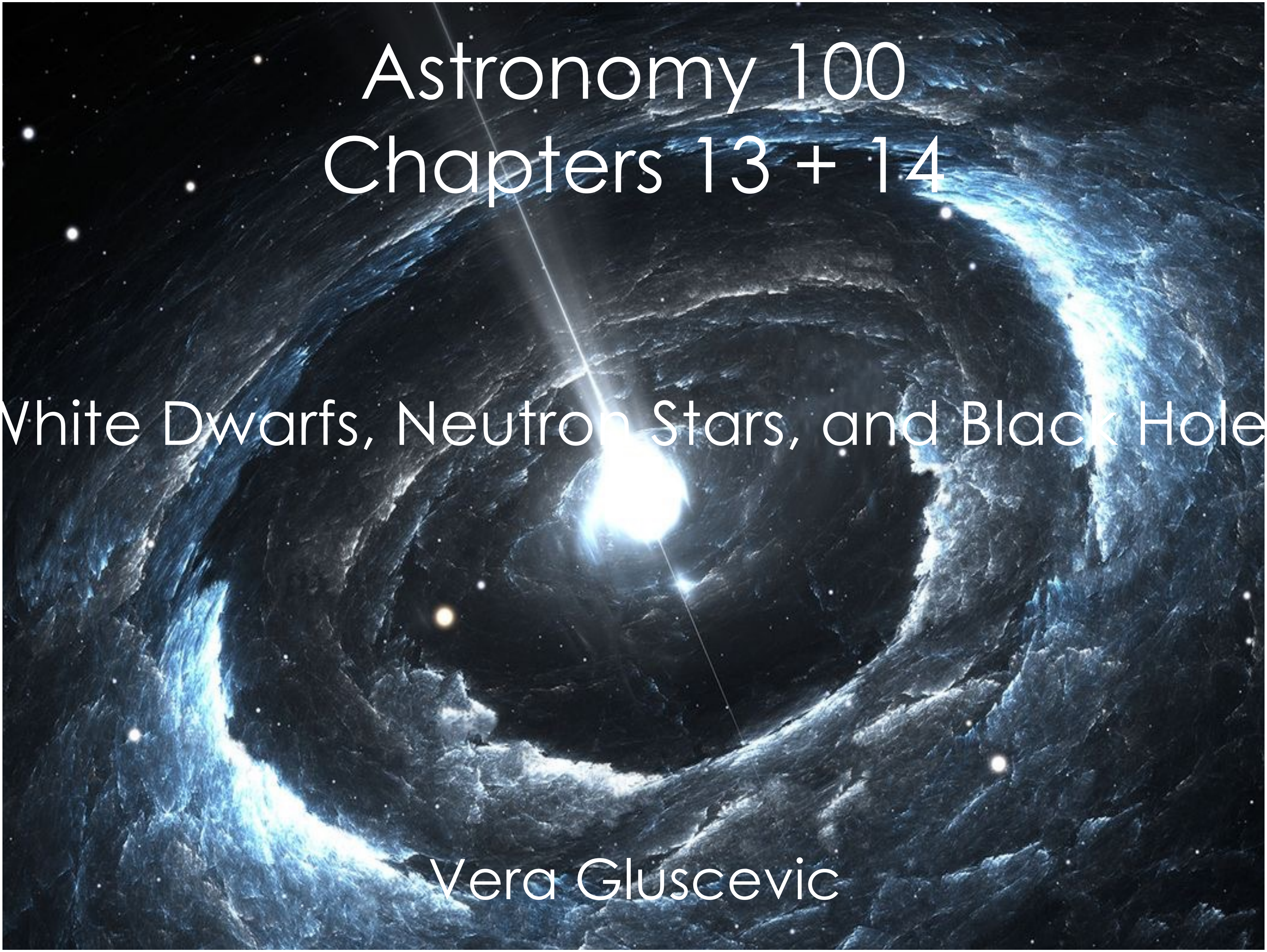


Astronomy 100
Chapters 13 + 14

White Dwarfs, Neutron Stars, and Black Hole

Vera Gluscevic

End of a low-mass star

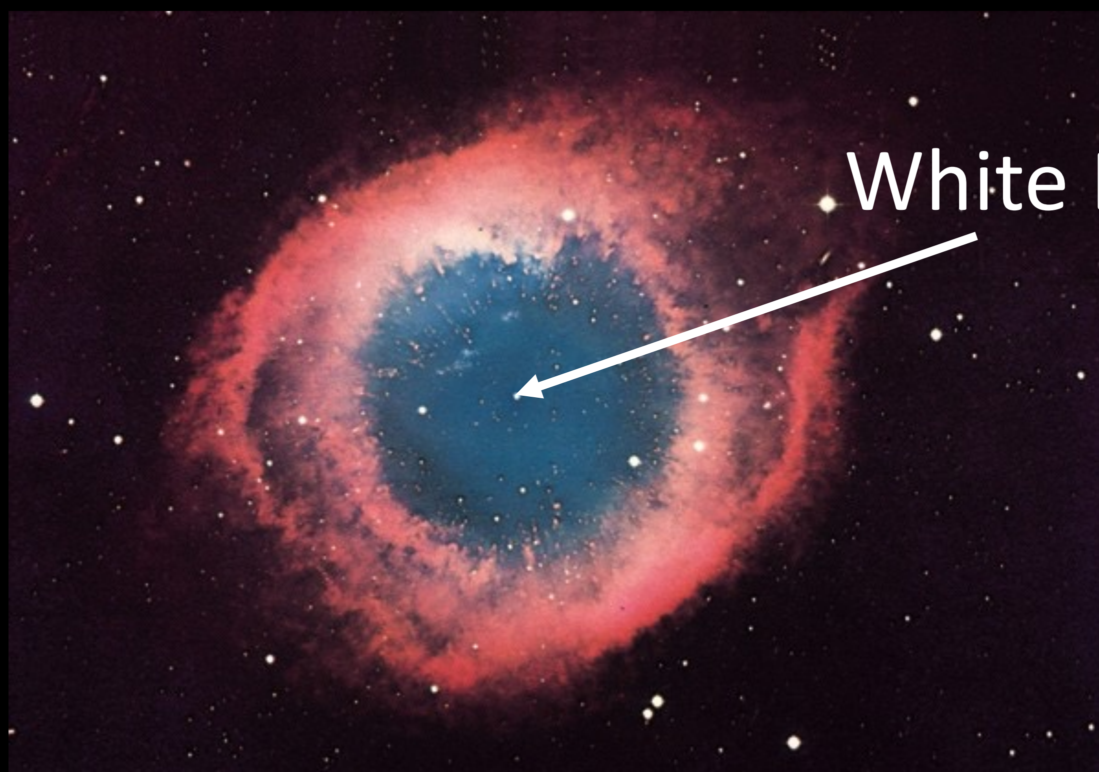
Low-mass stars ($< 8\ M_{\odot}$)

- The core runs out of fuel and shell fusion begins.
- Eventually, shell fusion crates too much outward pressure which explosively pushes out the outer layers of the star and produces a ***planetary nebula***.

Ring nebula.

Low-mass stars (< 8 $M_{\odot}$)

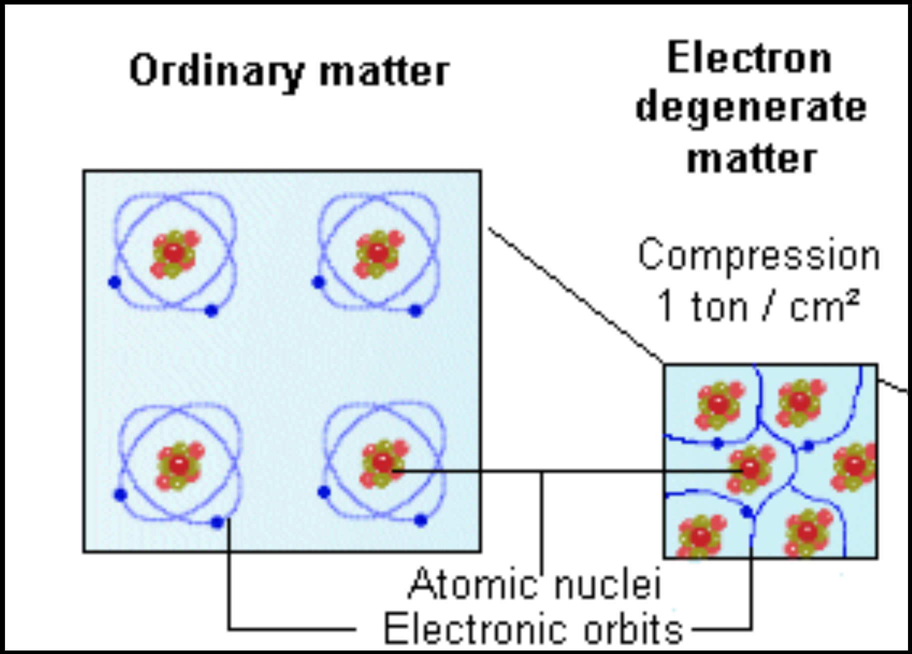
- **White dwarf** is the compressed core of a dead star.
- It ionizes the outer layer of the star, forming a glowing planetary nebula. Planetary nebula dissipates in ~100,000 years.

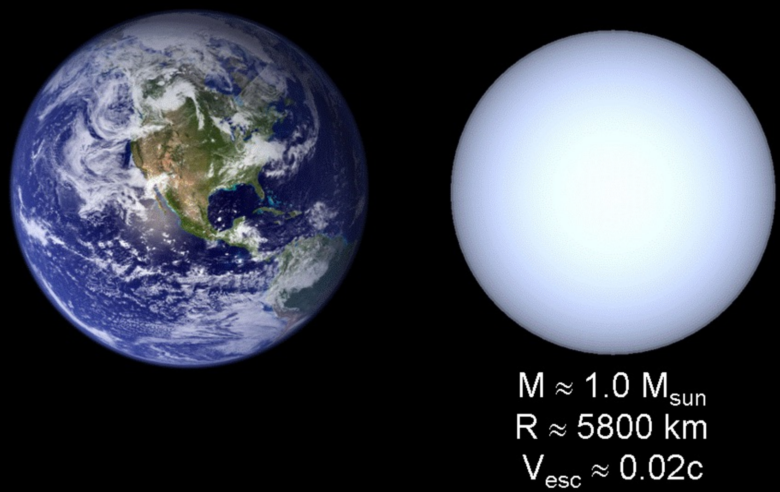


Ring nebula.

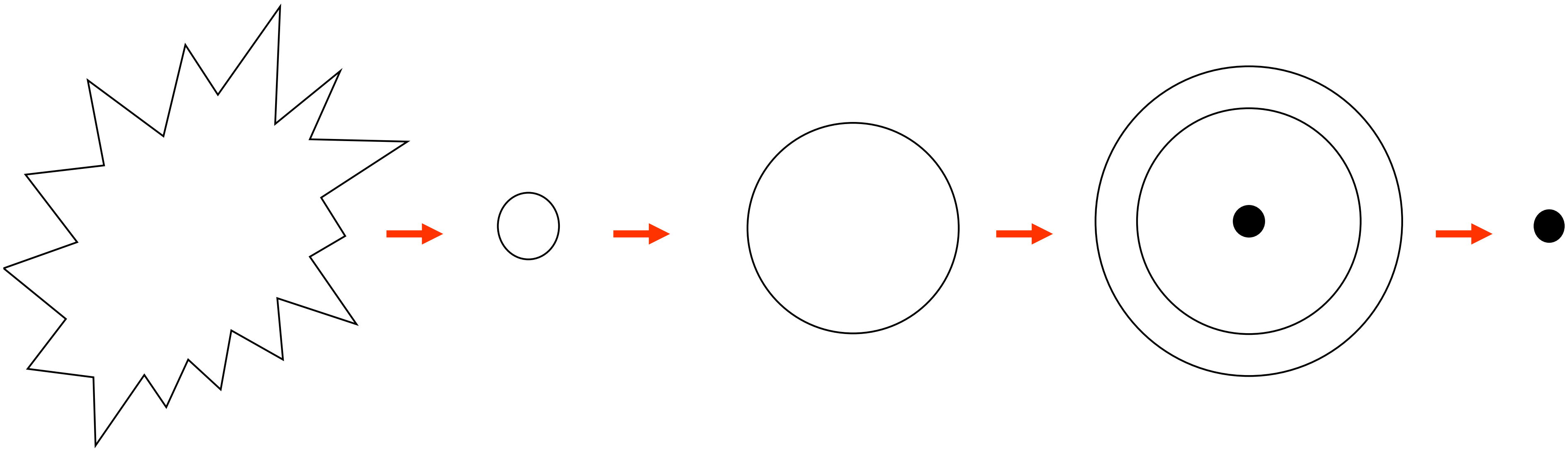
White Dwarfs

- White dwarfs are Earth-sized cores of small dead stars, **with less than 1.4 Msun**, composed of helium or carbon.
- **Electron degeneracy pressure** prevents the inward collapse of the white dwarf (also partially supports the cores of brown dwarfs).





Low mass stars (< 8 $M_\odot$)



Interstellar Cloud (gas and dust)

Main Sequence Star

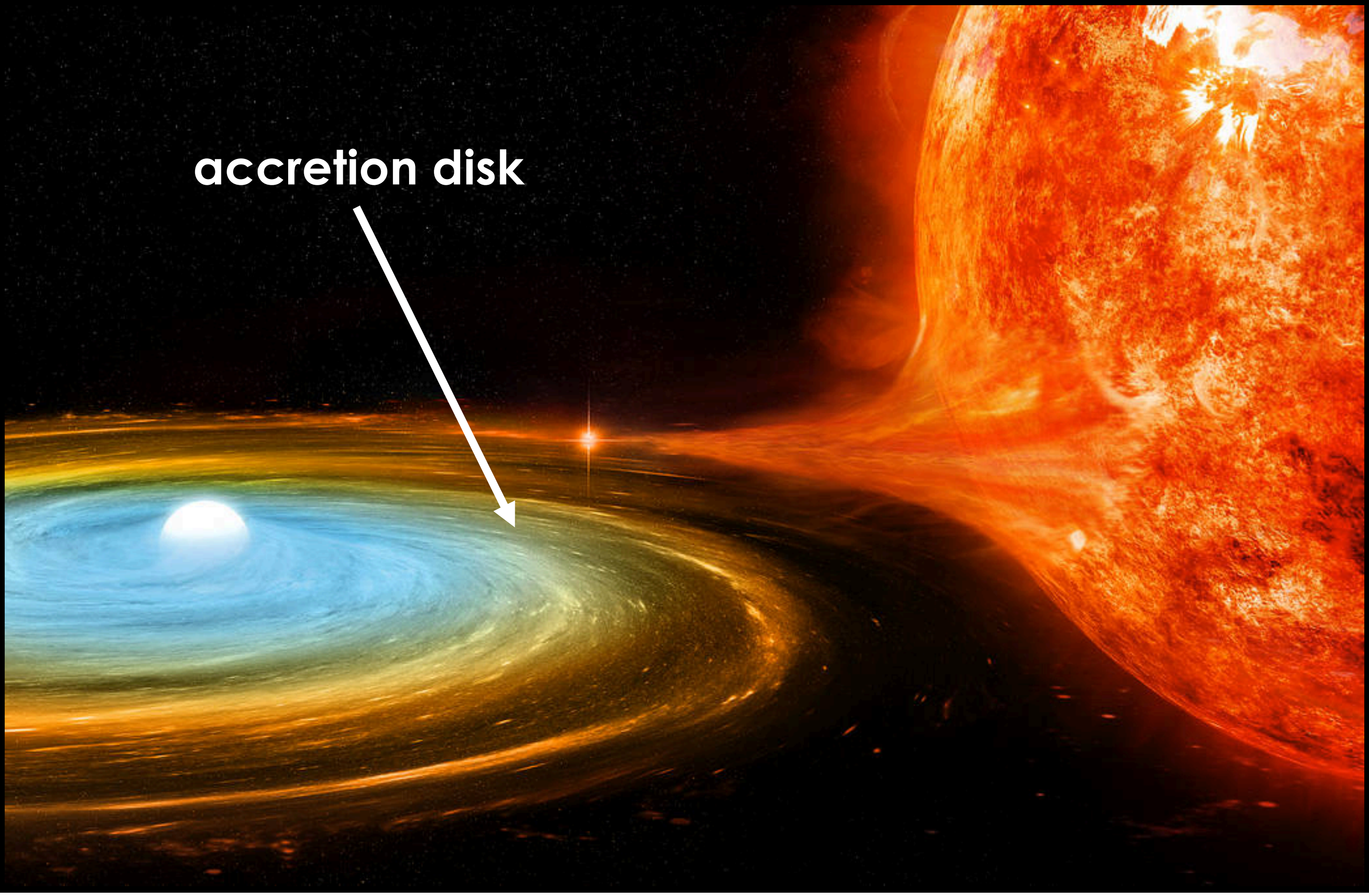
Red Giant

Planetary Nebula

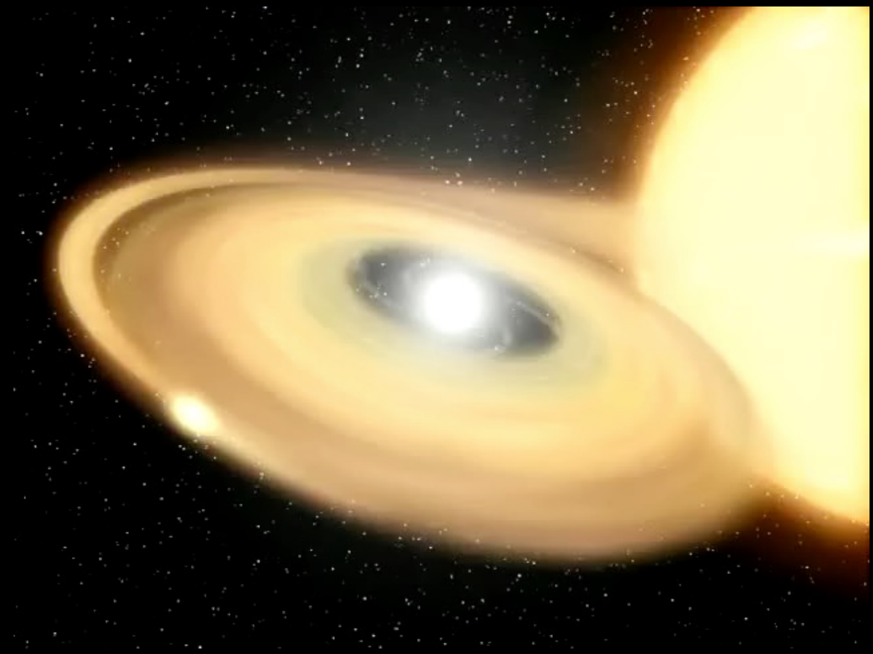
White Dwarf

Mass Transfer in Binary Systems

White dwarfs are not always left alone. Sometimes they can have a companion star! As its companion evolves and gets bigger, the white dwarf can steal mass from it. Their **Roche limits** are in contact and tidal forces pull on the other star.



Nova

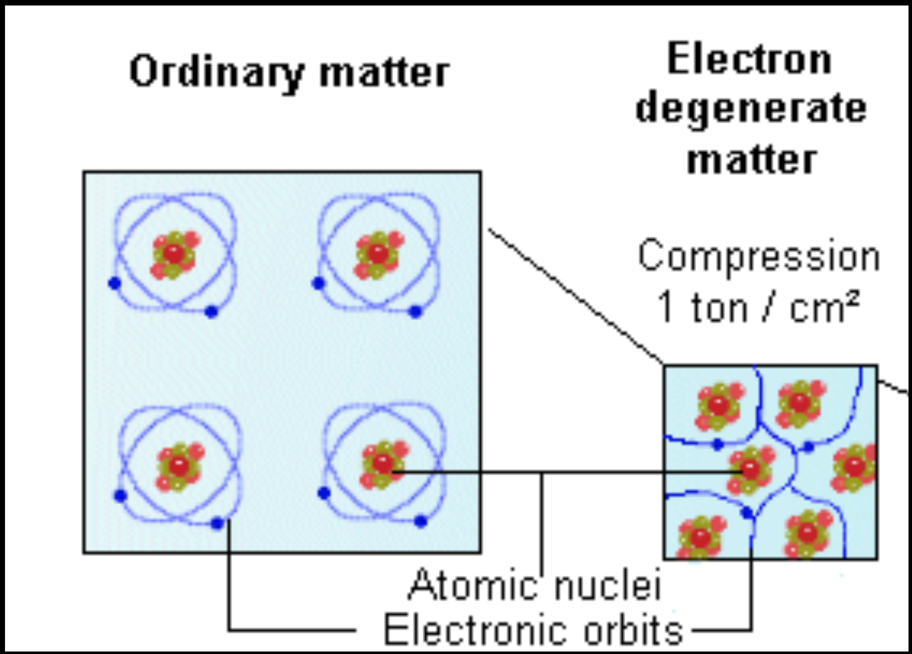


Explosions In The Z Camelopardalis System Movie

- A **nova** is a relatively gentle explosion of hydrogen gas on the surface of a white dwarf in a binary star system.
- It occurs in **contact binary** systems where a white dwarf is pulling mass from its companion.
- The material can reach high enough temperature to ignite fusion into helium.
- This process does not damage the white dwarf and it can repeat (every few years)

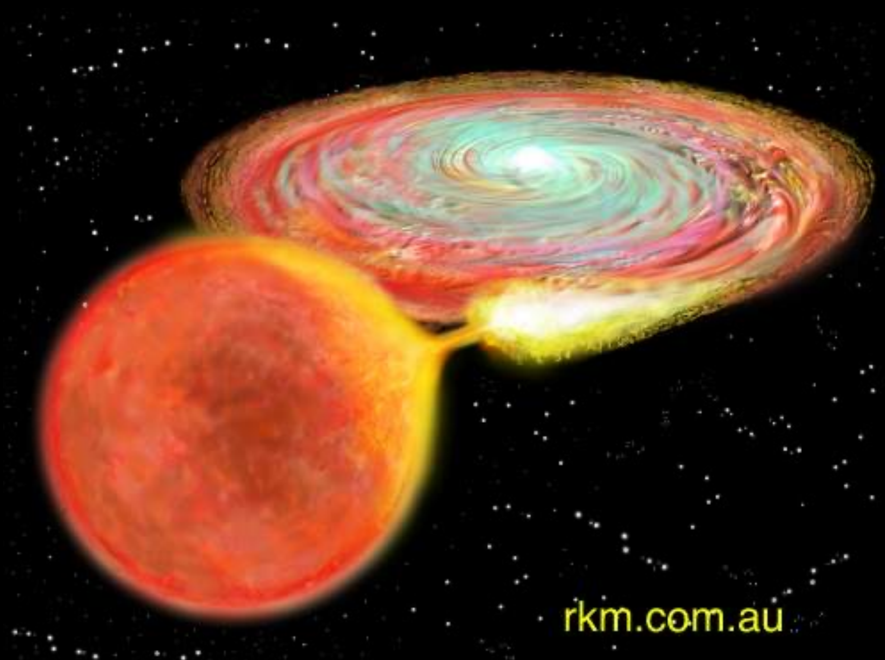
Maximum size for white dwarfs

- **Electron degeneracy pressure** prevents the inward collapse of the white dwarf and does <u>not</u> depend on temperature.
- Subrahmanyan Chandrasekhar established a maximum size for a star supported by degeneracy pressure: the **Chandrasekhar limit is 1.4 Msun.**



Type Ia Supernova Explosions

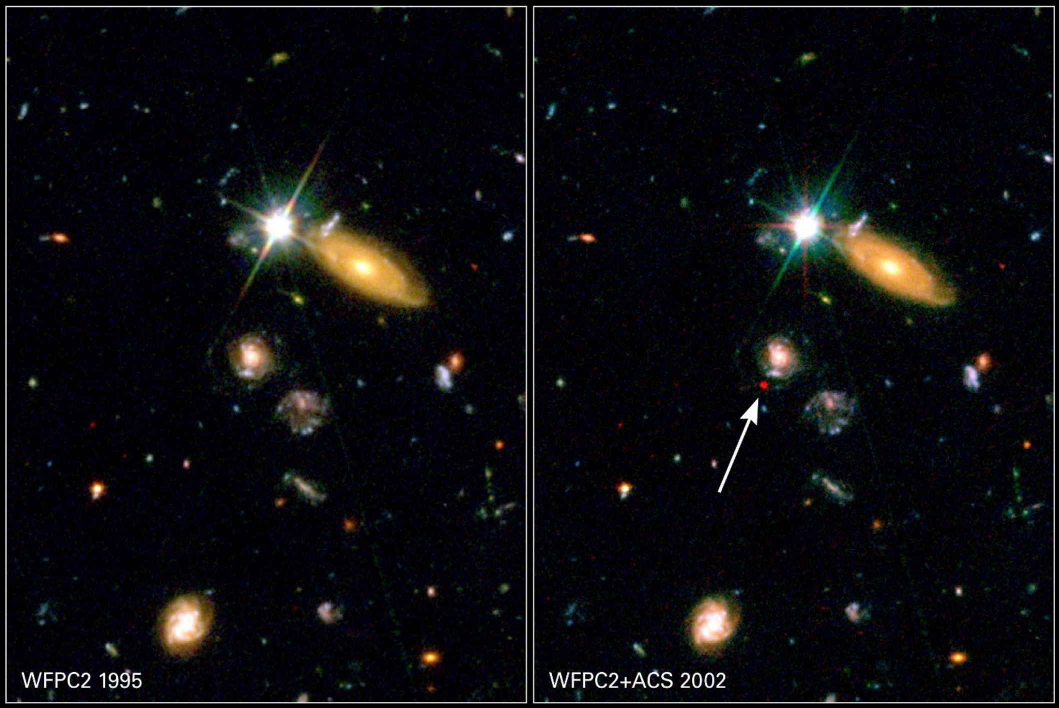
- When a white approaches the Chandrasekhar limit, it collapses because degeneracy pressure is overcome. This can happen either in contact binaries, or through 2 white dwarfs merging.
- The collapse heats the white dwarf, but the degeneracy pressure does not depend on the temperature so the star does NOT expand to reach balance again.
- **Runaway carbon fusion** is initiated in the entire white dwarf and it **unbinds** (explodes) the star.



www.eso.org

Type Ia Supernova Explosions

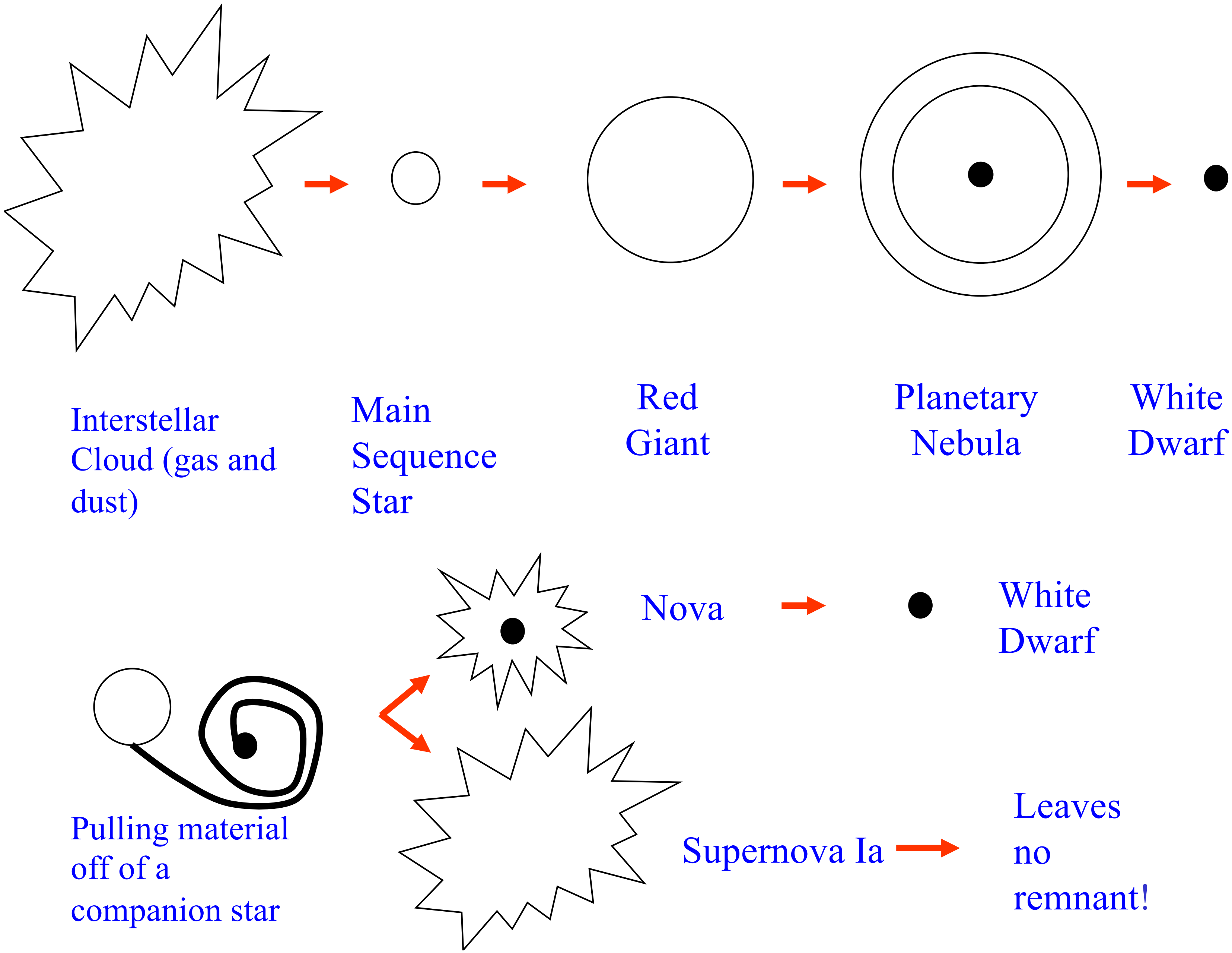
Type Ia supernovas have the same absolute magnitude of **–19.6**, and can be used to measure distances to distant galaxies (they are **standard candles**).



Supernova SN2002dd in the Hubble Deep Field
Hubble Space Telescope ▪ WFPC2 ▪ ACS

NASA and J. Blakeslee (Johns Hopkins University) ▪ STScI-PRC03-12

Low mass stars ($< 8\ M_{\odot}$)



question for you

Our Sun will end its life as an object called

A. Red giant
B. Nova
C. White dwarf
D. None of the above

question for you

Our Sun will end its life as an object called

A. Red giant
B. Nova
C. White dwarf
D. None of the above

Since the Sun has a mass less than 8 $M_\odot$ and since it is alone without a companion, it will become a White Dwarf and then slowly cool into a **Black Dwarf**

End of a high-mass star

High-mass stars (> 8 $M_\odot$)

- The core and outer layers run out of fuel.
- The star collapses due to gravity.
- The mass is high enough that nothing can balance the gravitational collapse.

- An implosion and rebound of outer layers against the compact core creates an expolsion, sending out a shockwave. This is a **Type II Supernova**!
- During the Supernova, elements heavier than Fe are crated from fusion events (magnesium, lead, gold, and everything else).

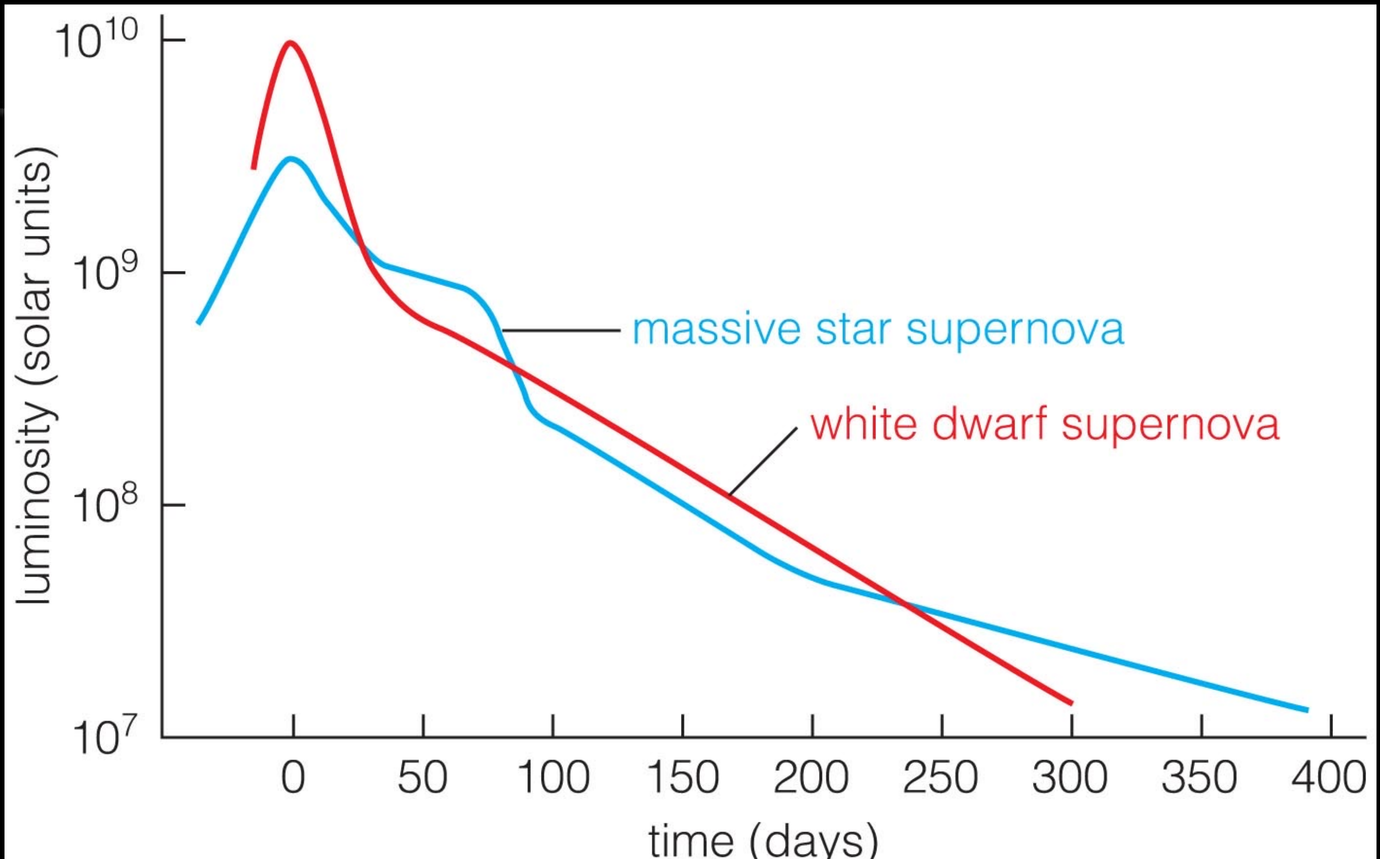
Type II Supernova

Kepler space telescope captured brilliant "shock breakout" flash of supernova 1.2 billion ly away, animated here.

Animation- The Early Flash of an Exploding Star, Caught by Kepler Movie

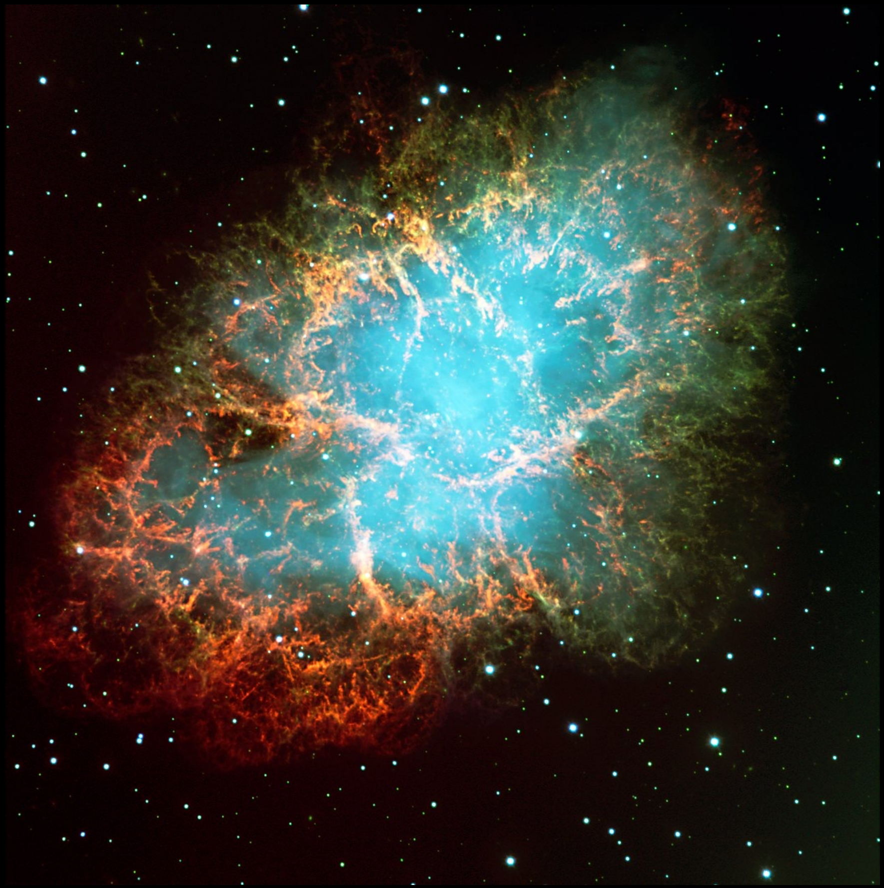
Light curves of supernovae

Initial brightness of supernova is **a few billion Suns**, as bright as the entire Milky Way! Then it slowly fades away.



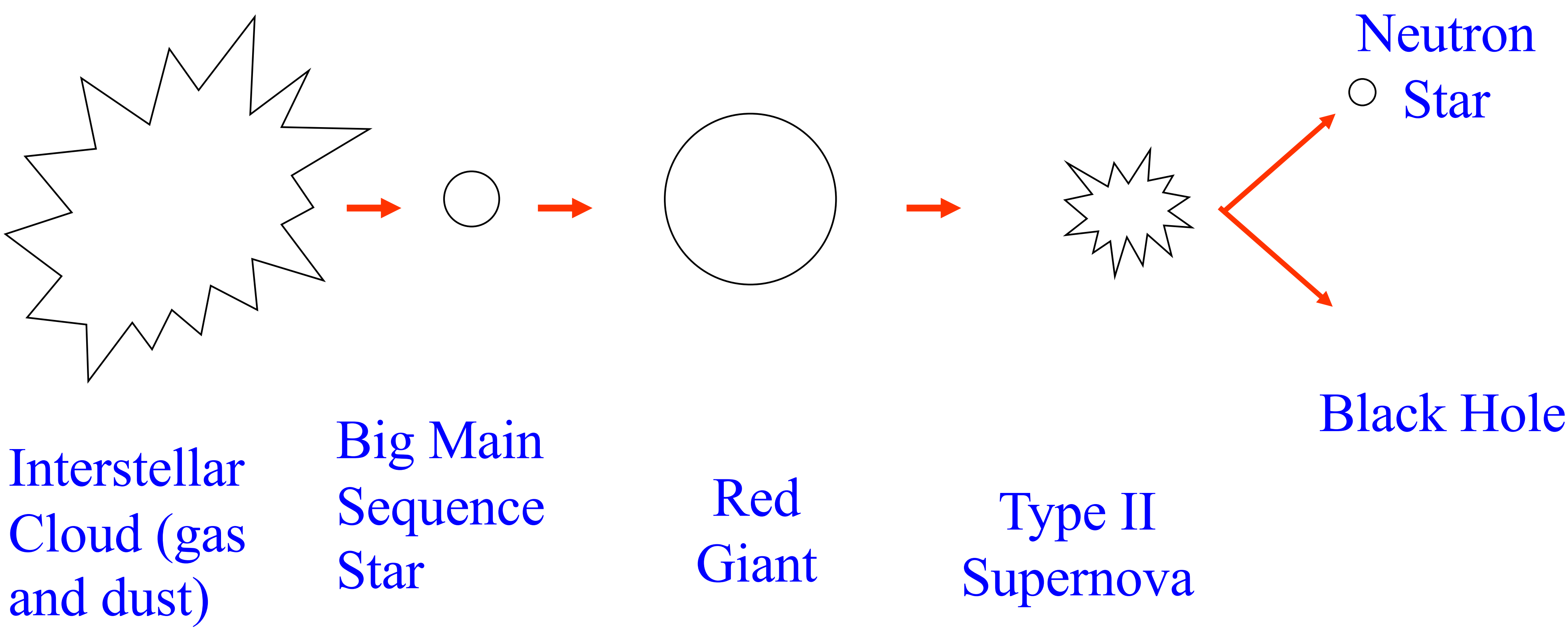
Supernova Remnants

What's left behind? Emission nebulae enshrouding either a neutron star or a black hole.



Crab nebula

High-Mass Stars (> 8 $M_\odot$)



question for you

Which is more common in our galaxy: a planetary nebula forms, or a Type II supernova explosion occurs?

A. Both occur at the same rate.
B. Planetary nebula formation.
C. Supernova explosion.
D. It’s not possible to say.

question for you

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The Star-Gas-Star Cycle

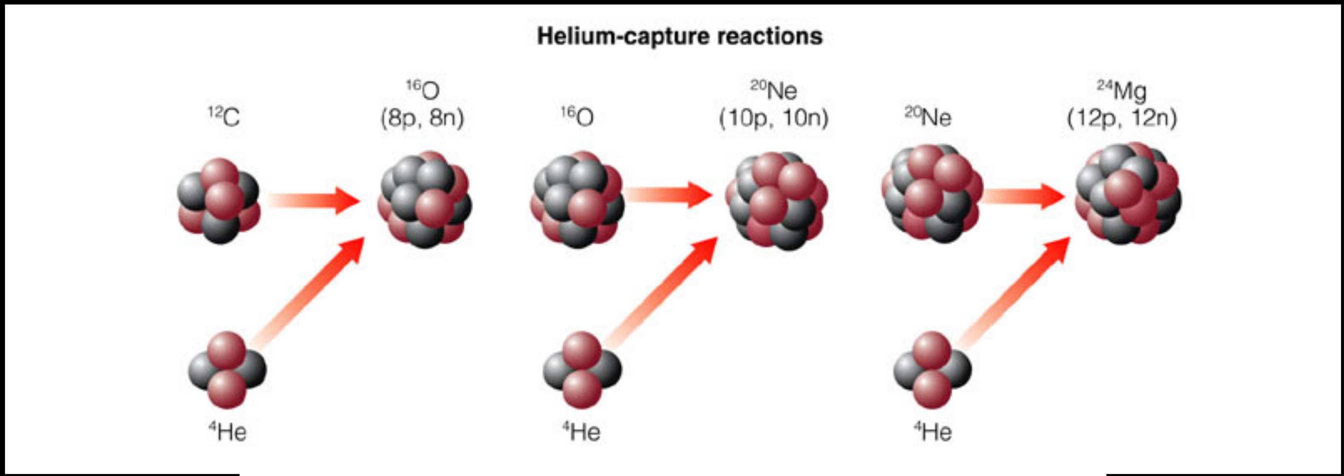
1. The interstellar medium (ISM, gas and dust between stars, provides the matter from which **stars form.**
2. Stars evolve and create "heavy" elements (metals) through **stellar nucleosynthesis and supernovae**.
3. These elements are returned to the ISM through stellar winds, planetary nebula, and supernovae (not all material is returned resulting in the gas being "**used up**")
4. The **enriched** gas is used by the next generation of stars.
5. Currently, **2% by mass** of heavier elements in the ISM.
6. In the Milky Way, gas is converted to stars at a rate of a **few solar masses per year.**

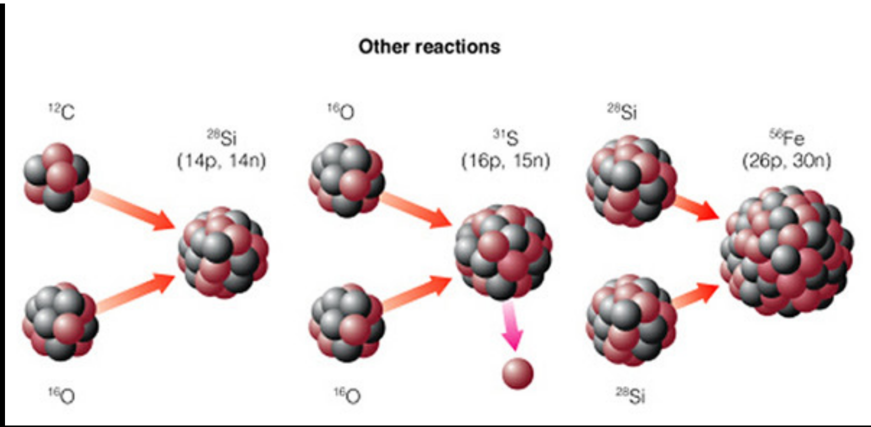
7. **The Universe is past its prime in terms of star formation (peak was 10 Gy ago)!**

We are stardust.

We are "Star Dust"

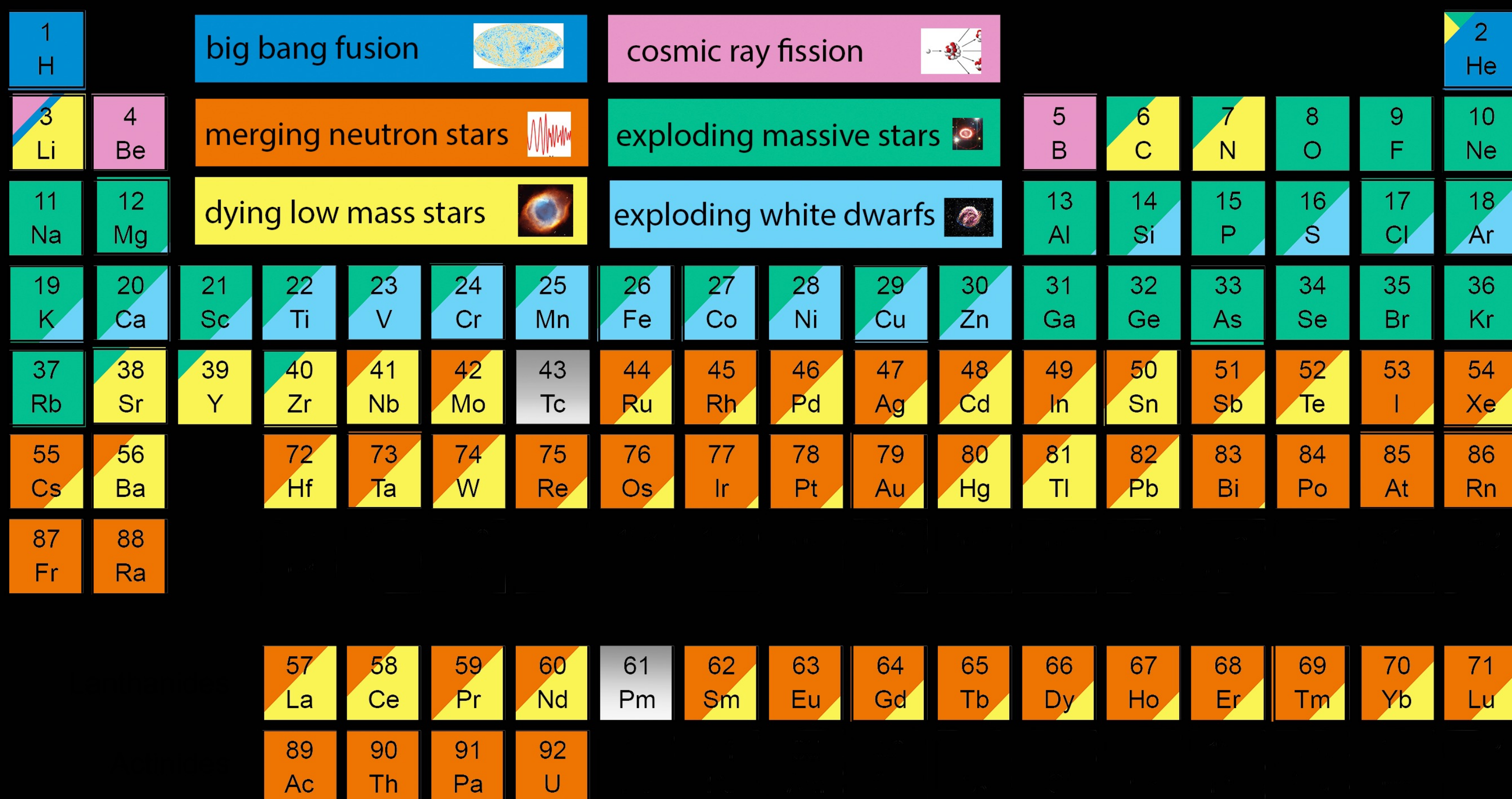
- Carbon fusion ignites at 600 million K.
- Helium capture reactions also begin, producing oxygen, neon, magnesium.
- Oxygen fusion ignites at 1 billion K.
- Other reactions create silicon (C+O), sulfur (O+O), Iron (Si+Si).





We are "Star Dust"

- Hydrogen (75%) and helium (25%) created with the Big Bang. All other elements created inside stars.

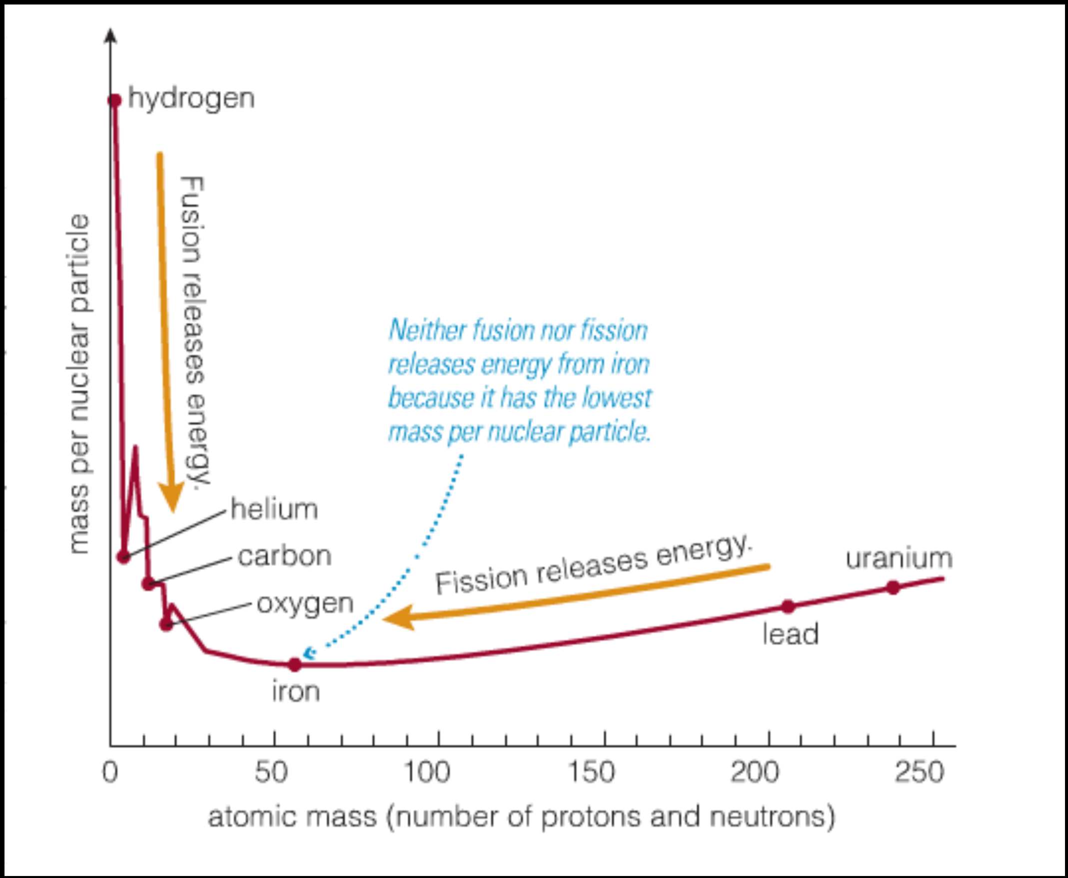


Astronomical Image Credits: ESA/NASA/AASNova

Graphic created by Jennifer Johnson

Why is Iron no good for star fuel?

- Fusion of elements lighter than iron generates energy, while fusion of elements heavier than iron requires the input of energy.
- Nuclear fission of elements heavier than iron liberates energy.
- **Iron** is the death of a high mass star: **it cannot be fused**.



What happens after a supernova?

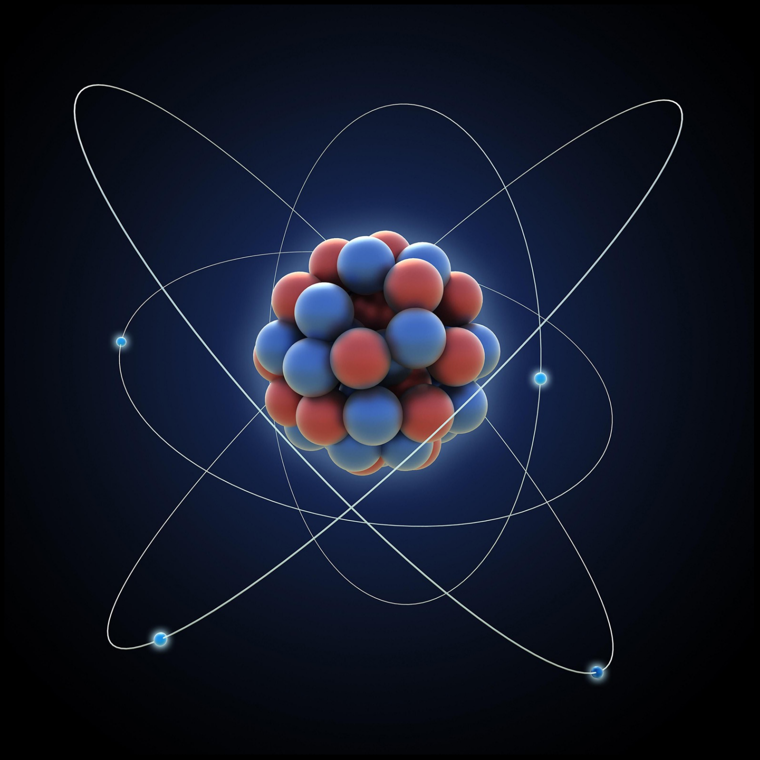
Depends on the mass of the remnant!

- **neutron star**
  - remaining mass of 1.4 - 3 $M_{\odot}$
- **black hole**
  - remaining mass greater than ~3 $M_{\odot}$

Neutron stars

Birth of a neutron star

- When iron core forms in a massive star, it collapses inward in fraction of a second
- Pressure of the hot gas and electron degeneracy pressure are insufficient to stop the collapse.
- Electrons and protons are compressed together to form neutrons.



Neutron stars

- A star made entirely of neutrons is a **neutron star**.
- **Neutron degeneracy pressure** stops further collapse.
- Size ~20 km across; density is equivalent to the mass of the entire human population compressed to the size of a sugar cube.

Manhattan
(spaceimaging.com)

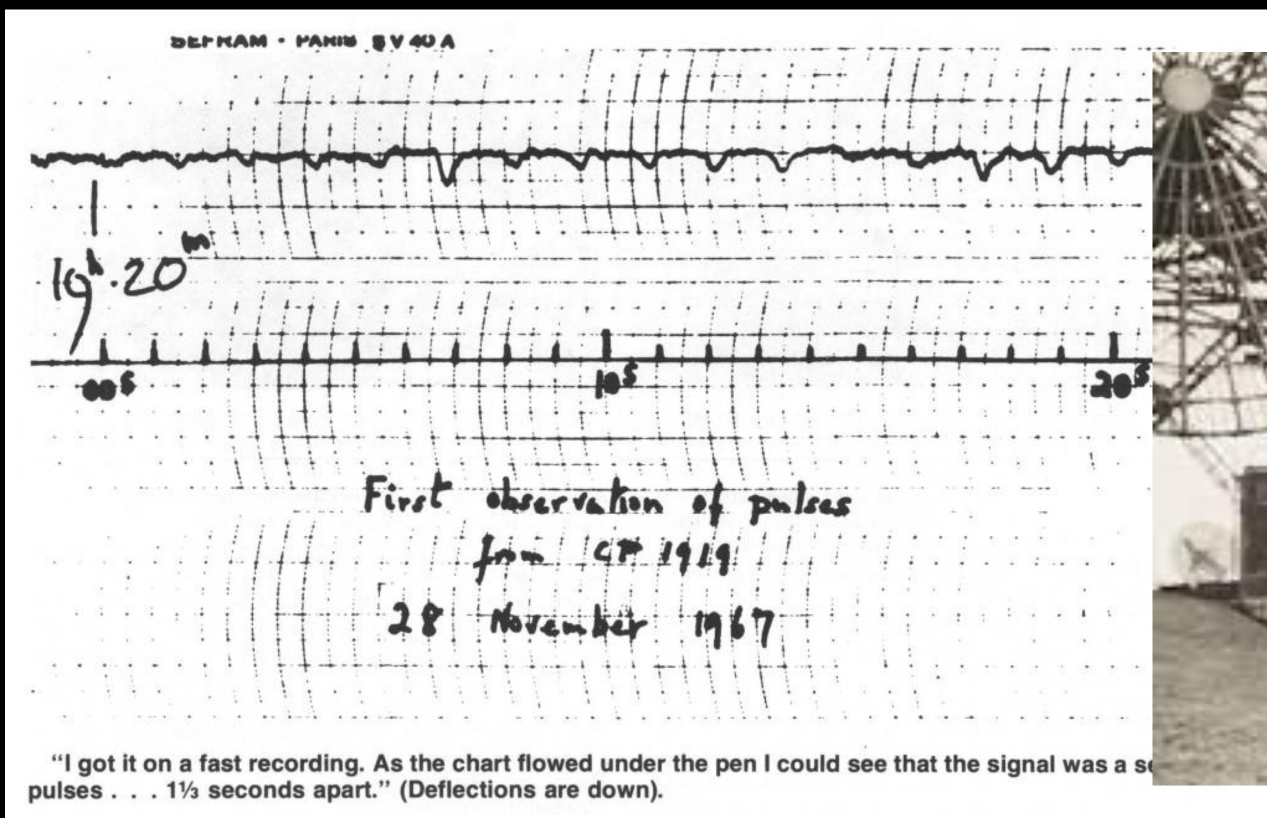
$M = 1.5\ M_{sun}$
$R \approx 10$ km
$V_{esc} \approx 0.7c$

Neutron stars

Since the escape velocity is a significant fraction of speed of light, we can “see” more than half of the neutron star!

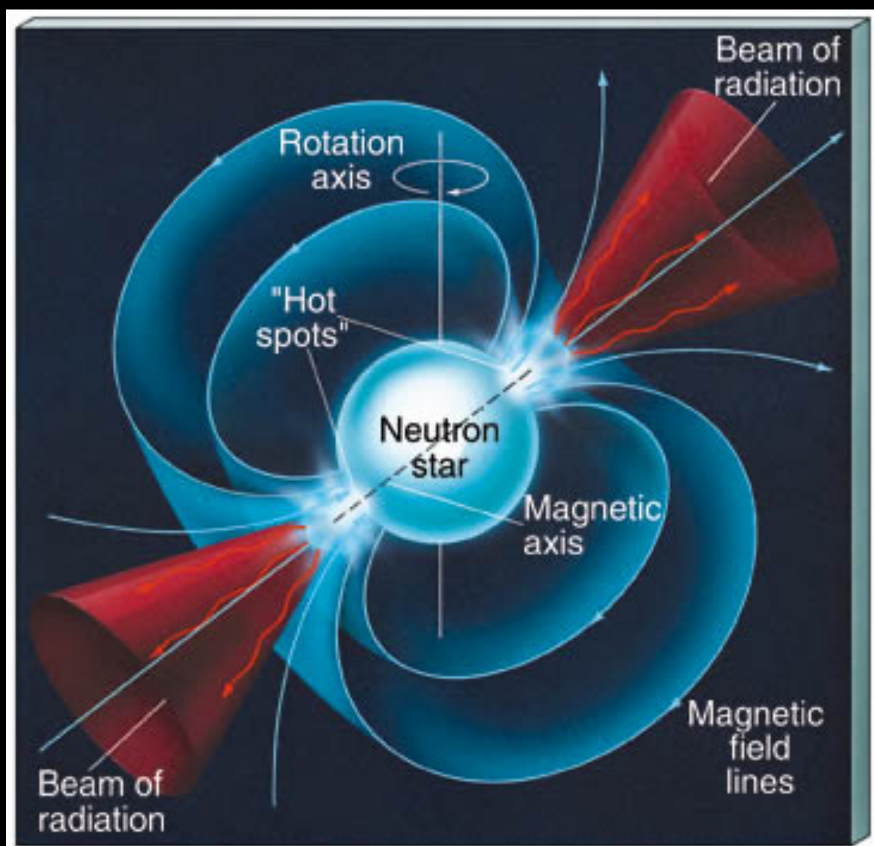
Discovery of pulsars

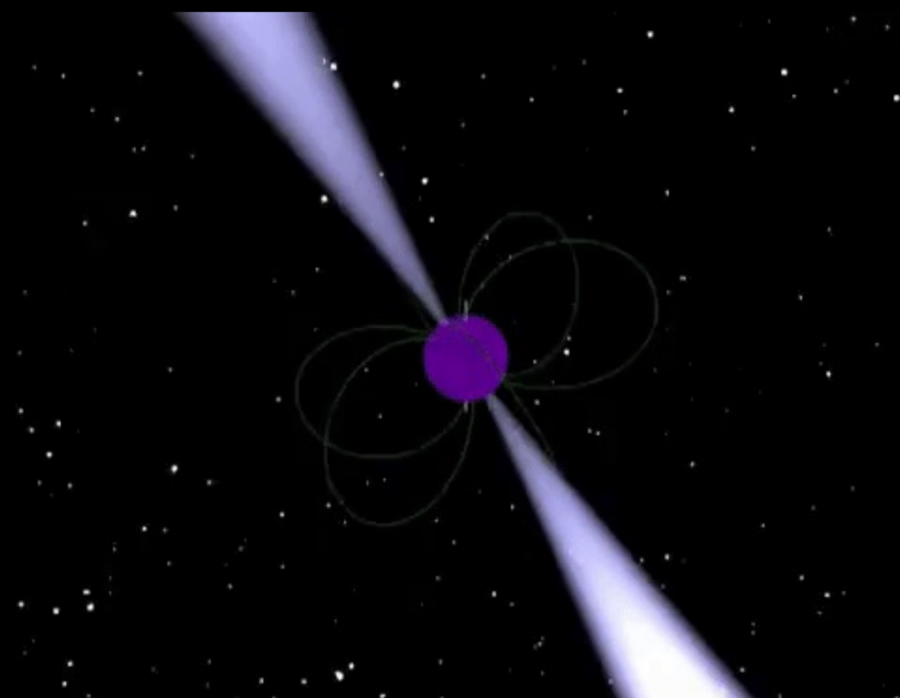
- Postulated to exist a year after a neutron star was first discovered.
- 1967: first pulsar discovered by Jocelyn Bell.
- Pulsars = highly magnetized rotating neutron star that emits beams of electromagnetic radiation out of its magnetic poles.



Pulsars

- Pulsar rotates very rapidly.
- Enormous magnetic field is created during the collapse.
- Particles are streaming out of its polar regios, sending out jets of radiation, which rotate like a lighthouse





Almost like...

What if a neutron star is too big??

While this limit is not as certain as the Chandrasekhar limit, we know that if the mass of a neutron star is more than 1.5 - 3.0 M_{SUN}, (corresponding to an original star's mass of 15 – 20 M_{SUN}) not even the neutron degeneracy pressure can halt the inward collapse of the core...

Black holes

Black holes are massive compact objects that even light cannot escape from.

THE ANATOMY OF A BLACK HOLE

Event horizon is the distance from its center where the escape velocity is equal the speed of light.

Accretion disk

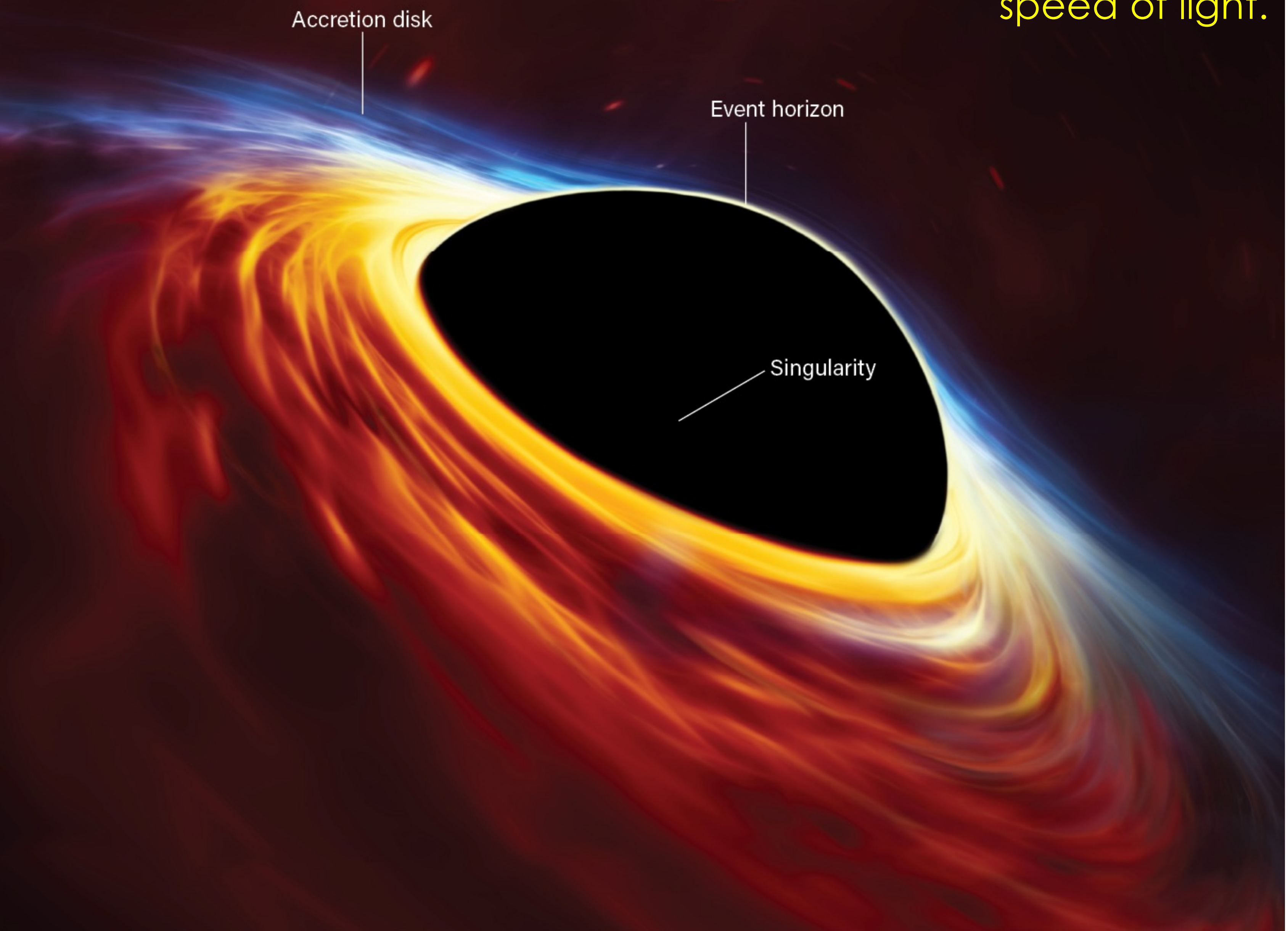
Any material torn apart by the black hole circles these monsters like water swirling down a drain. A buildup of friction between the material causes it to glow, revealing the location of the black hole.

Event horizon

The so-called point of no return around a black hole. This shadow is the point inside of which nothing, not even light, can escape the gravitational pull of the black hole.

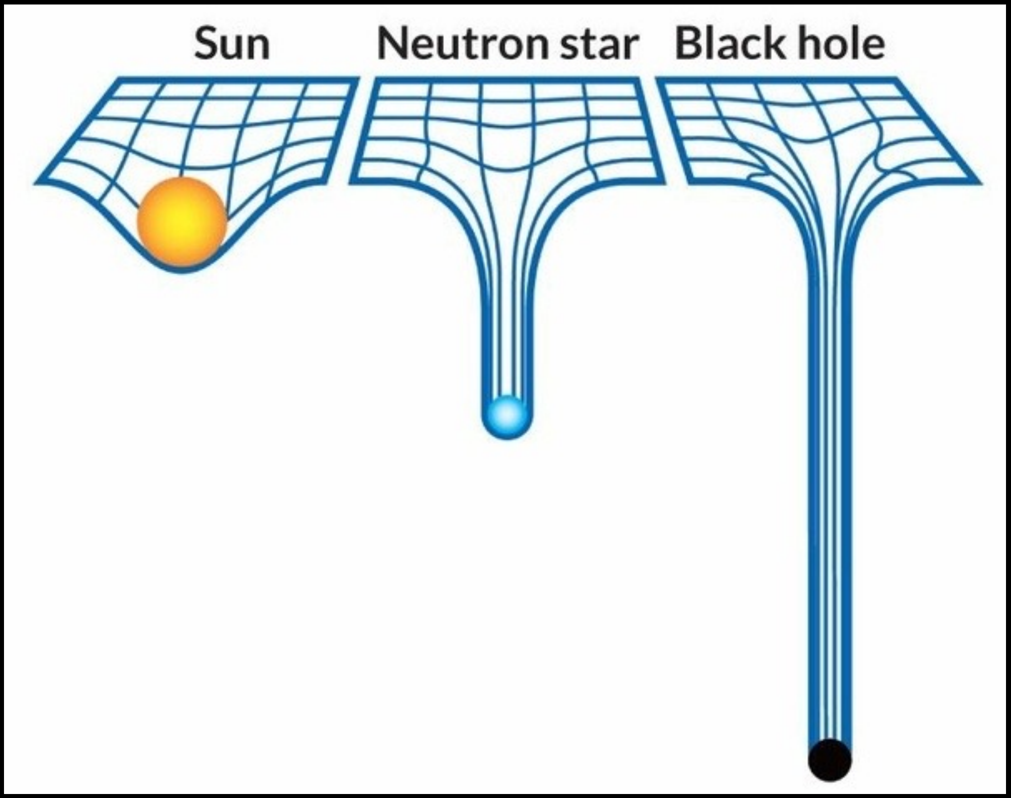
Singularity

The very center of a black hole, where general relativity breaks down and gravity becomes infinite. ESO, ESA/HUBBLE, M. KORNMESSER



Black Holes

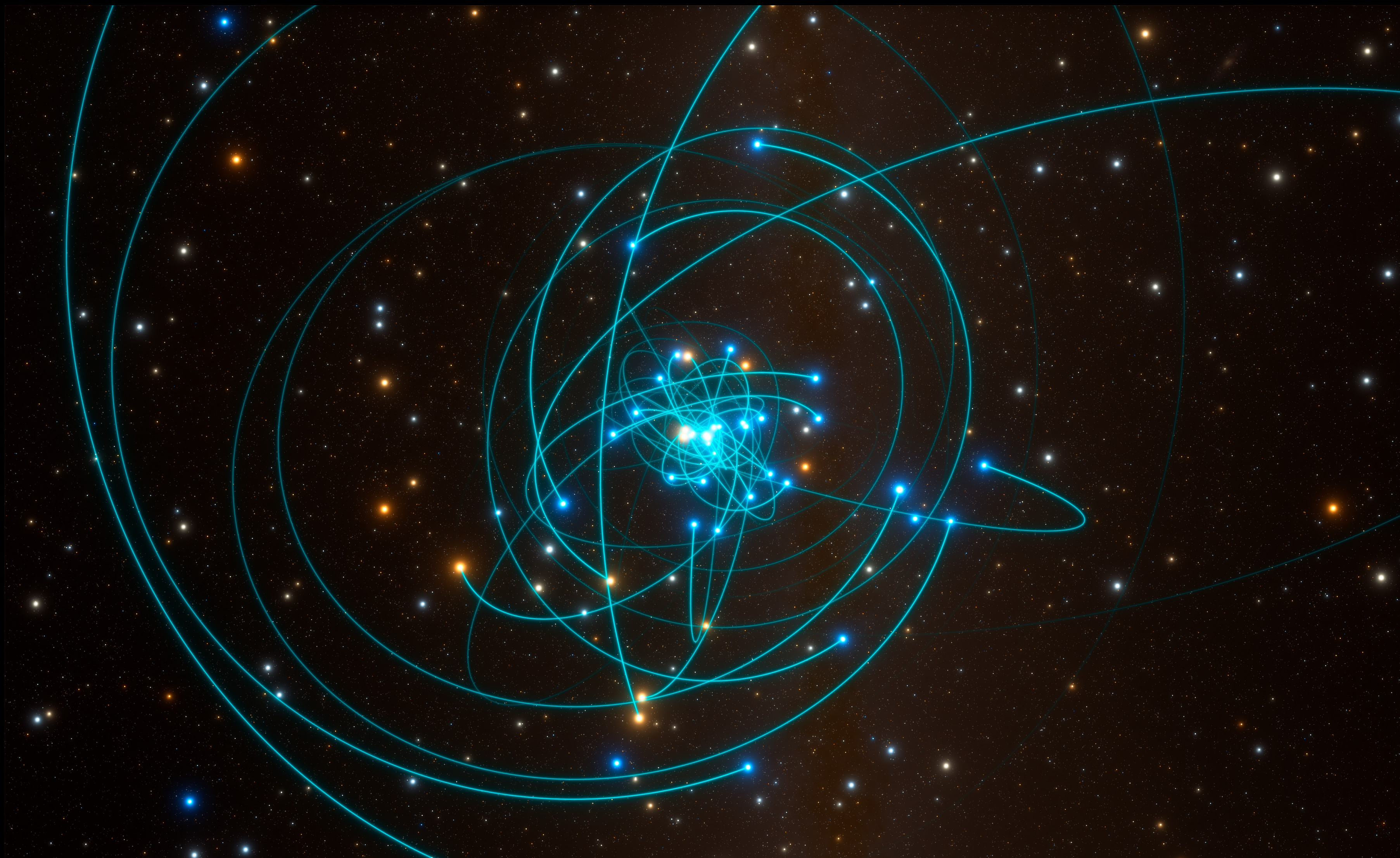
- Black holes are massive compact objects that even light cannot escape from.
- Some black holes originate from stars, some are formed at centers of galaxies, when galaxies first assemble. They are supermassive black holes, billions of solar masses.



What would a black hole in a complete vacuum look like?

Detecting Black Holes

... or by observing how they exert gravity on objects around them.



Detecting Black Holes

... or by gravitational lensing of the light passing by them.

Detecting Black Holes

Black holes are often detected indirectly, via their interaction with nearby matter, often through **accretion disks.**

Event Horizon Telescope (2019):
Imaging the shadow of the <u>supermassive</u> black hole at a heart of a galaxy.

Scientists have obtained the first image of a black hole, using Event Horizon Telescope observations of the center of the galaxy M87. The image shows a bright ring formed as light bends in the intense gravity around a black hole that is 6.5 billion times more massive than the Sun. This long-sought image provides the strongest evidence to date for the existence of supermassive black holes and opens a new window onto the study of black holes, their event horizons, and gravity. Credit: Event Horizon Telescope Collaboration

Black hole shadow, like in "Interstellar"…

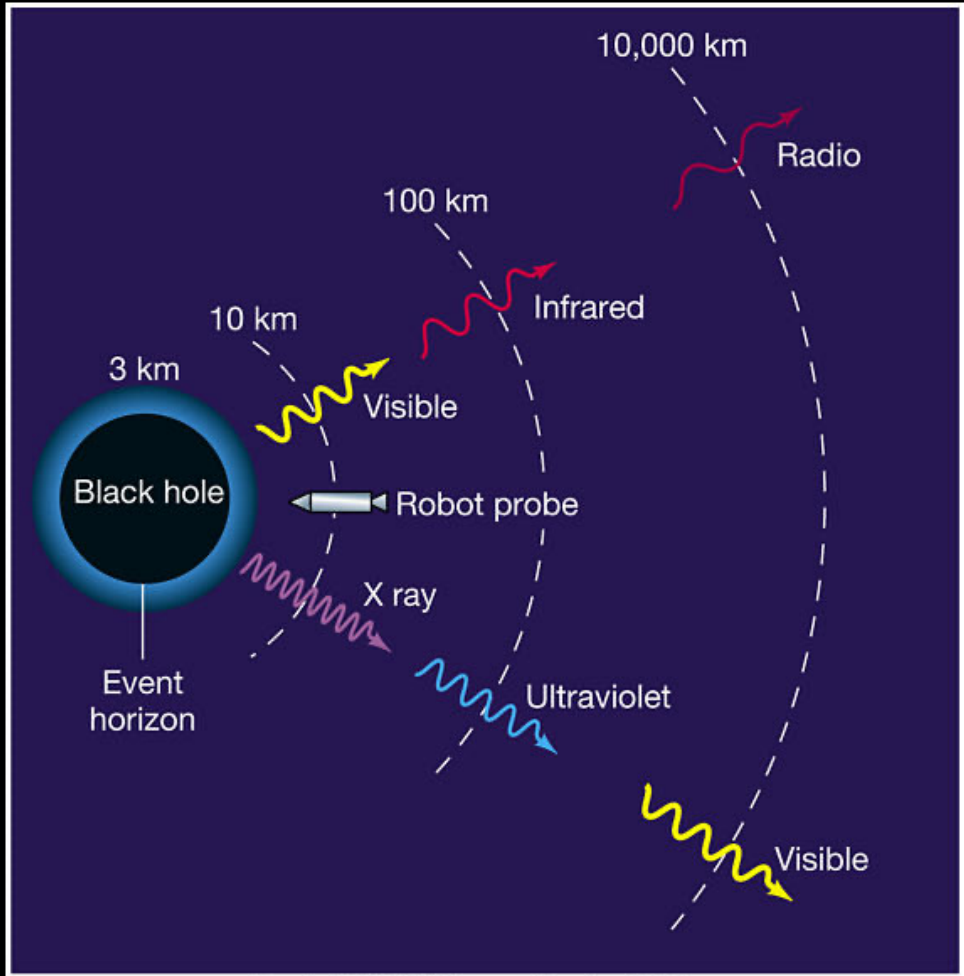
The Gargantua black hole from Interstellar. Credit: Double Negative

Neutron Stars and Black Holes

Neutron Star Formation Black Hole Formation Movie

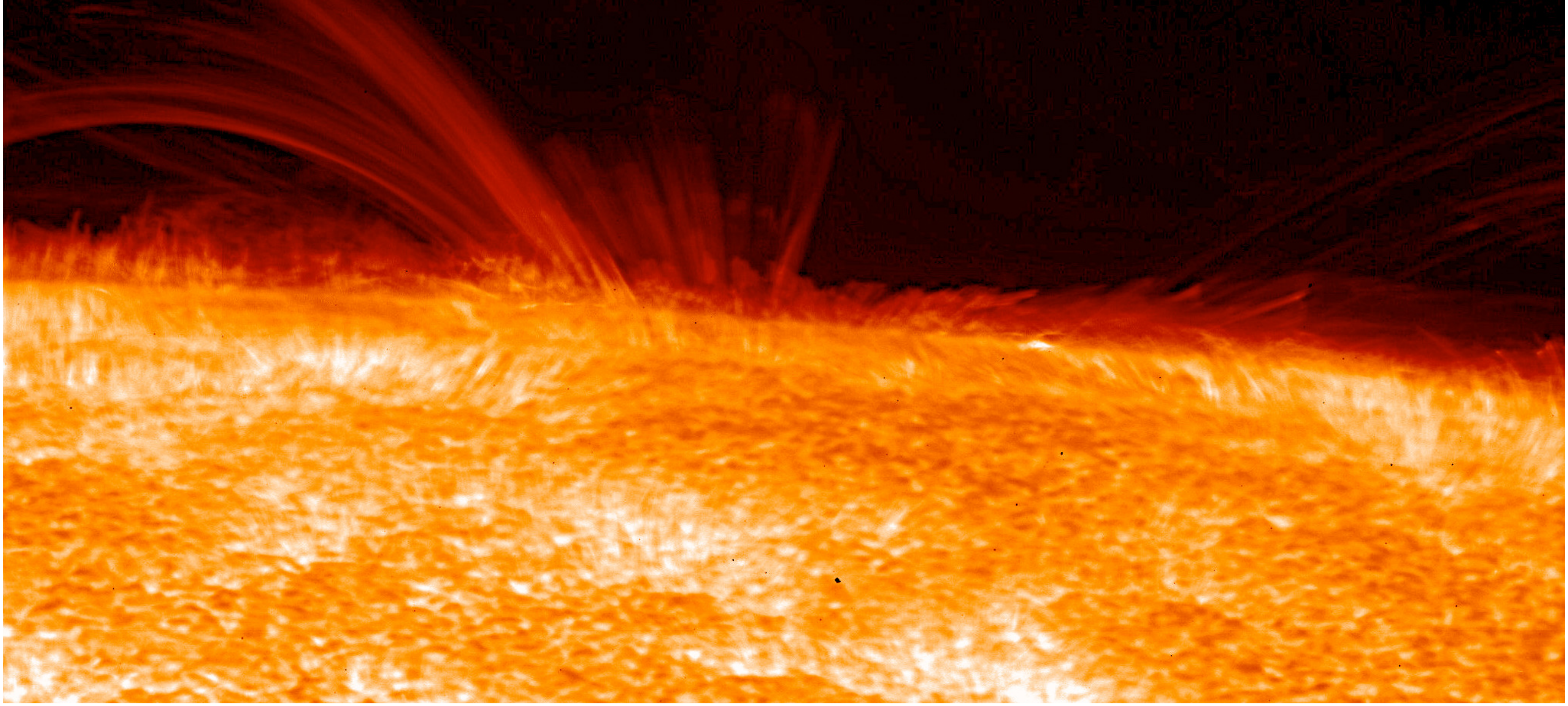
Gravitational Redshift

- Energy is required to escape the gravitational field of a massive object.
- As photons of light move away from a black hole, they lose energy. Energy and wavelength are related, and less energy means a "redder" light.



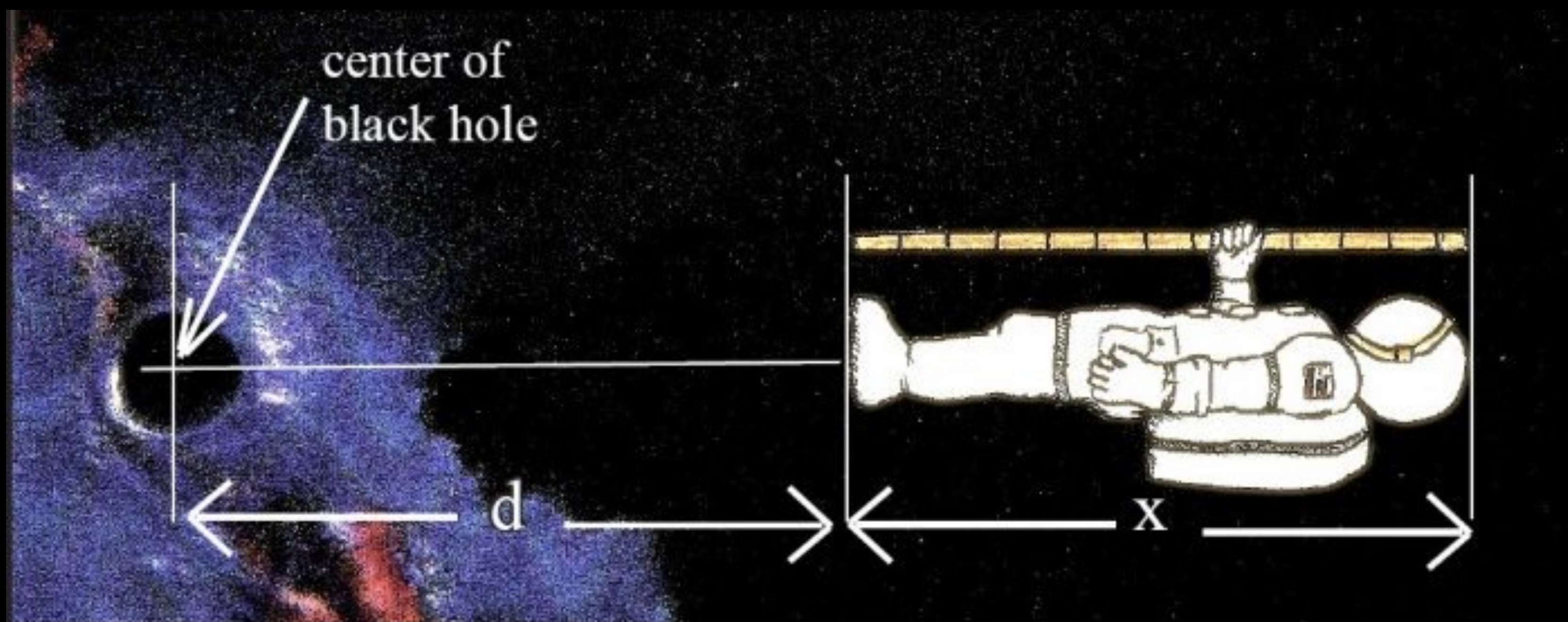
Gravitational Time Dilation

- According to general relativity, clocks run slower as gravity increases.
- A clock near the surface of the Sun would run about a minute slower per year than the same clock on the surface of the Earth.



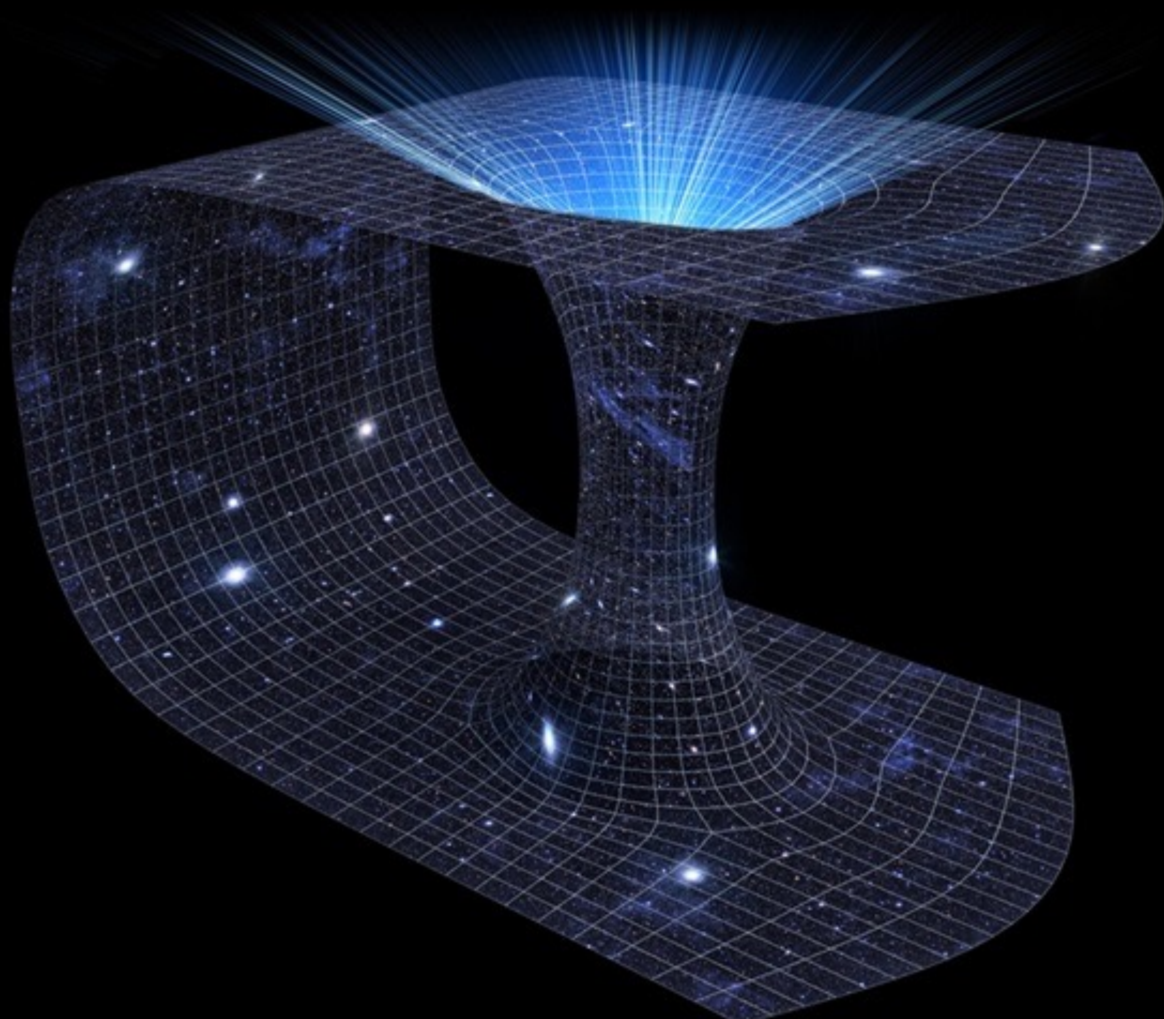
Falling toward a black hole…

- Tidal forces immense as event horizon is neared: spaghettification!
- …but not if it's a supermassive black hole.

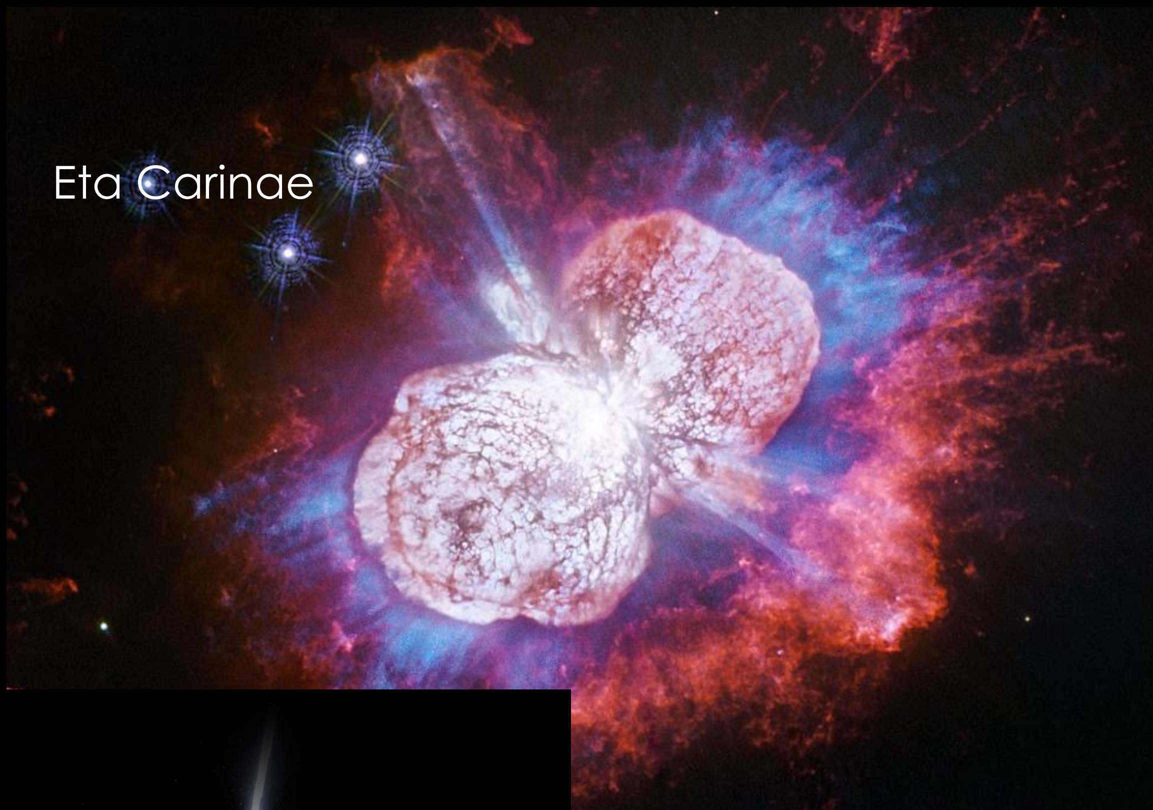


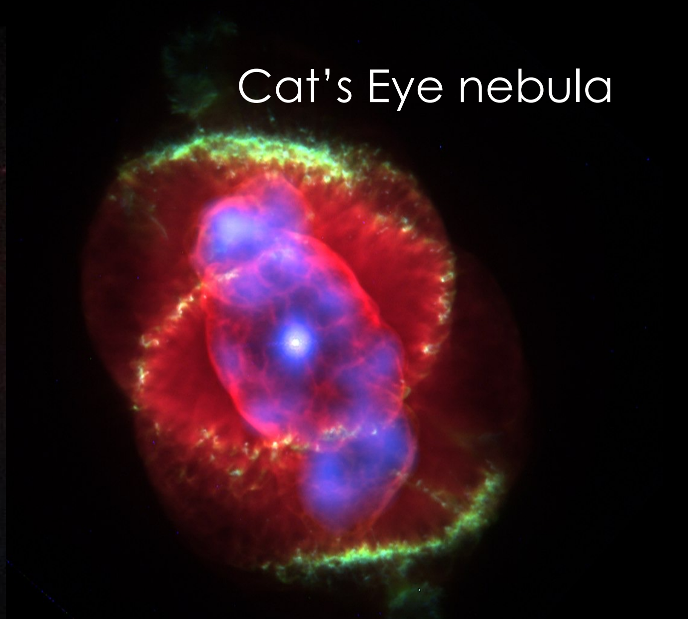
If someone magically turned the Sun with a black hole of the same mass in an instant, what would happen to the Earth’s orbit?

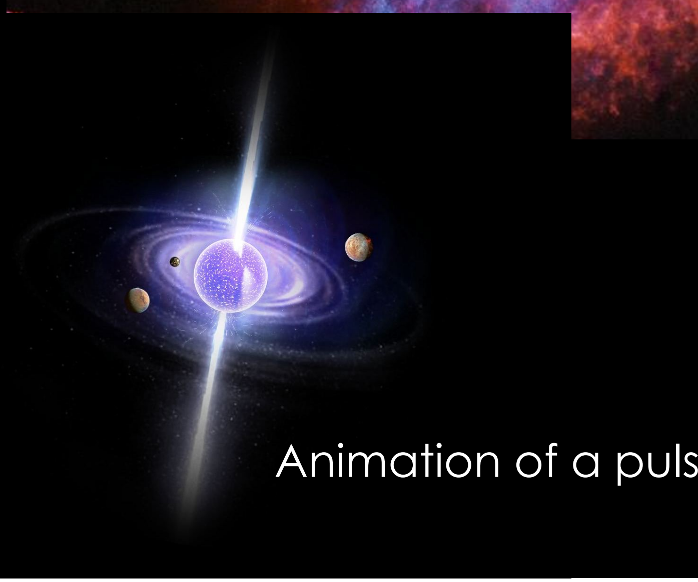
Bonus: What about wormholes?



Summary: Where does it all come from?



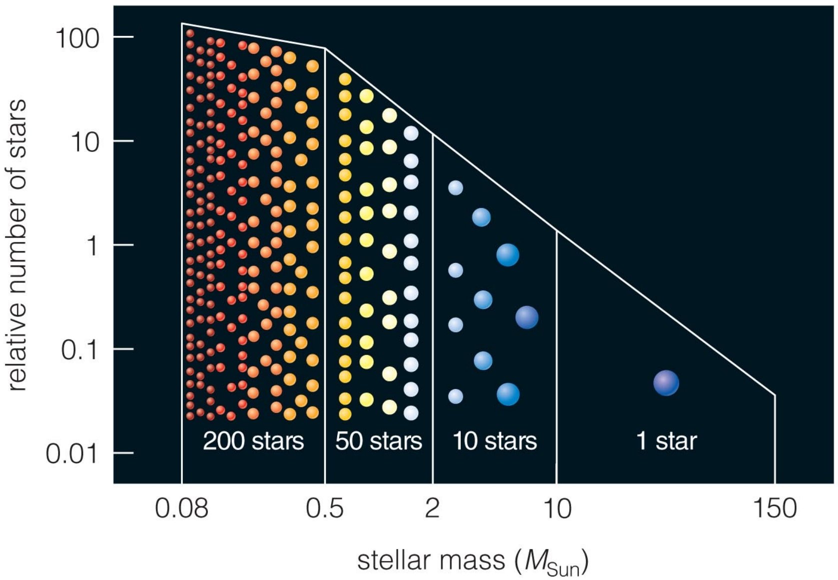




question for you

If I start with ~260 stars born in the same cluster, how many neutron stars will I likely have in the end?
Use the graph.

A. More than 60.
B. More than 10, less than 60.
C. Exactly 11.
D. Less than 11.



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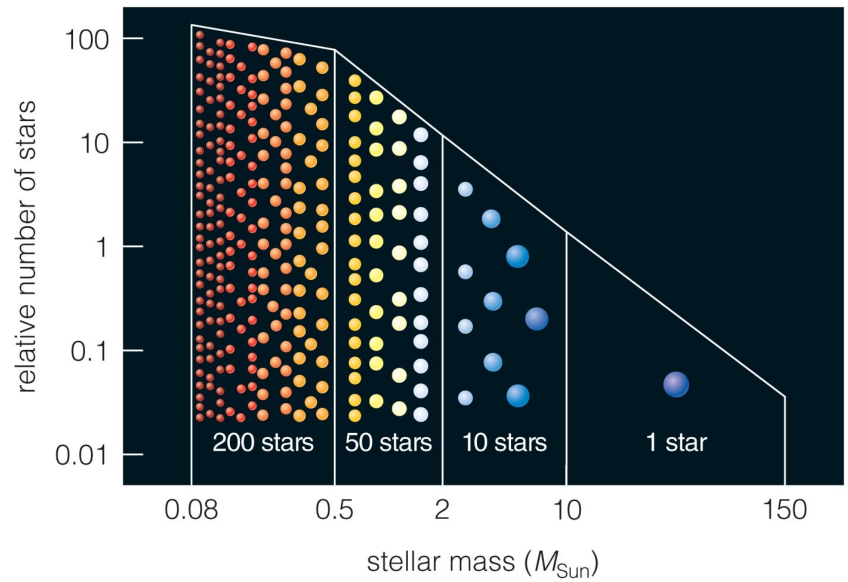

question for you

Where did most helium atoms form?

A. In cores of low mass stars
B. In cores of high mass stars
C. During supernovae
D. In the Big Bang

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What did we learn in Chapters 13+14?

- If a white dwarf is in a close binary system, then material from its companion star forms an accretion disk around the white dwarf.
- If the layer of hydrogen on the white dwarf reaches 10 million K, fusion ignites the hydrogen, and a nova occurs.
- The white dwarf survives the nova and recurring nova explosions can occur.
- If the white dwarf reaches Chandrasekhar's limit before a nova can occur, electron degeneracy pressure is overcome, and the white dwarf ignites in a Type 1a supernova explosion.

What did we learn in Chapters 13+14?

- Type 1a supernova explosions consume the entire star, igniting the entire mass of the star. Type 1a supernovae are even brighter than Type II (massive star) supernovae.
- Because the same amount of mass is always ignited in a Type 1a supernova, the explosion has the same absolute magnitude and can be used as a "standard candle."

What did we learn in Chapters 13+14?

- When a core of iron with a mass equal to 1.4 solar masses (Chandrasekhar's limit) forms within a high-mass star, it begins to collapse, and explodes in a supernova explosion, releasing more energy than a hundred stars like our sun will during their entire lifetimes.
- After the supernova explosion, a high-mass star leaves behind either a neutron star or a black hole.

What did we learn in Chapters 13+14?

- In a Type II supernova explosion, the core of the star collapses inward, overcoming electron degeneracy pressure and pressing electrons into protons to form a neutron star. The inward collapse of the neutron star is halted by neutron degeneracy pressure.
- A neutron star is very very dense… 1 solar mass packed into a sphere 20 km across.
- Neutron stars often spin very rapidly, becoming pulsars.

What did we learn in Chapters 13+14?

- Neutron stars in binary systems can have their own (much hotter) accretion disks, emitting x-rays as the infalling matter heats up.
- If a neutron star is too big, neutron degeneracy pressure is (instantly) overcome, and a black hole forms.
- A black hole is infinitely dense, so much so that not even light can escape from its gravitational field.

What did we learn in Chapters 13+14?

- Black holes can be detected when they are in binary systems and have very hot accretion disks that emit x-rays.
- The gravitational field of the black hole also causes gravitational time dilation.
- The formation of a black hole, the merger of black holes, and the merger of neutron stars causes the emission of gamma ray bursts that can briefly outshine galaxies.