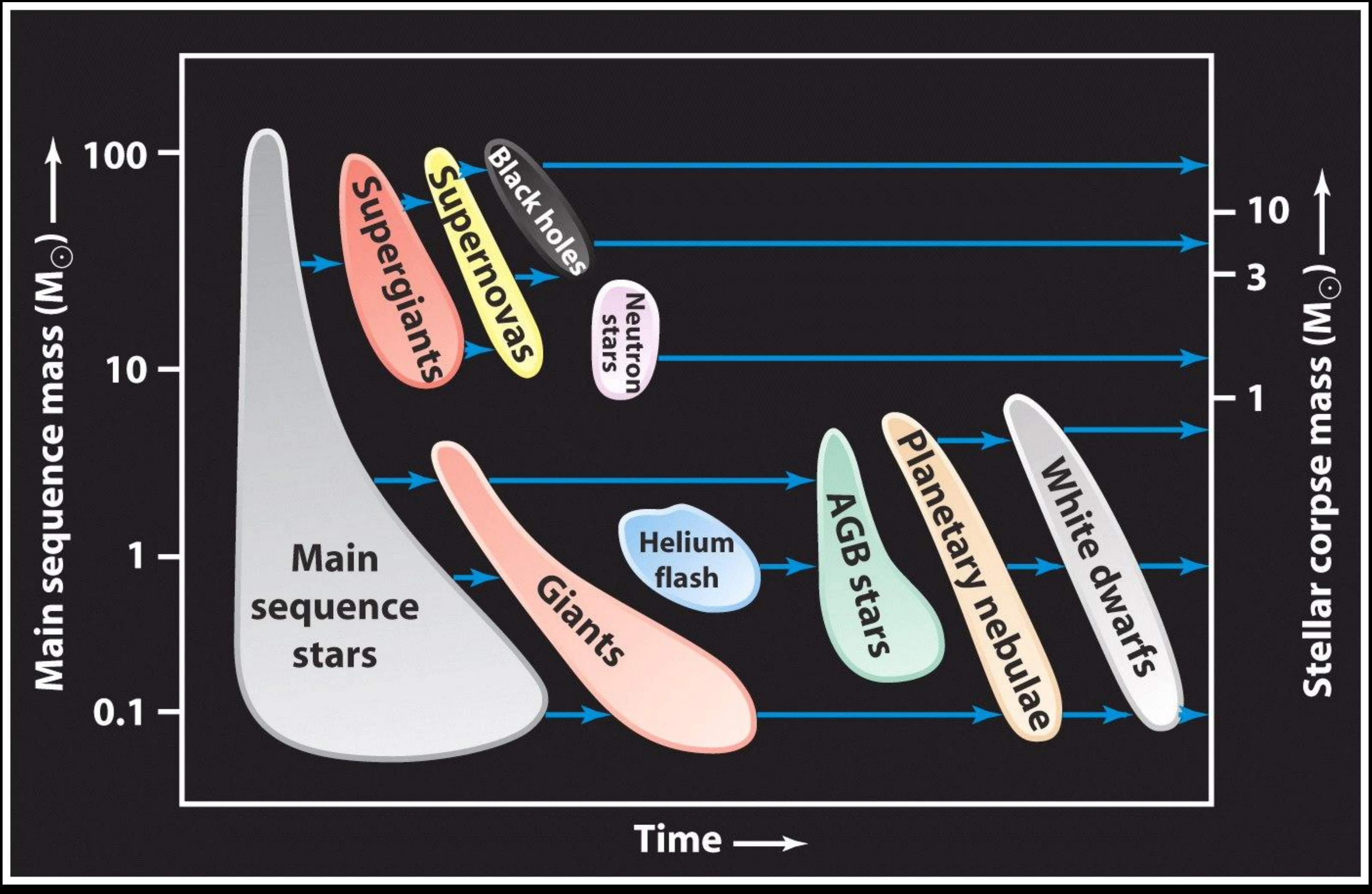
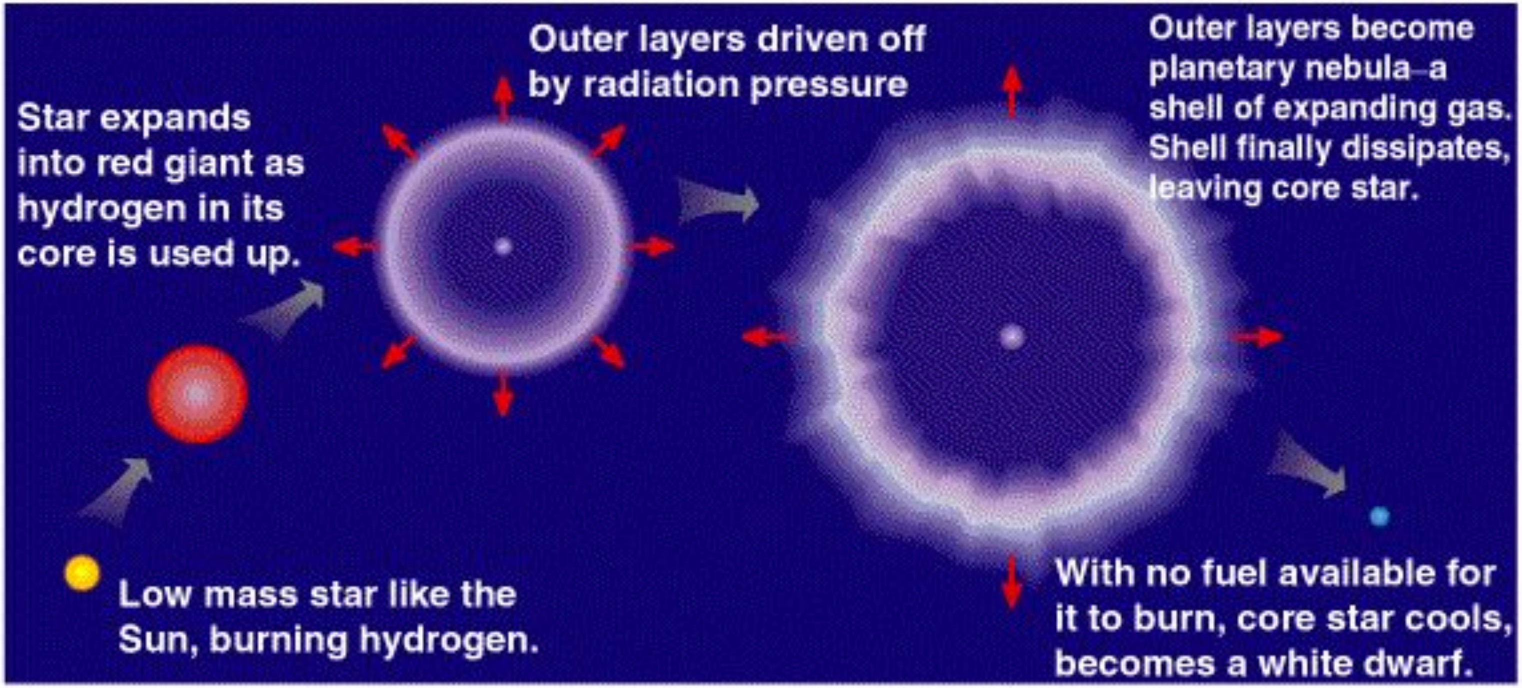
Stellar Remnants

Pathways of Stellar Evolution



Origin of White Dwarf Stars



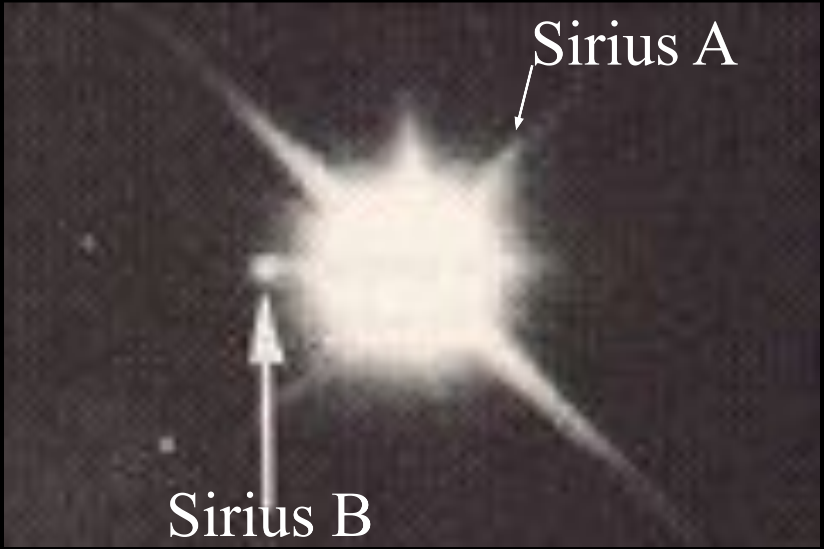
The Helix Nebula

The Cat's Eye Nebula

HST views of Planetary Nebulae
~10,000 have been observed.

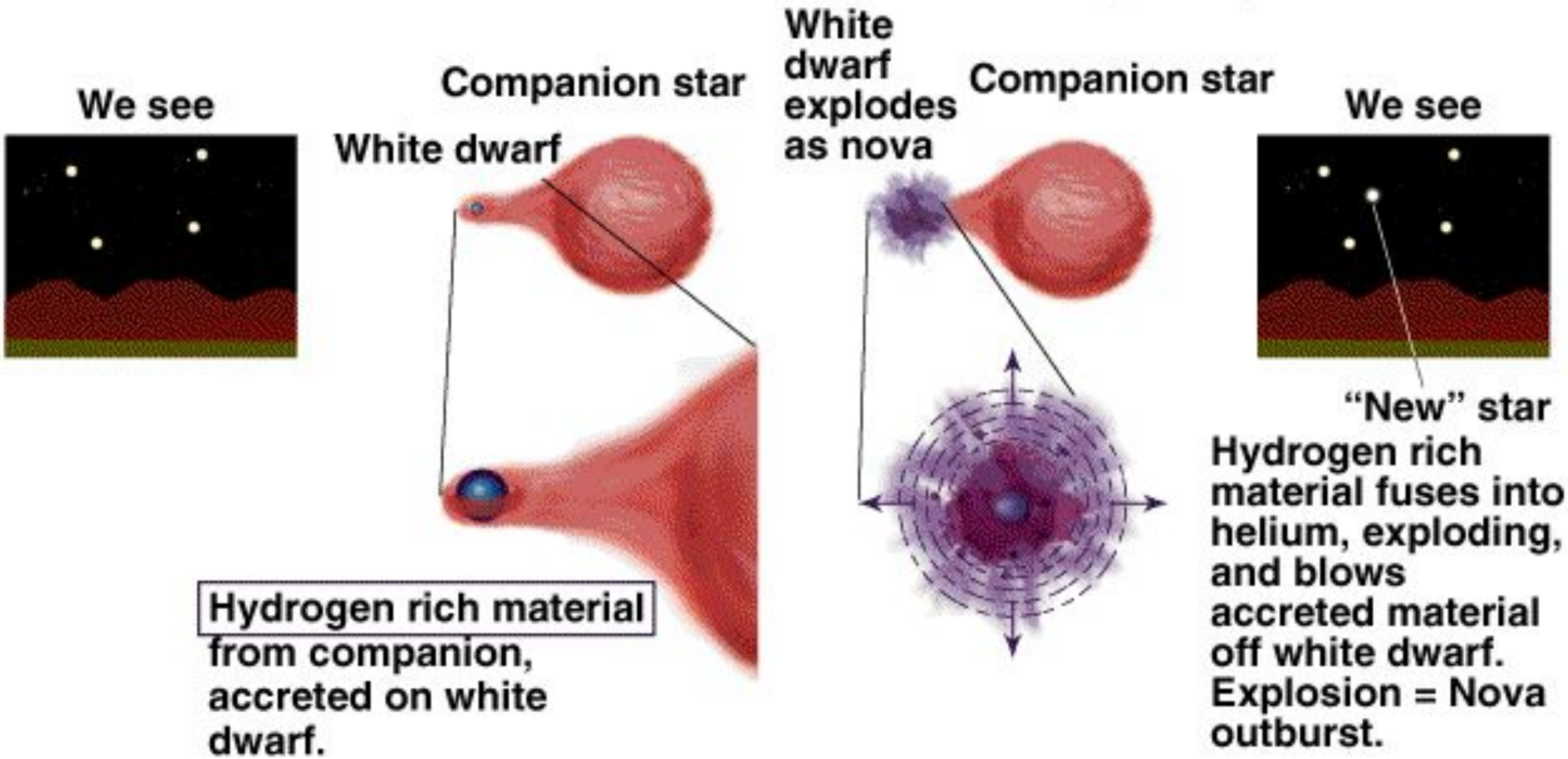
Cocoon of a New White Dwarf
HST

White Dwarfs...



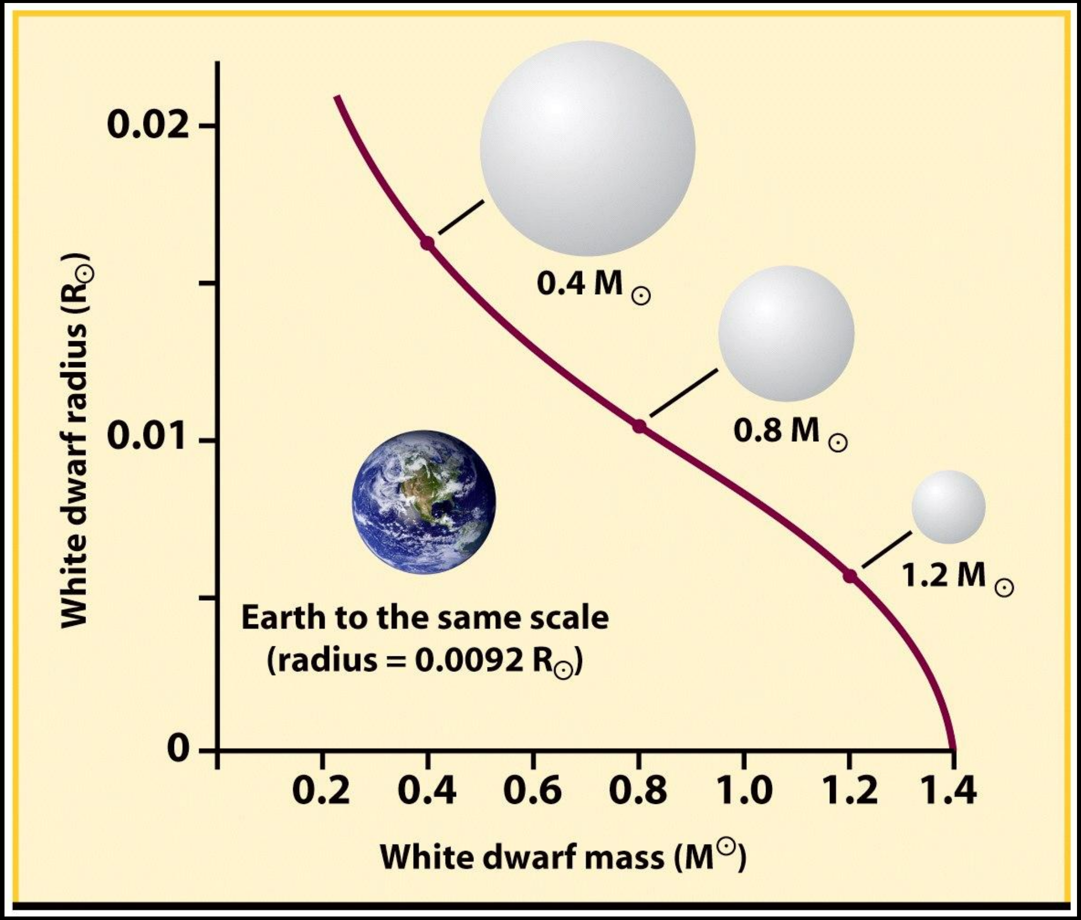
- ...are stellar remnants for <u>low-mass</u> stars (less than 8 $M_\odot$)
- ...are found in the centers of <u>planetary nebula</u>.
- ...have diameters about the same as the Earth's.
- ...have masses less than the <u>Chandrasekhar mass</u> (1.4 Solar Masses).
- …cores are held up by electron degeneracy.
- …a teaspoon full of WD material would weigh 5 tons.
- …nuclear fusion isn't happening in its core.
- …have temperatures ~30,000 K (~54,000ºF)
- …take billions of years to cool off.

Nova Outburst in a Binary System



Nova – a stellar explosion that doesn't mark the end of a star.

White Dwarf
Mass-Radius Relationship



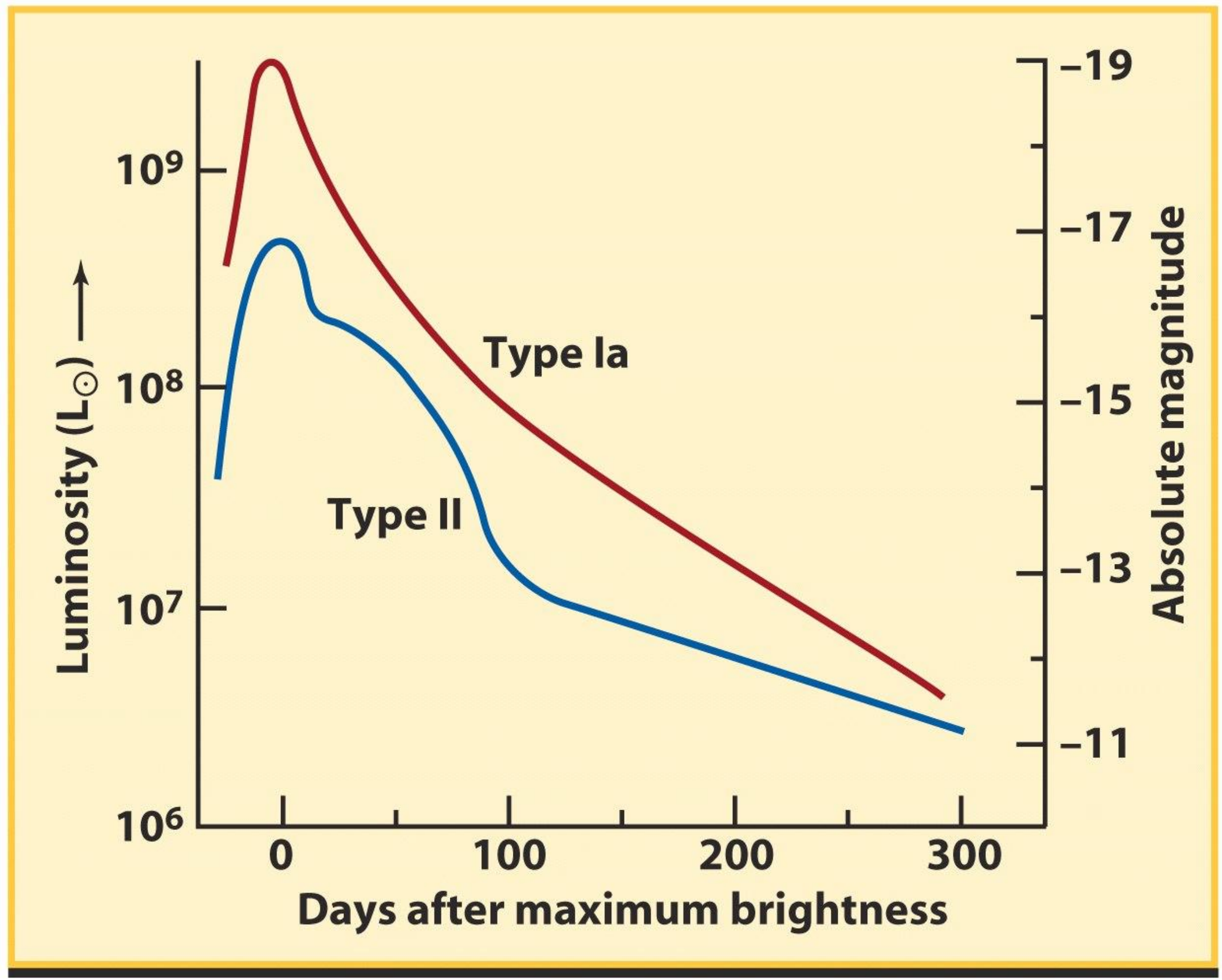
- The more massive the WD is, the smaller it is.
- All WD have a mass smaller than 1.4 solar masses.
- WD size is maintained by the electron degeneracy balancing gravitational collapse.

Remnants of High Mass Stars

- …have masses higher than 8 solar masses.
- …can create the temperatures and pressures inside their cores to fuse elements heavier than carbon and oxygen (nucleosynthesis).
- …eventually explode as supernovae.
- …seed the universe with heavy elements through this process.
- …leave behind an expanding nebula of material.
- …also leave behind a neutron star or a black hole (depending upon core mass).

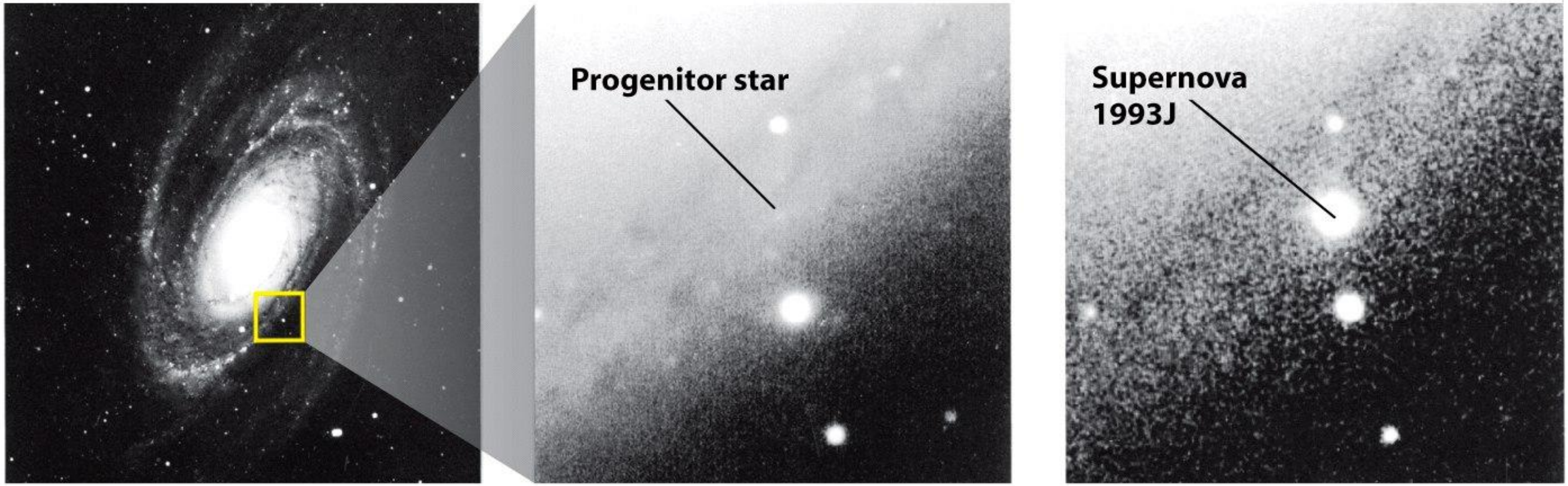
Supernovae

- Supernova - a stellar explosion that marks the end of a star's evolution
  - Type Ia Supernovae
    - » Occur in binary systems in which one is a WD.
    - » Produced by runaway C fusion in WD core.
    - » No H or He lines; strong ionized Silicon II lines
  - Type Ib and Ic Supernovae
    - » Mark the end of a high mass star when the core collapses.
    - » No H or He lines because most of it was lost when star 'puffed' off its outer layers long before the explosion.
  - Type II Supernovas
    - » Occur when a massive star's iron core collapses.
    - » Envelope intact at time of explosion, therefore H and He lines are prominent in spectra.
- Supernovae can be classified by the shape of their light curve.



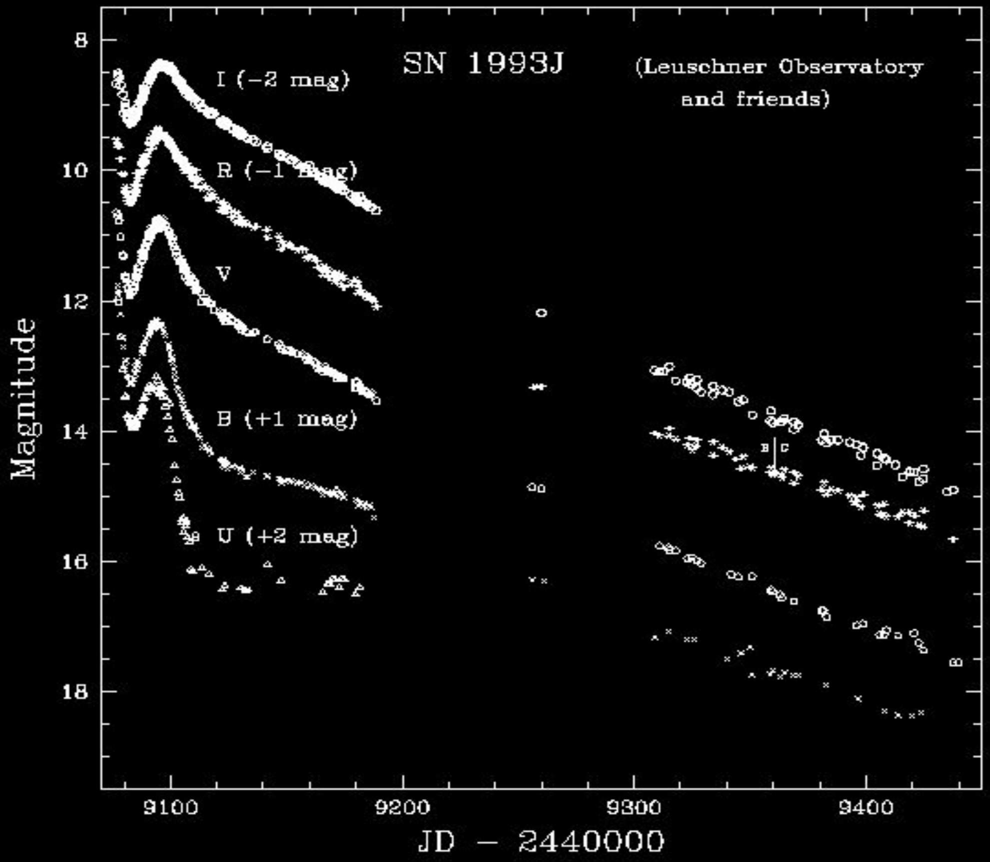
Luminosity ($L_\odot$) ⟶
10^9
10^8
10^7
10^6
Type Ia
Type II
−19
−17
−15
−13
−11
Absolute magnitude
0
100
200
300
Days after maximum brightness

Case Study: SN 1993J



(a) Spiral galaxy M81 (b) Before the explosion (c) After the explosion

Case Study: SN 1993J



- The shape of the light curve indicates that SN 1993J was a Type II supernova.

Supernova 1987a

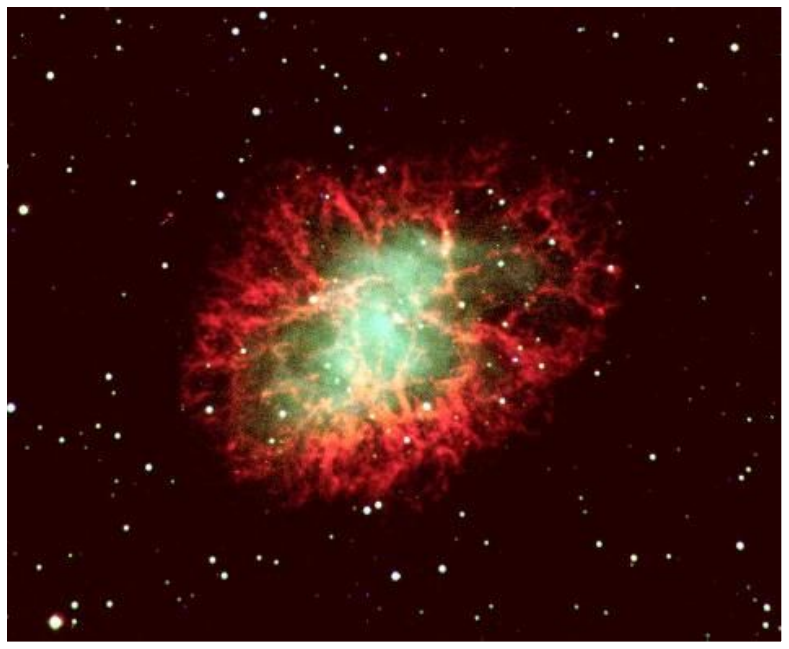
Near the Tarantula nebula in the LMC.

Supernova 1987a

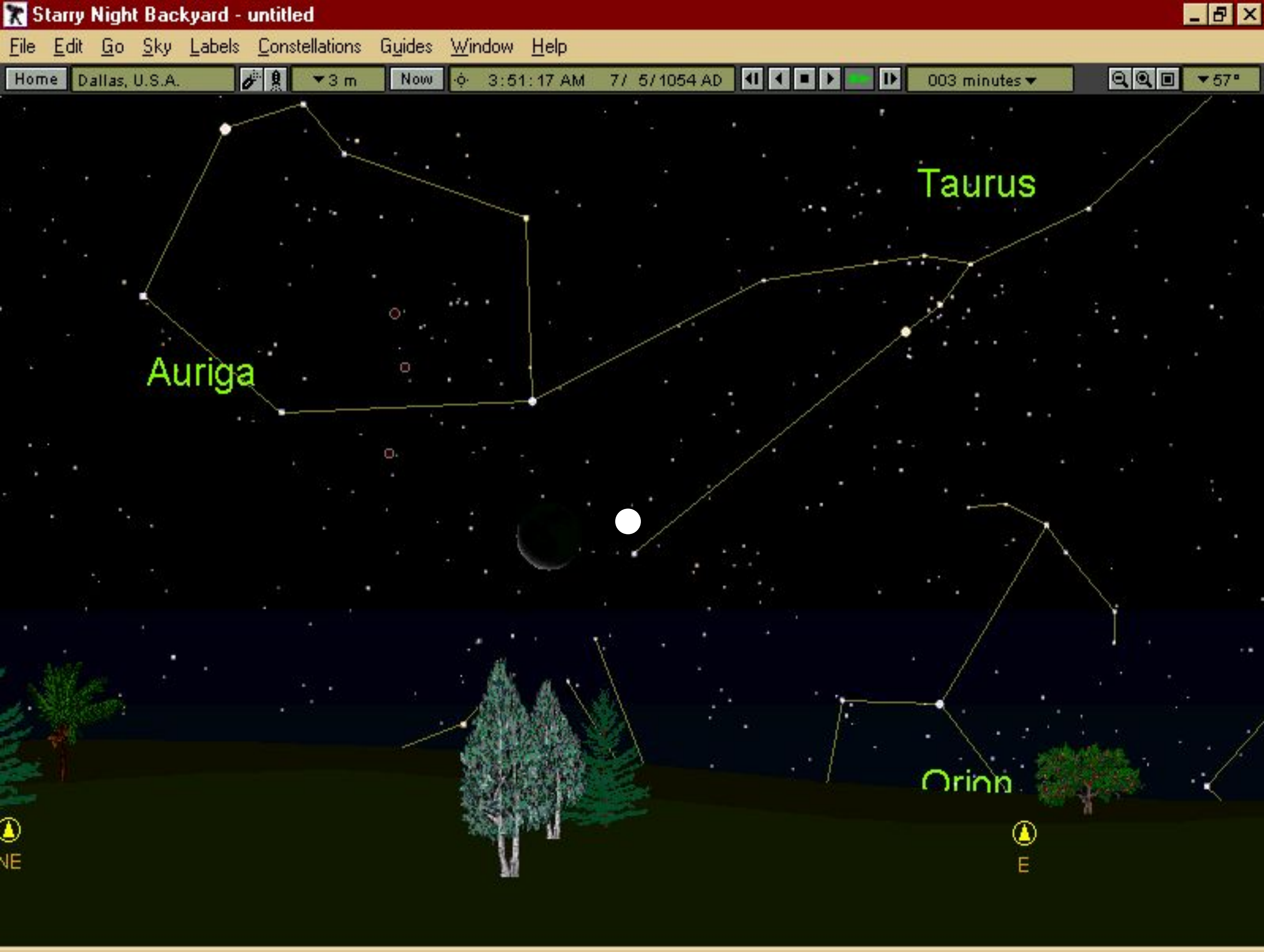
- 1st nearby supernova since 1604.
- Progenitor Star Info: B3I (blue supergiant)
  - T=16,000 K
  - L=100,000 solar luminosities
  - M=20 solar masses
- Neutrino detectors detected ~20 neutrinos.

The Crab Nebula

- SN 1054 – Crab Nebula Supernova
- Became visible in the morning sky early July 1054 before sunrise.
- 4 times brighter than Venus.
- Stayed visible for 23 days.
- Recorded by both Chinese and Native Americans.



This is what we see today!


Starry Night Backyard - untitled
File Edit Go Sky Labels Constellations Guides Window Help
Home
Dallas, U.S.A.
3 m
Now
3:51:17 AM 7/ 5/1054 AD
003 minutes
57°
Taurus
Auriga
Orion
NE
E

Anazasi Pictographs

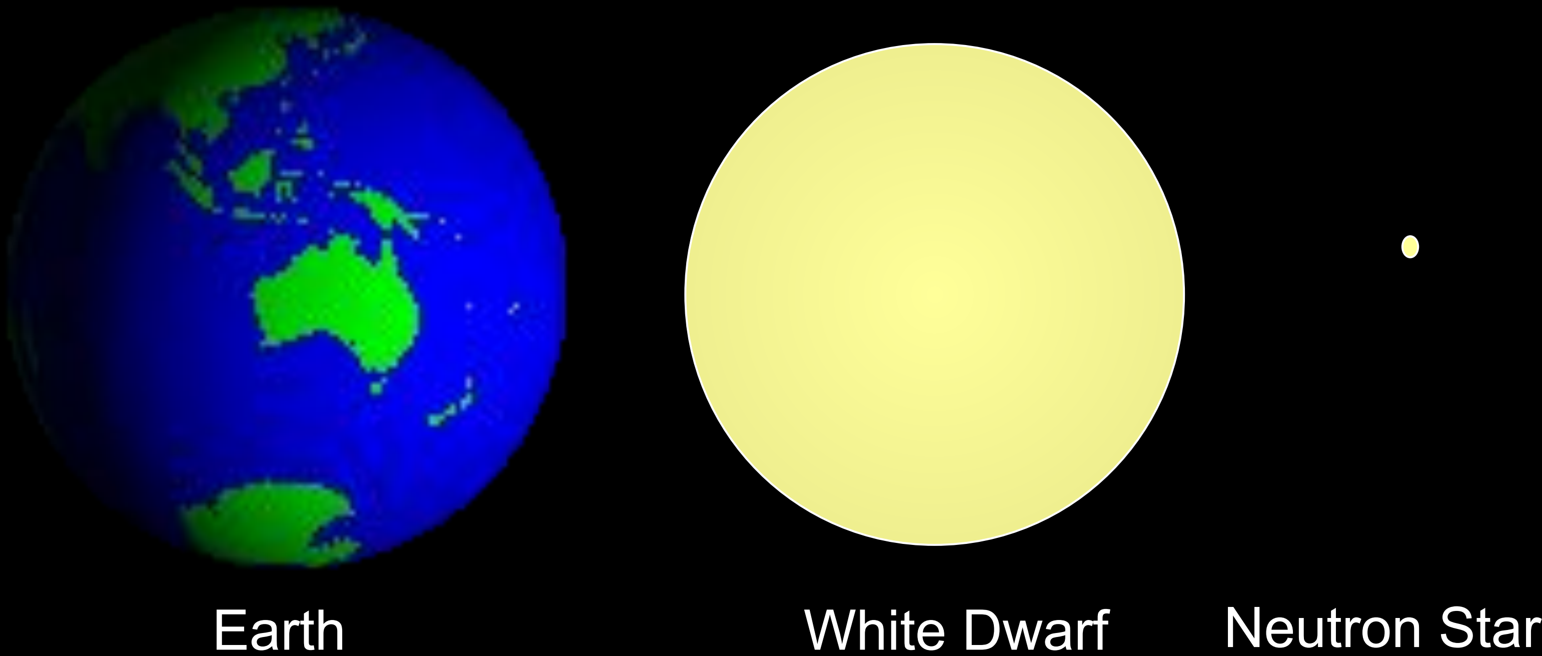
Large Mass Star - Core Remnants

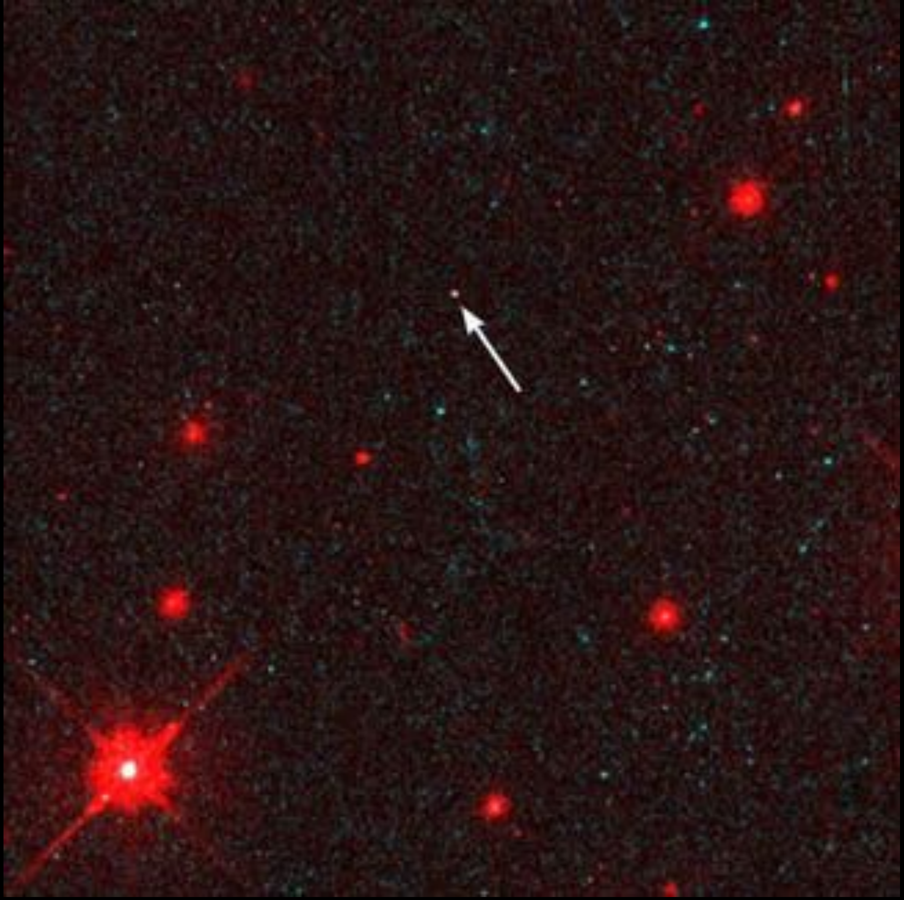
- Too massive for electron degeneracy to halt collapse ($M > 1.4\ M_\odot$)
  - Electromagnetic force

- Neutron Degeneracy can halt collapse
  - $M < 3\ M_\odot$
  - Strong nuclear force
  - Neutron Star

- Quark Stars
  - Discovered by Chandra X-ray Observatory
  - Quark's are the building blocks of neutrons.
  - Held up by 'quark pressure'
  - Smaller than Neutron Stars

Relative sizes

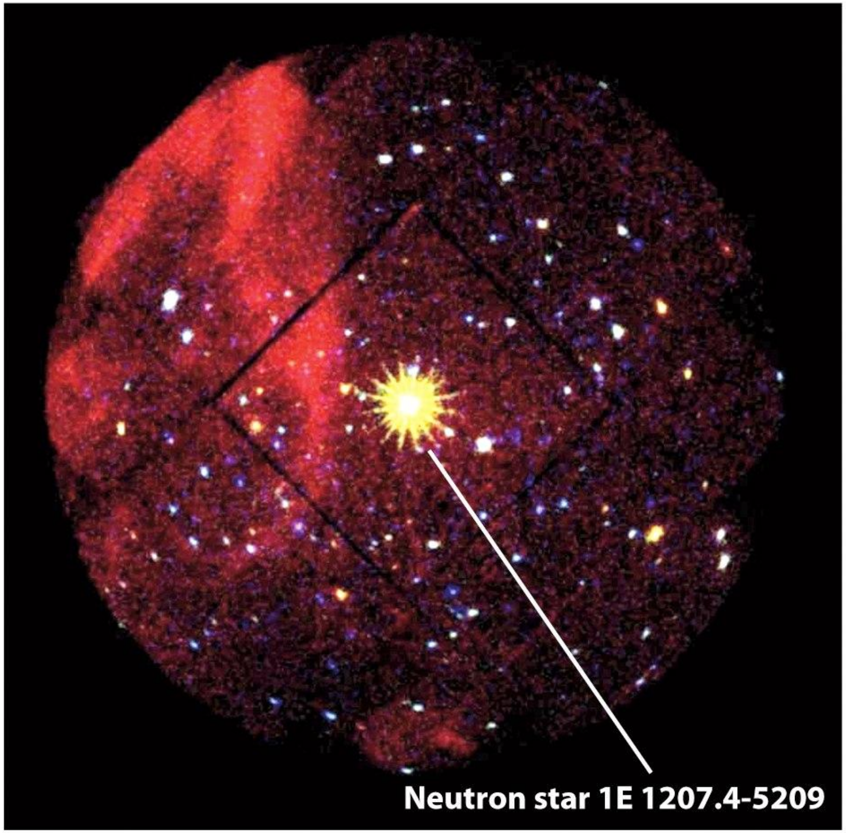




The Hubble Space Telescope succeeded in taking an image of a neutron star located less than 400 light-years away from Earth.

This star was previously detected by its X-ray radiation, indicating a surface temperature around 40,000K (700,000°F).

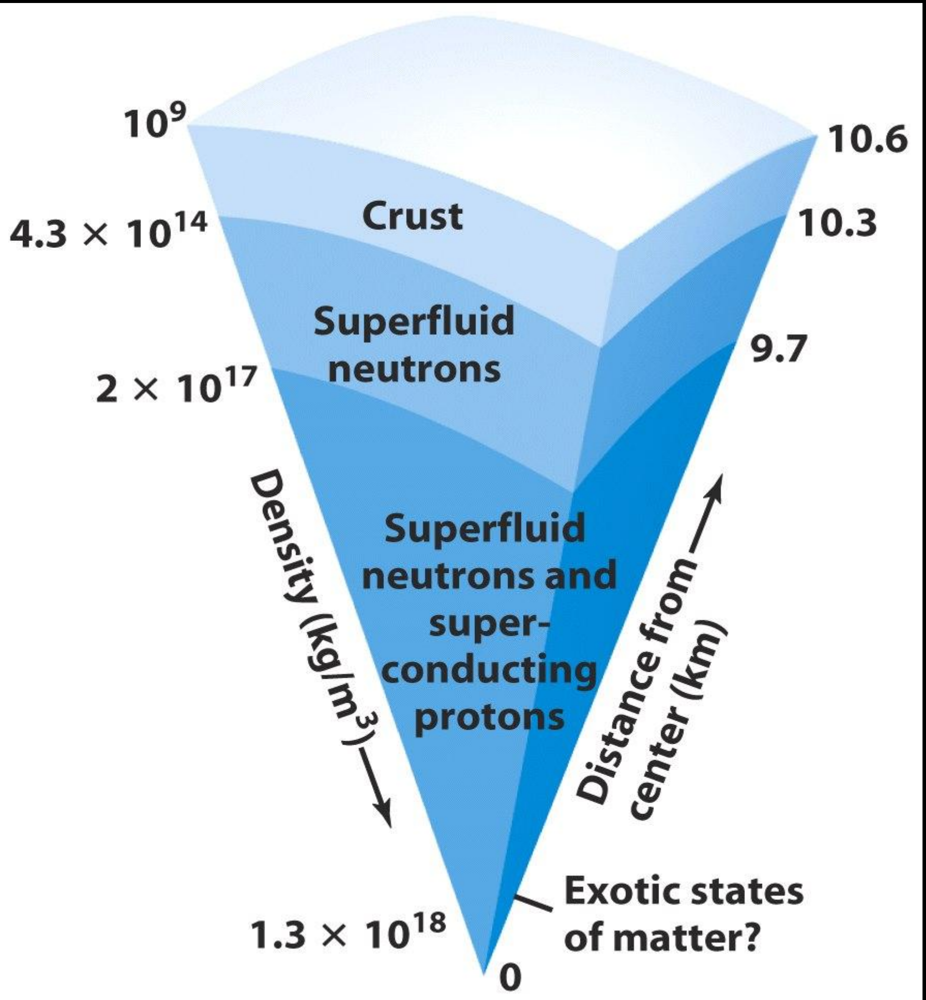
Neutron Stars



X-ray image

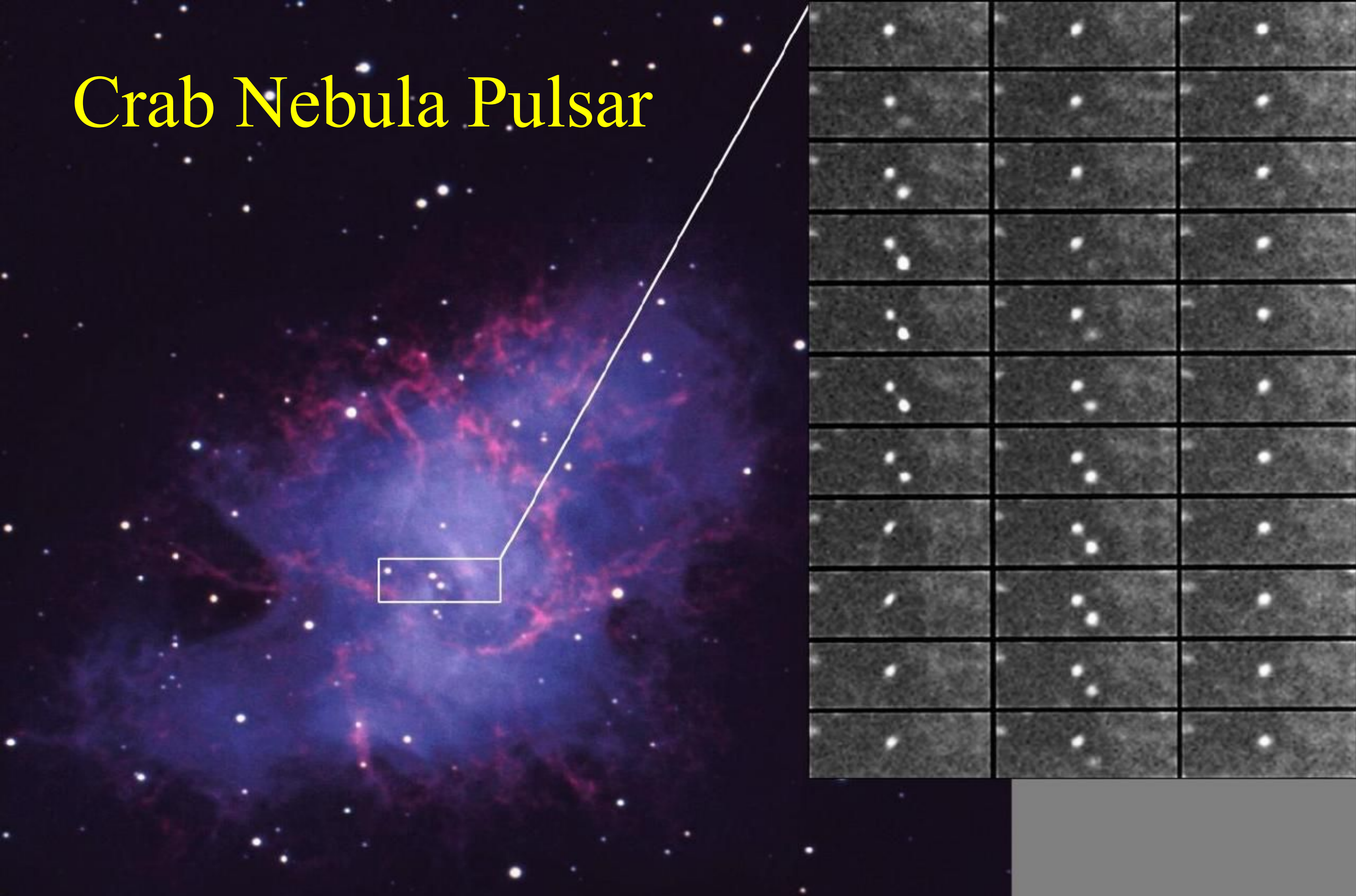
- Very small diameters (~6-12 miles)
- Composed of mostly neutrons.
- A teaspoon of NS material would weigh 1 billion tons.
- Very rapid rotation and strong magnetic fields.
- Sometimes have EM hot spots.
- A.K.A. Pulsars

Strange Properties of Neutron Stars



- Tenuous Atmosphere
  - Soft X-rays
  - Plasma state
- Brittle Crust
- Superfluid Neutrons (no friction)
- Superconducting Protons (make magnetic field)

Crab Nebula Pulsar



…rotates about 30 times per second.

…emits double pulse each rotation (RF to Gamma)

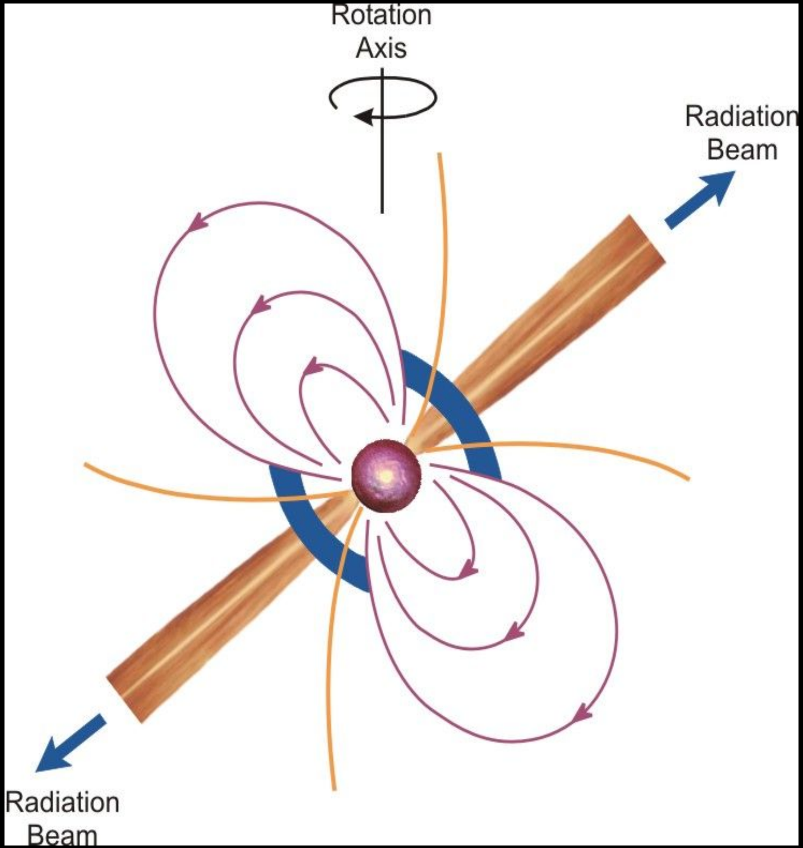
Pulsars

- *The first pulsar was discovered November 28, 1969.*
- *The first pulsars observed was originally thought to be a signal from extraterrestrials. (They were labeled as LGM sources (little green men) for a short time!)*
- *This was later shown to be unlikely after many other pulsars were found all over the sky.*
- *Also, it was found that each pulse had a total power output equal to that of all the resources of Earth.*

Pulsars

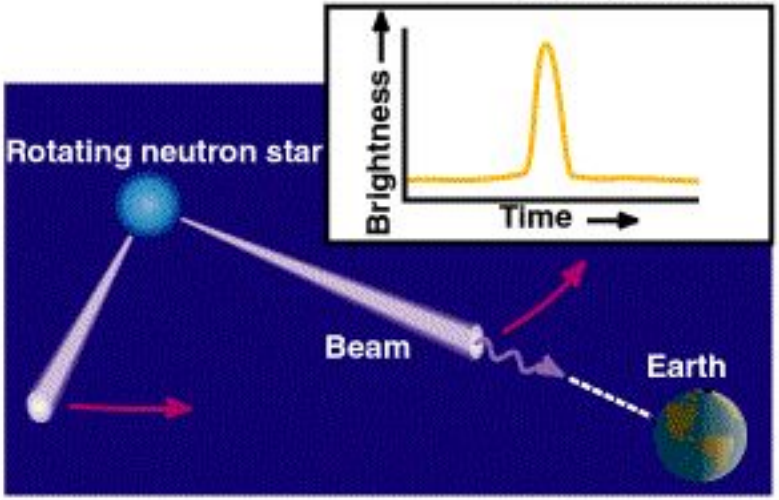
- Pulsars are rotating, magnetized neutron stars.

- <u>Light House Model</u>
  - Beams of radiation emanate from the magnetic poles.
  - As the neutron star rotates, the beams sweep around the sky.
  - If the Earth happens to lie in the path of the beams, we see a pulsar.

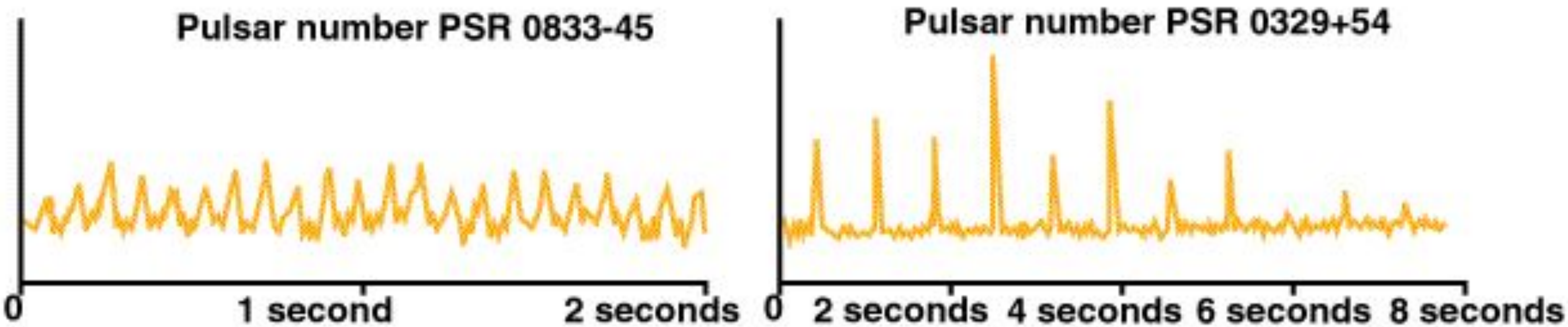


Pulsar Beaming

We see a pulse
when beam
points at Earth.



Graph of Pulsar Pulses



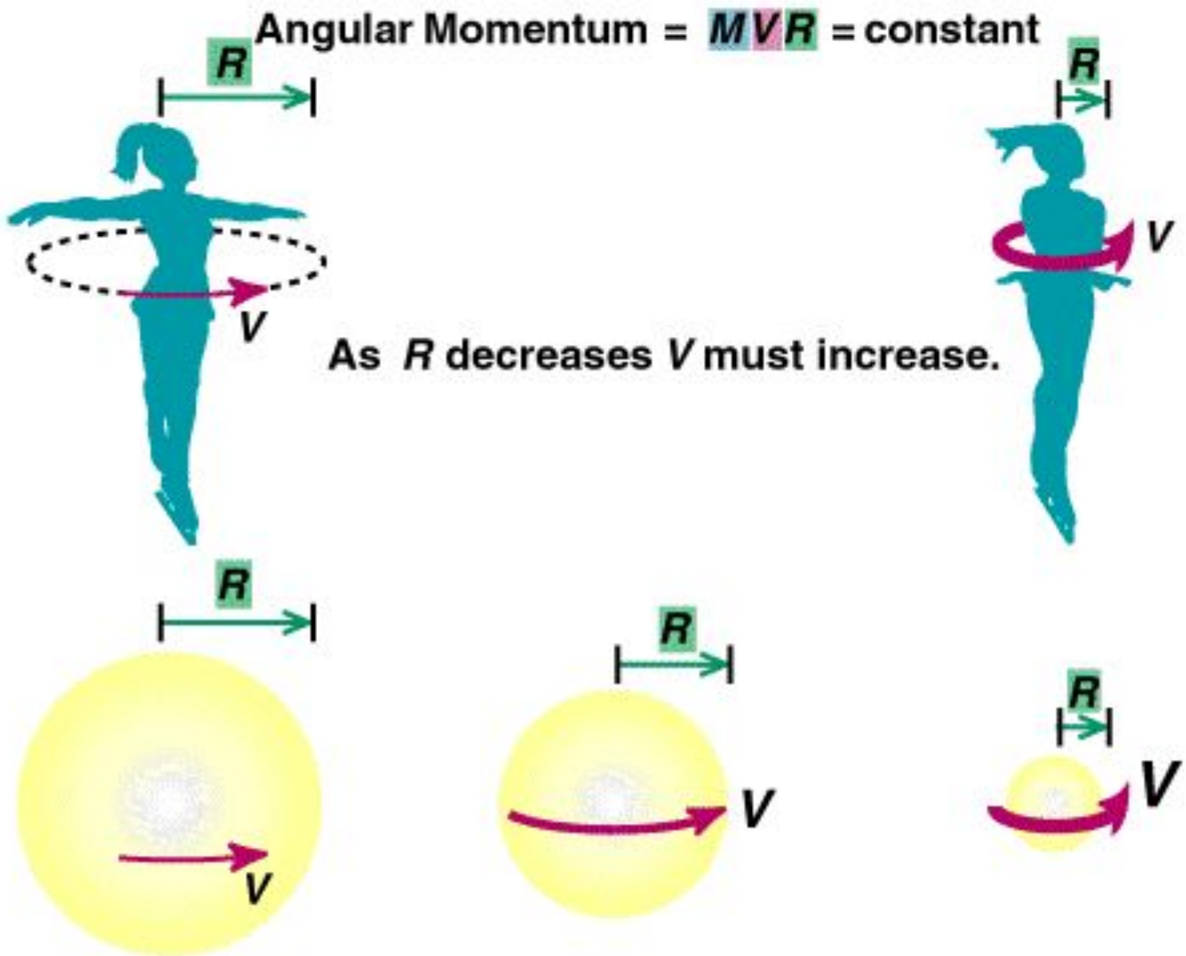
Rotation Rates of Pulsars

- The neutron stars that appear to us as pulsars rotate about once every second.

- Before a star collapses to a neutron star it probably rotates about once every 25 days.

- Why is there such a big difference in rotation rates?
- Answer: Conservation of Angular Momentum

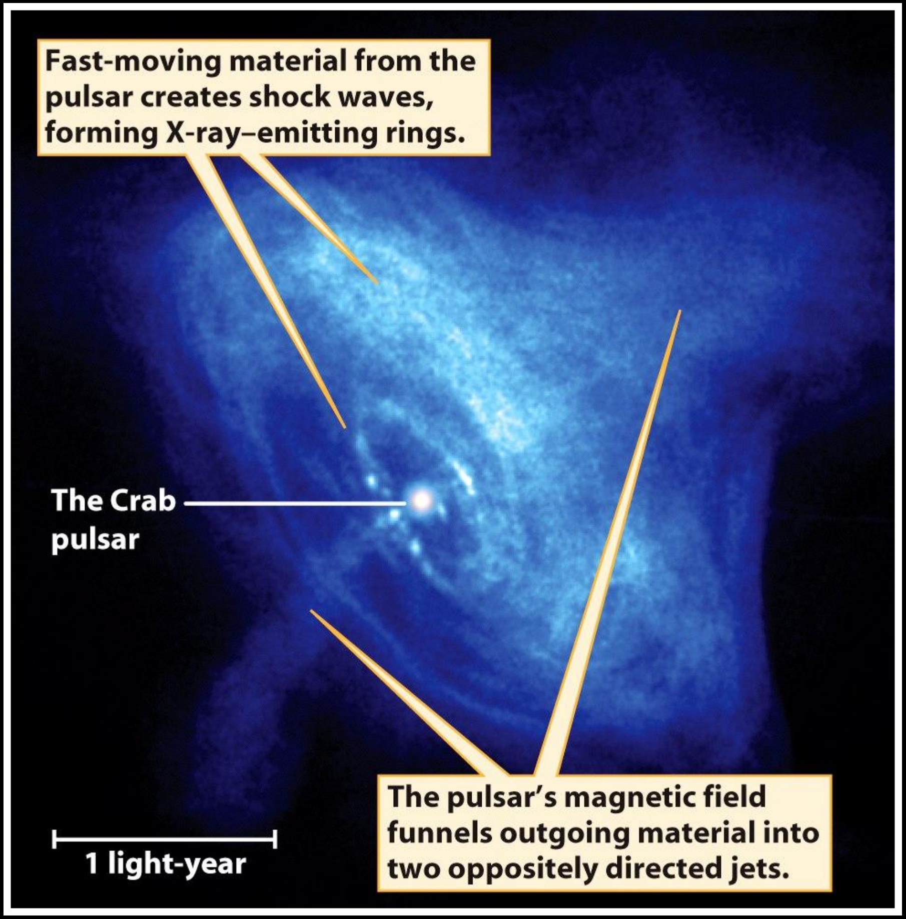
Conservation of Angular Momentum

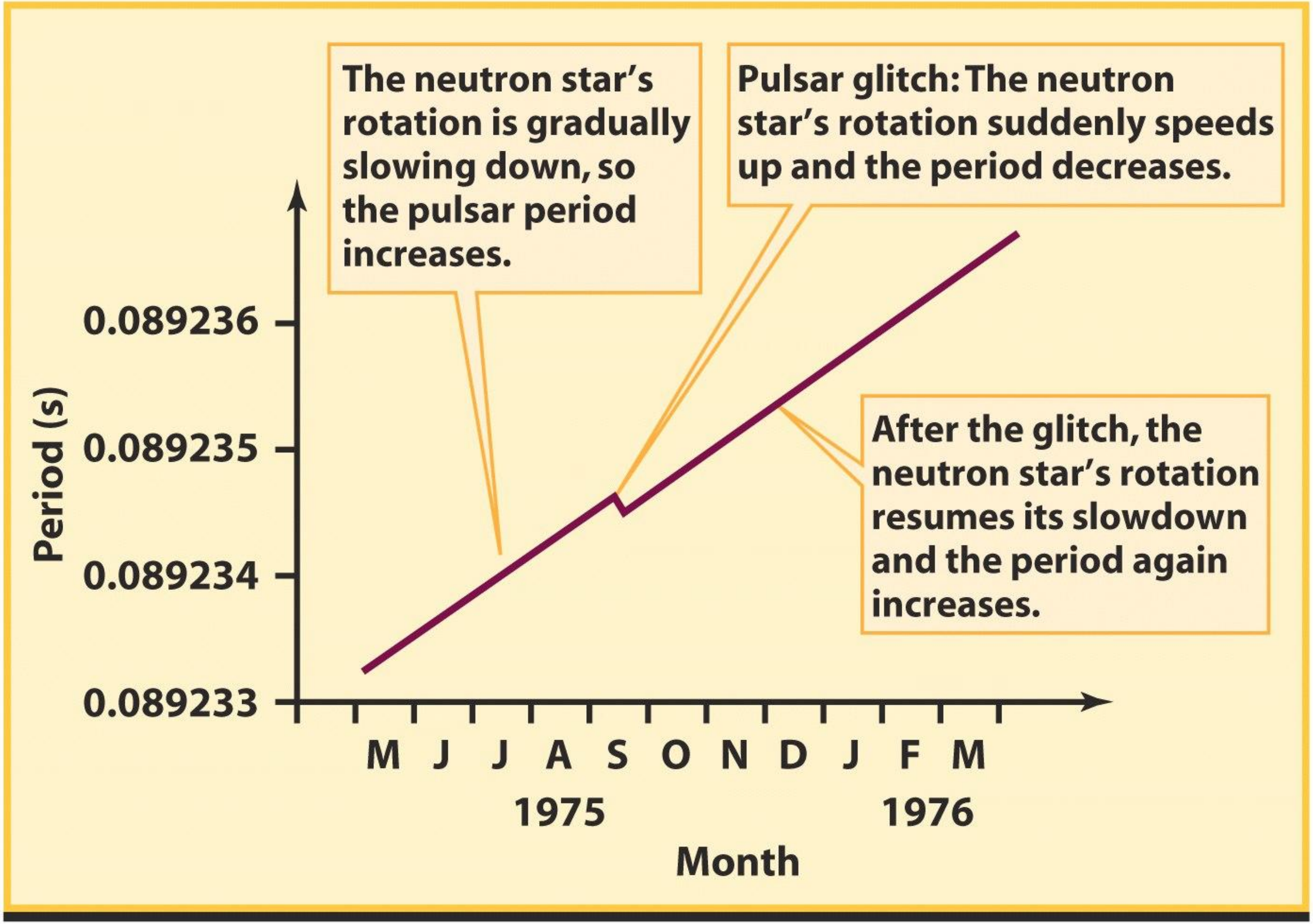


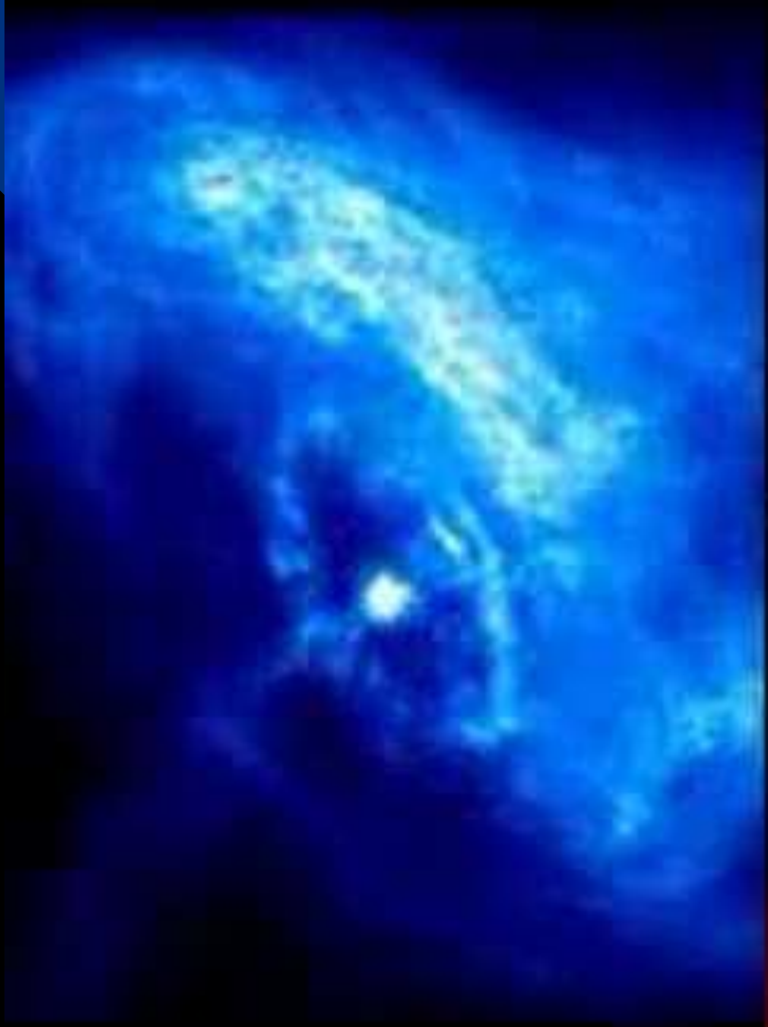
Neutron Stars and Pulsars Slow Down over time

- Periods typically increase by a few billionths of a second each day.

- Rotational energy is transferred to electrons via the NS magnetic field (seen as synchrotron radiation).




The neutron star's rotation is gradually slowing down, so the pulsar period increases.
Pulsar glitch: The neutron star's rotation suddenly speeds up and the period decreases.
After the glitch, the neutron star's rotation resumes its slowdown and the period again increases.
Period (s)
0.089236
0.089235
0.089234
0.089233
M J J A S O N D J F M
1975
1976
Month



X-ray light (Chandra)

Visible light (HST)

End Points of Stellar Evolution

- Low Mass Stars
  - $M^* < 8\ M_\odot$
  - Become White Dwarf ($M_{core} < 1.4\ M_\odot$)
    - » Electron Degeneracy Pressure
    - » Density = 1 ton/cc

- Medium Mass Stars
  - $8\ M_\odot < M^* < 25\ M_\odot$
  - Become Neutron Stars ($3\ M_\odot < M < 1.4\ M_\odot$)
    - » Neutron Degeneracy Pressure
    - » Also possible, Quark Degeneracy Pressure
    - » Density = 200 million ton/cc

- High Mass Stars
  - $M^* > 25\ M_\odot$
  - Hypernovae (subclass of Type II Supernovae)
  - Become Black Holes ($M > 3M_\odot$)
    - » Density = Infinite

Black Holes

- ...are stellar remnants for high-mass stars.
- …have a gravitational attraction that is so strong that light cannot escape from it.
- …are found in some binary star systems and there are super-massive black holes in the centers of some galaxies.

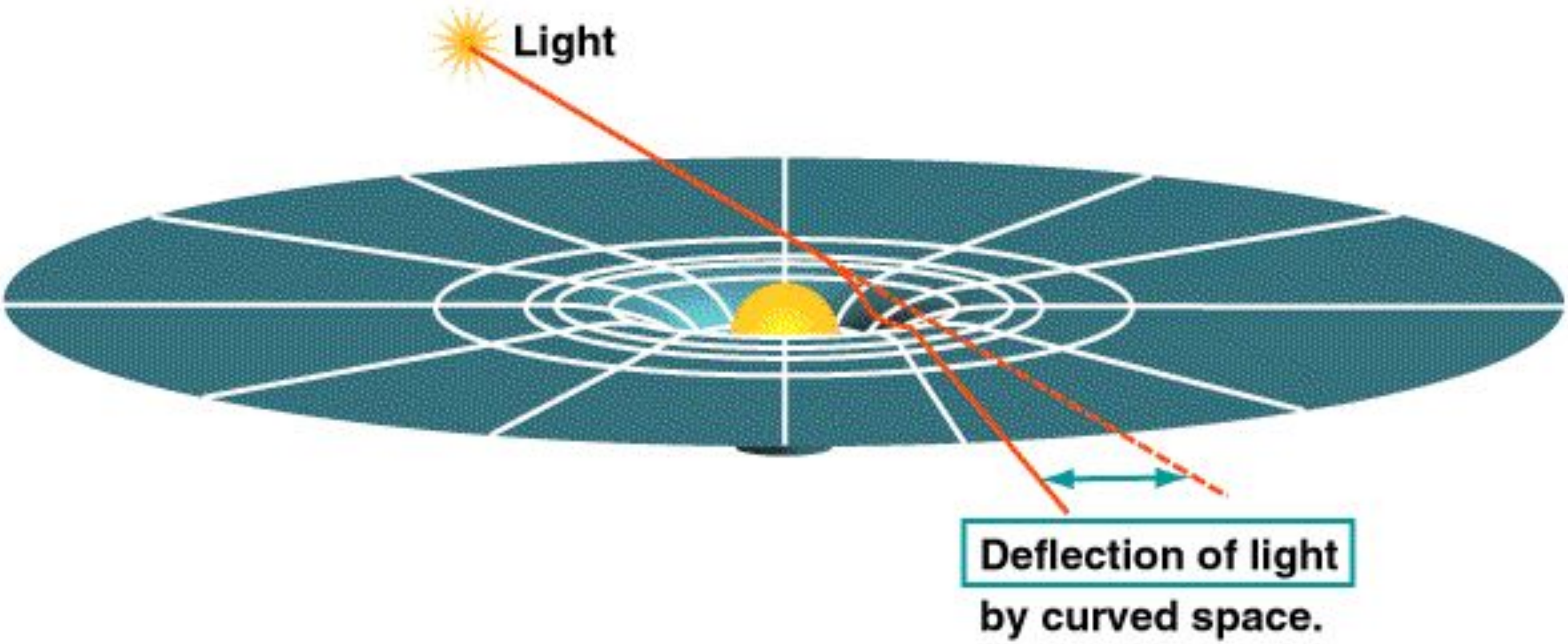
Black Holes and Einstein

- The following tools help us understand some of the properties of black holes.

- Special Theory of Relativity (1905)
  - Speed of light is always constant
    - » Verified by the Michelson-Morley Experiment (1881 & 1887)
  - Consequences of Traveling Near the Speed of Light
    - » Time Dilation* **Maxwell's Laws*
    - » Length Contraction*
    - » Mass Inflation

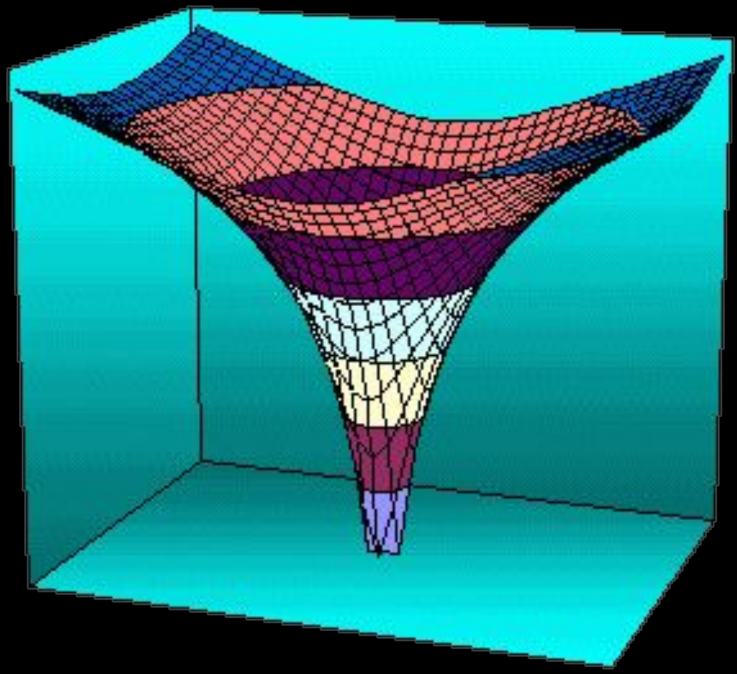
- General Theory of Relativity (1915)
  - Gravity is a result of a distortion in the fabric of "space-time".
  - Gravity can bend (and slow) light.

Bending of Light by Curved Space



Tested during Solar Eclipse in 1919 (West Africa & Brazil) by observing the stars in the Hyades and by radio astronomers using 3C279 solar occultation.

Space-Time



Distortion caused by mass

Black Hole Properties

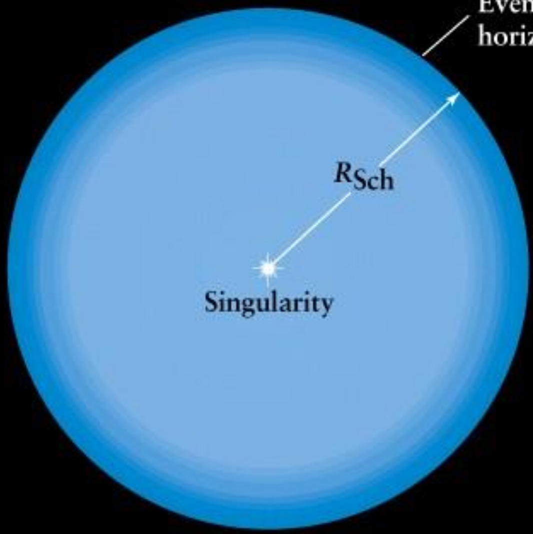
- Singularity – at the center
  - infinitesimally small
  - infinite density

- Energy radiates in the form of gravitational waves.

- Only retains 3 former properties.
  - Mass
  - Angular Momentum
  - Electrical Charge

- Two basic types:
  - Non-rotating black holes (Schwarzchild)
  - Rotating black holes (Kerr)

Schwarzschild Black Hole Radius



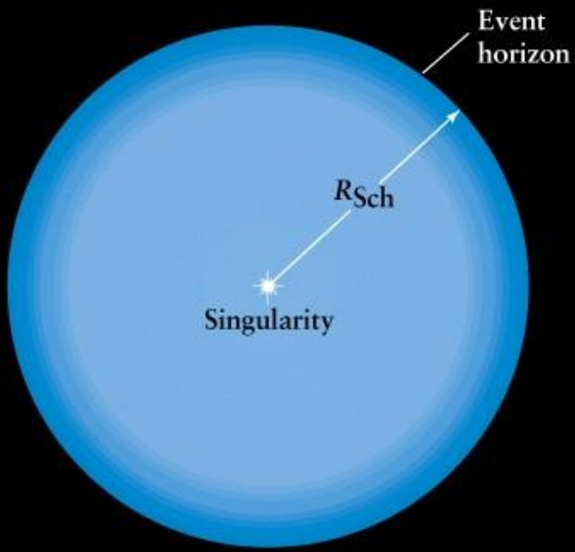
$R_s = 2Gm/c^2$

$2G/c^2 = 2.95$ km/solar mass

~ 3

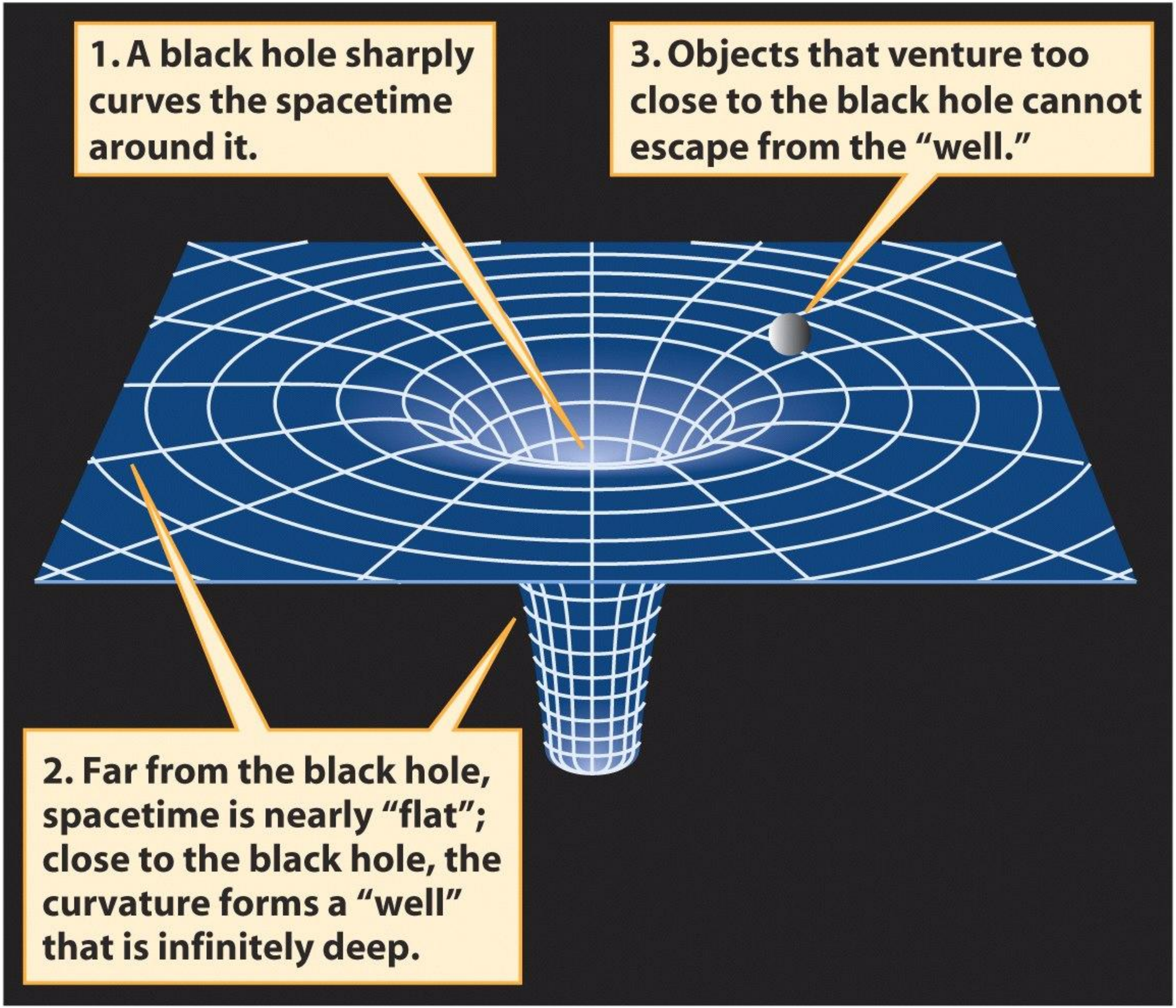
$\underline{R_s = 3(\text{Mass})}$

Schwarzschild Black Hole Radius

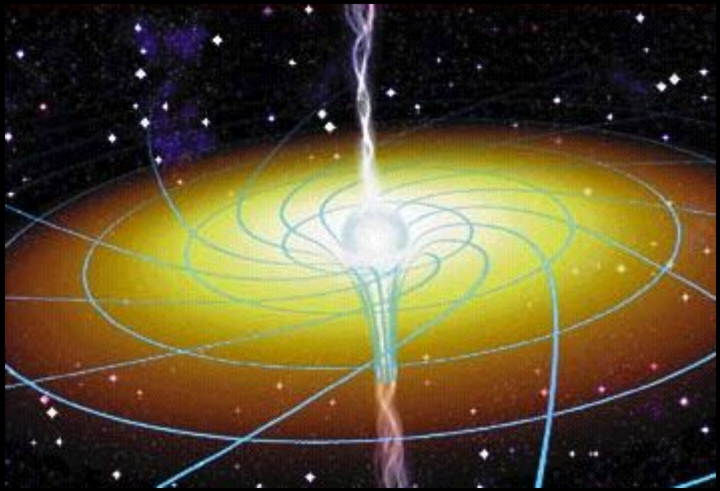


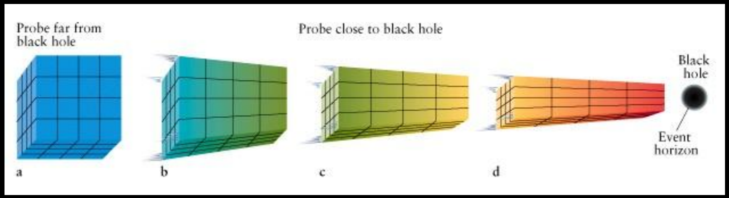
R_s = 3(Mass)

Mass	R_s
3 $M_{\odot}$	9 km
5	15
10	30


1. A black hole sharply curves the spacetime around it.
3. Objects that venture too close to the black hole cannot escape from the "well."
2. Far from the black hole, spacetime is nearly "flat"; close to the black hole, the curvature forms a "well" that is infinitely deep.

Near a Black Hole





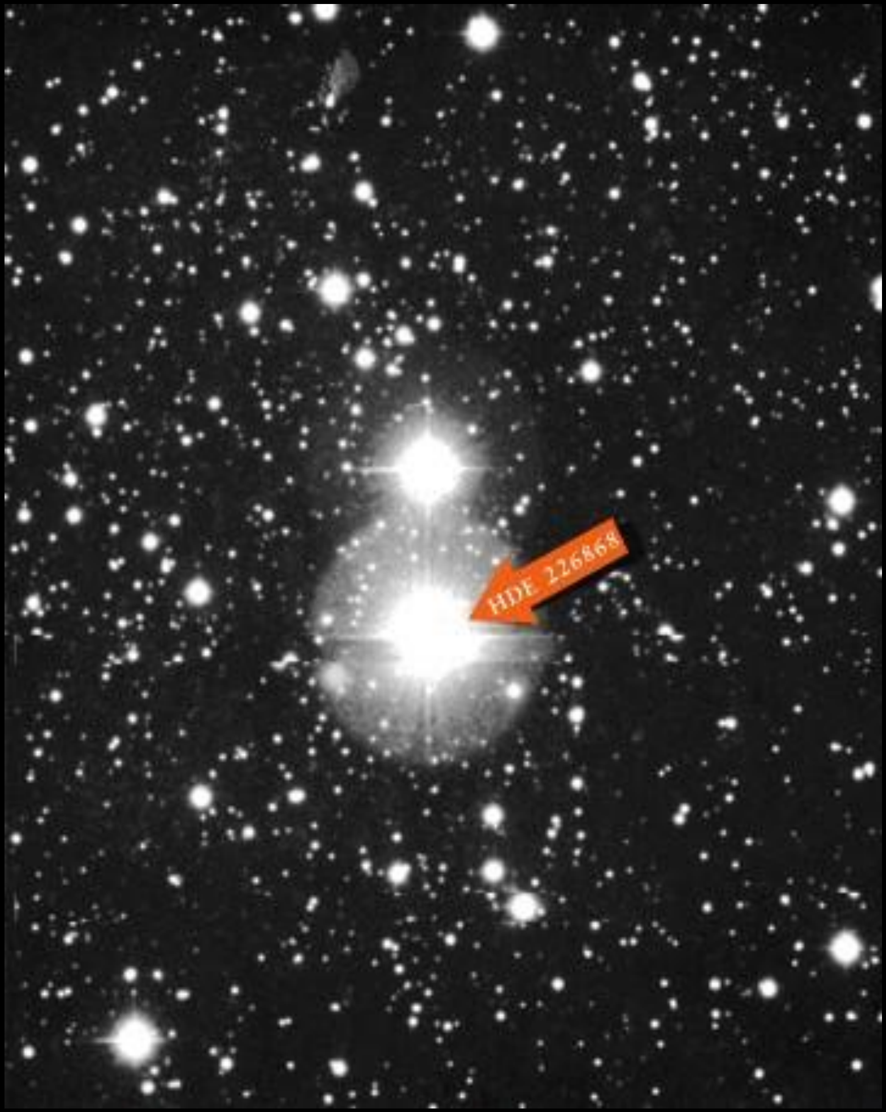
- Escape speed = Speed of light
- Event Horizon – the boundary between the black hole and normal space. Light can't pass this point.
- Gravitational Tidal Forces (ripples in space time) caused by the Singularity. Tidal forces cause matter to be elongated due to the differential pull of gravity.
- Time Dilation

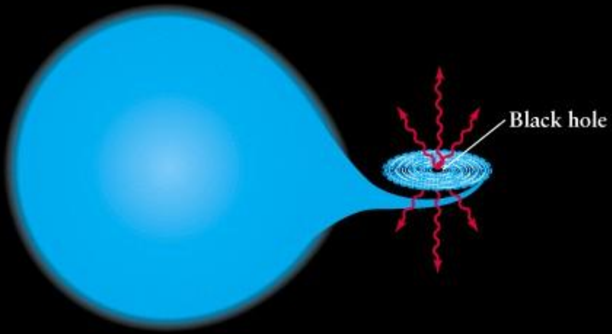
Relativistic Effect – Time Dilation

- The Twin Paradox
  - Bill and Jill are twins.
  - At age 21, Jill travels at 99.5% the speed of light to Aldebaran (32 ly distant) while Bill stays on earth.
  - To Jill, the trip takes 3.2 years there and 3.2 years back (she also measures the distance to be 3.2 lys!). -- 6.4 years total.
  - Bill measures the time for Jill’s trip as 32 year there and 32 years to return – 64 years total!
  - Upon return, Jill is 27 years old while Bill is 85!

- This effect has been confirmed many times in high energy particle accelerators and by using atomic clocks on supersonic aircraft.

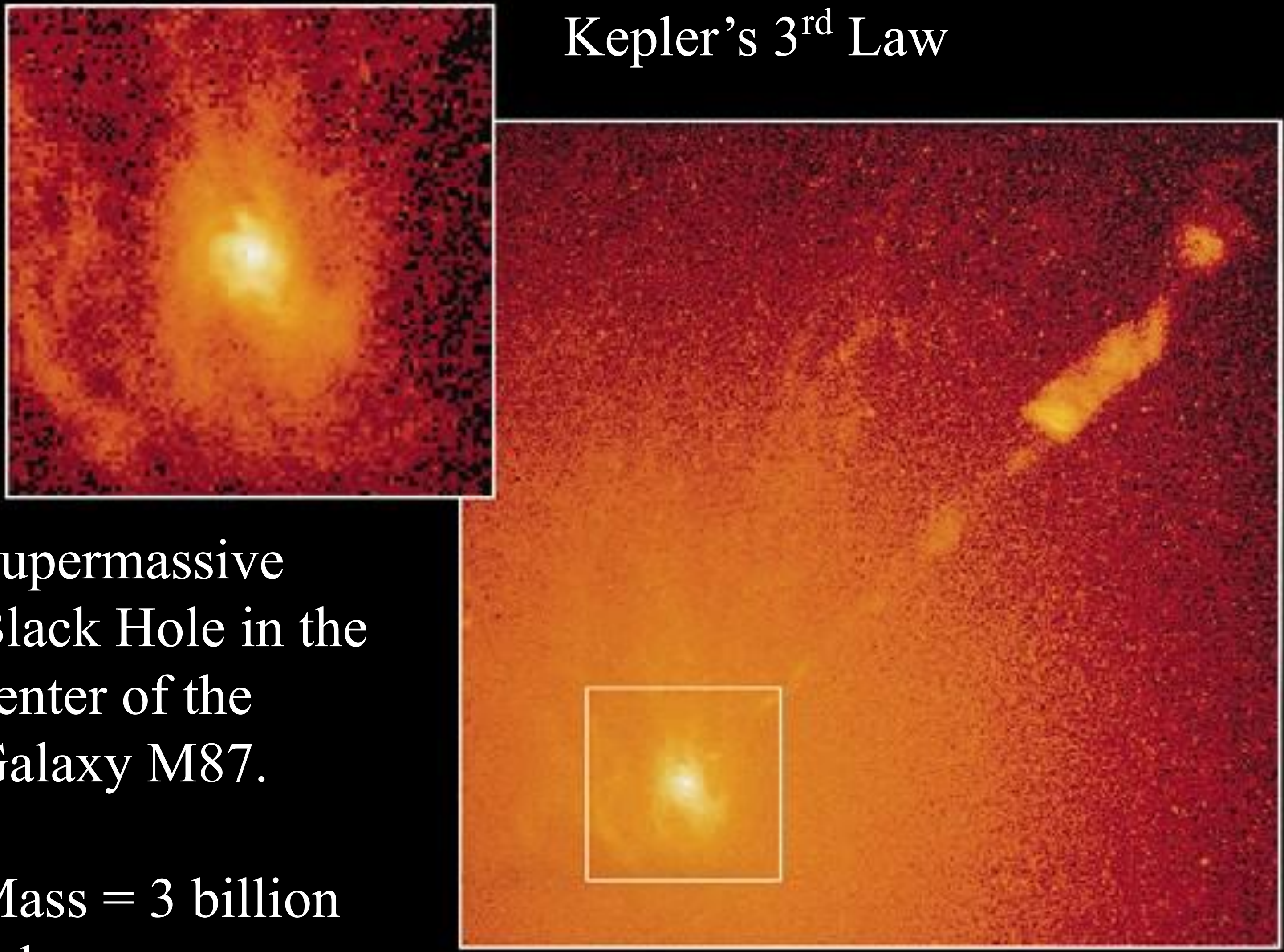
Black Hole Cygnus X-1





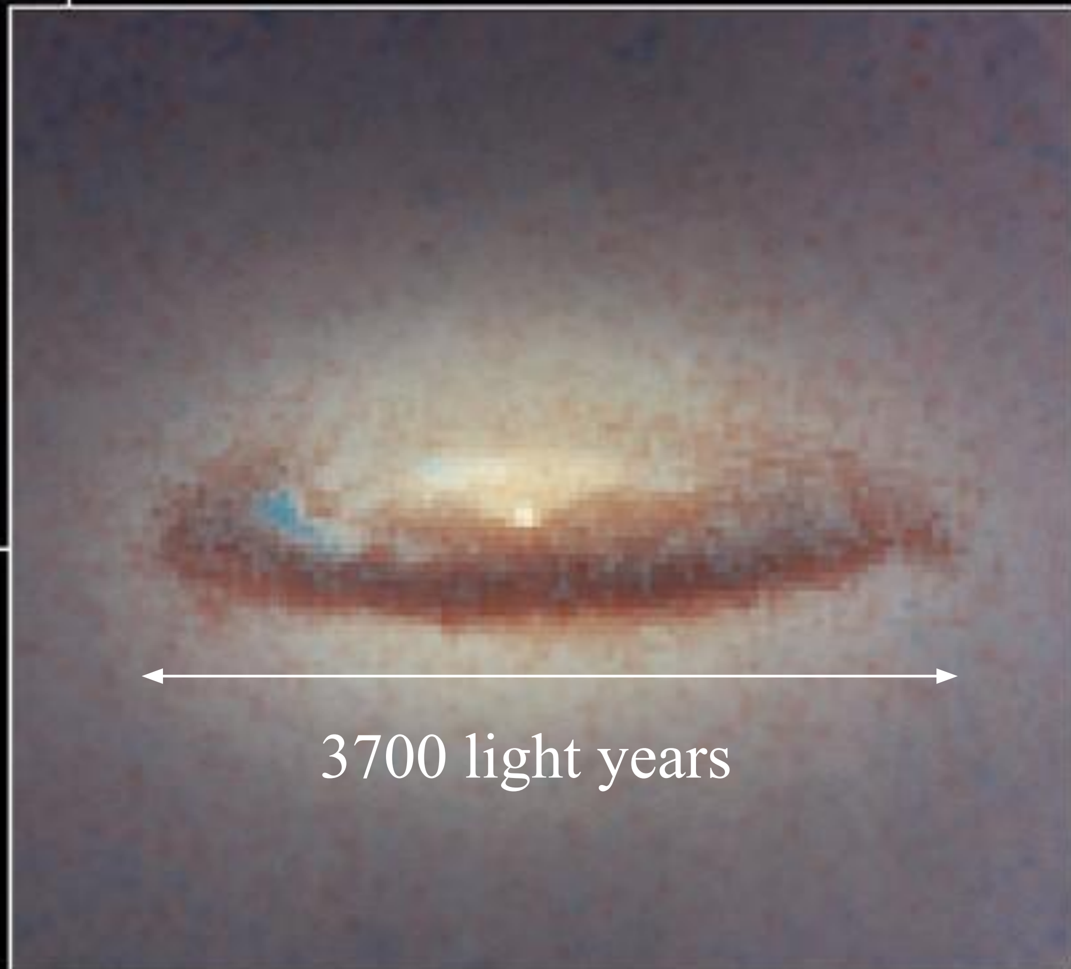
Discovered first as an X-ray source.

Detected by Doppler Shift and Kepler's 3rd Law



Supermassive Black Hole in the center of the Galaxy M87.

Mass = 3 billion solar masses

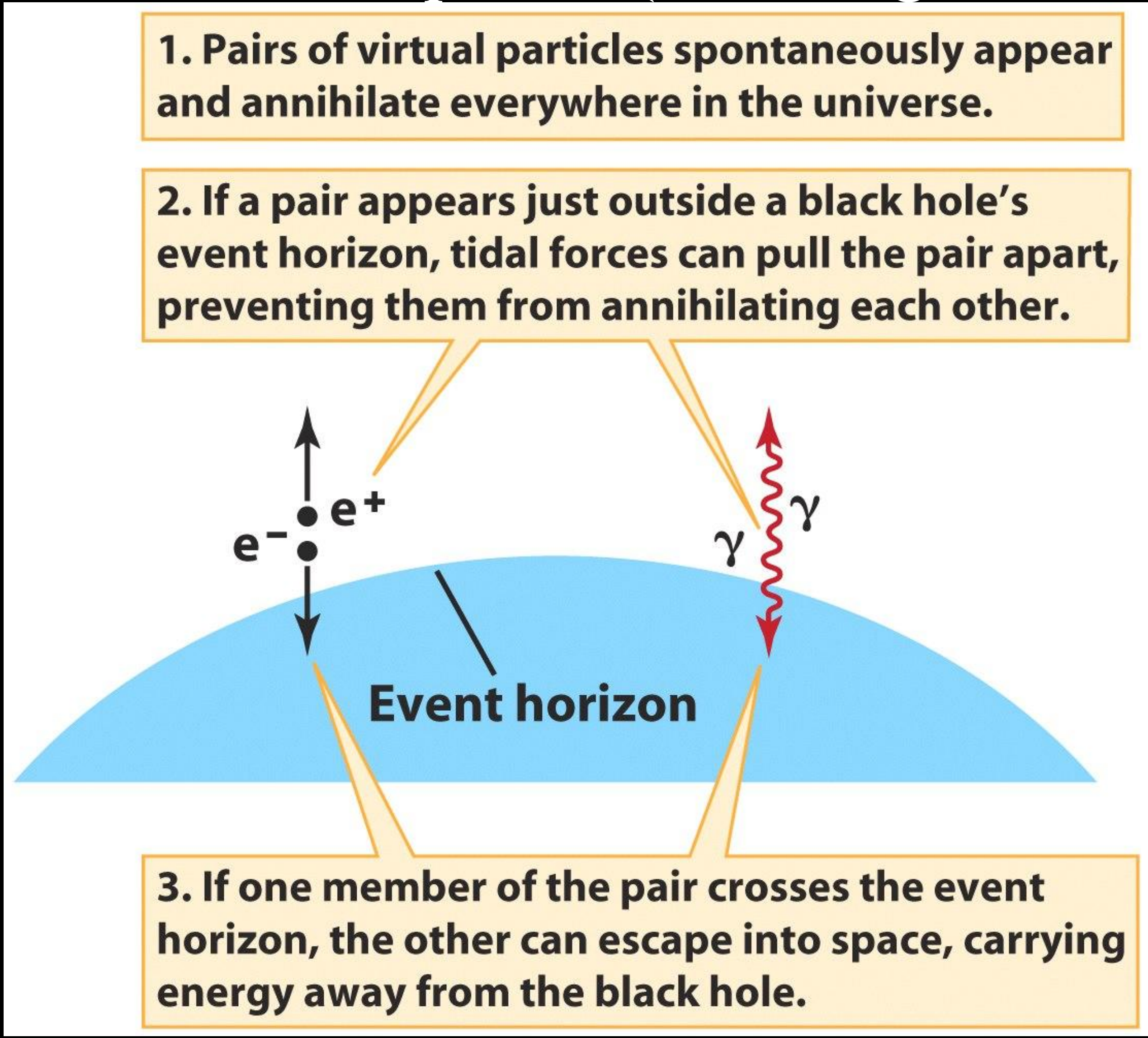


Supermassive Black Hole in the Center of Galaxy NGC 7052 with a mass of 300 million solar masses.

More on Black Holes…

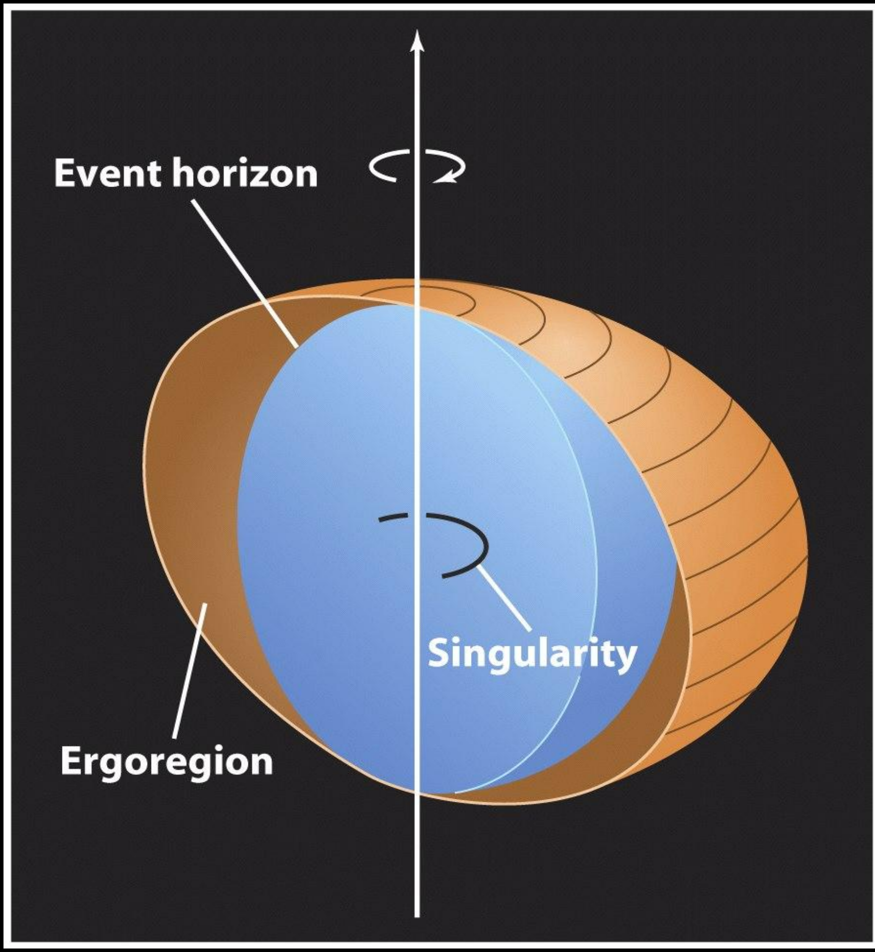
- Are black holes connected to another part of the universe (wormholes)?
  - Probably not. Skeptics cite cosmic censorship: nothing can leave the region of space containing a singularity.
- Will a black hole last forever?
  - No. It eventually *evaporates* according to current models.
  - BH matter is slowly converted to gravitational energy through the process of 'virtual' particle production (Hawking process).
  - Bigger black holes last longer than smaller black holes because of the R_s. Example: a 5 solar mass BH will take 10^{52} years to evaporate.

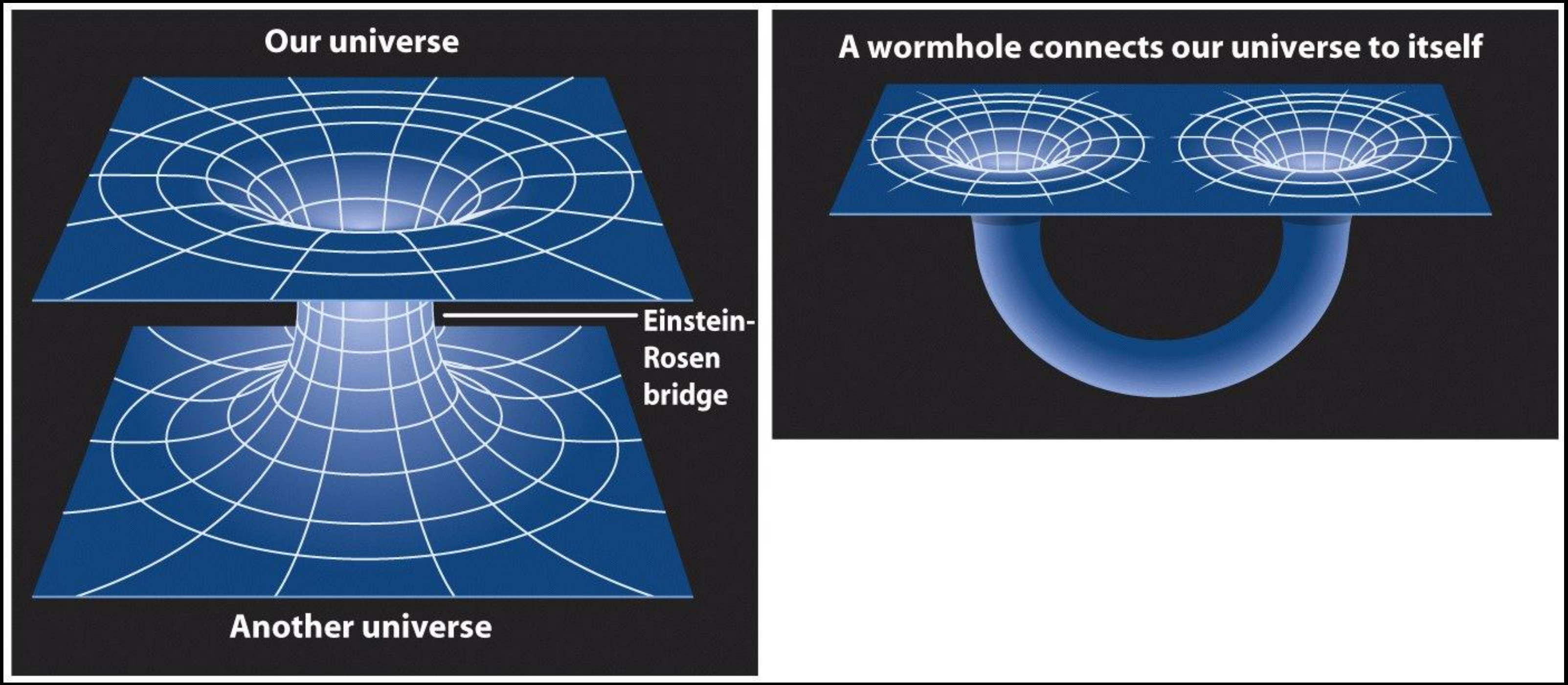
Black holes evaporate (Hawking's theory)



- A rotating black hole (one with angular momentum) has an ergoregion around the outside of the event horizon

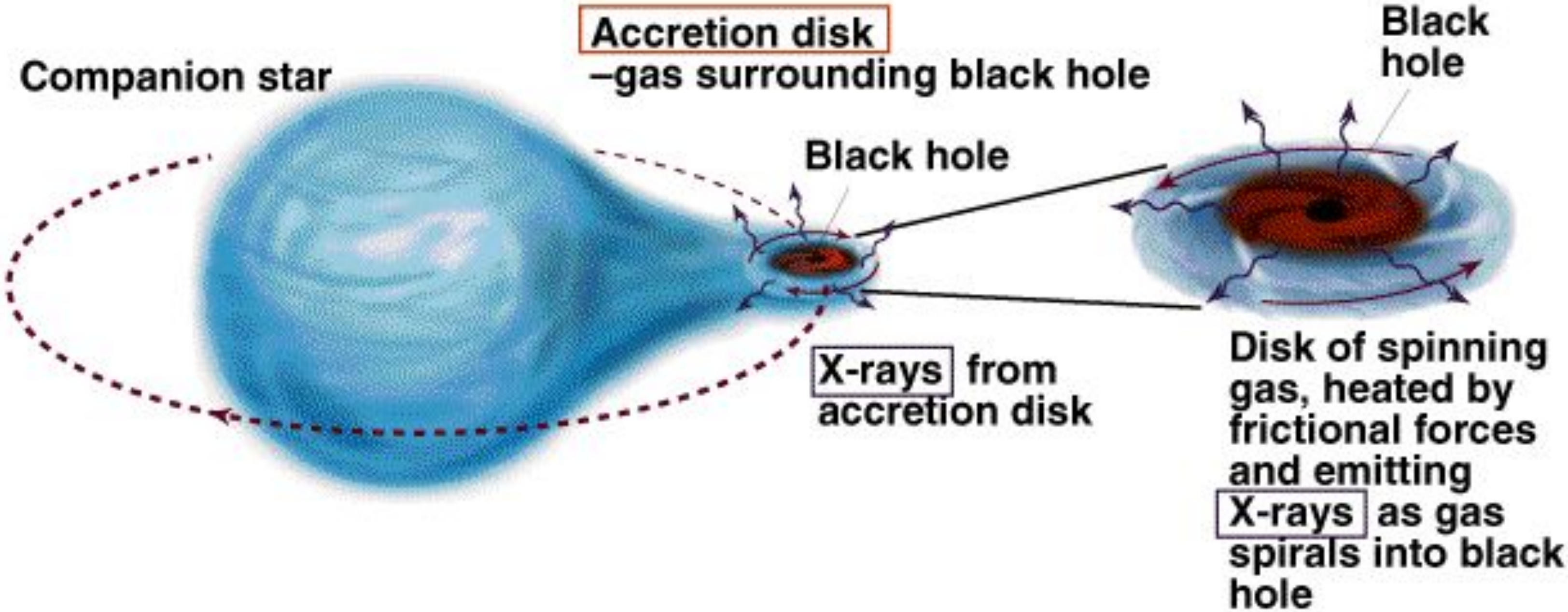
- In the ergoregion, space and time themselves are dragged along with the rotation of the black hole

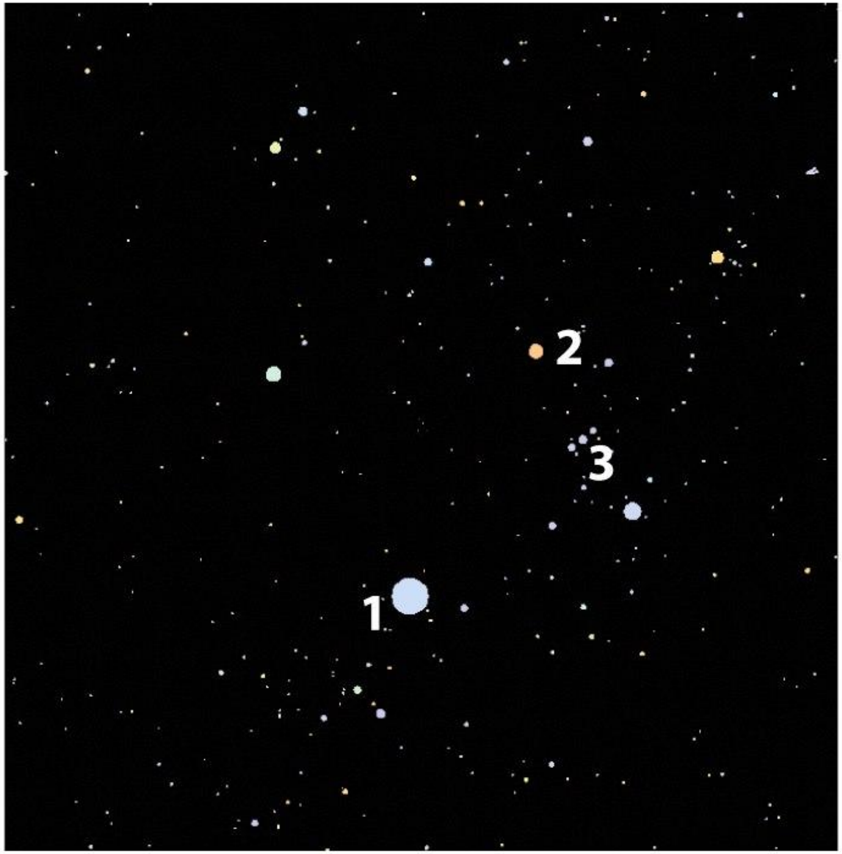




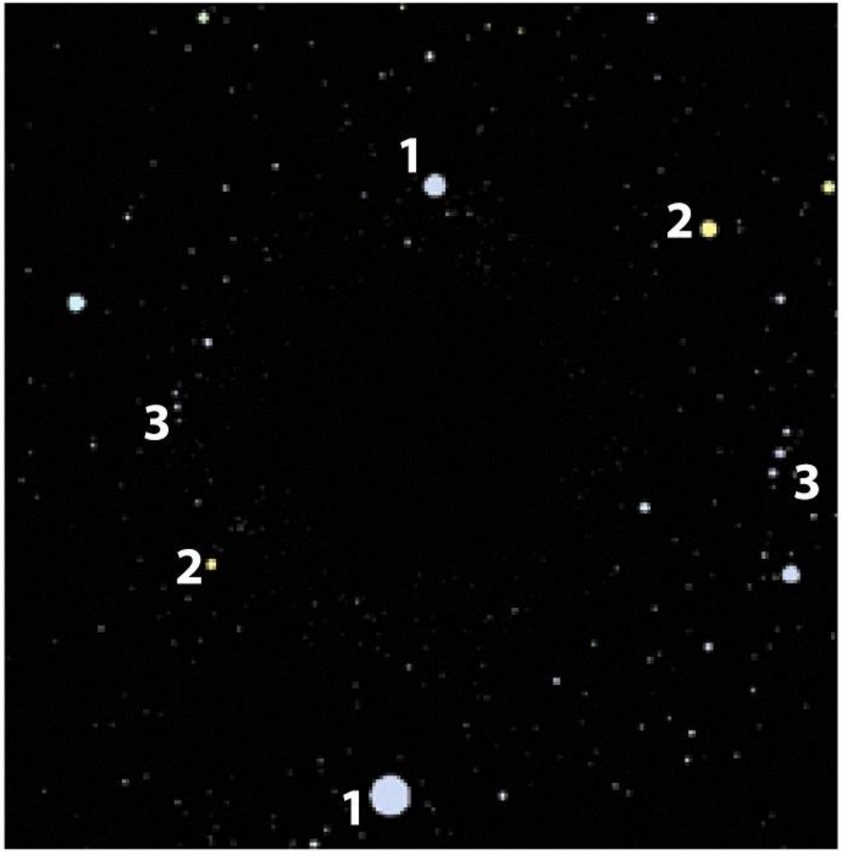
- Could a black hole somehow be connected to another part of spacetime, or even some other universe?
- General relativity predicts that such connections, called wormholes, can exist for rotating black holes.
- Problems: The BH's gravitation would close the wormhole almost as soon as it opened which means you would have to travel faster than light to pass through.

Accretion Disk Around a Black Hole

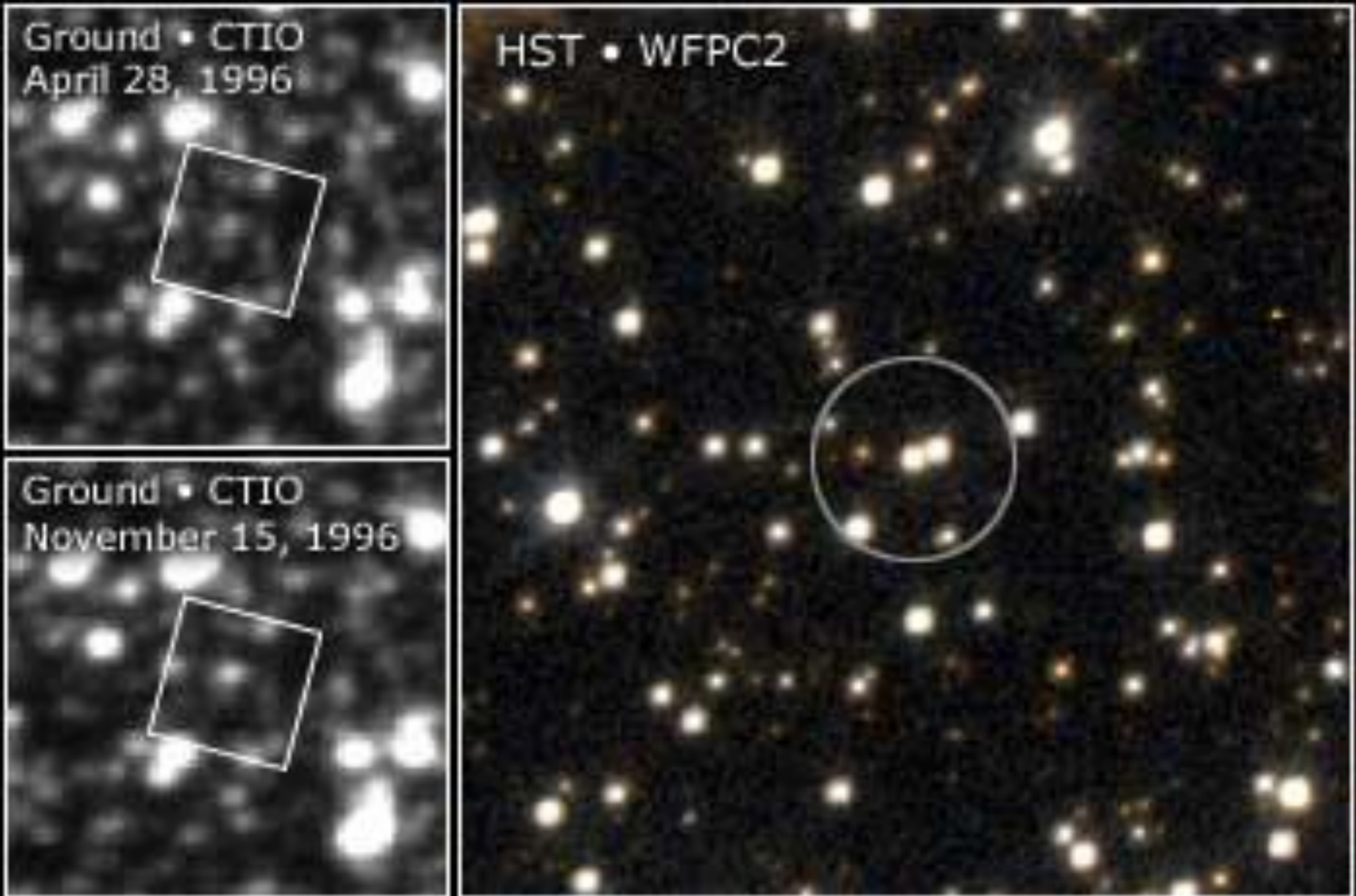




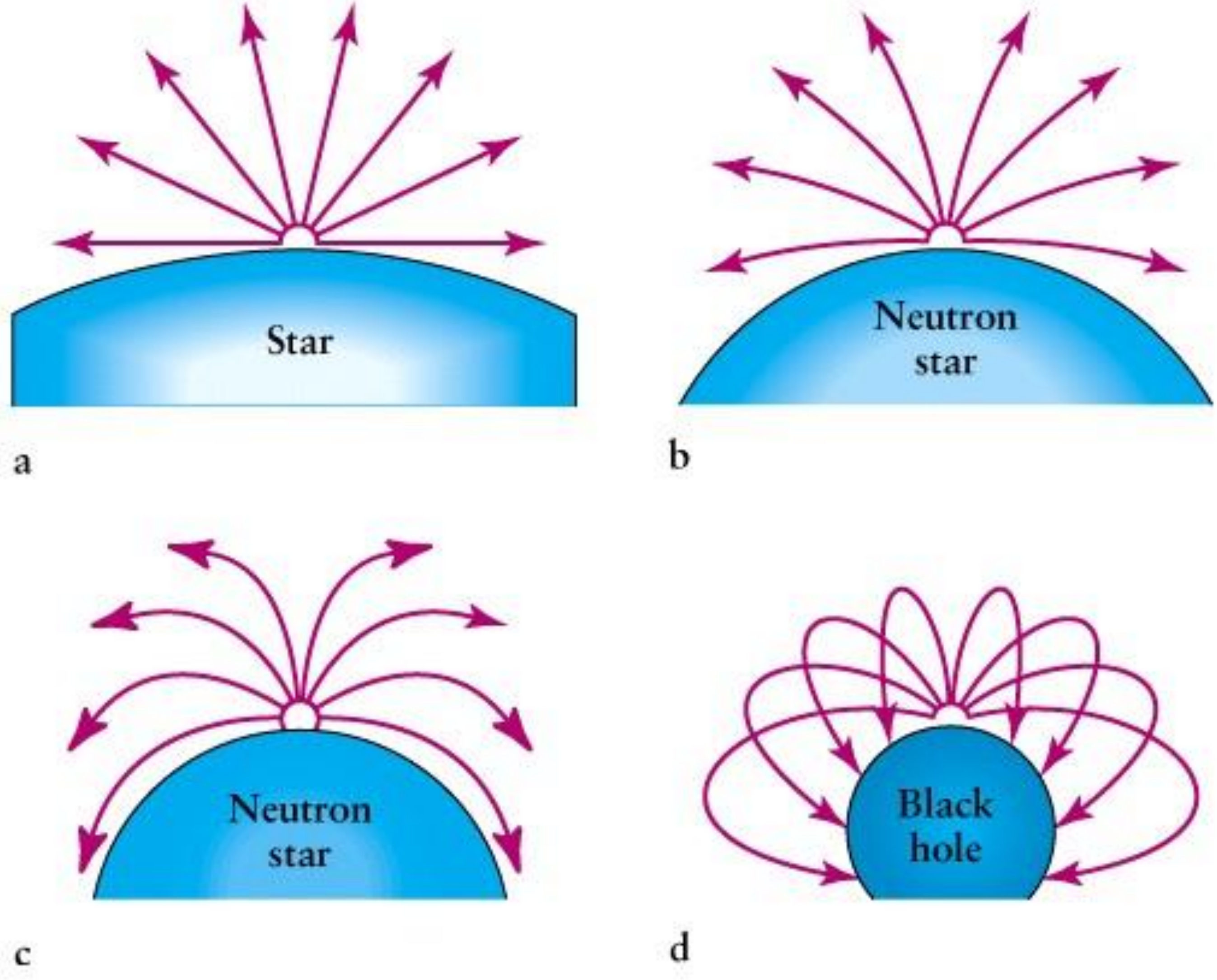
(a) Looking directly toward the black hole from a distance of 1000 Schwarzschild radii: Note positions of stars 1, 2, and 3.



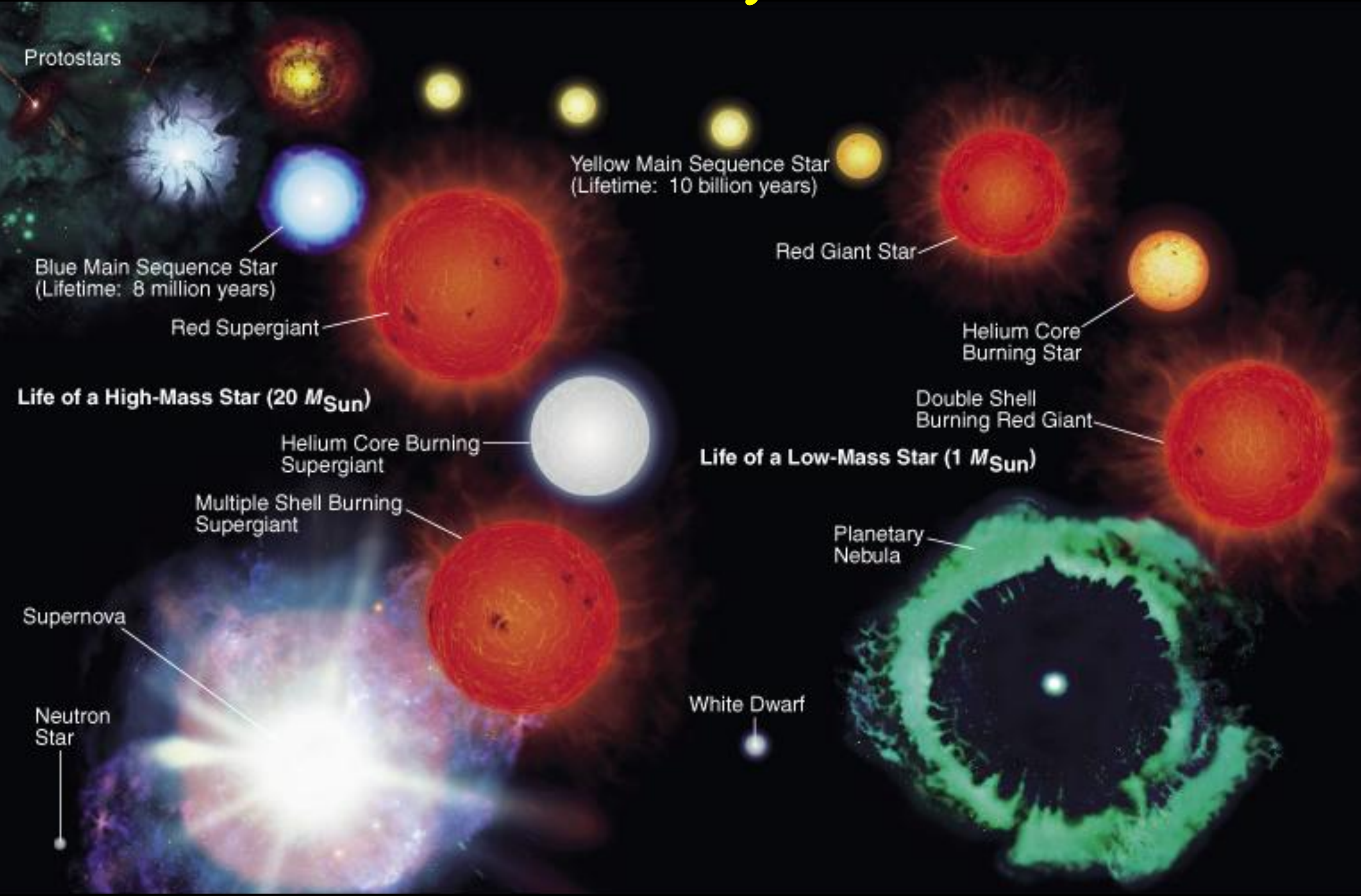
(b) Looking directly toward the black hole from a distance of 10 Schwarzschild radii: Light bending causes multiple images.



Detecting a BH by Gravitational Lensing


Star
a
Neutron
star
b
Neutron
star
c
Black
hole
d

Summary…



Protostars
Yellow Main Sequence Star
(Lifetime: 10 billion years)
Blue Main Sequence Star
(Lifetime: 8 million years)
Red Giant Star
Red Supergiant
Helium Core
Burning Star
Life of a High-Mass Star (20 M_{Sun})
Double Shell
Burning Red Giant
Helium Core Burning
Supergiant
Life of a Low-Mass Star (1 M_{Sun})
Multiple Shell Burning
Supergiant
Planetary
Nebula
Supernova
White Dwarf
Neutron
Star