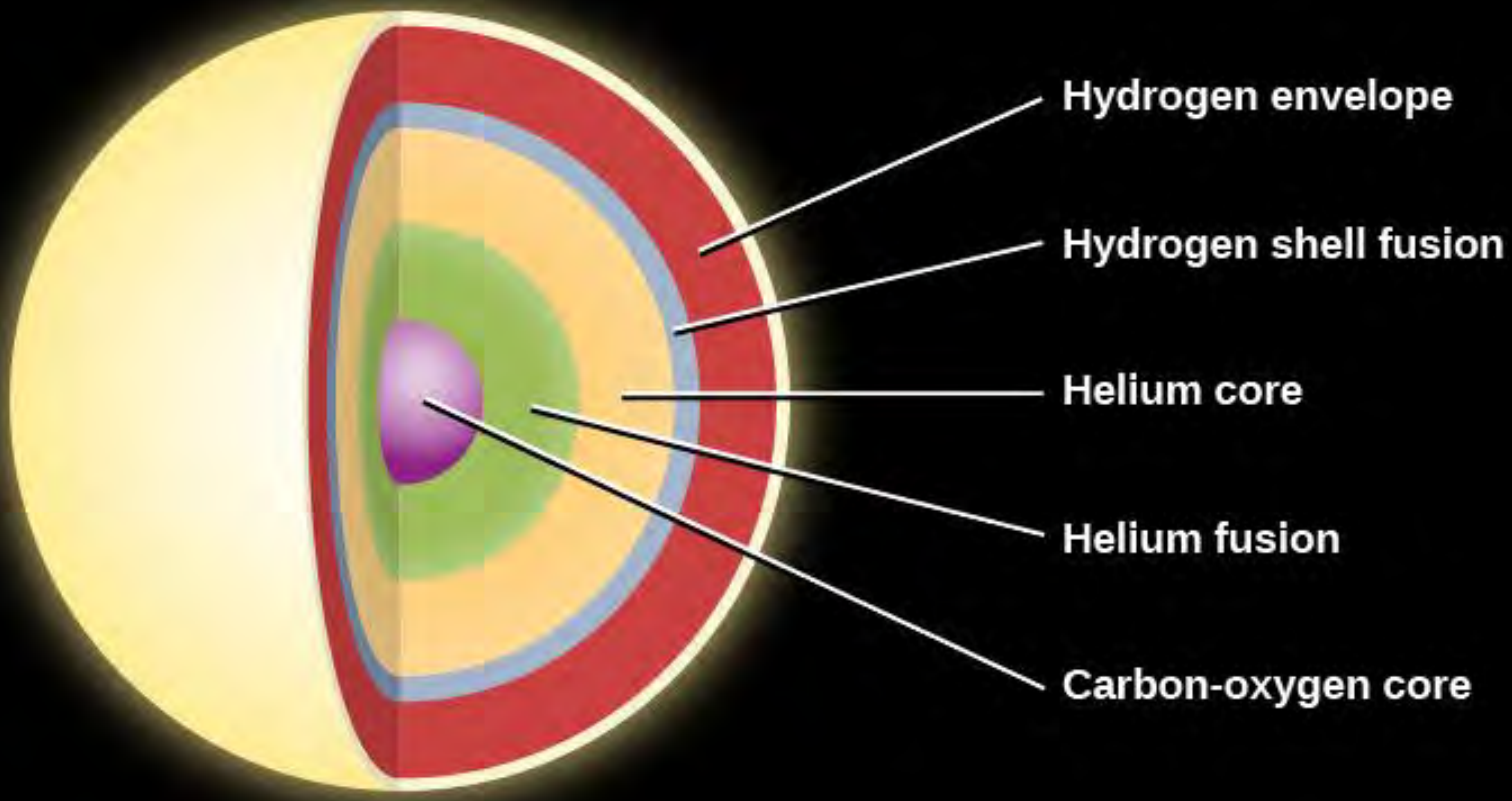
- After the helium flash, the surface temperature of the star increases and its luminosity decreases.
- In the H-R diagram, the star moves down and to the left.
- The star continues to fuse helium for a while, regaining equilibrium between pressure and gravity.
- However, this period of stability is far shorter than the main-sequence stage.
- Soon, all the helium hot enough for fusion will be used up, gravity will take over, and the core will start to shrink again.

Further evolution: low-mass stars

- So essentially, the same thing that happens when hydrogen is used up also happens when helium is used up.
- We can think of stellar evolution as a constant struggle against gravitational collapse.
- A star can avoid collapsing as long as it can use energy sources, such as hydrogen fusion or helium fusion, in order to push back.
- But once a particular fuel is used up, the star begins to collapse again.

Further evolution: low-mass stars

- Remember that after hydrogen was depleted in the core, a shell around the helium core became hot enough to fuse hydrogen.
- A similar thing happens after the helium in the core is depleted.
- The core is now made of carbon and oxygen, and no fusion is happening there.
- But helium fusion is still happening in a shell around the core, and even hydrogen fusion is still happening in a shell farther out.
- The star obtains an onion-like structure.

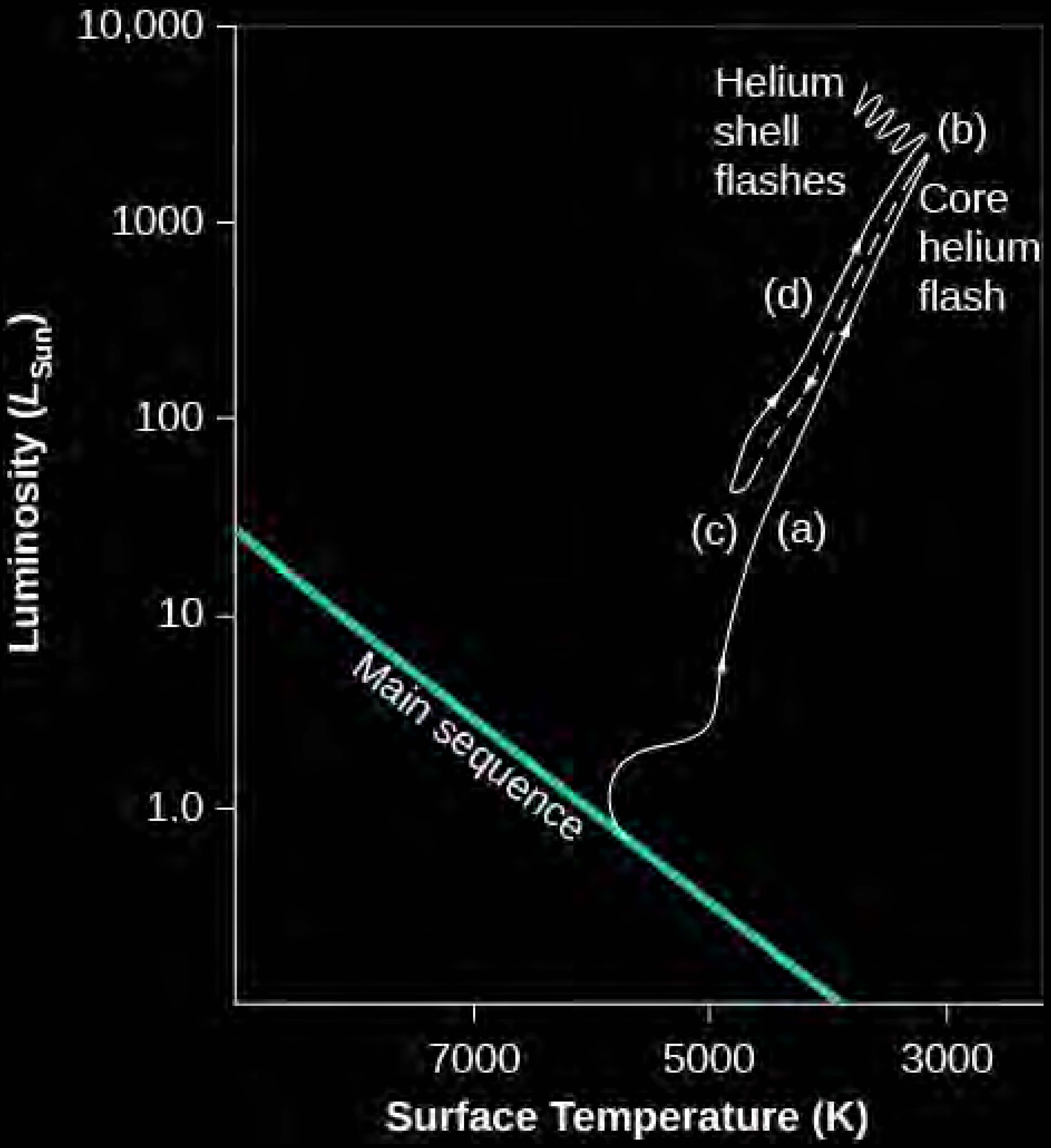


The onion-like structure of a star near the end of its life.
Credits: OpenStax Astronomy

Further evolution: low-mass stars

- As energy flows outward from the two fusion shells, once again the outer regions of the star begin to expand.
- The star then moves back to the red-giant region of the H-R diagram, but only for a short time.
- Toward the end of its life, it experiences several helium shell flashes. Each flash corresponds to reigniting fusion in the helium shell, after it stopped for a while.

(a) Evolution from main sequence to red giant (hydrogen fusion in shell, not in core)
(b) Helium flash (helium fusion begins, star contracts)
(c) Helium fusion (brief period of stability)
(d) Helium core exhausted (star becomes red giant again)



Evolution of a star with the same mass as the Sun.
Credits: OpenStax Astronomy

Evolution of star with the Sun's mass

Stage	Time in This Stage (years)	Surface Temperature (K)	Luminosity ($L_{\odot}$)	Radius ($R_{\odot}$)
Main sequence	11 billion	6000	1	1
Becomes red giant	1.3 billion	3100 at minimum	2300 at maximum	165
Helium fusion	100 million	4800	50	10
Giant again	20 million	3100	5200	180

Further evolution: low-mass stars

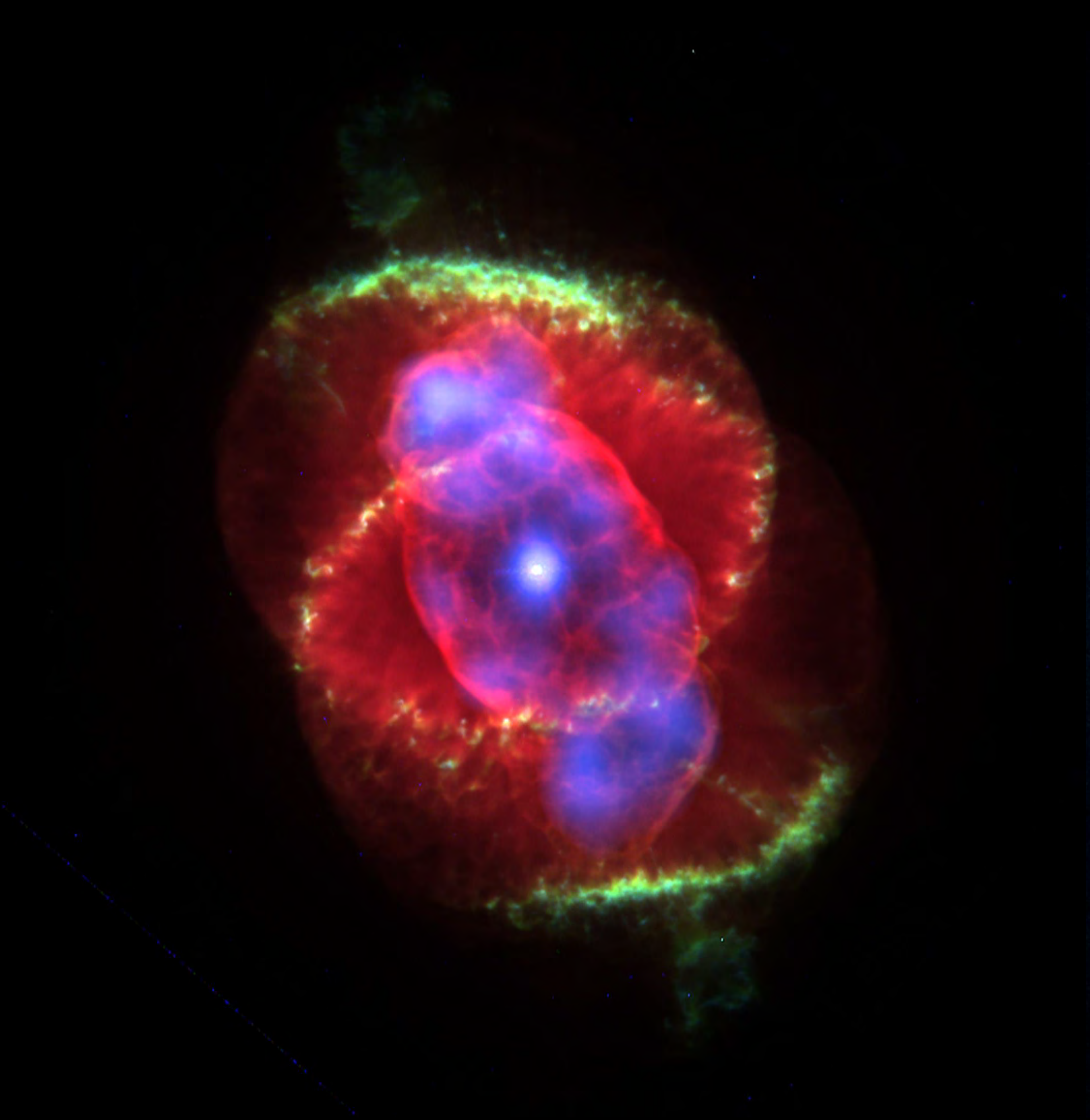
- During the red giant stage, it's easier for matter to escape from the star, because atoms on the surface are very far from the center, so they experience much weaker gravity.
  - Remember, the force of gravity decreases as the square of the radius.
- In addition, violent events such as helium flashes can help push matter out from the star into space.
- As a result, the star is eventually surrounded by one or more expanding shells of gas, each containing ~0.1-0.2 $M_\odot$.

Further evolution: low-mass stars

- When nuclear fusion stops, there is nothing to stop the star from collapsing due to gravity.
- The star begins to shrink again, and becomes very hot, reaching surface temperatures as high as $\sim$100,000 K.
- Such hot stars emit strong stellar winds and UV radiation, which heat the shells of material around the star.
- This heat ionizes the shells and makes them glow (similar to what happens in H II regions).

Further evolution: low-mass stars

- This results in a glowing nebula with a round shape.
- The round shape reminded early astronomers of planets, so they called it a planetary nebula, but it has nothing to do with planets!
  - This is just another one of these cases where we're using a confusing name for historical reasons.
- Planetary nebulae typically have a radius of ~1 light-year. They are very short-lived, lasting only ~10,000 years.
- They are (arguably) the most beautiful nebulae, due to their well-defined shape.



Hubble images of NGC 6543, a planetary nebula also known as the Cat's Eye Nebula. Left: X-ray/optical composite, right: enhanced image showing concentric rings of ejected material.
Credits: Left: NASA / X-ray: Y. Chu (UIUC) et al., Optical: J. P. Harrington, K. J. Borkowski (UMD), Composite: Z. Levay (STScI), right: NASA, ESA, HEIC, Hubble Heritage Team (STScI/AURA)

The Cat's Eye Nebula (in the middle) is surrounded by a much larger halo of gas, ~3 light-years across, likely ejected in earlier stages of the star's evolution, ~50,000-90,000 years ago.
Credits: Nordic Optical Telescope and Romano Corradi (Isaac Newton Group of Telescopes, Spain)

James Webb Space Telescope images of NGC 3132, a planetary nebula also known as the Southern Ring Nebula. Left: near-infrared (wavelength 0.6-5 µm), right: mid-infrared (5-28 µm).
Credits: NASA, ESA, CSA, and STScI

NGC 7293, a planetary nebula also known as the Helix Nebula. Left: visible light (Hubble), right: infrared (Spitzer).
Credits: Left: NASA, ESA, and C.R. O'Dell (Vanderbilt University), right: NASA/JPL-Caltech/Univ. of Ariz.

Further evolution: massive stars

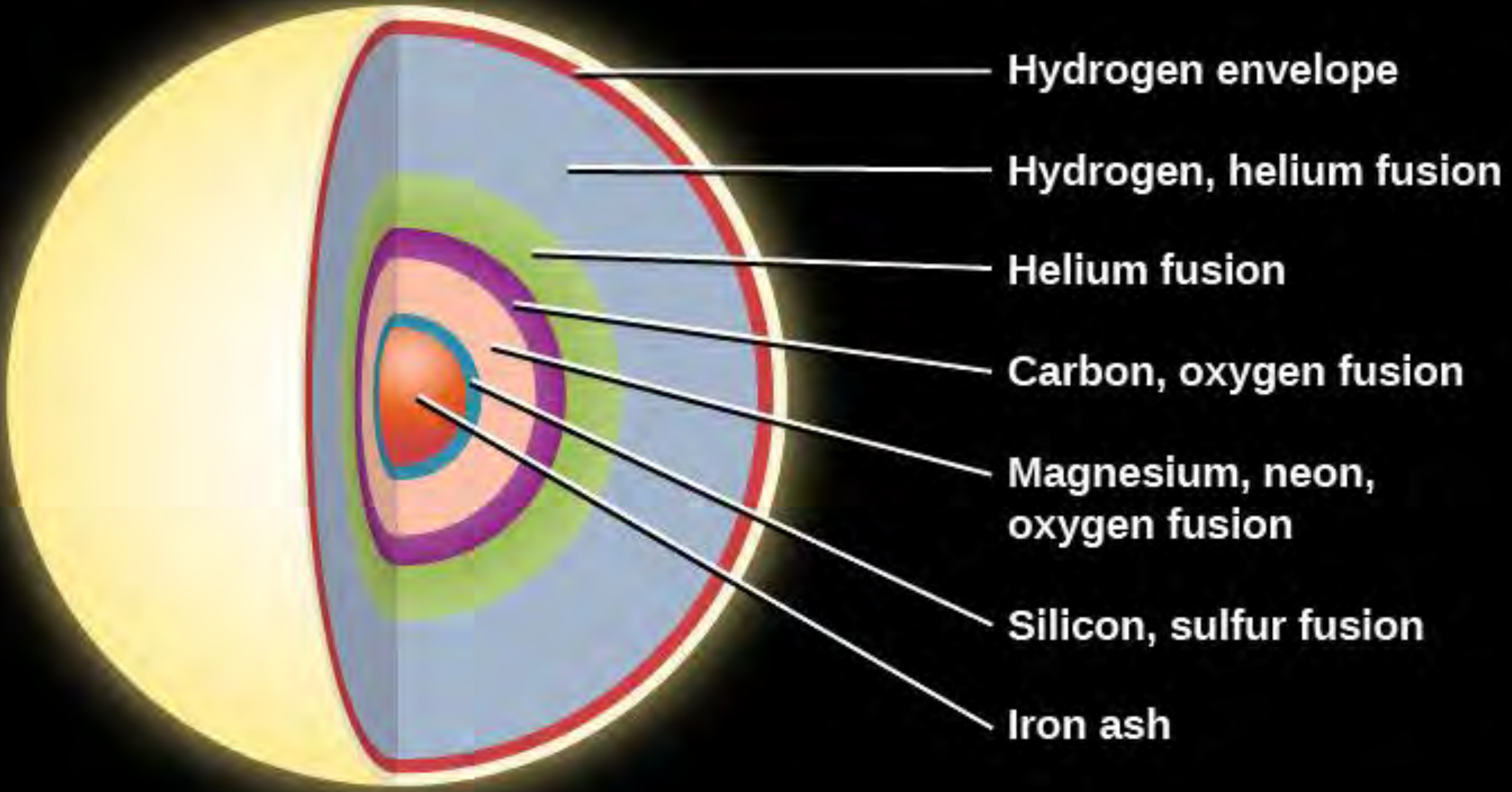
- Low-mass stars can only reach temperatures hot enough to fuse the two lightest elements, hydrogen and helium.
- More massive stars can reach higher temperatures, and fuse heavier elements.
- The evolution of massive stars is very similar to low-mass stars up to the formation of the carbon-oxygen core, with some differences:
  - The evolution is much faster.
  - Helium fusion begins more gradually, with no helium flash.
  - They become supergiants, not giants.
  - They don’t form planetary nebulae.

Further evolution: massive stars

- If a star is heavier than $\sim 8\ M_{\odot}$, fusion doesn't stop after the carbon-oxygen core is formed.
- Such stars are hot enough to fuse heavier elements: carbon, oxygen, neon, magnesium, and silicon.
- However, fusion ends at iron.

Further evolution: massive stars

- Normally, when nuclei are fused, mass is lost. This means the initial nuclei are more massive than the final nucleus.
- For example, in the proton-proton chain, the initial 4 hydrogen nuclei are more massive than the final helium nucleus.
- The lost mass is converted to energy of the generated photons.
- However, if we try to fuse iron, the initial nuclei are actually less massive than the final nuclei.
- This means that iron fusion doesn’t generate energy, it costs energy!



The interior structure of a massive star just before it exhausts its nuclear fuel. Shells closer to the core fuse heavier elements. The iron in the core cannot be fused to generate energy.
Credits: OpenStax Astronomy

Further evolution: massive stars

- Essentially, all chemical elements up to iron (atomic number 26) can be created by some fusion process inside massive stars.
- This is called stellar nucleosynthesis.
- However, elements heavier than iron cannot be created in this way. We will learn how they are created later.
- Our understanding of stellar nucleosynthesis allows us to explain why some elements like oxygen, carbon, and iron are common, while others like gold, silver, and uranium are much less common.

Video

- In this video, we see a visualization of how the stars in the globular cluster Omega Centauri are sorted on the H-R diagram.
- We can determine which lifetime stage each star is in by its location on the diagram.
- The video can be found at this URL:

https://youtu.be/mY2edzGYWyU

Simulation

- In this simulation, we can explore the evolution of stars of different masses on the H-R diagram, as well as their size, temperature, luminosity, and mass at each stage.
- You will notice that low-mass stars end up as white dwarfs and massive stars end up as supernovae. We will learn more about that in the next lecture.
- The simulation can be found at this URL:

https://starinabox.lco.global/

Conclusions

- In this lecture we learned how stars are formed from molecular clouds, and how they evolve over their lifetime, until they are close to death.
- In the next lecture, we will learn what happens when stars die.

- <u>Reading:</u> OpenStax Astronomy, chapters 20-22.
- <u>Exercises:</u> Practice questions will be posted on Teams. Additional questions are available in the textbook, at the end of each chapter.