

Neutron Stars, Pulsars, Magnetars, and Black Holes – the “corpses” of high-mass stars



**Combination X-ray & visible
light image of the Crab Nebula
Pulsar**

From Chandra X-ray Observatory and
Hubble Space Telescope

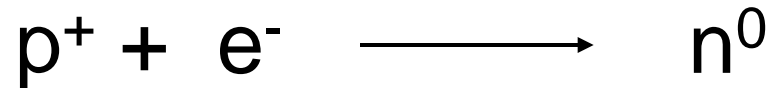
What is a Neutron Star?

- The collapsed core of a medium-sized star, 3 to 8 times the mass of our sun.
- The core of this star had to have a mass greater than the Chandrasekhar Limit, 1.4 times the sun's mass.

Why?

Inverse Beta Decay or “Neutronization”

- When the core is heavier than 1.4 solar masses, its gravity is so strong that the protons and electrons in the star’s atoms are squeezed together, becoming neutrons.



- The density of a neutron star can be as high as 10^{17} kg/m³. A single teaspoon (5 mLs) of neutron star material would weigh 500 million kilograms!
- A neutron star is about 80% neutrons. The rest is uncombined protons & electrons.
- There is no empty space between the particles in the star. The pressure of the neutrons pushing against each other is what prevents the star's further collapse.

Diameters of
12 to 30 miles.

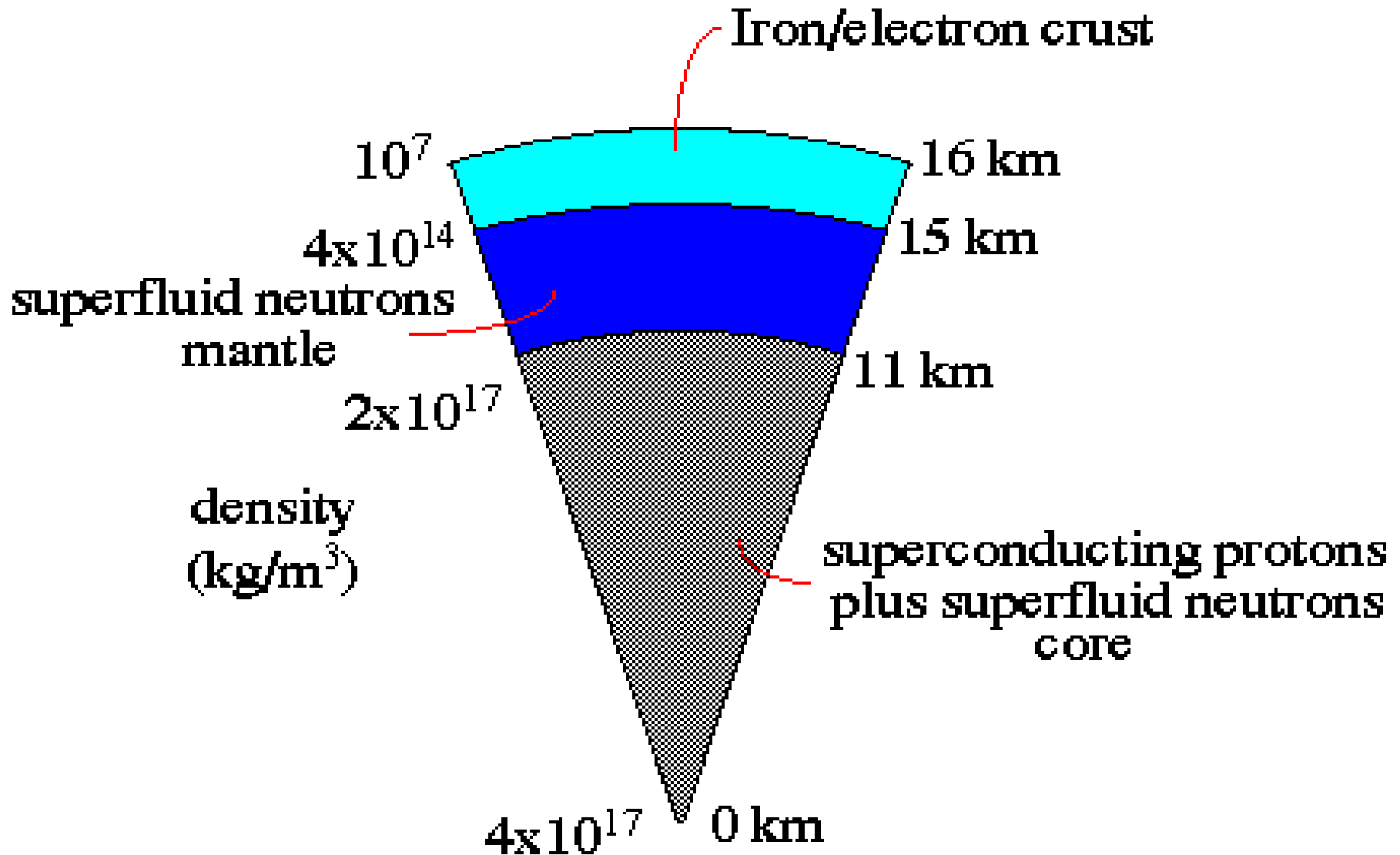
More massive
= smaller in
diameter.

Why?



Neutron Star Interior

Crust is crystalline iron.
Atmosphere of iron atoms.

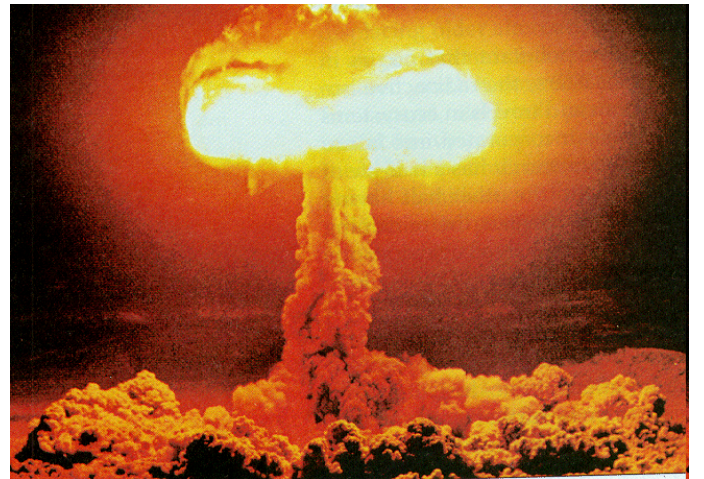


How much gravity?

- Even the lowest mass neutron stars have surface gravities that may be 100 billion G's.
- Escape speed may be up to 80% of the speed of light.
- A neutron star warps or bends the space around it, causing nearby gas to fall onto its surface at incredible speeds.



=



Pulsars are *Spinning* Neutron Stars

- We know pulsars are spinning, because they give off regularly-timed **radio** signals.
- The first signals were detected by a Cambridge University grad student, Jocelyn Bell, in 1967.
- Project L.G.M.



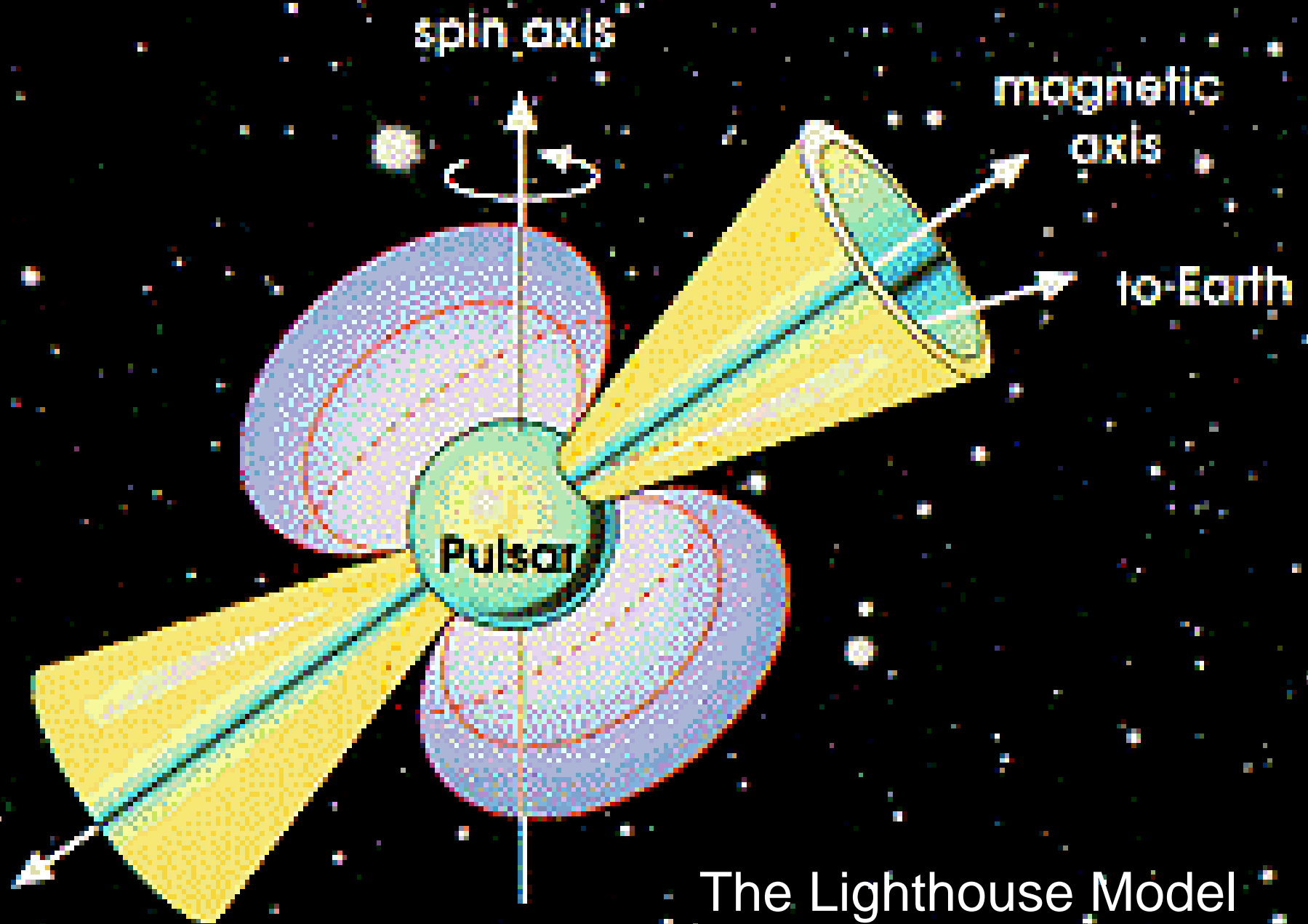
Pulsar Characteristics

- To date, more than 1800 pulsars have been identified and studied.
- The time interval between pulses can be as short as 1.6 milliseconds, or as long as 10 seconds. Over time, the pulse frequency slows down.

How are the signals made?

- Superconducting core + rapid spinning = strong **dynamo**.
- Strong electrical current (dynamo) produces strong magnetic field.
- Pulsar has much leftover heat, rotational energy, and acquires even more energy from gas falling onto its surface.

- The pulsar gets rid of some of this energy by shining a radio beam out along the magnetic field.
- Only a few pulsars “shine” in more than radio waves.
- If the magnetic field of the pulsar is tilted relative to its spin axis, this light beam flashes through space like the beam from a lighthouse.



The Lighthouse Model

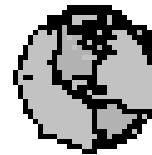


1

Axis of rotation

α

Radio waves



2

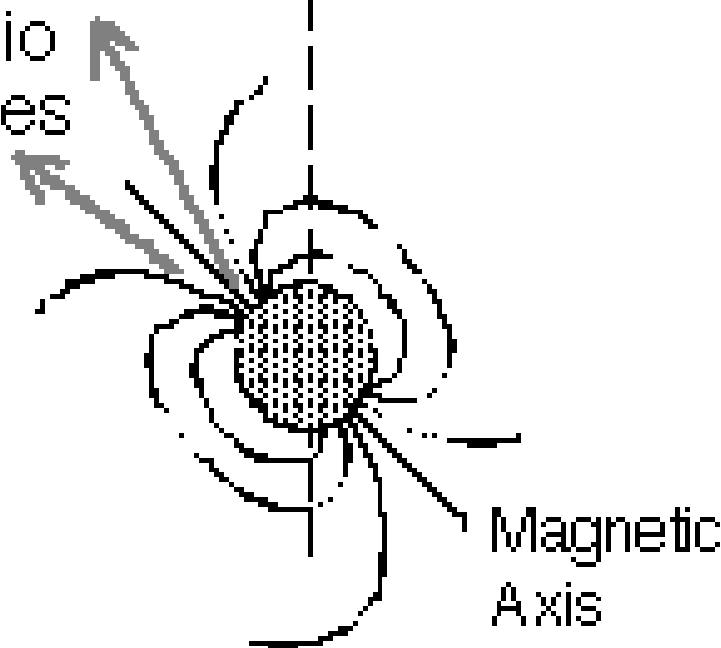
Axis of rotation

α

Radio waves



The pulse is "off."
The Earth does not detect the radio waves



... APPEARS TO BE SOME SORT OF PRIMITIVE TRACTOR BEAM, CAPTAIN...



... il semble que ce soit quelque sorte de phare de tracteur primitif, capitaine

AVICK

Listen to some pulsar sounds

- A slowly-rotating pulsar
- A quicker pulsar
- A fast pulsar
- A millisecond pulsar
- A really fast millisecond pulsar
- <http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html>

Imagine What This Means....

- This model implies that an object with at least 1.4 times the mass of the sun, and 20 miles in diameter can rotate in as little as 0.0016 seconds!
- What an incredible amount of energy!

Famous Pulsars

- The most famous pulsar in our sky is PSR 0531+121, the Crab Nebula pulsar in Taurus.
- This pulsar (and the nebula around it) is all that's left of a supernova that exploded in 1054 A.D.
- The Crab pulsar still rotates about 30 times per second – a fairly fast rate.

The Crab Nebula Pulsar

- The Crab pulsar gives off all types of electromagnetic radiation, from radio to gamma rays. This is the only pulsar known to “shine” in the entire frequency spectrum.
- The Crab pulsar emits so much energy in its “lighthouse” beams that the flashes are equivalent to 100 times the sun’s luminosity.

Credit: NASA, STScI, Hubble Team



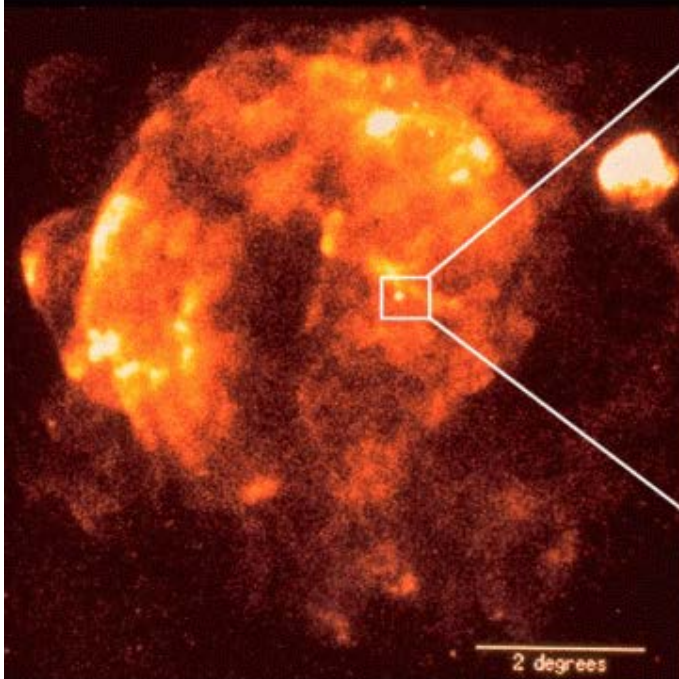
Chandra X-ray Observatory and
Hubble Space Telescope



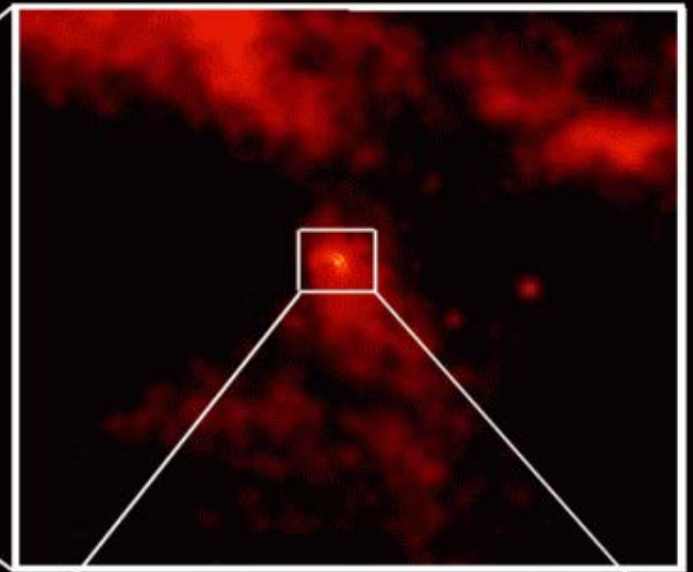
Another Famous Pulsar

- Another famous pulsar is PSR 0833-45, in the constellation Vela.
- This pulsar is in the Gum Nebula, part of the cloud that is the Vela supernova remnant. Vela is a far southern constellation.

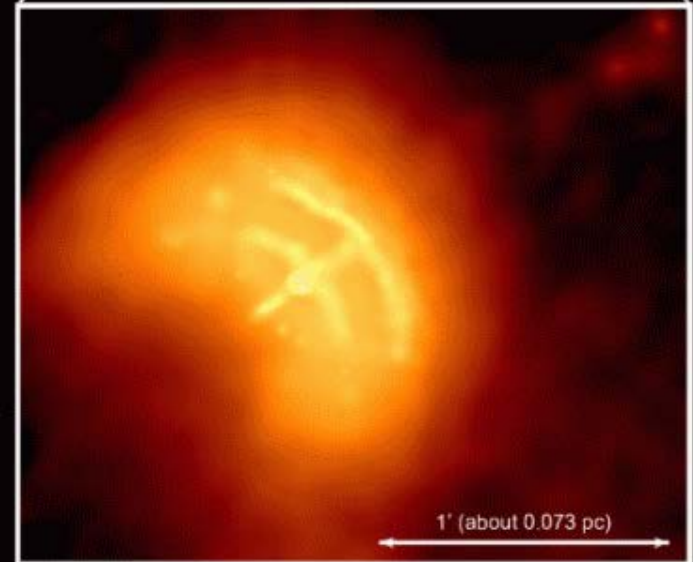
PSR 0833-45



↑
Rosat PSPC image of Vela SNR.



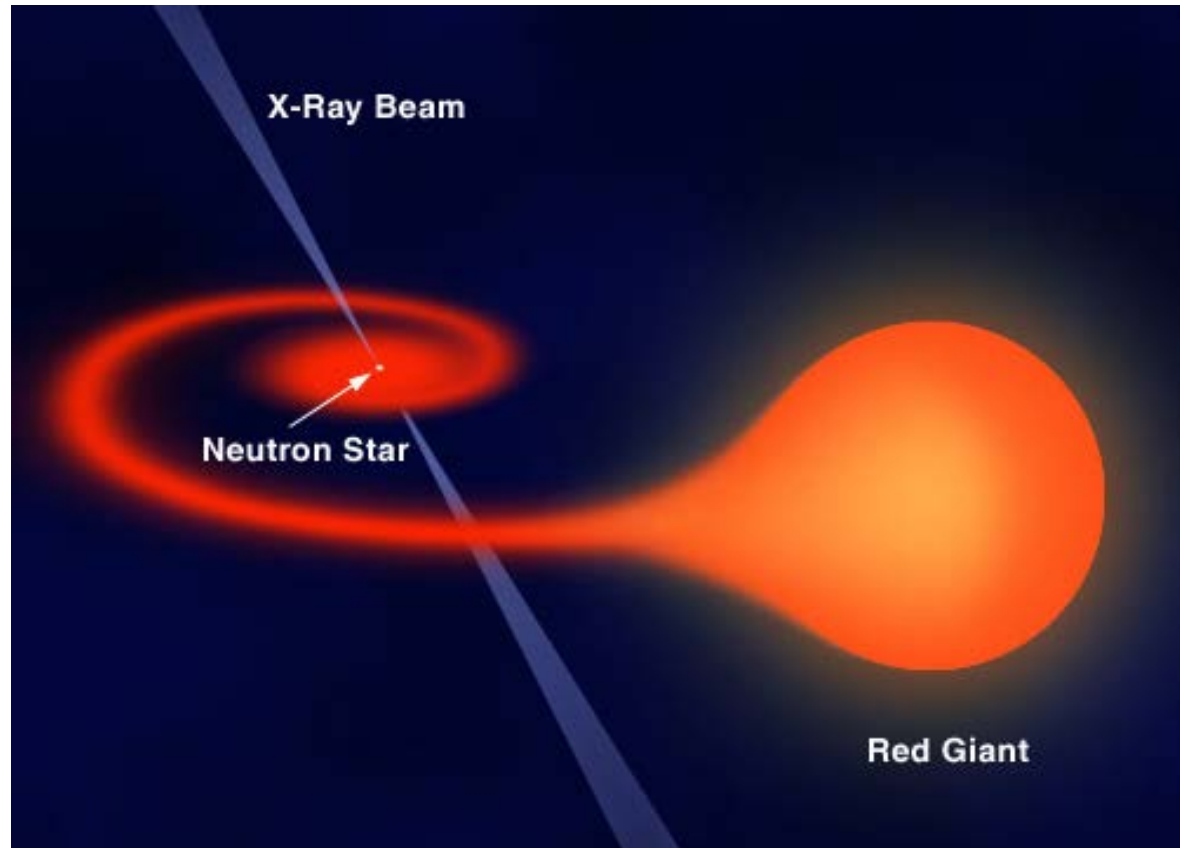
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**Chandra ACIS image of
Vela PWN**



Acronyms: Position Sensitive Proportional Counters, Pulsar Wind Nebula

Pulsars also exist in Binary Systems

- Pulsar PSR 1913+016 in Aquila (the Eagle) is in orbit with a red giant star.



- Doppler shifts in the pulsar's radio signals show that the neutron star and the red giant are only a few million miles apart, about $1/8^{\text{th}}$ the distance between the sun and Mercury.
- The two stars are bleeding energy away into space in the form of **gravity waves**.
- Eventually the two stars will spiral together, collide, and explode as a supernova, forming a black hole.

Some binary pulsars speed up

Old pulsars should have slowed down, but...

If the pulsar can steal enough gas from the red giant, it will grow smaller (more dense) and accelerate its spin.

A pulsar can speed up from a few seconds between pulses to just milliseconds between pulses. These are known as “millisecond pulsars.”

Most of these pulsars are very old, because we find them in globular clusters.

These pulsars are spinning so fast, that a point on their surfaces would be moving about 10% of the speed of light.

A cool millisecond pulsar animation:

<http://heasarc.gsfc.nasa.gov/docs/xte/Snazzy/Movies/millisecond.mov>

“On March 5, 1979, gamma ray detectors on nine spacecraft across our solar system recorded an intense radiation spike (of gamma rays). It was just 0.2 of a second long - with as much energy as the sun releases in 1,000 years - followed by a 200-second emission that showed a clear 8-second pulsation period. The position tied the burst to a supernova remnant known as N49 in the Large Magellanic Cloud.”

“Immediately, scientists recognized something odd. SGR 1900+14's youth - it's only a few thousand years old - contrasted with its 8-second spin, typical of a much older neutron star.

Something was putting the brakes on it.”

Quote from:

‘Magnetar discovery solves 19-year-old mystery’ from
Science @NASA...science.nasa.gov

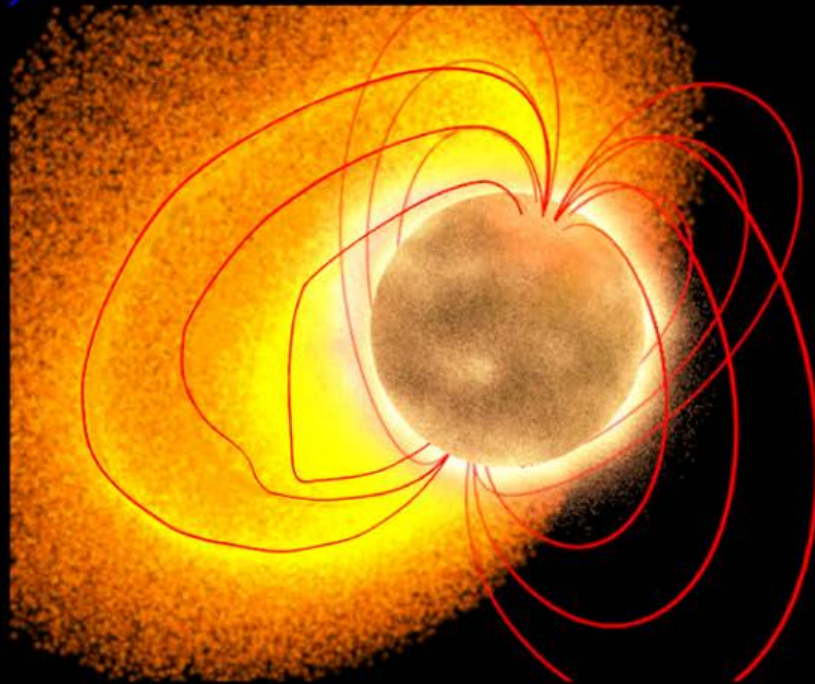
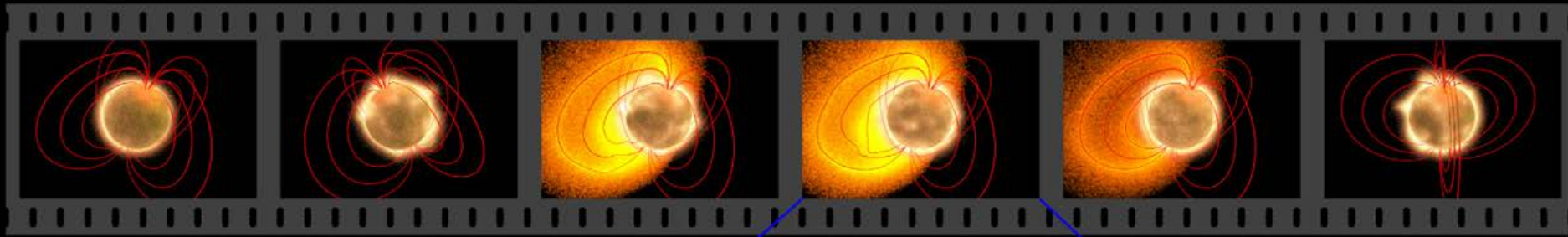
Intense Magnetic Field

- Some neutron stars appear to be able to form a more intense magnetic field than others...some as strong as 1000 trillion times the strength of the earth's magnetic field. These stars are magnetars (magnetic stars).
- This intense magnetic field slows the pulsar's rotation and causes intense "star quakes" that release enormous amounts of energy.

Soft Gamma Ray Bursts

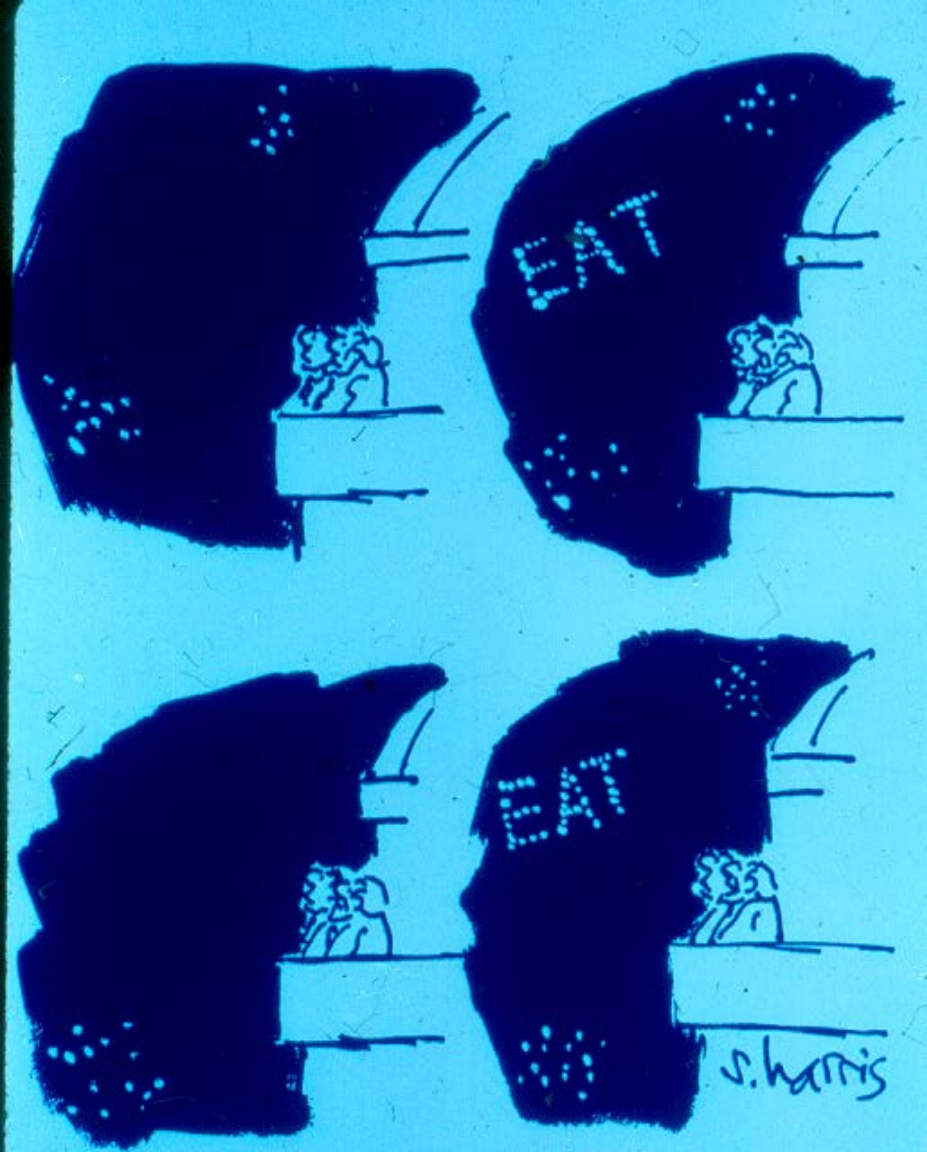
- The energy of the star quakes is released along the poles of the magnetar's magnetic field, in the form of “soft” gamma rays.
- (“Soft” gamma rays are longer in wavelength than “hard” gamma rays – more like a high energy X-ray.)

Magnetar burst sequence



Magnetar Animation

- http://science.msfc.nasa.gov/newhome/headlines/ast20may98_1.htm#anchor484339
- Go to the bottom of the web page & choose Internet connection speed.



"I don't care what it looks like —
they're pulsars."

Black Holes



Artist's representation of massive binary black hole and O-class supergiant, in M-33 galaxy (M33 X-7).

Credit: Chandra X-ray Observatory

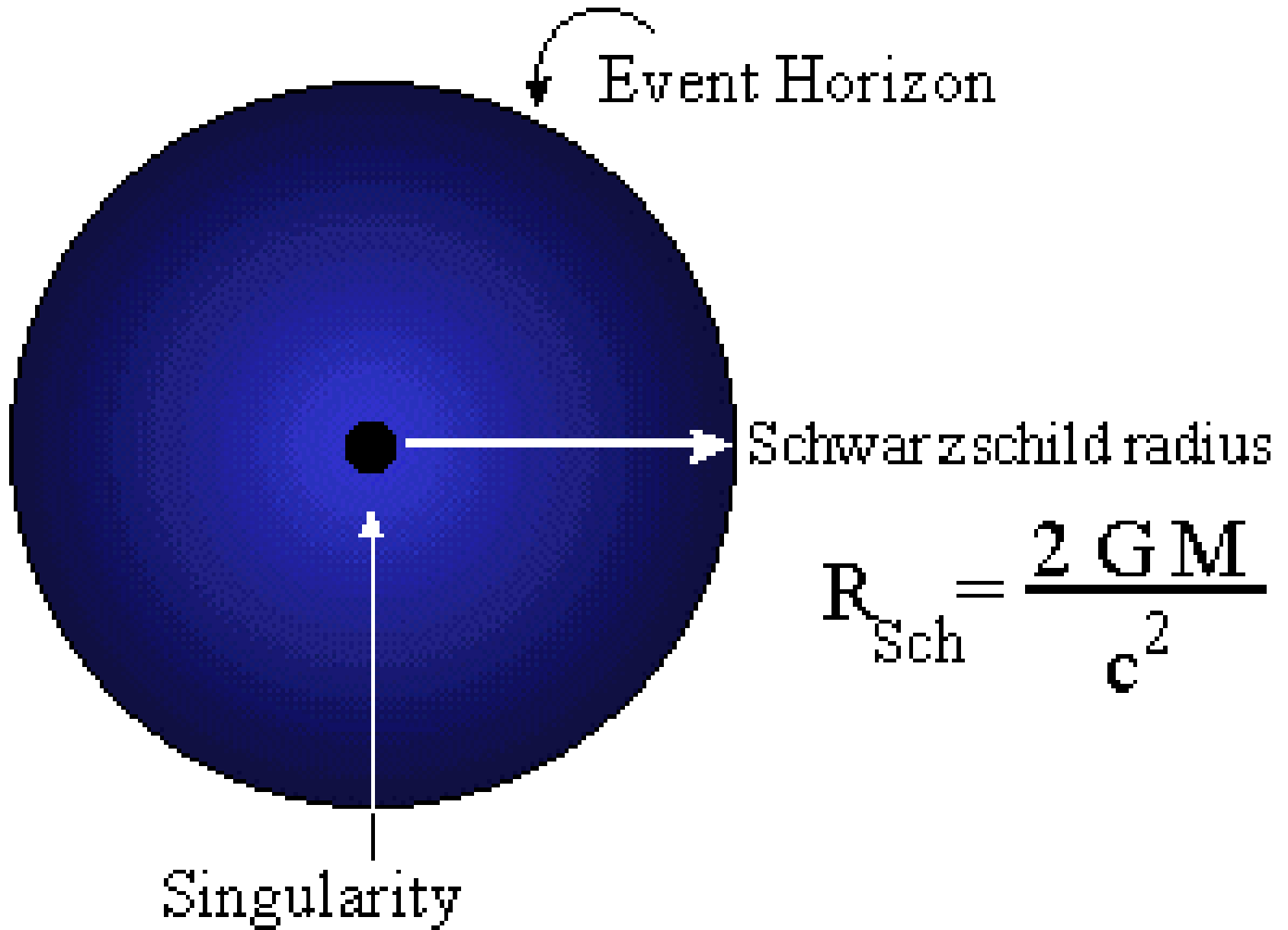
How are they made?

- Only the very largest stars, beginning with at least 8+ solar masses, are able to form black holes.
- As the iron core forms in the last day of the star's life, it gets massive fast enough that it reaches about 3 solar masses before it can collapse into a neutron star.

- At 3 solar masses, when collapse begins, the core's gravity first overcomes the repulsion of electrons, then squeezes all the space out between the neutrons, then finally turns the matter into something we can't adequately describe....

- As the density increases, the gravity at the surface of the core continues to get stronger & stronger, until the escape speed passes the speed of light.
- At this point, the core of the former star effectively exits our universe!

- The core of the star continues to contract into a single point – the **singularity**, with zero size (?) and infinite density (??).
- However, what we “see” as the black hole is that distance from the singularity where the escape speed is faster than **c**, the speed of light.
- This distance is the Schwarzschild radius, or event horizon.





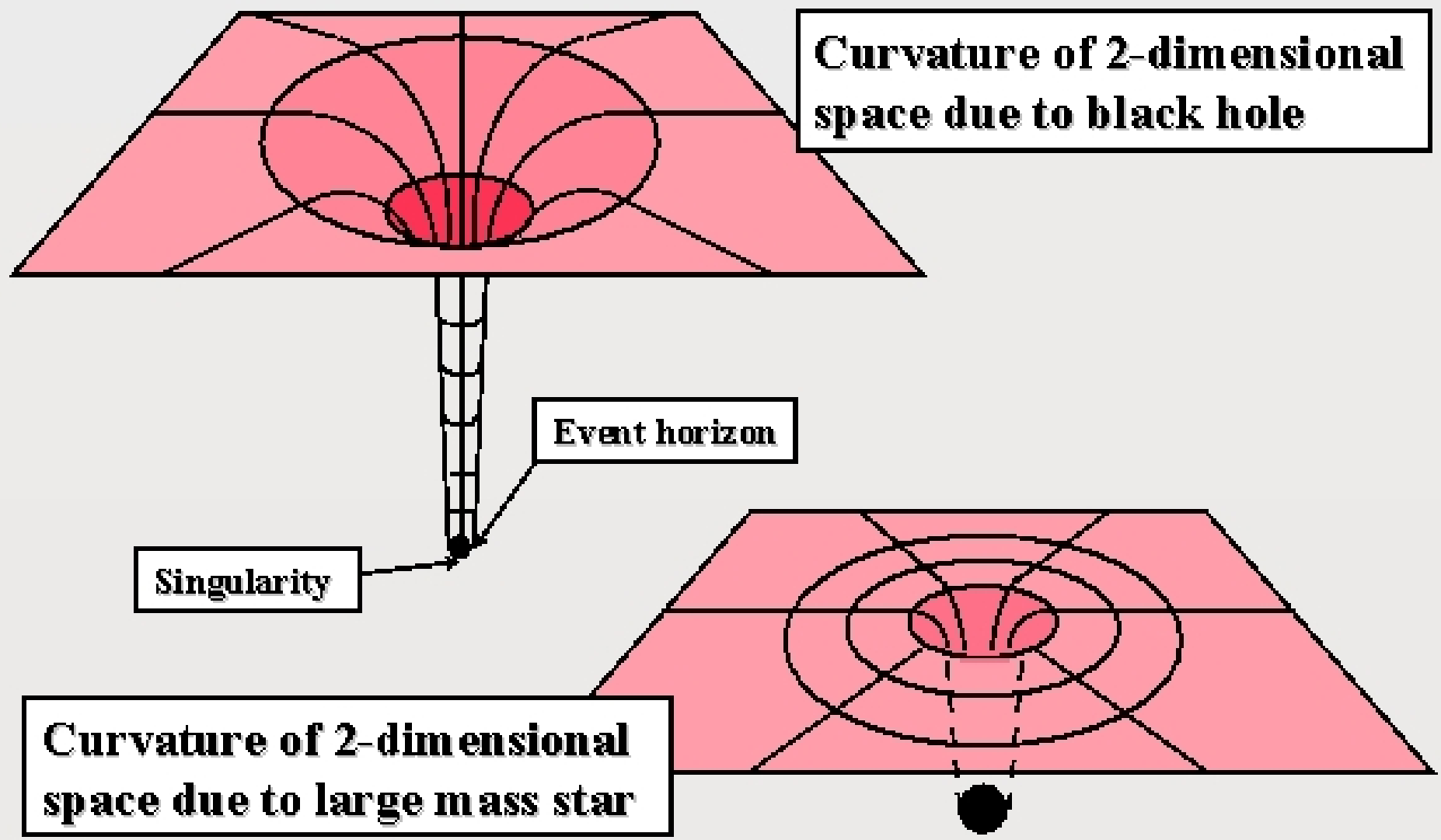
The mass of the star's core disappears, leaving only its "smile", its gravity behind!



How does a Black Hole affect the universe?

- Einstein's Theory of General Relativity says that a mass bends or warps the space-time around it, creating a gravity well.
- The gravity well of a black hole is so deep that nothing escapes, at least not by normal physics.

Black Hole Spacetime Curvature - 2-D



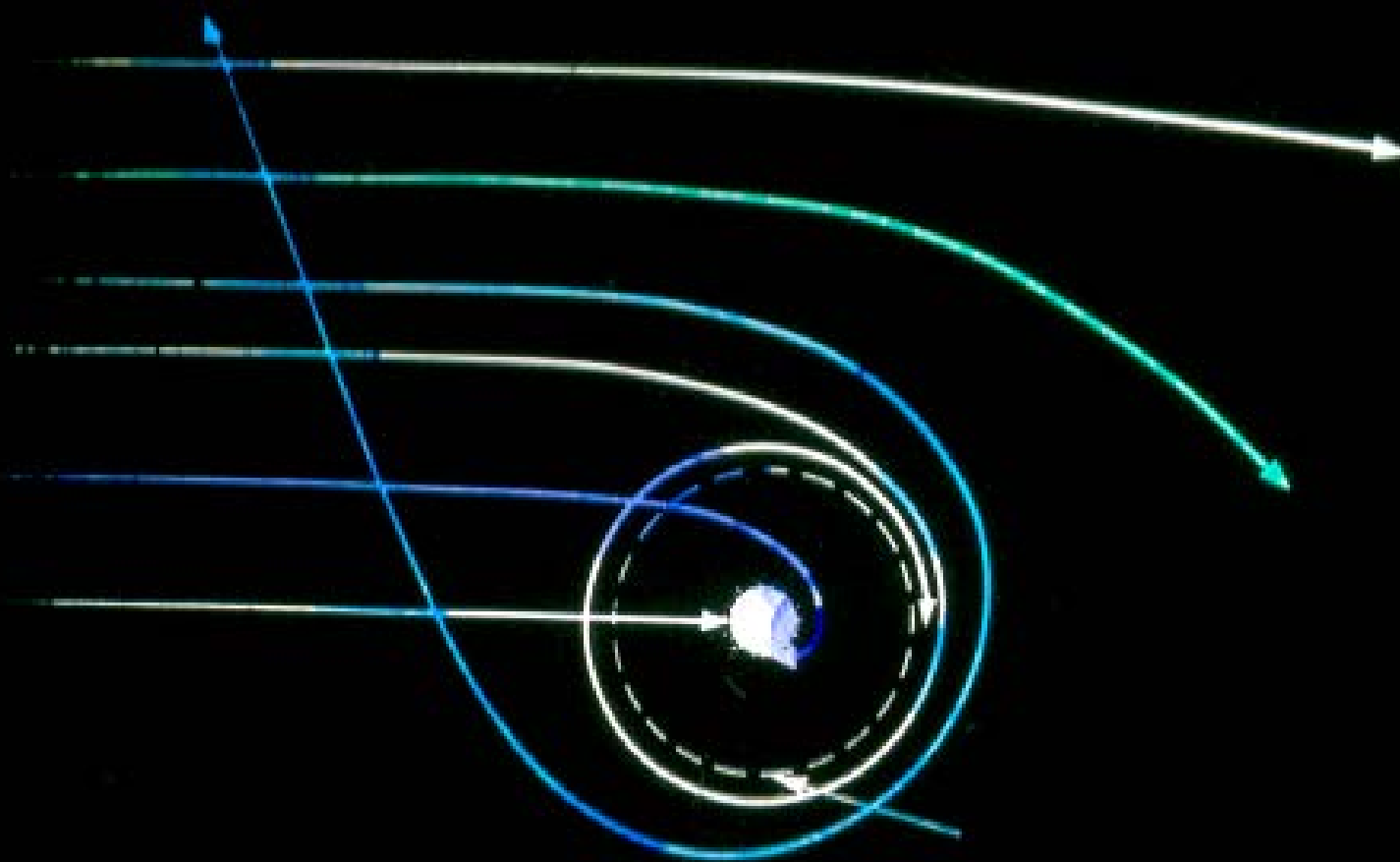
Curvature of 2-dimensional space due to black hole

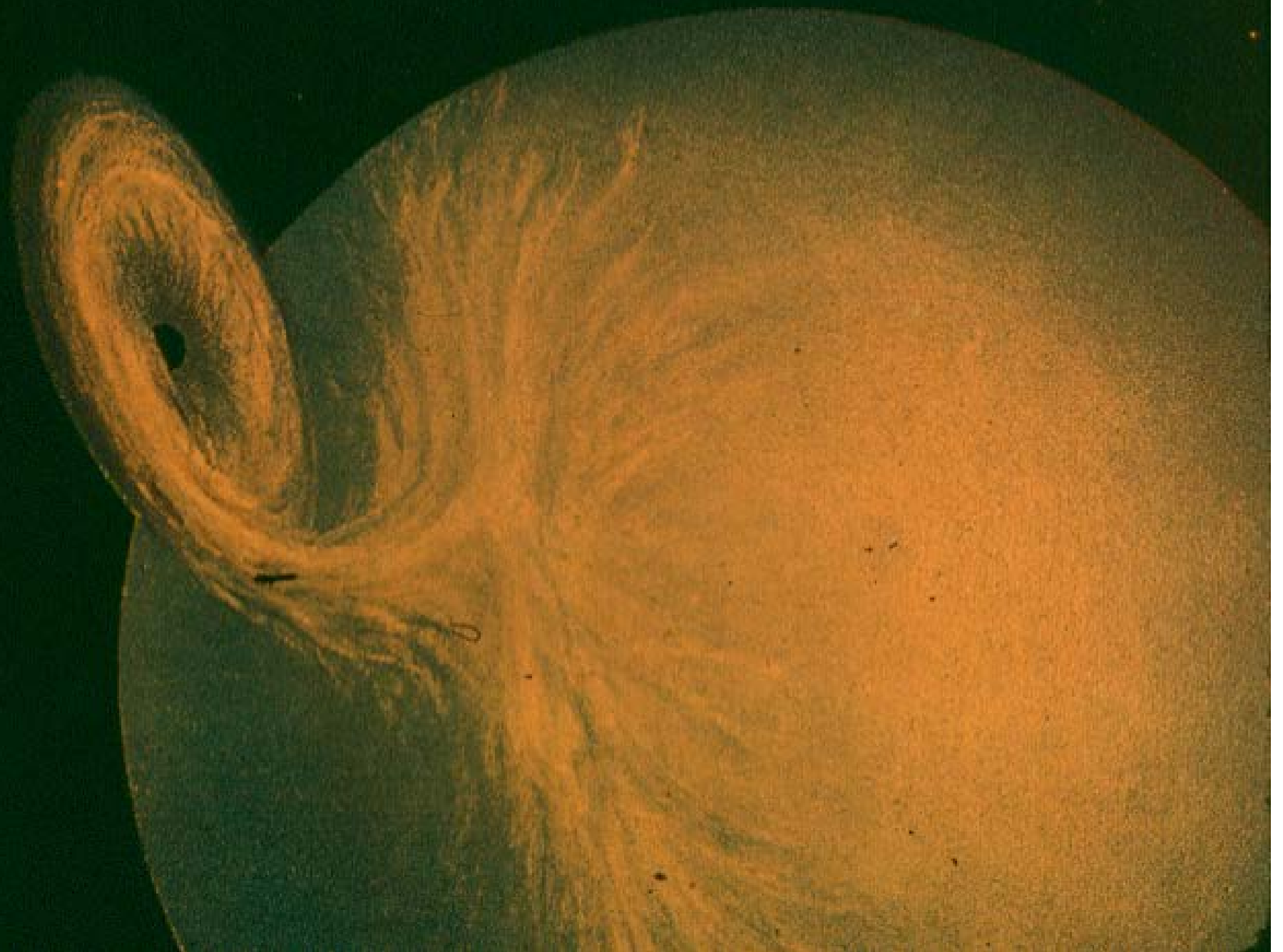
Event horizon

Singularity

Curvature of 2-dimensional space due to large mass star

- Anything that gets close to a black hole, even light, changes its path as it encounters curved space.
- If there is a source of matter nearby, say that the black hole is part of a binary star system, the other star will “feed” gas to the black hole.

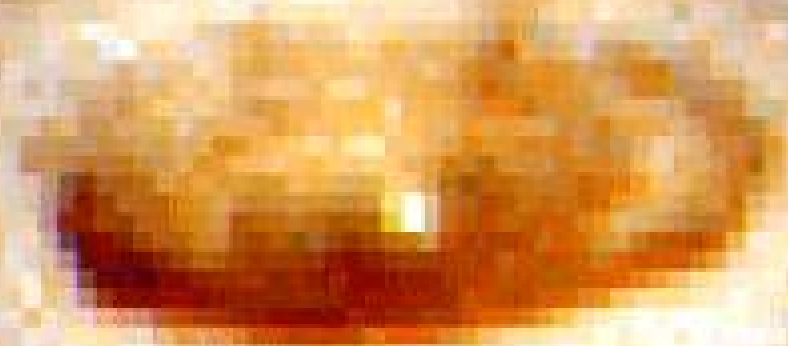




Accretion Disks

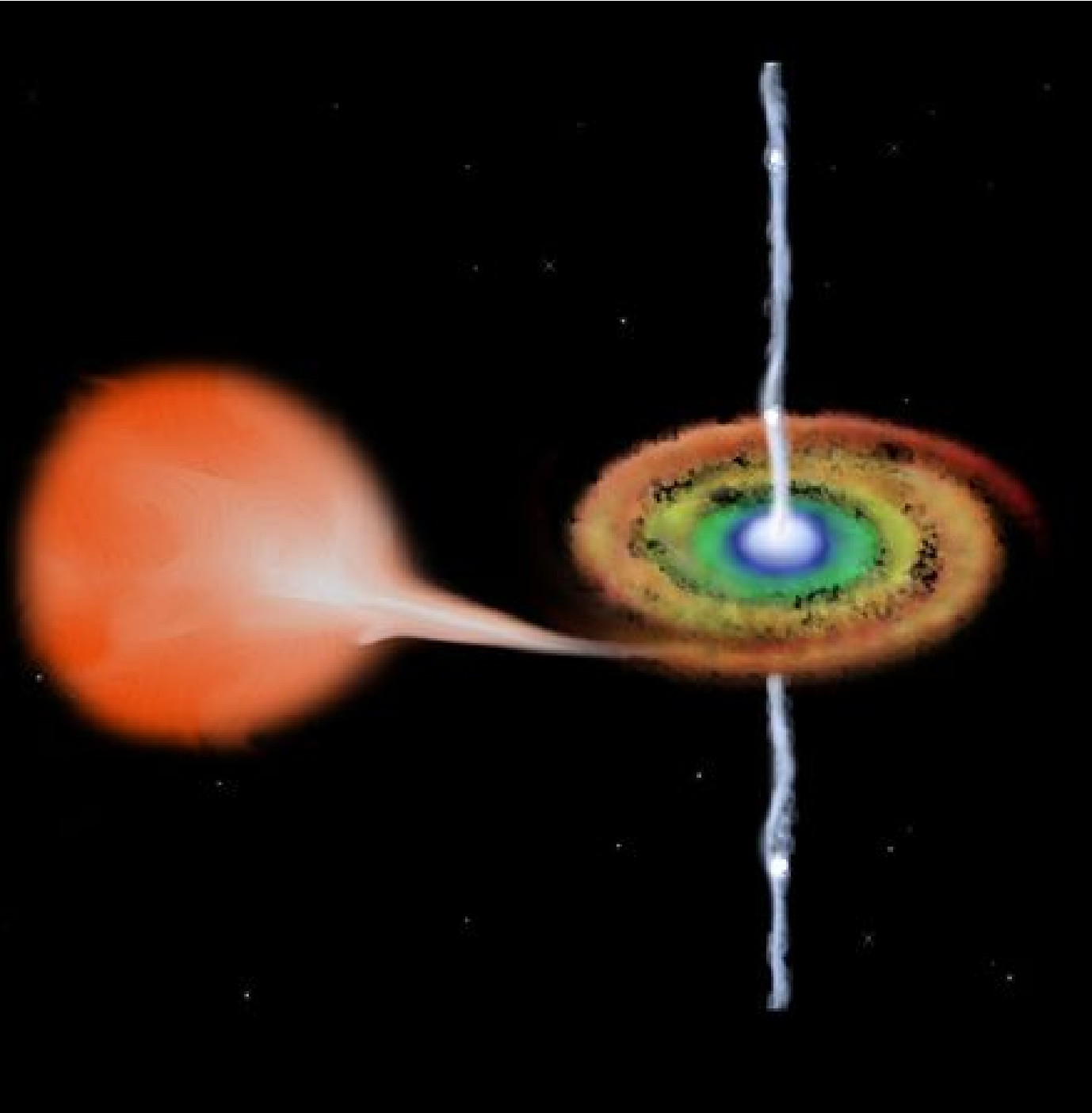
- The gas flowing in from the companion star forms an accretion disk around the black hole.

The accretion disk around a black hole in the center of the M87 galaxy.



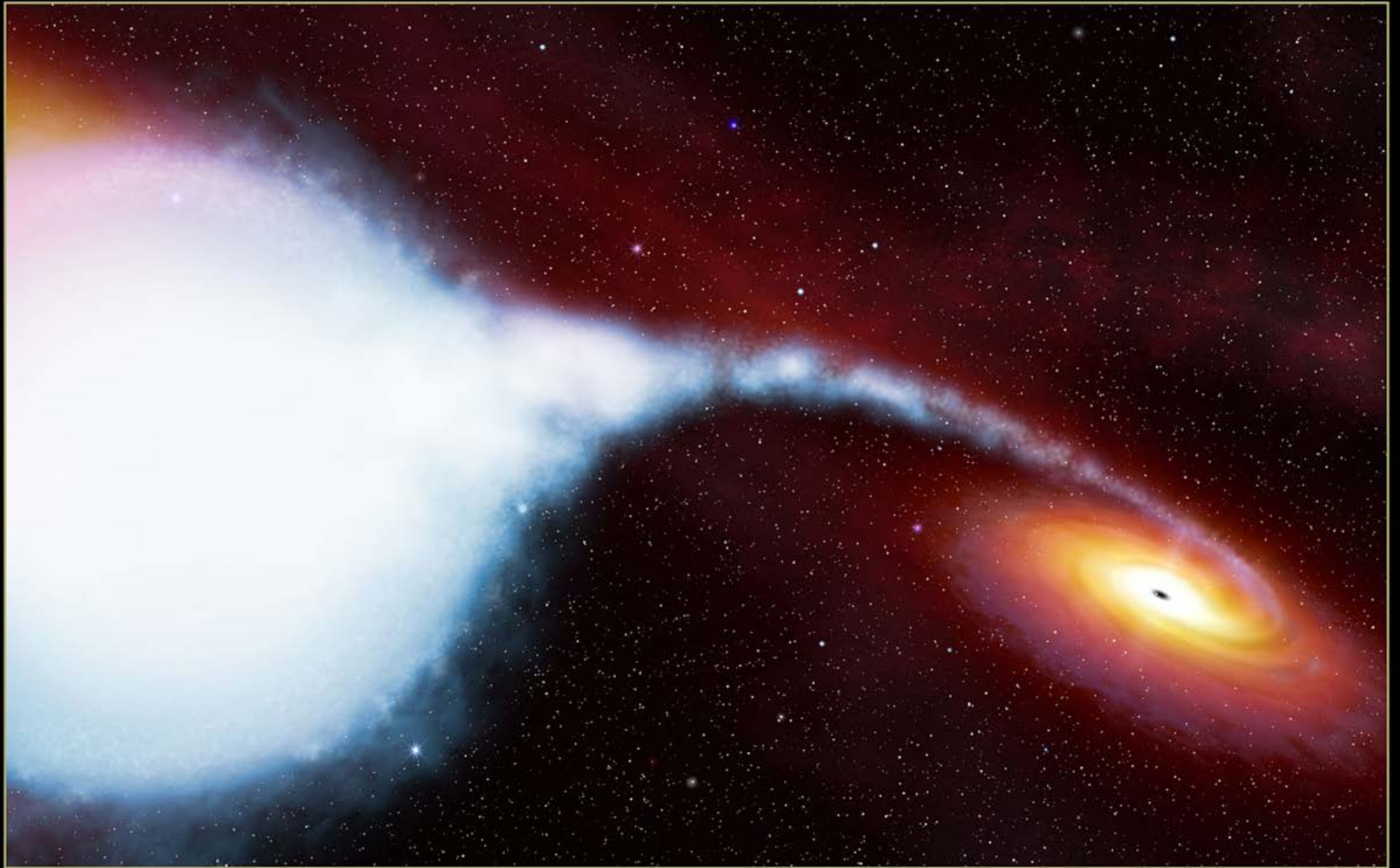
Just before the gas crosses the event horizon, it's compressed and heated to the point that it gives off X-rays.

- The magnetic field of the black hole pushes the energy & some of the hot gas away from the poles in jets.
- The gas in these jets is traveling at nearly the speed of light.



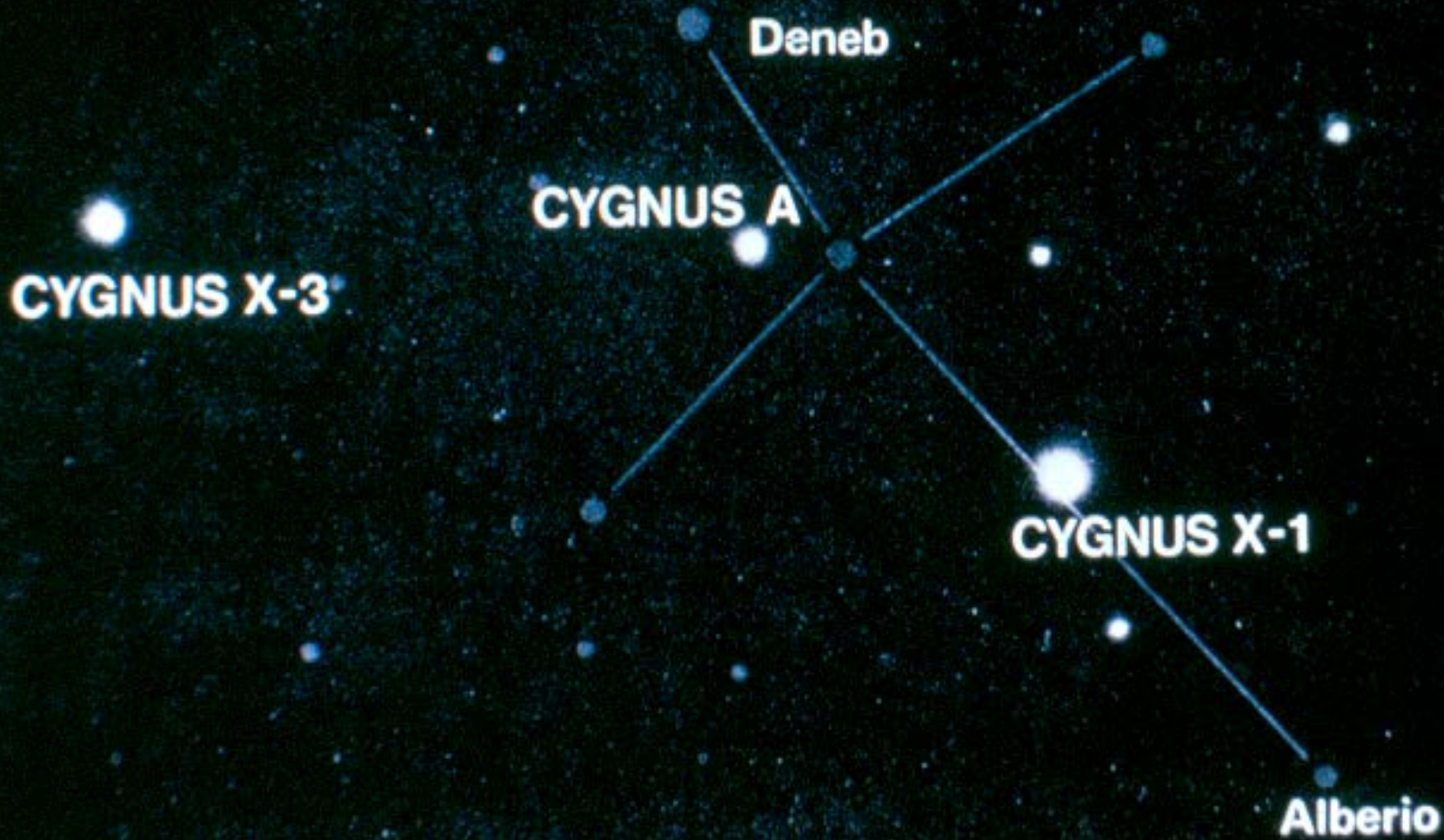
Black Hole Candidate

- Our best candidate for a black hole is a binary star system, Cygnus X-1, in the swan.
- The companion star is a large blue supergiant. This star will eventually become a black hole also!



CYGNUS-X1 *Black hole*

Credit: NASA, ESA, Spacetelescope.org



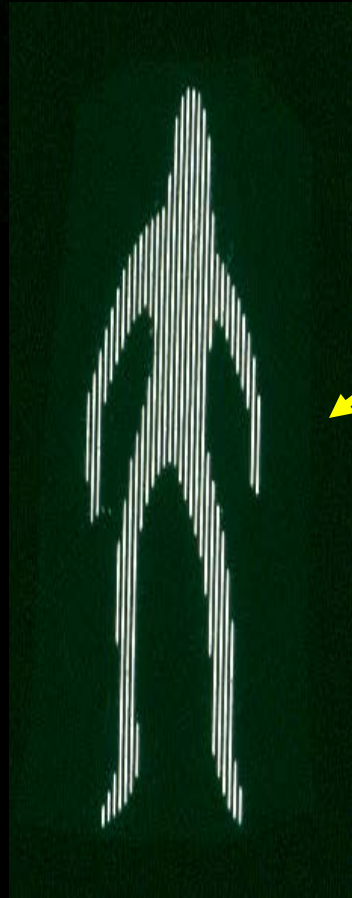
What would happen if you were to fall into a black hole?

- Let's consider the case of someone who leaves their spaceship & falls towards a black hole, while his friend observes what happens from the spaceship.
- The fellow falling in would experience changes in both space and time....



As an astronaut nears a black hole, the difference in the gravitational force on different parts of his body will exert a force on him.

The tidal forces of the BH would begin to stretch the person falling in.



We measure time in terms of movement. When things around us are moving at the



same speed we are, they appear to be standing still to us.



- As our volunteer falls in towards the black hole, he accelerates. He begins moving at the same speed as the things falling in around him. To him, time seems to slow down.
- As the astronaut falls in, light reflected off his body is red-shifted more and more.



clock
300 km.
above
black hole
runs
5% slower



clock
120 km.
above
black hole
runs
15% slower





clock at 90 km,

runs

22 %

slower



clock at 60 km,

runs

41 %

slower





clock at 33 km.
runs
330 %
slower



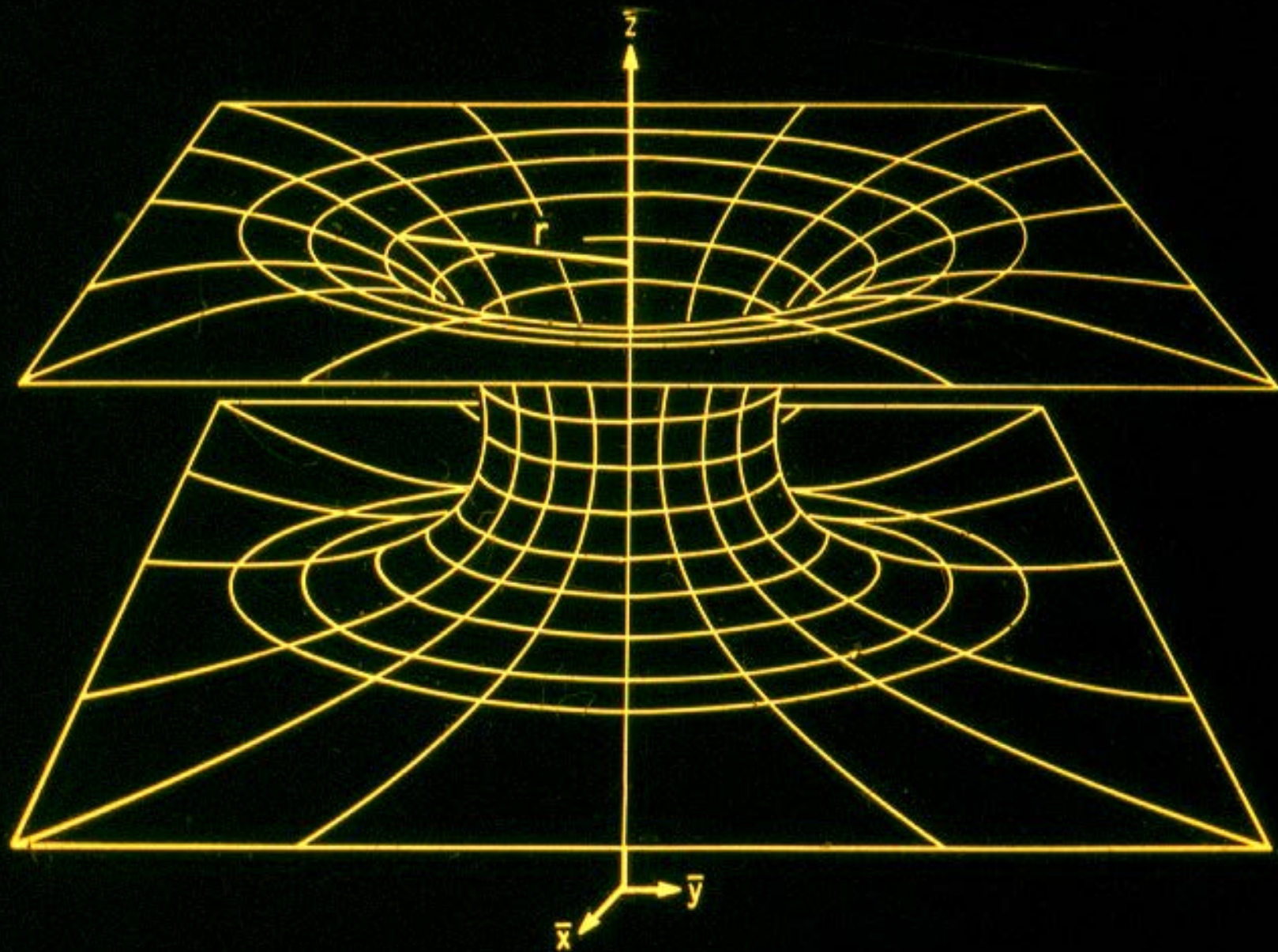
Just as the astronaut reaches the event horizon, time stops for him. His buddy back in the spaceship would see his image remain forever, “floating” at the event horizon.

What happens at the singularity?

- When our volunteer finally reached the singularity, what would happen?
- Stephen Hawking believes that his body would be infinitely crushed. Sometime later, the black hole would release his mass (turned into energy) in the form of gravity waves.

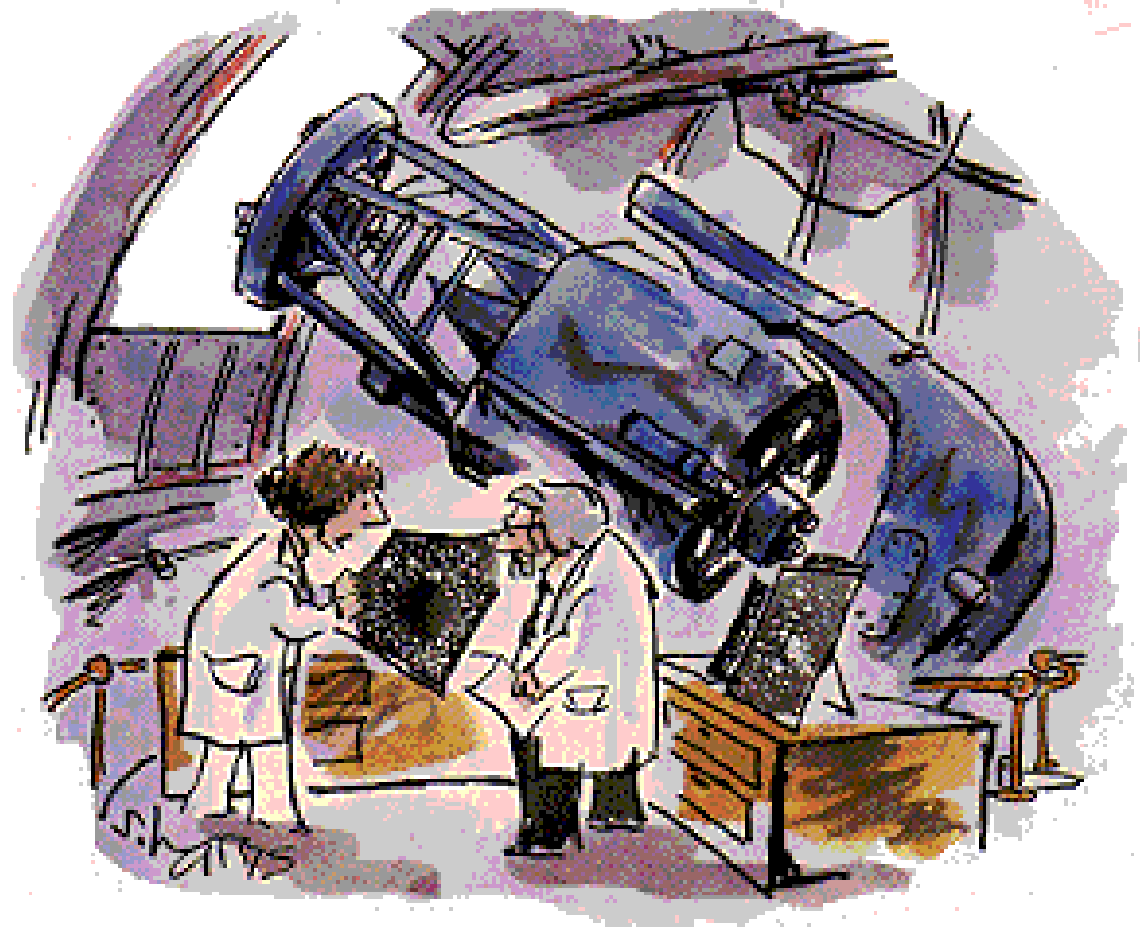
That's not the only idea!

- Other theorists suggest that instead, our volunteer might pass into another universe, that a black hole is just one end of a connector tube called a wormhole.
- However, we have no evidence that wormholes actually exist.



The other side

- What's on the “other” side of a black hole, if there is an “other” side?
- Black holes censor all information about themselves, so the only way to know...is to go.
- Unfortunately, only you would ever know, because there's no way to get the story back to our side again.



"It's black, and it looks like a hole.
I'd say it's a black hole."