Stellar Remnants

Dr Ken Rice

(wkmr@roe.ac.uk)

The Cosmic Perspective

- Based mainly on material in Chapter 18 (sixth edition).

What are stellar remnants?

- Stellar remnants are what is left after the death of a star.

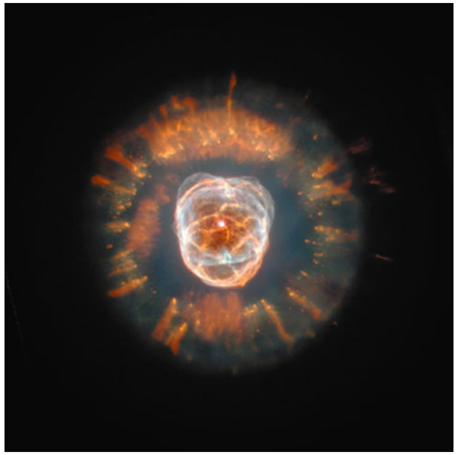
- Three types of stellar remnants
  - White dwarfs
  - Neutron stars
  - Black holes

- White dwarfs
  - Remnant of a low- or intermediate mass star

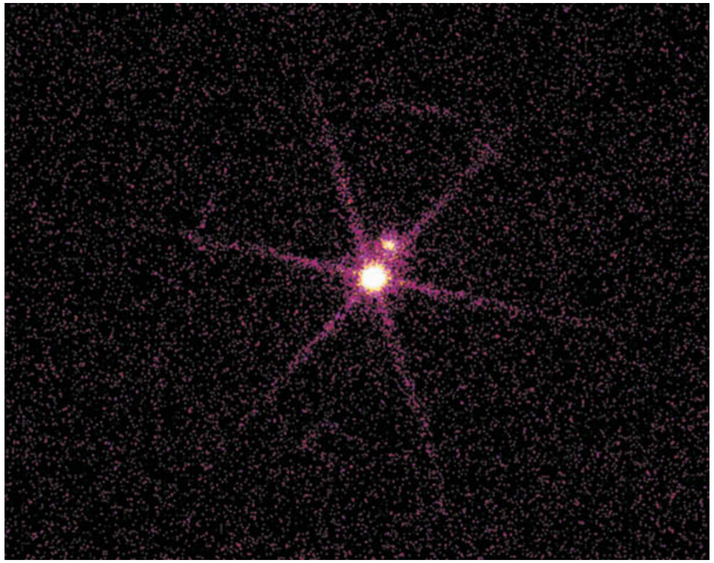
- Neutron stars
  - Remnant of a massive star

- Black holes
  - Remnant of a massive star in which the resulting neutron star is massive enough to collapse further.

White dwarfs



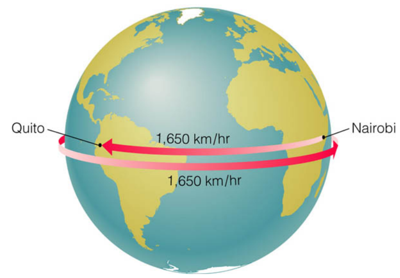
- A white dwarf is the exposed core of a star that has died and shed its outer layers in a planetary nebula.
- Initially hot, but cools with time.
- Small radii mean that they are dim relative to an average star.
  - May shine brightly in high-energy light - x-rays or ultraviolet.
- Small radii and stellar mass means strong gravity.
  - Supported by electron degeneracy pressure - closely packed electrons.

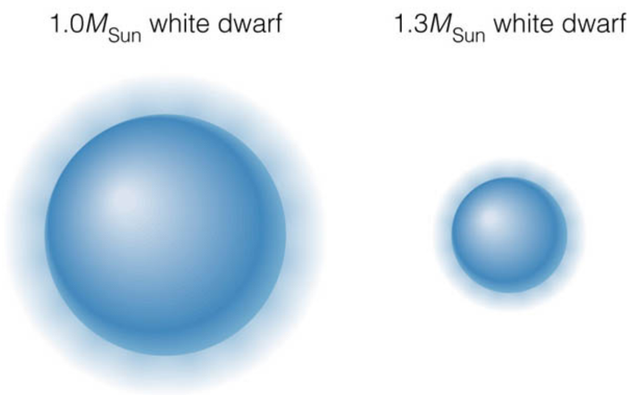


Chandra X-Ray image of Sirius . The white dwarf companion is much brighter in this image than Sirius - one of the brightest stars that we can see.

White dwarf composition

- White dwarf composition reflects the products of the star's final nuclear-burning stage.
- Solar-mass star
  - White dwarf remnant mainly carbon.
- Very-low-mass stars
  - Cores never become hot enough to fuse helium.
  - White dwarf mainly helium.
- Intermediate mass stars
  - Sometime progress to carbon burning
  - White dwarf may contain oxygen and heavier elements - never iron.
- Typical white dwarf
  - Mass of the sun.
  - Size of the earth!



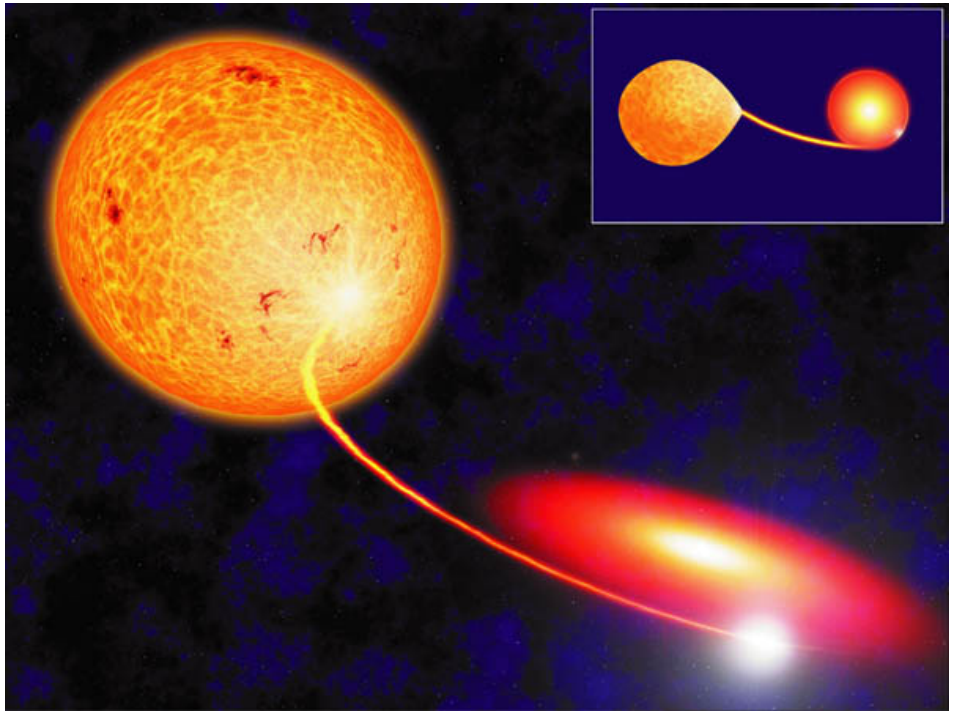


White dwarf limit

- Electron speeds increase as the white dwarf mass increases.
- Nothing can travel faster than the vacuum speed of light!
- Calculations show that the electron speed would reach the speed of light in a white dwarf with a mass 1.4 times that of the sun.
- No white dwarf can have a mass greater than 1.4 solar masses.
  - White dwarf limit or Chandrasekhar limit.
- Observational evidence supports this limit
  - No white dwarf has ever been observed with a mass greater than 1.4 solar masses!

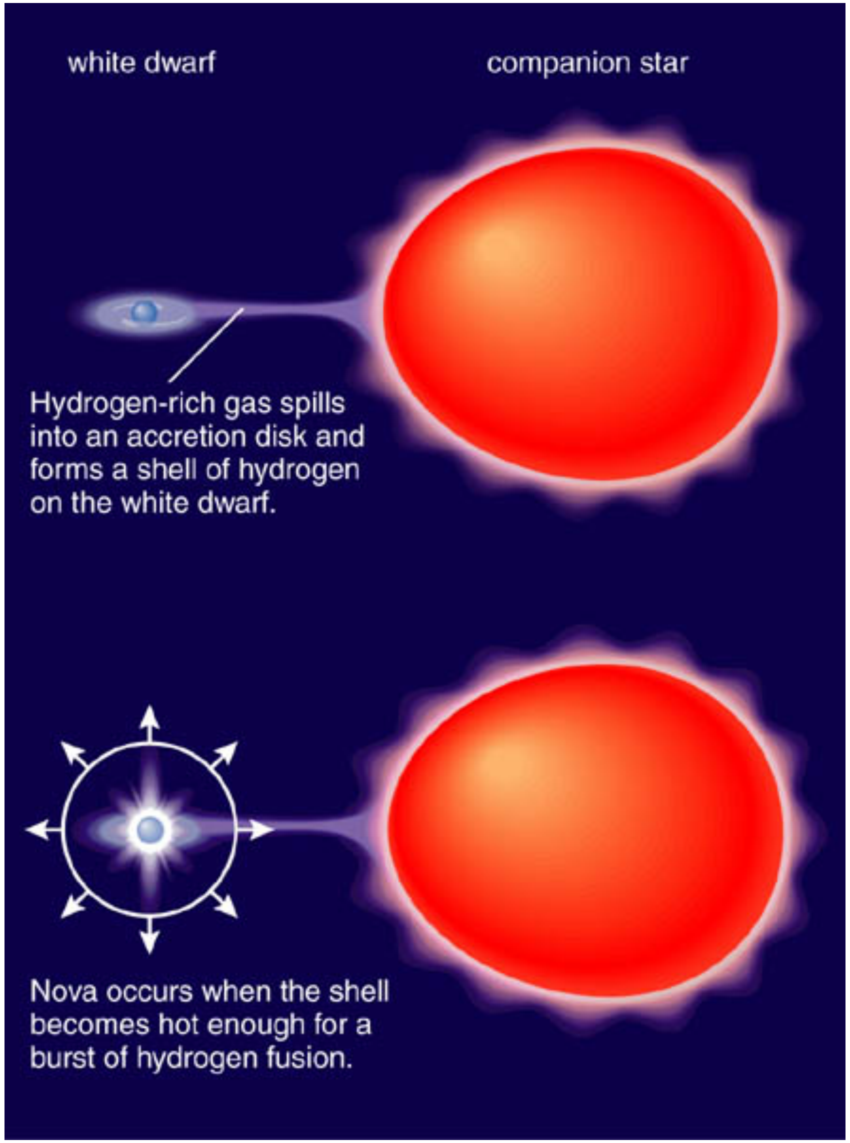
White dwarfs in close binary systems.

- A close binary system is a system in which two stellar objects orbit very close to each other.
- A white dwarf in a close binary system can gain mass if its companion is a main-sequence or giant star.
- This process leads to the formation of an accretion disc around the white dwarf.
- Accretion can provide a ‘dead’ white dwarf with a new energy source.
- These white dwarfs can be detected via their intense UV or X-Ray radiation
  - These systems can be highly variable.
  - May brighten for a few days and then fade away.
  - Dwarf novae!



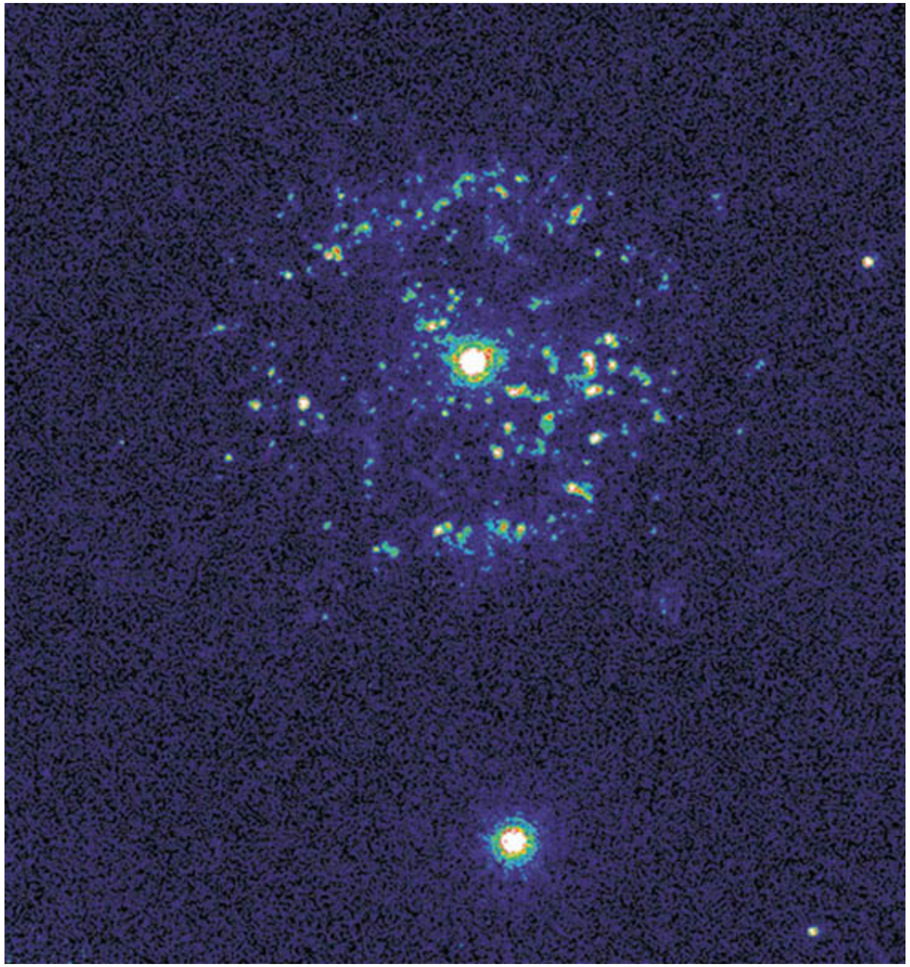
Novae

- Accreting white dwarfs may occasionally flare up even more dramatically.
- Gas accreting onto the white dwarf is predominantly hydrogen from the companion star.
- White dwarf's gravity compresses this hydrogen into a thin surface layer.
- When the temperature of this hydrogen reaches 10 million K, hydrogen fusion ignites.
- White dwarf will then shine brightly for a few weeks,
  - May be as bright a 100000 Suns
  - Nova remnant may be visible for many years.
- Process may repeat.



Novae and Supernovae

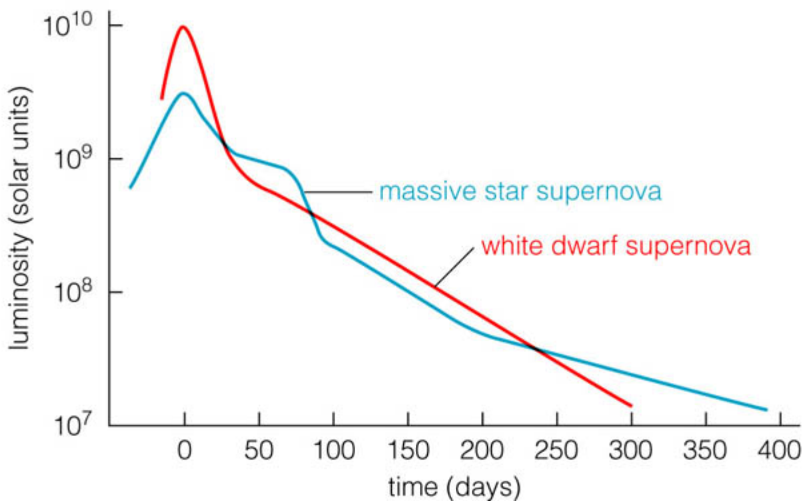
- Novae and supernovae are different.
- Novae
  - Bright as 100000 Suns
  - Repeat
    - every few decades for the most massive white dwarfs.
    - More commonly every 10000 years.
- Supernovae
  - Death of a massive star
  - Bright as 10 billion Suns.
- Historically a nova was any star that appeared to the naked eye where none was visible before
  - Only recently could we distinguish between novae and supernovae.



Hubble Space Telescope images showing blobs of gas ejects from a white dwarf nova (T Pyxidis). The bright spot at the centre is the binary system that generated the nova.

White dwarf supernovae

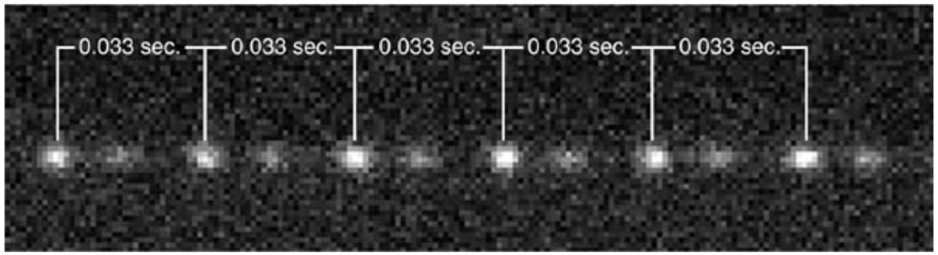
- Each time a nova occurs, the white dwarf ejects some mass.
- After each nova, the white dwarf begins to accrete matter again.
- Observations suggest that in some cases the mass of the white dwarf actually increases.
  - Maximum mass = 1.4 solar masses.
- If the white dwarf approaches the white dwarf limit, carbon fusion may ignite.

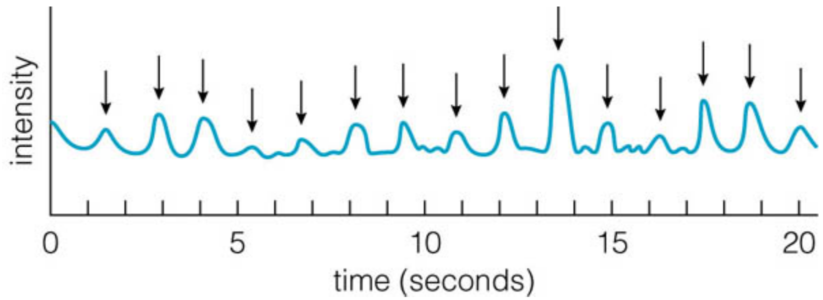


- This fusion ignites throughout the star almost instantaneously
  - "Carbon bomb"
  - White dwarf supernova
- This differs from the iron catastrophe that cause massive star supernovae.
  - No hydrogen lines in WD supernovae
  - Luminosity decays differently.
- All white dwarf supernova have the same luminosity
  - Very important for measuring large distances in the universe - cosmology!

Neutron stars

- Ball of neutrons created by the collapse of the iron core in a massive star supernova.
- Typically 10 km in radius - more massive than the sun.
- Supported by neutron degeneracy pressure.
- Discovered in 1967 by Jocelyn Bell
  - Noticed peculiar pulses of radio signals coming from somewhere near the constellation of Cygnus

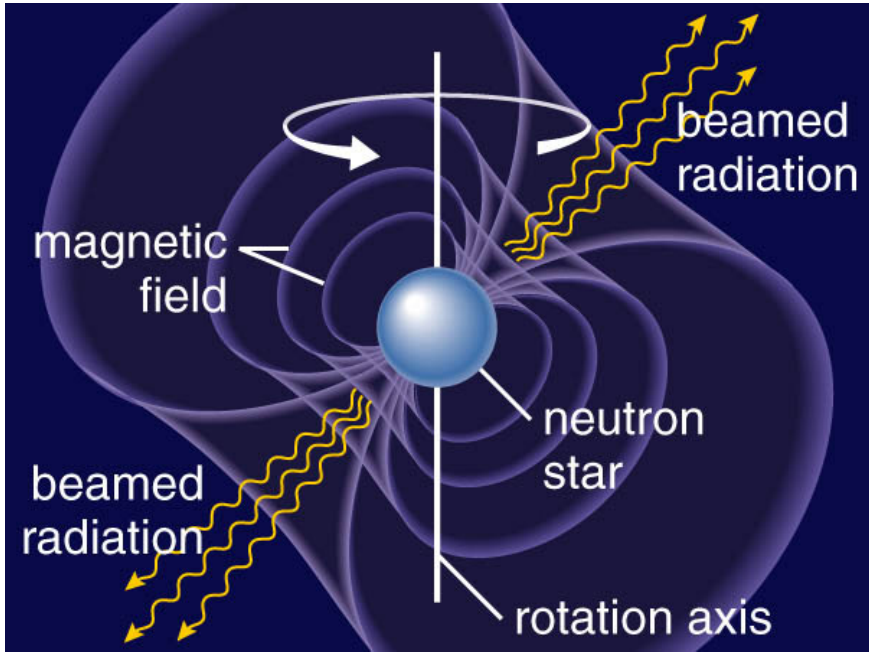


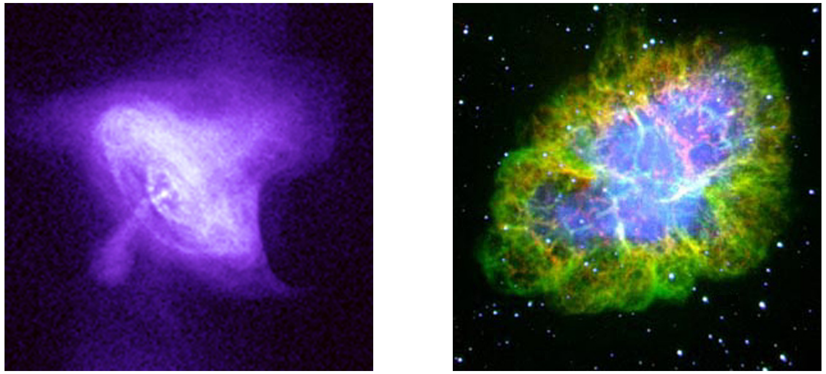


Discovering Astronomy

Pulsars

- The pulses coming from Cygnus were strange because no known astronomical object pulsed so regularly.
- Originally called ‘LGM’ - Little Green Men.
- Astronomers soon found pulsars in the centres of supernova remnants
  - Pulsars are neutron stars left behind after supernova explosions.
- Pulsations due to the rapid spinning of the neutron star
  - Conservation of angular momentum.
- Intense magnetic field directs beams of radiation out along the poles.
  - Like a lighthouse.
- Pulsars must be neutron stars because no other massive object could spin this fast.





Cab nebula in x-ray (left) and optical (right).

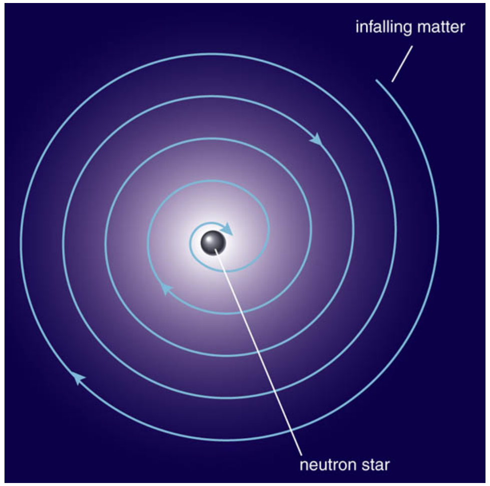
Pulsar evolution

- The electromagnetic radiation emitted by a pulsar carries away energy and angular momentum.
- Over time, pulsars can spin down (spin more slowly)
  - The Crab pulsar currently spins 30 times per second, in two thousand years time it will probably spin less than 15 times per second.
- Pulsar also beam their radiation
  - This means there will be some pulsars that we don't see because their beams do not sweep past the Earth.

Golden rule : All pulsars are neutron stars, not all neutron stars are pulsars.

Neutron stars in close binary systems

- Just like white dwarfs, neutron stars may exist in close binary systems with main-sequence or giant star companions.
- Gas overflowing from the companion can create a hot accretion disc around the neutron star.
- The strong gravity of the neutron star means that the accreting matter releases enormous amounts of energy.
  - Dropping a brick onto a neutron star would release as much energy as an atomic bomb.
- Large amount of energy released makes a neutron star disc much hotter and more luminous than the disc around a white dwarf.
- The high temperatures mean that it radiates in the x-ray.
  - 10000 times more energetic than the sun
  - Often called X-Ray binaries
- Matter accreting onto a neutron star can cause the rotation to speed up
  - Some rotate so fast that they pulsate every few thousands of a second - *millisecond pulsars.*



X-Ray Bursts

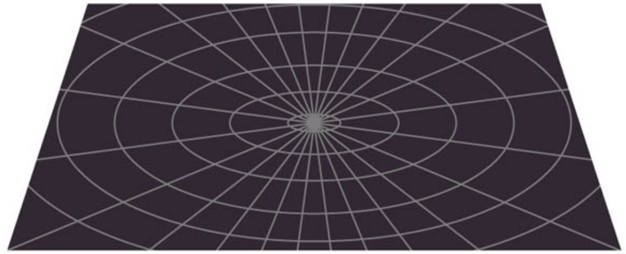
- Like acreting white dwarfs that occasionally erupt in novae, accreting neutron stars sporadically erupt.
- Energy primarily released in X-Rays
  - X-Ray bursts (X-Ray bursters)
- Result from sudden ignition of nuclear fusion
  - Hydrogen-rich material from the companion forms a thin layer on the surface of the neutron star that undergoes steady fusion.
  - When the temperature reaches 100 million K the helium 'ash' ignites, generating the X-Ray burst.
- X-Ray bursts last only a few seconds
- Process can repeat.

Black Holes

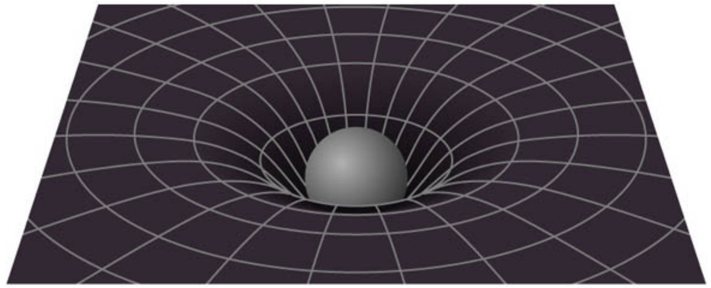
- Sometimes a stellar remnant is massive enough that it continues collapsing.
- Remember : A white dwarf has a mass limit of 1.4 solar masses.
  - Above this mass - white dwarf supernova – “carbon bomb”.
- A neutron star has a mass limit of between 2 and 3 solar masses
  - Above 2-3 solar masses, neutron degeneracy pressure can no longer support the neutron star.
- Remember : A massive star supernova occurs when the electron degeneracy pressure supporting the iron core succumbs to gravity.
  - Core collapses catastrophically into a ball of neutrons - neutron star.
- If the massive star has not blown away all of its upper layers, some mass may fall back onto the neutron star.
- If the mass exceeds the neutron star limit (2-3 solar masses), core collapses again.
  - No known force can keep the core from collapsing into a black hole!

What is a black hole?

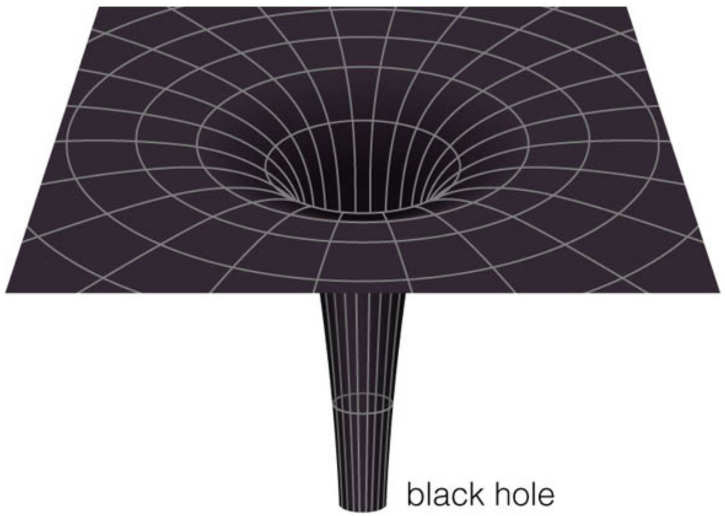
- Escape velocity from an object depends on its mass and size
  - Escape velocity increases as an object becomes more compact.
- A black hole is so compact that nothing can escape - not even light!
- Space and time are bound together as a four-dimensional spactime
  - Gravity acts to curve spacetime
- The boundary between the inside of a black hole and the universe is the **event horizon**
  - Nothing that passes this boundary can escape!
- A black hole is like a bottomless pit in spacetime!



Flat spacetime.



Curved spacetime



The curvature of spacetime

Properties of black holes

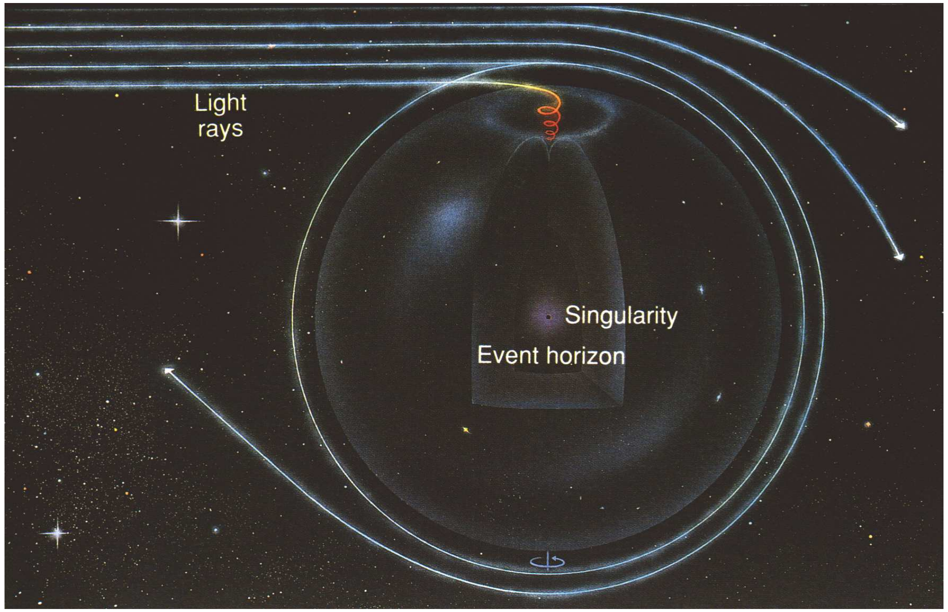
- Size
  - The radius of the event horizon is known as the Schwarzschild radius.
  - A collapsing stellar core becomes a black hole at the moment it is smaller than its Schwarzschild radius
  - A one solar mass black hole has a 3km Schwarzschild radius.
- Mass
  - The material that forms the black hole can still exert a gravitational force on its surroundings.
- We cannot know anything about the interior of a black hole
  - No information can ever emerge from within the event horizon (we have no way of knowing anything about events that take place within this region).
  - All material inside a black hole should be crushed into an infinitely tiny and dense point - SINGULARITY!
  - If we added mass to a black hole, it would make no difference what type of material we added.
- If we (observe!!!)/detect a black hole we cannot tell how it formed
  - Death of a massive star
  - Collision of two neutron stars
  - Other???

Mass is one of the only measurable properties of a black hole.

Black Holes have no Hair

- A black hole has only three physical properties: mass, electric charge, and spin (angular momentum)

- they forget about composition, shape, smell etc…



Schwarzschild vs Kerr Black Holes?

Schwarzschild radius – radius of event horizon

Karl Schwarzschild (1873 – 1961)

- Nothing can travel faster than the speed of light!
- If the escape velocity of an object exceeds the speed of light, then the object must be a black hole.
- The radius at which the escape velocity equals the speed of light is the Schwarzschild radius

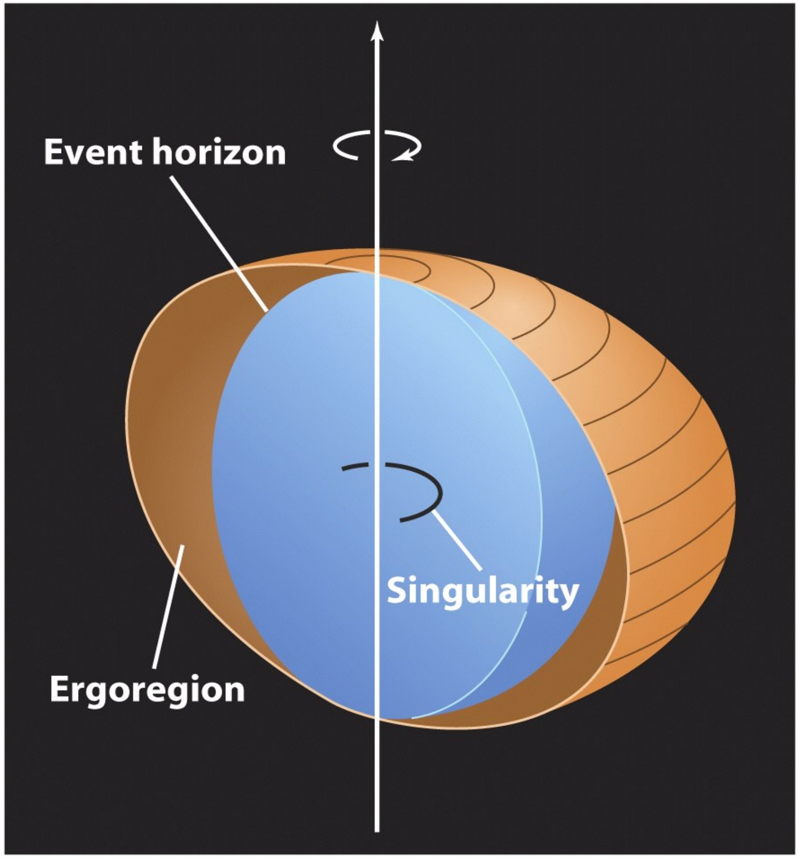
$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

$$v_{esc} = c \Rightarrow R_s = \frac{2GM}{c^2}$$

- If the Sun were to become a black hole, the Schwarzschild radius would be about 3km.

$$R_s = 3\frac{M}{M_{sun}}\,\mathrm{km}$$

Kerr Black Hole



- A rotating black hole is known as a Kerr black hole.
- A body collapsing to a black hole with non-zero angular momentum would become a Kerr black hole
  - Spherical inner event horizon
  - Ergosphere between event horizon and stationary limit
    - Objects moving at the speed of light at edge of the ergosphere are stationary with respect to the universe
- Inside ergosphere, spacetime is dragged along with the black hole (frame dragging)
  - Bodies escaping from the ergosphere can take some of the black holes energy and spin.

Energy extraction from a black hole

- Consider a black hole of mass M
  - Schwarzschild radius is then

$$R_S = \frac{2GM}{c^2}$$

- If an object of mass m falls into the black hole, starting from a large distance from the event horizon, the maximum amount of energy that can be released is

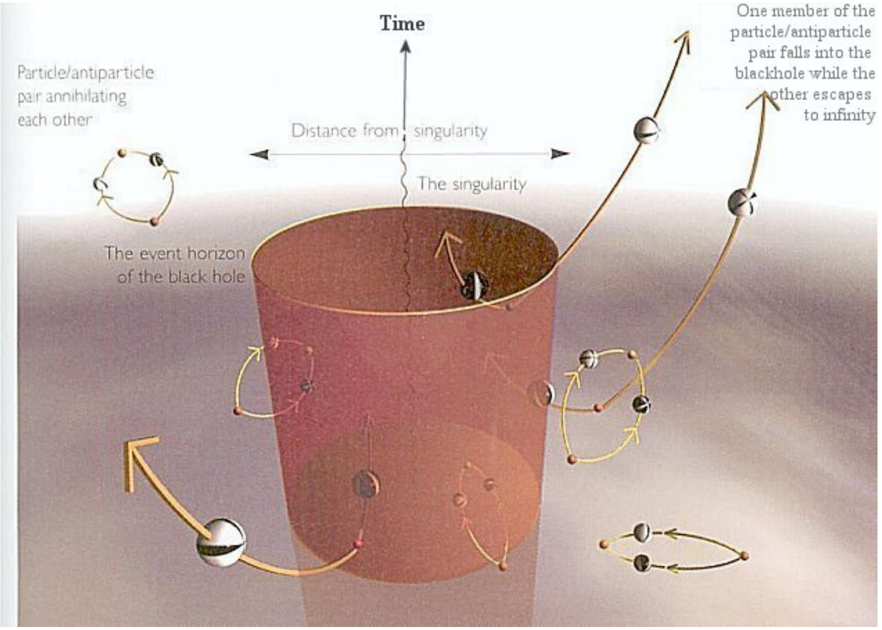
$$\Delta E_{\max} \approx \frac{GMm}{R_S}$$

- Using the expression for Schwarzschild radius we get $\Delta E_{\max} = \frac{1}{2} mc^2$

Half of the rest mass energy can be released by material falling into a black hole
• hydrogen fusion in the core of a main sequence star only release 0.7% of the rest mass energy.
•Accreting black holes can be very "bright".

Can black holes lose mass?

Nothing can escape from inside the event horizon but…

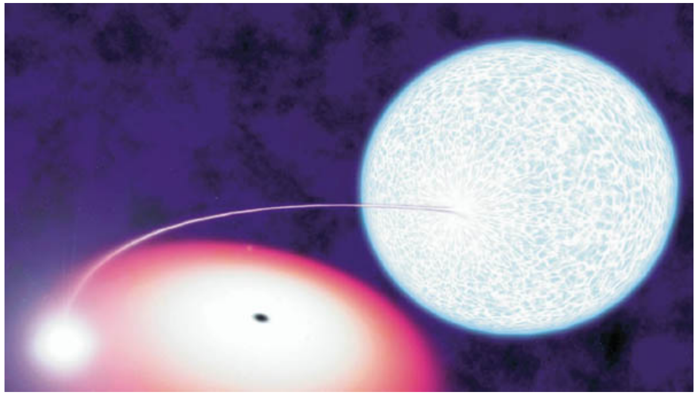


- Quantum mechanics predicts (shows) that particle-antiparticles pair can come into existence in a vacuum
  - Normally annihilate each after a very short time
- Stephen Hawking showed that this could result in energy extraction from a black hole
  - One of the pair can cross the event horizon.
  - Other particle survives which is equivalent to mass and energy being extracted from the black hole.

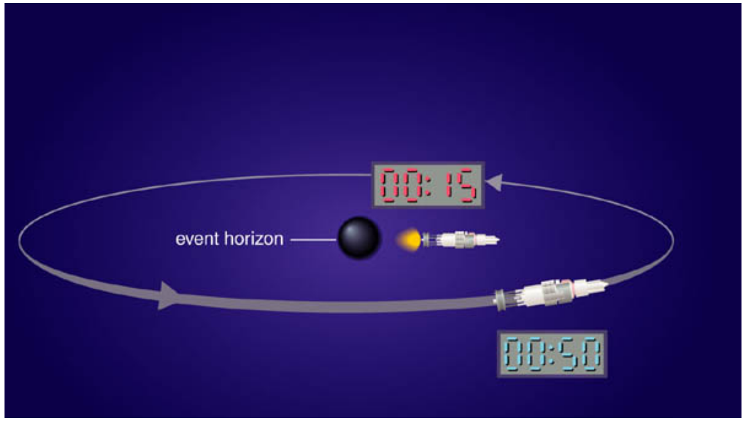
Also don't forget rotating (Kerr) black holes – objects that escape from inside the ergosphere can extract energy and angular momentum from the "dragged" spacetime. Discovering Astronomy

Do black holes really exist?

- General relativity predicts the existence of black holes and has passed all tests to date!
- Gravity
  - Many observations of objects that appear to be being influenced by an unseen object that could be massive enough to be a black hole!
- X-Ray binaries
  - Some X-Ray binaries are black holes.
  - Cygnus X-1
    - 18 solar mass star orbiting a 3 solar mass compact object
    - Compact object too massive to be a neutron star - black hole!
- Supermassive black holes - galactic center!
  - Can observe stars orbiting an unseen, massive object.

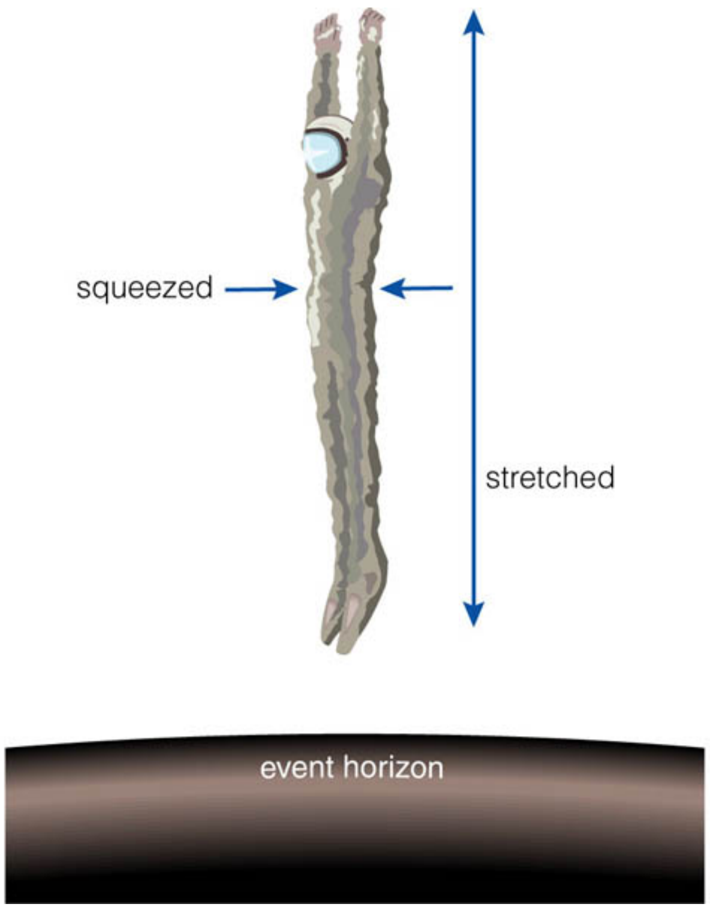


Some interesting things about black holes



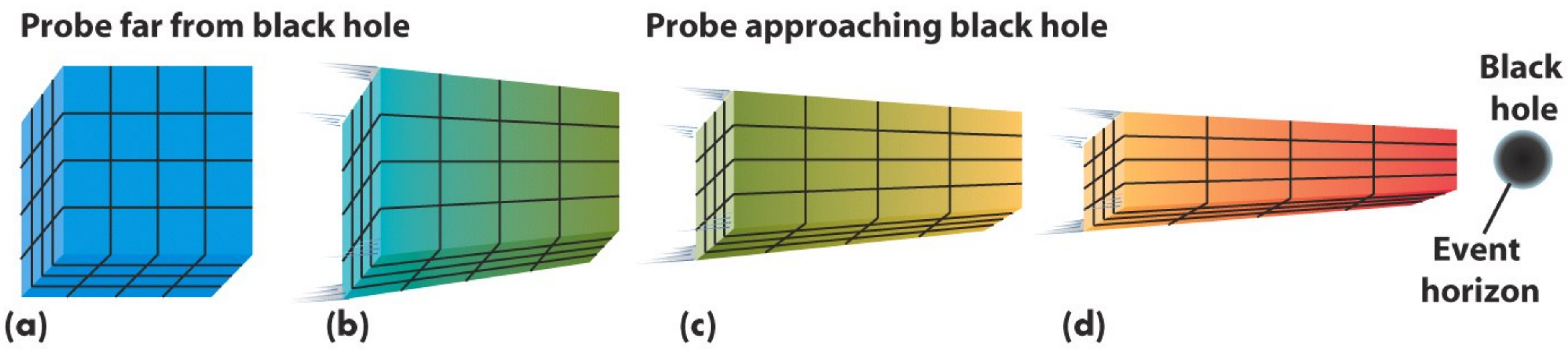
Time runs more slowly for objects near a black hole.

- You can safely orbit a black hole if far enough from the event horizon!!
- An object failing into a black hole will appear to take forever to eventually be swallowed by the black hole!
  - Clocks run more slowly
  - Light is redshifted
- It will occur very quickly for an observer on the object being swallowed by the black hole!



Strong tidal force!

Falling into a black hole is an infinite voyage

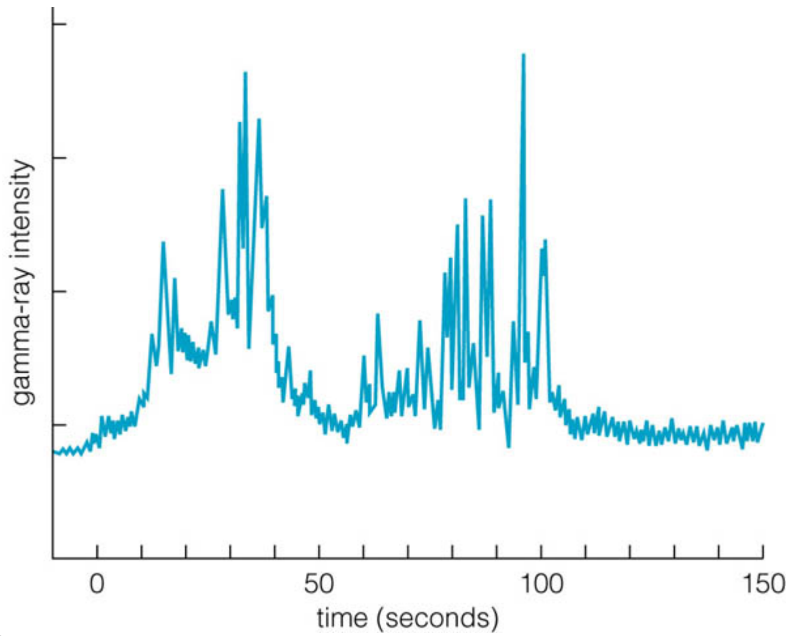


- Time appears to run slowly as an objects nears a black hole
  - $t \rightarrow \infty$ as $r \rightarrow R_S$
- An outside observer will never actually see an object cross the event horizon!

Gamma-Ray bursts

- Initially detected by secret US military satellites looking for gamma rays from nuclear blasts.
- 1991 - launch of NASA's Compton Gamma Ray observatory.
- Detected about one per day
  - Soon had enough to see where they come from.
- Appear to come from random directions - not concentrated in the disc of our galaxy like X-ray bursts.
  - Must come from outside our galaxy!

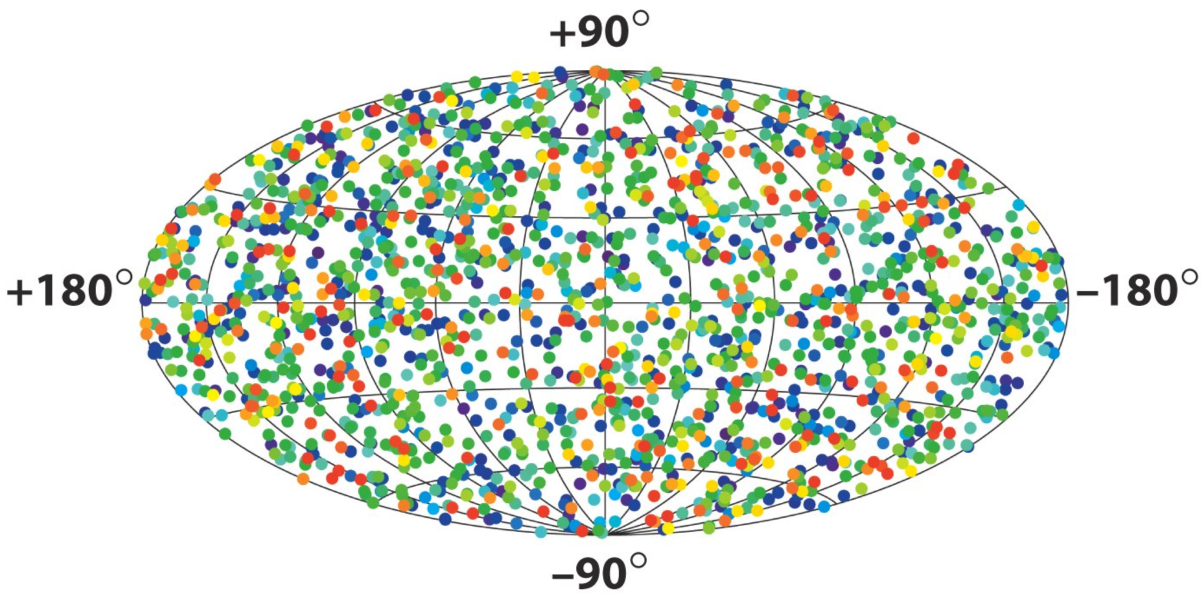
- At least some gamma-ray bursts must occur in galaxies billions of light years away
  - Must be extremely powerful



Discovering Astronomy

What causes gamma-ray bursts

- If these gamma-ray bursts shine equally in all directions they would be as bright as a million galaxies!
  - Must beam their radiation like a searchlight.
- Some gamma-ray bursts come from powerful supernovae
  - Must be one in which the stellar remnant is a black hole!
  - Sometimes called a hypernova.
- May actually be more than one type of gamma-ray burst.



Summary

- Three types of stellar remnants
  - White dwarfs – Low- and Intermediate-mass stars
  - Neutron stars – high-mass stars
  - Black holes – high-mass stars.
- White dwarf (Chandrasekhar limit) – 1.4 Solar masses
  - A white dwarf in a binary can reach this limit and explode as a white dwarf supernova
  - Very important for determining distances since they all have the same brightness
- Some neutron stars spin and give off pulses (pulsars)
  - All pulsars are neutron stars, not all neutron stars are pulsars.
- A black hole only has mass, spin and charge
- Schwarzschild radius – radius of event horizon
  - $3 (M_{bn}/M_{sun})$ km
  - Black holes can lose mass – Hawking radiation - very slowly though!
- Near a black hole, time dilates and light is redshifted – GR!