The Bizarre Stellar Graveyard

Chapter 13


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Quantum Mechanics

Where QM meets GR

* In the vast Universe, there are a few places where two irreconcilable (for now) worlds meet
* Quantum Mechanics, the physics of the smallest objects Nature is made of
* General Relativity, the physics of the largest (and densest) objects

Quantum Gravity Needed

- Gravity is a very weak force compared to the other 3
- When doing particle physics, Gravity can be ignored
- But when studying Nature at the Planck length scale (10^{-34} cm), Gravity is as strong as the other 3 forces

Where QM meets GR...

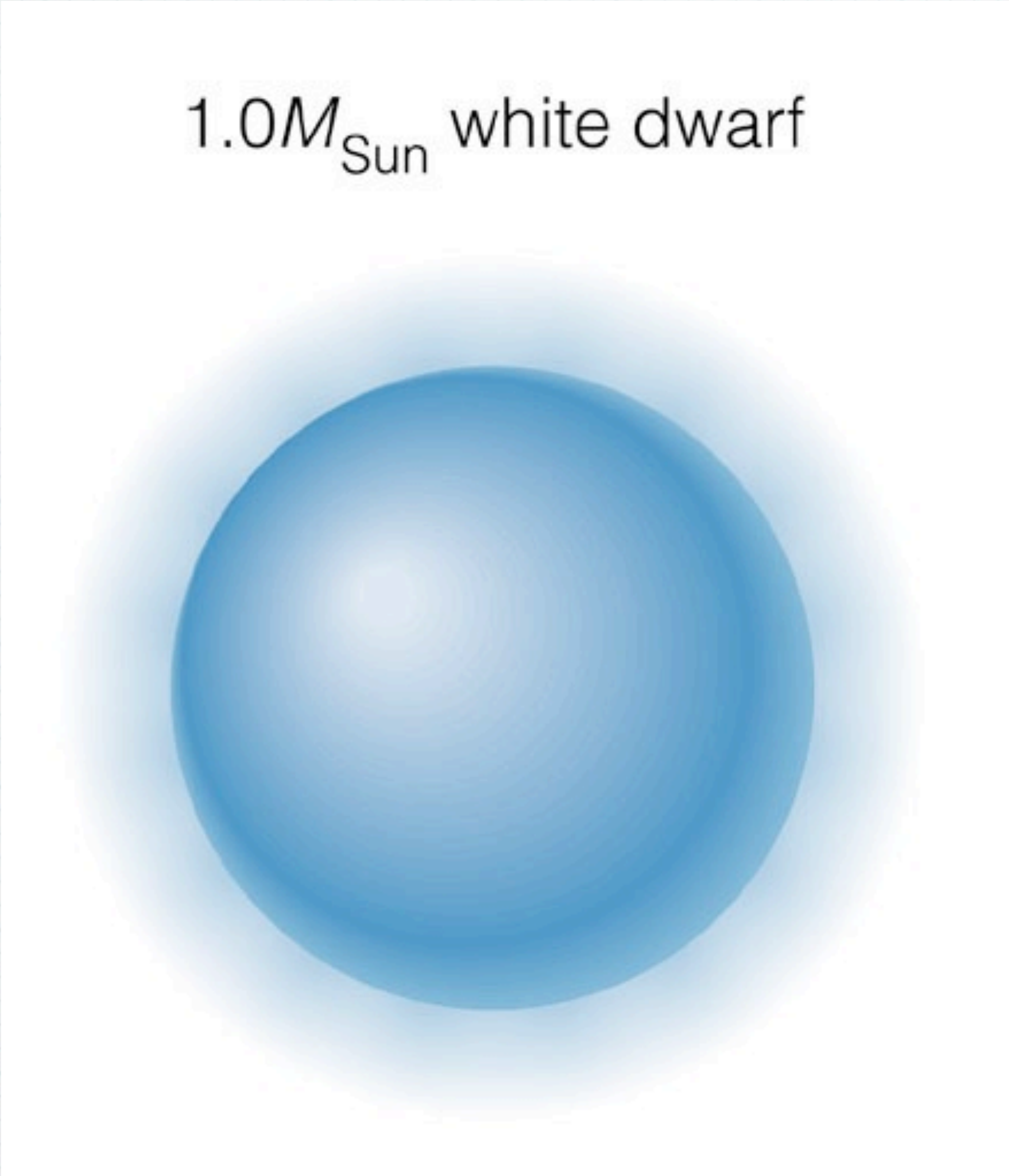
* Usually these two worlds live far apart but, in the stellar graveyard, they meet and challenge our current understanding of Nature
* In white dwarfs and neutron stars where degenerate matter exists, and in black holes, QM & GR both apply and both theories give different answers

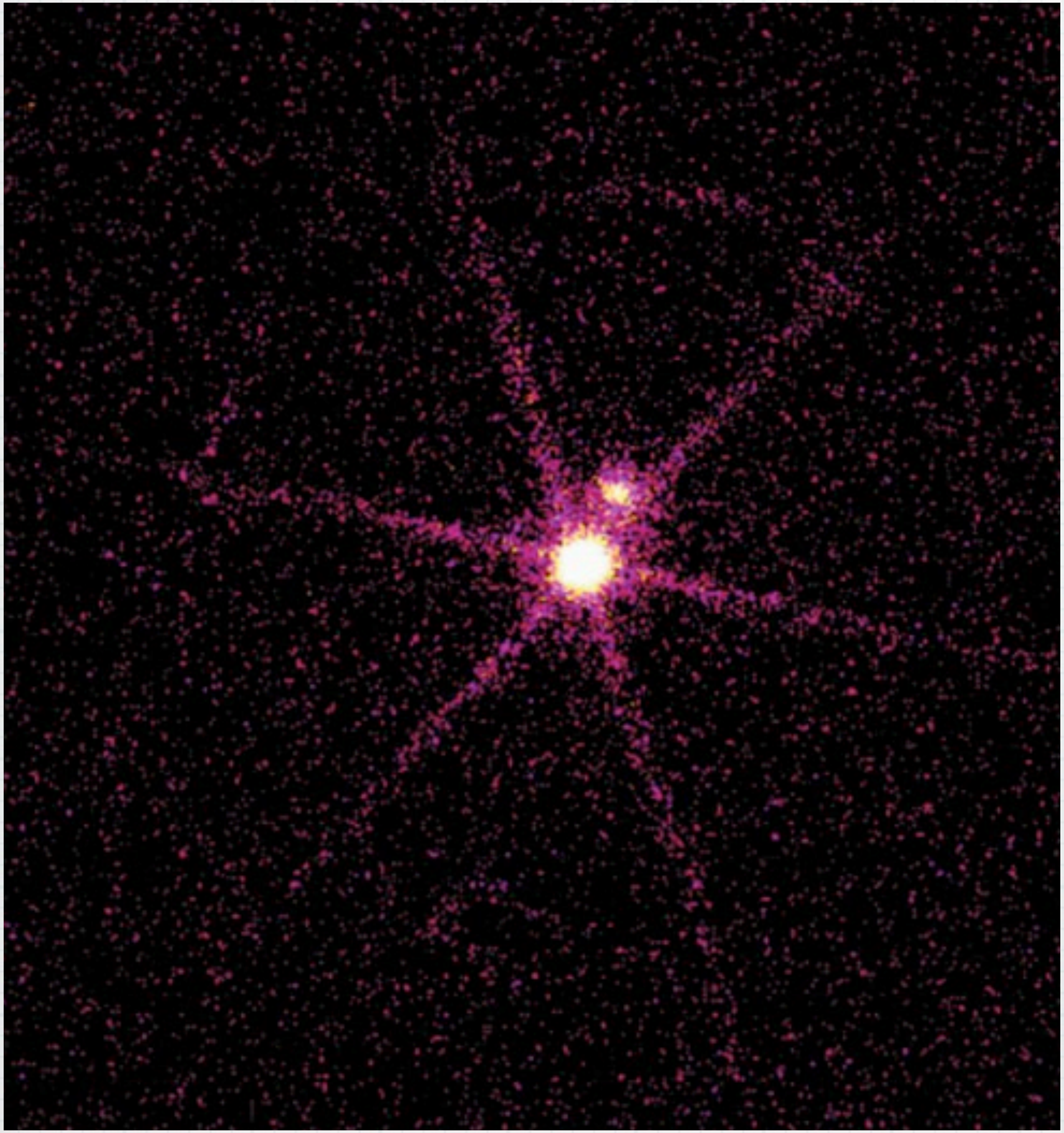
What is a White Dwarf?

* A white dwarf is the exposed core of a low-mass star that has died
* and previously shed its outer layers in a planetary nebula
* It is a lot of mass (0.17 <-> 1.33 M_{Sun}) in a small size (about Earth-size) -> It is a dense object

A white dwarf is about the same size as Earth

A teaspoon of white dwarf matter weighs several tons!

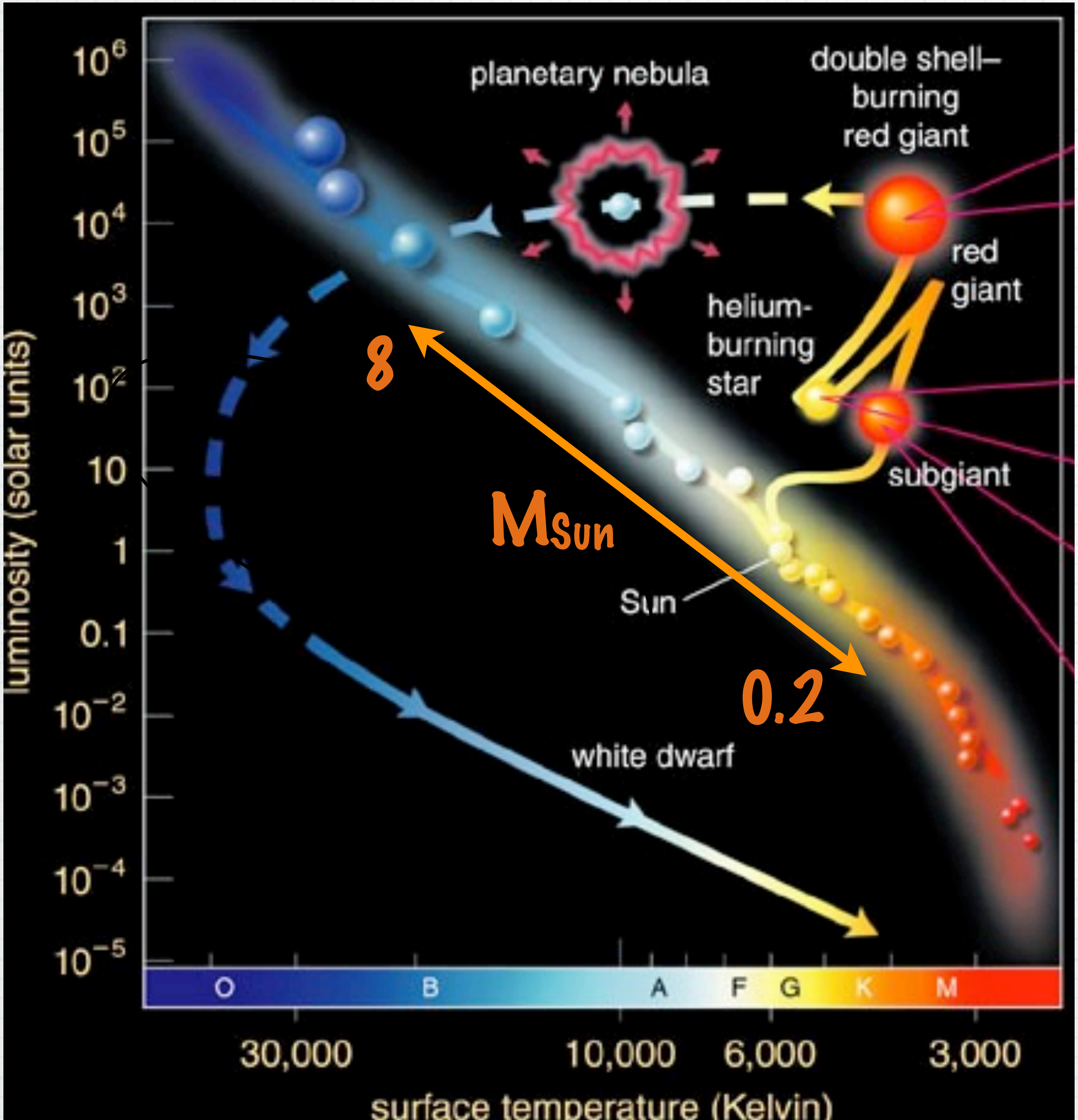




White dwarfs are the remaining cores of dead stars

Electron degeneracy pressure supports them against gravity

Sirius A and B as seen in X-rays.
Sirius A is the brightest star we can see but, in X-ray light, Sirius B (a white dwarf) is brighter

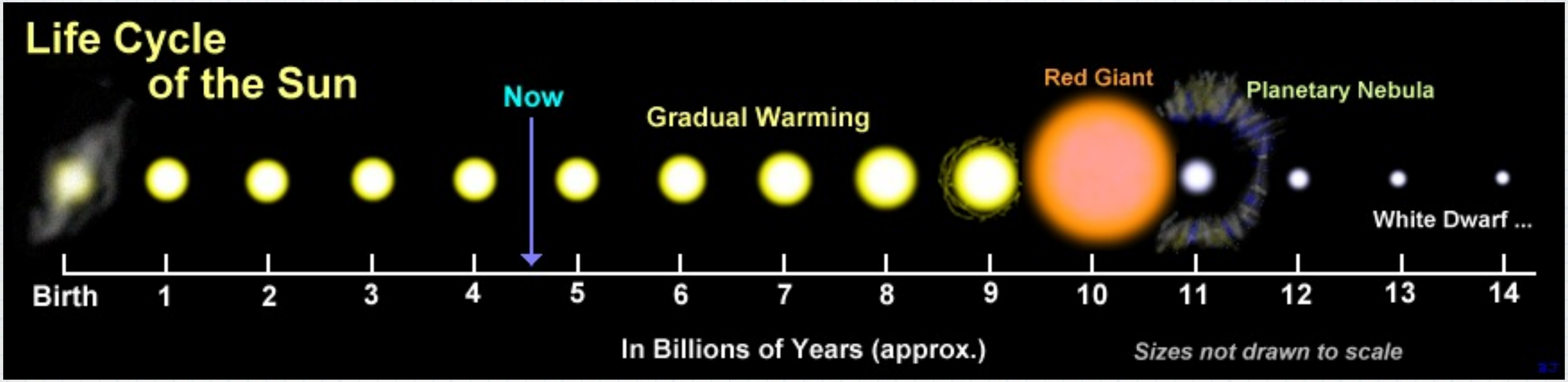


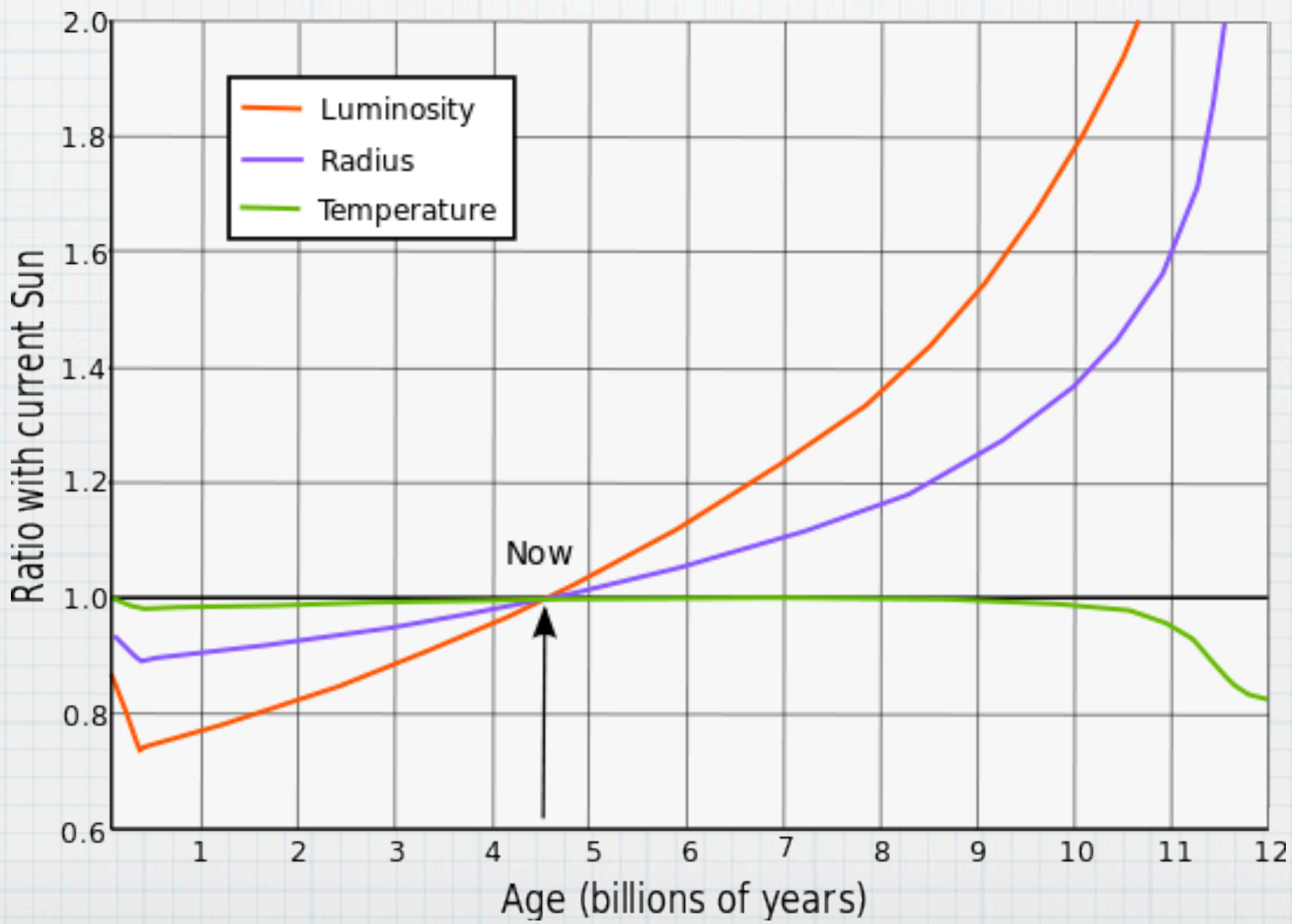
White dwarfs cool off and grow dimmer with time

Intermediate-to Low-mass stars can become white dwarfs

A few trillion years later, they'll cool off and become black dwarfs

Our Sun's Life

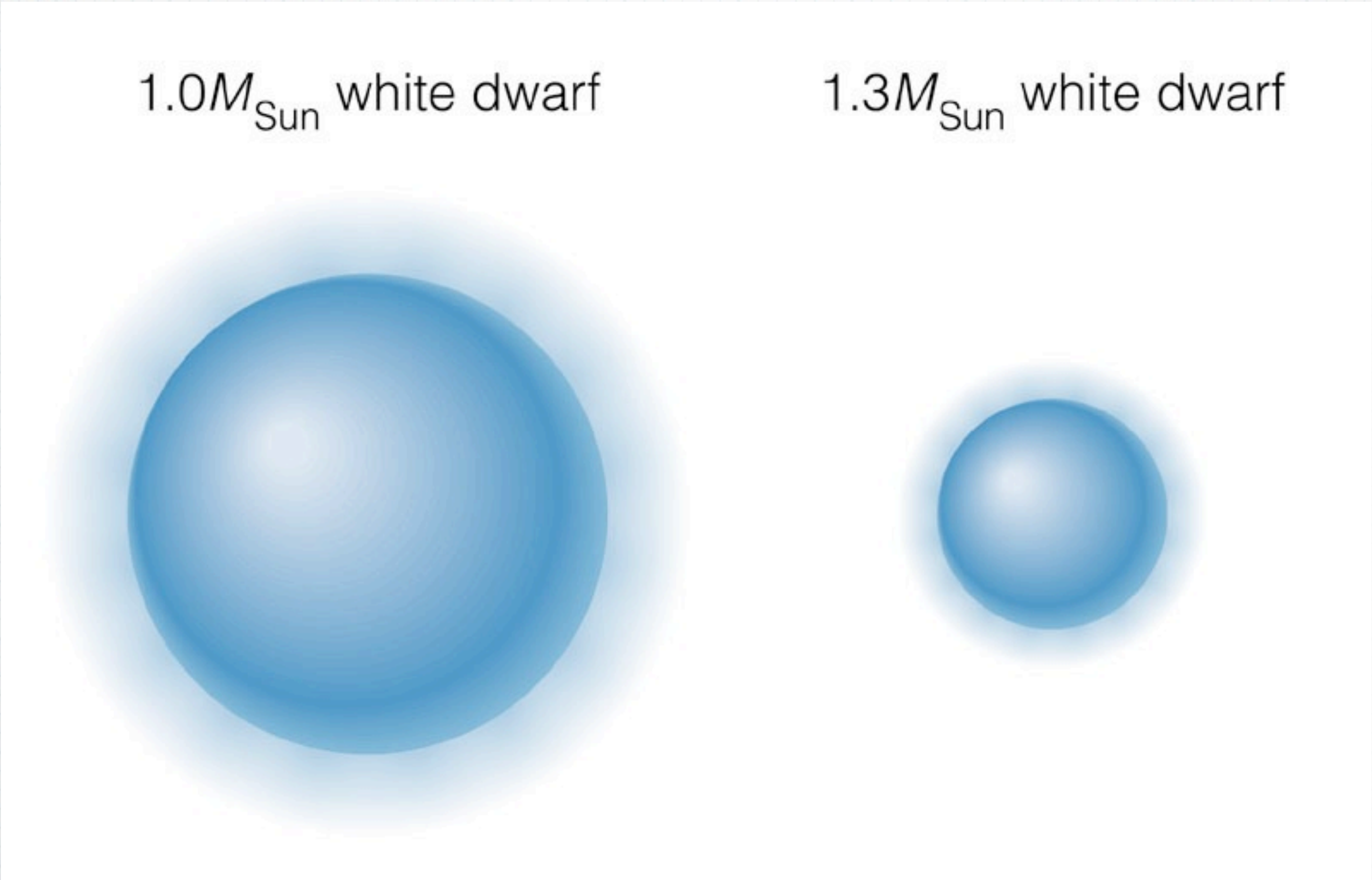




Shrinkage of White Dwarfs

* Quantum mechanics says that electrons in the same place cannot be in the same state
* Adding mass to a white dwarf increases its gravity, forcing electrons into a smaller space
* In order to avoid being in the same state some of the electrons need to move faster
* Is there a limit to how much you can shrink a white dwarf?

White dwarfs shrink when you add mass to them because their gravity gets stronger and this puts more pressure on the electron degeneracy pressure



What is a White Dwarf?...

* Gravity is trying to crush it even further but...
* electron degeneracy pressure opposes it
* Electrons are as closely packed as the laws of Quantum Mechanics permit it:
* and those closely packed electrons speed up and increase their momentum

The White Dwarf Limit


S. Chandrasekhar

* Einstein's theory of relativity says that nothing can move faster than light
* When electron velocities, in a white dwarf, approach the speed of light, electron degeneracy pressure can no longer support the star
* Chandrasekhar found (he was 20) that this happens when a white dwarf's mass reaches about 1.4 M_{Sun}

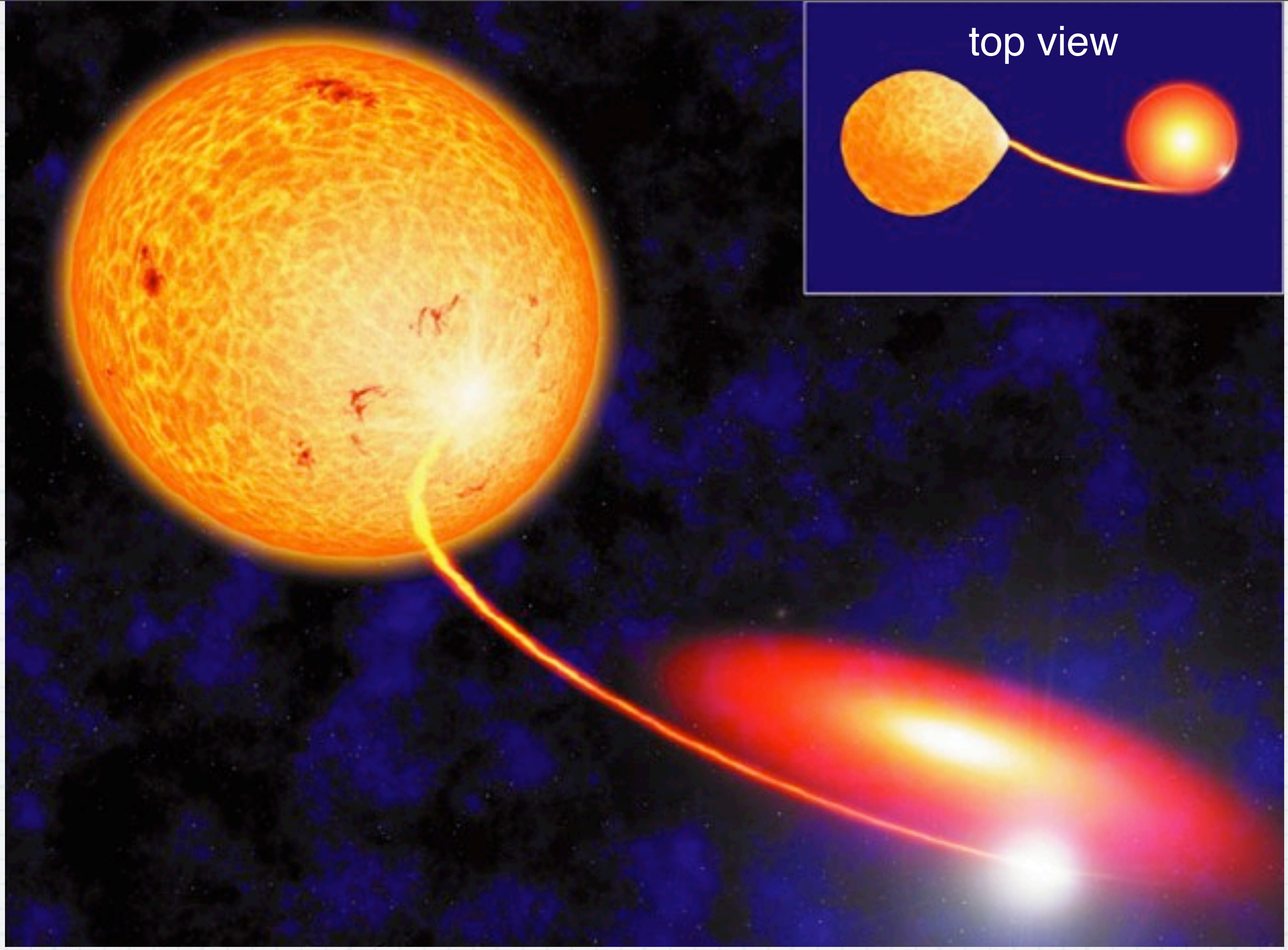
The White Dwarf Limit...

S. Chandrasekhar

* A white dwarf is also called a degenerate dwarf as it is a small star whose electrons are mostly all in a degenerate state
* It is a star which is highly "excited", very hot, but not undergoing fusion
* Left alone, it will slowly cool off with time (trillion and trillion of years) and eventually become a black dwarf (none exist yet as the Universe is not old enough)

A white dwarf in a close binary system

* A "stand-alone white dwarf" will cool off with time
* A white dwarf in a close binary system can gain (steal) mass from its companion



White dwarf's gravity pulls matter off of a companion, but angular momentum prevents the matter from falling straight in

Infalling matter forms an accretion disk around the white dwarf

Novae

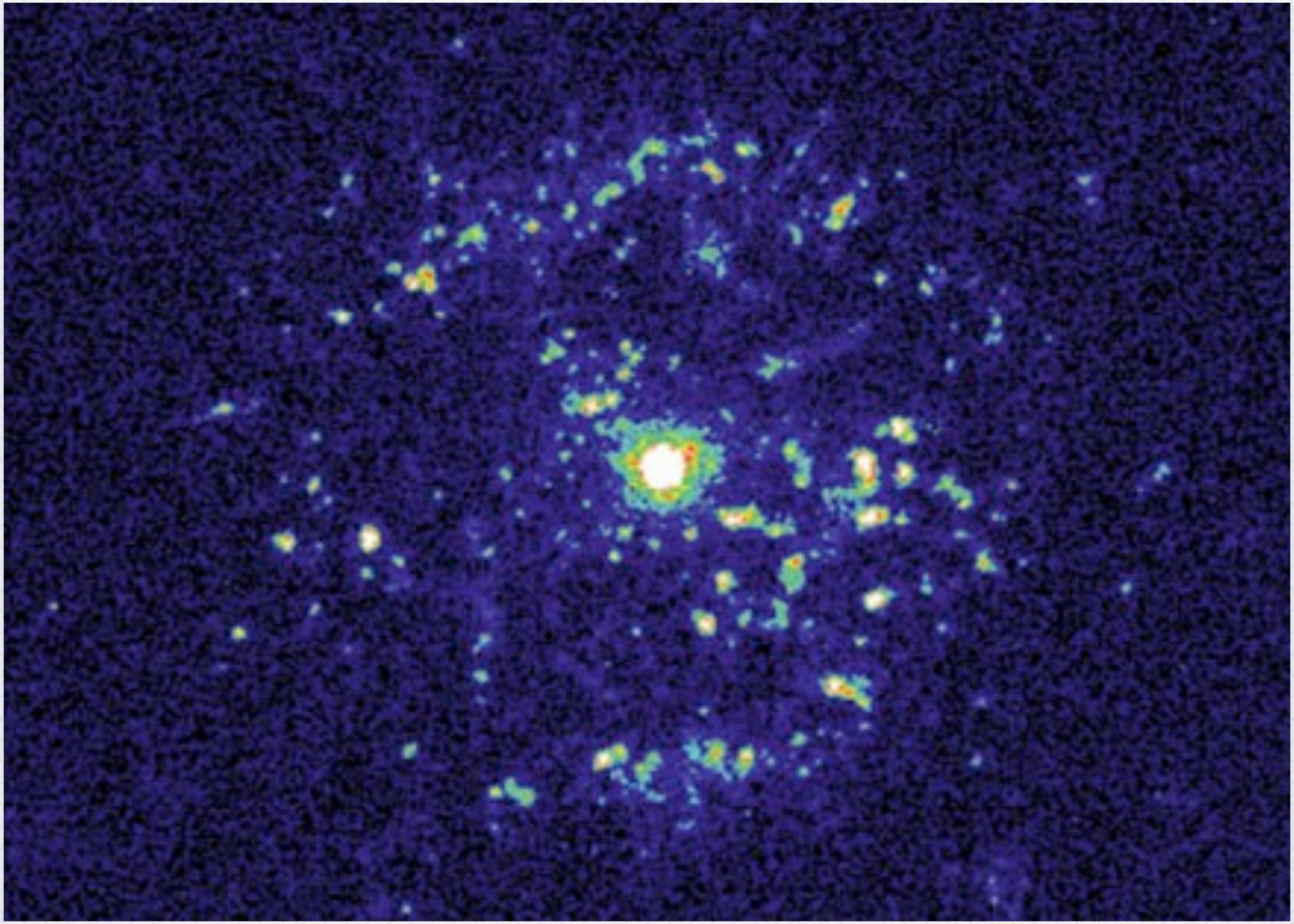
Hydrogen that accretes onto a white dwarf builds up in a shell on the surface

When base of shell gets hot enough, hydrogen fusion suddenly begins leading to a nova

Novae

* The nuclear flash will last a few weeks
* It will shine as 100,000 Suns
* The hydrogen shell on the white dwarf and the accretion disk are blown up
* The accretion process then resumes
* Nova outbursts will happen between 10,000 years to a few decades, depending on the mass accretion rate

Nova explosion generates a burst of light lasting a few weeks and expels much of the accreted gas into space



White Dwarf Supernovae

* Recall that a white dwarf is primarily carbon (with some oxygen) as it is the core of a star who died
* After each nova event, the white dwarf accumulates more mass
* When the white dwarf's mass approaches 1.4 M_{Sun}, its interior temperature is hot enough to fuse the carbon

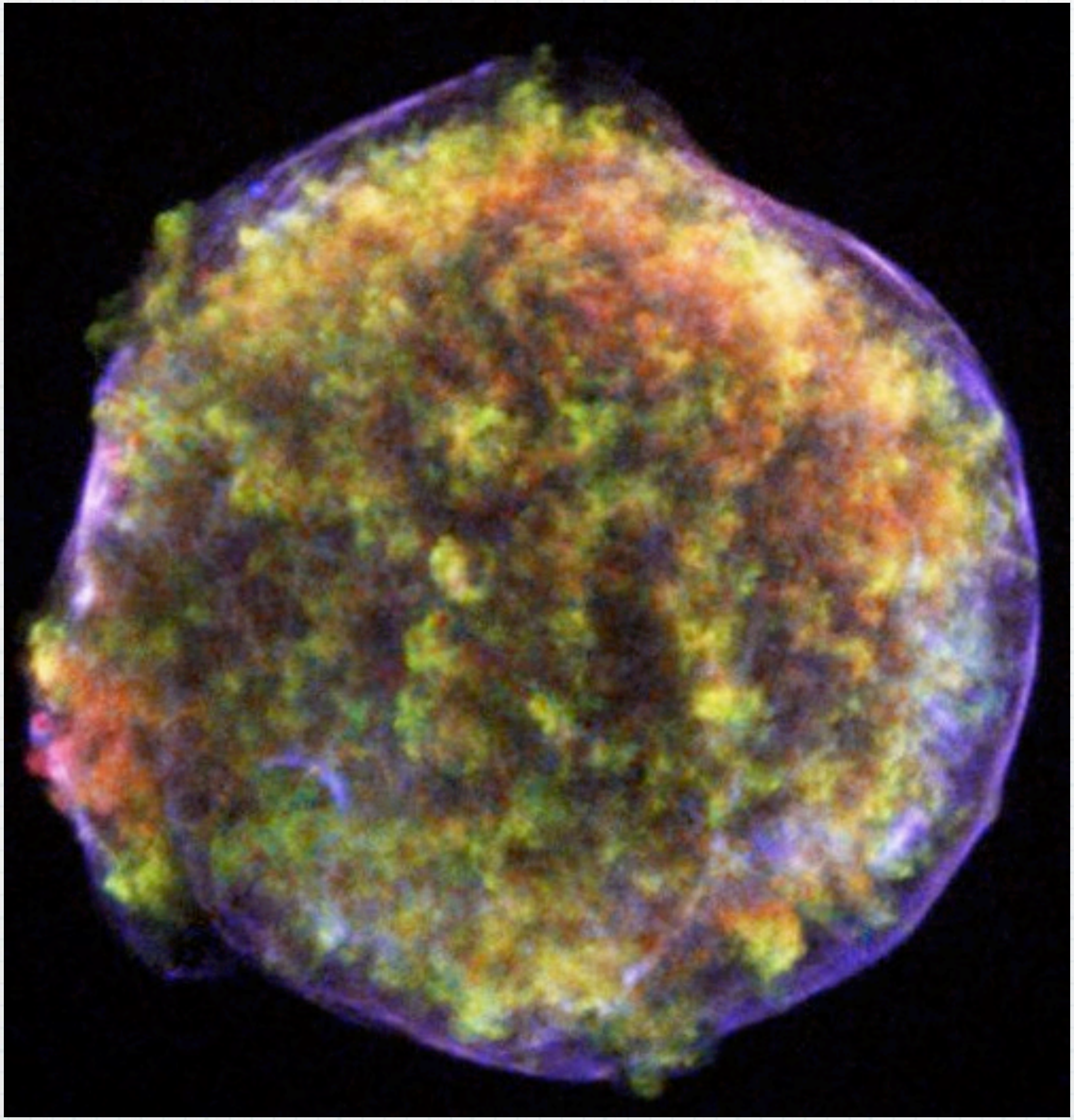
White Dwarf Supernovae...

* Because the star is under intense electron degeneracy pressure, fusion is then instantaneous and throughout the star: it is a carbon flash

* The star explodes in an event called a white dwarf supernova (Type Ia)

* It is a different supernova type than a massive star supernova when a star iron core cannot resist gravitational compression (Type Ib, c & II)

Type Ia Supernova



Multiwavelength X-ray image of SN 1572 or Tycho's star (observed in 1572)

Colored according to X-ray energy intensity, this supernova remnant's bluish shockwave bubble is twice as hot as the mottled gaseous debris expanding behind at 10 million degrees Celsius

White Dwarf Supernovae... (Type Ia)

* The entire white dwarf blows up: there is nothing left
* The nuclear flash will last a few months and is due to radioactive decay
* The supernova will shine as 10 billion Suns
* This is usually more luminous than the entire galaxy the star is in

White Dwarf Supernovae... (Type Ia)

* It is also possible (but rarer) to have 2 white dwarf stars merge
* This event is called a super-Chandrasekhar mass white dwarf
* This also will cause a Type Ia supernova and it will be brighter because the final mass will be greater than the 1.4 mass theoretical limit

Question

* What happens to a white dwarf when it accretes enough matter to reach the 1.4 M_{Sun} mass limit?

A. It completely explodes

B. It collapses into a neutron star

C. It gradually begins fusing carbon in its core

Question

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Nova or Supernova?

* A supernova is MUCH MUCH more luminous than a nova (from 100,000 times to 10 million times that of a nova depending on the nova's brilliance)
* Nova: H to He fusion of a surface layer, the white dwarf is left intact
* White dwarf supernova: complete explosion of the white dwarf, nothing is left behind

Types of Supernovae

I. No hydrogen spectral lines present

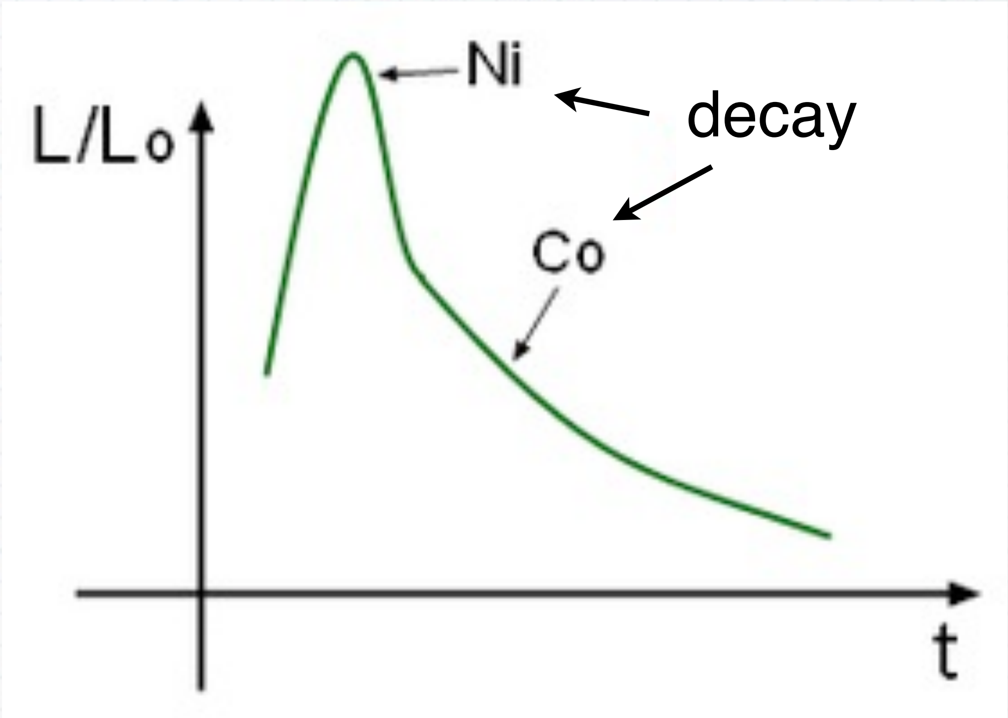
   a. Type Ia: White dwarf supernova

   b. Type Ib and Ic: Core collapse of massive stars (which previously lost their hydrogen layer)

II. Hydrogen spectral lines present

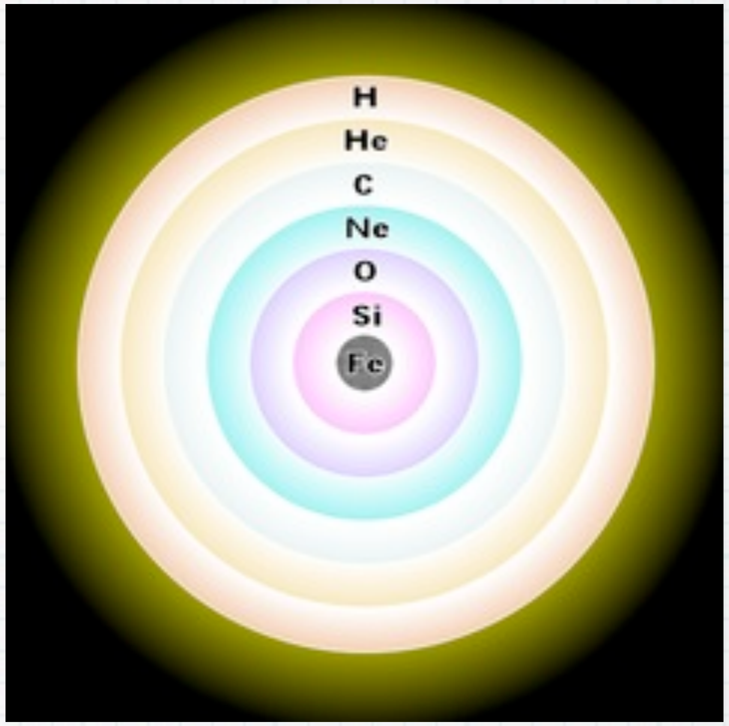
   a. Type II: Core collapse of massive stars

Type Ia



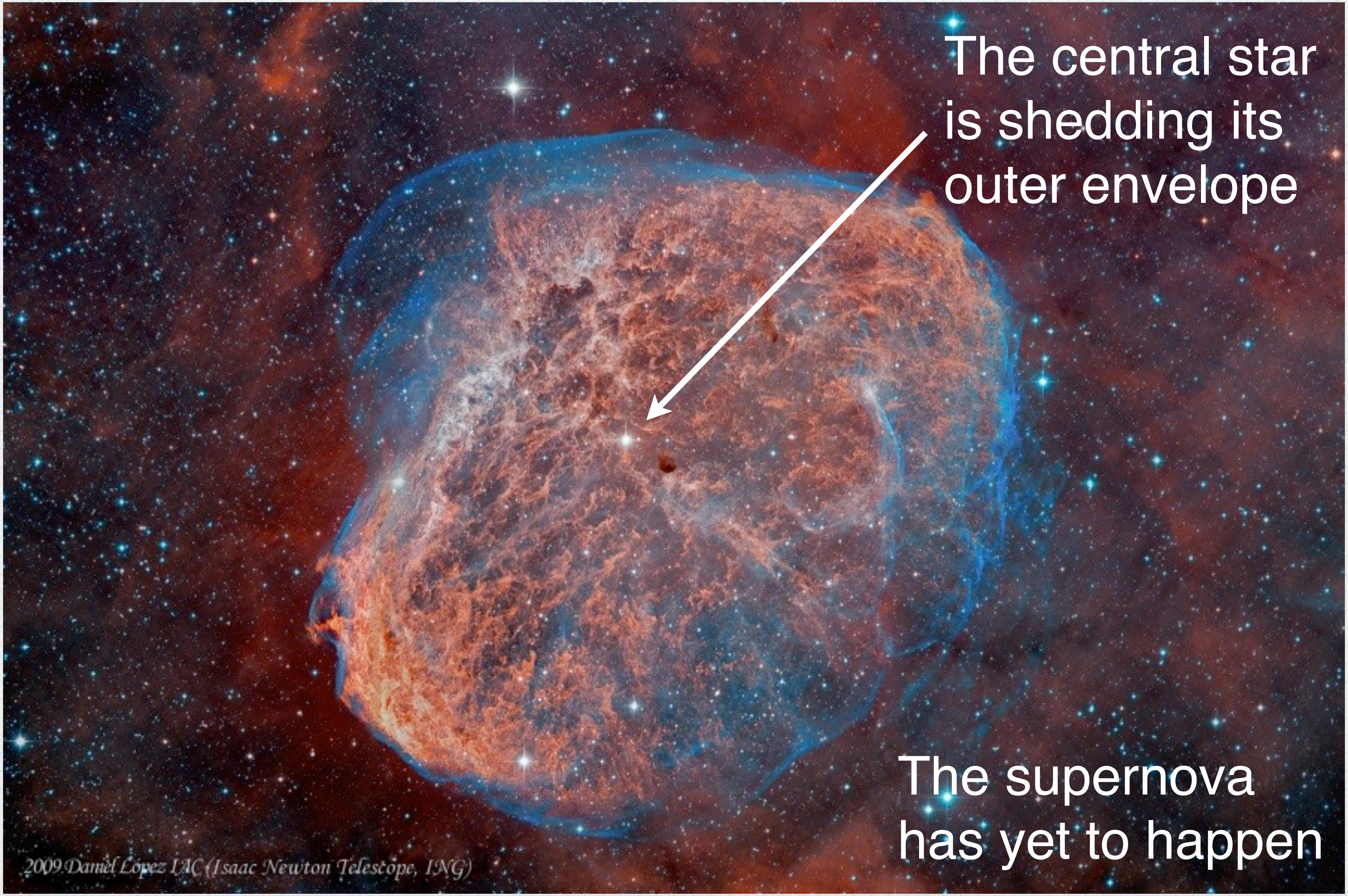
* Carbon-Oxygen fusion suddenly begins as white dwarf in close binary system reaches white dwarf mass limit
* In a few seconds, the energy unbinds the star causing total explosion (no part of the white dwarf survives)
* There is no hydrogen present

Type Ib, c

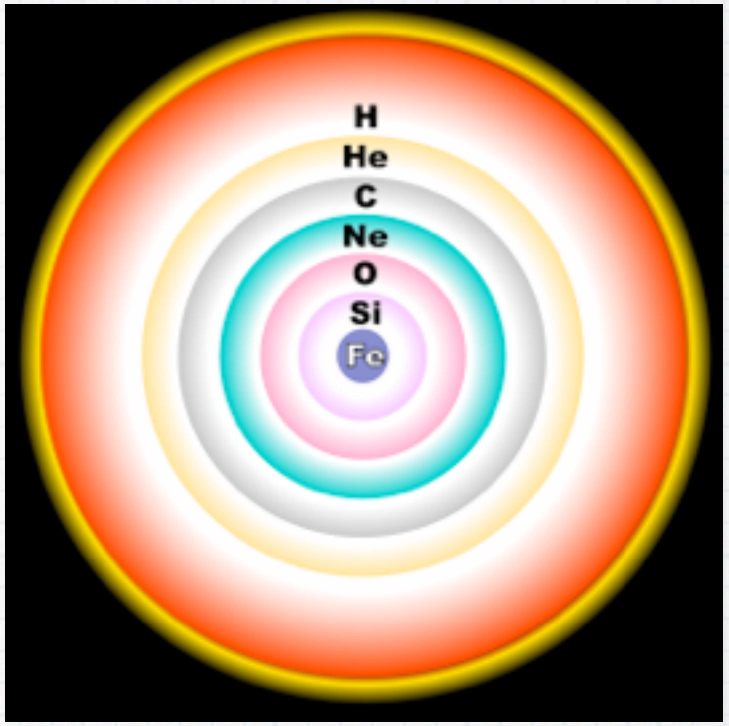


* Stripped core-collapse of massive stars
* They have shed their outer hydrogen-helium envelope due to very high stellar winds
* The explosion is due to the iron core having reached the white dwarf mass limit which causes its collapse into a neutron star

NGC 6888



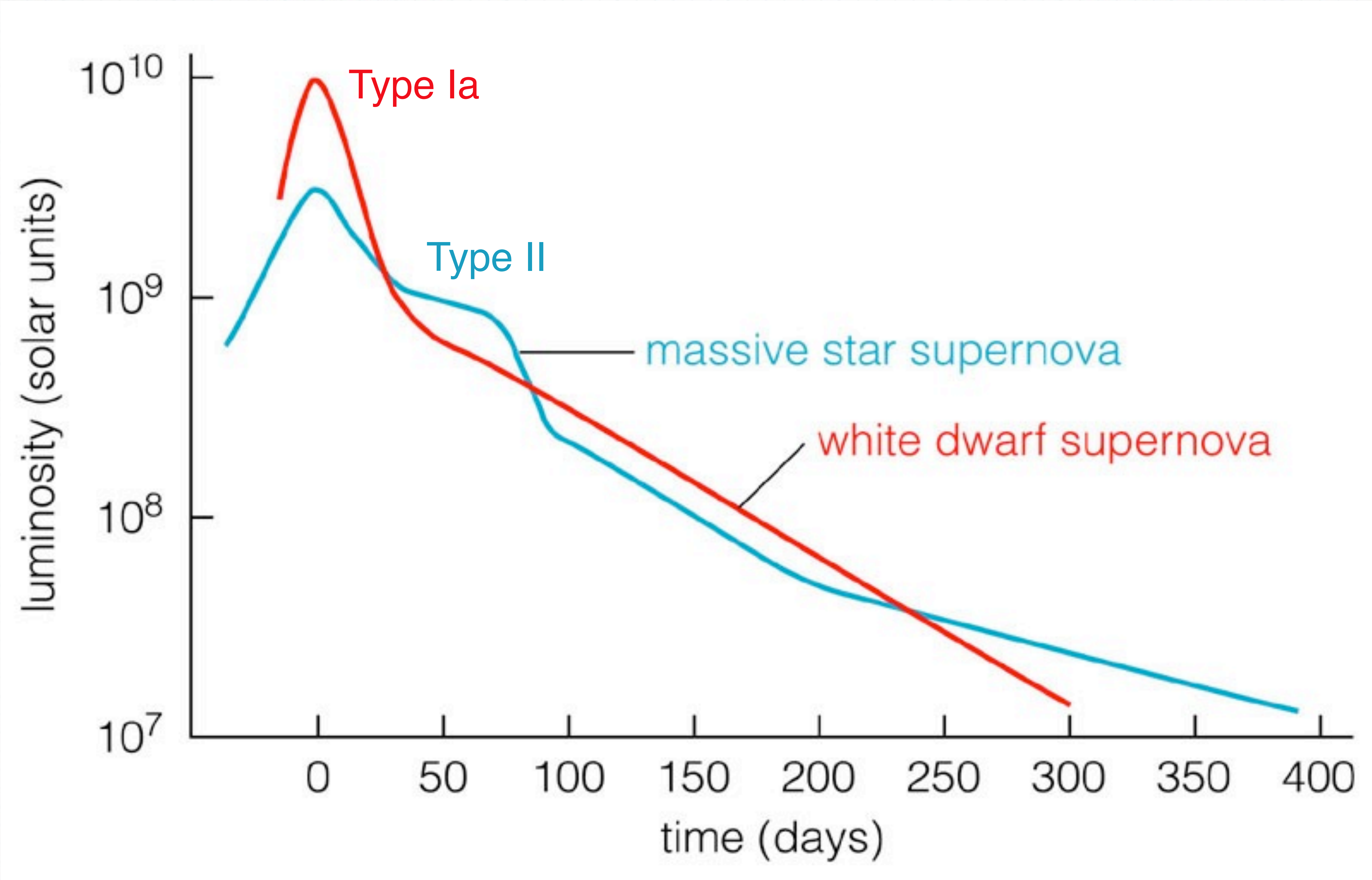
The central star is shedding its outer envelope
The supernova has yet to happen
2009 Daniel López IAC (Isaac Newton Telescope, ING)



Type II

* Core-collapse of massive stars
* Presence of hydrogen in its spectrum
* The explosion is due to the iron core having reached the white dwarf mass limit which causes its collapse into a neutron star if the star is above 9 M_{Sun} and below 20 M_{Sun}
* Above that limit, the core collapses into a black hole

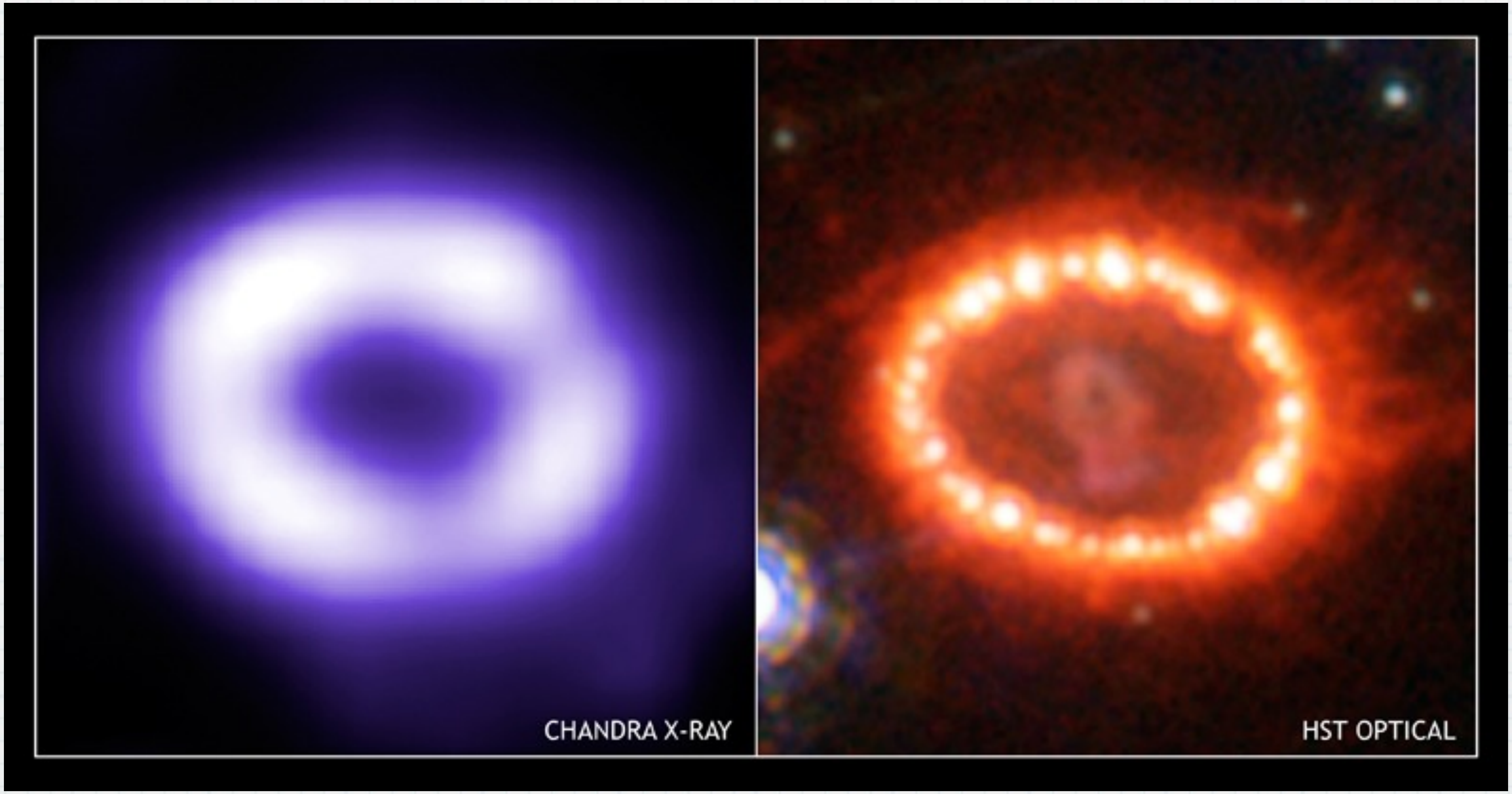
One way to tell supernova types apart is with a light curve showing how luminosity changes



Type II Supernova

SN 1987a

About 3 hours before we detected its visible light, a burst of neutrinos was detected



The remnant neutron star has not been detected yet

Supernova: what astronomers see

visible

A supernova in the Centaurus A galaxy

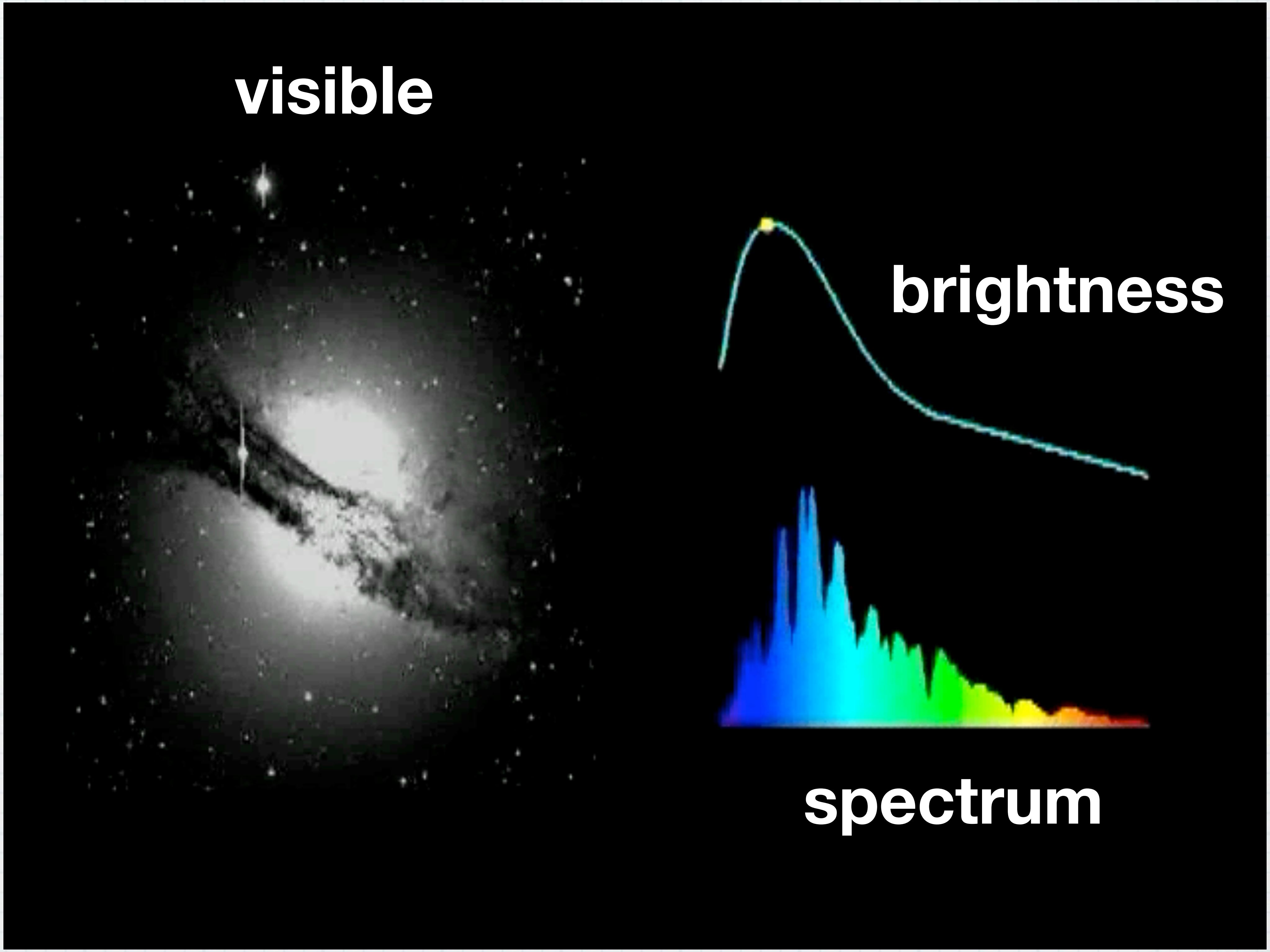
brightness

spectrum

This clip was prepared by the Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center

Supernova: what astronomers see

A supernova in the Centaurus A galaxy



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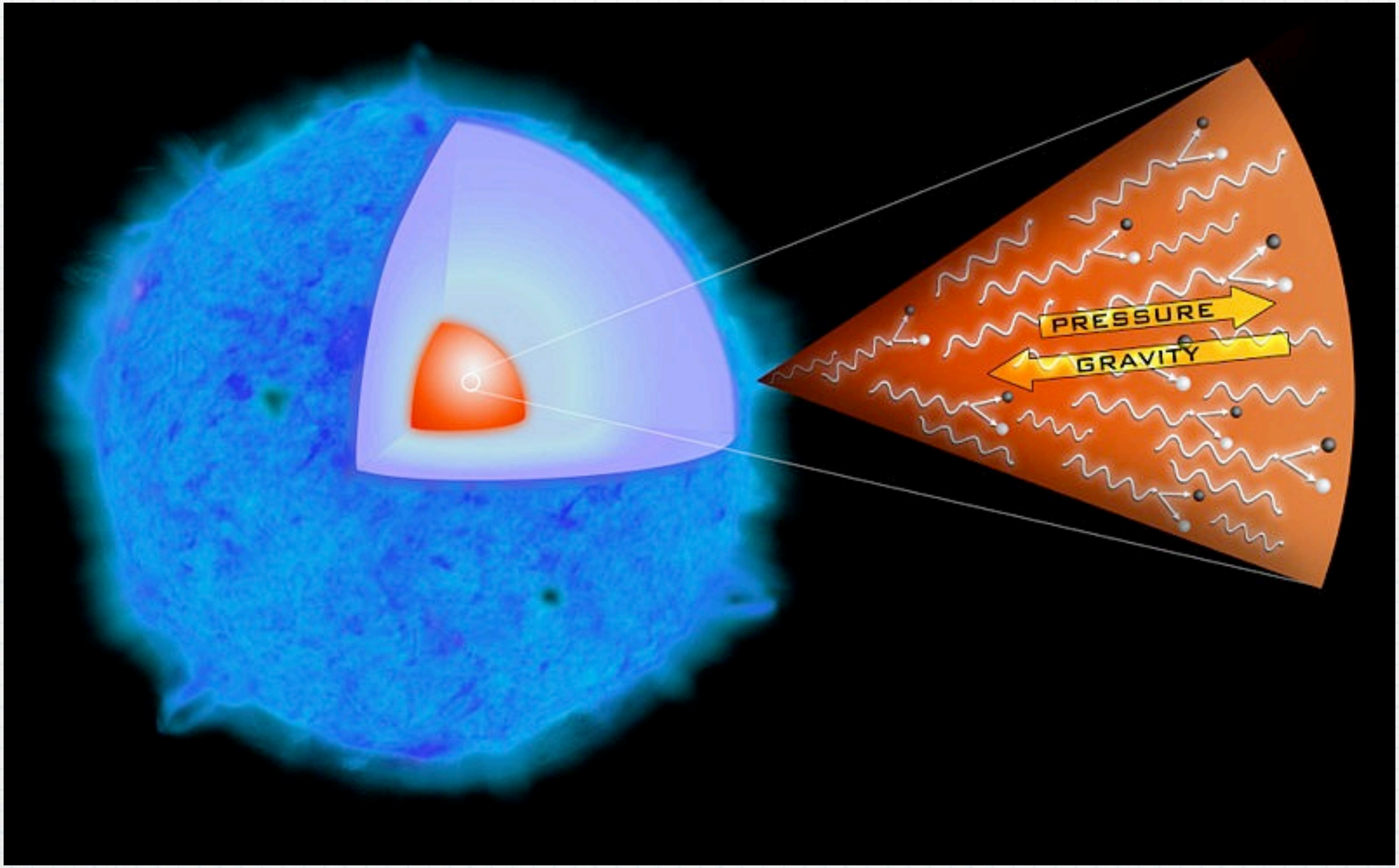
Super-Supernovae

* A new type of supernova was identified in 2006: a "pair instability" supernova
* As we shall see in the last lecture, very energetic gamma rays can convert to matter (particle & anti-particle pair)
* When a star is very massive (130 to 250 solar mass) and has few heavy elements the gamma rays produced in its core can produce matter

Super-Supernovae...

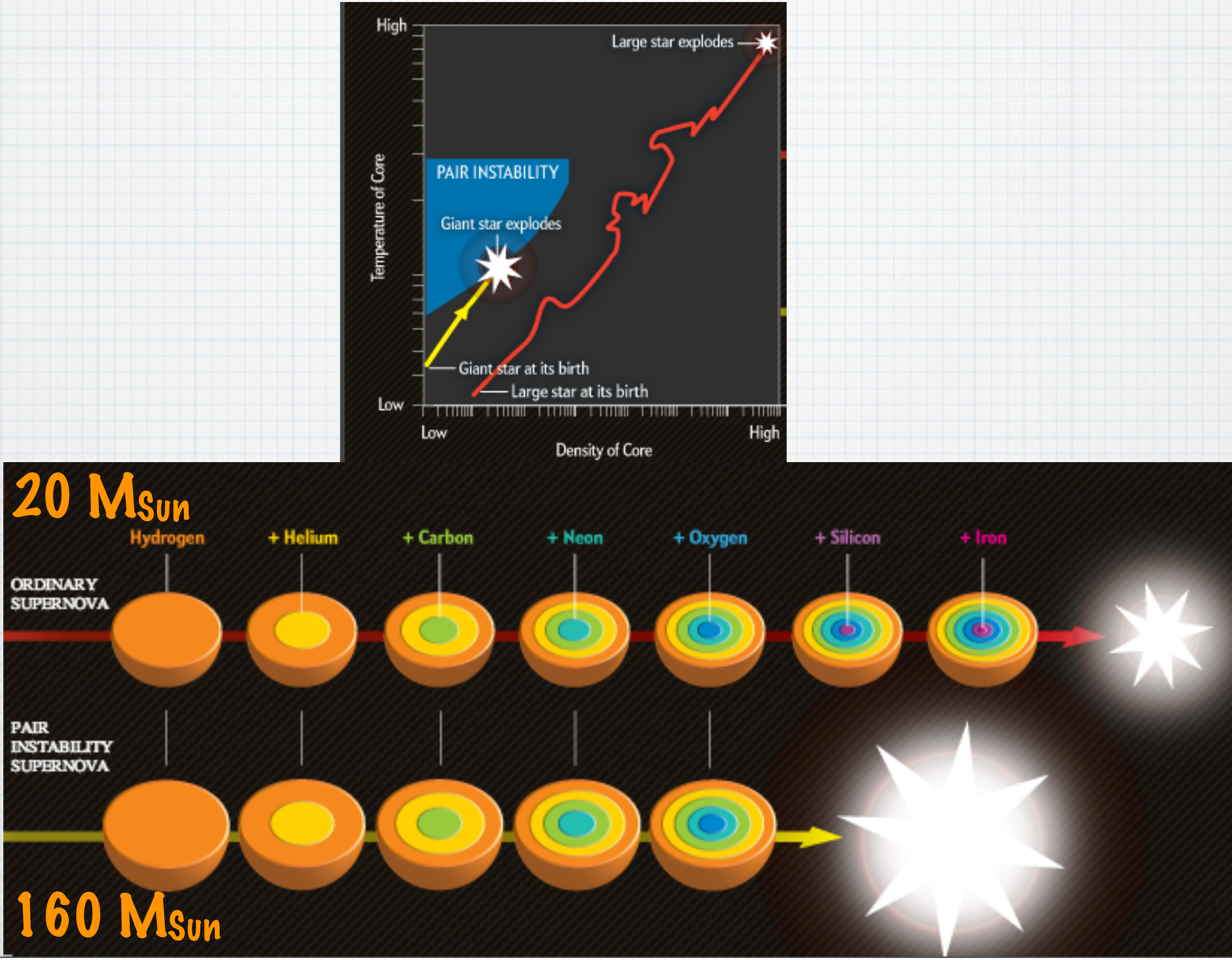


What may have happened: Supernova Sn2006gy

Super-Supernovae...

* The resulting drop in outward pressure causes the star to partially collapse under its own huge gravity
* After this violent collapse, runaway thermonuclear reactions ensue and the star explodes, spewing the remains into space: no neutron star or black hole can form

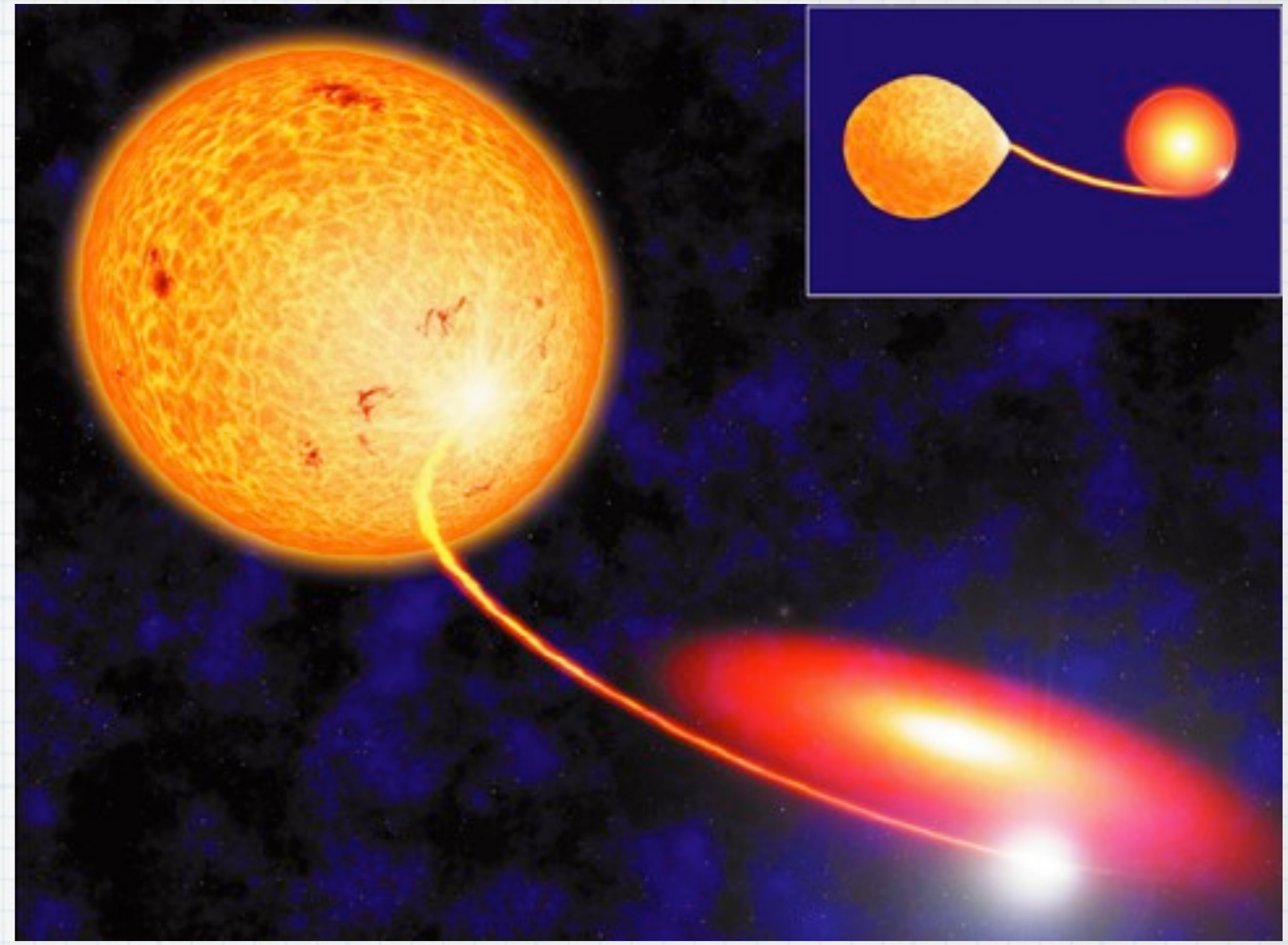
Super-Supernova versus a Supernova



Snapshot

* What is a white dwarf?
* A white dwarf is the core left over from a low-mass star, supported against the crush of gravity by electron degeneracy pressure

Snapshot



* What can happen to a white dwarf in a close binary system?
* A white dwarf in a close binary system can acquire hydrogen from its companion through an accretion disk
* As hydrogen builds up on the white dwarf's surface, it may ignite with nuclear fusion to make a nova

Snapshot

* What is a white dwarf supernova?
* A white dwarf with a close companion star will acquire mass from the companion
* When the white dwarf's mass approaches 1.4 M_{Sun}, it completely blows up
* White dwarf supernovae have the same energetic profile

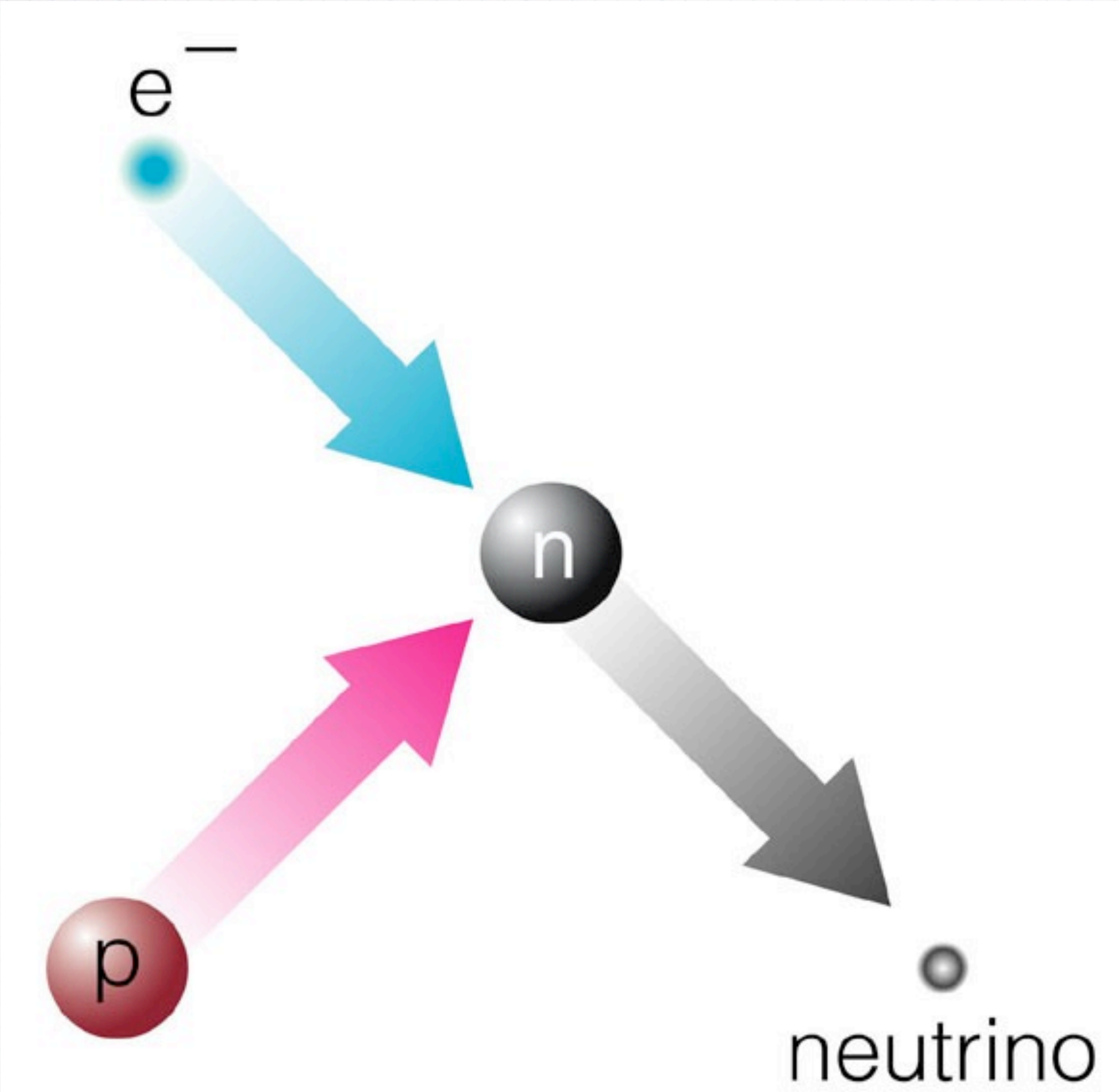
Snapshot

* What is a super-Chandrasekhar mass white dwarf?
* Two white dwarfs in close orbit will merge and the resulting mass will be greater than 1.4 M_{Sun}
* The resulting Type Ia supernova will be brighter than when only one white dwarf is involved

Neutron Stars

* White dwarfs have densities of several tons per teaspoon
* Neutron stars have densities of up to 10 billion tons per teaspoon
* More massive than the Sun with a radius of 10 to 12 km (6.3 to 7.5 miles)

Forming neutrons in a core

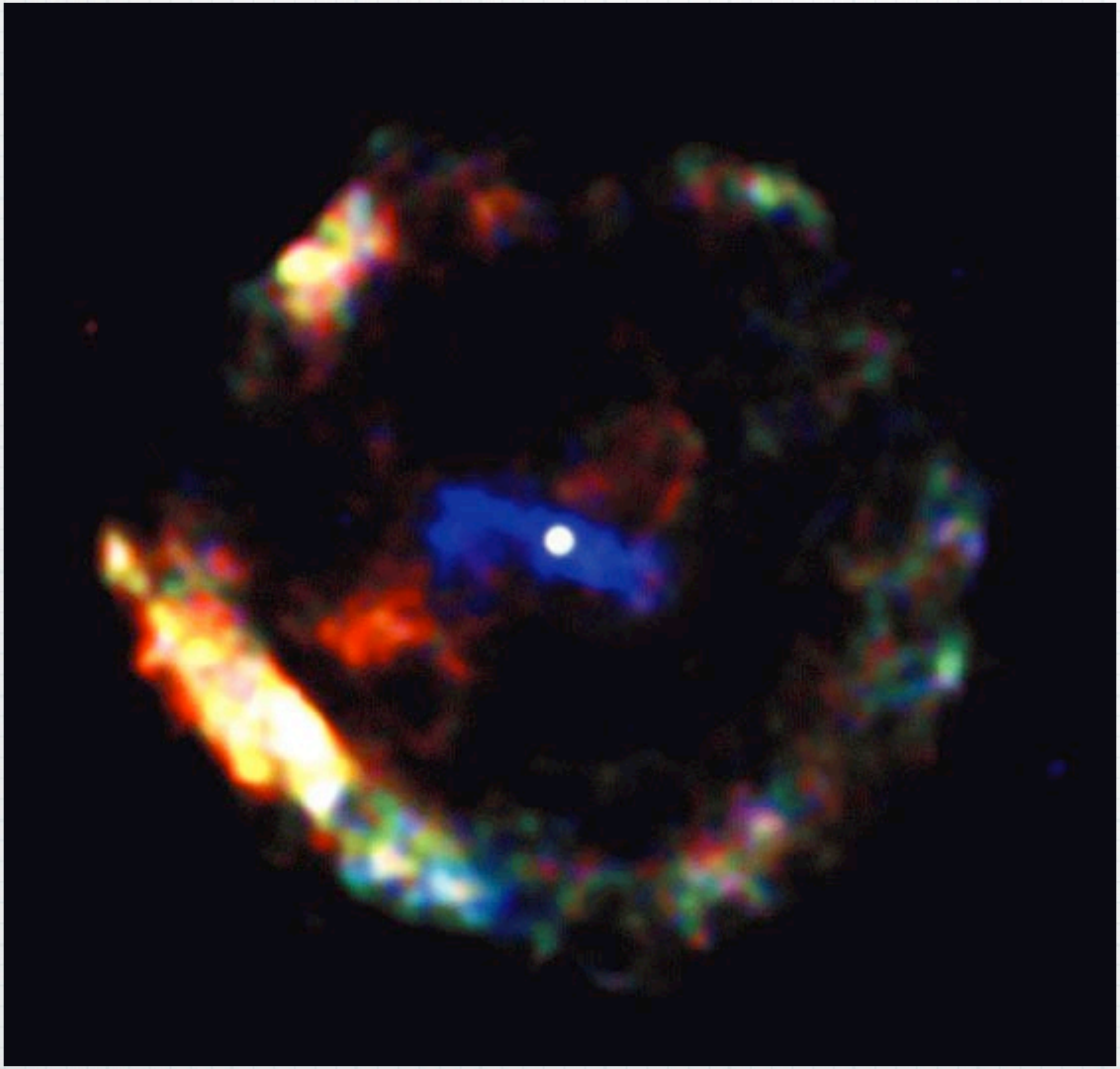


Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos

Neutrons collapse to the center, forming a neutron star

Neutron Stars...

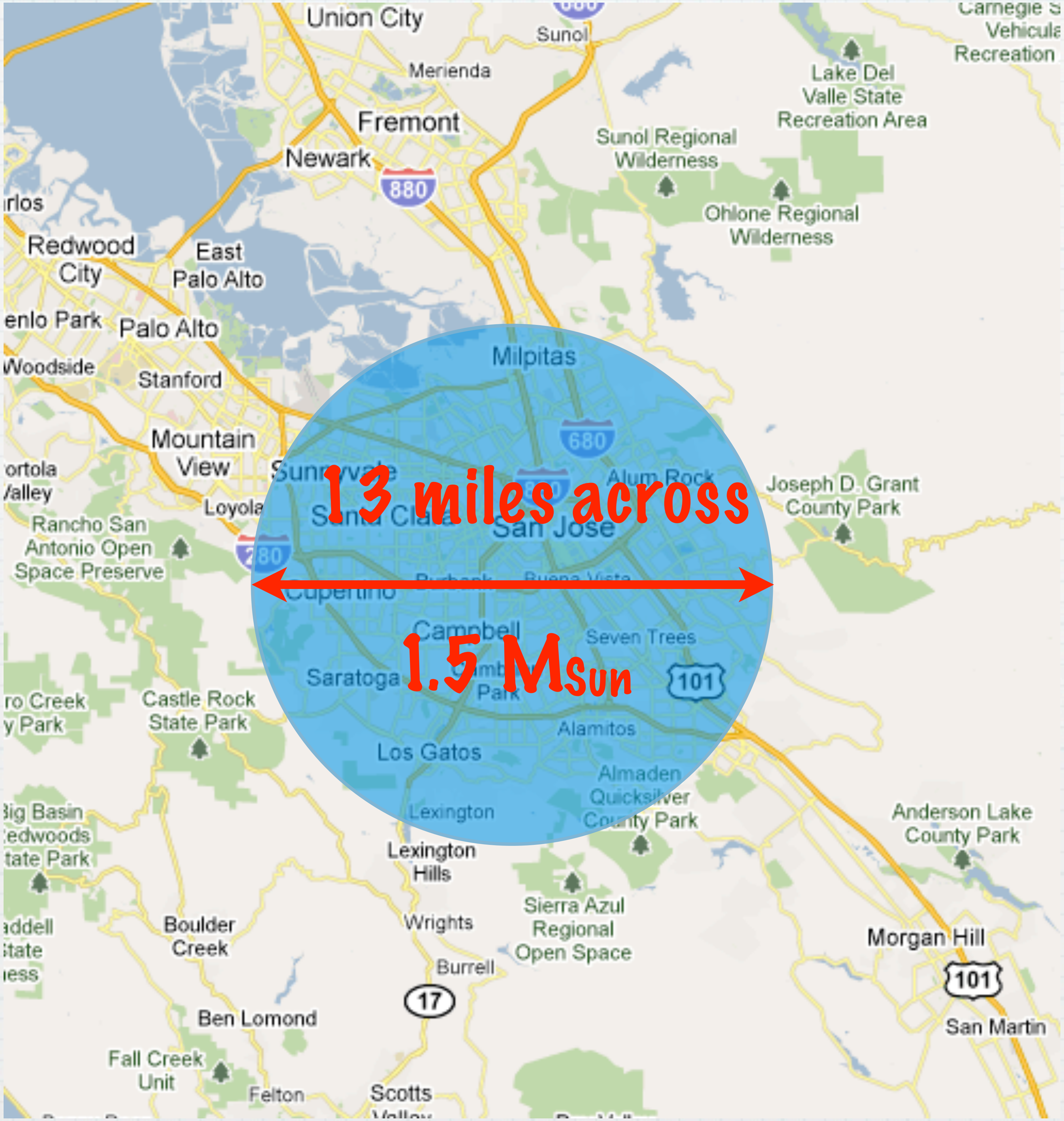
* They are essentially a giant atomic nucleus made up (almost entirely) of neutrons and held together by gravity
* They resist further crushing by having their own **neutron degeneracy pressure**
* **Their maximum mass is around 3 M_{Sun}**



A neutron star is the ball of neutrons left behind by a massive-star supernova

Degeneracy pressure of neutrons supports a neutron star against gravity

A neutron star is about the same size as a small city



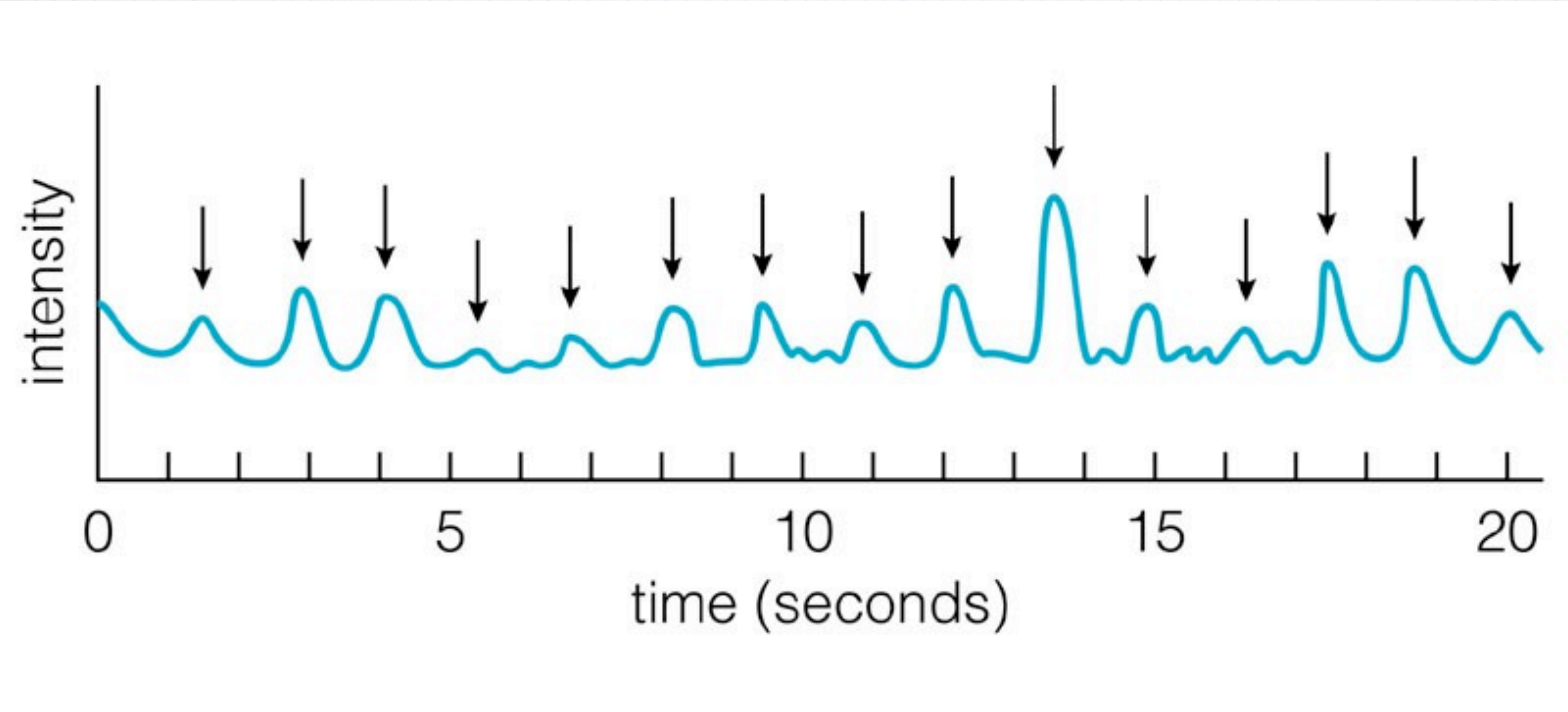
How were neutron stars discovered?

* The first neutron star was discovered by Jocelyn Bell Burnell in 1967
* Using a radio telescope she noticed very regular pulses of radio emission coming from a single part of the sky
* The object was called a **pulsar**

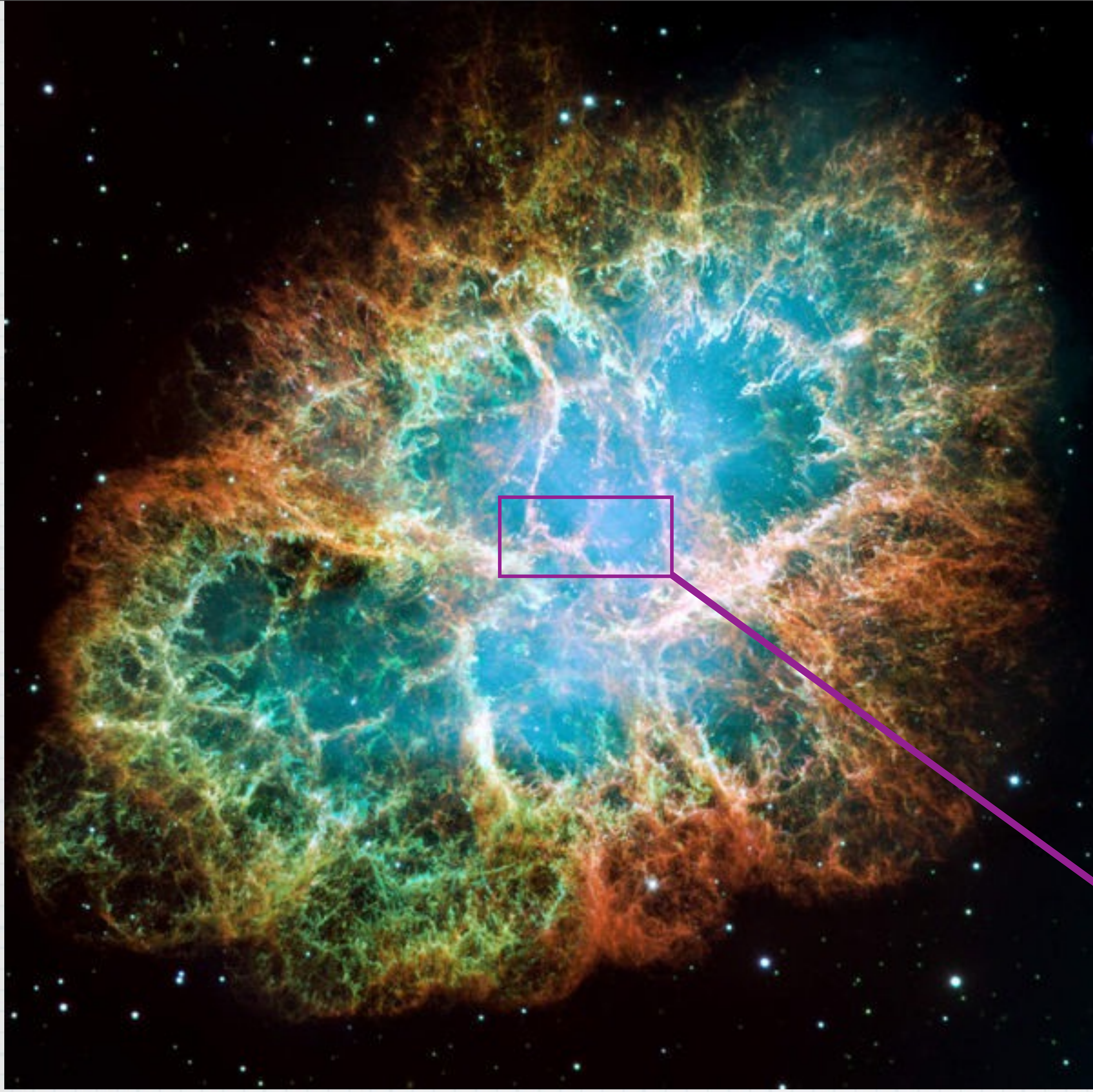
How were neutron stars discovered?...

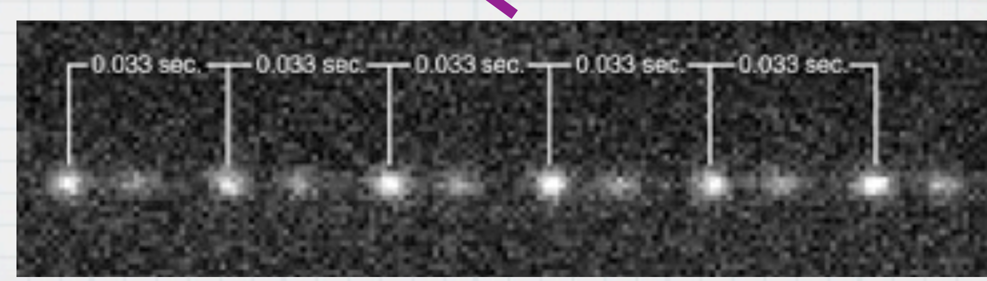
* Their signatures were very regular pulses of radio waves
* Pulsars were linked to neutron stars in 1968 when two more were discovered at the very centers of the Crab and Vela Nebulae (both supernovae remnants)

Pulsars are neutron stars that give off very regular pulses of radiation



Pulsar at center of Crab Nebula pulses 30 times per second





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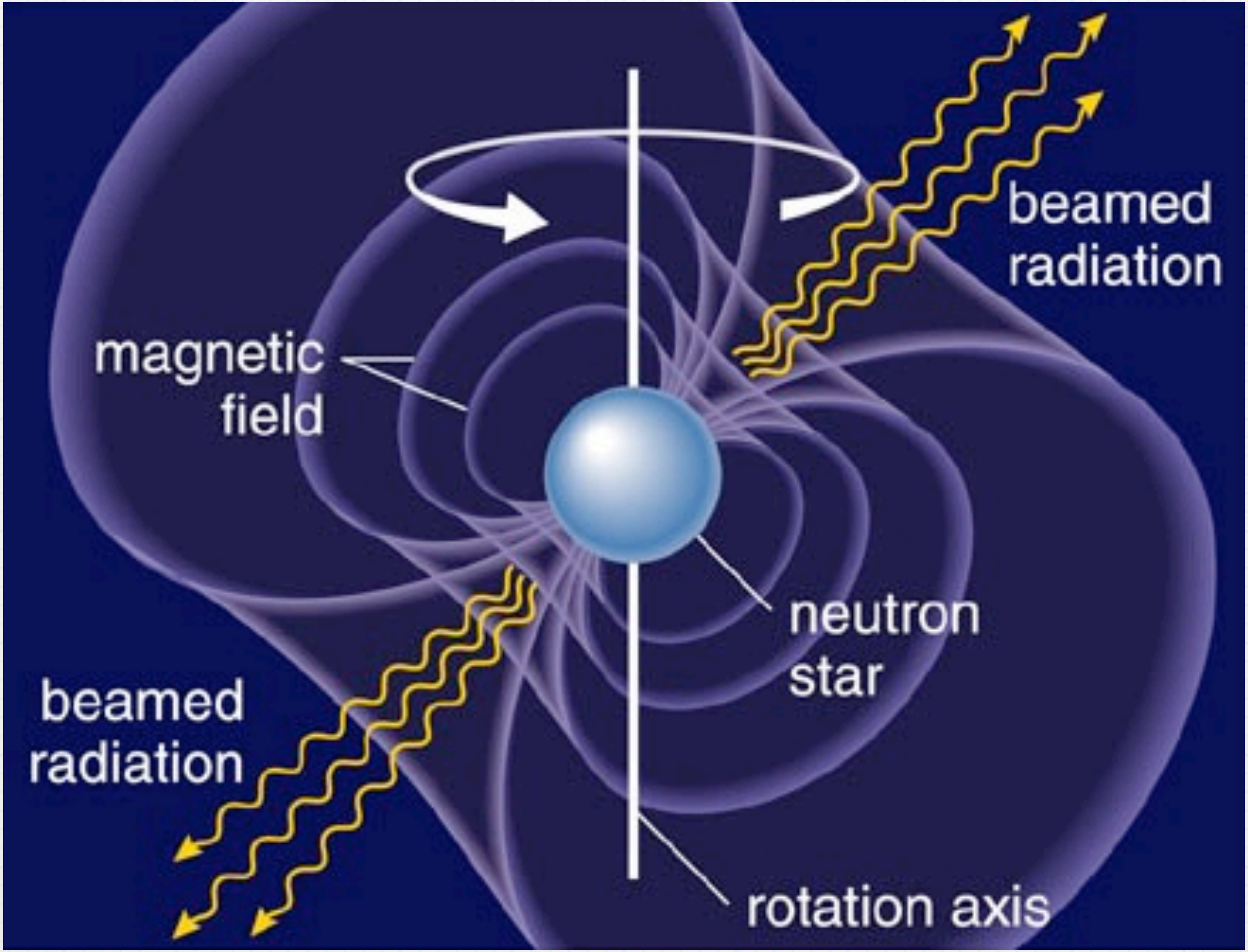
Pulsars are rotating neutron stars that act like lighthouses

Beams of radiation coming from poles look like pulses as they sweep by Earth

Pulsars' spins do slow down with time as rotational energy is lost via photons generated by the spinning magnetic field

A pulsar's rotation is not (necessarily) aligned with its magnetic poles



Why Pulsars must be Neutron Stars

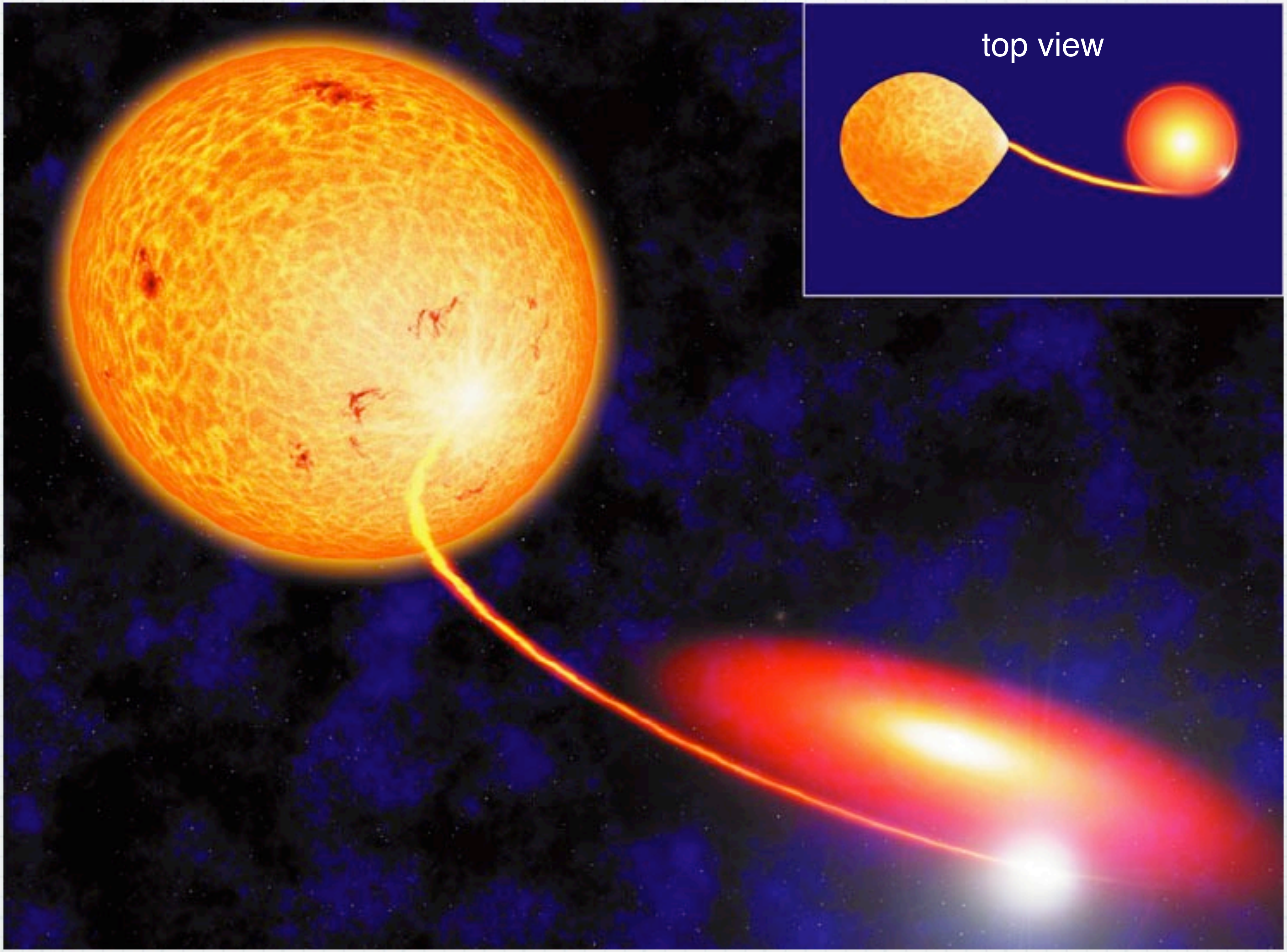
- Circumference of star = 2π (radius) ≈ 60 km
- Spin Rate of Fast Pulsars ≈ 1,000 revolution/s
- Surface Rotation Velocity ≈ 60,000 km/s

  ≈ 20% speed of light
- Anything but a neutron star would be torn to pieces

Neutron stars in close binary systems

* Like white dwarfs, neutron stars can get a second life if their companion star is close
* Gas will flow from the companion and form an accretion disk around the neutron star
* This accretion disk is much hotter and denser due to the neutron star's strong gravity than a white dwarf's accretion disk

Matter falling toward a neutron star forms an accretion disk, just as in a white-dwarf binary

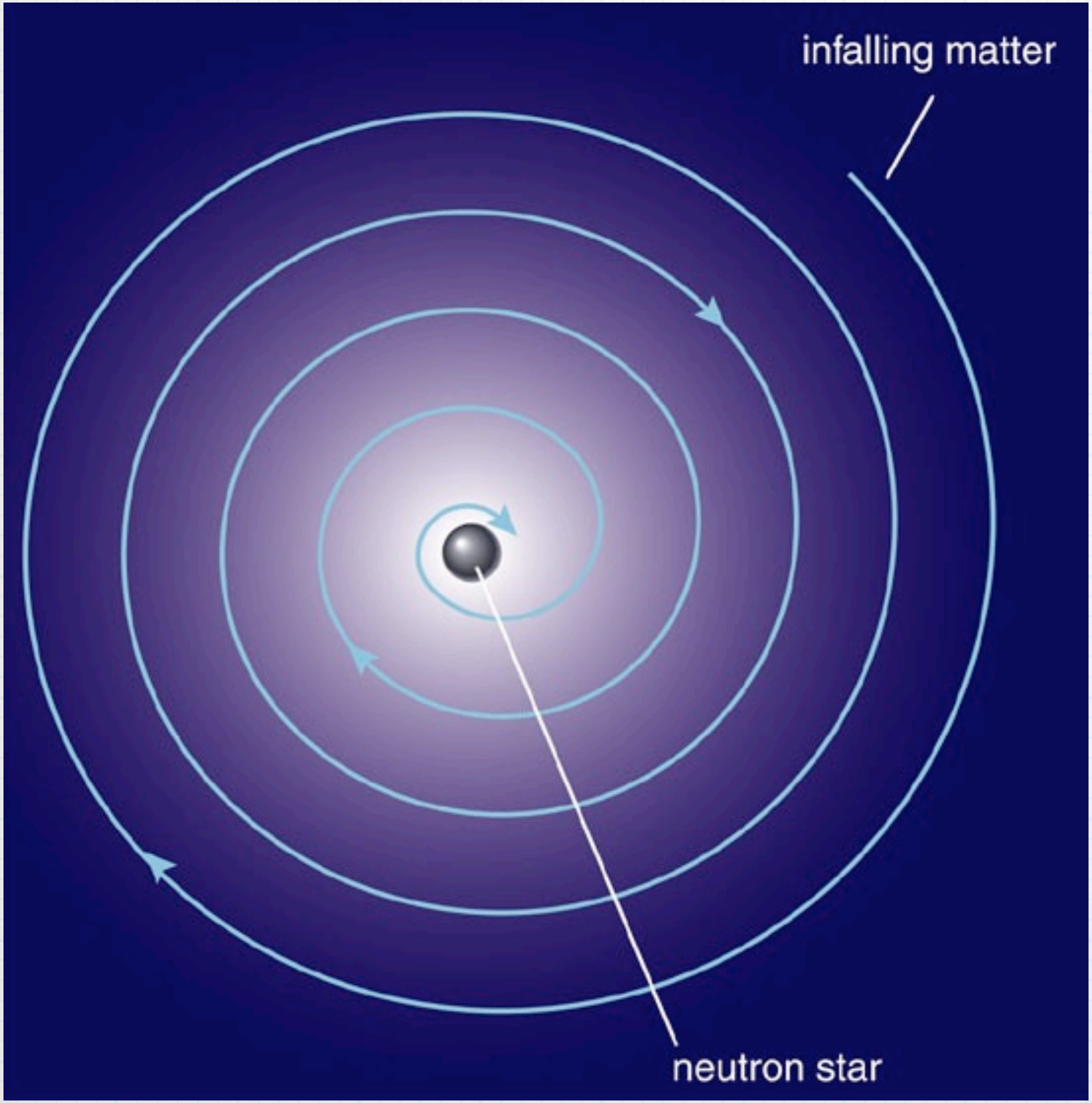


Slowly adding matter

* Hydrogen-rich material falls from the accreting disk onto the surface of the neutron star
* The neutron star slowly adds matter
* A fusing hydrogen layer (about one meter thick) exists permanently
* Helium is created underneath the hydrogen layer

X-ray Bursters

* Helium fusion happens when the temperature of this layer reaches 100 million K and lasts only a few seconds
* This creates an X-ray burst
* This event happens every few hours
* These events are 100,000 times as luminous than the Sun but only in X-ray light
* Neutron stars in that phase of their life are called X-ray bursters



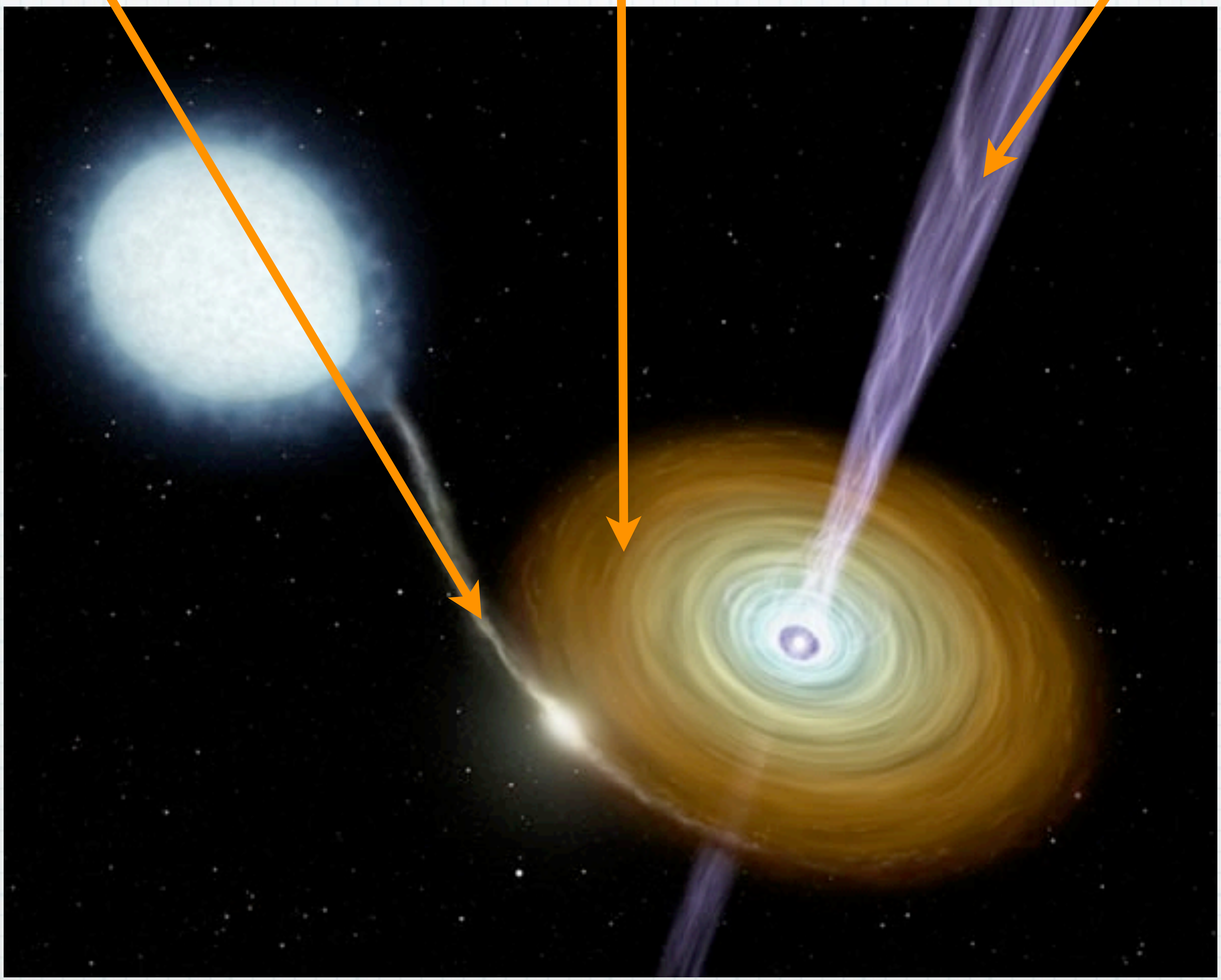
Accreting matter adds angular momentum to a neutron star, increasing its spin

The inner regions of the accretion disk emit X-rays

Episodes of fusion on the surface lead to X-ray bursts

Compact Jets in Neutron Stars

Falling matter from the accretion disk is shot out



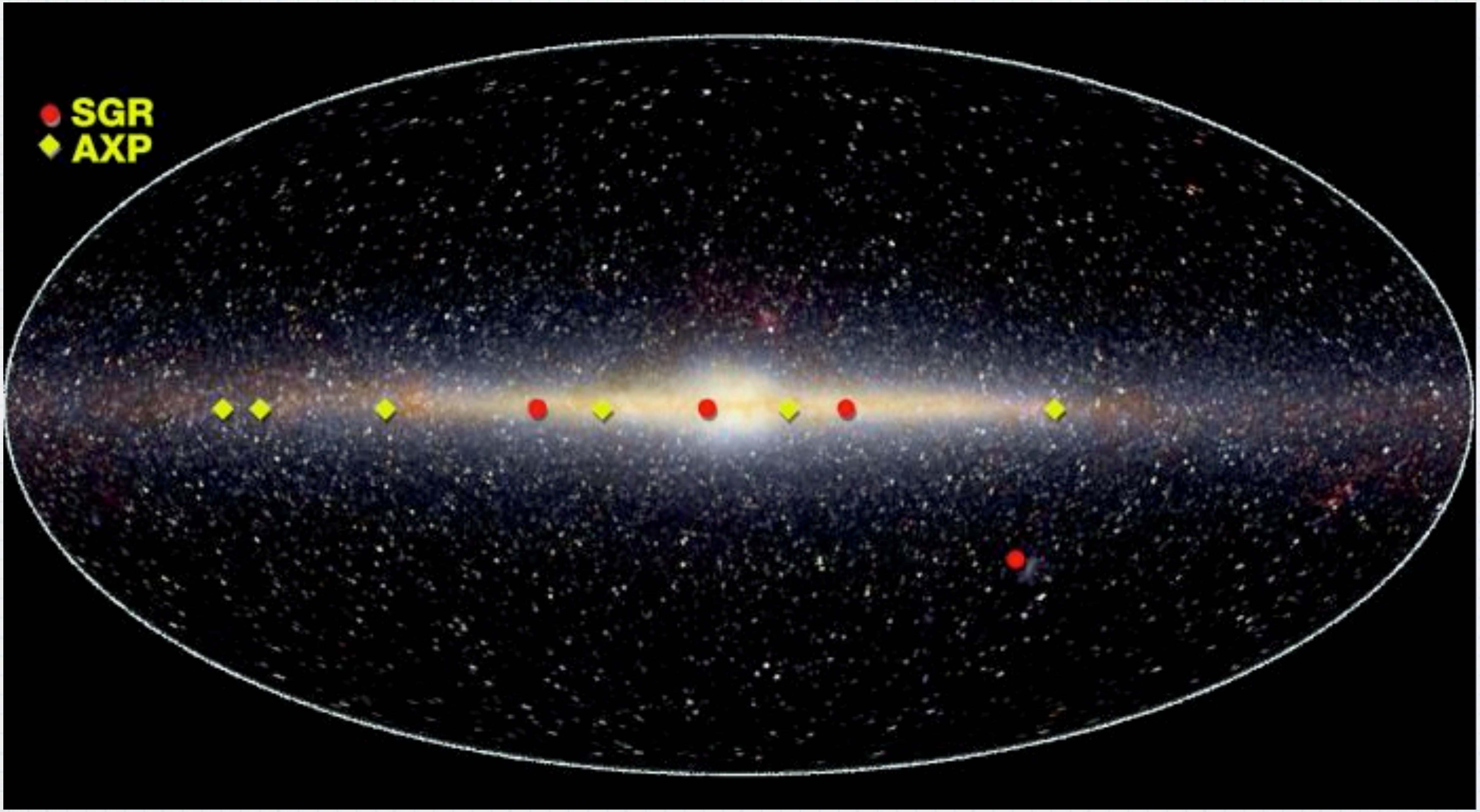
Magnetar

* **Magnetars** are young neutron stars that are wrapped in magnetic fields of gigantic strengths
* Field strength is around 1 quadrillion Gauss (1,000,000,000,000,000 = 10^{15} Gauss)
* Magnetars are the only deep-space objects that can directly affect Earth
* If a magnetar were to magically appear at half the Moon's distance from Earth, its magnetic field would wipe the details off every credit card on Earth

Magnetar...

* Magnetars are powered by starquakes which trigger matter-antimatter reactions
* The quakes are created because the intense magnetic fields distorts the neutron stars' crusts
* In about 10,000 years, the magnetic field is weakened (to about 2 trillion gauss) and a "normal" neutron star emerges

Known Magnetar Candidates in the Milky Way

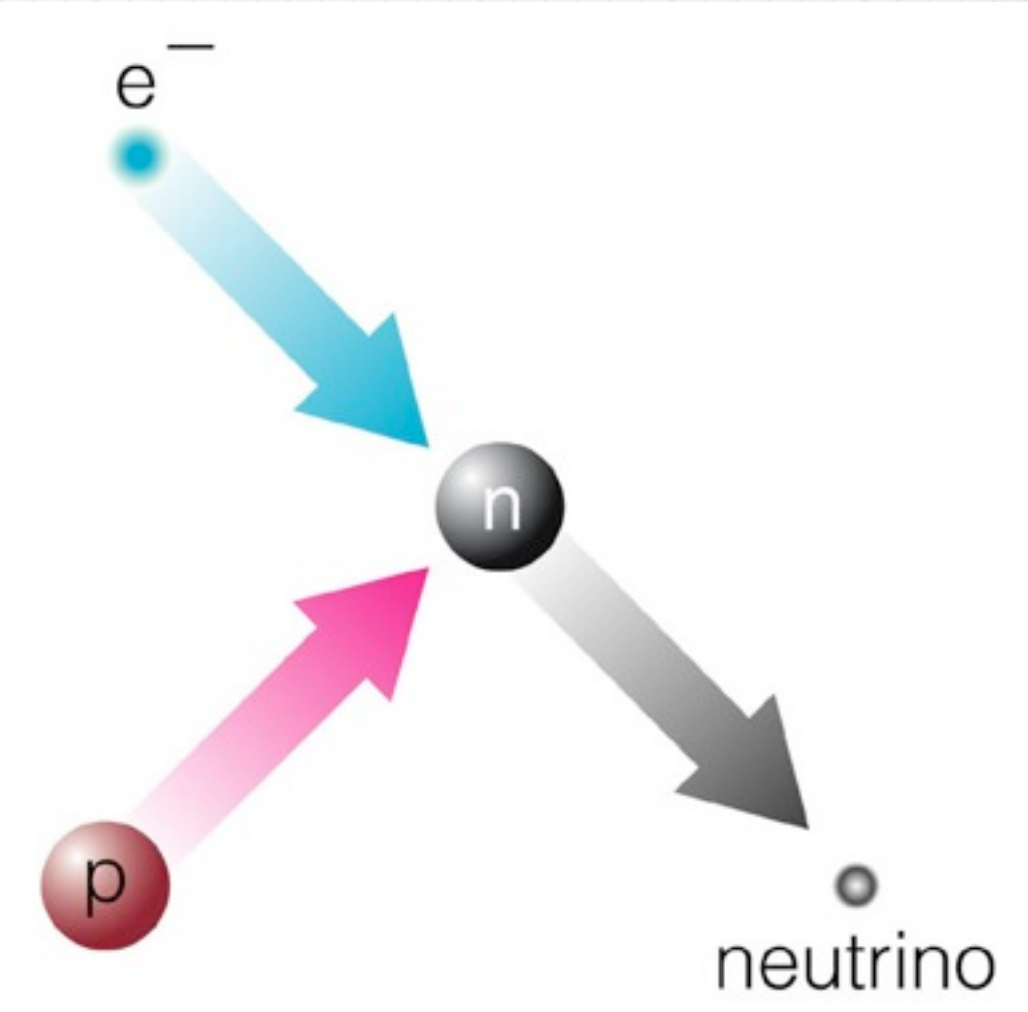


Picture Credit: E. L. Wright (UCLA), COBE Project, Courtesy MSFC, NASA

SGR: Soft Gamma Repeaters
AXP: Anomalous X-ray Pulsars

Snapshot

* **What is a neutron star?**
* **A neutron star is** the ball of neutrons **created by the collapse of the iron core in a massive star supernova** as the electron degeneracy pressure fails and electrons and protons combine



Snapshot

* How were neutron stars discovered?
* Neutron stars spin rapidly when they are born, and their strong magnetic fields can direct beams of radiation that sweep through space as the neutron star spins. We see such neutron stars as pulsars and they were discovered first before identified as neutron stars

Snapshot

* What can happen to a neutron star in a close binary system?
* Neutron stars in close binary systems can accrete hydrogen from their companions, forming dense, hot accretion disks. The hot gas emits strongly in X rays, so we see these systems as X-ray binaries. In some of these systems, frequent bursts of helium fusion ignite on the neutron star's surface, emitting X-ray bursts

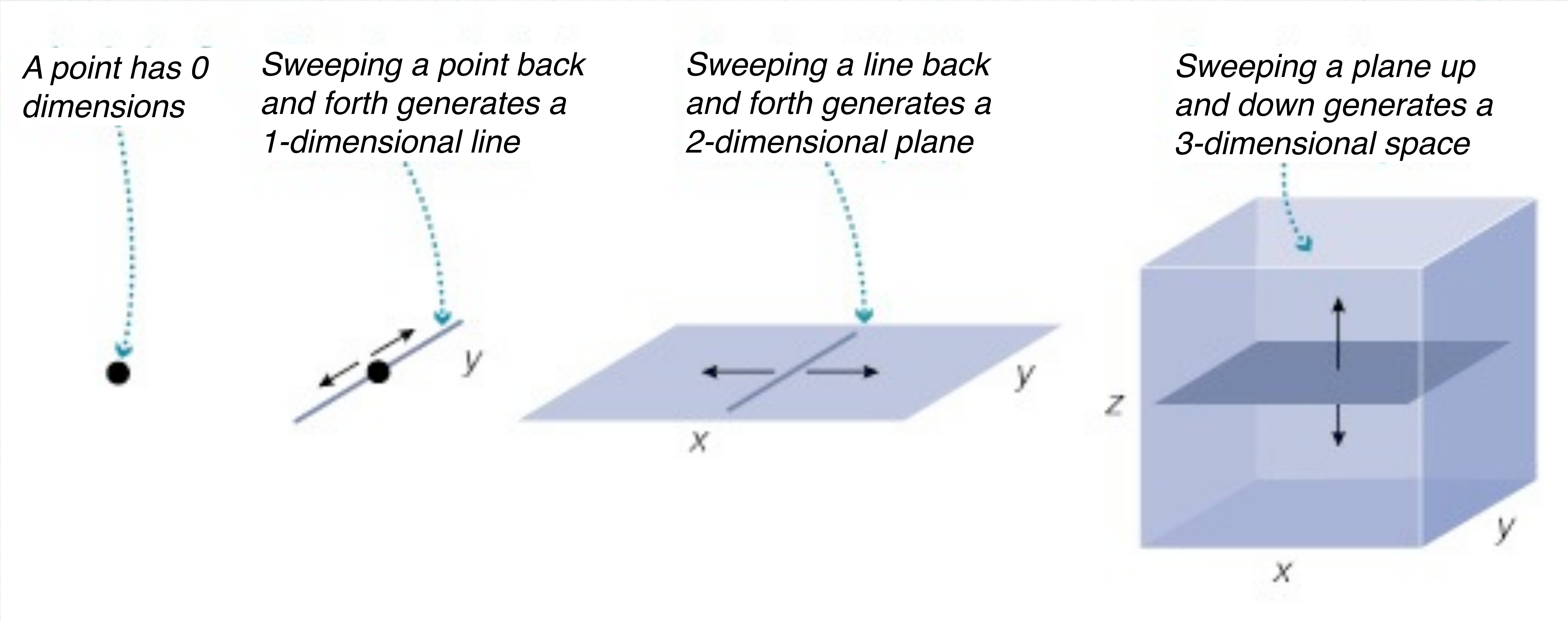
Beyond Neutron Stars: Black Holes
(Gravity's Ultimate Victory)

* White dwarfs and neutron stars are weird enough
* Yet, there are more strange and esoteric objects out there:
* Black holes or the total collapse of matter upon itself

First: A Review of Spacetime - The Fabric of the Universe

* Einstein's Special Relativity Theory showed that space and time are not absolute
* Instead they are inextricably linked in a four-dimensional fabric we call spacetime

Dimensions of Space



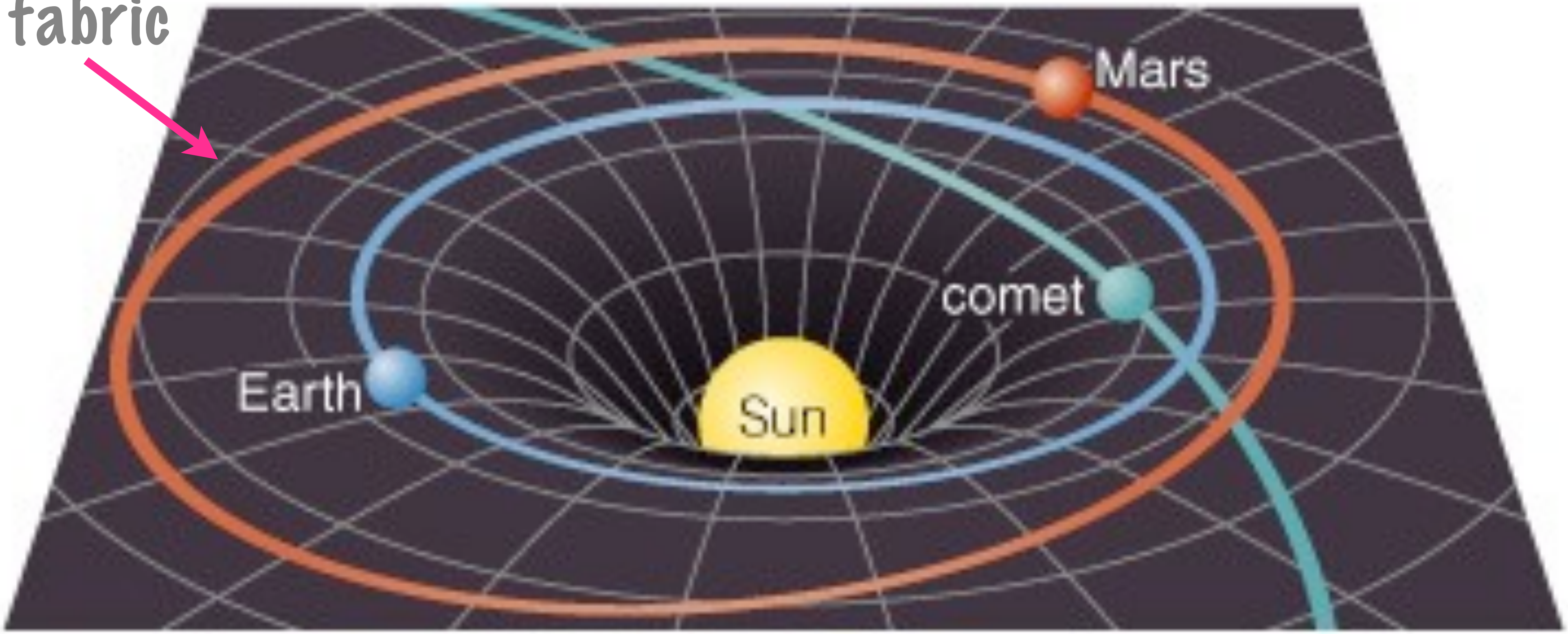
* An object's number of dimensions is the number of independent directions in which movement is possible within the object

Dimensions of Spacetime

* We can move through three dimensions in space (x,y,z), back and forth
* Our motion through time is in one direction only (t), where t increases
* Spacetime, the combination of space and time, has four dimensions (x,y,x,t)

What is gravity really?

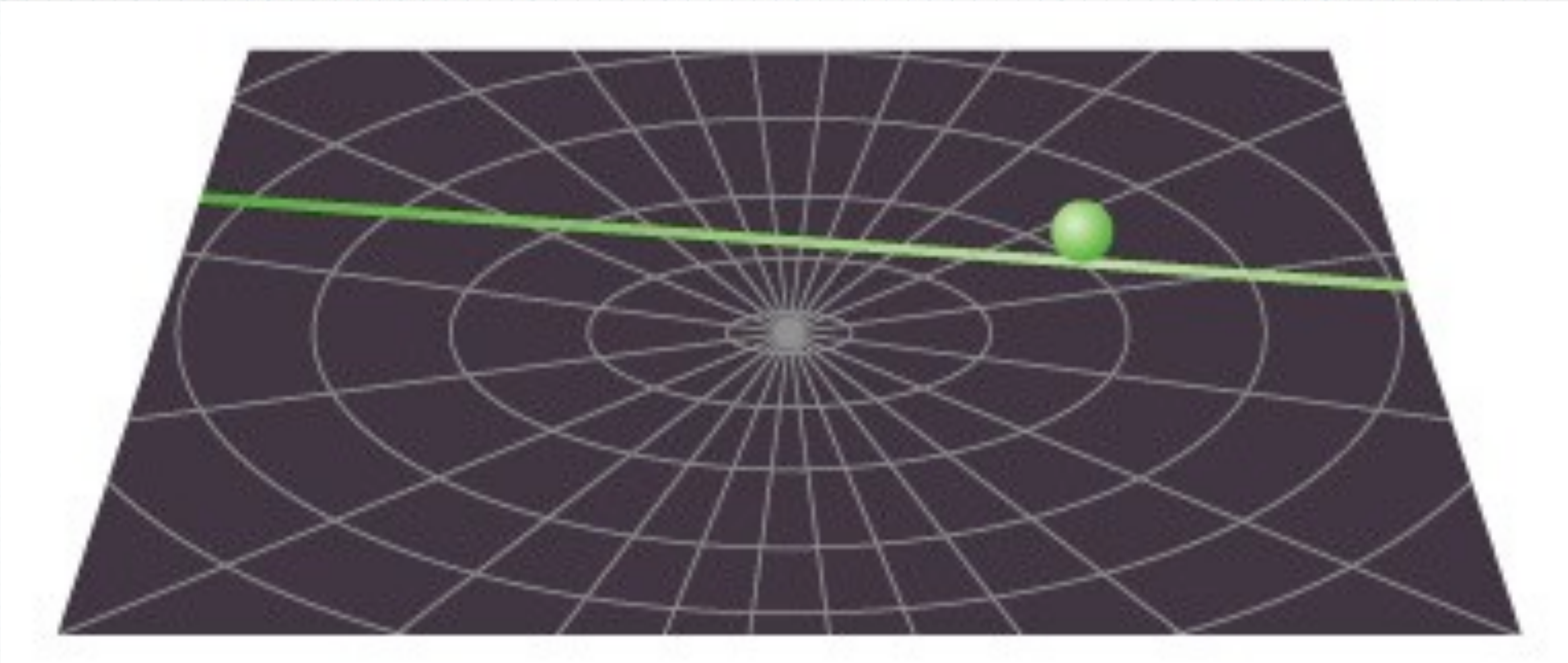
spacetime fabric



Gravity, Newton, and Einstein

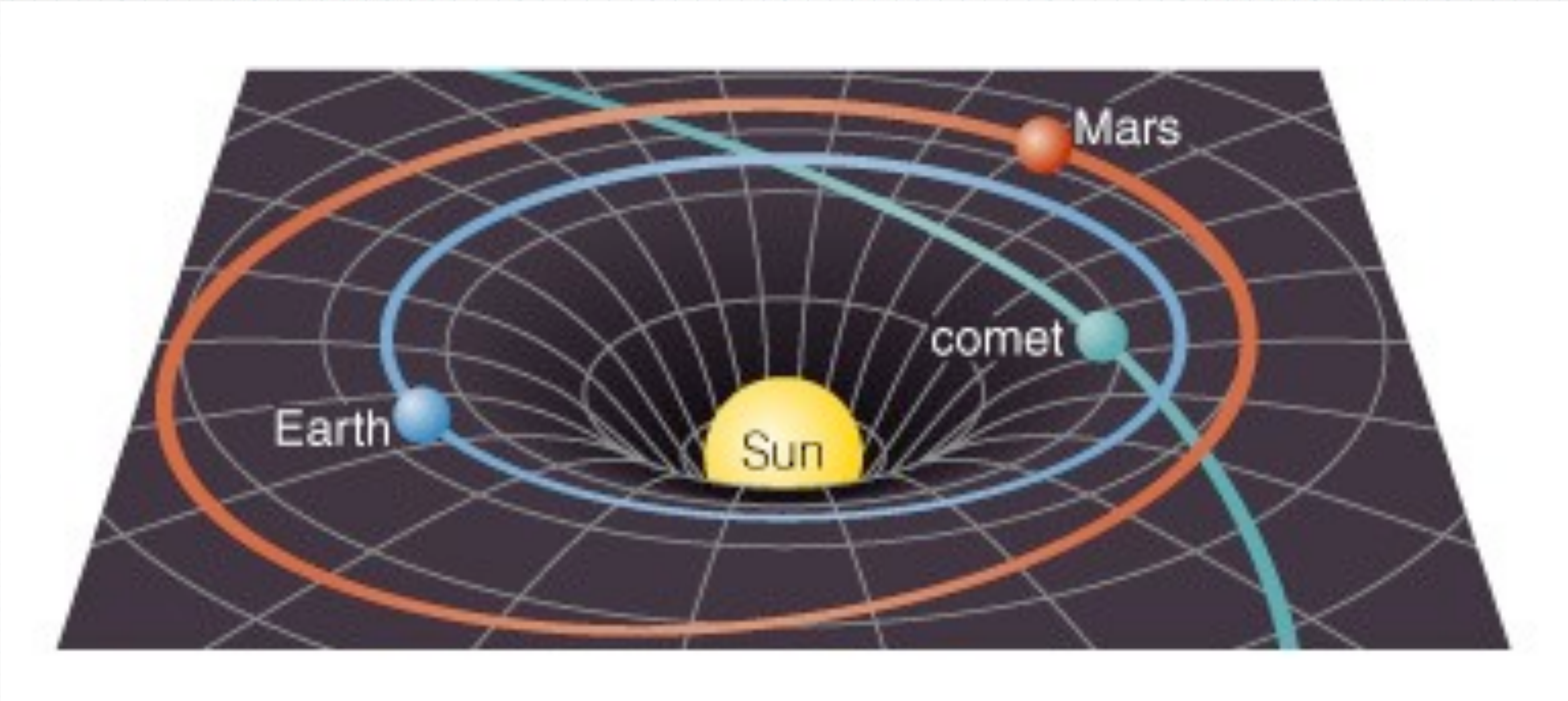
* Newton viewed gravity as a mysterious "action at a distance"
* Einstein removed the mystery by showing that what we perceive as gravity arises from curvature of spacetime

Rubber Sheet Analogy



* On a flat rubber sheet
  * Free-falling objects move in straight lines
  * Circles all have circumference 2πr

Rubber Sheet Analogy

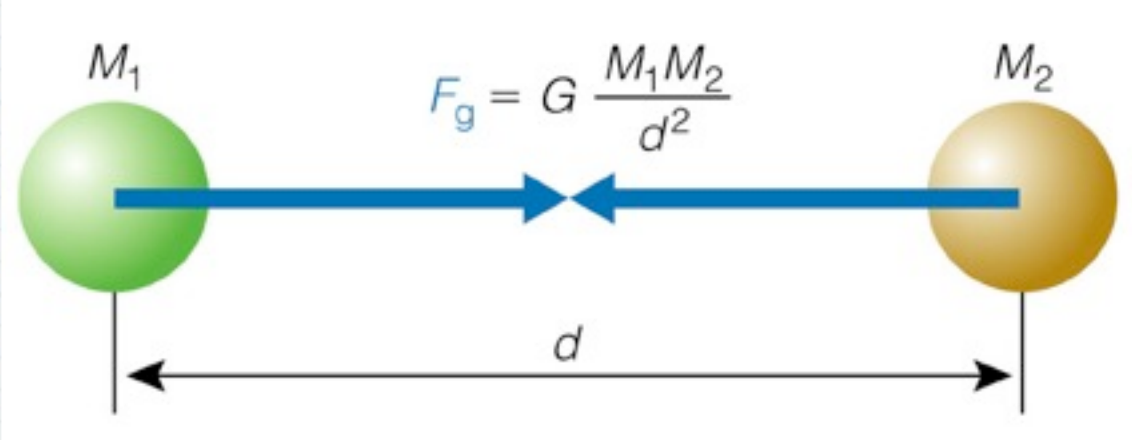


- Mass of Sun curves spacetime:
  - Free-falling objects near Sun follow curved paths
  - Circles near Sun have circumference < $2\pi r$

Limitations of the Analogy

* Masses do not rest "upon" the spacetime like they rest on a rubber sheet
* Rubber sheet shows only two dimensions of space, not four dimensions of spacetime

Question



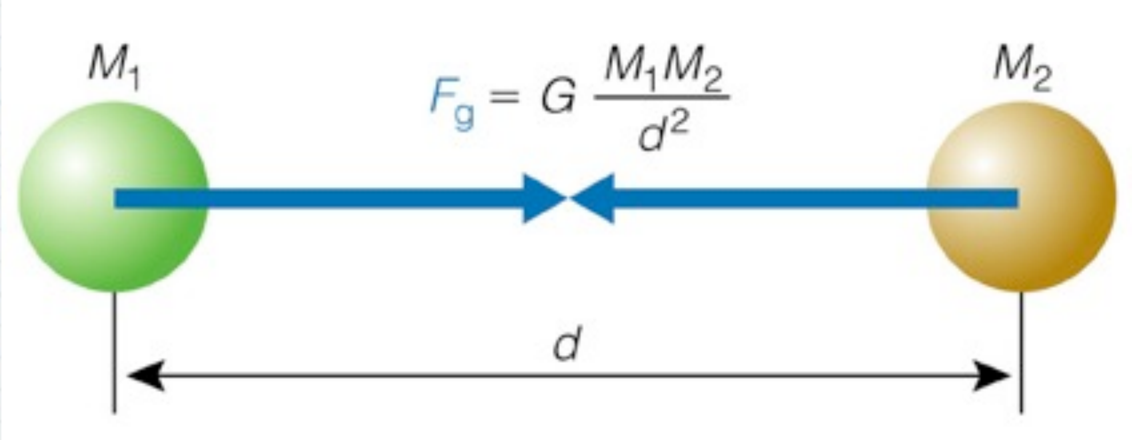
- What happens to the escape velocity from an object if you shrink it?

A. It increases

B. It decreases

C. It stays the same

Question



* What happens to the escape velocity from an object if you shrink it?

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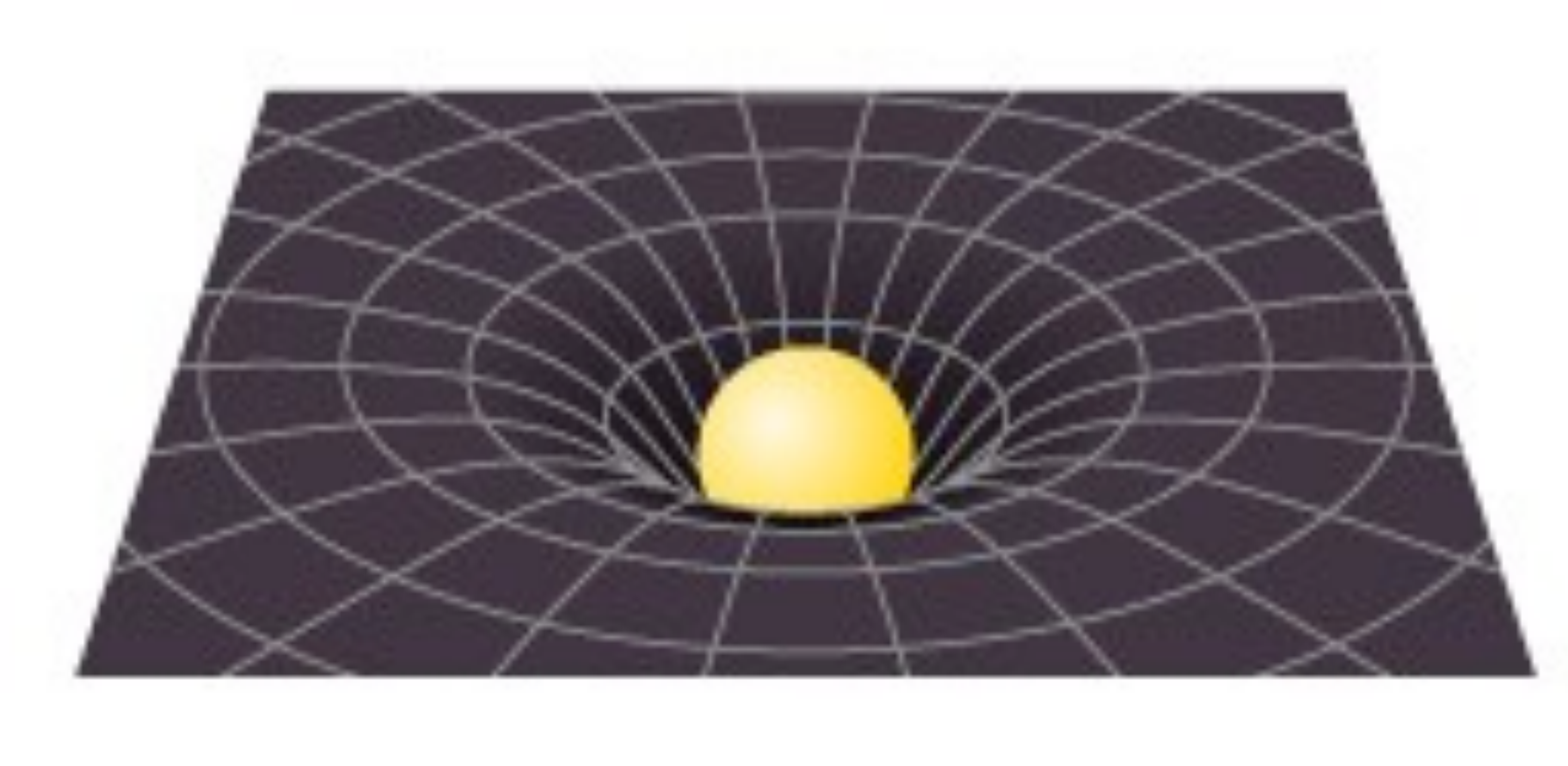
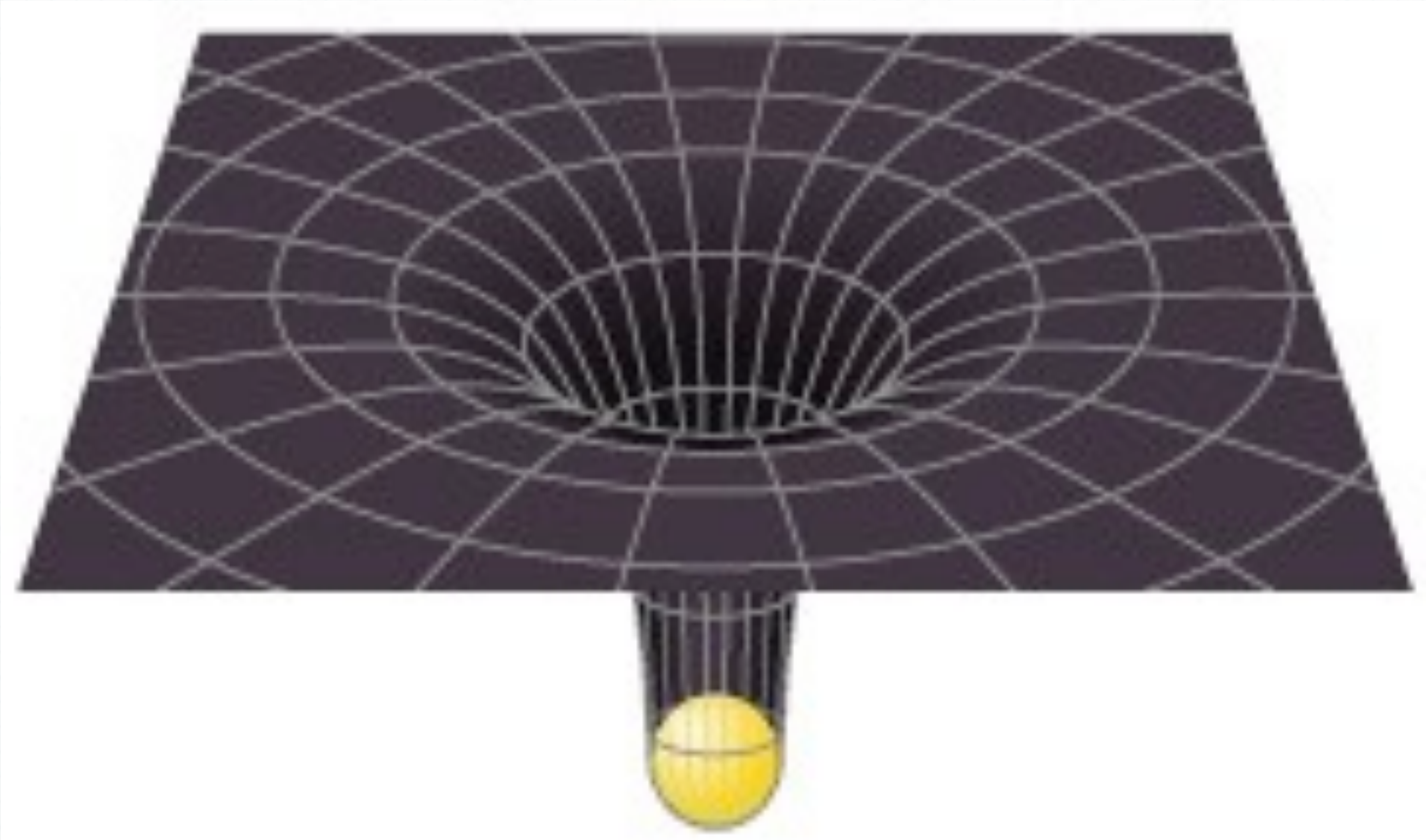
Curvature near Sun



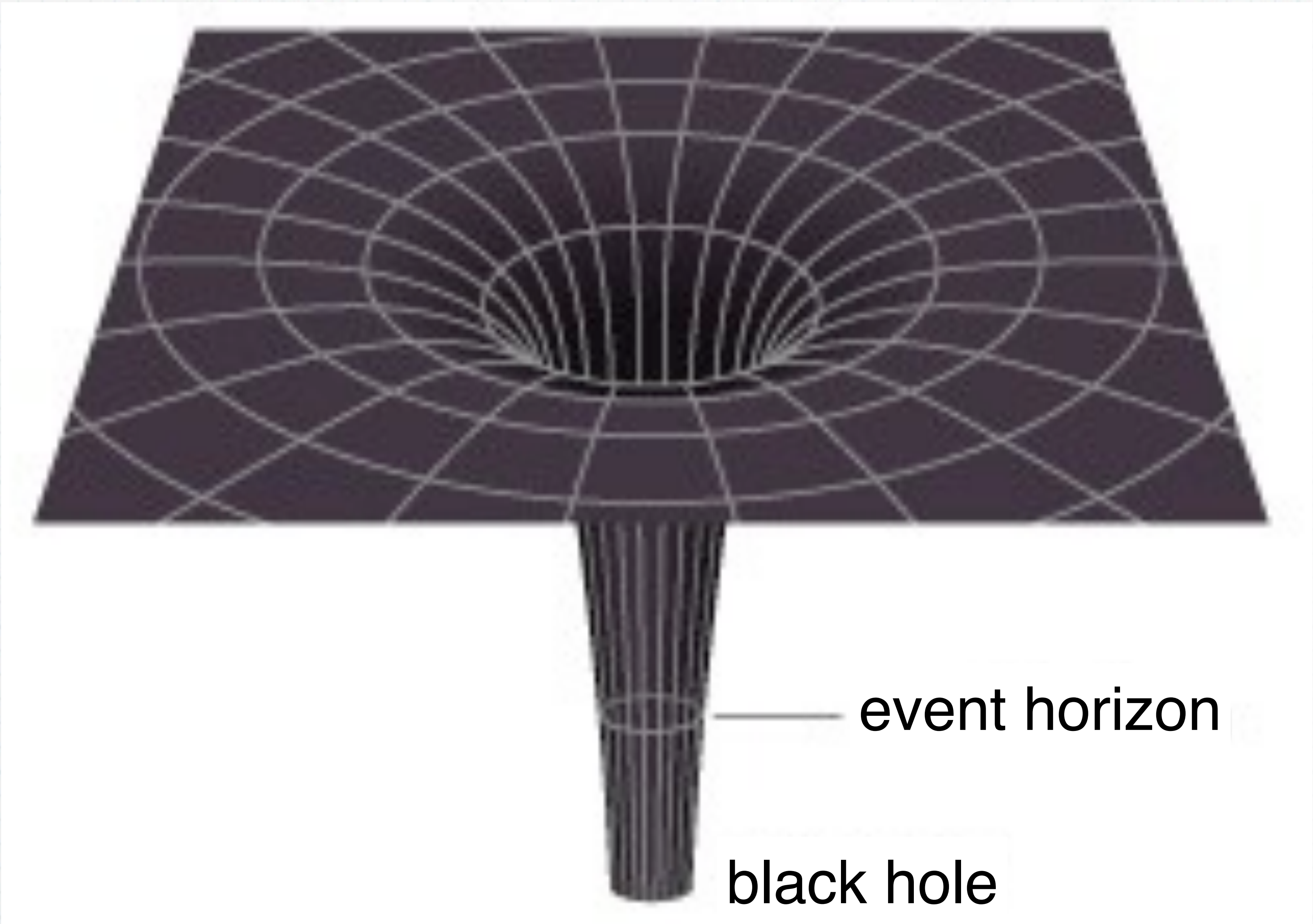
Sun's mass curves spacetime near its surface

Curvature near a Neutron Star



The curvature of spacetime is much greater near a neutron star, as is the local strength of gravity

Curvature near Black Hole



A black hole curves the local spacetime to a bottom less pit

What is a black hole?

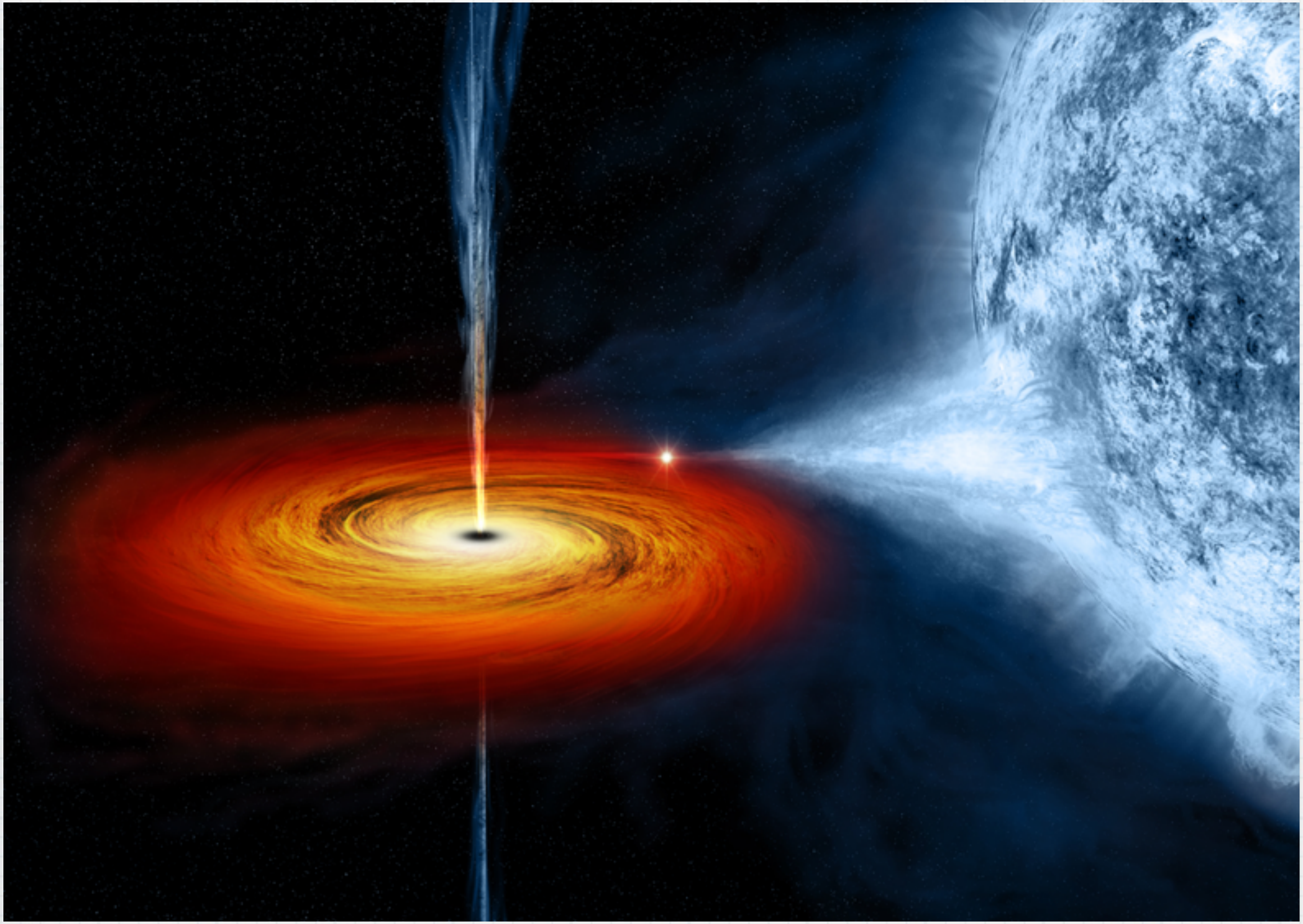
* A black hole is an object whose gravity is so powerful that nothing even light can escape it

➡ The escape velocity of a black hole is greater than the speed of light

* Black holes cannot be analyzed without involving Einstein's complete theory of general relativity

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Cygnus X-1



14.8 M_{Sun} - 800 rev. per seconds - 6,070 light-years away

How does a black hole form?

* We saw how a neutron star forms: the electron degeneracy pressure fails (as the electrons reach the velocity of light) and electrons combine with protons to form neutrons
* Quantum mechanics says that neutrons in the same place cannot be in the same state

How does a black hole form?...

* Hence to find a free quantum state, the neutrons move quickly around, this creates a degeneracy pressure
* Then the neutron degeneracy pressure resists further crushing from gravity

Neutron Star Limit

* In a white dwarf, electron degeneracy pressure resists the crush of gravity until the white dwarf's mass becomes 1.4 M_{Sun}: **the Chandrasekhar limit**
* In a neutron star, neutron degeneracy pressure resists the crush of gravity. Yet with enough mass, gravity can overcome it as well.
* The limit is about 3 M_{Sun}. The limit is called **the Tolman-Oppenheimer-Volkov limit (TOV)**

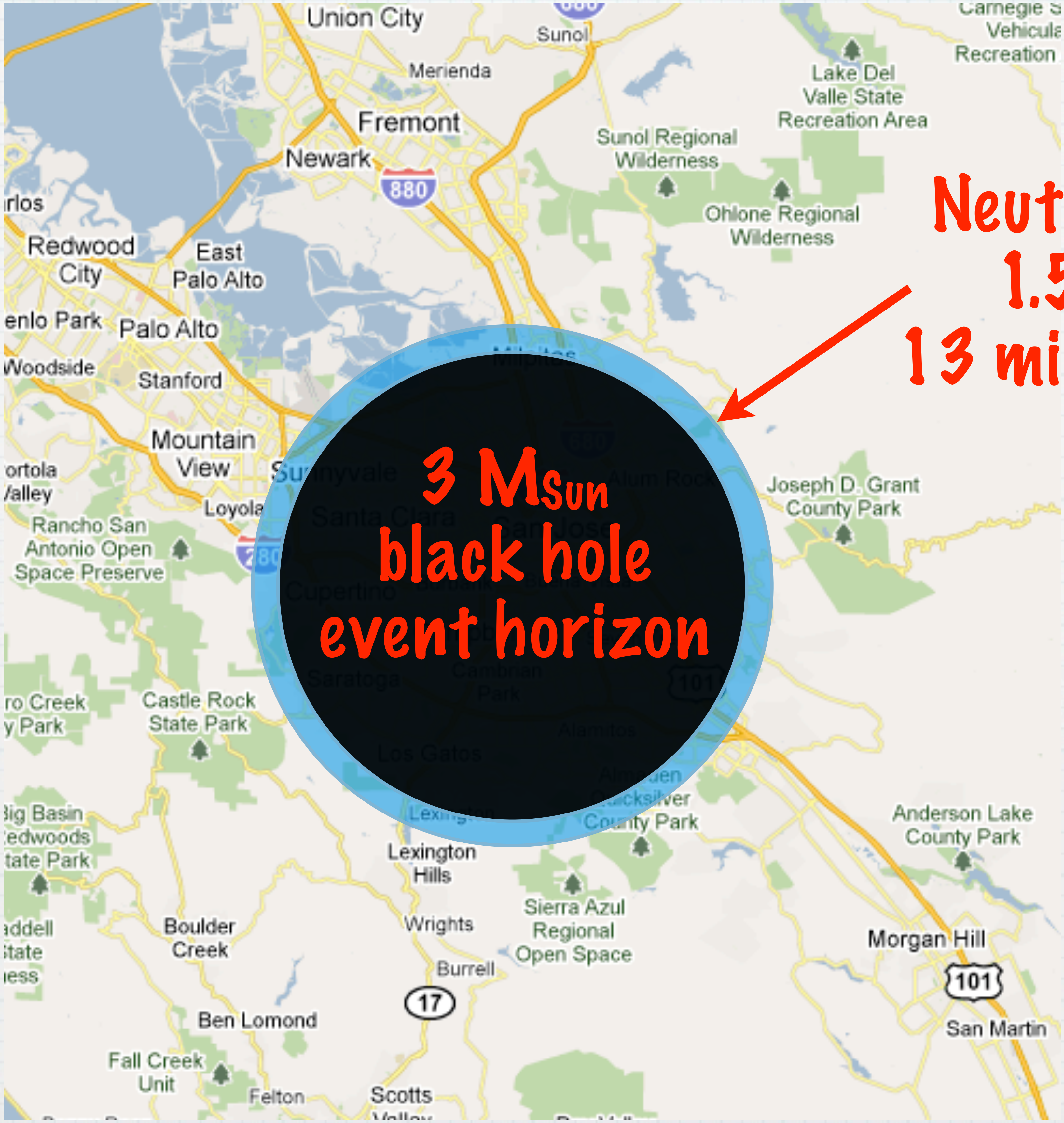
Neutron Star Limit

* If further mass is added to a neutron star by a giant companion star...
* **Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about 3 M_{Sun}**
* Or if a massive star supernova does not blow all its outer material and it falls back onto the core it can make a black hole (**hypernova**)

Neutron Star Limit...

* A black hole forms when the neutron degeneracy pressure fails (as the neutrons reach the speed of light)
* There is a gravitational collapse of matter: the geometry of spacetime is deformed near infinity at the center and the hole is formed
* The Schwarzschild radius is smaller than the radius of the neutron star that formed it

A neutron star is about the same size as a small city

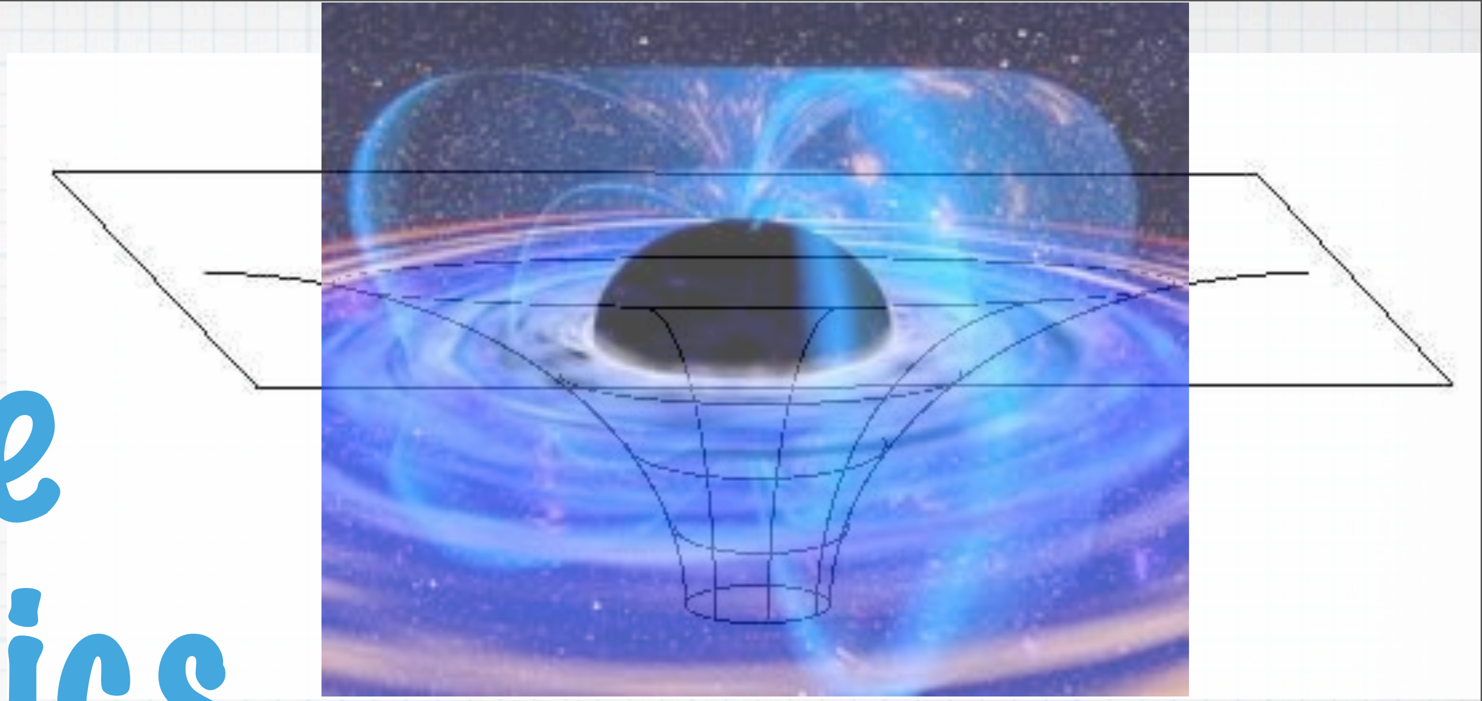


Neutron star
1.5 MSun
13 miles across

Black Hole Characteristics

* The "surface" of a black hole is the radius at which the escape velocity equals the speed of light
* This spherical surface is known as the event horizon
* The radius of the event horizon is known as the Schwarzschild radius

Black Hole Characteristics...



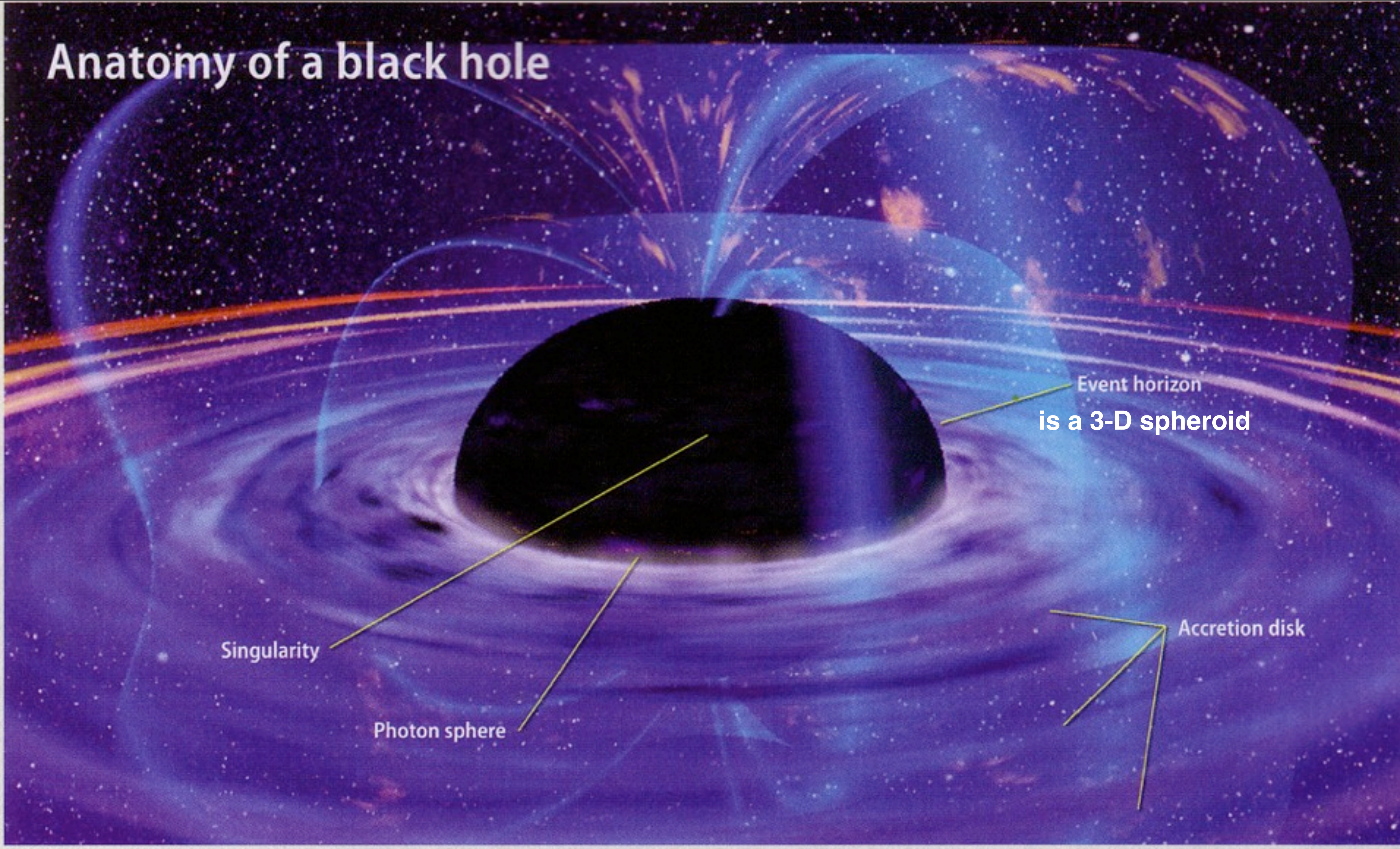
* the three characteristics of a black hole are its
  * 1) mass, 2) angular momentum, and 3) electric charge. Mass is the most important
* the event horizon is derived mainly from the mass (rotation will make the event horizon smaller)

No Escape

- Nothing can escape from within the event horizon because nothing can go faster than light
- No escape means there is no more contact with something that falls in
- Whatever falls in increases the black hole mass, changes its spin or charge, but otherwise loses its original identity

Singularity

* Beyond the neutron star limit, no known force can resist the crush of gravity (except - perhaps - quarks and electroweak degenerate pressures)
* As far as we know, gravity crushes all the energy (of that matter) into a single point known as a singularity
* In Physics, whenever we encounter singularities, we know our equations and our understandings are incomplete



Accretion disk — Matter (usually gas) captured by a black hole's gravitational pull; as the gas swirls toward the black hole, friction makes the gas glow and emit energy. Near the event horizon, accretion-disk material moves rapidly and emits X rays.

Event horizon — A black hole's gravitational boundary, where the escape velocity equals the speed of light. Any object passing through the event horizon will disappear forever, and no object within the event horizon is observable from outside.

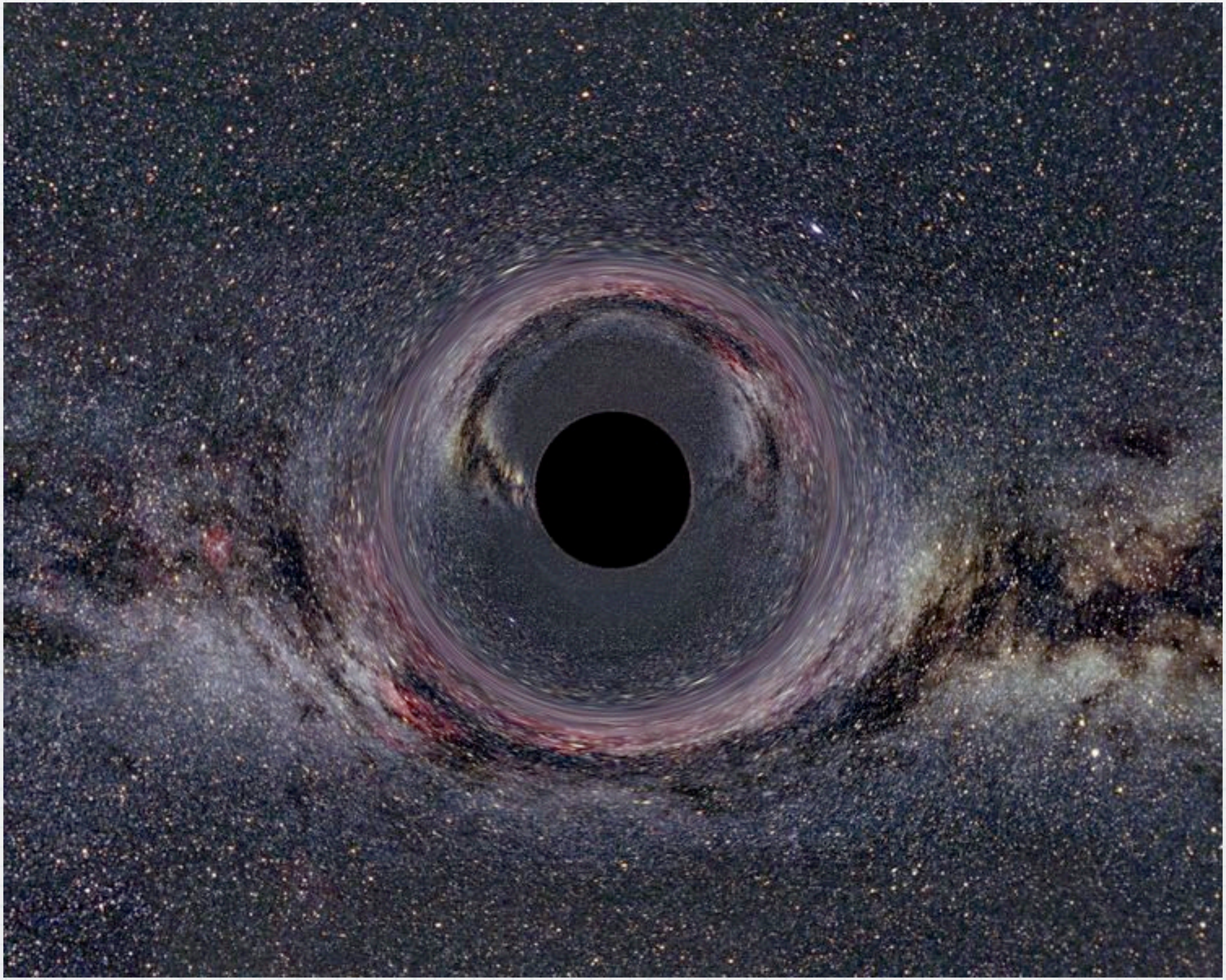
Photon sphere — A bright region surrounding the black hole where any light created must be directed outward to escape the black hole's gravity. The photon sphere's radius equals 1.5 times the radius of the event horizon.

Singularity — A black hole's central point, where all matter ends up and both the curvature of space-time and the density are infinite. This point is unobservable. The singularity's mass defines the size of the black hole's event horizon.

Inside a Black Hole

* The physics of a black hole are not yet complete
* Quantum Mechanics and General Relativity do not agree and express the same realities in them
* Our comprehension of the Universe is lacking some fundamental traits
* We need a theory of quantum gravity

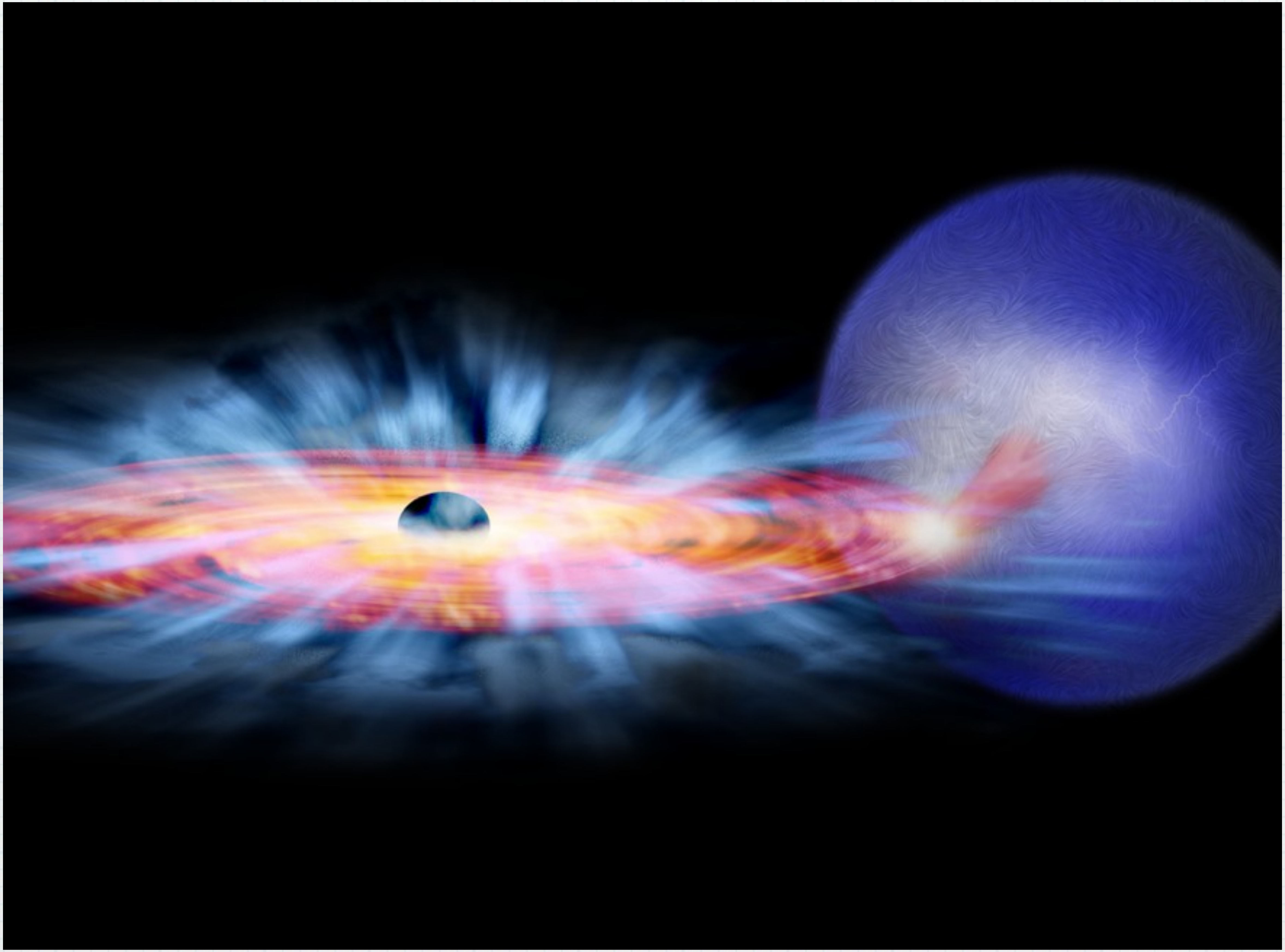
View of a simulated black hole of 10 M_{Sun}, from 600 km away



Adding Mass to a Black Hole

* A black hole gets more mass due to its accretion disk
* If it has a close stellar companion, the accretion disk will get bigger when that star becomes a red giant
* Adding mass to a black hole just makes the black hole bigger

A black hole and a close companion star



Question

* How does the radius of the event horizon change when you add mass to a black hole?

A. Increases

B. Decreases

C. Stays the same

Question

* How does the radius of the event horizon change when you add mass to a black hole?

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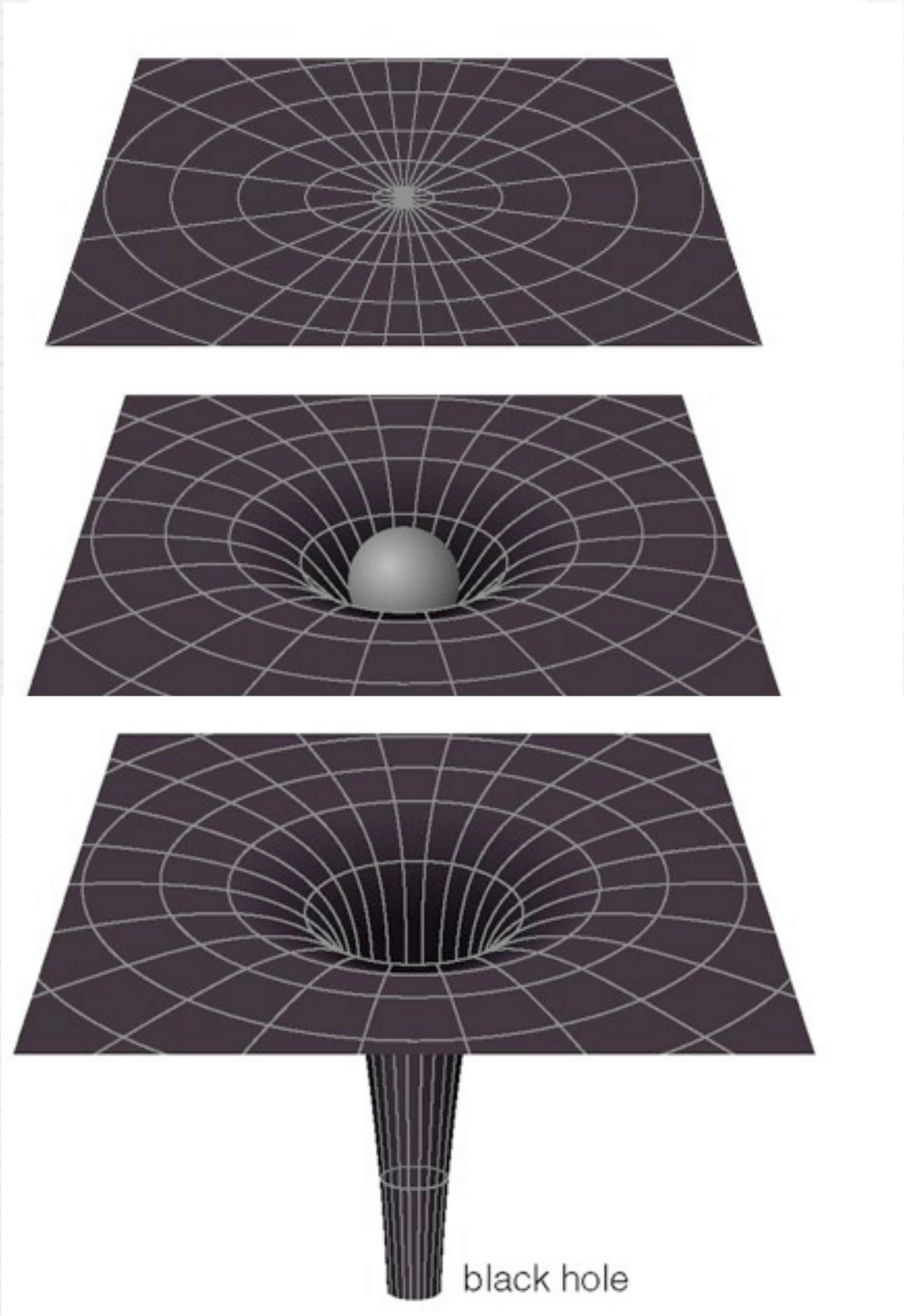
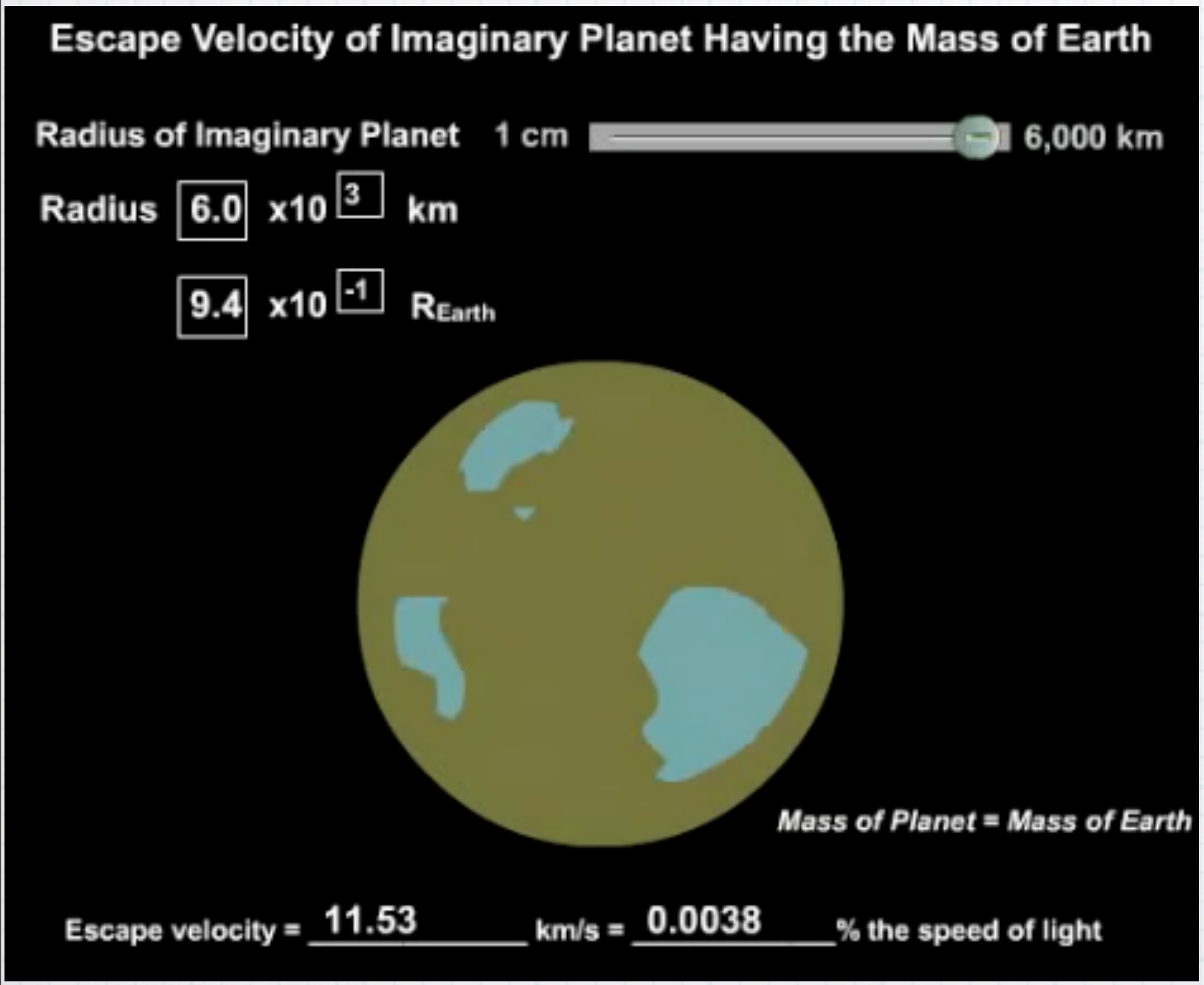


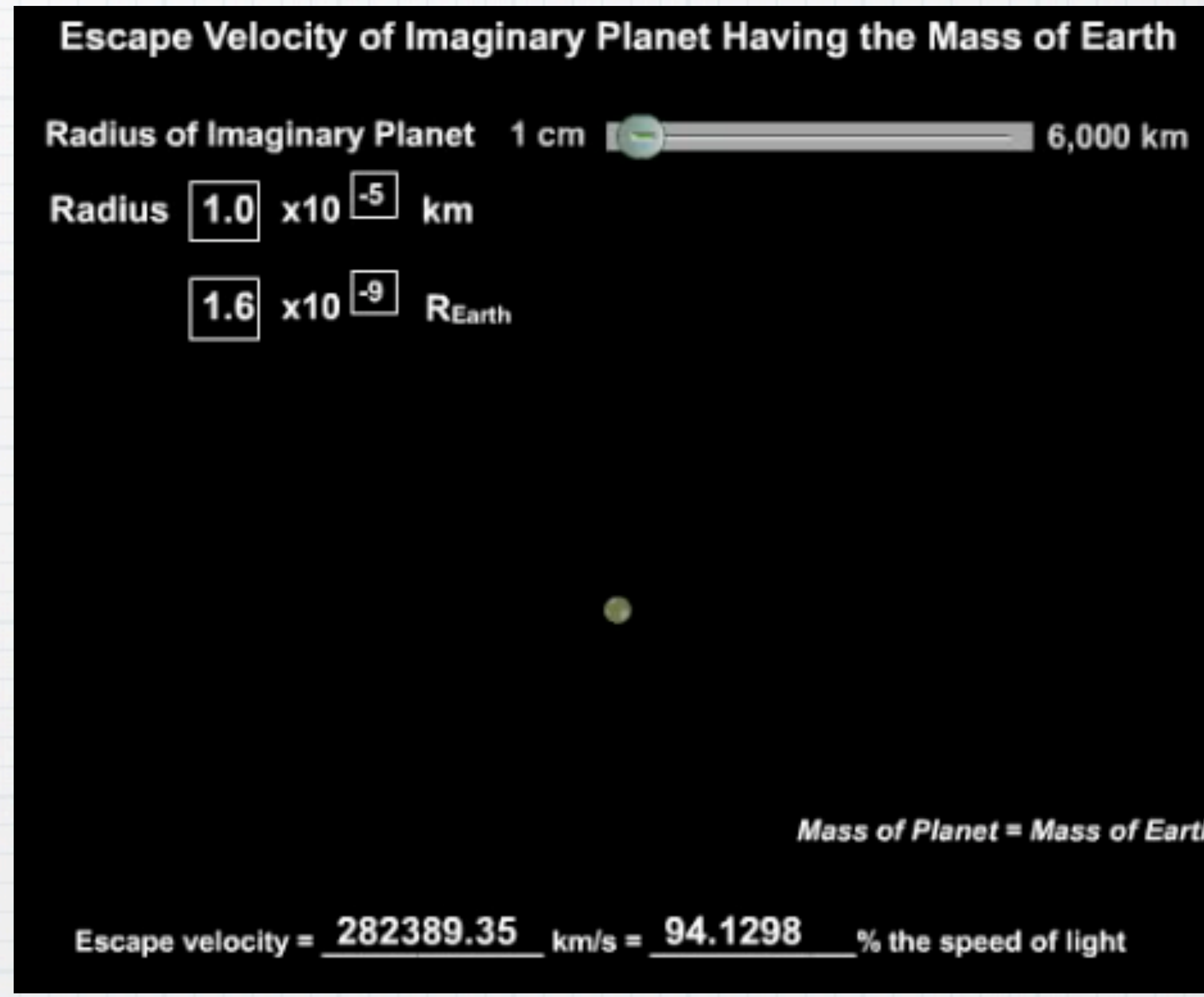
If the Sun shrank into a black hole, its gravity would be different only near the event horizon

Science Fiction movies have it all wrong: Black holes do not suck

Relationship between Escape Velocity and Planetary Radius

Light would not be able to escape Earth's surface if you could shrink it to < 1 cm





Question

* Is it easy or hard to fall into a black hole?

A. Easy

B. Hard

Hint: A black hole with the same mass as the Sun wouldn't be much bigger than a college campus

Question

* Is it easy or hard to fall into a black hole?

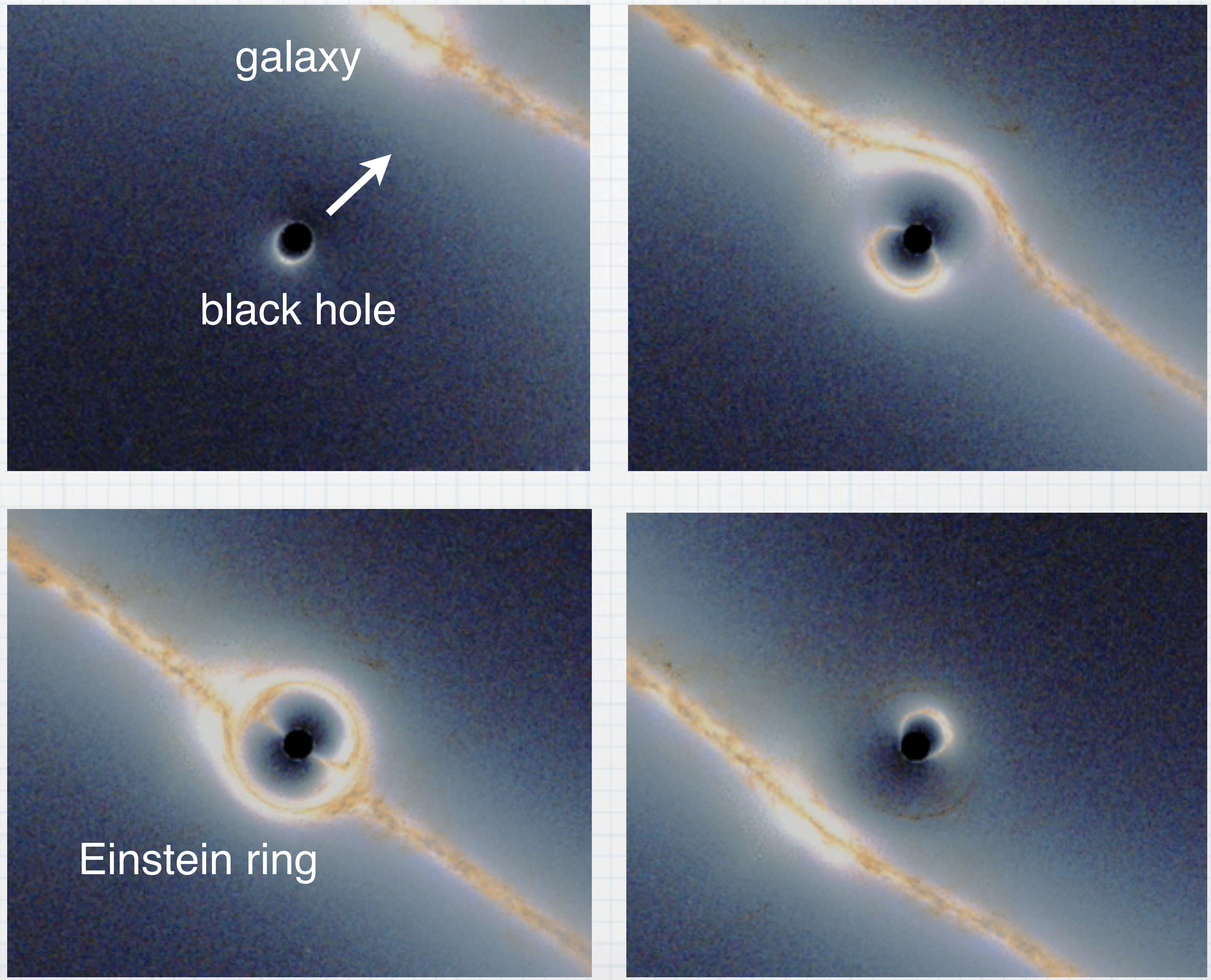
A. Easy

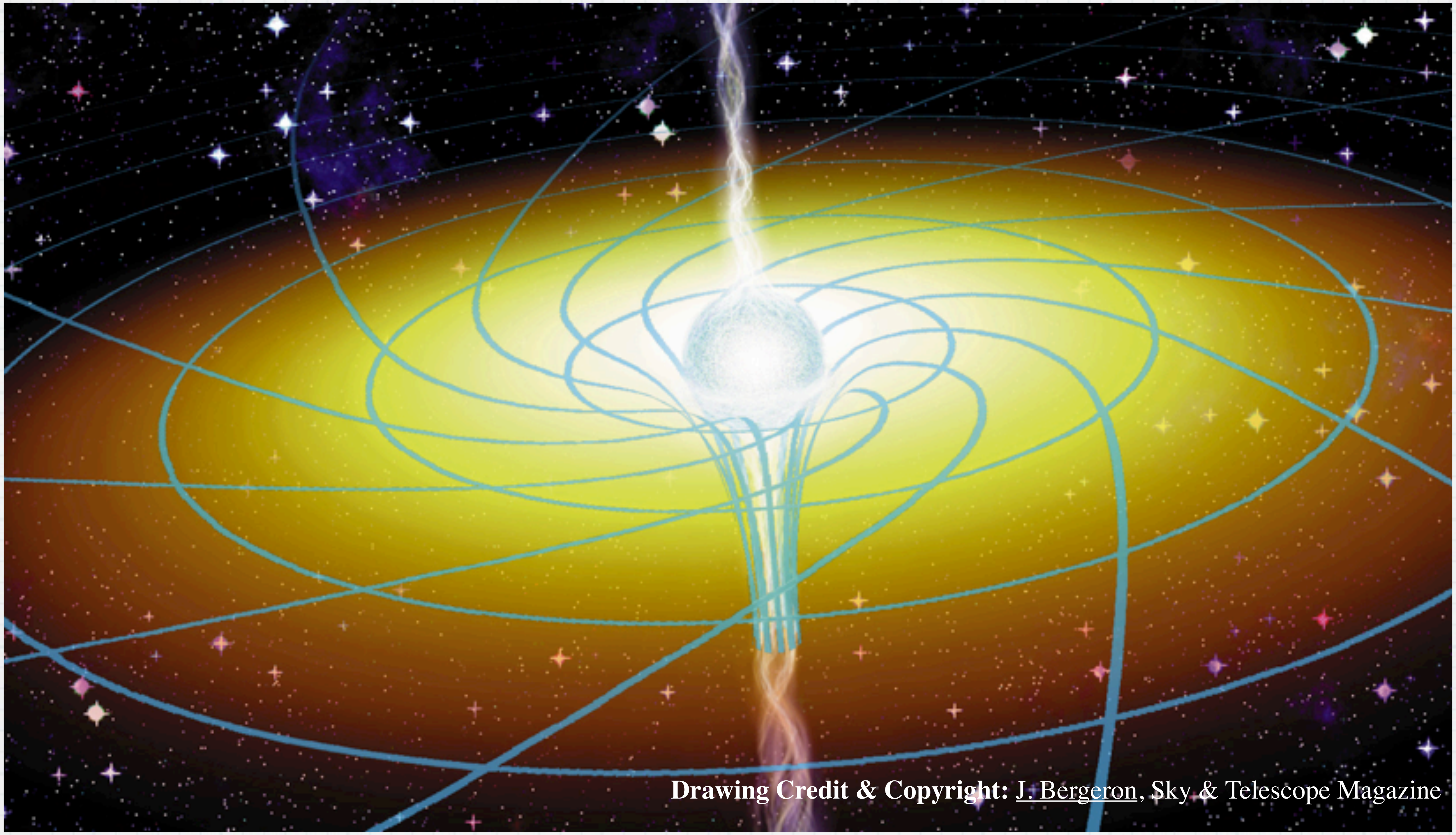
B. Hard

What would it be like to visit a black hole?

Lensing Effect

Moving in front of a background galaxy





Near the event horizon, spacetime is twisted and stretched. This alters the behavior of

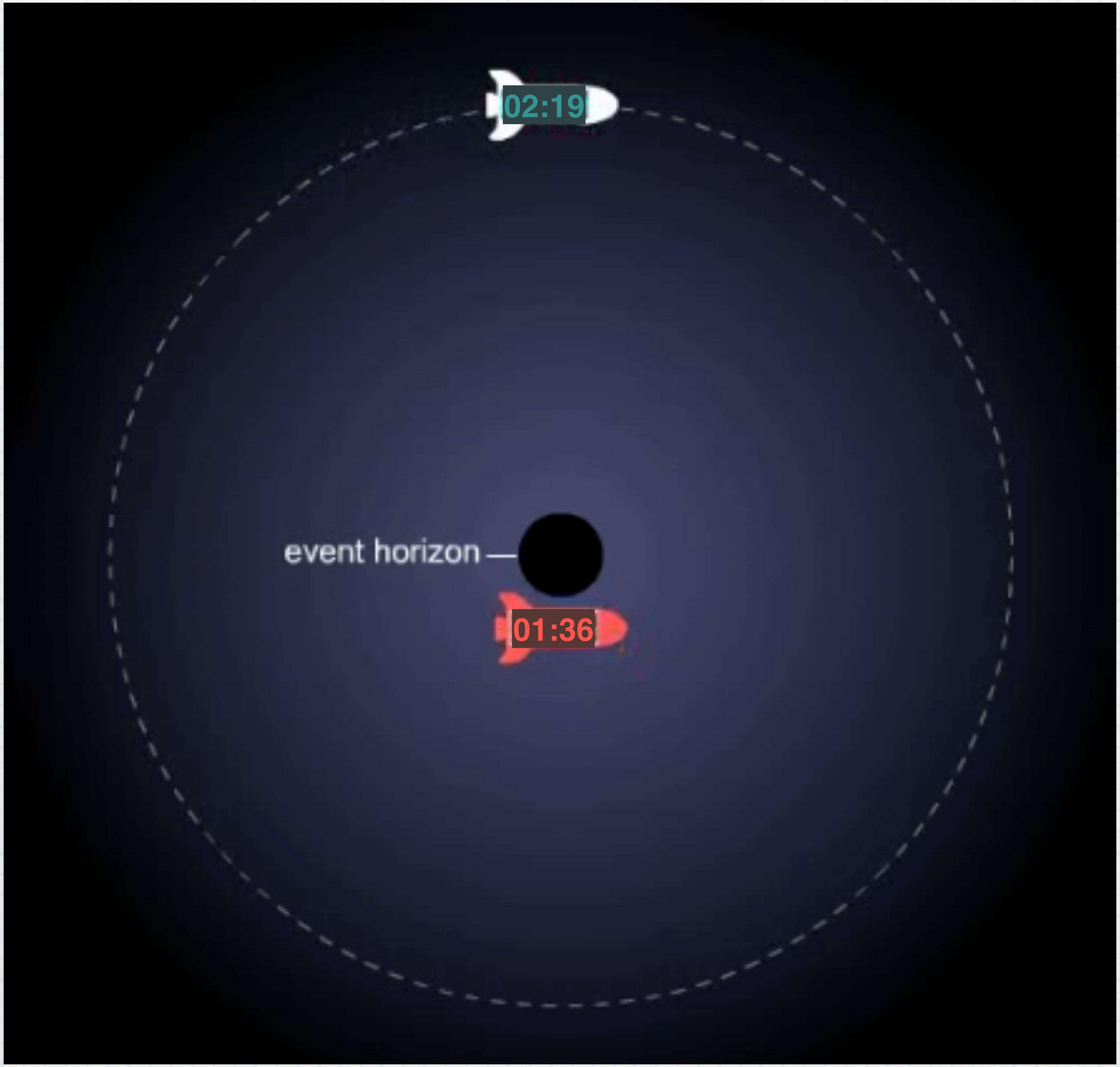
1) time (dilation)

2) lengths (stretching and compression)

3) light (redshift)

Time passes more slowly near the event horizon

This effect is called **time dilation** and is due to **the fabric of spacetime getting stretched**



Time Dilation

* An external observer will never see matter fall inside an event horizon
* From their perspective, matter slows down as it approaches the e.h. (because the matter's time frame is slowing) and becomes redder and fainter
* From the matter's perspective, time flows regularly and it is the external observer's time frame that is being accelerated

Time Dilation...

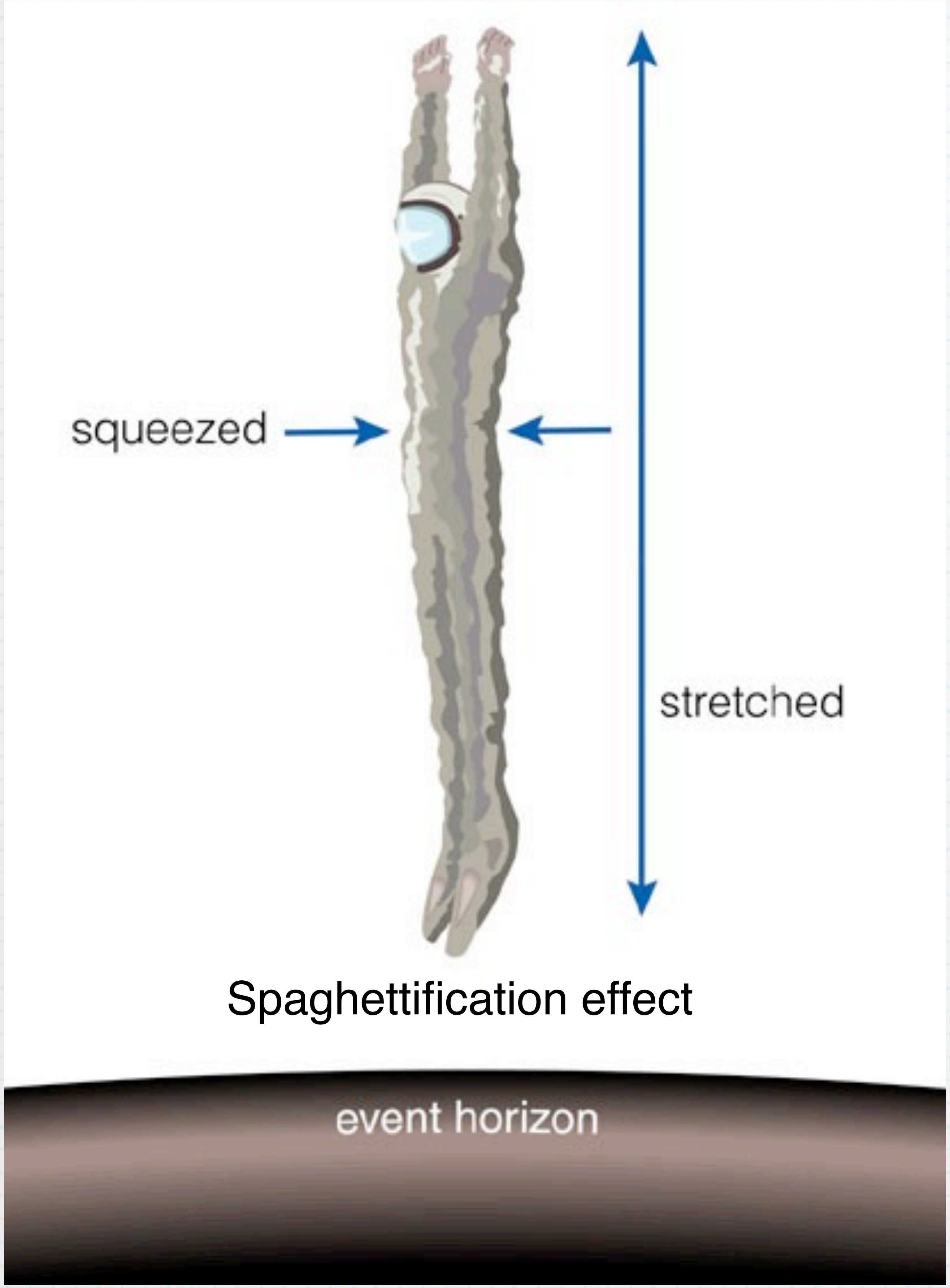
* At the event horizon itself, time has stopped flowing (as seen from an external observer)
* So... does matter fall in?
* Yes from the point of view of that matter
* No from the point of view of the external observer

Time Freeze

* Once something has entered the black hole, it cannot communicate with the rest of the Universe
* Time stops at the Schwarzschild radius
* but it resumes inside and points straight to the singularity (the future is dictated) because time and space are switched inside the event horizon

Time Dilation...

* The object certain and only future: it will reach the singularity at the center of the black hole
* New physics is needed to express events very near and at the singularity as General Relativity and Quantum Mechanics do not agree (they give wildly different results)



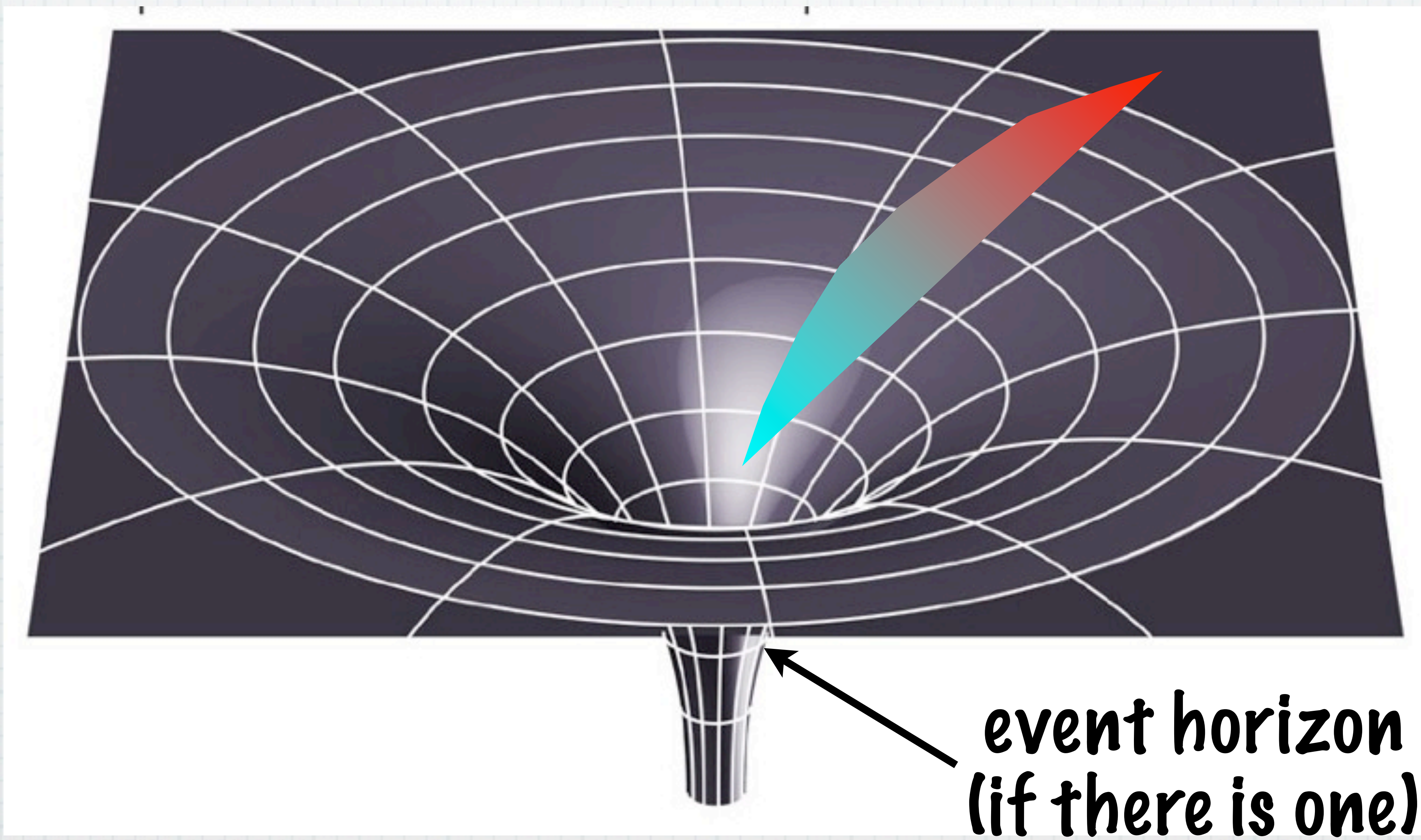
2) - Spaghettification, or the alteration of lengths

Tidal forces near the event horizon of a 3 M_{Sun} black hole would be lethal to humans

Tidal forces would be gentler near a supermassive black hole because its radius is much bigger

3) - Gravitational Redshift

Light loses energy to climb out of a deep hole in spacetime which leads to a redshift we call a gravitational redshift

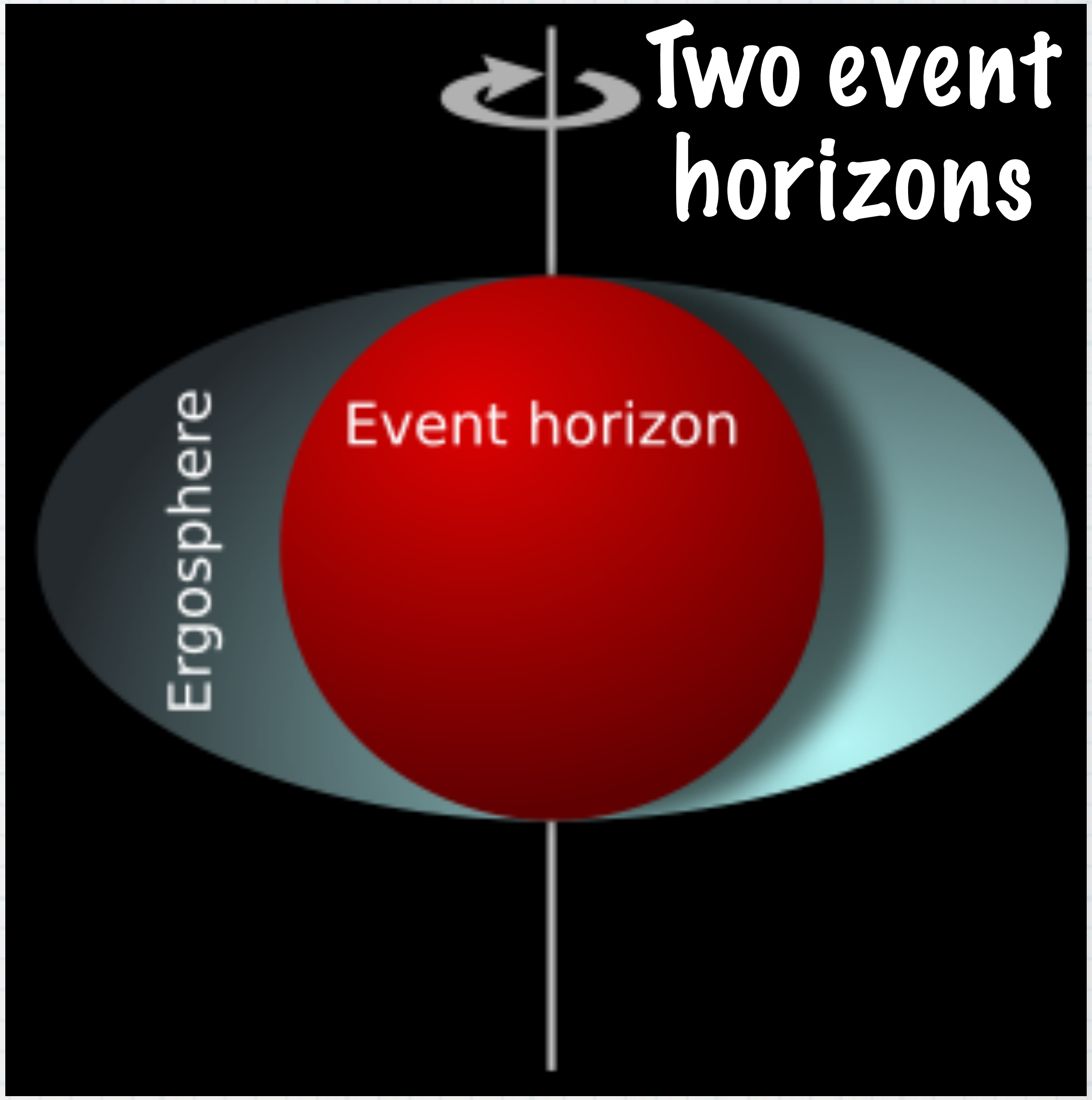


More Black Holes Details

* A non-rotating uncharged black hole has a spherical event horizon and matter that falls in has only one future: the singularity
* A rotating or/and charged black hole has a lot more complex physics:
  * it can even slowly evaporate
  * and then eventually revert back to our "Universe" via an incredible explosion

More Black Holes Details...

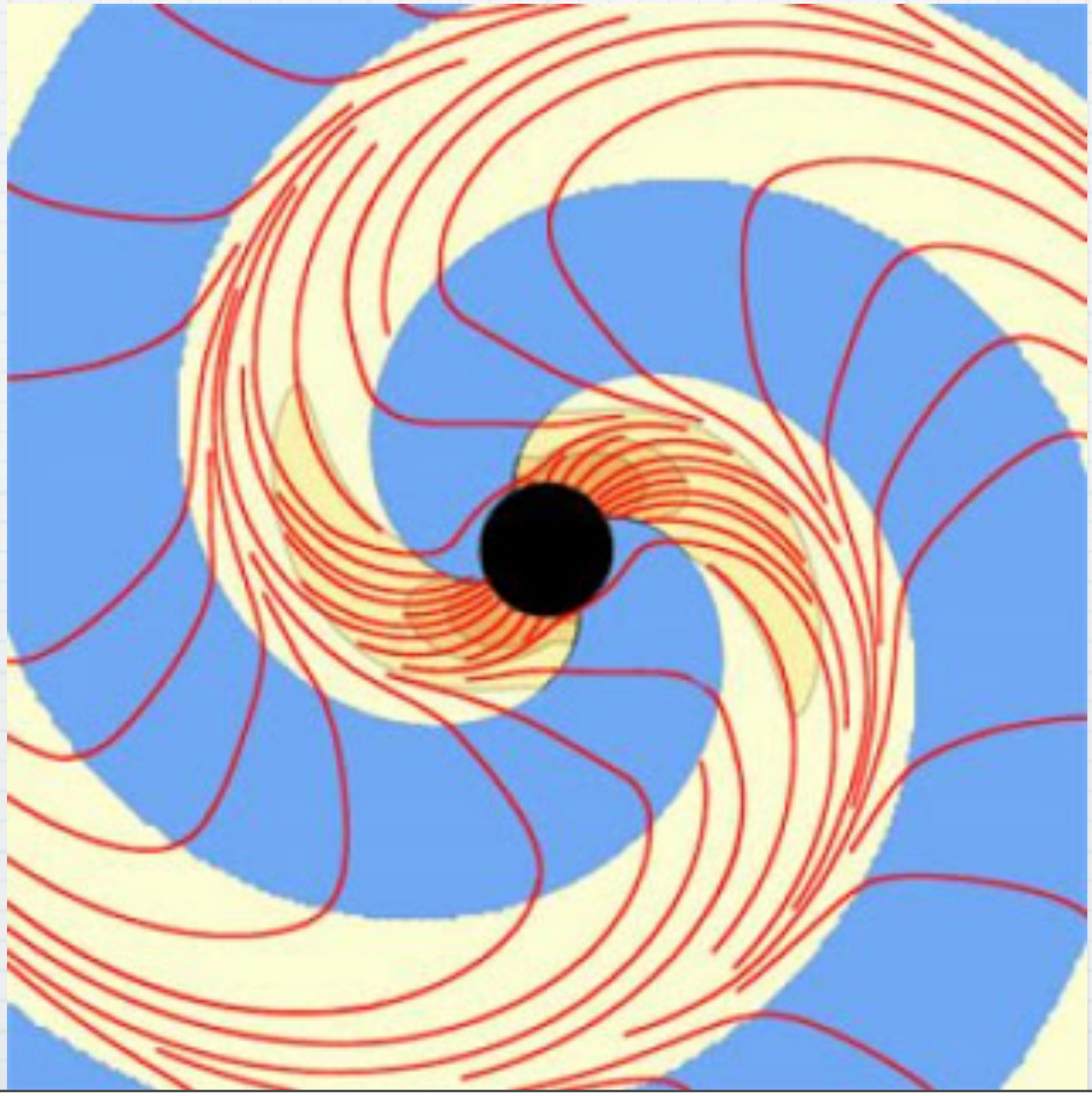
* A spinning black hole has a smaller event horizon than a non-spinning one
* A spinning black hole significantly twists the fabric of spacetime, something physicists call "frame dragging"



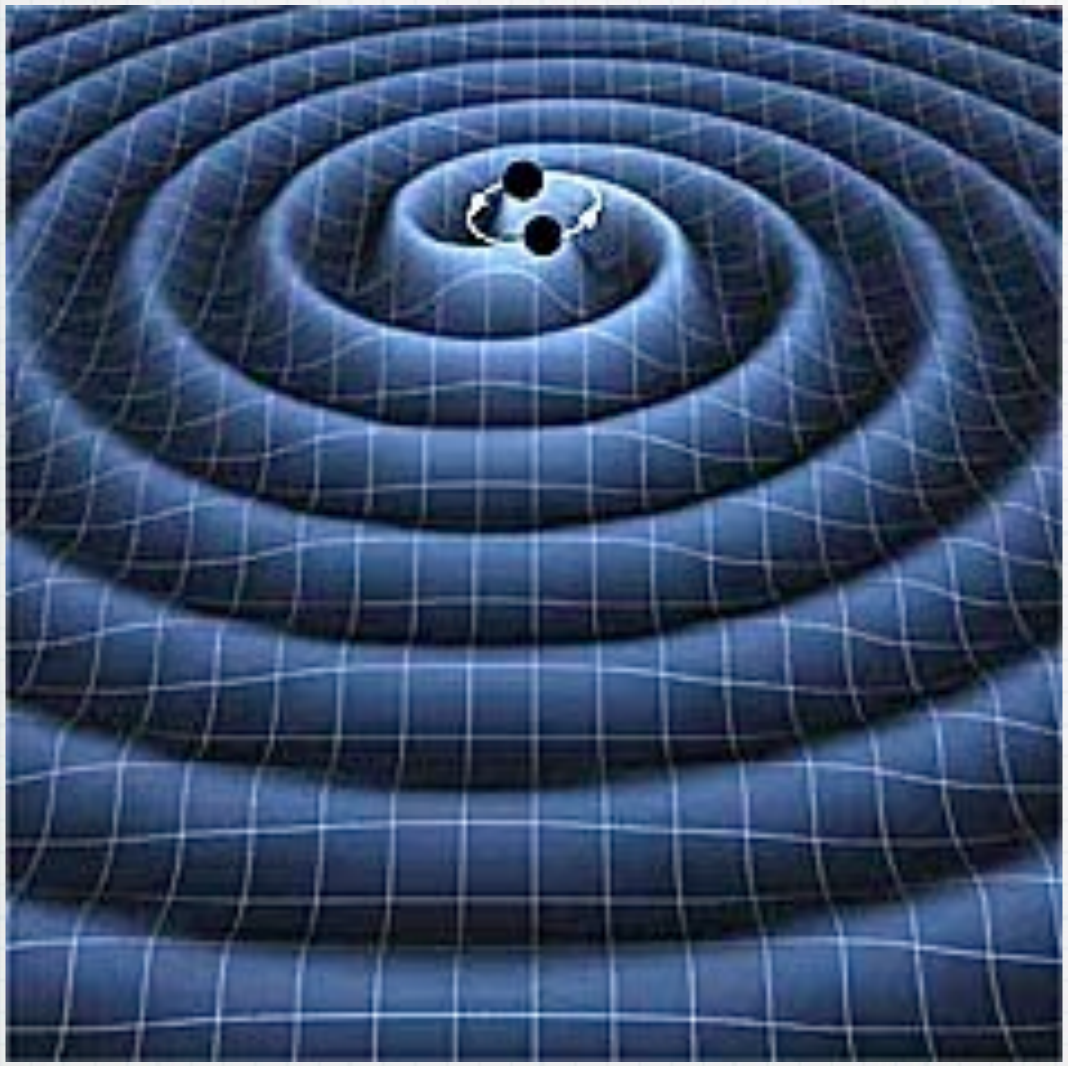
Ergosphere: where space flows faster than speed of light

Frame Dragging

* Where space is deformed and time flows "like" a river in rapids



Black Holes Merging

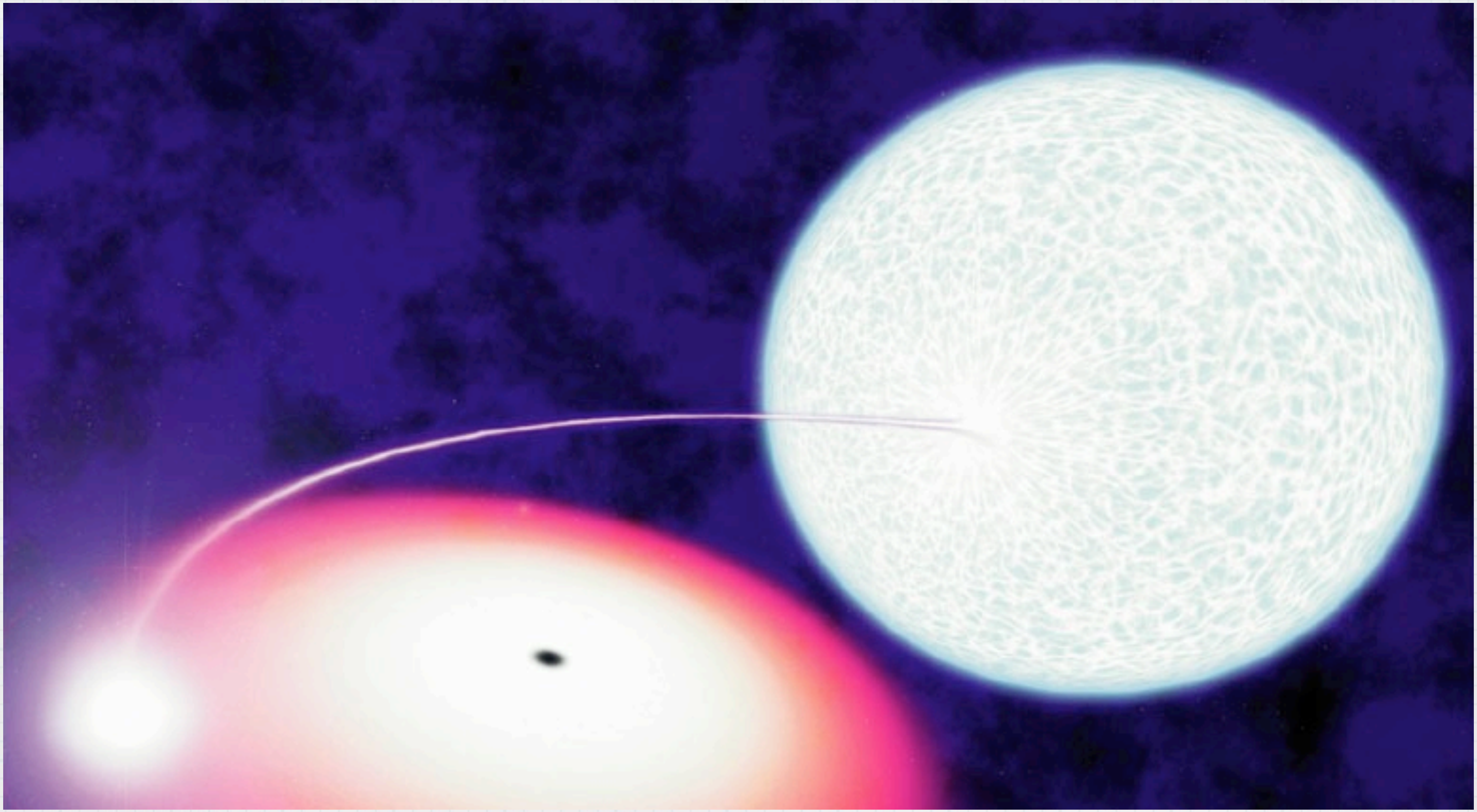


Colliding/merging black holes (or neutron stars) will create ripples in spacetime called gravitational waves

Black Hole Verification

* Need to measure mass
  * Use orbital properties of companion
  * Measure velocity and distance of orbiting gas
* It's a black hole if it's not a star and its mass exceeds the neutron star limit (≈3 M_{Sun})

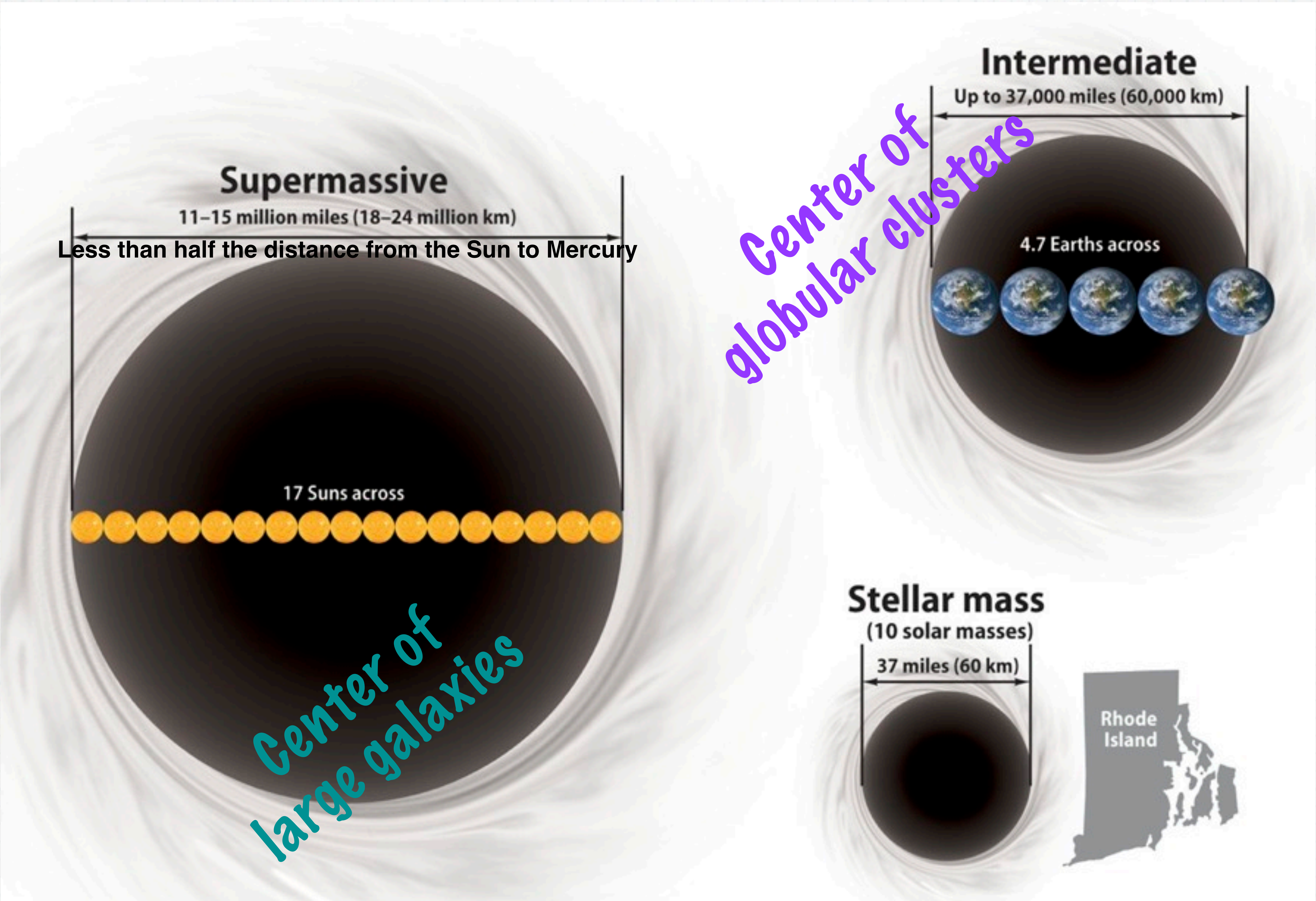
Some X-ray binaries contain compact objects of mass exceeding 3 M_{Sun} which are likely to be black holes



One famous X-ray binary with a likely black hole is in the constellation Cygnus

Specific X-rays are emitted when matter from a red or blue giant star is ripped by the black hole and falls on the accretion disk

How Big Can They Get?



Intermediate Black Holes

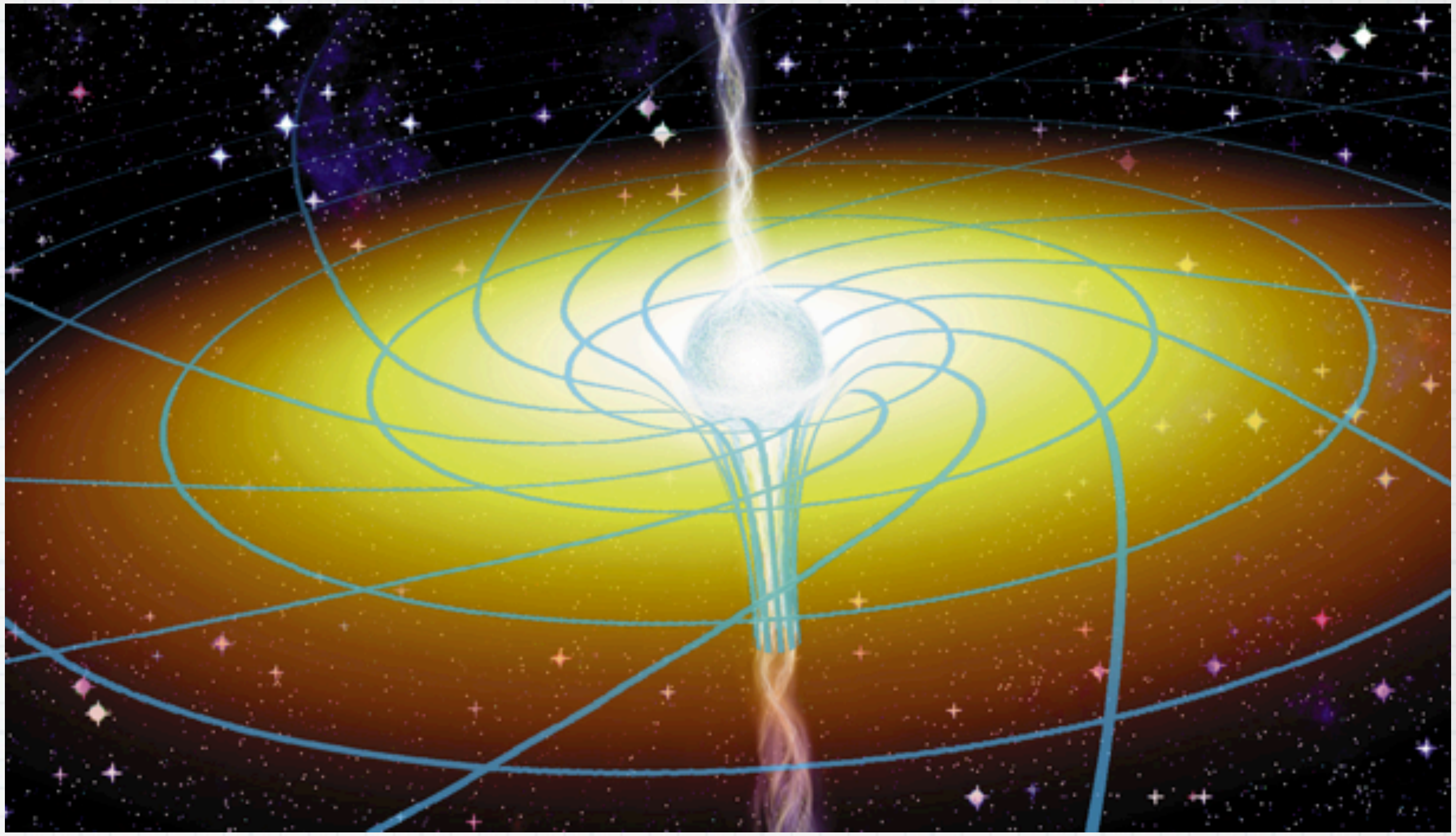
* They are around 40-100 M_{Sun}
* Not quite sure how they form: too big to be the result of a core collapse
* So far only found in globular clusters
* Probably formed due to collision and merger of several single star black holes

Supermassive Black Holes

* Interestingly enough, supermassive black holes would not tear matter apart as it crosses the event horizon
* They distort the spacetime continuum more gently than a "normal" black home but their reach is, of course, much greater
* 100,000s to billions of M_{Sun}

Supermassive Black Holes / AGN

Snapshot



* What is a black hole?
* A black hole is a place where gravity has crushed matter into oblivion, creating a true hole in the Universe from which nothing can ever escape, not even light

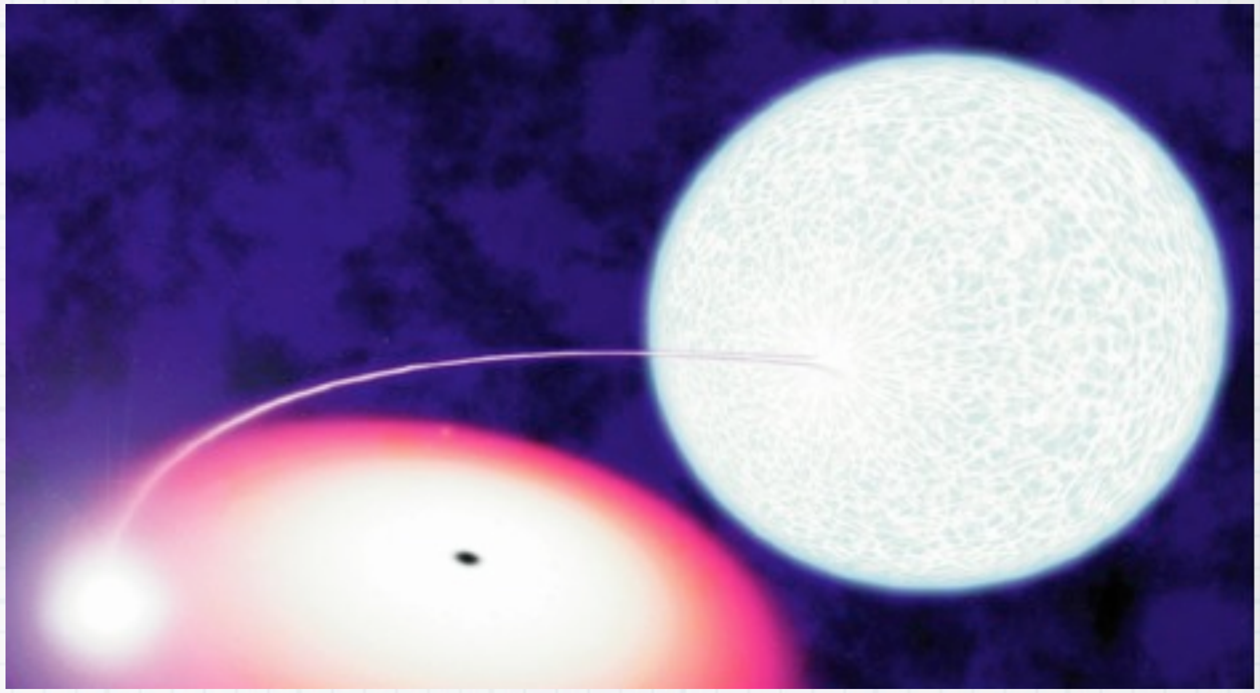
Snapshot

* What would it be like to visit a black hole?
* You could orbit a black hole just like any other object of the same mass. However, you'd see strange effects for an object falling toward the black hole: such as:

Snapshot...

* Time would seem to run slowly for the object
* Its light would be increasingly redshifted as it approached the black hole
* The object would never quite reach the event horizon, but it would soon disappear from view as its light became so redshifted that no instrument could detect it

Snapshot



* Do black holes really exist?
* No known force can stop the collapse of a stellar corpse with a mass above the neutron star limit of 2 to 3 solar masses, and theoretical studies of supernovae suggest that such objects should sometimes form. Observational evidence supports this idea

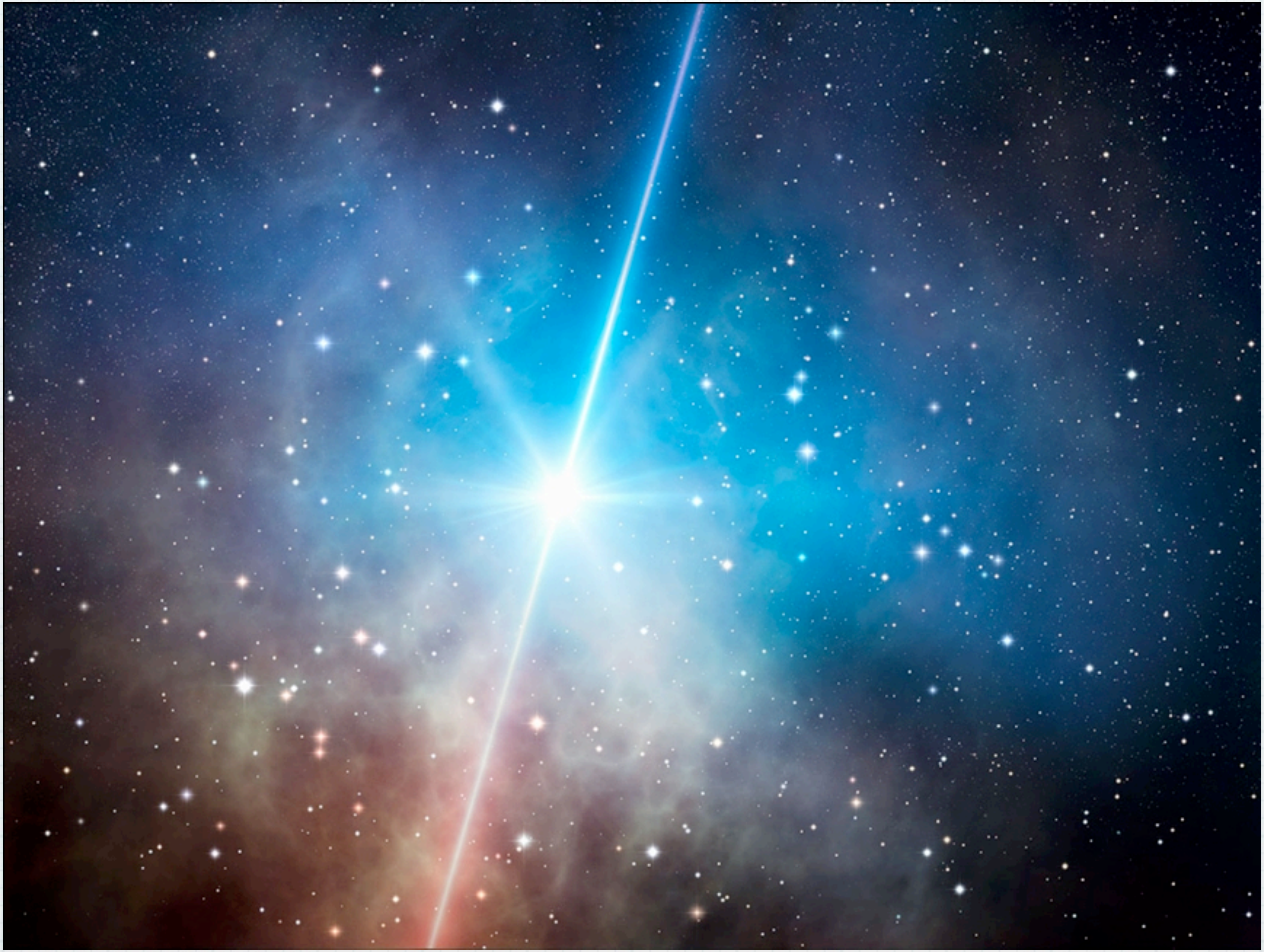
Other Effects of Stellar Corpses

1. Gamma-Ray Bursts
2. Microquasars
3. Cosmic Rays

1 - Gamma Ray Bursts

* Gamma-ray bursts (GRBs) occur about once a day on average
* They come from all over the sky so they are extragalactical
* They are the most powerful bursts of energy that ever occur in the universe
* The most powerful ones can outshine 100 million galaxies!

Illustration of a Gamma Ray Burst



Gamma Ray Bursts...

- GRB's comes in two categories

1. Long-duration bursts
   - They last tens of seconds
   - They lie at great distances, flaring when the Universe was less than a few billion years old
   - They are created by the birth of a rapidly spinning black hole (death of a massive star)

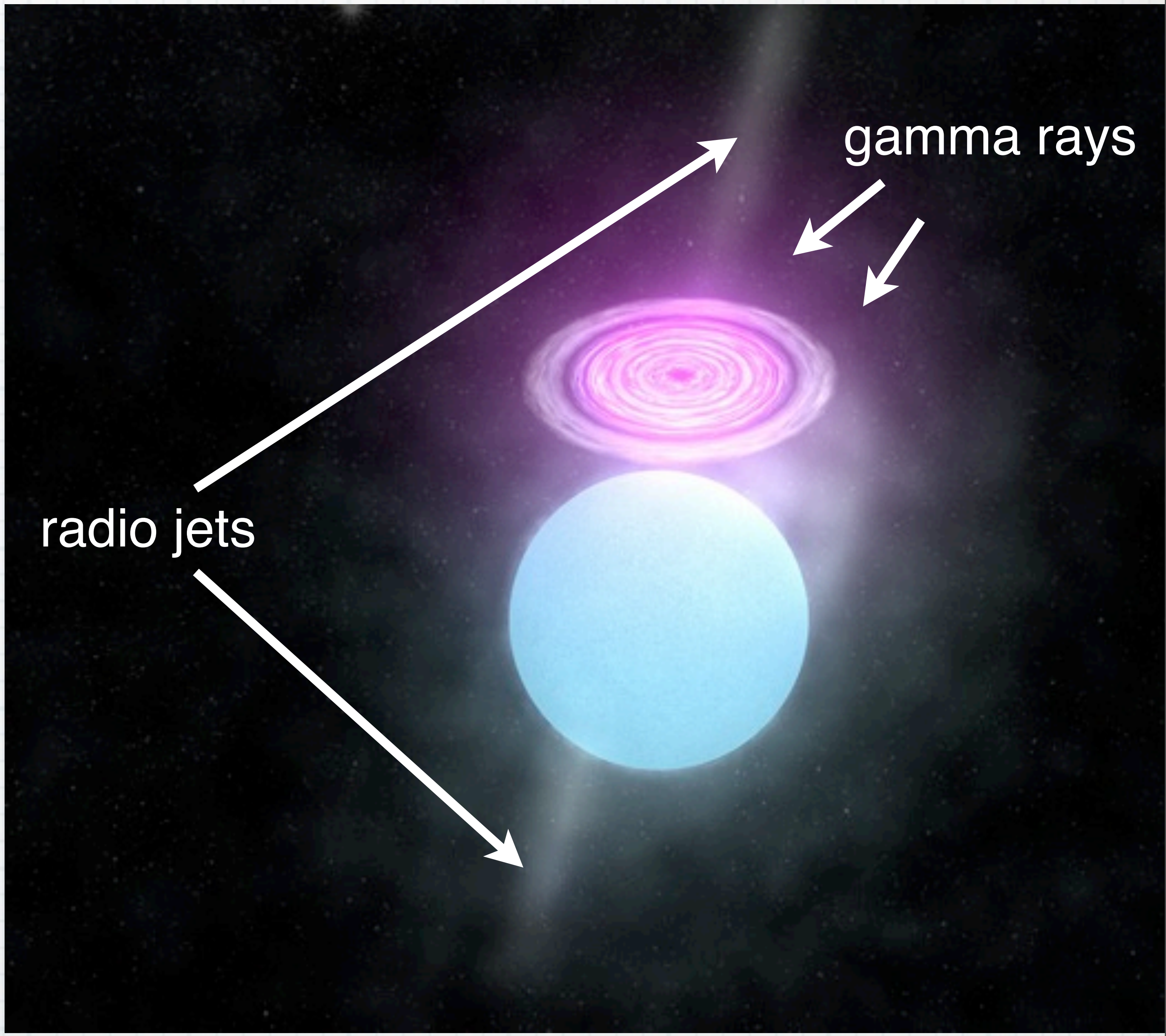
Gamma Ray Bursts...

2. Short-duration bursts, produced when 2 neutron stars collide or when a black hole absorbs a neutron star

* They last a fraction of a second
* They are recent events (e.g.: they can happen "nearby")

2 - Microquasars

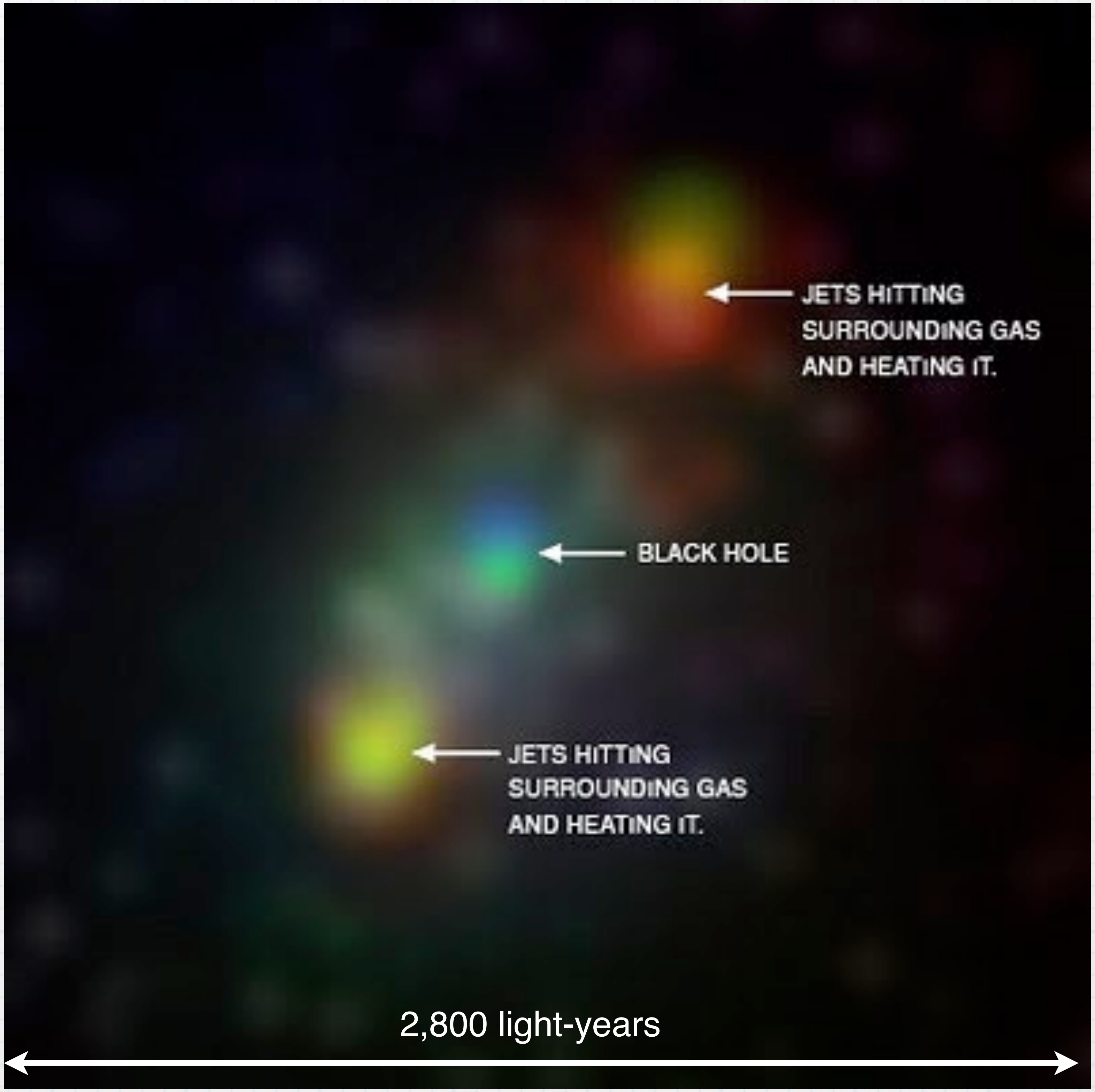
The system pairs a hot, massive star with a compact object — either a neutron star or a black hole — that blasts twin radio-emitting jets of matter into space at more than half the speed of light



Cygnus X-3 - Credit: NASA's Goddard Space Flight Center

NGC 7793 - black hole microquasar

At the edge of a galaxy 12 million light-years away exist a black hole microquasar that if it were shrunk to the size of a soccer ball, each jet would extend to beyond the orbit of Pluto



Credit: NASA/CXC/Univ of Strasbourg/M. Pakull et al

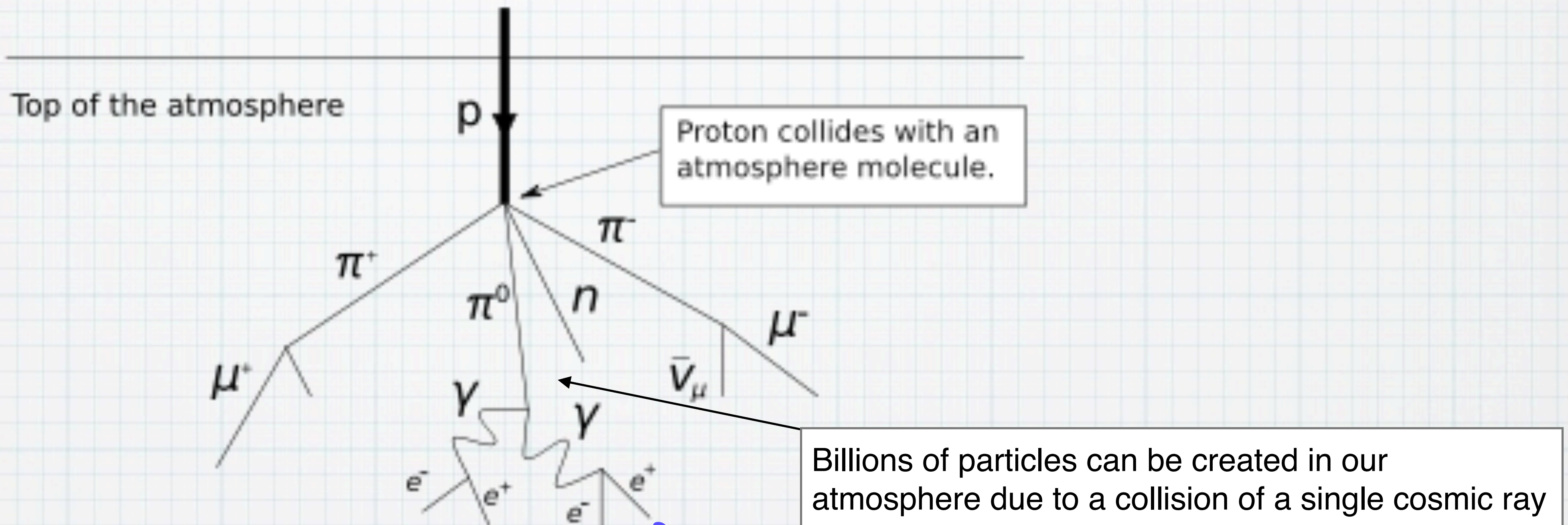
3 - Cosmic Rays

* They are the fastest bits of matter in the Universe, traveling through space at virtually the speed of light
* They were first discovered in 1963
* They are not "rays" at all but primarily ionized atoms ranging from a single proton up to an iron nucleus and beyond, but being typically protons and alpha particles (solar wind component)

What causes Cosmic Rays?

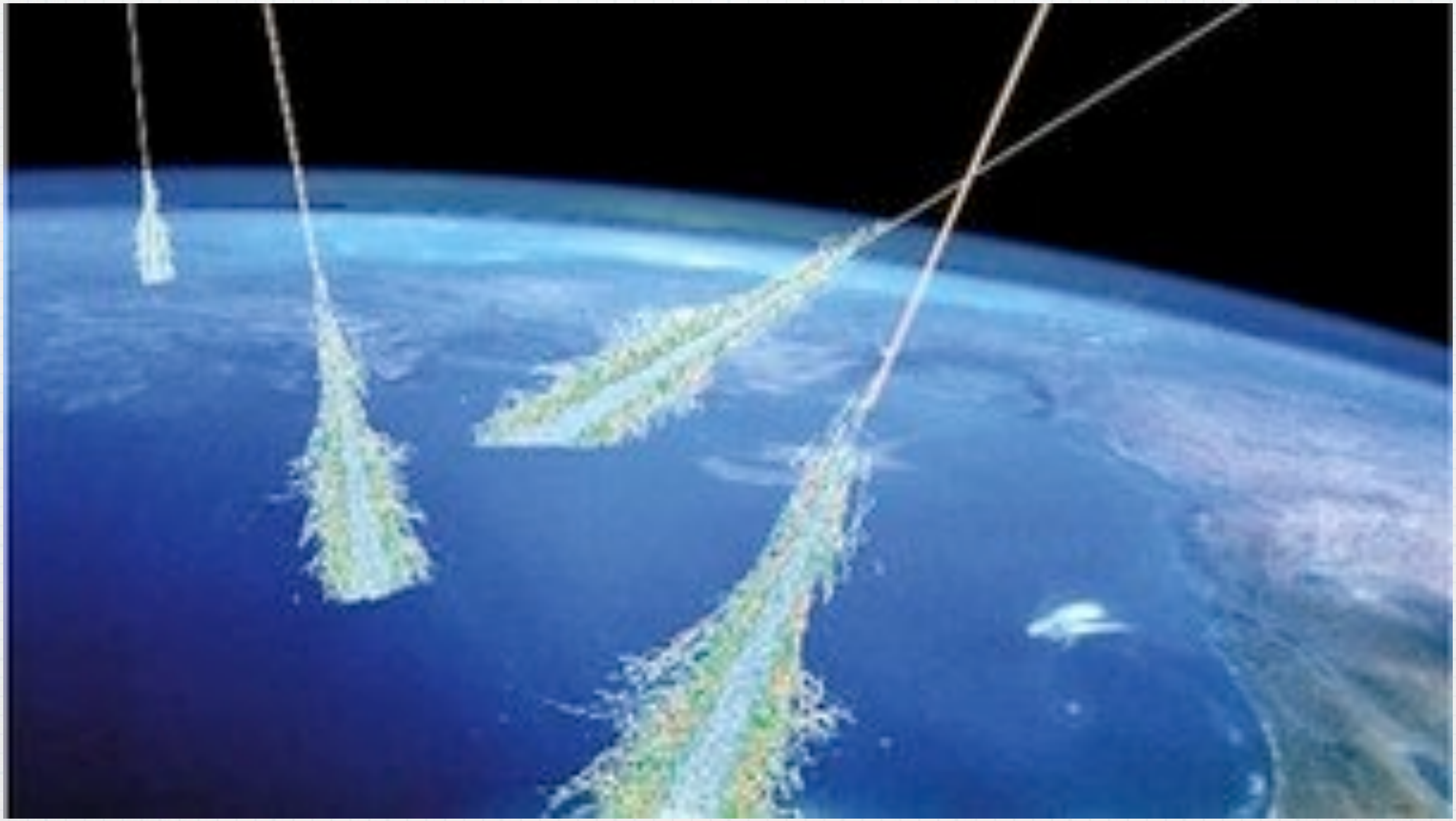
* The "low" energy ones com from the Sun
* The ultra-high-energy ones are generated when a supermassive black hole absorbs stars and gas (via its ergosphere)
* These events generate spewing jets of radiation and subatomic particles into intergalactic space

What causes Cosmic Rays?



* The energy carried by these nuclei is vastly greater than what we can achieve in our fastest particle accelerators
* Since micro black holes are not created by cosmic rays we should not fear the CERN accelerator

Cosmic Rays Hitting the Atmosphere



Additional Material

* http://www.youtube.com/watch?v=E0i0xA9GvX8
* http://www.youtube.com/watch?v=Cyuc-ncs1 1k
* http://www.youtube.com/watch?v=el9CvipHI_c
* http://www.youtube.com/watch?v=KCADH3x56eE
* http://www.youtube.com/watch?v=noBqyoiZ0Cw