Neutron stars

Compress matter to very high density:

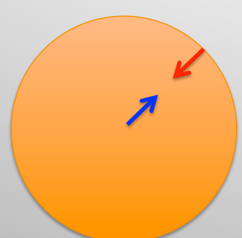
$$p + e \rightarrow n + \nu_e$$

proton, electron, neutron, neutrino

Form a star made almost entirely out of neutrons!

Neutrons normally *decay*, but at high enough densities they can't: no quantum states for electrons

Neutron stars

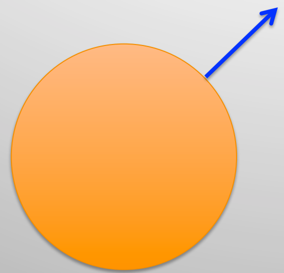


Balance of forces:
- gravity
- gradient of neutron degeneracy pressure

Size: radius of about 10 km
Density: about 5 x 10^{17} kg m^{-3}

same density as atomic nucleus

Neutron stars



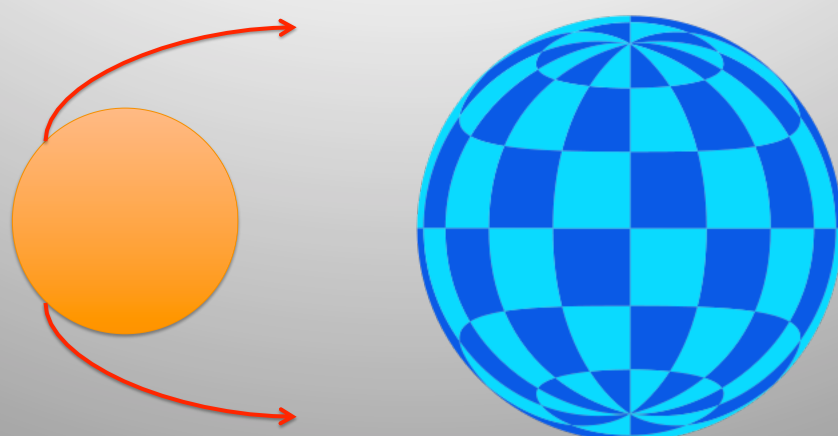
Quite "close" to being a black hole

Newtonian estimate of escape speed

$$v_{esc} = \sqrt{\frac{2GM}{R}} \approx 0.6c$$ for $M = 1.4\ M_{sun}$ and $R = 10$ km

Surface gravity would crush any mountain more than a mm high

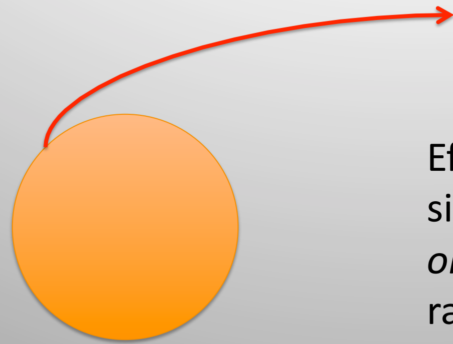
Neutron stars



Relativistic bending of light strong near surface

Can "see" more than half the surface

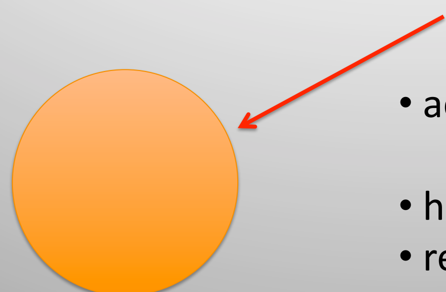
Neutron stars



Expect light from the surface to be strongly redshifted

Effect is hard to observe since don't know the *original* wavelength of radiation that is emitted

Neutron stars



Matter falling in is:

- accelerated to very high velocity
- has large kinetic energy
- releases energy when hits surface

Release about 10% of the $E = mc^2$ rest mass energy

Compare to nuclear fusion: 0.8% for H to He

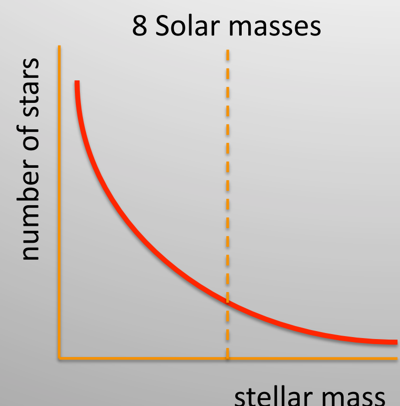
Neutron stars

Idea: neutron stars might be formed in supernova explosions – proposed by Walter Baade & Fritz Zwicky (1934)

Detailed models of neutron stars – Robert Oppenheimer & George Volkoff (1939)

…but how to detect?

Neutron stars



Massive stars are less common than low mass stars

Need a mass of above about 8 Solar masses to make a neutron star

About 0.3% of all stars

100 billion stars in the Milky Way
0.003×10^{11} = 300 million neutron stars!

Young neutron stars are hot: radiate X-rays and can be seen in the optical if they are very close

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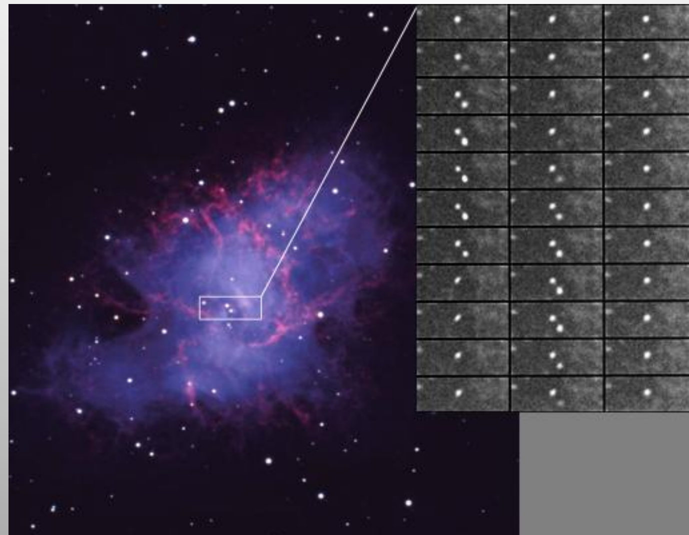
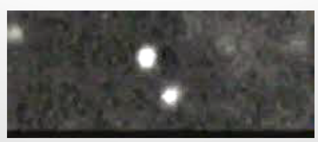
But first discovered via pulsed radio emission

Jocelyn Bell (1967)… completely unexpected discovery

Pulsars



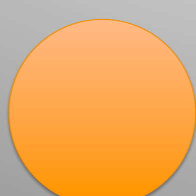
Young pulsars are associated with supernova remnants – here the Crab Nebula



Crab pulses 30 times per second

Suppose due to rotation

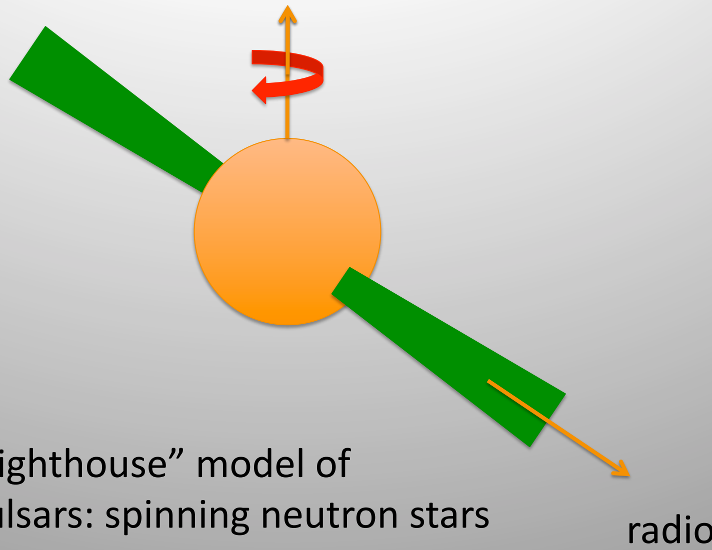
Imagine a white dwarf, radius 10,000 km, spinning that fast



Circumference: 2π x 10,000 km
= 63,000 km

Rotation speed = 30 x 63,000 km s^{-1}
= 1,890,000 km s^{-1}

Greater than speed of light: can't be a white dwarf



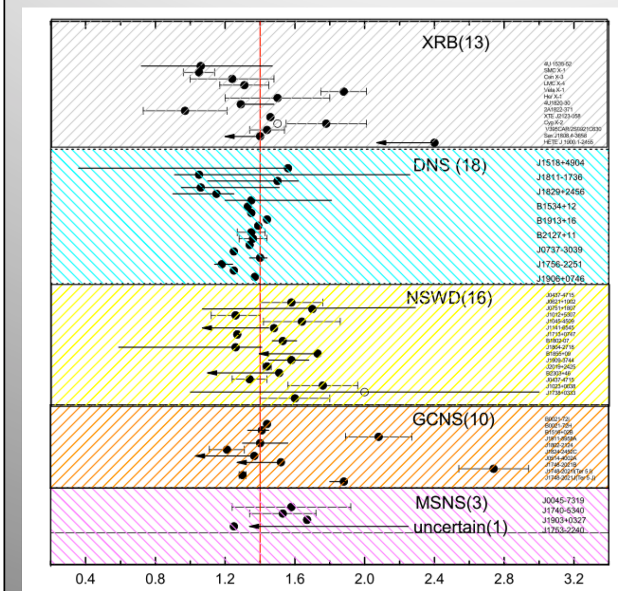
“Lighthouse” model of pulsars: spinning neutron stars emitting beams of radio waves, see pulses when come into line of sight

Maximum mass of a neutron star is not known

- limited in the same way as Chandrasekhar limit for white dwarfs
- neutron degeneracy pressure won’t hold up a star if neutrons become relativistic (v ~ c)
- but details complicated by unknown nuclear physics at very high density
- thought to be no more than 3 Solar masses

Core collapse supernova in which more than 3 Solar masses reaches the core will be unable to avoid collapse to a black hole

Maximum mass of a neutron star is not known



Observations: most known neutron stars have masses of about 1.4 Solar masses