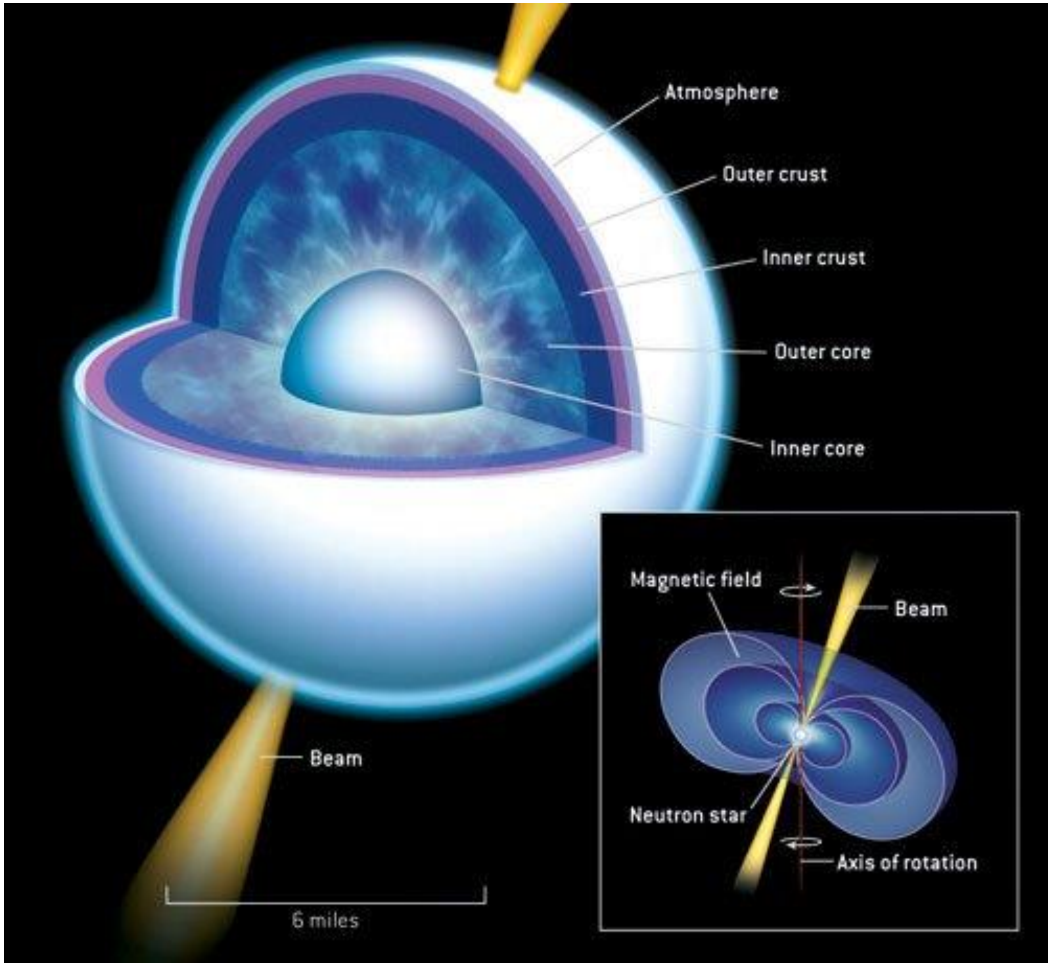
Neutron Stars

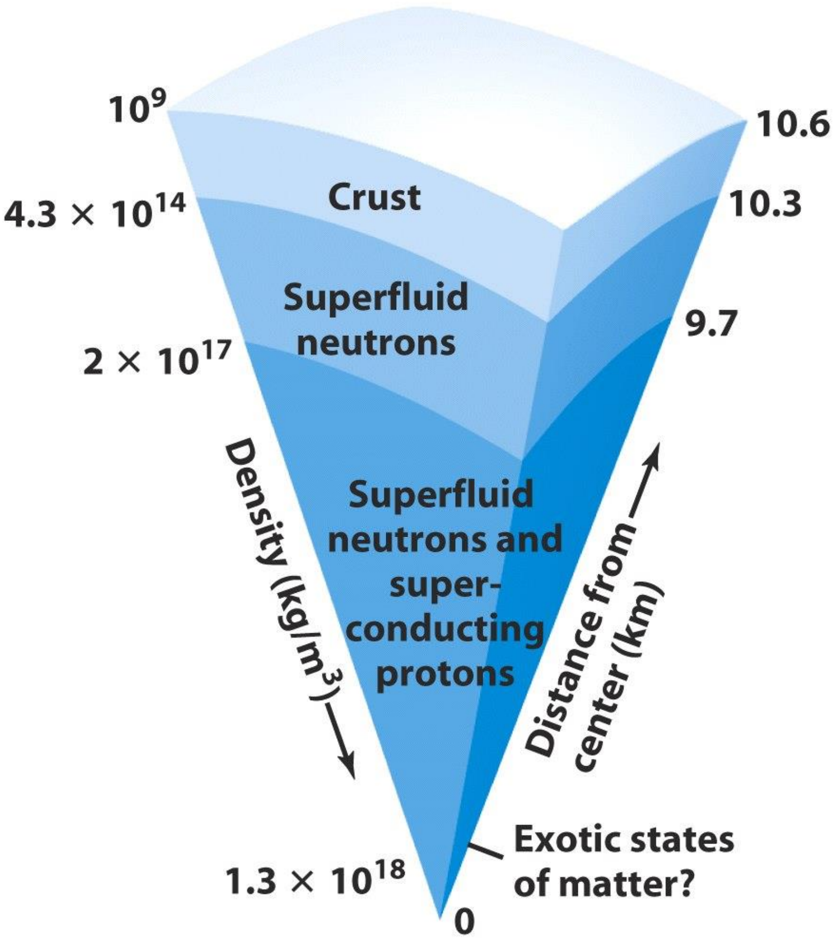
- A neutron star forms during the supernova explosion if the mass of the collapsing core exceeds the Chandrasekhar limit of 1.4 $M_{\odot}$
- Degenerate neutron pressure count-balances the gravitation
- A neutron star is a dense stellar corpse consisting primarily of closely packed degenerate neutrons
- Proposed in 1930's, not verified until 1960's

Properties of Neutron Stars

- Diameter of about 20 km
- Mass less than 3 $M_{\odot}$
- Magnetic field 10^{12} times stronger than that of the Sun
- Rotation period of roughly 1 second



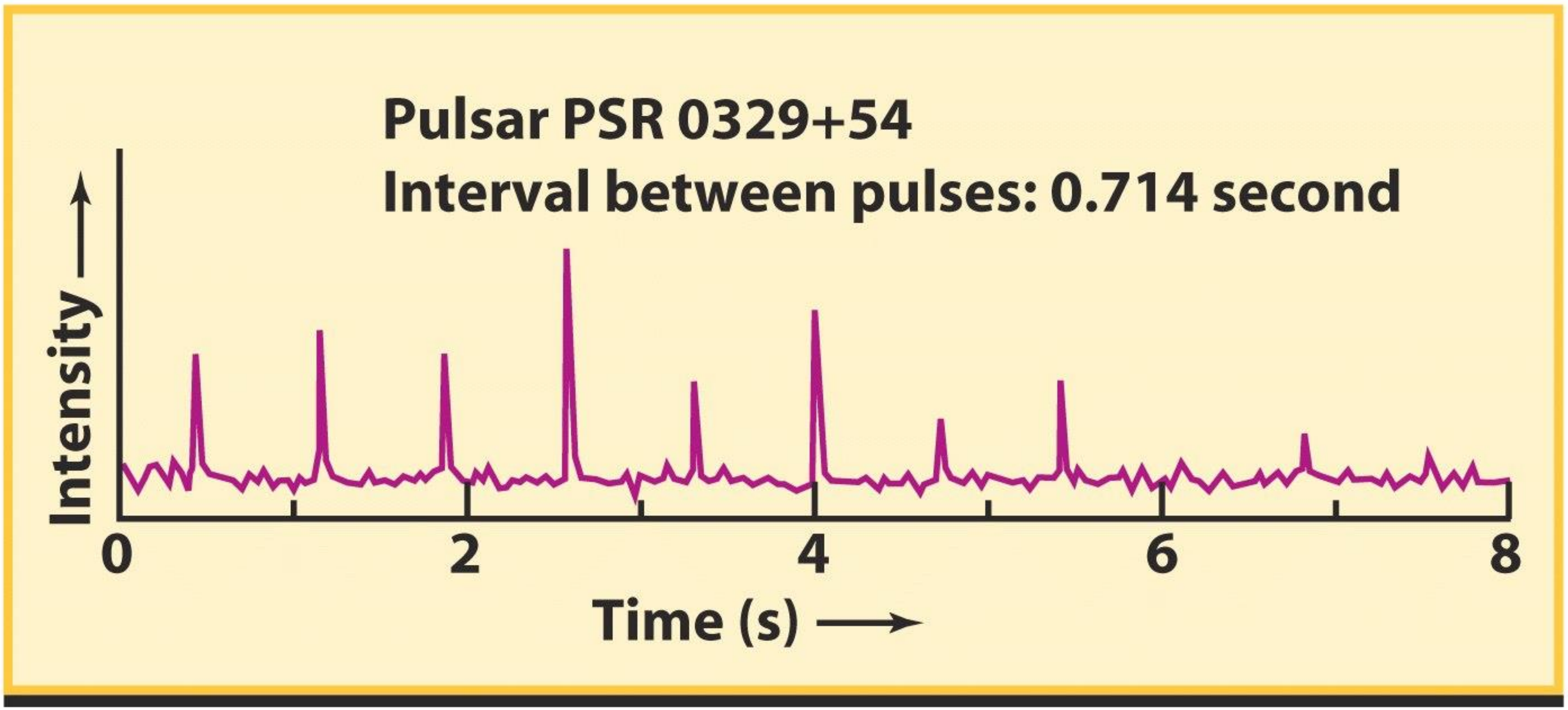
A Model of Neutron Star Structure



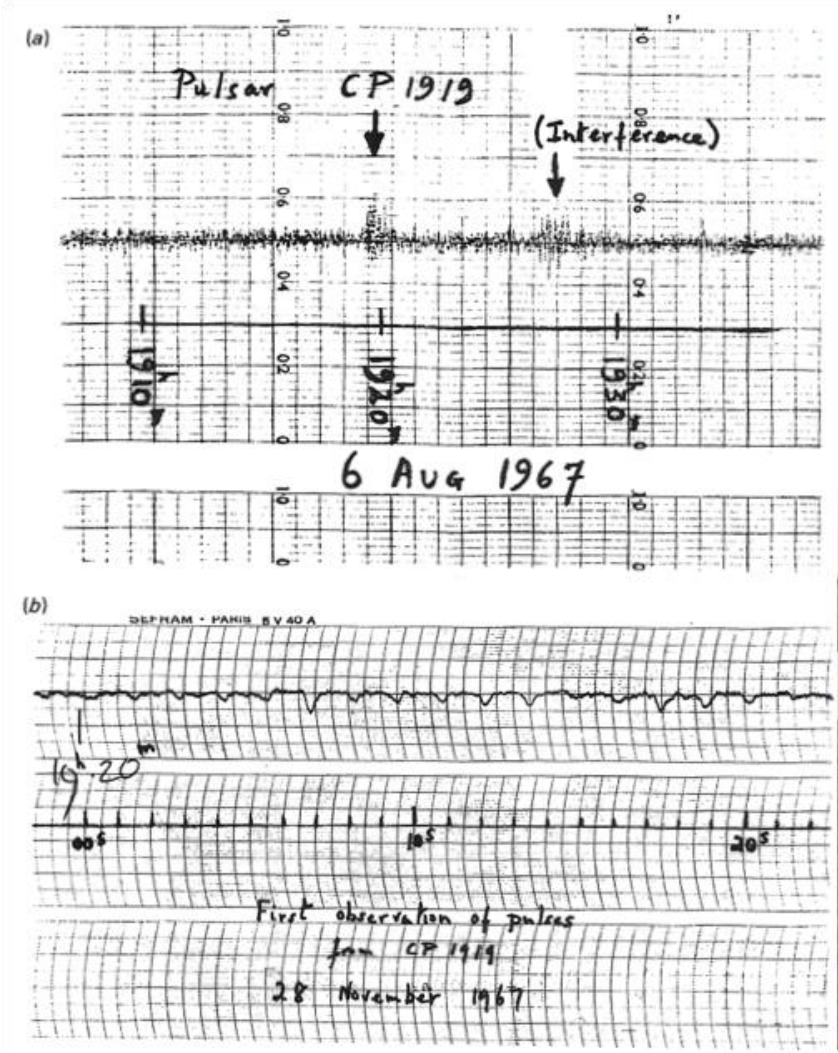
- A neutron star consists of a superfluid, superconducting core surrounded by a superfluid mantle and a thin, brittle crust
- There is evidence for an atmosphere

The discovery of pulsars in the 1960s

- A pulsar is a source of periodic pulses of radio radiation



Discovery - **Jocelyn Bell Burnell**



She was graduate student at the University of Cambridge

Discovery - **Jocelyn Bell Burnell**

Observation of a Rapidly Pulsating Radio Source

by

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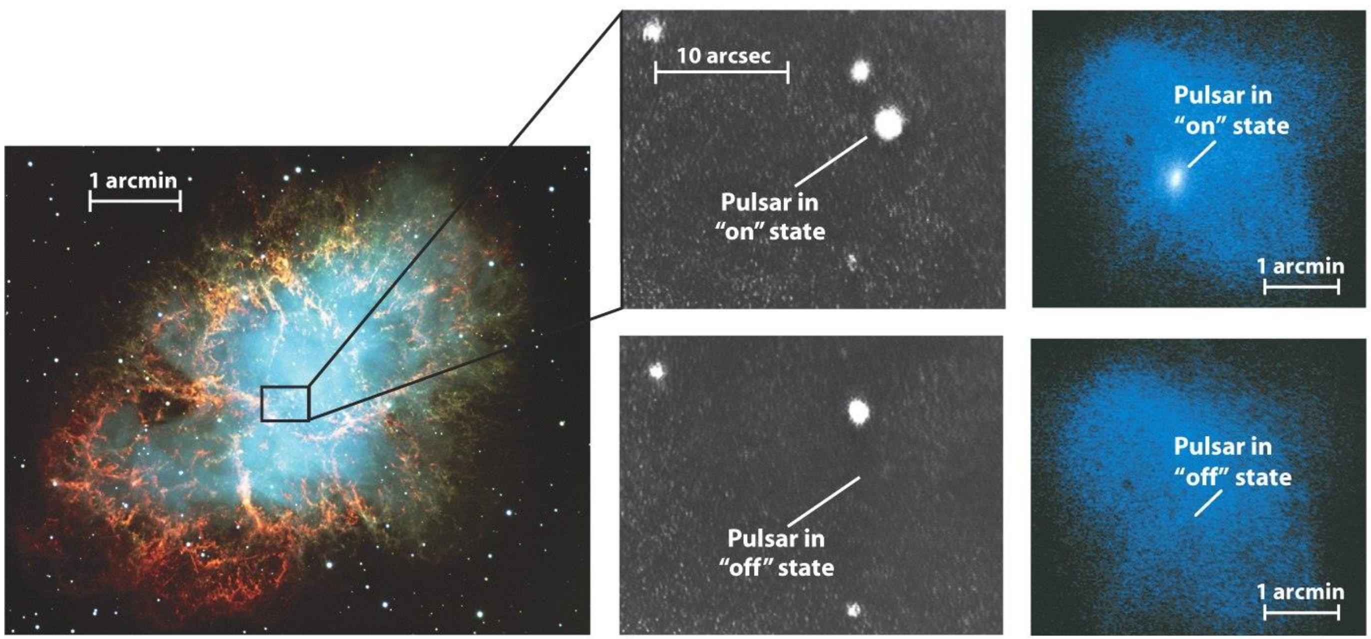
Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the gala‹y, and may be associated with oscillations of white dwarf or neutron stars.

Her PhD supervisor Anthony Hewish was granted the Nobel Prize in 1974. She was not even mentioned.

Pulsar Found in the Crab Nebula

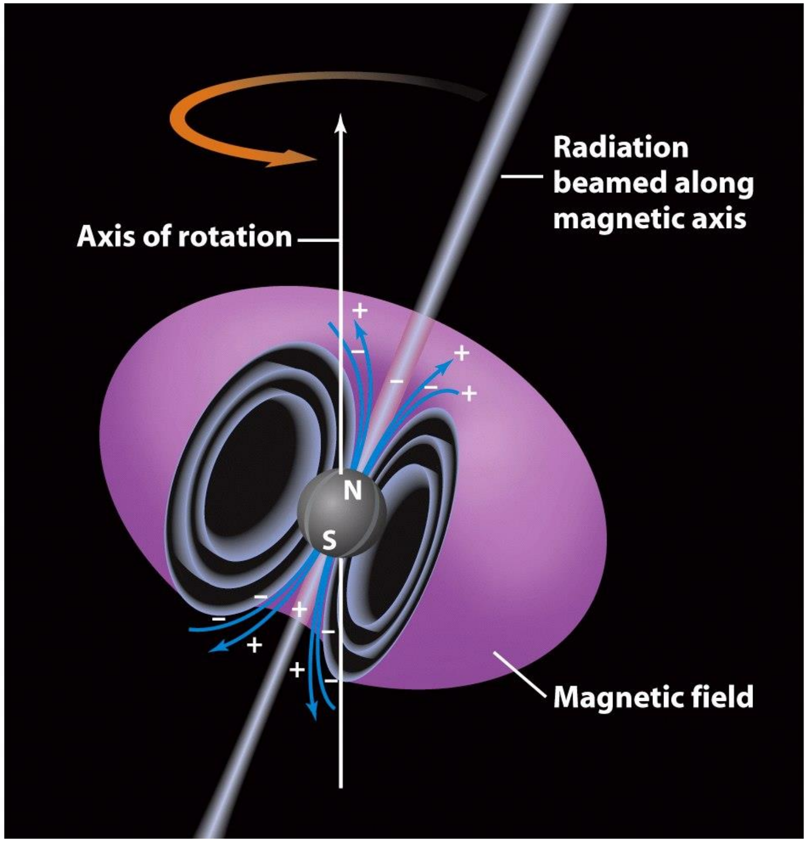
- Crab nebula was created by the supernova explosion occurred on July 4, 1054, recorded by Chinese astronomer
- A fast rotating pulsar, with period of 0.033 second, or 30 times per second, is discovered at the center of the Crab nebula
- Such fast spin can not be from a white dwarf



(a) The Crab Nebula **(b)** The Crab pulsar in visible light **(c)** The Crab pulsar in X rays

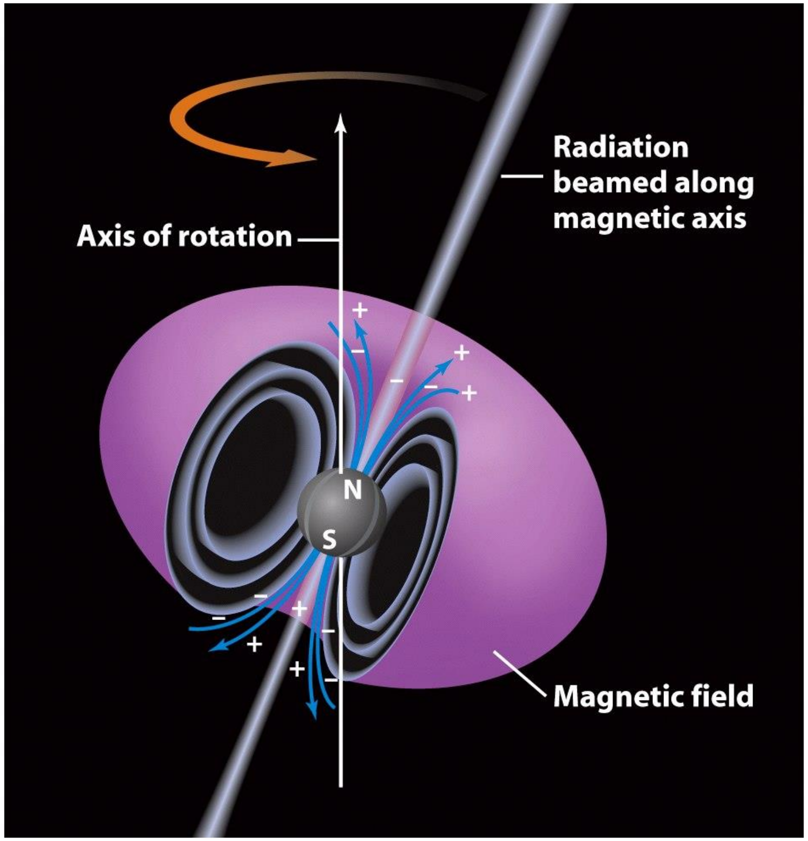
Pulsars are rapidly rotating neutron stars

- A neutron star can spin very fast because of its small size
- Magnetic field is strong because all magnetic field in the progenitor star is squeezed and concentrated into the neutron star size
- Magnetic axis is inclined to the rotation axis
- Charged particles from the surface are accelerated along the intense magnetic field, and radiate electromagnetic radiation



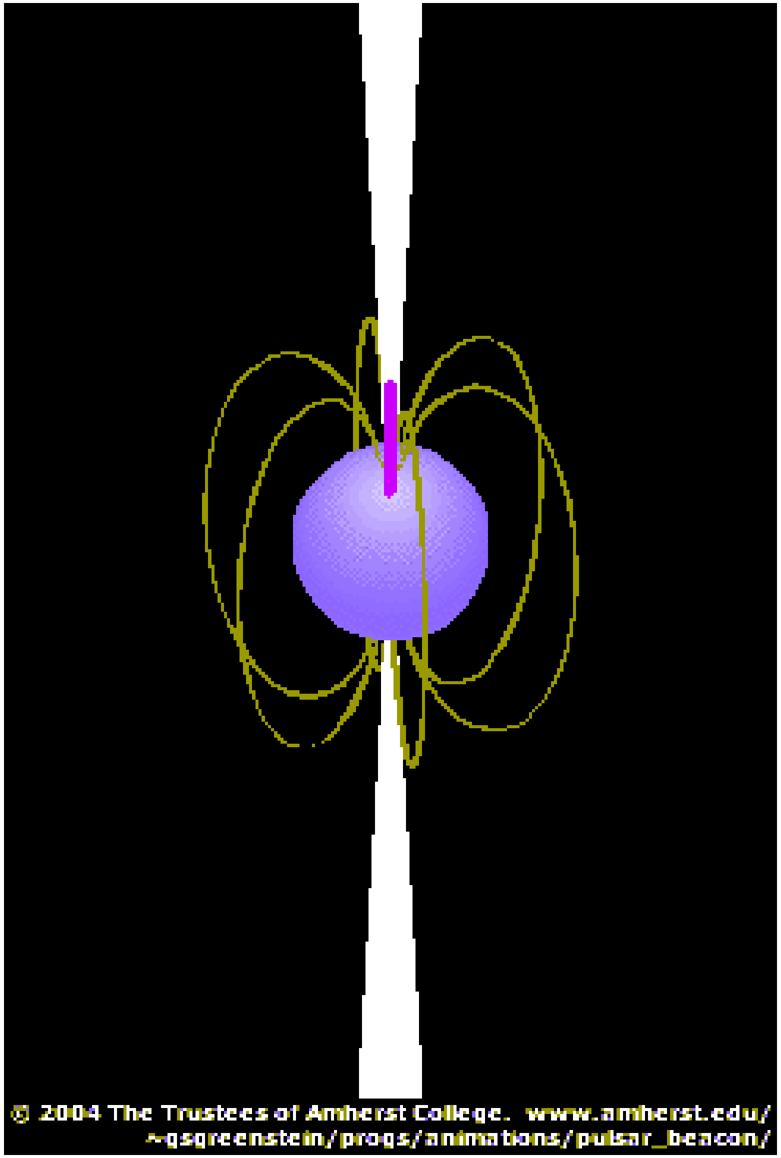
Pulsars are beamed radiation sweep the Earth

- Because charged particles move along the magnetic field lines
- The radiation is also along the magnetic field lines, forming a radiation beam in parallel with the magnetic axis
- The beam sweeps around the sky as the star rotates
- If the Earth happens to lie in the path of the beam, the pulsar can be detected



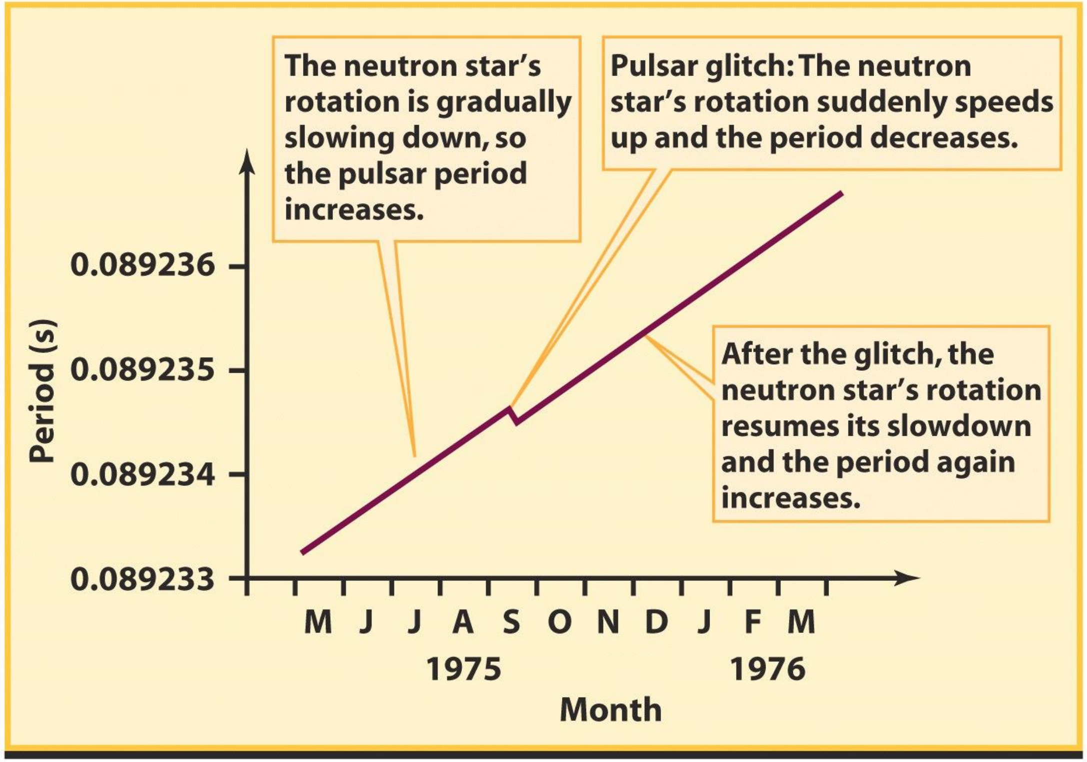
Pulsars is like a lighthouse beacon

- Pulsar is a rotating neutron star whose radiation beam happens to sweep the Earth



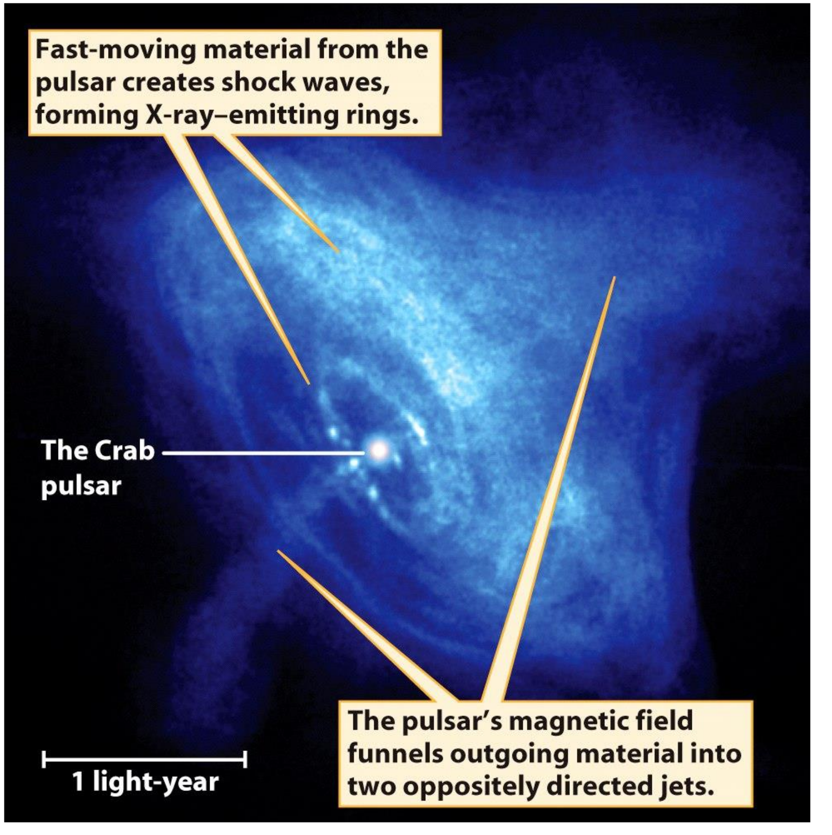
Periods of Pulsars

- Radio telescopes have found more than 1000 pulsars
- Their rotation period is in a wide range from 1 ms (mili-second or 0.001 sec) to 10 second
- An isolated pulsar slows down as it ages, so its period increases



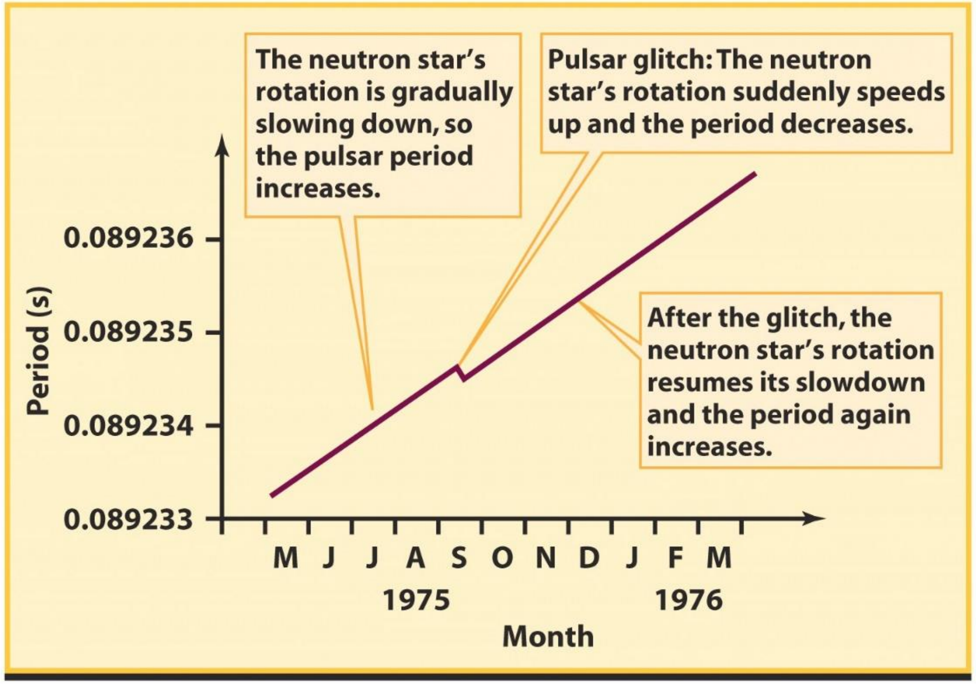
What powers the Crab Nebula?

- The ultimate energy source for the luminous nebula is the spinning of the neutron star
- The spinning or rotation energy is transferred into the surrounding nebula, which results in the gradual slow down of the star
- The nebula shines due to the radiation from the energetic electrons accelerated along the magnetic fields



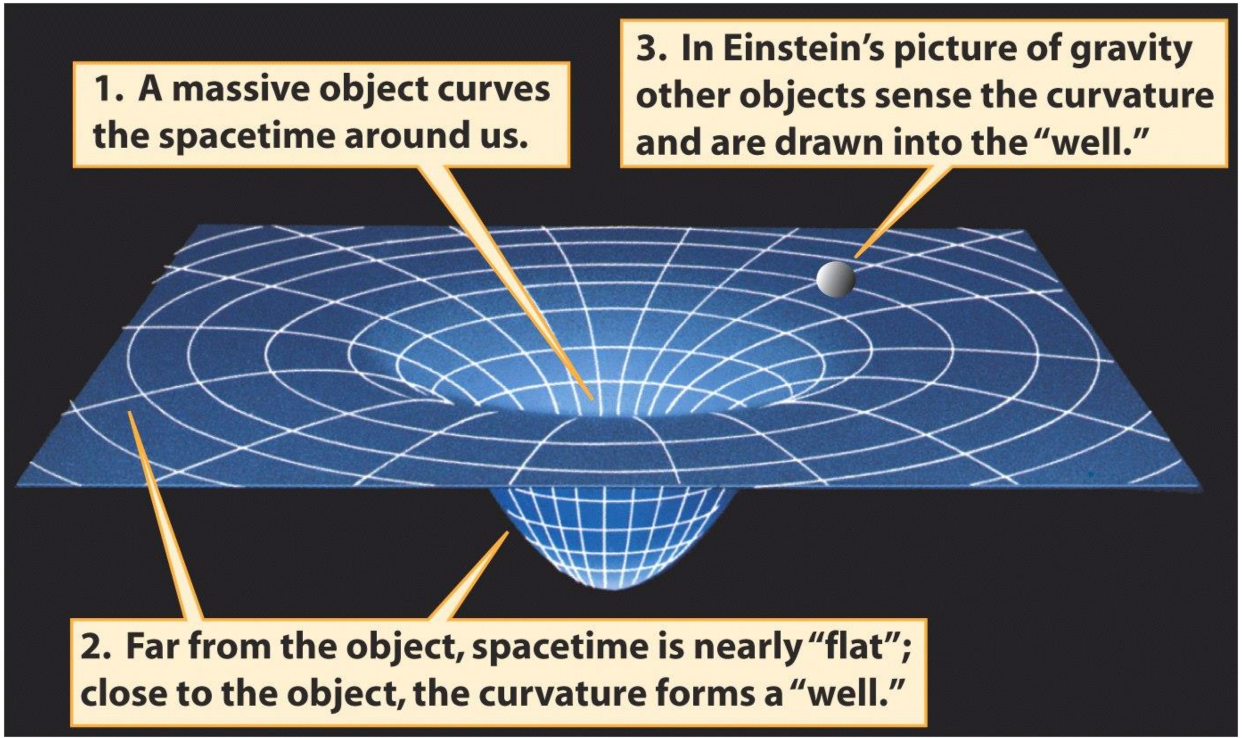
Pulsars gradually slow down, but have glitches

- The pulse rate of many pulsars is slowing steadily
- Sudden speedups of the pulse rate, called glitches, may be caused by interactions between the neutron star's crust and its superfluid interior



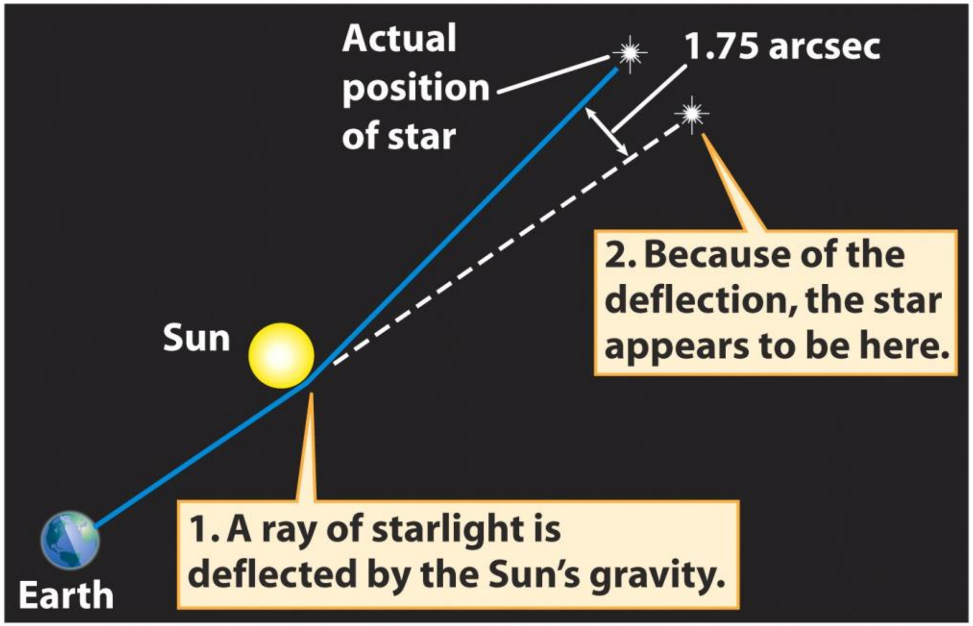
Gravity Equivalent of Curvature of Space

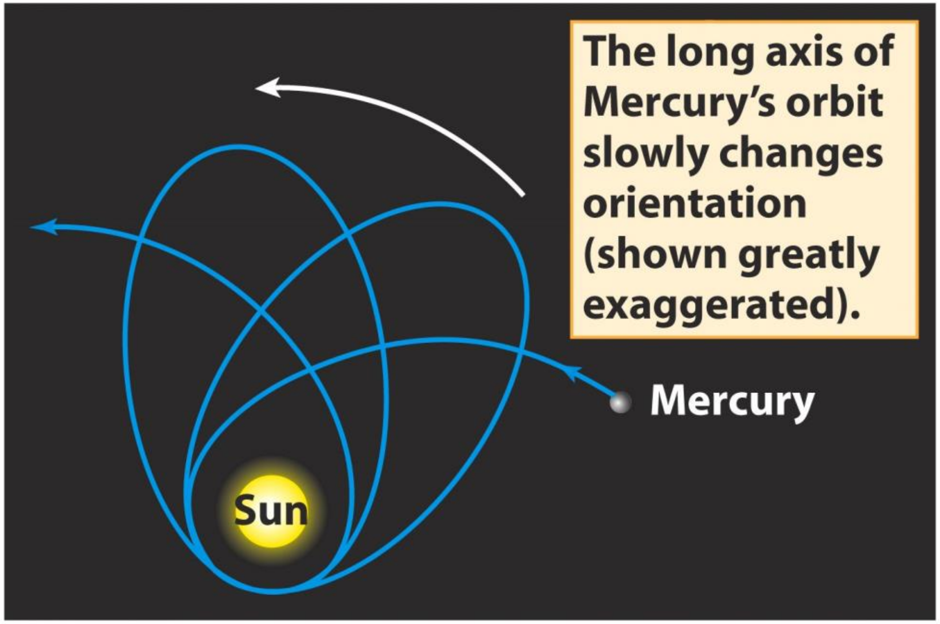
- The curved space not only acts on the object with mass
- The curved space also acts on the light, even though light does not have mass
- The light seeks to move across the shortest distance between tow points; in a curved space, the light bends instead of moving in a straight line



Proof of Theory of Relativity

1. During the solar eclipse, the starlight is deflected by the Sun's gravity by an amount of 1.75 arcsec (1919)
2. Mercury, the closest planet to the Sun, shows an excessive precession that perfectly fits the slightly curved space near the Sun.

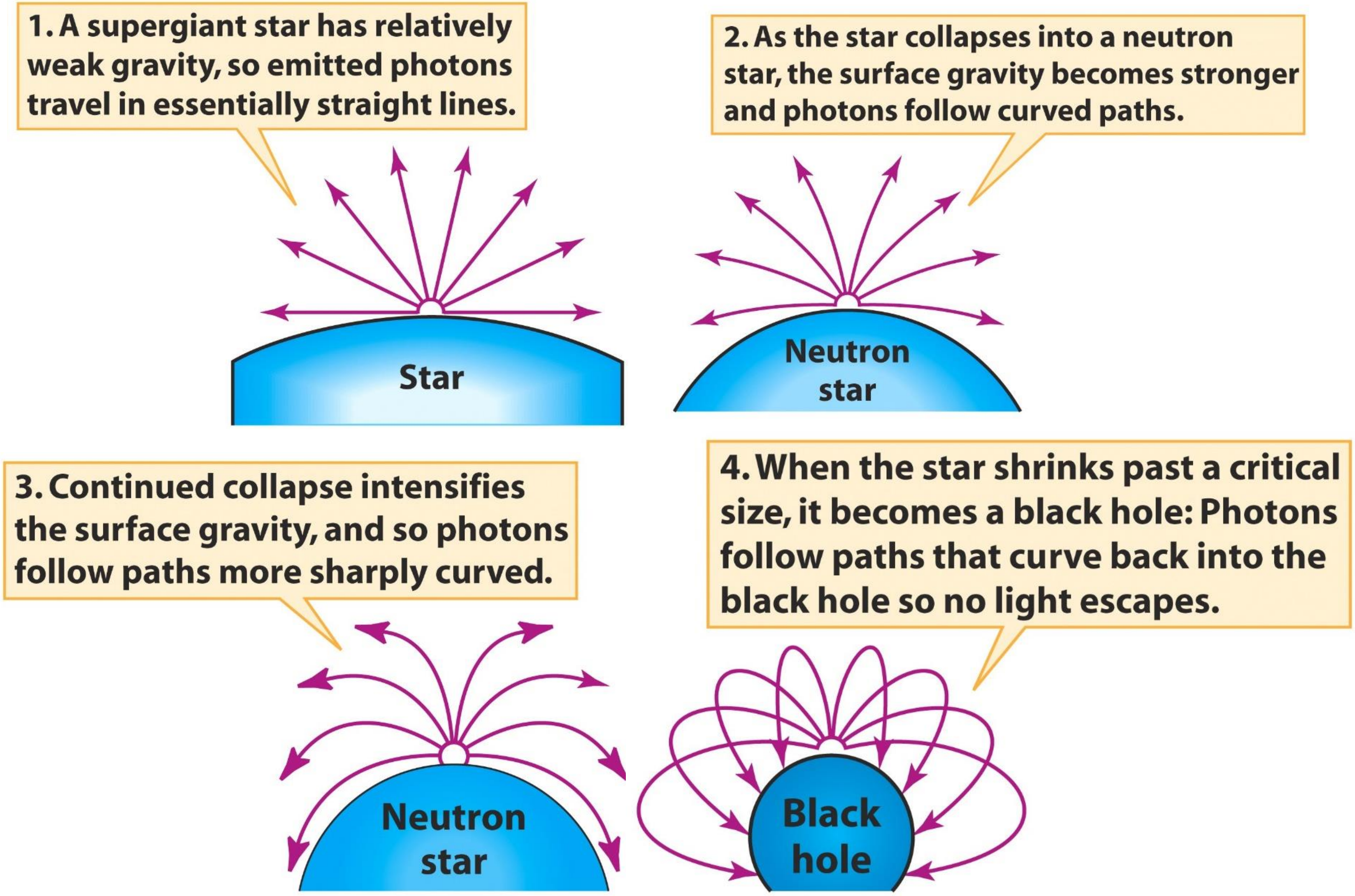




Gravitational Red Shift

- Because of the time dilation, the period of light wave from the surface of a strong gravity becomes longer, and thus the frequency becomes smaller
- Or equivalently, wavelength becomes longer; this is so called gravitational red shift
- On the surface of a white dwarf, red shift ($\Delta\lambda/\lambda$) is a factor of 10^{-4}
- On the Sun, the gravitational red shift is negligible

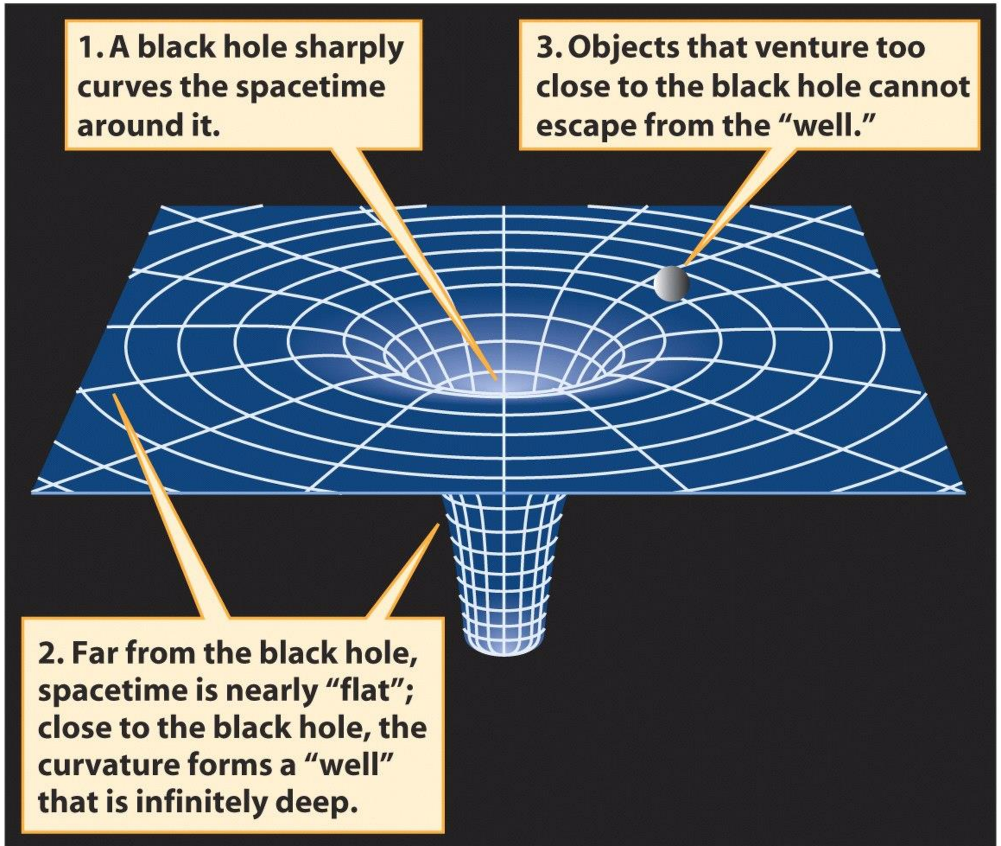
Theory of Relativity Predicts Black Holes



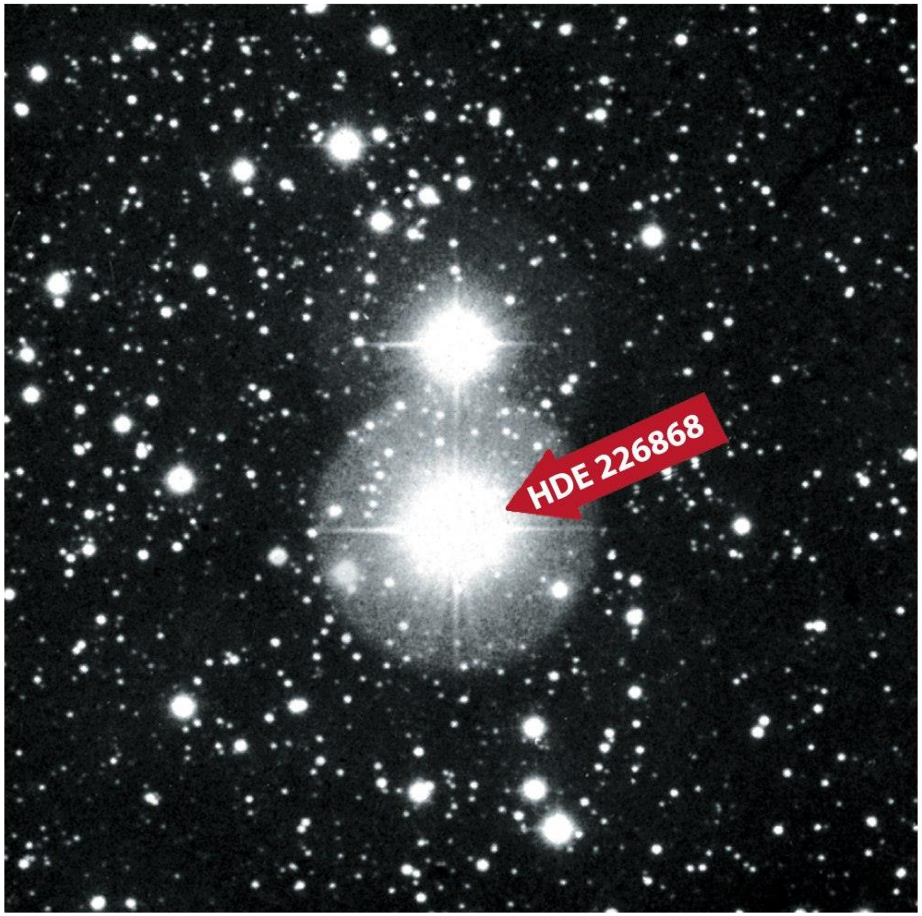
Stellar Black Hole

- If a stellar corpse has a mass greater than about 2 to 3 $M_\odot$, gravitational compression will overwhelm all forms of internal pressure, including degenerate neutrons and nuclear forces
- The stellar corpse will collapse to a singularity, immediately around which the escape speed exceeds the speed of light

- Far away from the black hole, the space is the same as in the case of a normal main sequence star



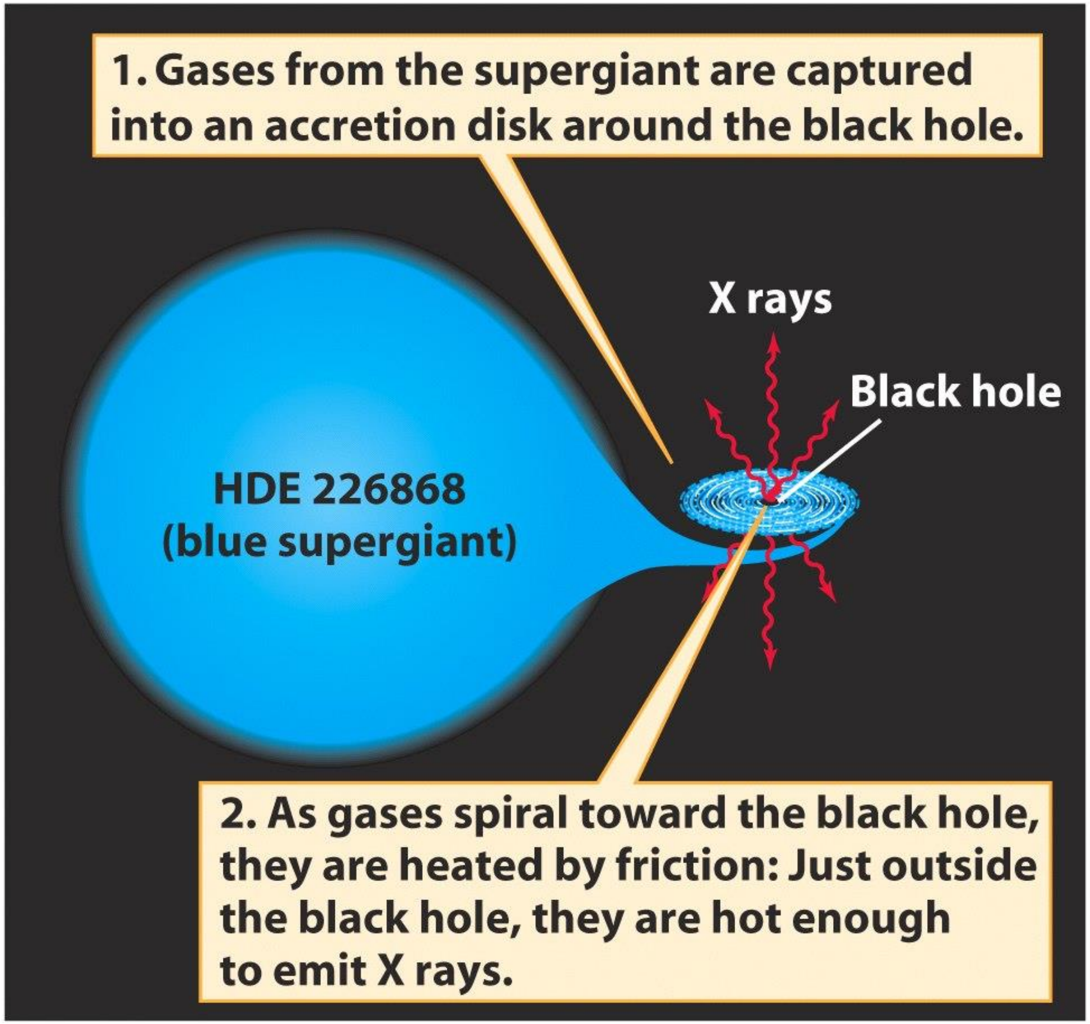
Certain binary star systems probably contain black holes



Cygnus X-1

- Black holes have been detected using indirect methods
- Some binary star systems contain a black hole
- In such a system (e.g., Cygnus X-1), gases captured from the companion star by the black hole emit detectable X rays

Stellar Black Hole



A schematic diagram of Cygnus X-1