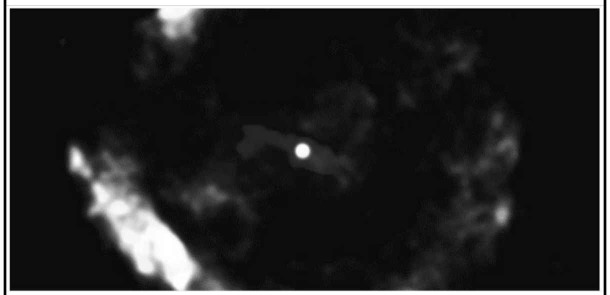
Chapter 18: The Stellar Graveyard
White Dwarfs, Neutron Stars, Black Holes



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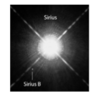
White Dwarfs



- Remaining cores of dead, low mass stars
- Electron degeneracy pressure supports them against gravity
- Slowly fade with time
- Sirius and its hot WD companion (Component **A** brighter in visual wavelengths)

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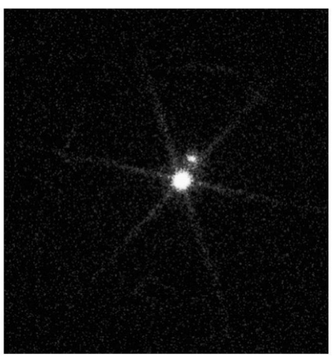
White Dwarfs



- Remaining cores of dead, low mass stars
- Electron degeneracy pressure supports them against gravity
- Slowly fade with time
- Sirius and its hot WD companion (Component **B** brighter in X-ray wavelengths)

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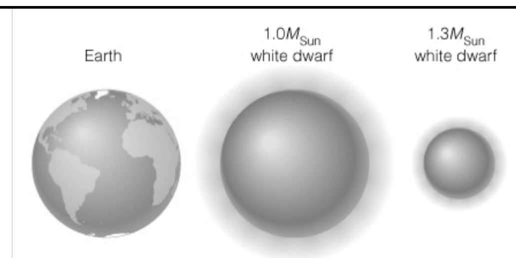

- White dwarfs with same mass as Sun are about same size as Earth; slowly cooling
- Higher mass white dwarfs are smaller
- Cannot be more massive than 1.4 M_{Sun}, the *Chandrasekhar limit*

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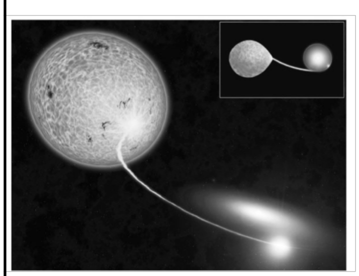
White Dwarfs in Close Binaries



- Mass falls toward white dwarf from binary companion
- Gas orbits white dwarf in an *accretion disk*
- Friction causes heating and accretion onto white dwarf

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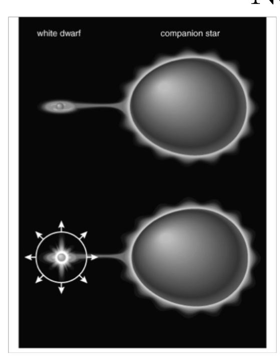
Nova



- Temperature of accreted gas may become hot enough for hydrogen fusion
- Fusion begins suddenly and explosively, causing a *nova* explosion

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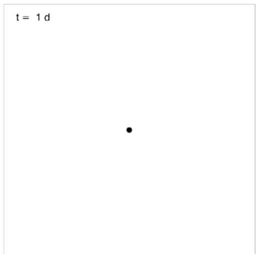
Nova



- The nova star temporarily brightens (Nova Del 2013)
- Explosion drives accreted matter out into space
- If accretion makes WD larger than 1.4 solar masses, then WD may totally explode …

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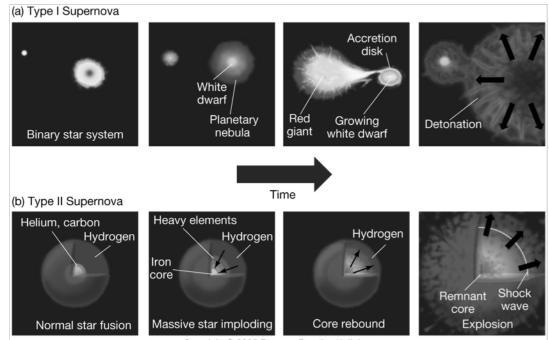
Two Kinds of Supernova

Type I = explosion of WD in binary (no H)
Type II = death explosion of massive star (H)



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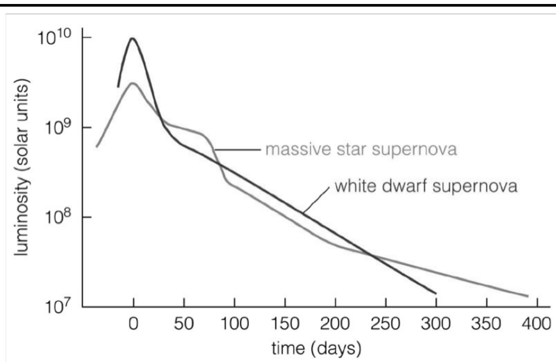

Light curves and spectra differ between types
(no H in Type I)

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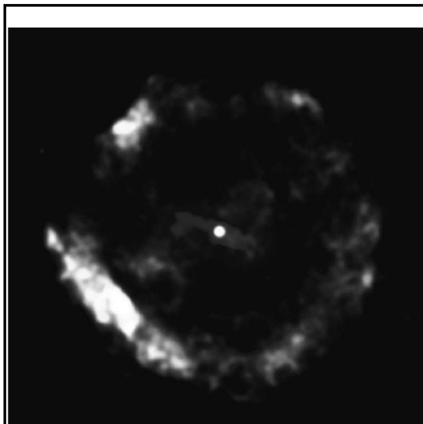

Neutron star: ball of neutrons left behind by a massive-star supernova (10 km radius)

Degeneracy pressure of neutrons supports it against gravity (maximum of 3 solar masses)

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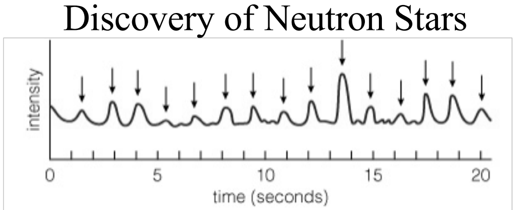
Discovery of Neutron Stars



- Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky
- The pulses were coming from a spinning neutron star—a *pulsar*

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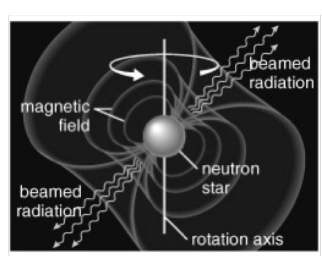
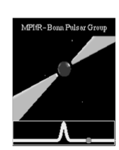
Pulsars



- Radiation beams along a magnetic axis that is not aligned with the rotation axis



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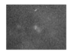
Pulsar at center of Crab Nebula pulses 30 times per second



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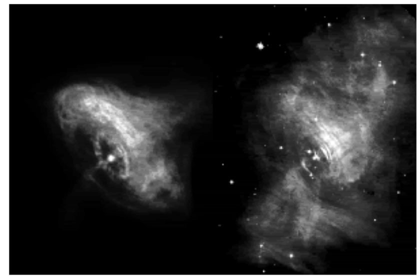

Dynamic rings, wisps and jets around the pulsar in the Crab Nebula in X-ray light by Chandra (left) and optical light by Hubble (right) between November 2000 and April 2001.

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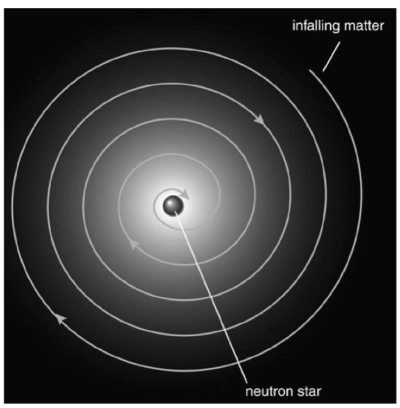

Neutron Stars in Close Binaries:

Hot gas in accretion disk forms X-rays: X-ray Binaries

Accretion may cause episodes of H fusion on the surface, leading to X-ray bursts

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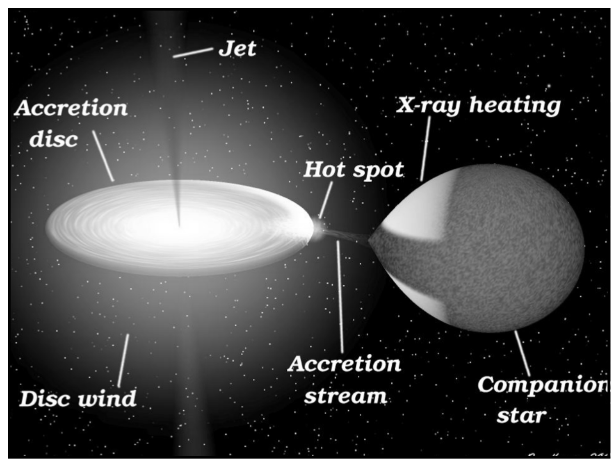

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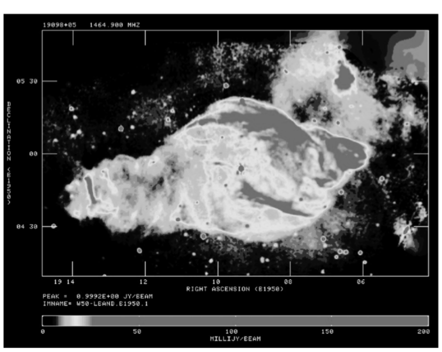
Example: SS433 in supernova remnant



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Radio jets from SS433 (26% of speed of light)

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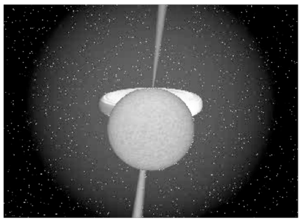
GSU discovery of light from mass donor star in SS433 (an A-supergiant feeding gas to a neutron star or black hole).



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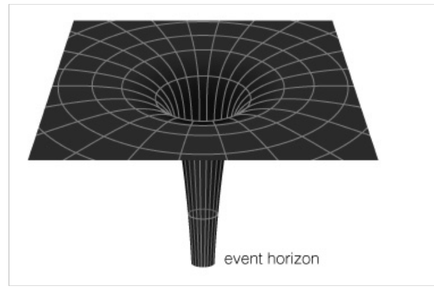
Black Holes



A ***black hole*** is an object whose gravity is so powerful that not even light can escape it.

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Escape Velocity

Initial Kinetic Energy	=	Final Gravitational Potential Energy

$$\frac{(\text{escape velocity})^2}{2} = \frac{G \text{ x (mass)}}{\text{(radius)}}$$

For escape velocity = speed of light,
need small radius and/or large mass.
Can occur in the collapse of a massive star.

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"Surface" of a Black Hole

- "Surface" of a black hole is the radius at which the escape velocity equals the speed of light = the ***event horizon.***
- Nothing can escape from within the event horizon because nothing can go faster than light.
- The radius of the event horizon is known as the ***Schwarzschild radius:*** 3 (M/M_{sun}) km (shrink Earth to size of a dime)

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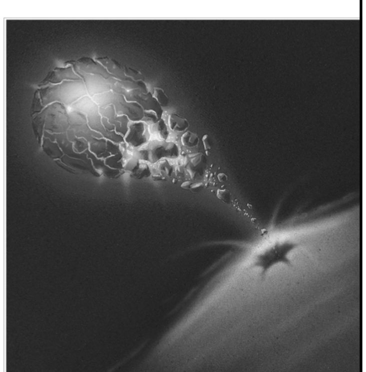
Space Travel Near Black Holes

Far from a black hole, the force of gravity same as for any massive object.

Close to a black hole, enormous tidal forces exist that stretch, heat, and tear apart



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Space Travel Near Black Holes

Imagine a spacecraft nearing the event horizon of a black hole:

Outside observers would observe clocks slowing down and photons with greater gravitational redshift. The spacecraft would begin to turn orange, then red, then fade from view.

In the spacecraft itself, however, time would appear to pass normally.

[consequences of Einstein's General Relativity]

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Space Travel Near Black Holes

What's inside a black hole?

Theory predicts that the mass collapses until its radius is zero and its density infinite (singularity).

This is unlikely to be what actually happens; we need a combined theory of gravity and quantum physics (big and small).

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Observational Evidence for Black Holes

- **Black holes cannot be directly seen BUT we can search for evidence of their gravitational tug on nearby stars and/or the emission of X-rays from the surrounding hot gas**
- **First direct evidence from the X-ray binary system Cygnus X-1**

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Observational Evidence for Black Holes

- **First X-ray satellites flown in 1970s led to the discovery of many X-ray sources**
- **Brightest source in constellation Cygnus named Cygnus X-1**
- **Very luminous and rapidly variable (suggesting a small size)**
- **Accurate position not known until a sudden change occurred in X-ray and radio brightness**

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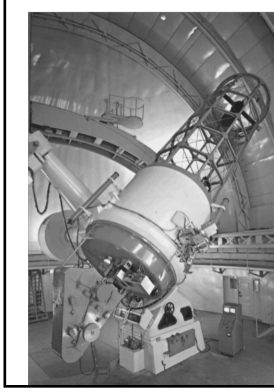
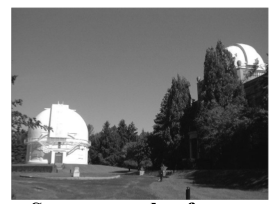
Observational Evidence for Black Holes





- **Spectra made of brightest star in vicinity HD226868 by Tom Bolton (David Dunlap Obs., Univ. of Toronto)**

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Observational Evidence for Black Holes

- **Study of spectra by Gies & Bolton (1986) found that HD226868 was a spectroscopic binary with an orbital period of 5.6 days**
- **Only spectrum of one star seen (O9.7 Iab) but the gravitational pull of the invisible companion was large**
- **Need to know <u>orbital inclination</u> and <u>mass ratio</u> to find the actual masses**

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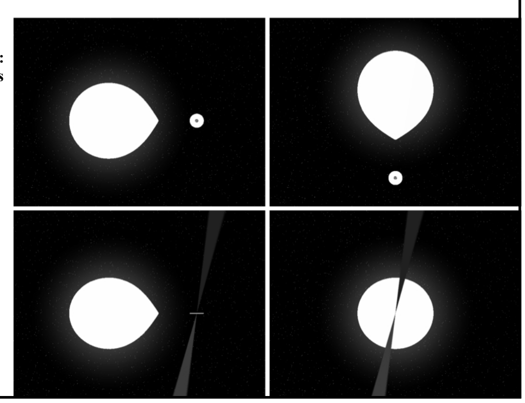
Orbital Inclination from Light Curve

Tidal distortion: brightness variation

i=0

i=90



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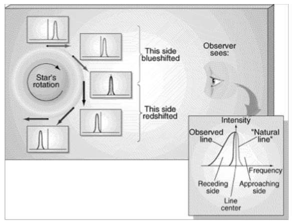
Mass Ratio from Rotation and Radius of Star

- Broadening of spectral lines gives rotation speed
- Since the star spins once each orbit (synchronous rotation), rotation speed gives us the radius of the supergiant



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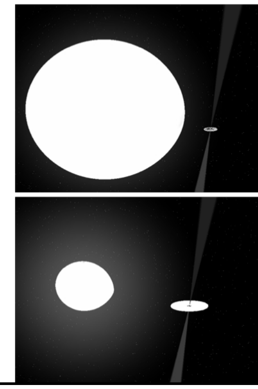
Stellar Radius and Mass Ratio

Relative size of supergiant is directly related to the mass ratio
q = mass(BH) / mass(supergiant)

q=0.1

q=10



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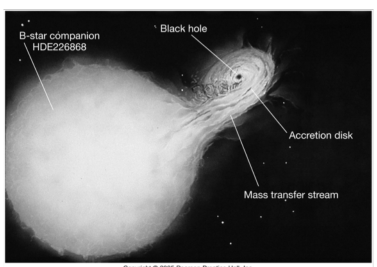
Result: Masses for Cygnus X-1

Supergiant mass = 23 solar masses
Companion mass = 11 solar masses
Much larger than limiting neutron star mass: BLACK HOLE
Accretion by enhanced wind capture.



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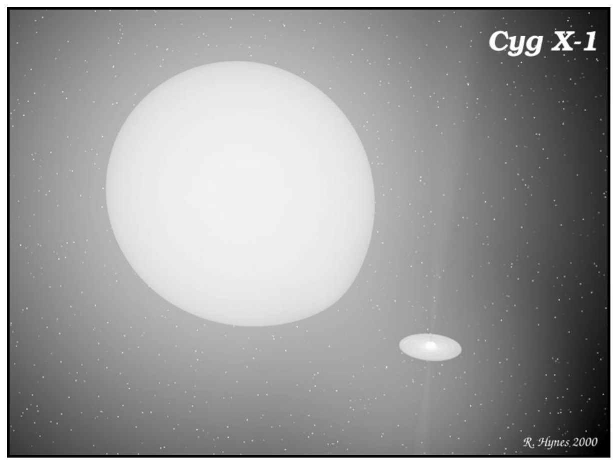

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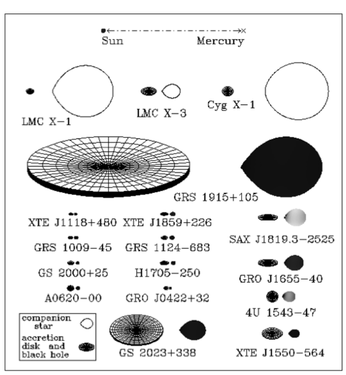
Observational Evidence for Black Holes

Many black hole binaries are known: some with massive companions and some with solar mass companions.



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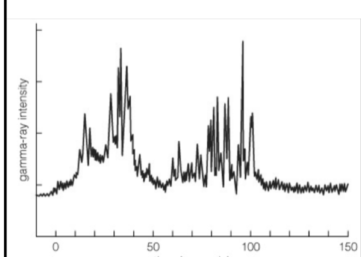
Gamma-Ray Bursts



- Brief bursts of gamma-rays coming from space were first detected in the 1960s

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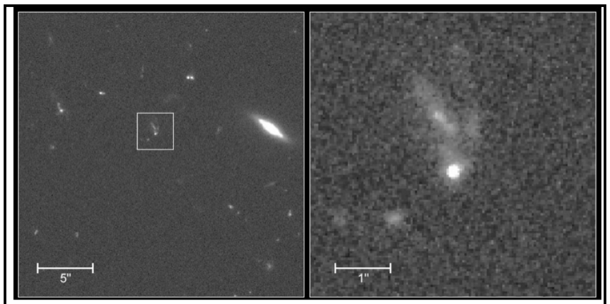

- Observations in the 1990s showed that many gamma-ray bursts were coming from very distant galaxies
- They must be among the most powerful explosions in the universe—could be the formation of a black hole

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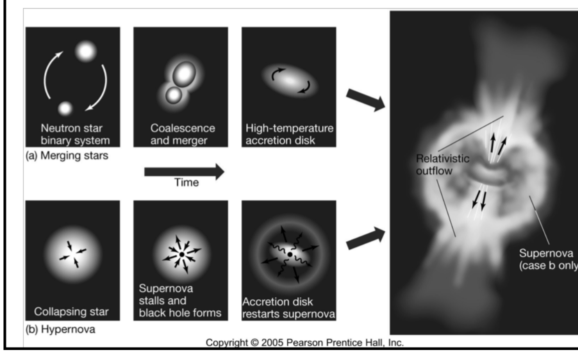
Gamma-Ray Bursts

Two models for gamma-ray bursts:
(1) merging neutron stars or (2) a hypernova



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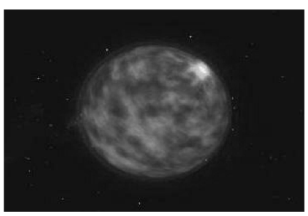
Gamma-Ray Bursts

In both models the energy is restricted to narrow jets of emission (like pulsars).

Hypernova: explosion of a very massive star that leads to the birth of a black hole.

http://imagine.gsfc.nasa.gov/Videos/news/GRBstar2.mov



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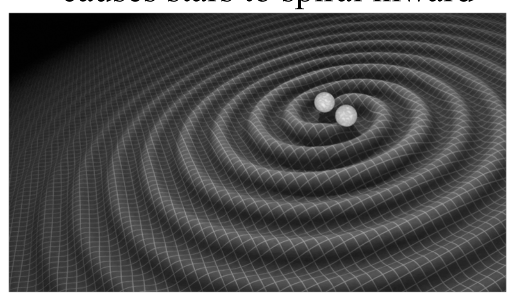
GW in space-time from closely orbiting stars: energy lost in GW causes stars to spiral inward



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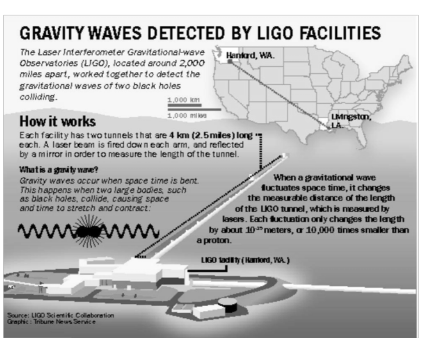
Laser Interferometer Gravitational-wave Observatories



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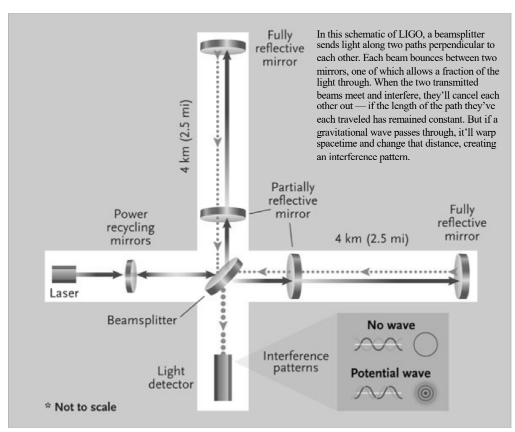

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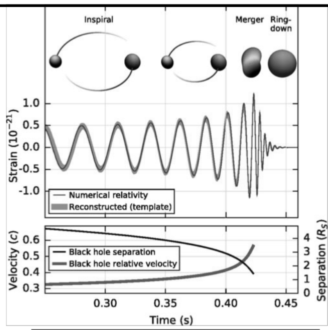

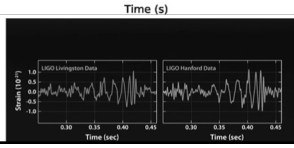

- First detection 2015: 36+29 solar mass BHs combine to make single 62 solar mass BH: 3 solar masses converted to GW energy
- LIGO didn't watch the whole many-year-long dance of the black hole duo, but it did see the last few cycles of the death spiral, the merger itself, and the "ringing" effect as the merged black hole settled into its new form.

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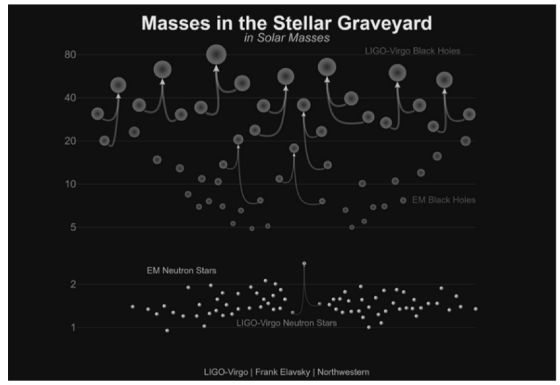

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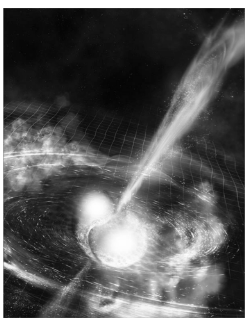
LIGO's 5th detection: NS+NS Merger in 2017



- accompanied by a gamma-ray burst
- optical counterpart found in distant galaxy: "kilonova"
- neutrons liberated create many heavy elements (10x mass of Moon in gold)

https://www.youtube.com/watch?v=x_Akn8fUBeQ

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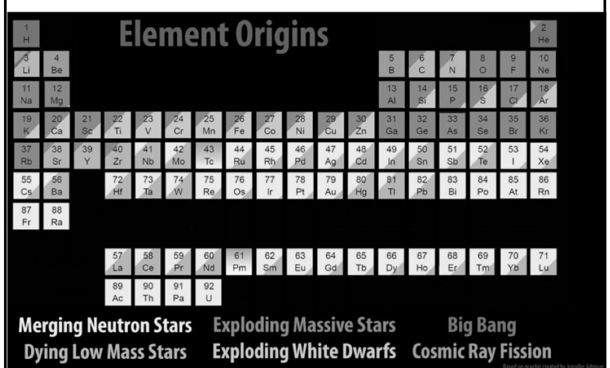

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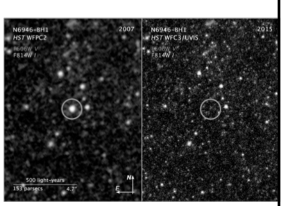
Final Outcomes for Massive Stars

- Identifications of pre-SN stars suggest that they are stars with mass less than 18 solar masses
- A few massive stars seen to disappear without SN
- Stars > 18 solar masses either collapse to form a BH with no SN or a hypernova in some cases



Disappearance of 25 solar mass star

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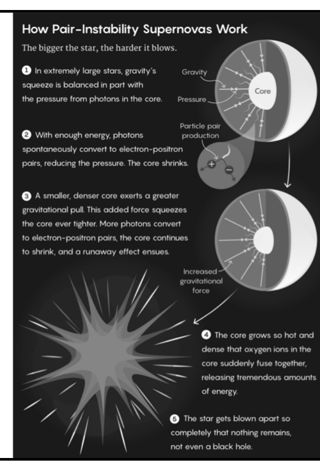
- Very large initial mass M>140 M(Sun) may create a pair-instability supernova that leaves no remnant at all

https://www.quantamagazine.org/long-lived-stellar-blast-kindles-hope-of-a-pair-instability-supernova-20190912/



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Summary of Outcomes by Initial Stellar Mass

- $M < 0.08\ M_{sun}$ Star cools as brown dwarf
- $0.08 < M < 10\ M_{sun}$ White dwarf remnant
- $10 < M < 18\ M_{sun}$ Neutron star remnant
- $18 < M < 140\ M_{sun}$ Black hole remnant
- $M > 140\ M_{sun}$ No remnant

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