ASTR 1P02

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Lecture 15: Dead stars and black holes

We will learn about…

- What happens to stars when they die.
- Stellar remnants, such as white dwarfs and neutron stars.
- Supernova explosions.
- General relativity and black holes.

An image of the supermassive black hole at the center of the galaxy M87. We will talk more about what we're actually seeing in this image later.
Credits: EHT Collaboration

Summary: stellar evolution

- In the previous lecture, we learned how stars form and evolve.
- Stars form when a molecular cloud undergoes gravitational collapse and forms a protostar.
- When the core becomes hot enough to fuse hydrogen into helium, the star achieves stable equilibrium between gravity and pressure, and enters the main sequence.
- The star will spend $\sim$90% of its life on the main sequence.
- The more massive the star is, the higher its luminosity and temperature will be, and the faster it will evolve.

Summary: stellar evolution

- Eventually, all the hydrogen is fused to helium, and the star leaves the main sequence.
- The core contracts until hydrogen fusion starts in a shell around the core.
- This causes the star to expand and cool, and become a red giant or supergiant.
- Later, the core becomes hot enough to fuse helium into carbon.
- Eventually, all the helium is fused, and the core contracts again until helium fusion starts in a shell around the carbon core.

Summary: stellar evolution

- What happens next depends on the mass of the star.
- Low-mass stars, with less than 8 $M_\odot$, never get hot enough to fuse anything heavier than helium. In the end, they form a "planetary" nebula.
  - As we will see, the dead star will become a white dwarf.
- More massive stars can fuse heavier elements up to (but not including) iron. They eventually achieve an onion-like structure, with an iron core surrounded by shells of lighter elements.
  - As we will see, the star will explode in a supernova and become either a neutron star or a black hole.

Stellar evolution for stars of different masses.
Credits: Encyclopædia Britannica

White dwarfs

- The number of stars is inversely proportional to mass: the lower the mass, the more stars of that mass are in the universe.
- Very massive stars are very rare.
- Most stars have a mass of less than $\sim 1.4\ M_{\odot}$ just before they die.
- Stars lose plenty of mass during their lifetimes, so even stars which started out with as much as $8\ M_{\odot}$ in the main sequence can be reduced to less than $1.4\ M_{\odot}$ by the end of their lives.

White dwarfs

- As we previously learned, two forces are always “at war” in a star: gravity (pulling inward) and pressure (pushing outward).
- Stars with low mass end up with a core of carbon and oxygen, but cannot ignite fusion in the core.
- Nuclear fusion generates pressure from heat. Without fusion, there is no pressure to oppose gravity, and the core begins to contract.
- However, the core eventually stops contracting because it reaches a density where a completely different kind of pressure is created.

White dwarfs

- Remember that fermions are particles with half-integer spin: 1/2, 3/2, 5/2, and so on.
- Examples of fermions include electrons, quarks, neutrinos, protons, and neutrons. All of them have spin 1/2.
- According to the Pauli exclusion principle of quantum mechanics, two fermions of the same type (e.g. two electrons) cannot be in the same quantum state at the same time.
- The quantum state of an electron includes both its position and speed. So no two electrons can be in the same position while moving at the same speed.

White dwarfs

- As the dying star’s core contracts, more and more electrons are being pushed into the same space.
- But according to the Pauli exclusion principle, they cannot be in the same place unless they move at different speeds.
- This means that the more electrons are pushed together, the faster they will have to move.
- The fast movement of the electrons generates pressure, called electron degeneracy pressure.
  - The word “degeneracy” here comes from the fact that the electrons are degenerate, meaning in the same place but at different speeds.

White dwarfs

- When the core cannot contract any further due to electron degeneracy pressure, we call the star a white dwarf.
- The maximum mass of a white dwarf is $\sim 1.4\ M_\odot$. This is called the Chandrasekhar limit (chaan-druh-SAY-kar).
- The more massive the white dwarf is, the smaller its radius. At the Chandrasekhar limit, the radius of the white dwarf is calculated to be zero, so white dwarfs cannot exist beyond this limit.

White dwarfs

- Stars with masses ranging from ~ 0.08 to $8\ M_{\odot}$ will end up as white dwarfs. This accounts for over 95% of the stars in our galaxy.
- Most white dwarfs have a mass similar to that of the Sun and a radius similar to Earth's radius. So they are very dense!
- A white dwarf has an average density of 1 billion kg/m^3 or 1,000 kg/cm^3. This is 1,000,000 times the density of water.
- A single teaspoon (5 cm^3) of white dwarf material has the same mass as a large elephant (5,000 kg or 5 tons).

White dwarfs

- The initial temperature of the white dwarf as it forms is extremely high, $\sim$100,000,000 K.
- So even though it no longer generates light from nuclear fusion, it still shines due to heat.
- Over time, the white dwarf will radiate away all of its heat.
- Because electron degeneracy pressure is a consequence of the Pauli exclusion principle, it does not depend on temperature.
- Therefore, this pressure can keep the white dwarf from collapsing even as it cools down.

White dwarfs

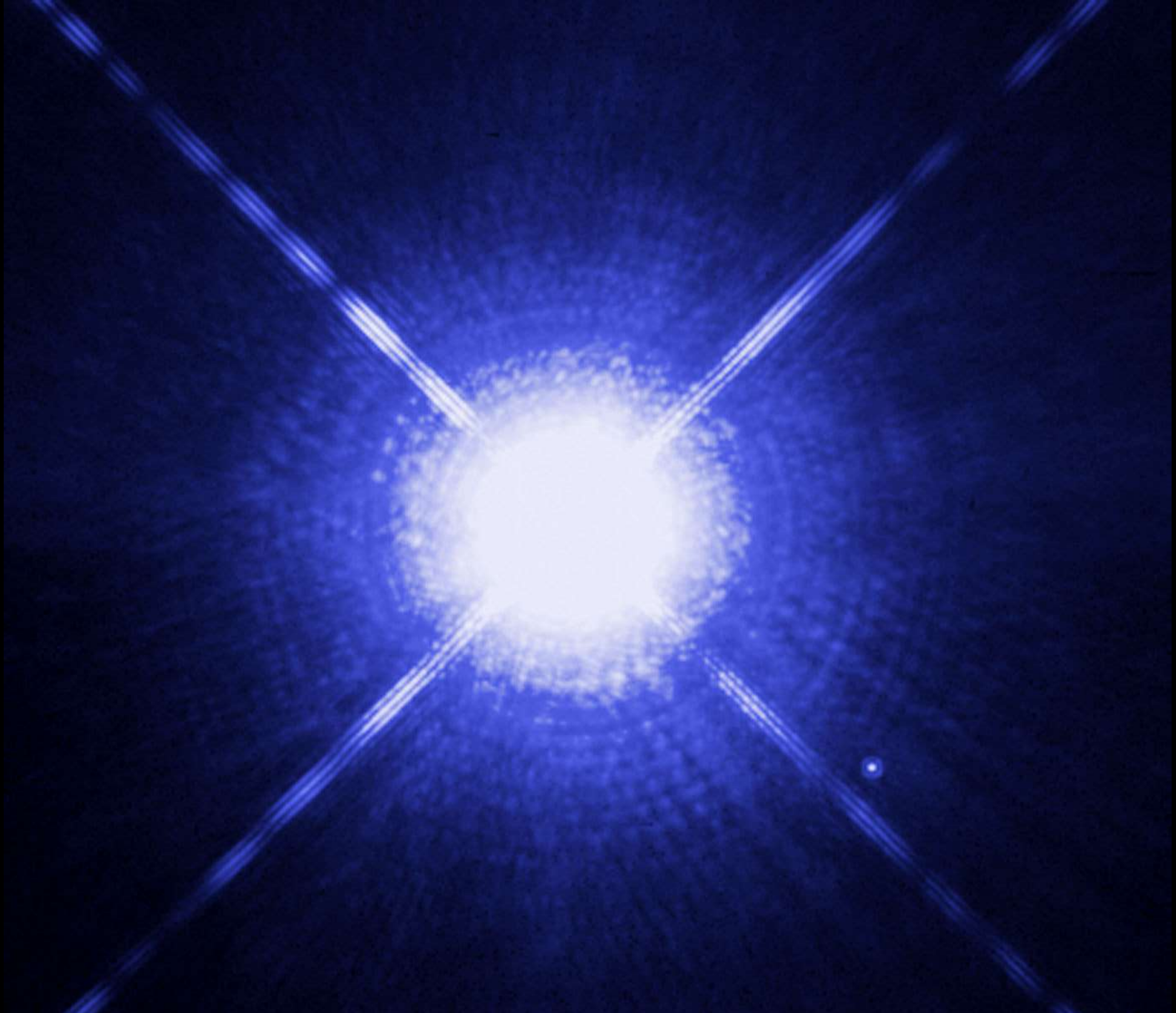
- After trillions of years, the white dwarf will cool down close to absolute zero, and will turn into a black dwarf, which no longer generates light.
- However, since the universe is only ∼13.8 billion years old, no white dwarfs have had time to turn into black dwarfs so far.
- As far as we know, a black dwarf can survive essentially forever. It’s just a cold, dead star floating eternally through space.

White dwarfs

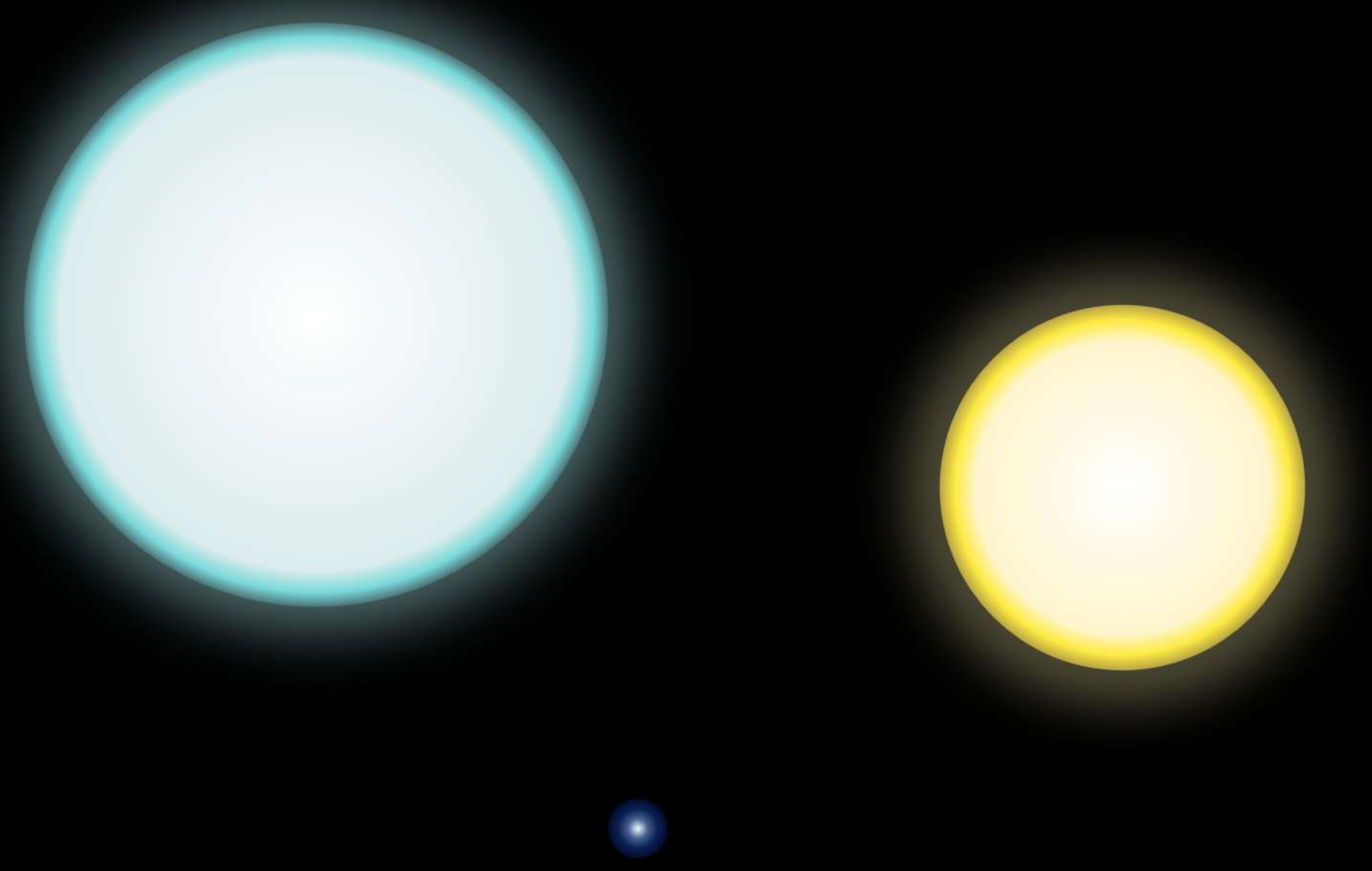
- A star is born when nuclear fusion first starts, and dies when no form of nuclear fusion is possible anymore.
- Therefore, a protostar is like an “embryo” of a star, and a white dwarf is like a “dead body” or “remains” of a star.
- White dwarfs are referred to as stellar remnants.
- Other types of stellar remnants, which we will learn about later in this lecture, are neutron stars and black holes.
- Stellar remnants are also called compact stars or compact objects, because they are very small and dense.

White dwarfs

- Both white dwarfs and neutron stars are also called degenerate stars because they resist gravitational collapse by degeneracy pressure, rather than thermal pressure like a normal star.
- White dwarfs have luminosity class VII, but it is rarely used because the usual spectral types (OBAFGKM) don’t apply to them.
- The spectral types for white dwarfs start with D (for degenerate) followed by 1-2 letters that indicate the atmospheric composition.
    - For example, DA is a white dwarf with a hydrogen-rich atmosphere.



The big star is Sirius A, the brightest star in our sky, a main-sequence star of spectral type A0. The faint, tiny star is Sirius B, a white dwarf of spectral type DA2.
Credits: NASA, ESA, H. Bond (STScI), and M. Barstow (University of Leicester)

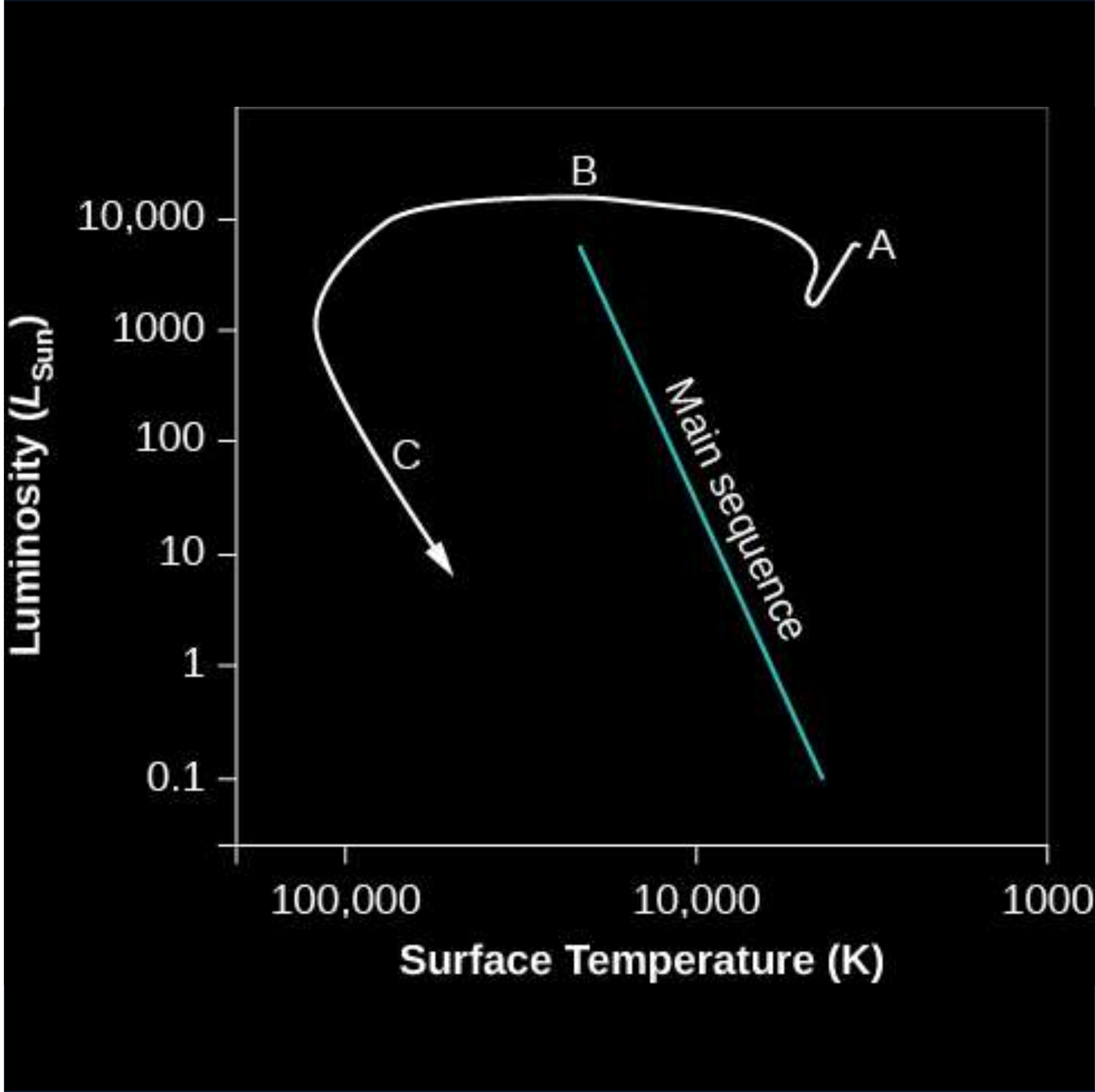


A comparison between the white dwarf IK Pegasi B (center), its A-class companion IK Pegasi A (left) and the Sun (right). This white dwarf has a surface temperature of 35,500 K.
Credits: RJHall (Wikipedia)

- A low-mass star usually becomes a planetary nebula before it collapses to a white dwarf.
  - Remember that despite its name, this nebula has nothing to do with planets!
- The star at the center of the Ring Nebula (M57), shown here, has a temperature of ~125,000 K and is ~200 times more luminous than the Sun.
- This star ceased nuclear fusion within the last 2,000 years, and is on its way to becoming a white dwarf.
  - After it does, the nebula will no longer be visible.

The Ring Nebula (M57).
Credits: The Hubble Heritage Team (AURA/STScI/NASA)

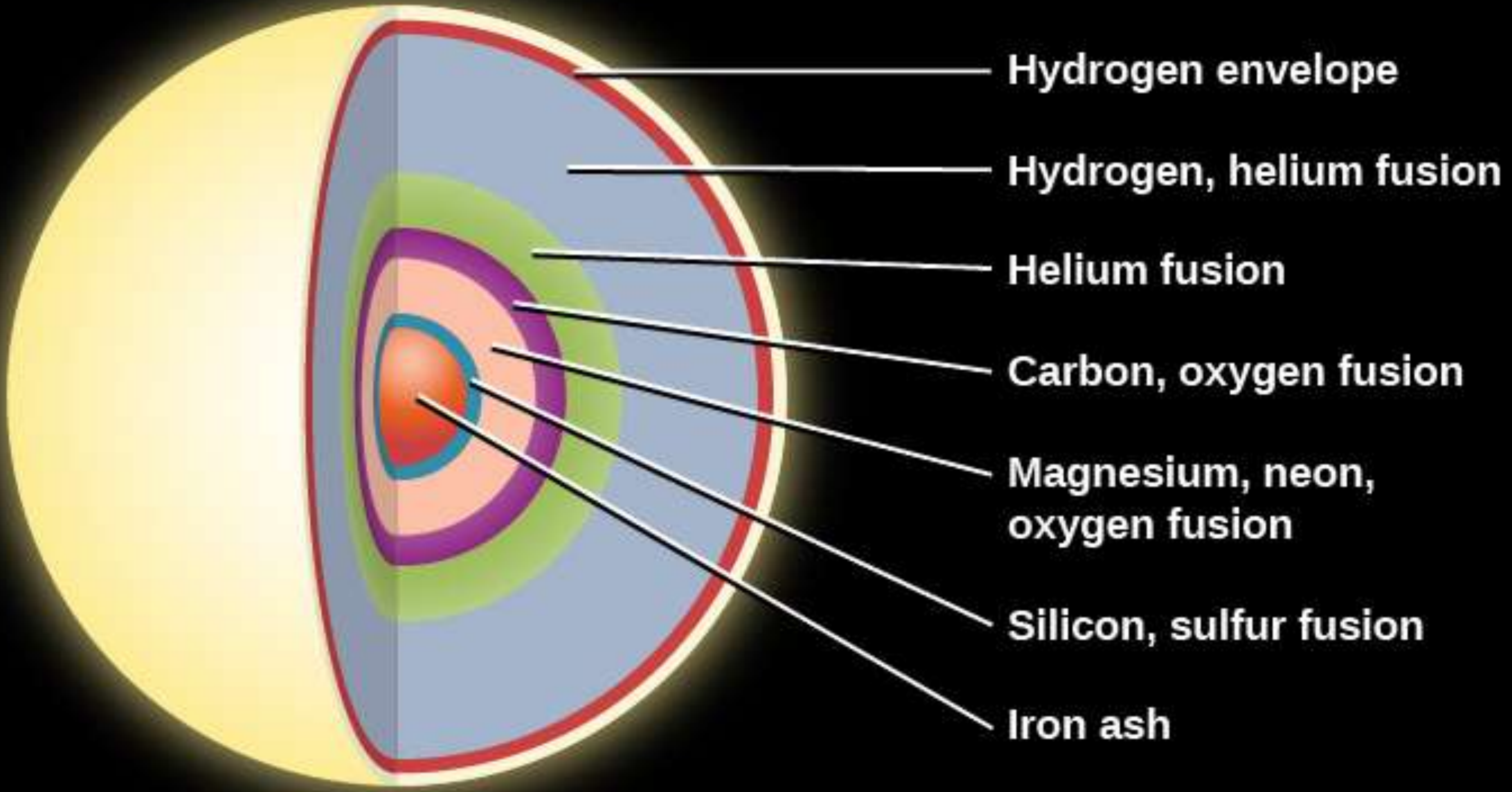
- This H-R diagram shows the final evolutionary stages for a star with 1 $M_{\odot}$.
- At point A, the star is a red giant.
- It then loses mass as the core begins to collapse.
- This exposes the core and creates a planetary nebula.
- The star becomes hotter and hotter and moves left (path B).
- As the star begins to cool off, luminosity decreases, and it moves down (path C) until it becomes a white dwarf.



H-R diagram of the final evolutionary stages of a star like the Sun.
Credits: OpenStax Astronomy

Supernovae

- Stars with initial mass of up to $\sim 8\ M_\odot$ will become white dwarfs.
- However, more massive stars have a very different kind of death.
- As we learned, massive stars do not stop nuclear fusion at helium, they can fuse heavier elements.
- Right before its death, the star resembles an onion. The core is made of iron, with lighter and lighter elements in shells around it.
- The iron cannot be fused, because fusing iron does not generate energy, it requires energy. So once the core turns into iron, no more fusion can occur.



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

Supernovae

- When nuclear reactions stop, the core of a massive star is supported by electron degeneracy pressure, just like a white dwarf.
- However, unlike a white dwarf, in a massive star, fusion still occurs in the shells surrounding the core.
- As the shells finish their fusion reactions and stop producing energy, the reaction products (or ashes) fall into the white dwarf core, increasing its mass.

Supernovae

- Remember that for a white dwarf, more mass means smaller radius. So the core continues to contract.
- At first, the electron degeneracy pressure is enough to resist the contraction.
- However, when the core mass exceeds the Chandrasekhar limit of $\sim 1.4\ M_{\odot}$, the electron degeneracy pressure is no longer sufficient.
- The core then collapses further, and temperatures increase to extreme heat of over ~ 5 billion K.

Supernovae

- Eventually, the density increases to $\sim$400 million kg/cm^3. This is 400,000 times the average density of a white dwarf.
- At this enormous density, electrons are squeezed into the atomic nuclei, and combine with protons to form neutrons and neutrinos:

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

- This is known as electron capture.
  - Note that charge is conserved because the charges of the proton and electron cancel each other, so there was zero total charge both before and after the capture.

Supernovae

- At this point, since neutrons are fermions, and therefore obey the Pauli exclusion principle, they create degeneracy pressure like electrons do. This is called neutron degeneracy pressure.
- This is stronger than electron degeneracy pressure, but still not enough to prevent the core from collapsing.
- However, the neutrons also repel each other due to the strong nuclear force, one of the 4 fundamental forces we learned about in lecture 11 (gravity, electromagnetism, strong, and weak).
- The two forces together are enough to halt the core collapse.

Supernovae

- Electron capture happens extremely fast. In less than a second, a core with a mass $\sim 1\ M_{\odot}$, collapses from the size of Earth to a diameter of less than 20 km.
- The infalling material moves very fast, at $\sim 1/4$ the speed of light.
- Remember that when the electrons and protons combined, the outcome was not just neutrons. but also neutrinos.
- The core stops contracting due to the pressure from the neutrons, and the neutrinos emerge all at once.

Supernovae

- The total power carried by the neutrinos can be $\sim 10^{46}$ W, greater than the total power of over a billion galaxies!
  - Remember: $W = J/s$ where W is power in watt, J is energy is joule, and s is time in seconds. So power $=$ energy per second.
- Normally, neutrinos rarely interact with matter. But since the star is so dense, the neutrinos do significantly interact with it.
- This causes an extremely powerful explosion called a supernova (plural: supernovae, soo-per-NO-vee).
- It can be as bright as an entire galaxy, and fades out over several weeks or months.

Supernova SN 1994D in galaxy NGC 4526. The supernova is the bright spot on the lower left. It happened on March 7, 1994 and reached peak brightness on March 22.
Credits: NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team

Video

- In this video, we see an artist's impression of a collection of distant galaxies, with occasional supernovae happening within them.
- This video is sped up. It is estimated that a supernova occurs every ~33 years in a galaxy like the Milky Way.
- The video can be found at this URL:

https://www.eso.org/public/videos/distantsupernovae/

Supernovae

- During a supernova, the core collapses into a neutron star.
- Neutron stars are the smallest and densest objects known, except for black holes.
- They are composed almost entirely of neutrons, and have a radius of ~10 km on average.
- The density of a neutron star is ~400 billion kg/cm^3. One teaspoon (5 cm^3) of neutron star material has a mass of ~2 trillion kg, about the same as the total mass of all humans on Earth.
- The temperature of neutron stars is initially ~1 trillion K, but they cool down to ~1 million K after a few years.

Supernovae

- Neutron stars have masses between $\sim 1.1\ M_\odot$ and $\sim 2\ M_\odot$.
- The upper limit of $\sim 2\ M_\odot$ for their mass is called the Tolman-Oppenheimer-Volkoff (TOV) limit.
- Beyond this limit, neutron degeneracy pressure and the strong nuclear force are not strong enough to hold against gravity, and the object collapses to a black hole (which we will learn about later).

The Crab Nebula is a supernova remnant, 6 light-years wide. It is the material that exploded out of a star in a supernova that was seen from Earth with the naked eye in the year 1054 CE.
Credits: NASA, ESA, J. Hester and A. Loll (Arizona State University)

Here we zoomed into the center of the Crab Nebula. The neutron star is the rightmost of the two bright stars near the center.
Credits: ESA/Hubble & NASA, Acknowledgement: Mahdi Zamani

A composite image of the Crab Nebula showing X-ray (blue) and optical (red) images superimposed. The neutron star is the red star at the center.
Credits: Optical: NASA/HST/ASU/J. Hester et al. X-Ray: NASA/CXC/ASU/J. Hester et al.

Video

- In this video, we will see an animation showing how the supernova SN 1054, which created the Crab Nebula, might have looked like.
- This supernova happened around July 4, 1054 and remained visible to the naked eye until April 6, 1056.
- The video can be found at this URL:

https://esahubble.org/videos/heic0515a/

Supernovae

- When a supernova explodes, all the elements created by nuclear fusion in the star are released into space and become part of the gas and dust that later forms new stars and planets.
- Therefore, supernovae are the reason we are alive! The atoms that make our bodies were created in massive stars, and then released into space when these stars exploded.
- This is called stellar nucleosynthesis.
- However, this only includes elements up to iron (26 protons). Heavier elements cannot be created by fusion inside stars.

Supernovae

- So where do heavier elements come from?
- A supernova produces a flood of energetic neutrons that fly through the expanding material.
- A neutron can be absorbed by iron or another nucleus, where it can decay into a proton (plus an electron and a neutrino) via beta decay – basically the opposite of electron capture.
- This process adds more protons to the nucleus, so it creates elements that have more protons than iron, such as silver (47 protons), gold (79), and uranium (92).
- Again, these elements would not have existed here on Earth without supernova explosions.

The fate of stellar objects by mass

Initial Mass ($M_\odot$)	Final State
< 0.01	Planet
0.01 to 0.08	Brown dwarf
0.08 to 0.25	White dwarf made mostly of helium
0.25 to 8	White dwarf made mostly of carbon and oxygen
8 to 10	White dwarf made of oxygen, neon, and magnesium
10 to 40	Supernova explosion that leaves a neutron star
> 40	Supernova explosion that leaves a black hole

Supernova types

- About a half of all star systems are binary stars: two stars that are gravitationally bound, and orbit each other.
- Sometimes the two stars in a binary system can exchange material, especially when one of them is a giant or supergiant, or has a strong stellar wind. This is called mass transfer.
- If mass transfers from a star to a white dwarf, the material will collect in an accretion disk around the white dwarf.

Artist’s impression of gas from a blue giant being stripped away and accumulated in an accretion disk around its companion white dwarf.
Credits: STScI

Supernova types

- This will cause a new layer of hydrogen to accumulate on the white dwarf’s surface.
- Eventually, the hydrogen can get hot enough to ignite fusion.
- In this case, hydrogen fusion begins suddenly and causes an explosion, blasting away much of the new material.
- The white dwarf briefly becomes much brighter, hundreds or thousands of times its previous luminosity.
- It fades away after a few months or years.

Supernova types

- If the star system was previously too dim to be seen with the naked eye, it now suddenly becomes visible.
- To observers before the invention of the telescope, it seemed that a “new star” suddenly appeared, so they called it a nova, which means “new” in Latin.
- The word “nova” was first used in this context in 1572.

GK Persei, a nova that appeared in 1901. It consists of a white dwarf and a subgiant star, and surrounded by a nova remnant called the Firework Nebula.
Credits: X-ray: NASA/CXC/RIKEN/D.Takei et al; Optical: NASA/STScI; Radio: NRAO/VLA

Supernova types

- Today, we differentiate between “nova” and “supernova”.
- “Nova” is used only for explosions of white dwarfs in binary systems, as we just described.
- “Supernova” was coined in 1931 to indicate a “new star” that is much more luminous than an ordinary nova.
- A Type II supernova is a supernova that results from the collapse of a massive star, as we discussed earlier in this lecture.

Supernova types

- A Type Ia supernova is a supernova that results from a white dwarf that accumulates matter from its companion star, like a nova, but at a much faster rate.
- This causes the mass of the white dwarf to approach the Chandrasekhar limit ($\sim 1.4\ M_{\odot}$), so it can no longer use electron degeneracy pressure to resist collapsing.
- The star contracts and heats up, over a century or so.
- Suddenly, in less than a second, an enormous amount of fusion, especially of carbon, ignites all at once, causing an explosion.

Supernova types

- This explosion completely destroys the white dwarf.
- Therefore, in a Type Ia supernova, no neutron star or black hole remains.
- Type Ia supernovae can also be caused by two white dwarfs merging into one big white dwarf, which similarly collapses due to having too much mass.
- Compared to Type II supernovae, Type Ia supernovae are $\sim$5 times more luminous.

G299, a remnant of a Type Ia supernova.
Credits: NASA/CXC/U.Texas

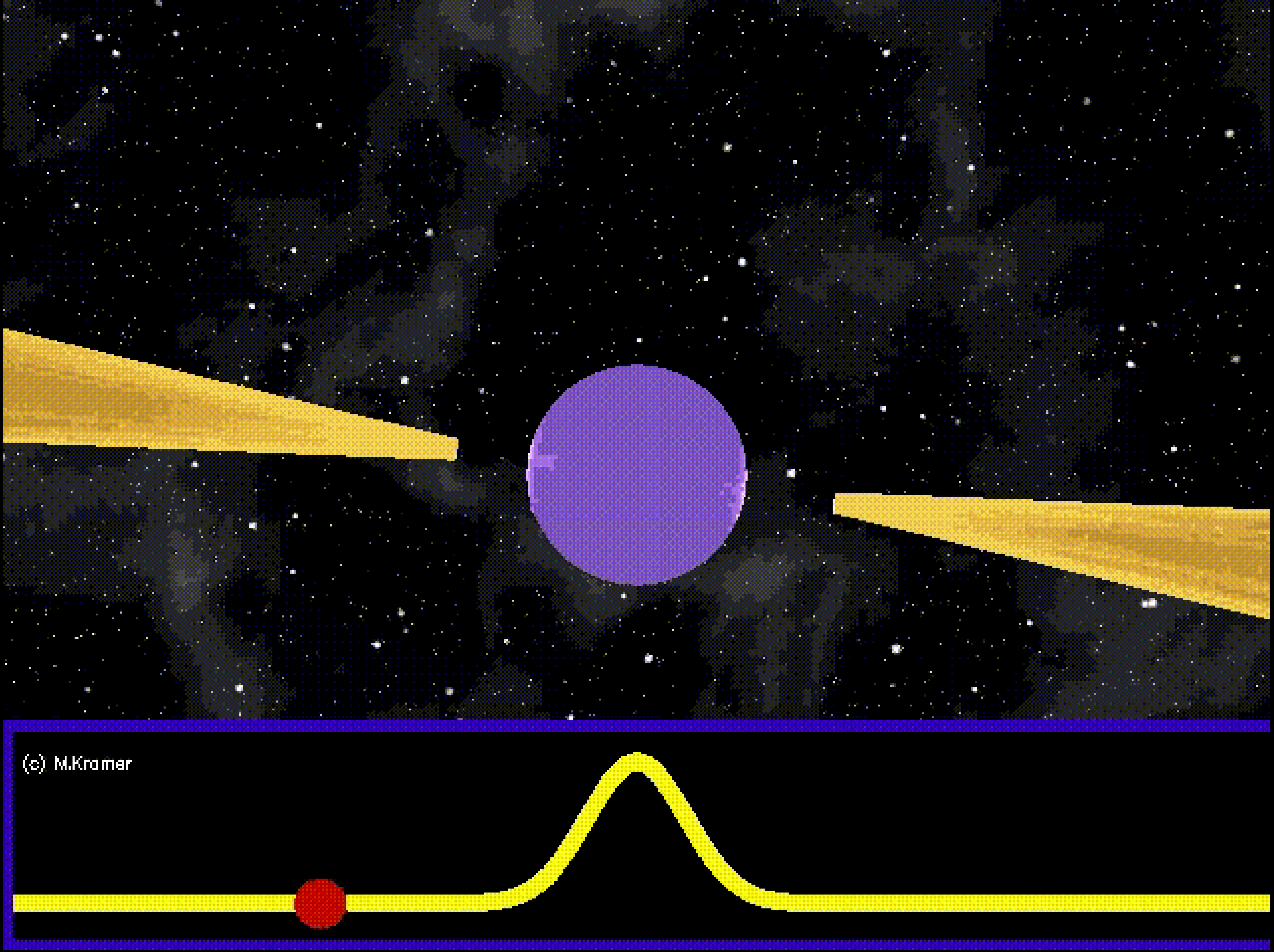
Video

- This artist's impression video shows the central part of the planetary nebula Henize 2-428.
- Inside there are two white dwarfs, each with mass a little less than that of the Sun.
- They are expected to slowly draw closer to each other and merge in around 700 million years.
- This event will create a Type Ia supernova and destroy both stars.
- The video can be found at this URL:

https://www.eso.org/public/videos/eso1505a/

Pulsars

- A pulsar (pulsating radio source) is a rotating neutron star that emits beams of electromagnetic radiation.
- The radiation is emitted from the magnetic poles, which may not be aligned with the rotation axis.
- Pulsars are like "lighthouses" in space; we can only see them when the beam is pointed directly at Earth.
- Neutron stars are very dense, and they spin very fast. This produces pulses in intervals ranging from milliseconds to seconds.
    - The fast spin is due to conservation of angular momentum. Even if the original star rotated slowly, when it collapses to just a few km it still has the same amount of angular momentum, so it spins a lot faster.



Animation of the "lighthouse" effect produced by a pulsar. Note the misalignment of the magnetic and rotation poles. The bottom graph shows the intensity of the signal as observed on Earth.
Credits: Michael Kramer (JBCA, U. Manchester). The animation is available at this URL: https://en.wikipedia.org/wiki/File:Lightsmall-optimised.gif

The neutron star at the center of the Crab Nebula, which we discussed earlier, is also a pulsar.
Credits: Optical: NASA/HST/ASU/J. Hester et al. X-Ray: NASA/CXC/ASU/J. Hester et al.

Pulsars

- Pulsars were first observed by Jocelyn Bell in 1967 using a radio telescope. She was a graduate student at the time.
- She and her supervisor, Antony Hewish, thought that it could be a sign of extraterrestrial intelligence, since the pulses were very regular, like a clock.
- However, later that year they discovered a second pulsar, which ruled out that hypothesis.
- Pulsars are designated PSR followed by right ascension + declination. The first pulsar was named PSR B1919+21.

Video

- In this video, Jocelyn Bell describes her discovery of the first pulsars.
- She also discusses her experience as a female scientist in the 1960s and her struggle with impostor syndrome.
- The video can be found at this URL:

https://youtu.be/z_3zNw91MSY

Pulsars

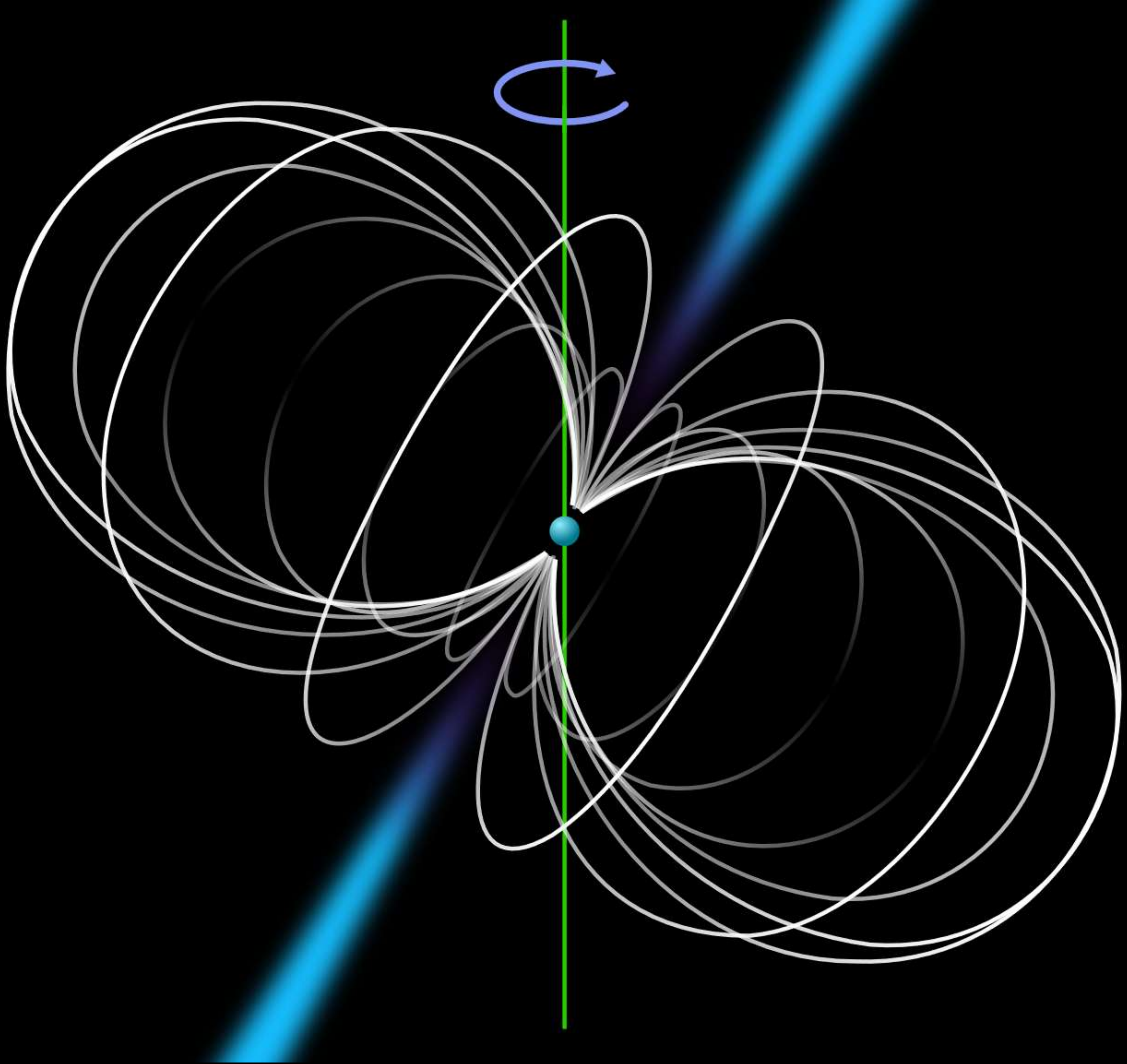
- There are an estimated ~1 billion neutron stars in the Milky Way.
- However, most are old and have cooled down, so they don't produce much radiation. Therefore, we cannot see them.
- Pulsars are very easy to detect because of their radiation, so out of the ~3,200 neutron stars currently known, most are pulsars.
- However, remember that a pulsar is like a lighthouse, so we can only detect it if its radiation points directly at us.
- There are probably many more pulsars that we cannot detect simply because they point away from us.

Pulsars

- There are 3 types of pulsars currently known, classified according to the source of the radiation beam.
- In rotation-powered pulsars, the beam comes from the rotational energy of the neutron stars.
- As was mentioned before, neutron stars rotate very fast, due to conservation of angular momentum.
- For the same reason, the neutron star also has a very strong magnetic field: the magnetic field of the original star has been compressed to a very high density.

Pulsars

- The rotating magnetic field accelerates charged particles – protons and electrons – to nearly the speed of light.
- These particles can only escape the strong magnetic field at the magnetic poles. Therefore, a beam of particles is emanated from the magnetic poles.
- Over time, the rotation of the neutron star slows, and eventually it "turns off". This can take ~10-100 million years.
- Based on this and the known age of the universe (~13.8 billion years), we can estimate that ~99% of the existing neutron stars have already turned off.



Schematic view of a pulsar. The curves indicate the magnetic field lines, the protruding cones represent the emission beams, and the green line represents the rotation axis of the neutron star.
Credits: Mysid, Jm smits (Wikipedia)

Pulsars

- In accretion-powered pulsars, gas is accreted from a binary companion and is channeled onto the magnetic poles.
- This produces two or more localized hotspots, where the infalling gas can reach half the speed of light before it impacts the surface.
- Gravitational potential energy, released from the gas as it falls, is converted to heat.
- The hotspots, $\sim$1 km^2 in area, can be $\sim$10,000 more luminous than the Sun and reach temperatures of millions of degrees.
- At these temperature, the pulsars produce radiation mostly in the X-ray range, so they are also called X-ray pulsars.

Pulsars

- The third type of pulsars is called magnetars. They have an extremely strong magnetic field, up to $\sim 10^{11}$ T.
  - T stands for tesla, a unit used to measure magnetic fields.
- For comparison:
  - A normal pulsar has a magnetic field of $\sim 10^{8}$ T.
  - The average magnetic field of Earth is $\sim 4.5 \times 10^{-5}$ T.
- Magnetars also rotate slower than other neutron stars. Their rotation period is $\sim$2-10 seconds, compared to $\sim$0.1-1 second for other neutron stars.

Pulsars

- The magnetic field of a magnetar is so powerful that if you stand 1,000 km from it, you will die immediately because it will distort the electron clouds of the atoms in your body.
- In a magnetar, the beams are caused by the strong magnetic field, and consist of X-rays and gamma rays.
- The magnetic field decays after ~10,000 years, and the magnetar is deactivated.
- Currently, only 24 magnetars are known, but the number of inactive magnetars in our galaxy is estimated at ~30 million.

The star cluster Westerlund 1. Left: visible light, with all stars appearing red due to interstellar reddening. Right: X-ray wavelengths, with the magnetar CXOU J164710.2-455216 marked.
Credits: NASA/CXC/UCLA/M.Muno et al.

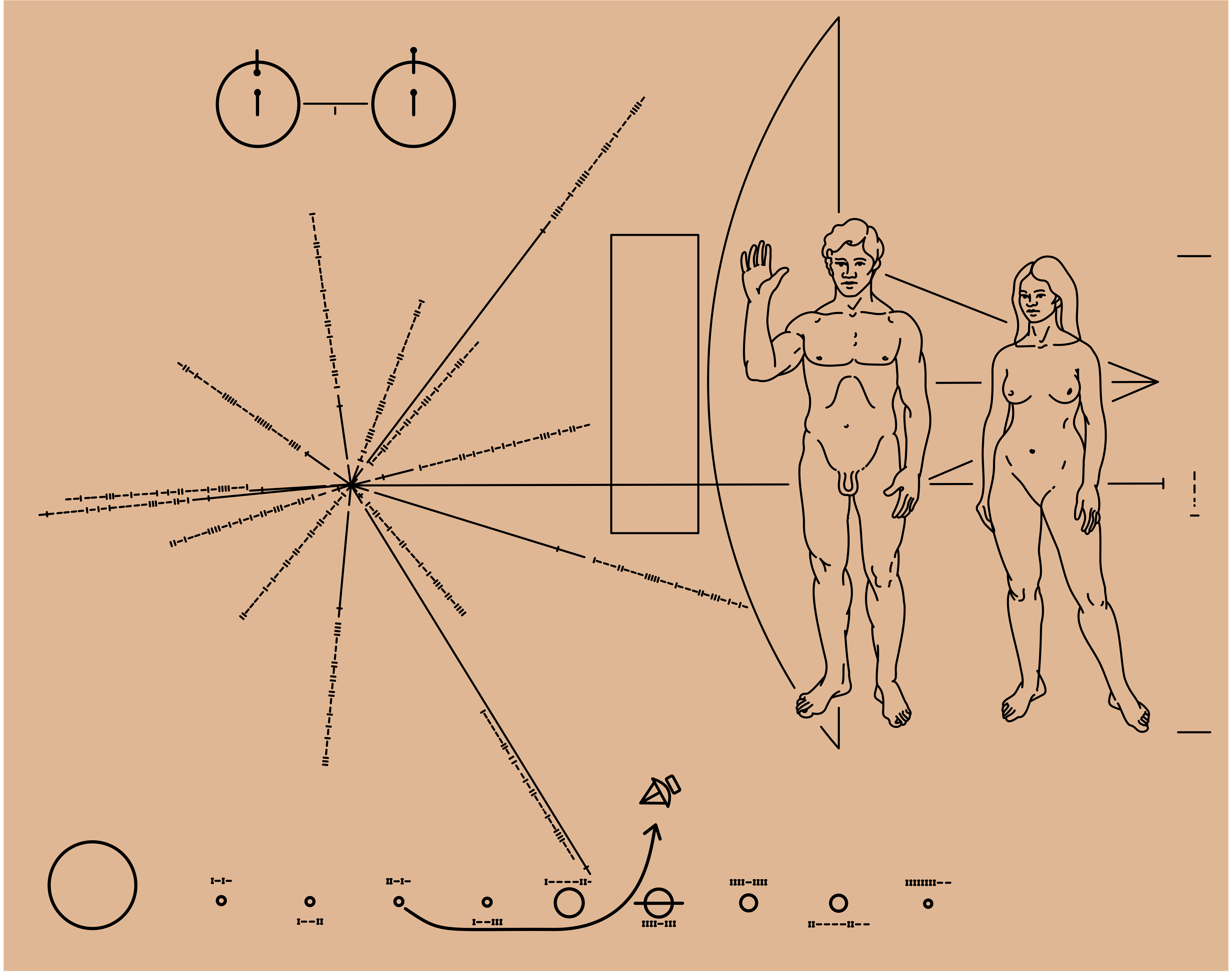
Artist's impression of the magnetar CXOU J164710.2-455216 in the star cluster Westerlund 1.
Credits: ESO/L. Calçada

Pulsars

- The Pioneer plaques are illustrations that were placed on the Pioneer 10 (1972) and Pioneer 11 (1973) spacecraft.
- The two spacecraft were sent out of the solar system, and the plaques are meant to be messages, in case any intelligent extraterrestrial life forms find them in the future.
- Because pulsars have very precise periods, they were used on the Pioneer plaques to indicate the position of the solar system.

Pulsars

- The frequency of the hydrogen spin-flip transition is used as a universal unit of time. This corresponds to ~0.704 nanoseconds.
- 14 pulsars were indicated in a diagram as lines emanating from the Sun. The lines have markings encoding the periods of the pulsars.
- The lengths of the lines encode the relative distances from the Sun to each pulsar.
- This will allow aliens to triangulate the location of the solar system using the locations of known pulsars.
- 14 pulsars were included because some pulsars may not be visible to the aliens (due to the “lighthouse” effect).



The Pioneer plaque.
Credits: Vectors by Oona Räisänen; designed by Carl Sagan & Frank Drake; artwork by Linda Salzman Sagan

General relativity

- The general theory of relativity (or general relativity) was published by Albert Einstein in 1915.
- It completely revolutionized our understanding of the universe.
- General relativity is a theory of gravity, but it is much more precise than Newtonian gravity.
- In general relativity, space and time are joined together into spacetime, and gravity is described as the curvature of spacetime.
- Since general relativity is also the theory of spacetime, it gives a precise description of space, time, and how they are related.

General relativity

- General relativity also describes the relation between spacetime and matter.
- On the one hand, matter tells spacetime how to curve. Different types and configurations of matter cause spacetime to curve in different ways. Matter with more mass causes more curvature.
- On the other hand, spacetime tells matter how to move. Both matter and light follow paths, called geodesics, which are dictated by the spacetime curvature.
- What we interpret as “the force of gravity” is actually not a force, it is due to the geodesics being influenced by the curvature.

- It is common to illustrate curved spacetime as a 2D grid.
- The more massive an object is, the more curvature it will create in the grid.

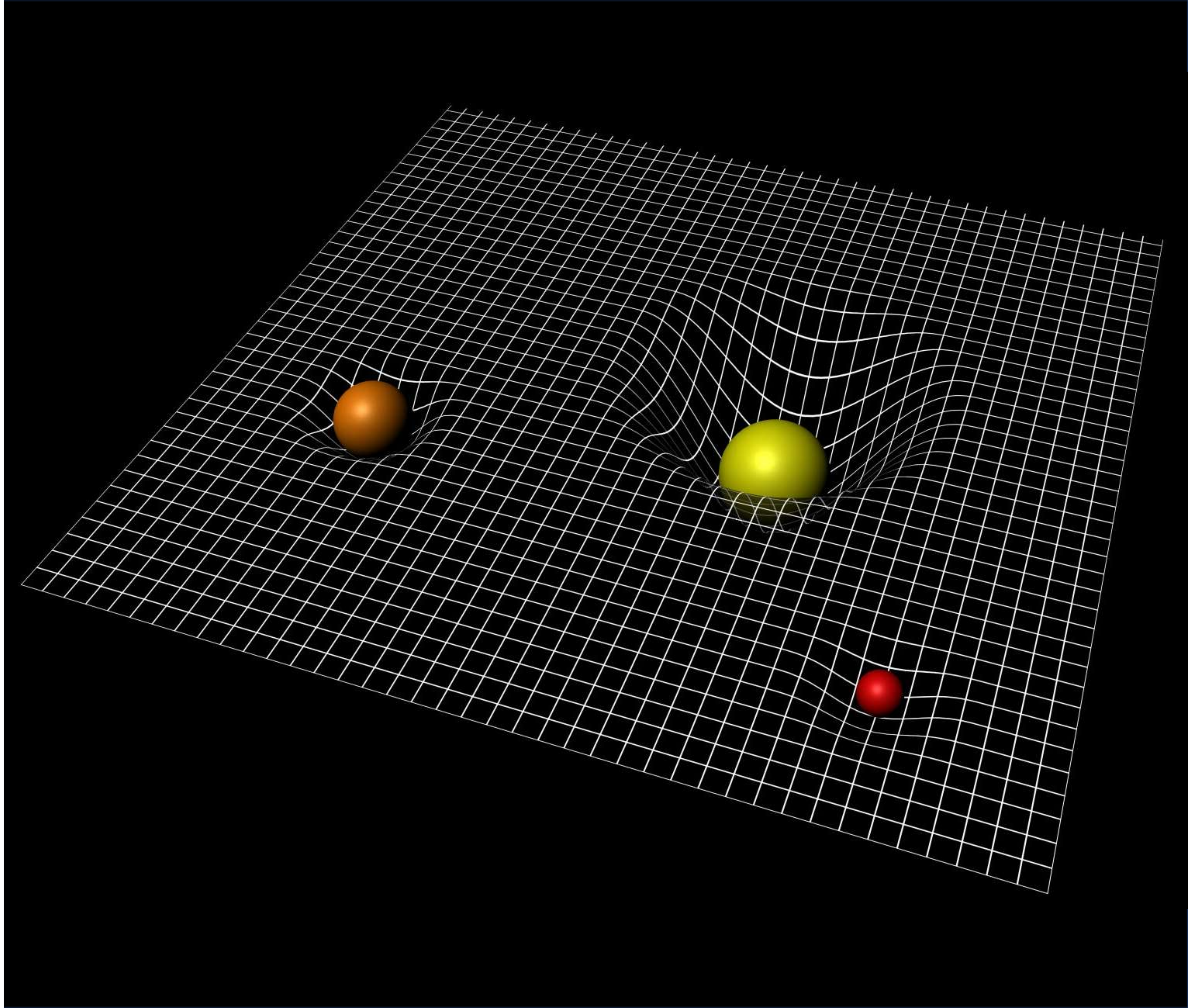


Illustration of spacetime curvature from different masses in 2D.
Credits: ESA–C.Carreau

- However, this illustration is a bit misleading.
- It looks like “gravity” is pulling the masses “down” and causing the curvature.
- In reality, the curvature itself is the source of gravity, not the other way around.

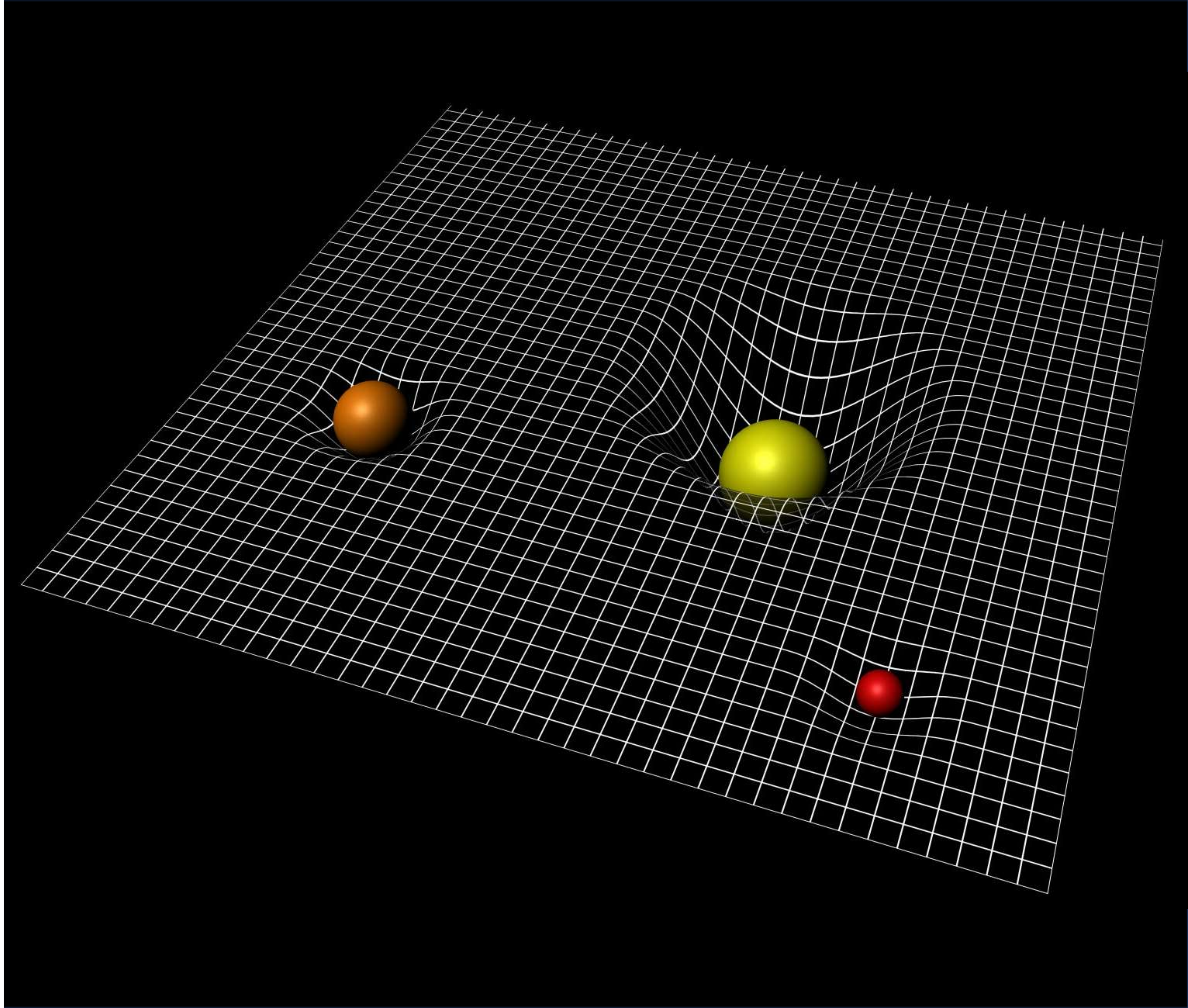


Illustration of spacetime curvature from different masses in 2D.
Credits: ESA–C.Carreau

- A slightly more accurate illustration uses a 3D grid.
- A mass, in this case Earth, is causing the grid to warp and bend in its vicinity.
- This is a better analogy for spacetime curvature than the 2D grid.
- In the 3D grid, there is nothing “pulling the mass down”, the mass itself is causing the curvature.

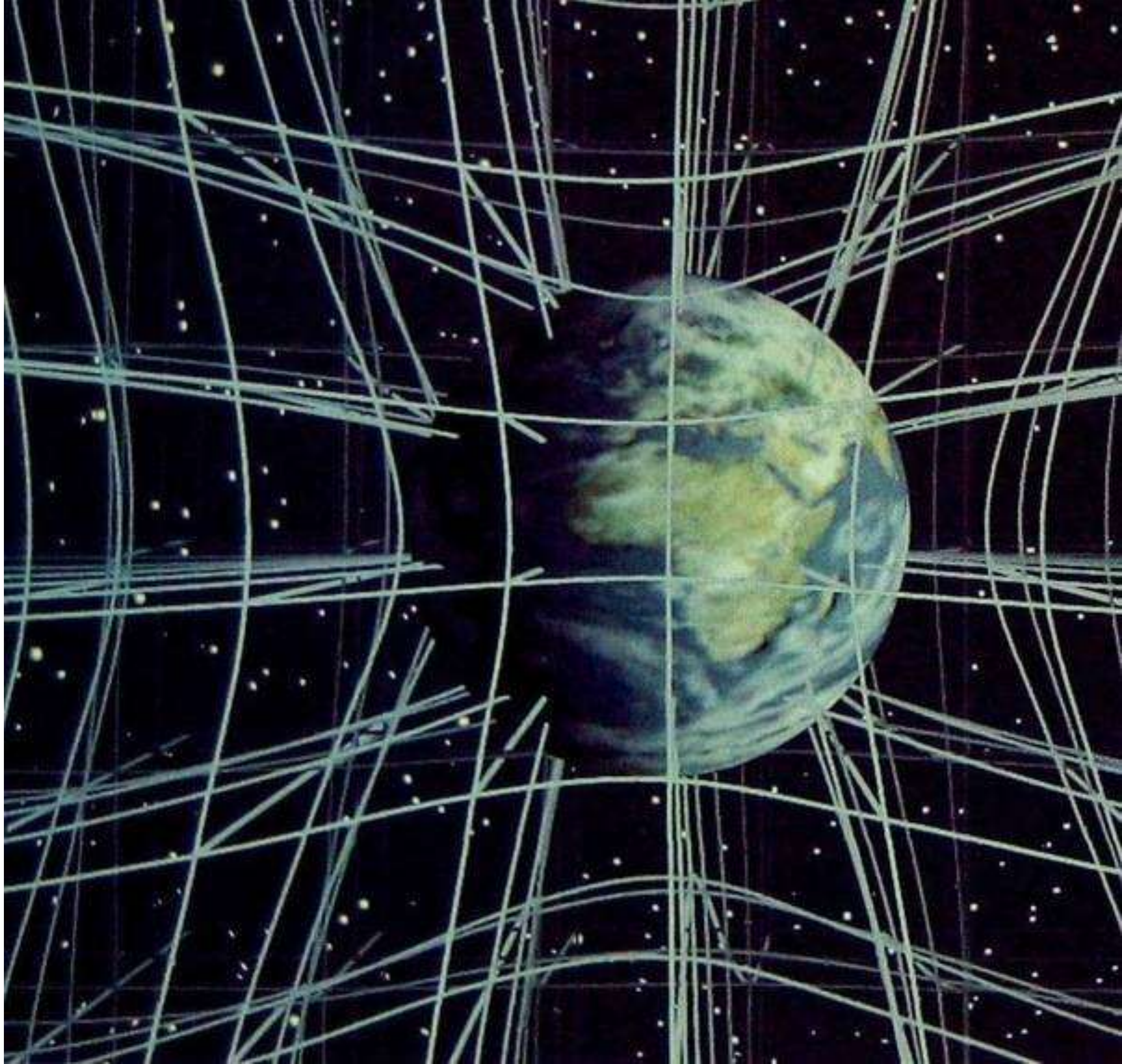


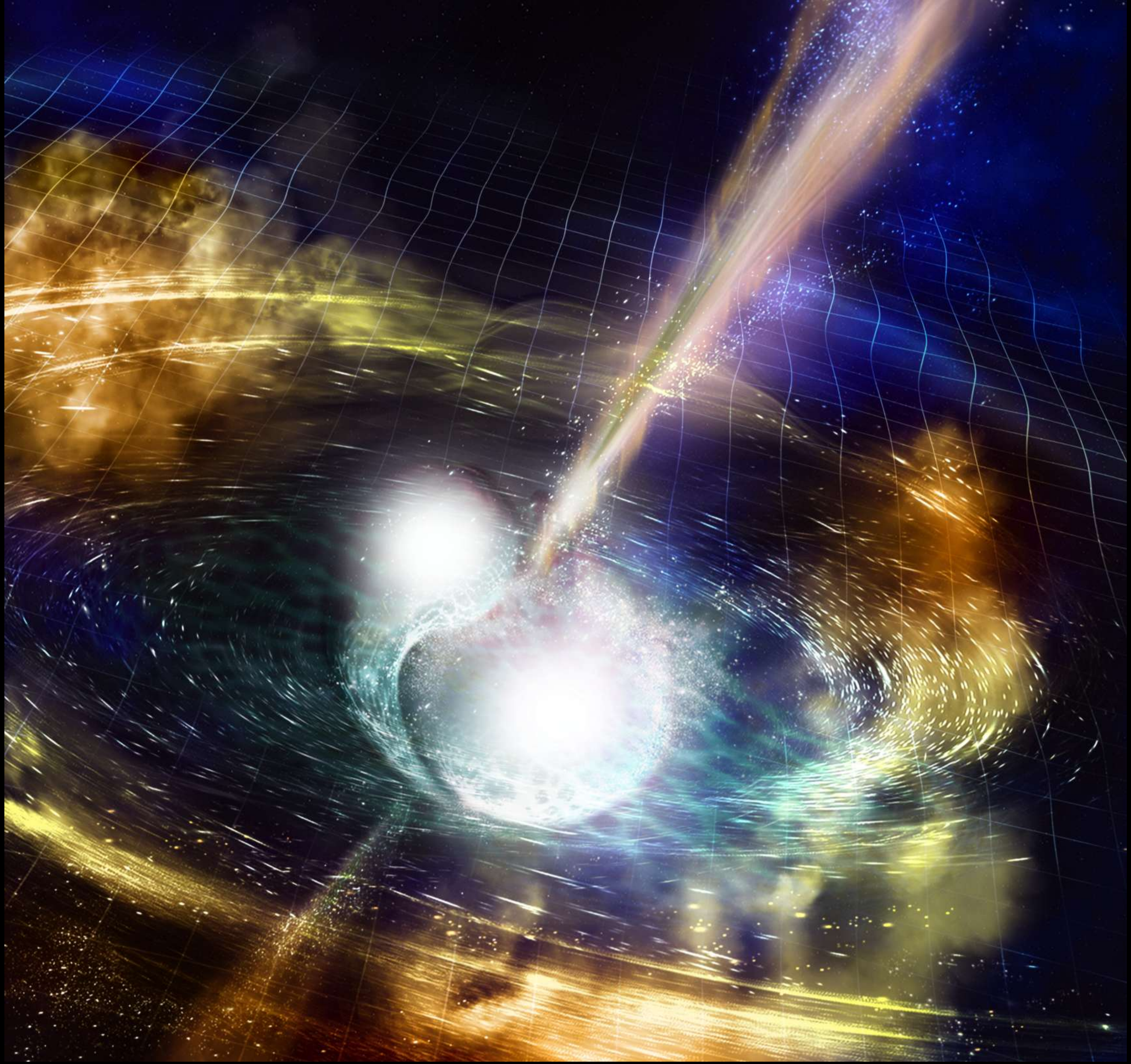
Illustration of spacetime curvature from a mass in 3D.
Credits: Christopher Vitale

Black holes

- Remember that there are two forces always trying to overcome each other in any star: gravity and pressure.
- A massive star can collapse into a neutron star if the neutron degeneracy pressure is sufficient to overcome gravity.
- The upper limit for a mass of a neutron star is the Tolman-Oppenheimer-Volkoff (TOV) limit, which is $\sim 2\ M_{\odot}$.
- Beyond this limit, neutron degeneracy pressure will no longer be sufficient, and the star will collapse under its own gravity.

Black holes

- There is no known mechanism that could stop the gravitational collapse if neutron degeneracy pressure is not enough.
- Therefore, in stellar remnants with mass above the TOV limit, the gravitational collapse simply continues with nothing to resist it.
- This can also happen when two neutron stars collide and merge into one big neutron star.



Artist’s illustration of two neutron stars merging – and causing ripples in the curvature of spacetime, called gravitational waves, which we will learn about later.
Credits: NSF/LIGO/Sonoma State University/A. Simonnet

Black holes

- Let us define the Schwarzschild radius r_s:

$$r_s = \frac{2GM}{c^2}$$

  - M is the mass of the star.
  - $G \approx 6.67 \times 10^{-11}\ \mathrm{m^3/kg \cdot s^2}$ is the gravitational constant.
  - $c \approx 3 \times 10^8\ \mathrm{m/s}$ is the speed of light.

Black holes

- The Schwarzschild radius depends on the mass, so different objects have different Schwarzschild radii.
  - The Sun ($M = 1\ M_{\odot} \approx 2 \times 10^{30}$ kg) has Schwarzschild radius $\sim$3 km.
  - The Earth ($M = 6 \times 10^{24}$ kg) has Schwarzschild radius $\sim$9 mm.
  - An average human ($M = 70$ kg) has Schwarzschild radius $\sim 10^{-25}$ m. This is 1 quadrillion (10^{15}) times smaller than an atom and 10 billion (10^{10}) times smaller than a proton.
- If the mass of an object collapses to a size smaller than its Schwarzschild radius, a black hole is formed.
  - So if we compressed the Sun to a radius of 3 km, or the Earth to a radius of 9 mm, we would create a black hole.

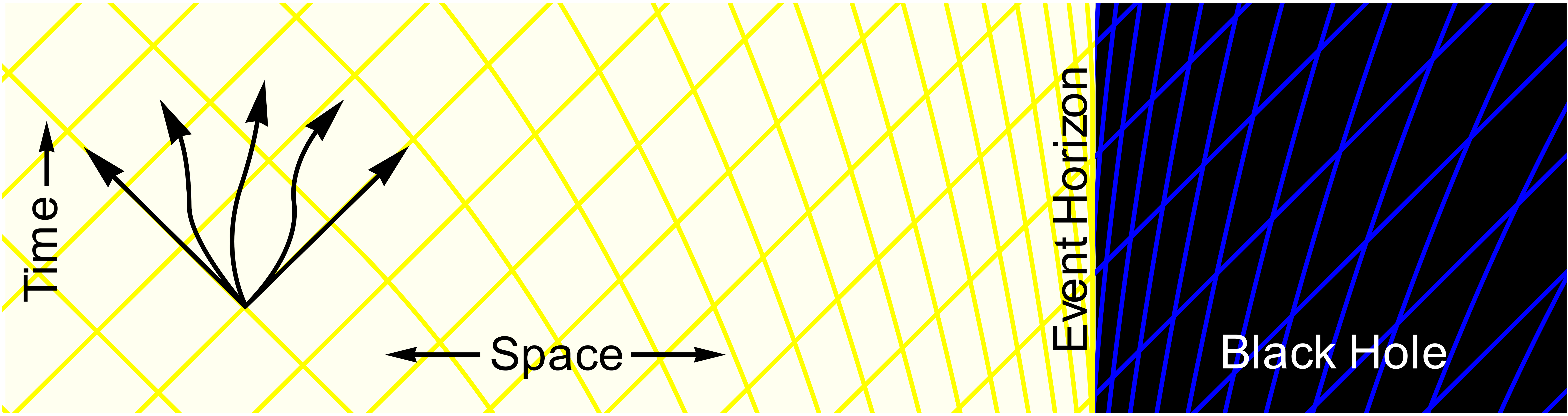
Black holes

- The defining feature of a black hole is an imaginary surface that exists at the Schwarzschild radius, called the event horizon.
- Anything that passes the event horizon into the black hole can never escape back out of the event horizon.
- This includes not just matter, but also light. Since light can never escape from the black hole, it is black, hence the name.

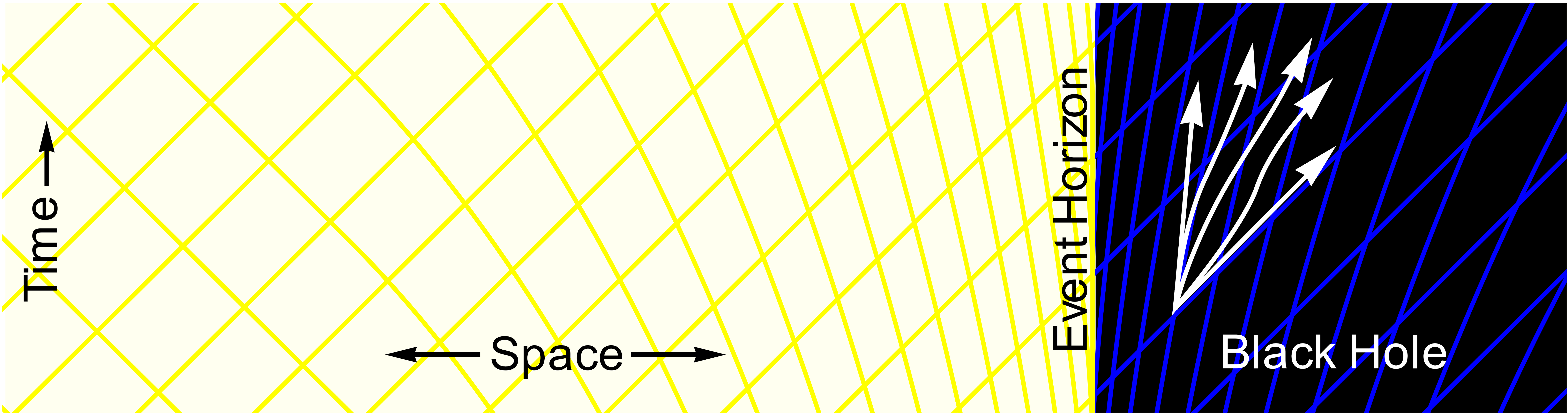
Black holes

- Remember that according to general relativity, both matter and light follow geodesics: paths dictated by the spacetime curvature.
- The reason nothing can escape the event horizon is that spacetime is curved in such a way that every possible geodesic must go further into the black hole.

Far away from the black hole, a particle can move in any direction.



Inside the event horizon, all paths bring the particle closer to the center of the black hole. It is no longer possible for the particle to escape.



Credits: Vanessaezekowitz & Avsa (Wikipedia)

Black holes

- At the center of a black hole, general relativity predicts that there is a singularity.
- The singularity is a single point that contains all the mass of the black hole.
- A single point has zero volume. Since density is mass divided by volume, the singularity can be thought of as having infinite density.
- Outside the singularity, the black hole is thought to be just empty space. In other words, the gravitational collapse continued with no pressure to stop it, so the mass collapsed to a single point.

Black holes

- However, most theoretical physicists think that singularities don't really exist.
- Singularities just indicate that the theory of general relativity is not valid at the center of a black hole, so its predictions at that point are incorrect.
- We think that the center of a black hole must be described by combining general relativity with quantum mechanics.
- This combined theory is called quantum gravity. However, so far, we have not been able to find this theory, so we don't really know what happens at the center of a black hole.

Black holes

- Black holes that result from gravitational collapse of stars are called stellar black holes.
- The first stellar black hole to be discovered was Cygnus X-1 (pronounced SIG-nus), in 1971.
- This object is estimated to have a mass of $\sim 21\ M_{\odot}$, but it is too small to be anything other than a black hole.
- It is located $\sim 7{,}300$ light-years from the Sun.

Black holes

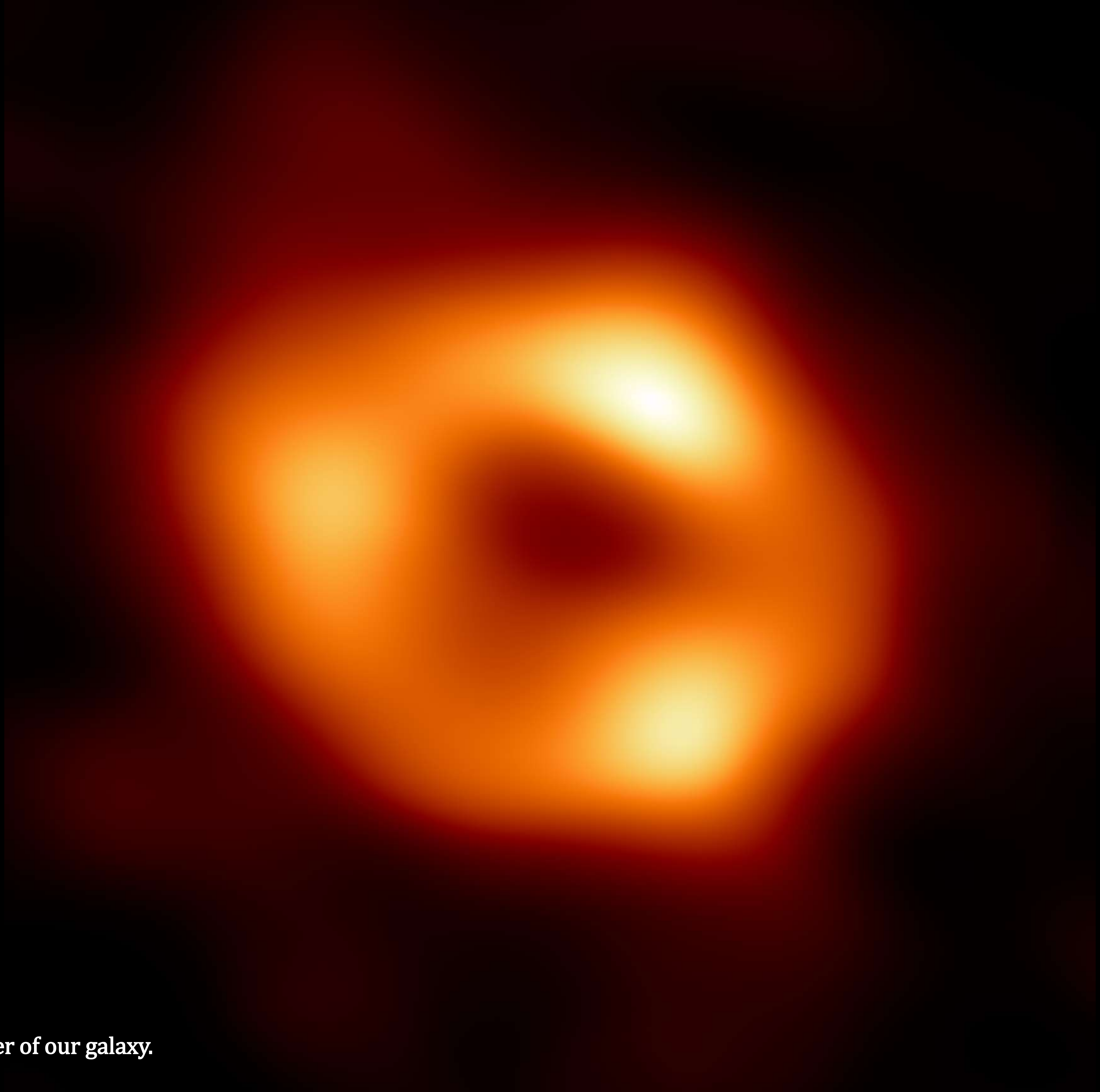
- Cygnus X-1 belongs to a binary system. Its companion is a blue supergiant of spectral class O9.7, designated HDE 226868.
- The companion has surface temperature $\sim$31,000 K and mass $\sim$20-40 $M_{\odot}$. It is $\sim$300,000-400,000 more luminous than the Sun.
- The shape of the companion is distorted by tidal forces from the black hole into a “tear drop” shape.
- Matter from the star accumulates in an accretion disk around the black hole.
- The matter in the disk is heated to millions of degrees, and generates very strong X-ray radiation that is detected from Earth.

Artist’s impression of the binary system. Matter from the blue supergiant HDE 226868 (left) is accreted in a disk around the black hole Cygnus X-1 (right).
Credits: ESA, Hubble

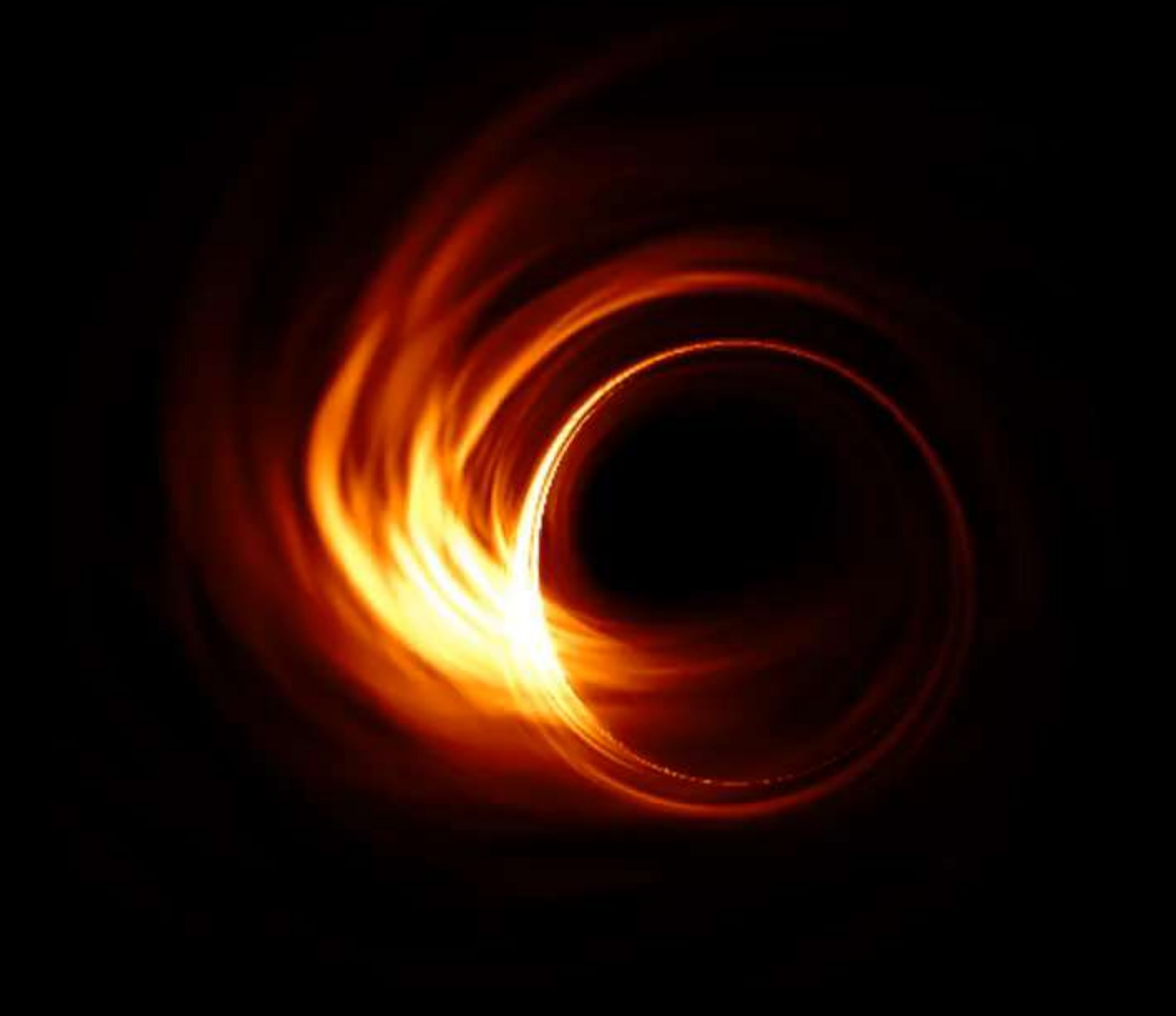
Black holes

- Another type of black holes are supermassive black holes, which have masses up to millions or even billions $M_\odot$.
- Almost every large galaxy has a supermassive black hole at its center, including the Milky Way.
- The Event Horizon Telescope took direct images of two supermassive black holes:
  - The black hole at the center of the galaxy M87, called M87*, in 2019. This was the first ever image taken of a black hole.
  - The black hole at the center of the Milky Way Galaxy, called Sagittarius A*, in 2022.

Black hole M87*. At the center is the shadow of the black hole, larger than the event horizon. It is surrounded by an accretion disk. This is a false color image; the disk is not actually orange.
Credits: EHT Collaboration



The black hole Sagittarius A*, at the center of our galaxy.
Credits: EHT Collaboration



This video shows a simulation of a black hole accretion disk. This is essentially what we see in the black hole images, but the images are very blurry, so we don't see all the details.
Credits: Hotaka Shiokawa; video available at https://eventhorizontelescope.org/simulations-gallery (under "Accretion Disk")

Video

- This animation shows a very detailed simulation of how we think the black hole M87* really looks like.
- It also explains other parts that are not seen in the image, such as the jets, which are collimated (parallel) beams of matter ejected from the black hole at close to the speed of light.
- The video is available at this URL:

https://youtu.be/1Sv7djCASDg

Video

- This video explains how the Event Horizon Telescope works.
- The video is available at this URL:

https://youtu.be/gy-jSMedpMw

Bonus Video

- In this video, Derek Muller (Veritasium) explains what exactly we are seeing in the black hole images.
- The video is available at this URL:

https://youtu.be/zUyH3XhpLTo

Conclusions

- In this lecture we learned what happens to stars when they die, and what they leave behind.
- We also learned a bit about general relativity and black holes. We will learn more in depth about these topics in the next lecture.

- Reading: OpenStax Astronomy, chapters 23-24.
- Exercises: Practice questions are available in the textbook and on the course website.