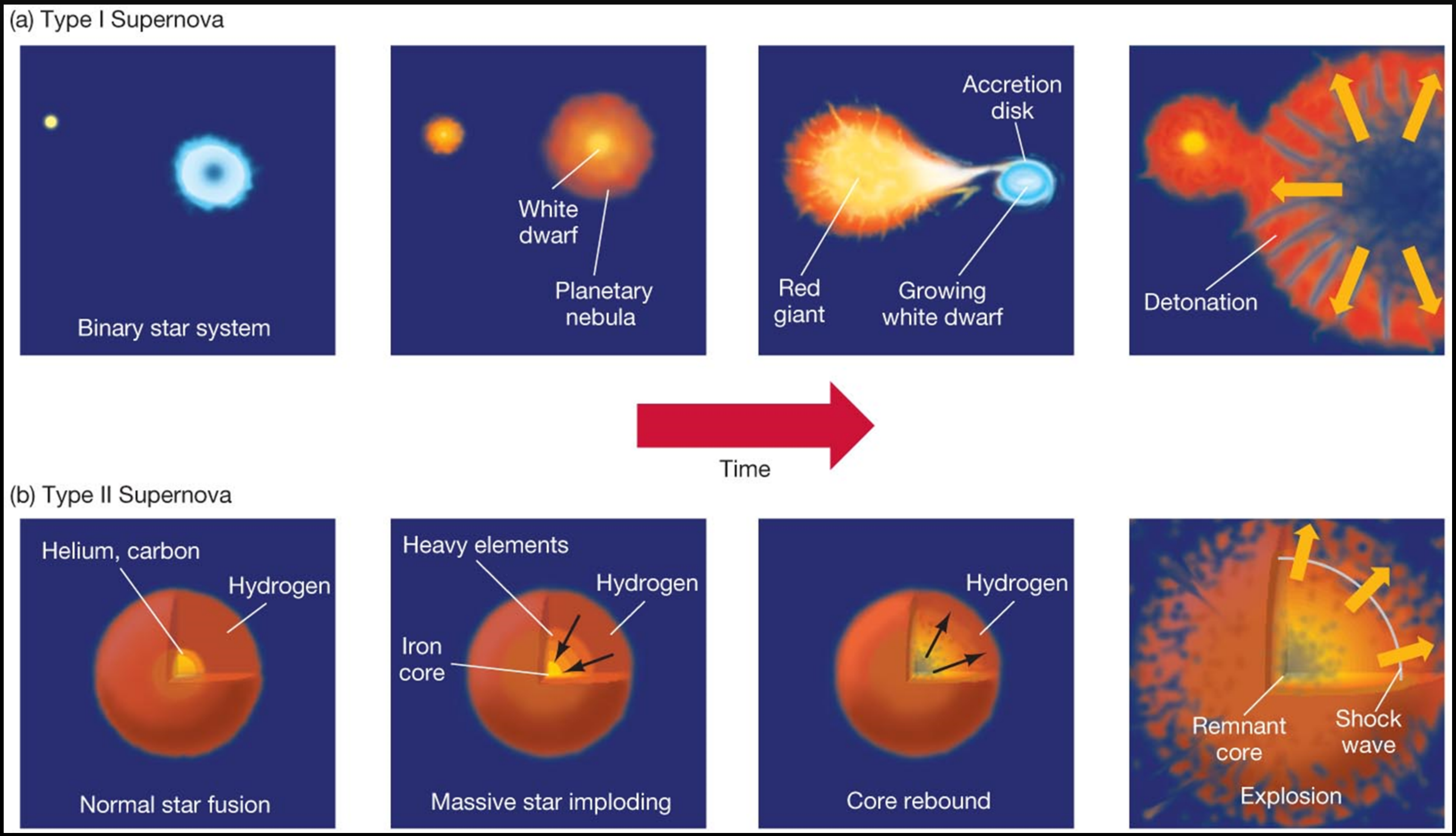
TYPE IA SUPERNOVAE

- What happens when the whole WD gets enough stuff to get so hot its carbon can fuse?
- The whole thing burns up at once
- For a few weeks, more light than a whole galaxy put together
- Called a Supernova
  - Type Ia

TYPE I VS. II

- Originally classified by their spectra
  - Type I, no Hydrogen lines
  - Type II, has Hydrogen lines
- Now we know why:
  - White dwarf has burnt up all its H: burnt out core of an old star
  - Large star has not: atmosphere if large star is still unburnt H

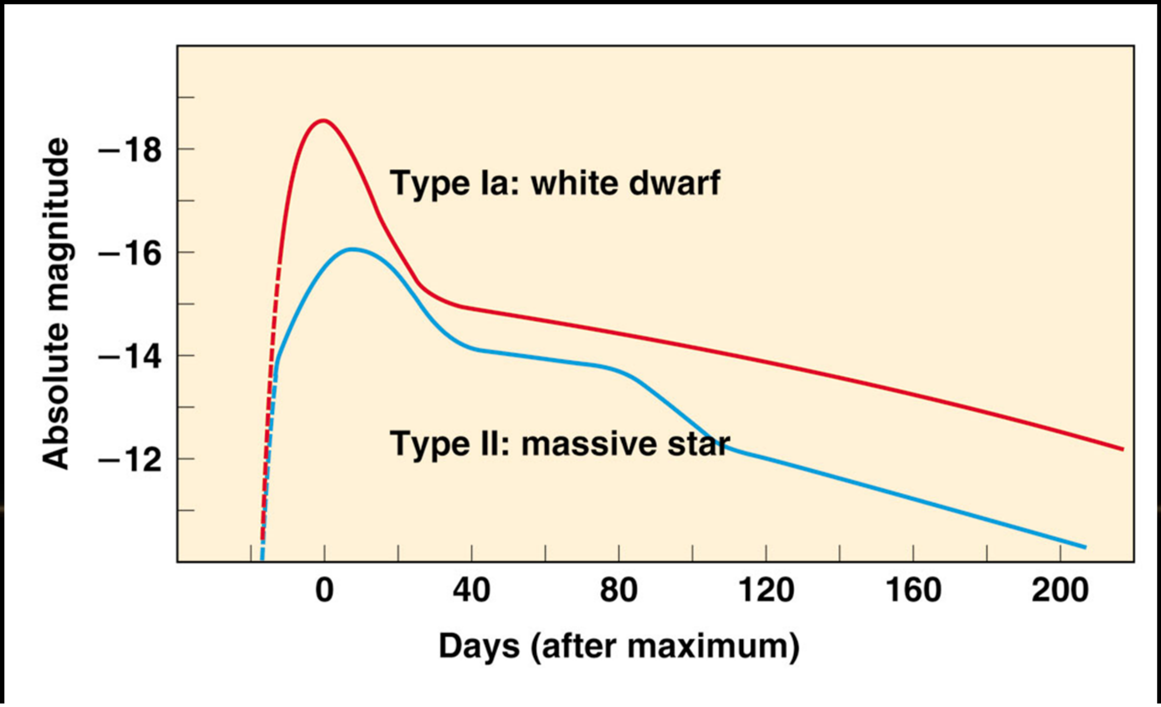
TYPE I VS. II


(a) Type I Supernova
Binary star system
White dwarf
Planetary nebula
Accretion disk
Red giant
Growing white dwarf
Detonation
Time
(b) Type II Supernova
Helium, carbon
Hydrogen
Normal star fusion
Heavy elements
Hydrogen
Iron core
Massive star imploding
Hydrogen
Core rebound
Remnant core
Shock wave
Explosion

TYPE I VS. II

- Other observed differences
- Brightness vs. time
  - Type I brighter, -19 M, sharper peak, all very similar
  - Type II dimmer, -17 M, broader peak, more varied

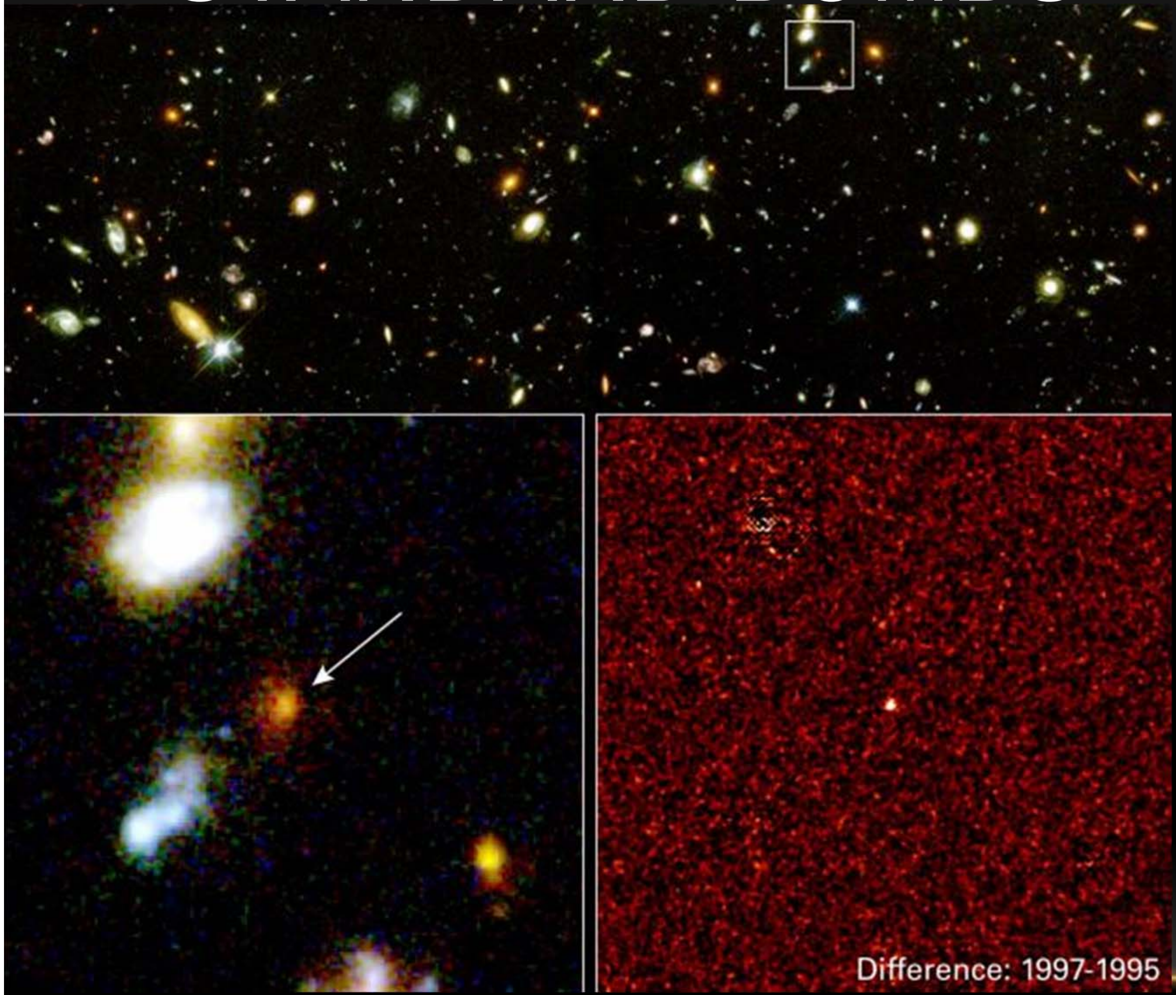
Sne
"Light Curves"



MASS EJECTION

- Type I
  - Bits of white dwarf blown into space
  - Only 0.5 $M_{\odot}$, of mostly heavy elements
  - Thrown out fast – 10,000 km/s
- Type II
  - Outer layers of a large star blown off
  - 5 $M_{\odot}$ ejected, mostly H, He
  - More stuff harder to move, only travels 5,000 km/s

STANDARD BOMBS



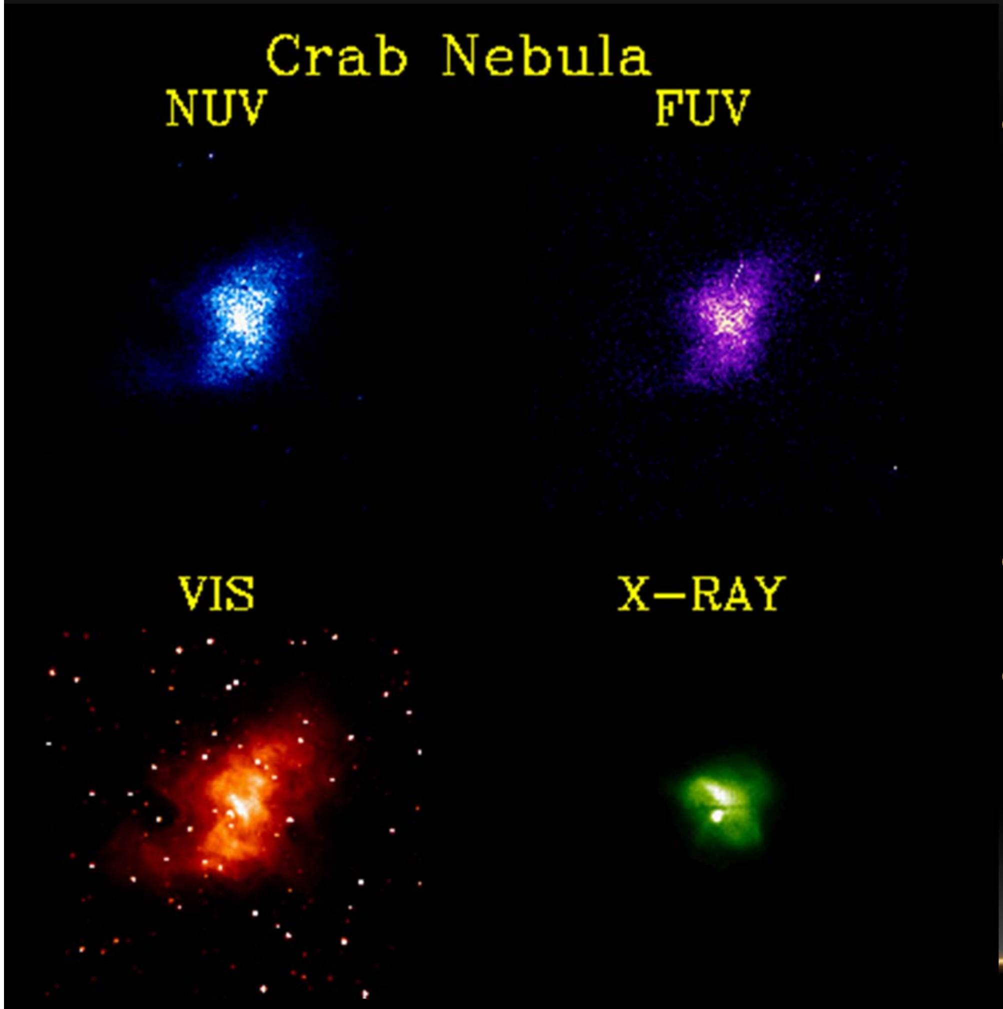
- These always involve WD's close to the Chandrasekar limit (1.4 $M_\odot$)
- So explode with about the same energy
- We know the real brightness, we can find the distance
- SN visible from a long way away

Photo by Adam Riess et al with HST

NOVA OR SUPERNOVA?

- Supernovae are MUCH MUCH more luminous than novae (about 10 million times)!!!
- Nova: H to He fusion of a layer of accreted matter; white dwarf left intact
- Supernova: complete explosion of white dwarf; nothing left behind

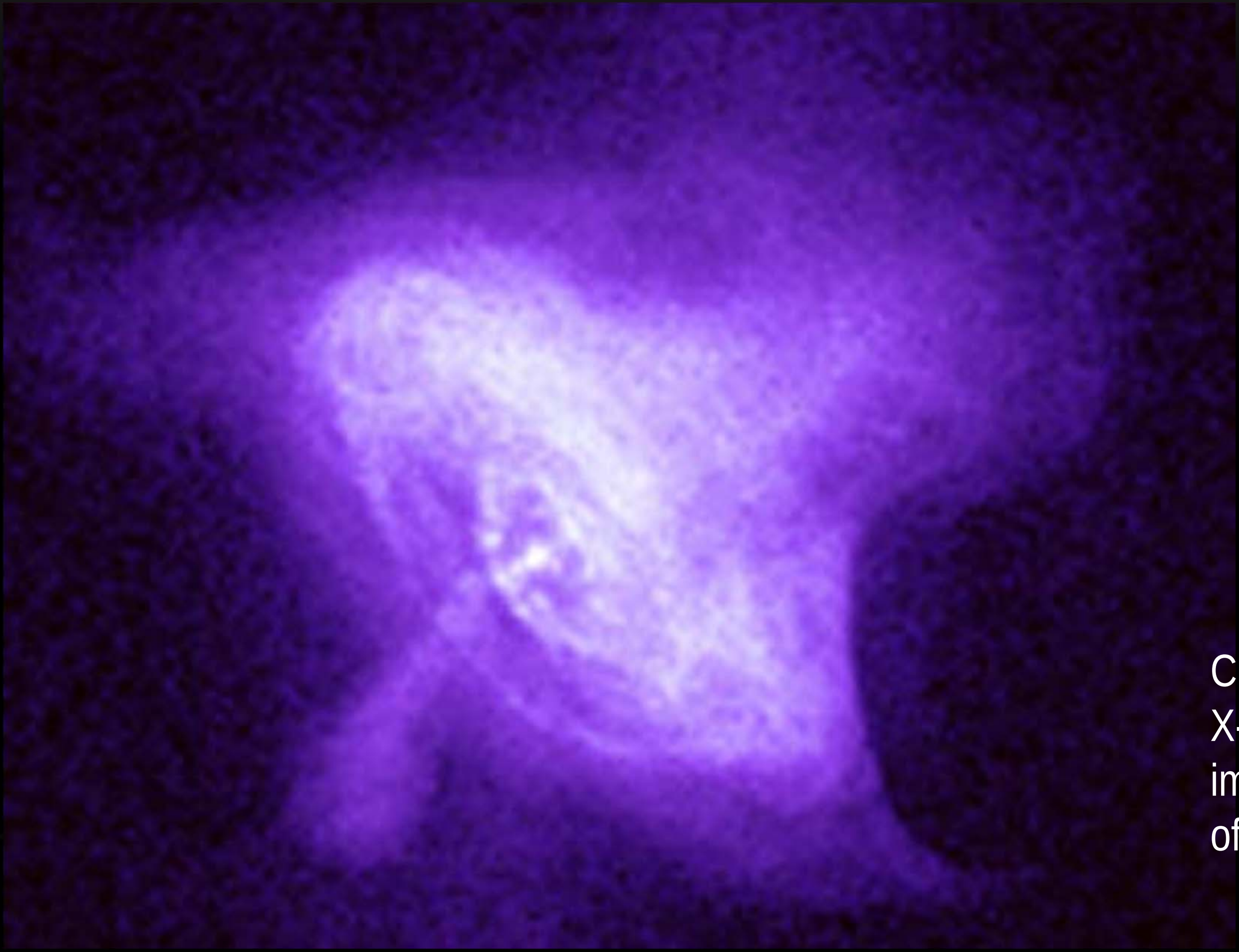
HOW ABOUT THE CORE OF A TYPE II SN?



Images by G. Hennessy, USNO

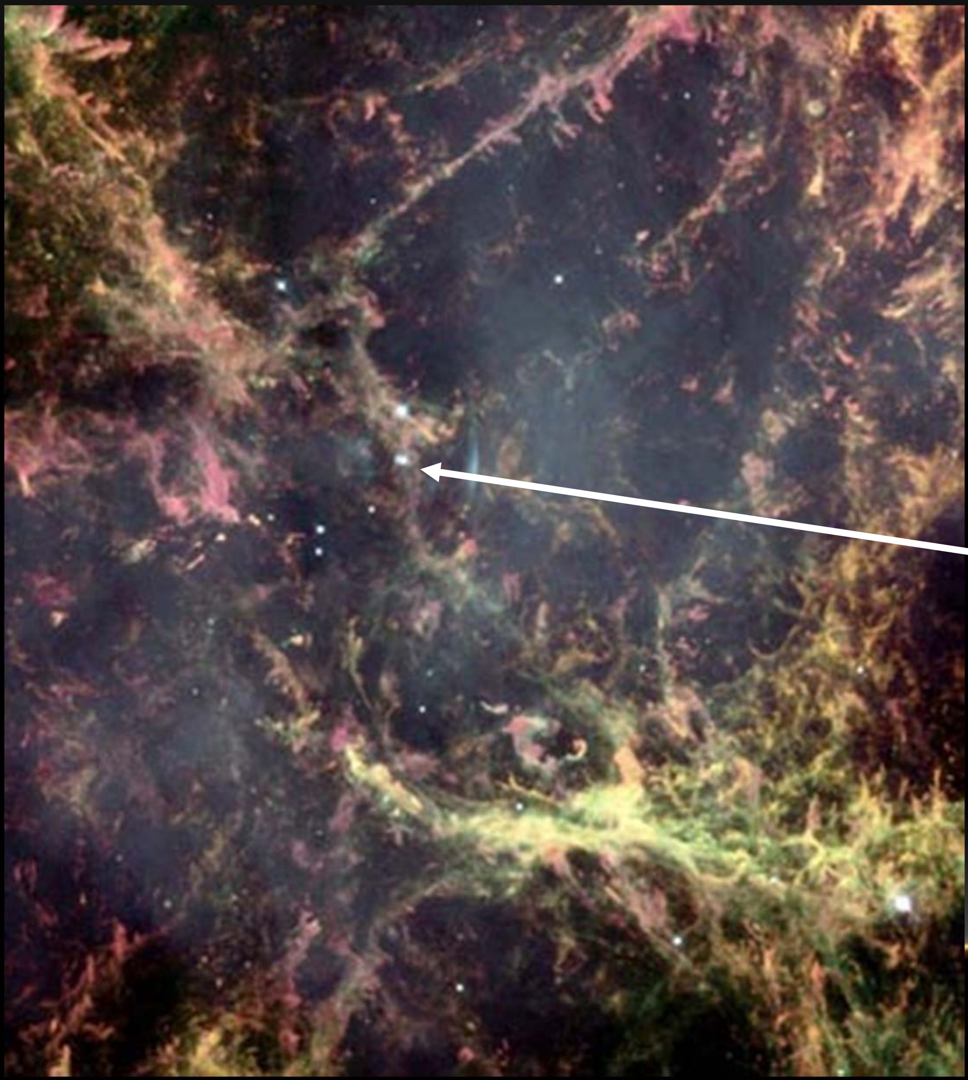
- While a type I blows about the white dwarf, a type II was caused by the collapse of the core to a neutron star
- Do we see these?
- We see something hot and energetic powering the nebula

CLOSE UP IN X-RAYS



Chandra
X-ray
image
of Crab

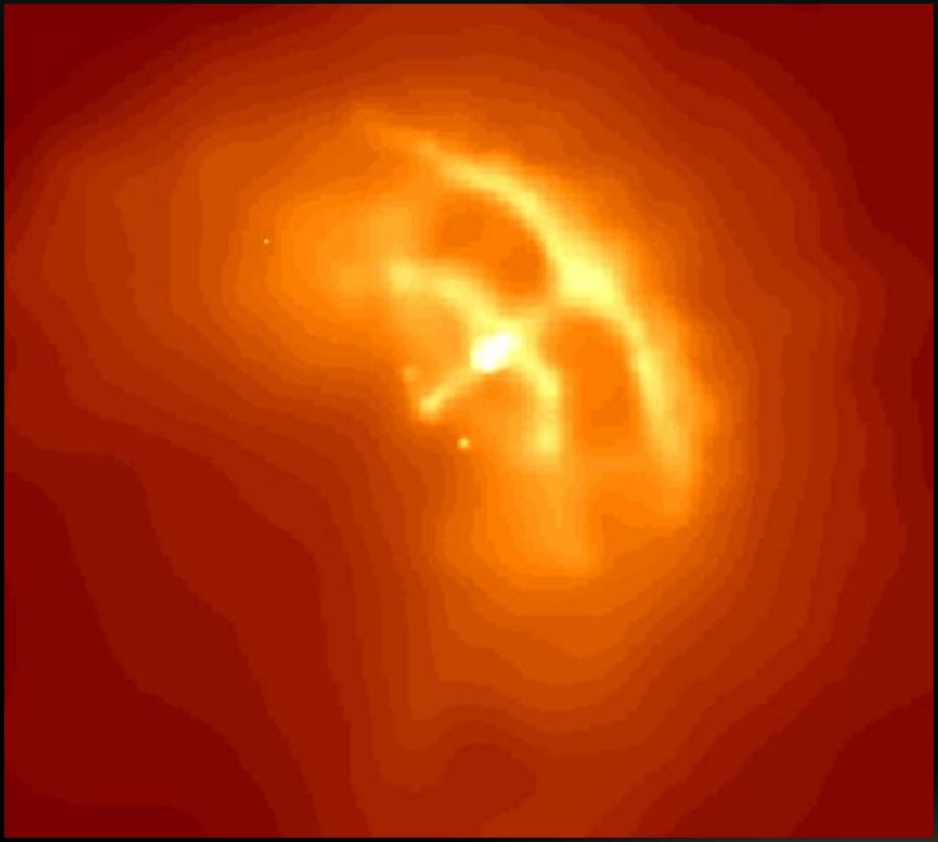
CLOSE UP IN OPTICAL



- The new neutron star in the Crab can be identified
- Behind the streamers of gas, here

William P. Blair *et al*
with HST

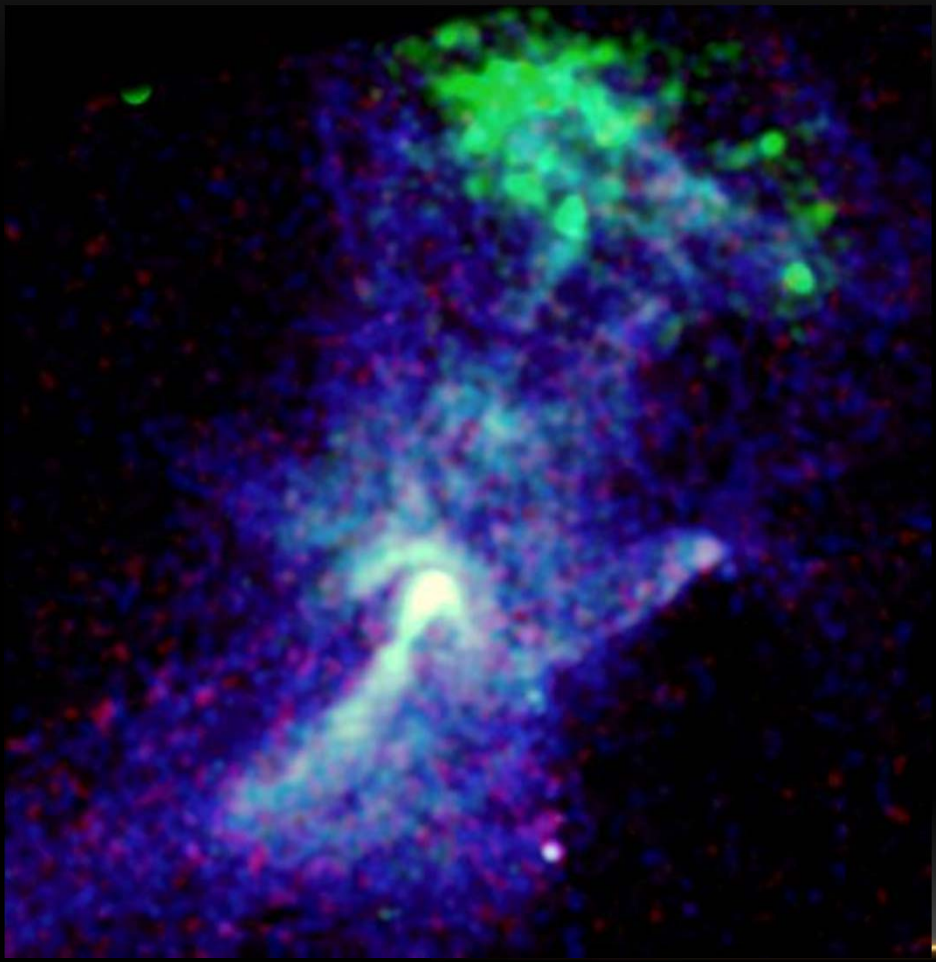
ALSO IN VELA



- Close-up of Vela neutron star shows it moving through the nebula
- Note bow shocks
- If the SN explosion is a little off-center, the neutron star will really get kicked around and fly off with 100’s of km/sec

G.Garmire *et al* with
Chandra X-Ray Obs.

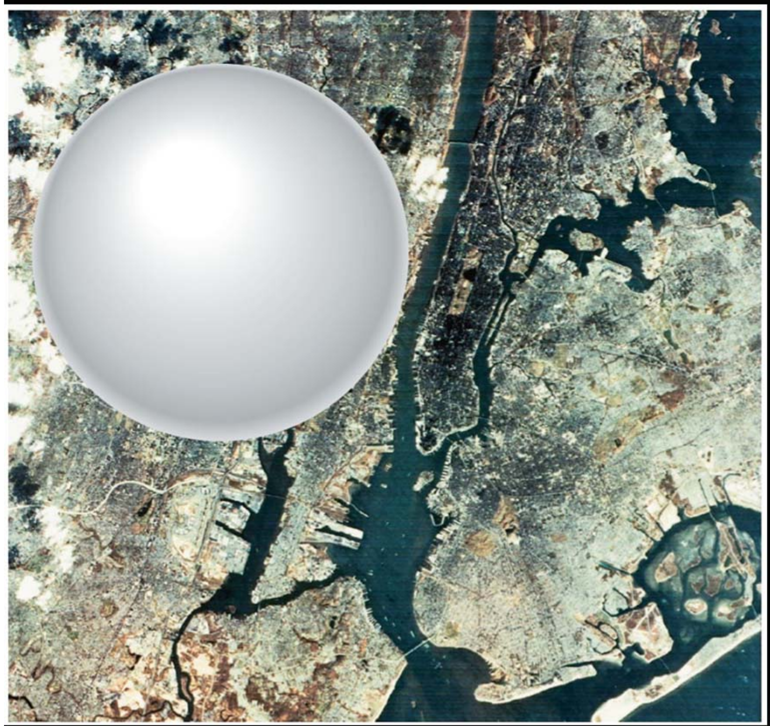
NEUTRON STARS?



Circinus Pulsar, Chandra X-ray image by B. Gaensler *et al*, MIT

- Gravity compresses the electrons into the nucleus when the mass exceeds the Chandrasekhar Limit (~$1.4M_{\odot}$)
  - Protons plus electrons make neutrons
  - A star of the density of the nuclei of atoms!
- More than 1.4 $M_{\odot}$ packed into the size of Duluth or a small asteroid
  - 10^{15} g/cm^3
  - 10 million K
- Note shocks, jets to left

HOW DO WE KNOW THE SIZE?

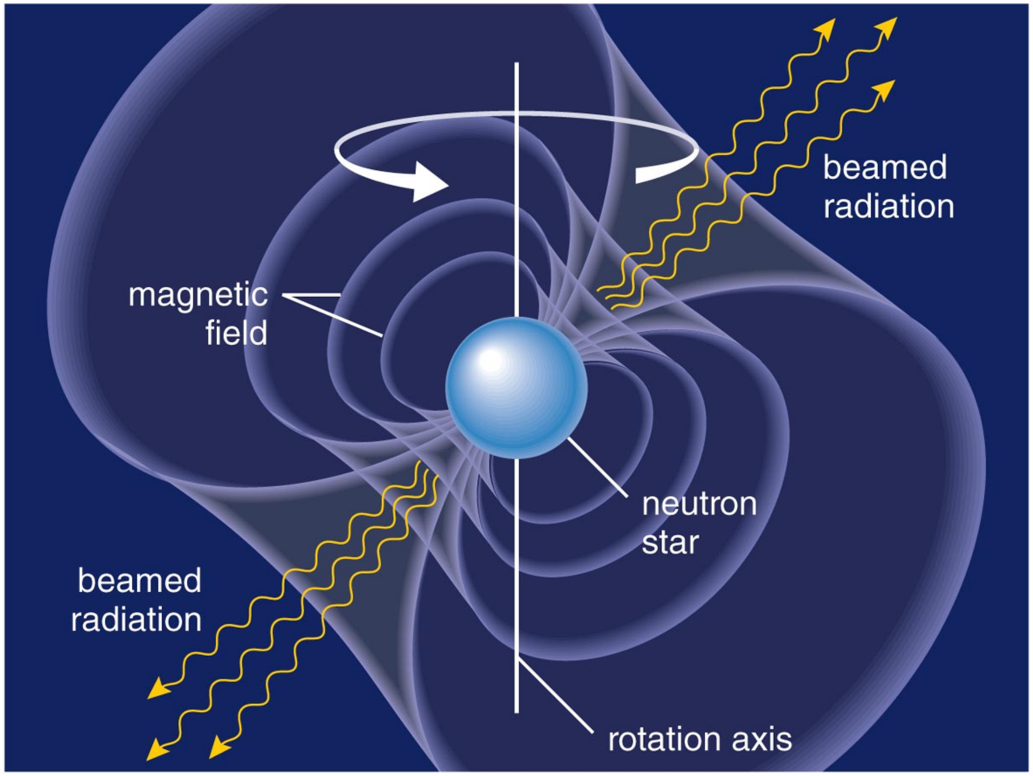


- These neutron stars change in brightness in 1/1000 seconds
- If it changes brightness that fast, it must have a diameter of less than a 1/1000 of a light second or so
- Larger sizes – one side would still be turning on or when the first side was already on, it would take longer for the whole thing to blink

SPINNING RAPIDLY

- Shrink something spinning and big into something small
  - Spins up really fast!
  - Rotates in seconds or less
  - Conservation of angular momentum, just like ice skater
- Also compress star’s magnetic field
  - Now have millions of times the Sun’s magnetic field

PULSARS

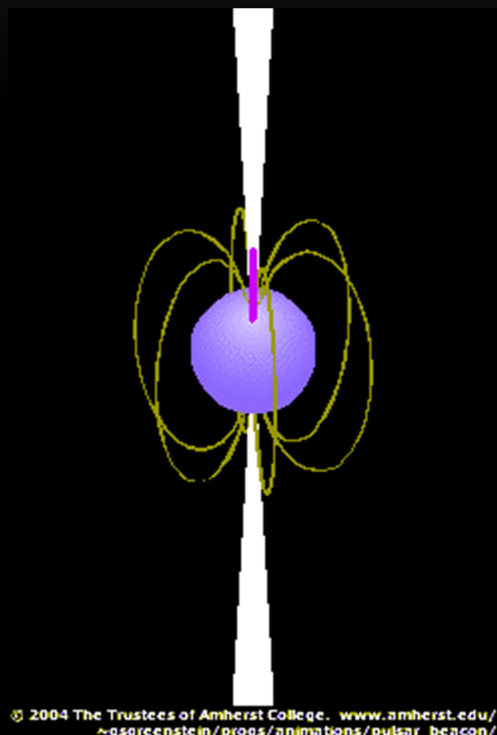


a A pulsar is a rotating neutron star that beams radiation along its magnetic axis.

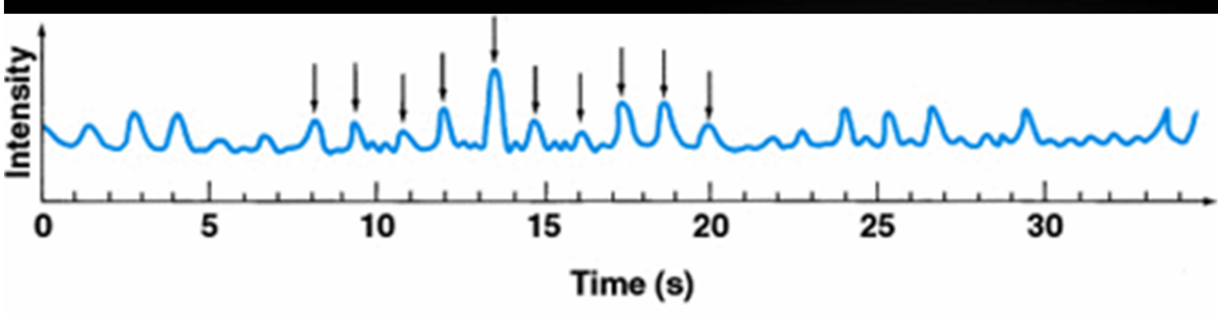
- Neutron stars spin fast
- Have a strong magnetic field
- Radiation travels along the magnetic field lines
- So comes out the poles
- Get twin beams of radiation sweeping around like a lighthouse

Fig.14.9a

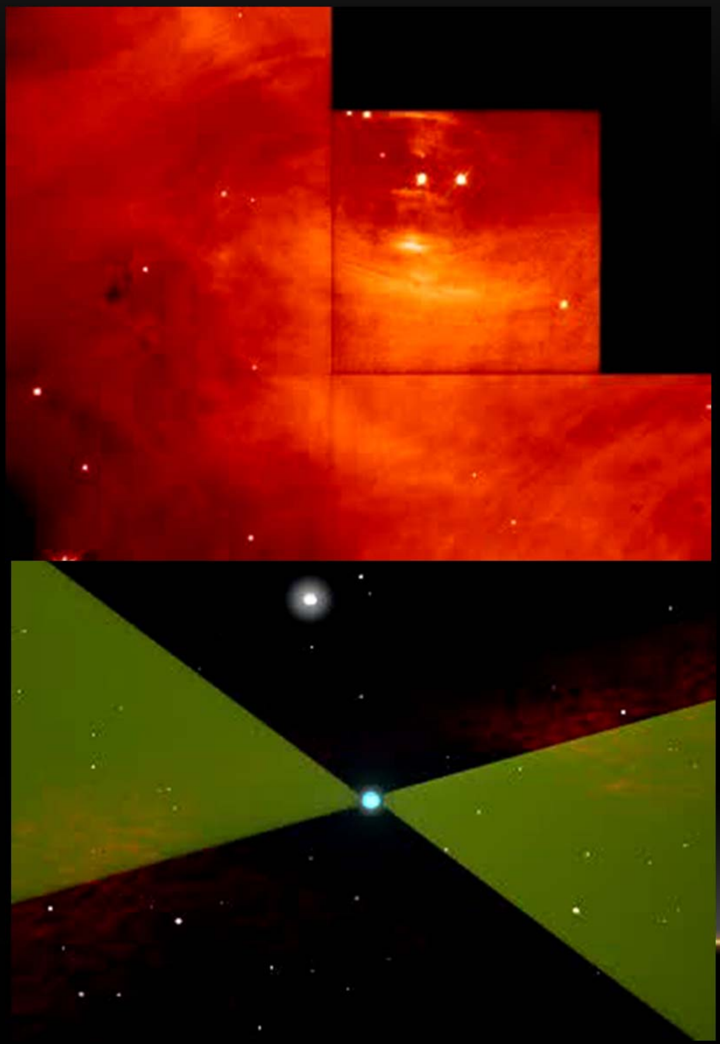
WHY PULSARS BLINK



- As the beam of energy coming out the magnetic pole sweeps by, we see a flash
  - Usually in the radio, but has been seen all across the spectrum

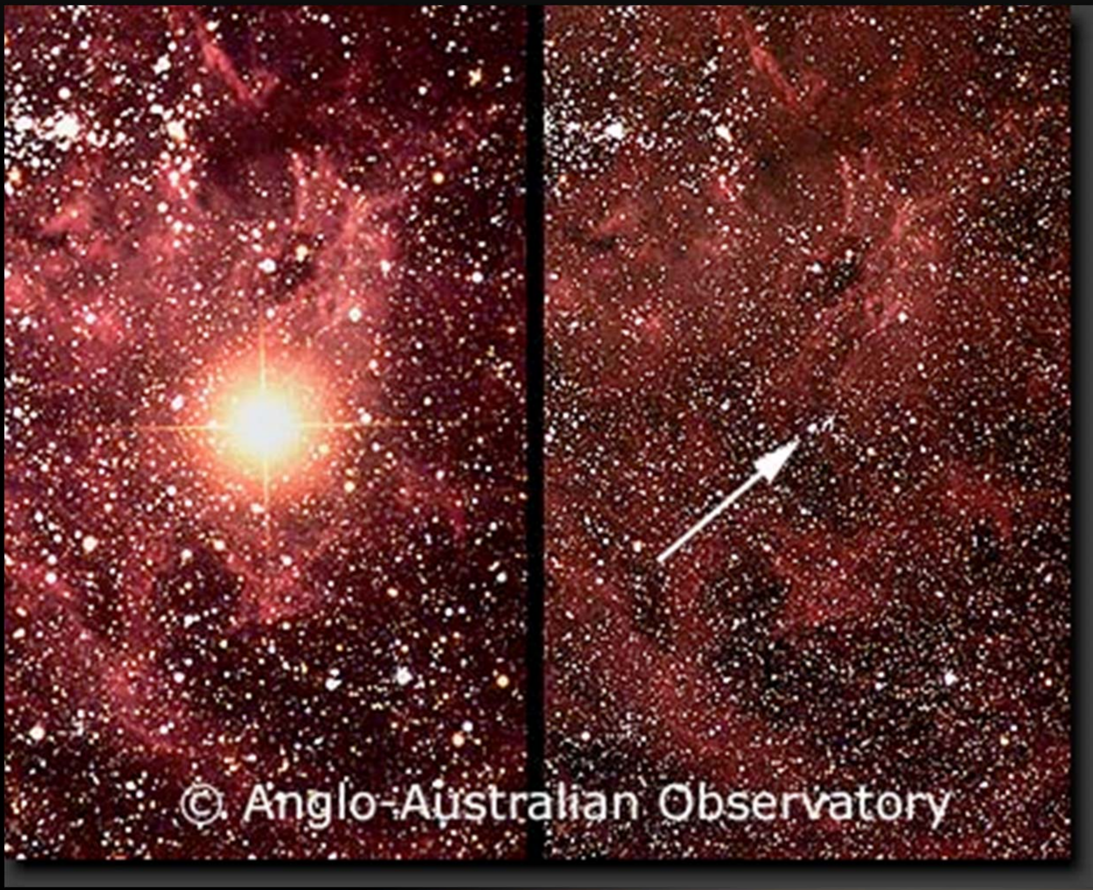


THE CRAB REALLY CLOSE UP



- Movie keeps zooming in
- Can see ripples of material headed away from pulsar at ½ the speed of light
- Mysterious “halo”
- Polar jets
- “Sprite” – shock front in a jet

SN1987A



- SNe get named by year, then sequentially by letter
- In Feb. 1987, a blue giant in the nearby Large Magellenic Cloud

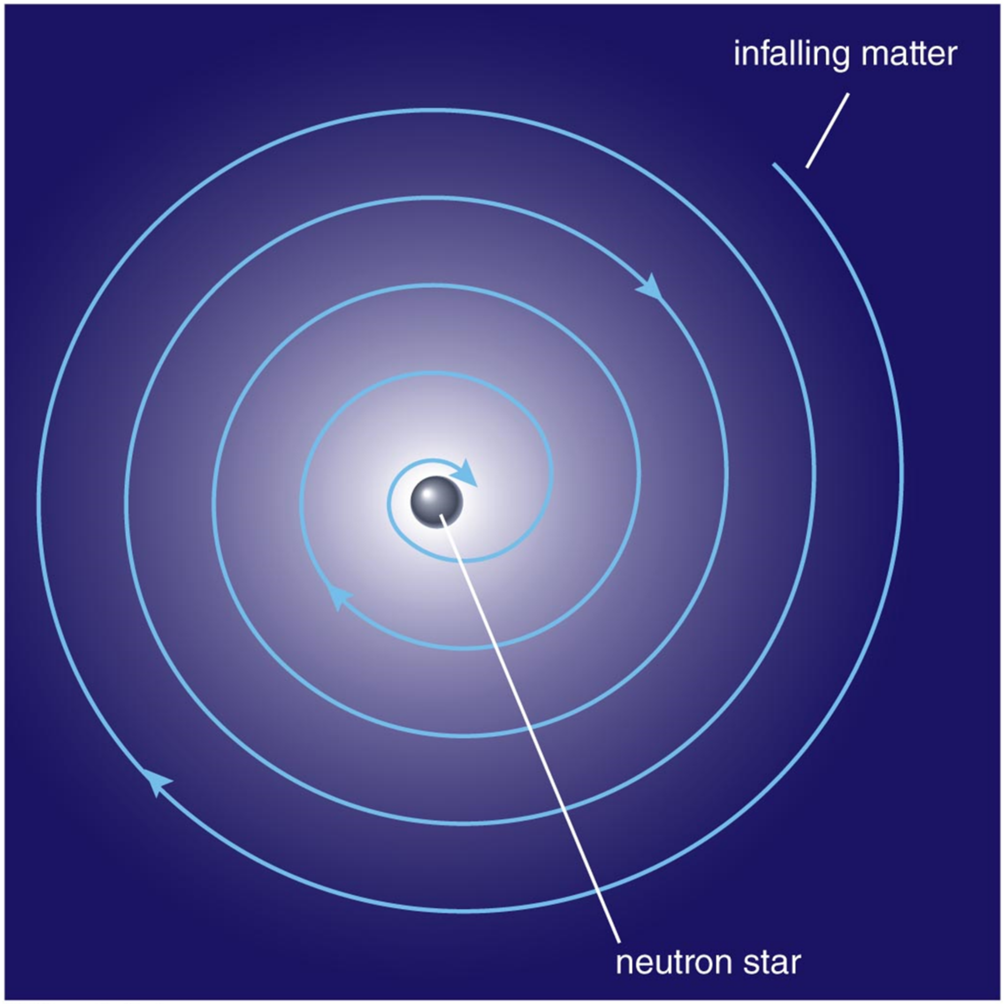
SN1987A

Blue Giant
SK -69 202

PULSAR IN SN1987A?

- In 1989, people thought they saw one:
  - 1968.629 Hz (0.0005 s per rotation) - Very fast!
  - Went away
- Many theories tried to explain things…
  - Turned out that a video camera in the observatory sometimes made electronic noise at 1968.629 Hz (Oops!)
- Still looking
  - Might not be there (black hole?)
  - Might be behind nebulosity
  - Might be beaming in a different direction

PULSARS IN BINARY SYSTEMS?



Same idea as with white dwarfs: infalling matter makes an accretion disk, friction decays the orbits and makes it spiral in

- Can either speed up or slow down the pulsar, depending on if it winds it up or winds it down

Fig.14.10

X-RAY BURSTS

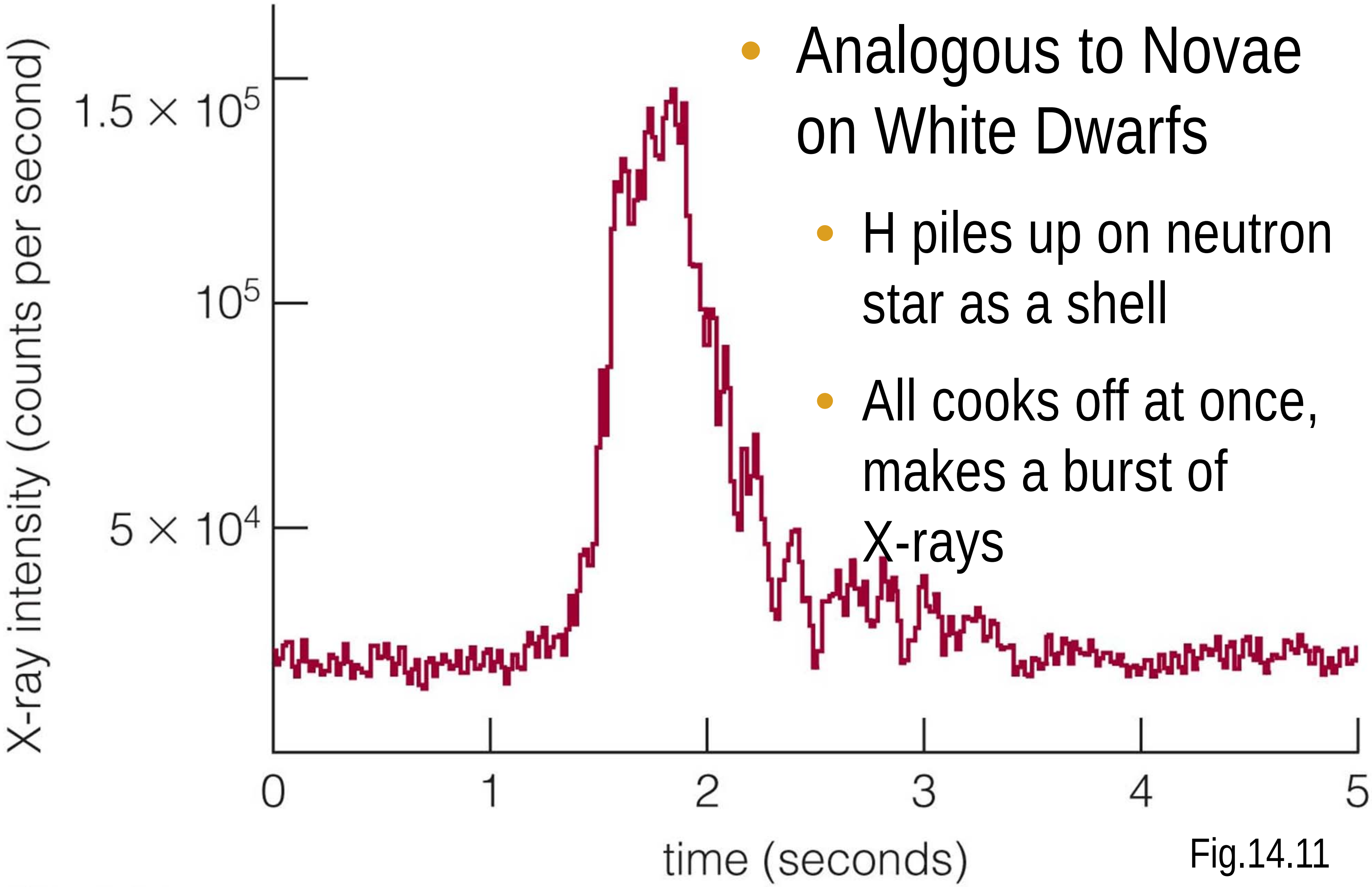
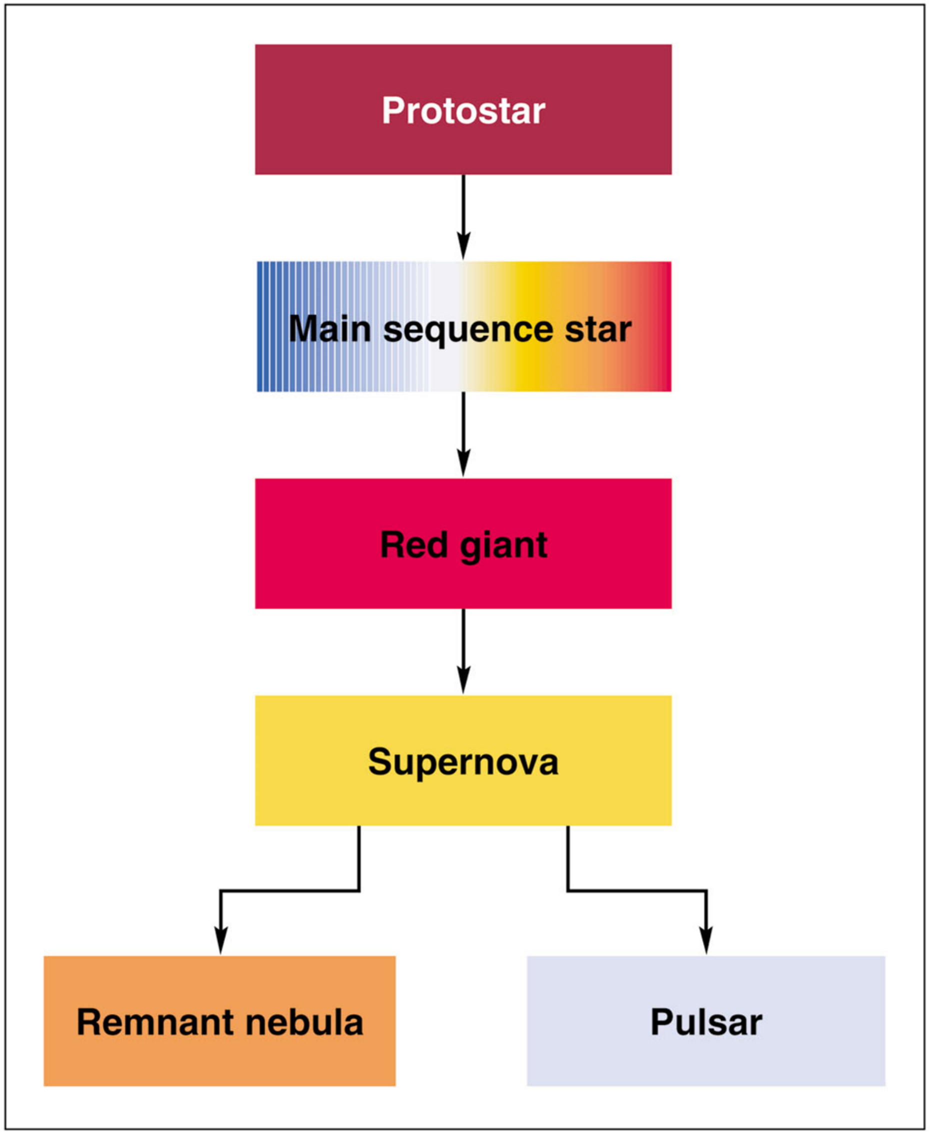


Fig.14.11

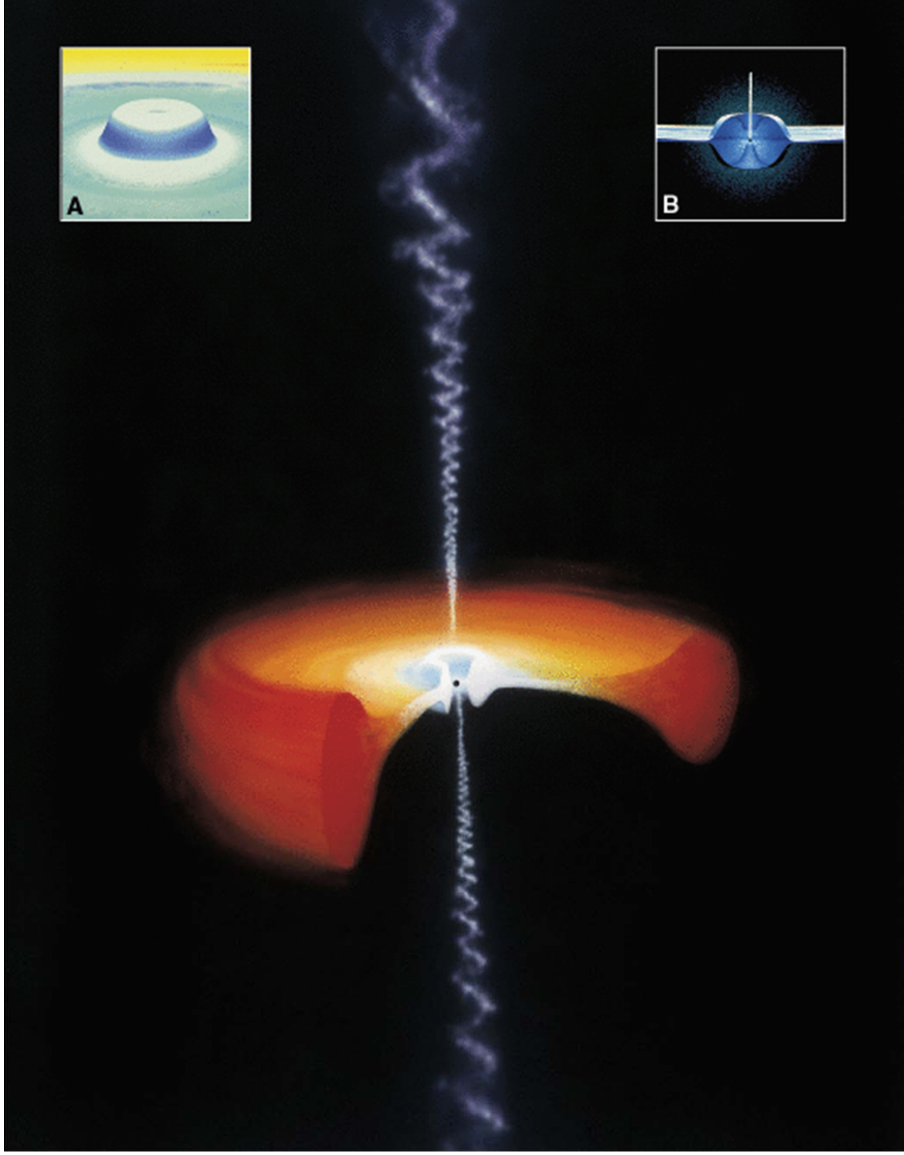
- Analogous to Novae on White Dwarfs
  - H piles up on neutron star as a shell
  - All cooks off at once, makes a burst of X-rays

LIFE OF A MASSIVE STAR



- A star of more than $4M_{\odot}$ will:
  - Collapse from a gas cloud into a protostar quickly
  - Burn brightly on the main sequence for only 100 million years or so
  - Become a red supergiant as heavier and heavier elements are fused in its core
  - Undergo core collapse and become a supernova
  - A remnant nebula and a pulsar will be left

ABOVE 20-25 $M_{\odot}$?



- So much gravity even the strong nuclear forces cannot hold up all that weight
  - If leftover core is greater than about 3 $M_{\odot}$
- Neutron star collapses to a Black Hole

In 1905

In the 1950's

ALBERT EINSTEIN

- German Physicist, early 1900's
- Work helped to lay the foundations of quantum mechanics
- "Relativity" theories are very important to our understanding the cosmos
  - Special
  - General

SPECIAL RELATIVITY

Observers moving left or right

Still see light going 186,000 mi/sec!

- Two “postulates” or assumptions:
  1. The laws of physics are the same for different (non-accelerating) observers, no matter what their speed
  2. The speed of light is the same for everyone, no matter what their motion is compared to the source of the light

CONSEQUENCES

Stopped

Moving

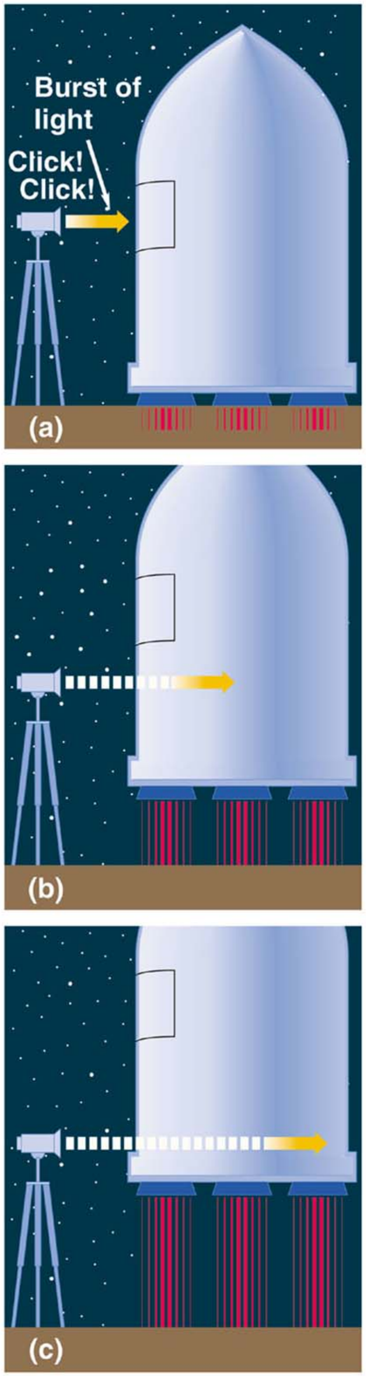
Normal clock

Slow clock

- If this hypothesis is true, the predictions are:
  - Clocks on Moving things run more slowly
  - Moving thing get shrunk in the direction of motion
- We don't notices this at our slow speeds, but near the speed of light (186,000 mi/sec), all experiments have verified it

GENERAL RELATIVITY

- Deals with accelerating views
- Principle of Equivalence
  - You can't tell the effect of acceleration from the effects of gravity
- Is the ball falling down at 9.8 m/s^2
  - Because of gravity?
  - Or because we're in a rocket accelerating upwards at that speed?
  - Can't tell!

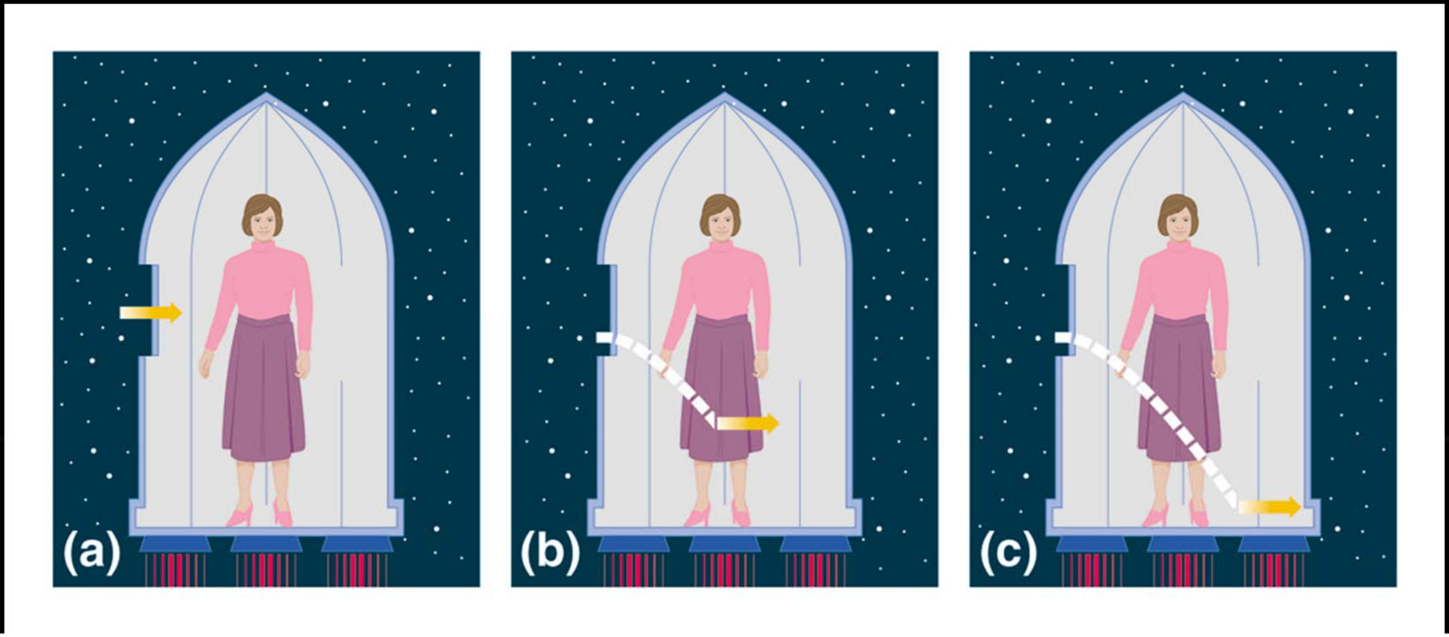


WORKS ON LIGHT, TOO

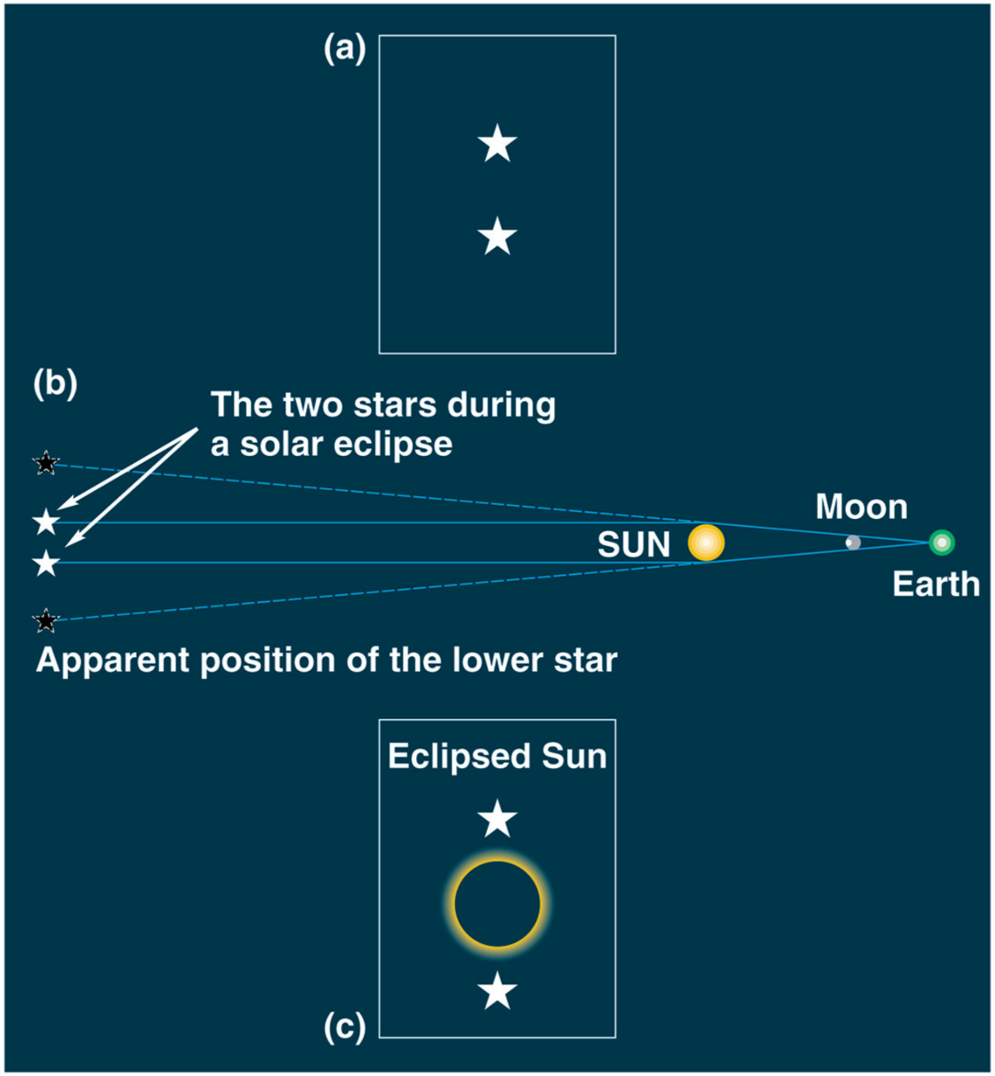
- Here the light beam goes straight across into the spaceship
- But the ship is going up quickly enough that the light is hit by the floor before reaching the other side

CURVED LIGHT?

- The person in the spaceship sees the light curve down and hit the floor
- The acceleration made the light curve!

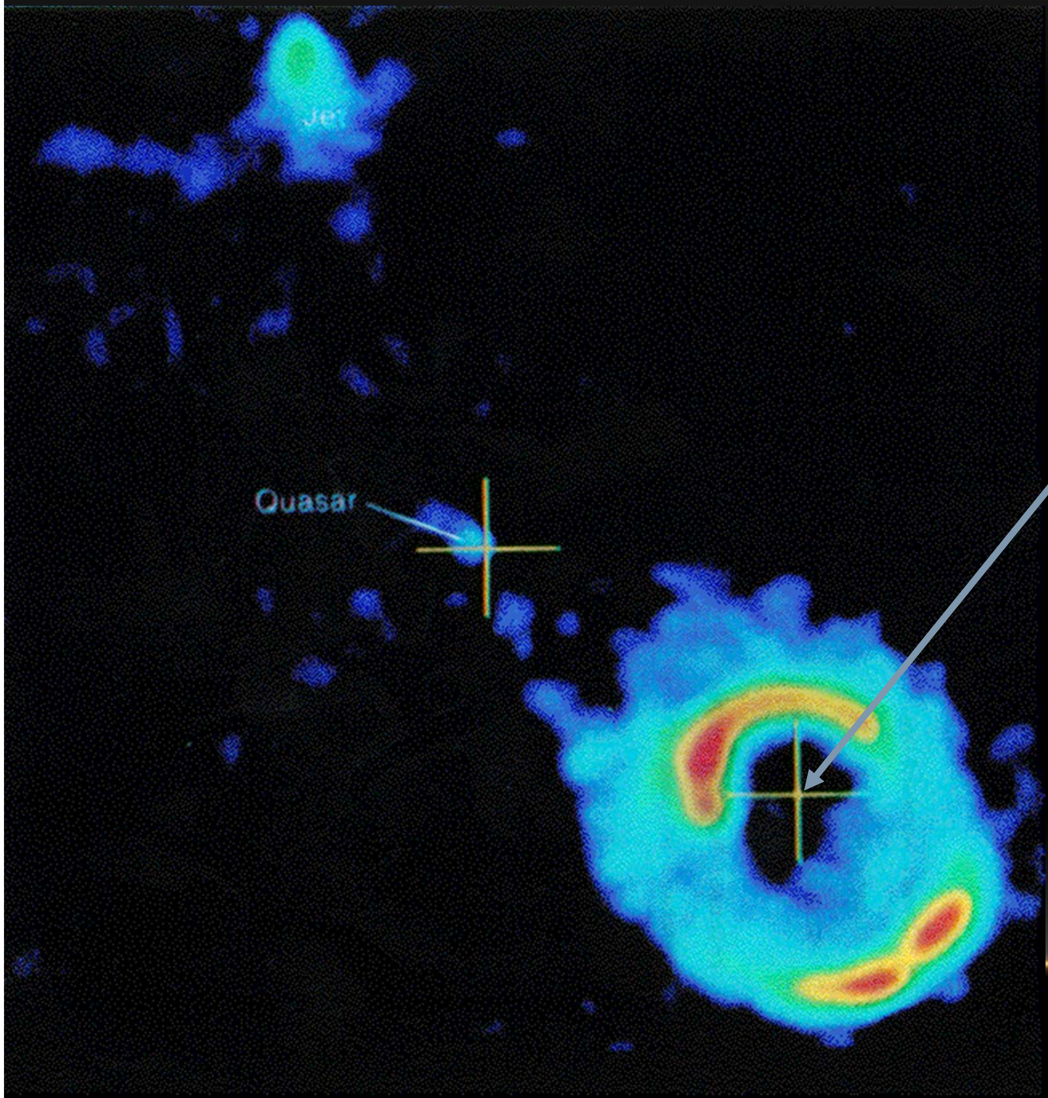


THIS REALLY HAPPENS



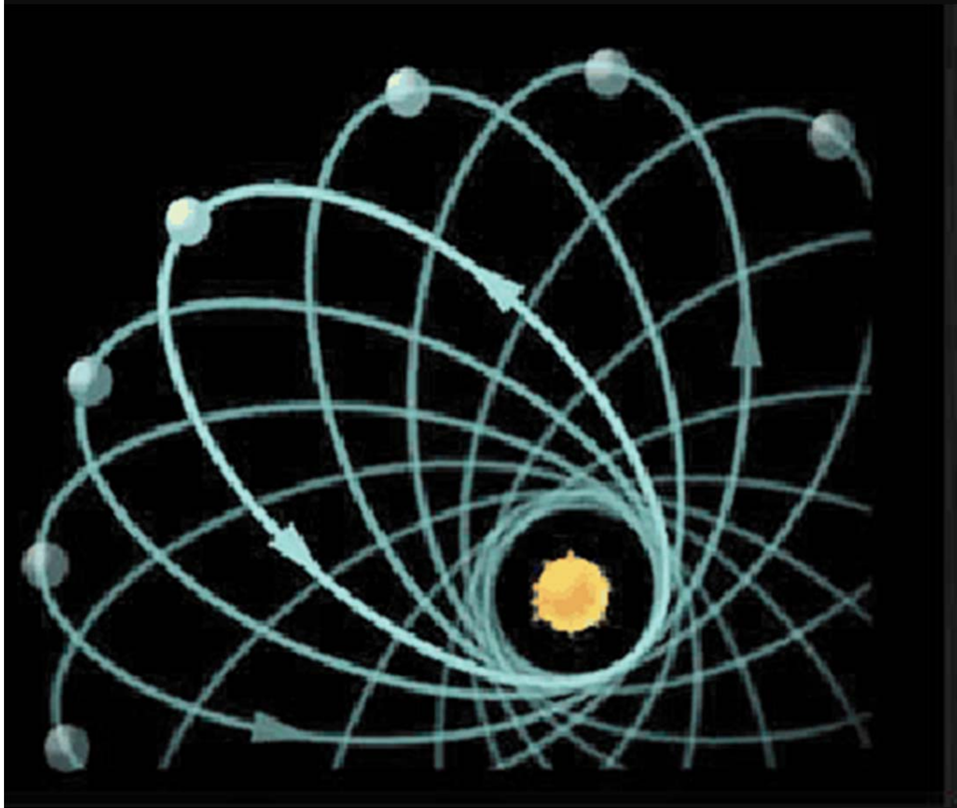
- The acceleration of the Sun's gravity also bends light
- Light rays from two stars bent around Sun
  - Observed during eclipse so the stars can be seen without the Sun's glare
  - Appear more separated than they should

AN EINSTEIN RING



- A radio telescope picture of a light from a distant Quasar jet being bent into a ring
- Something big, dark, and heavy is bending the light
- This one is known as MG 1654+1346
  - image by Glen Langston using a radio telescope called the Very Large Array

G.R. ALSO PREDICTS:

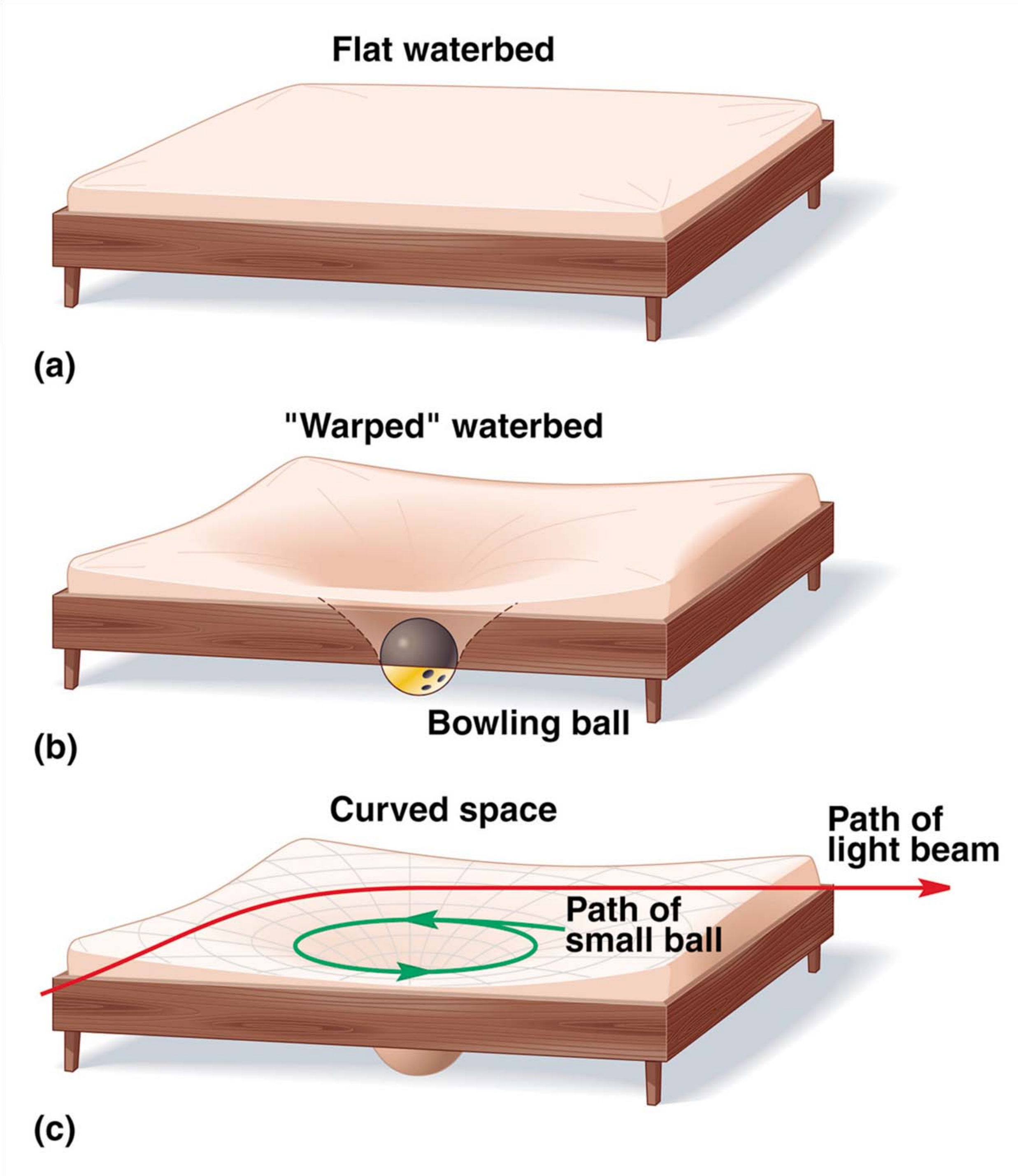


531 of 574 arcseconds due to other planets
The remaining 43 predicted by GR

- That Mercury's orbit precesses due to strong gravity of Sun
  - This is a small effect from Einstein not present in Newton's gravity
- As well as that light can be bent by gravity
- Both have been observed!

BEYOND NEWTON

- The consequence of this hypothesis:
  - Gravity explained as the warping of space caused by mass
    - Bigger mass, bigger warp, more gravity
- Newton’s model not perfect
  - Einstein corrects and further explains Newton’s gravity with General Relativity



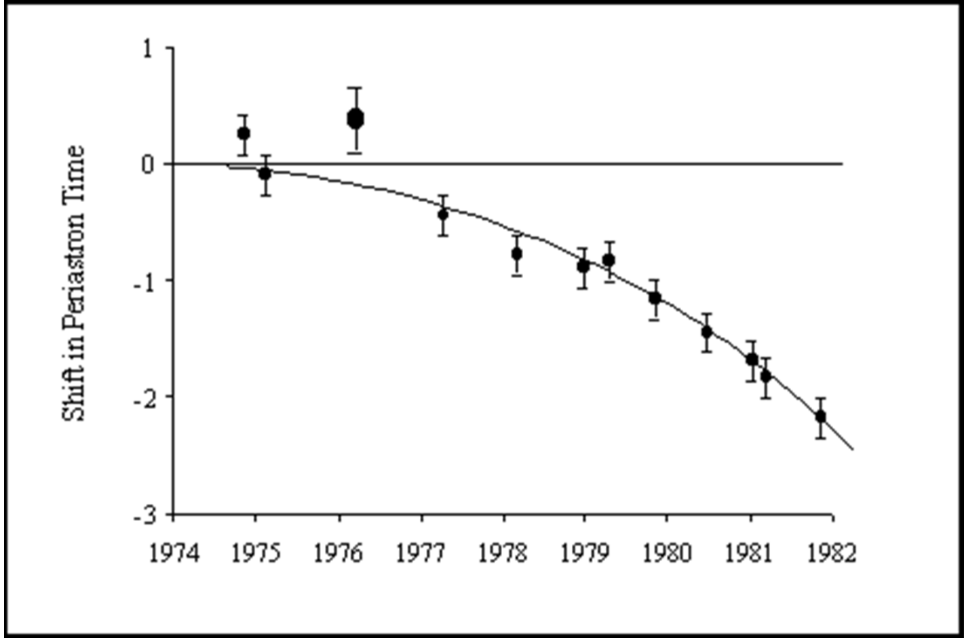
SPACETIME WARPED?

- Imagine space is a rubber sheet
- Big things bend it
- Light travels along the sheet

GRAVITY WAVES

- Massive things bend space and curve light
- Massive things moving make ripples in space
  - "Gravity Waves"
- Rare but useful binary pulsars show evidence of this
- Two very massive, compact, and rapidly orbiting things make quite the gravitational splash

INDIRECT OBSERVATIONS



- Making waves takes energy
- The energy is removed from the orbits of the NS's
- The NS's get closer together
  - Faster orbit
  - Orbit shifts by 76 ms/year
  - Matches GR calculations!
- A similar (but much smaller) effect observed with Mercury's orbit

1993 Nobel prize for Hulse & Taylor for this discovery

DIRECT OBSERVATIONS

- Laser Interferometer Gravitational-Wave Observatory (LIGO) will look directly for them
- Two 4 km long arms
- Two sites (Hanford, WA & Livingston, LA)
- Each can detect grav. waves changing their size 1/1000 of the diameter of the nucleus of an atom
- Saw the first one Sept. 14 2015!
  - And won the Nobel Prize for it last month

GRAVITY AND ESCAPE VELOCITY

$$a = G\frac{M}{r^2}$$

$$v_e = \sqrt{\frac{2GM}{r}}$$

- Gravitational acceleration gets Really Big as you get closer to a lot of mass
- Escape Velocity v_e
  - How fast you have to go to get away from something
  - Gets Really Big if *M* is big and *r* is small

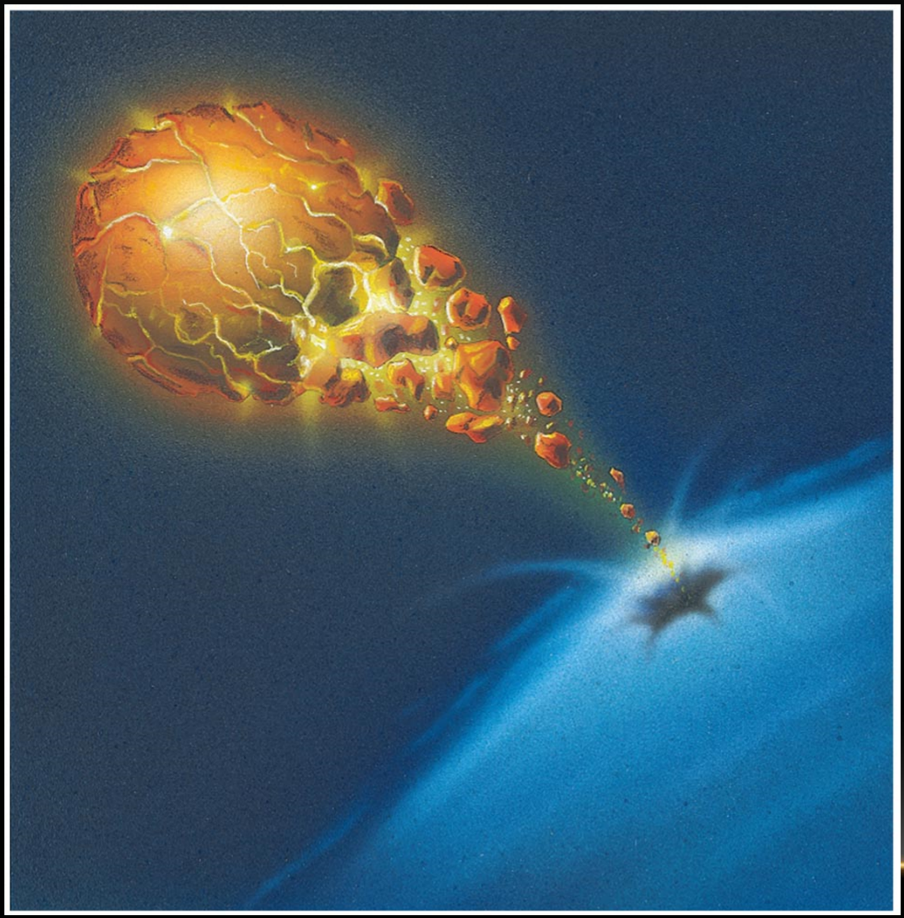
PLAY

SCHWARZSCHILD RADIUS

- How small can r get before v_e is equal to the speed of light?
  - $R_s = 3M$ (in km if M is in solar masses)
  - So need to get a Sun's worth of mass into a 3 km sized ball!
- If the acceleration is so large, then the beam of light falls back in
  - We can't see in
  - Also called the "Event Horizon" – a horizon beyond which we can't see

PLAY

DON'T PLAY TOO CLOSE…



- What would happen if you sent near?
  - Spaghettification!
  - Strong tidal forces

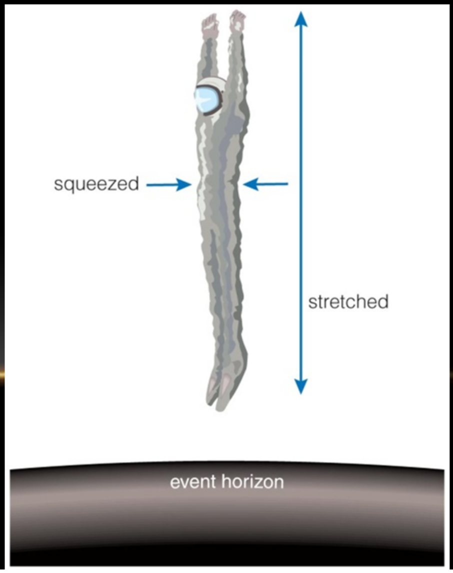
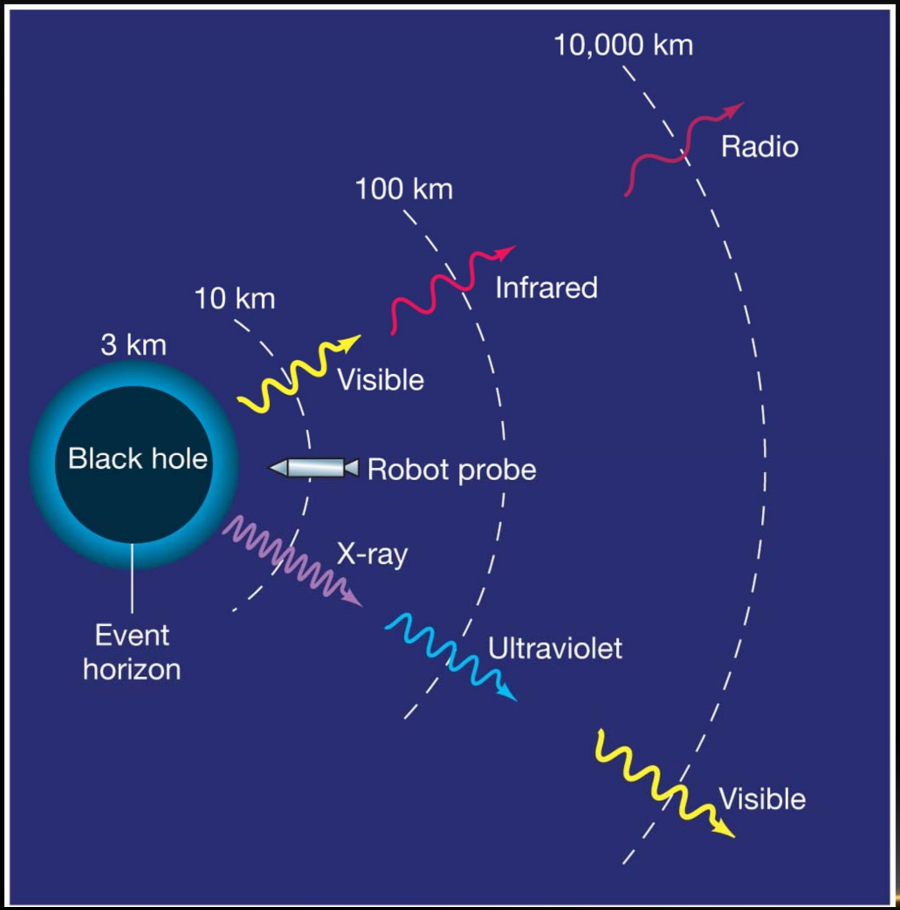


Fig.14.14

ALSO SPACETIME IS REALLY WARPED



- Time clock slows down for someone in a strong gravitational field
- So light made down there appears to us as a lower frequency
  - Gravitational redshift
  - We see this happening

HOW CAN THIS HAPPEN?

- Take one Really Big Star (> 20 $M_\odot$ or so)
- Big stars go Supernova, exploding as their cores collapse into neutron stars
  - Pile more stuff onto the neutron star
  - Gravity gets ever stronger with more mass
  - Eventually (M > 3 $M_\odot$ or so) crushes the star into a size less than the Schwarzschild Radius
- Forms a "Black Hole"

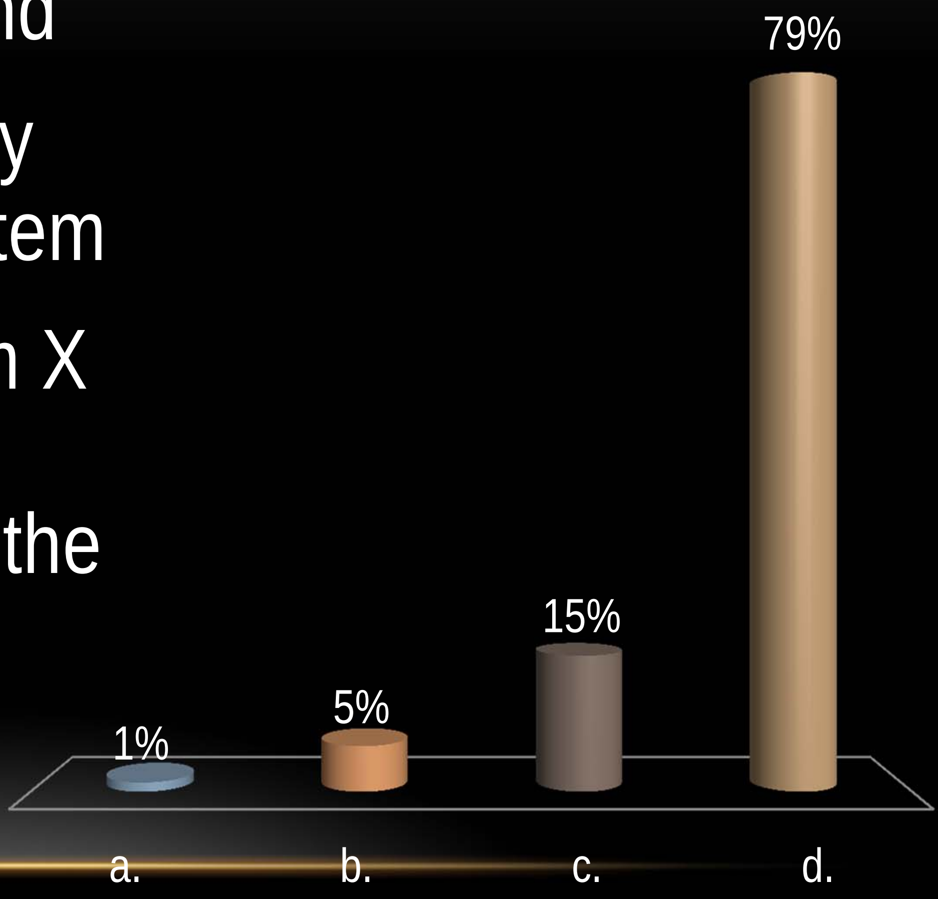
BLACK HOLES CAN'T BE SEEN. CAN THEY BE FOUND?

a. They can never be found

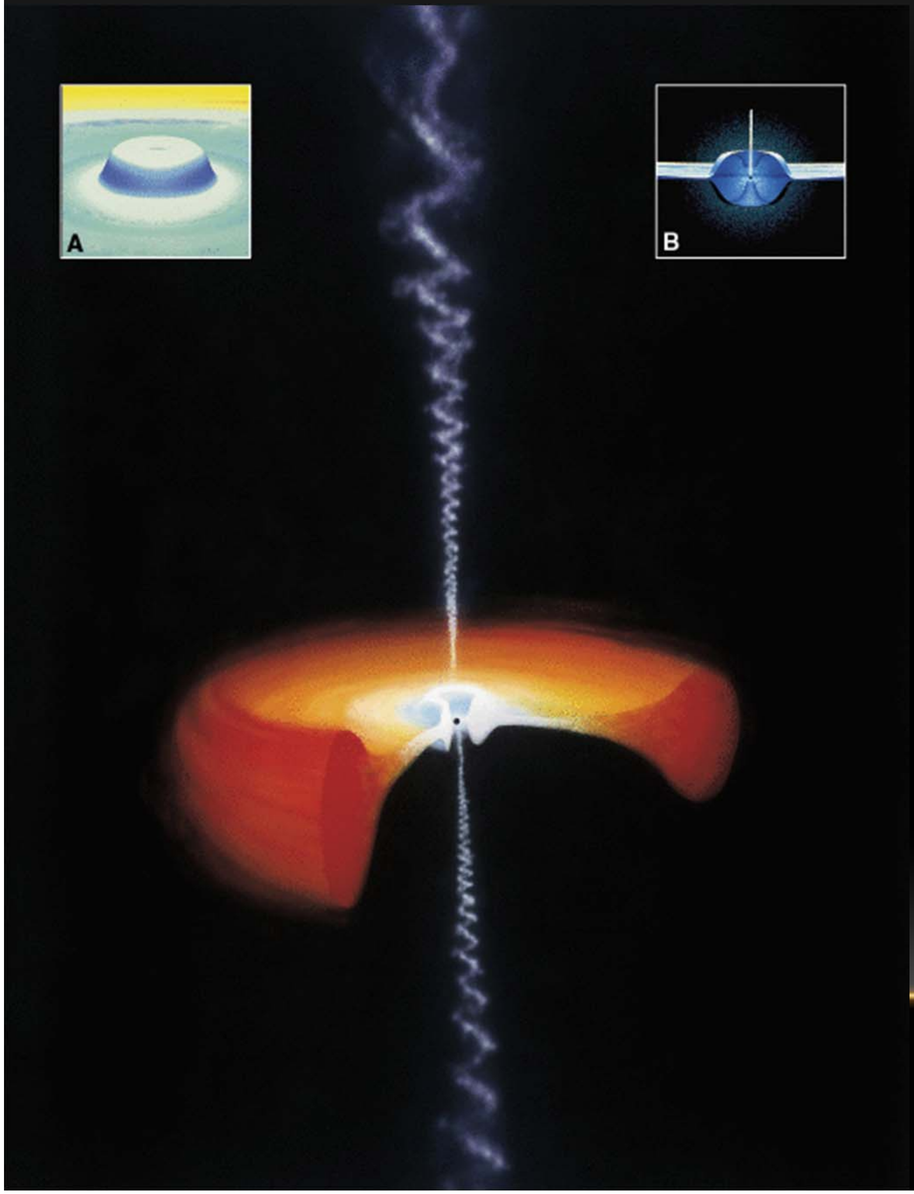
b. The can be found if they are in a binary star system

c. They can be found from X rays emitted from accretion disks around the black hole

✓ d. B and C



COULD WE SEE ONE?



- By definition, not directly
- But, we can see the effects of incredible gravity just outside the event horizon
- Things form an especially hot, fast accretion disk
- Very noticeable if the Black Hole has a binary companion to steal matter from

A BABY BLACK HOLE

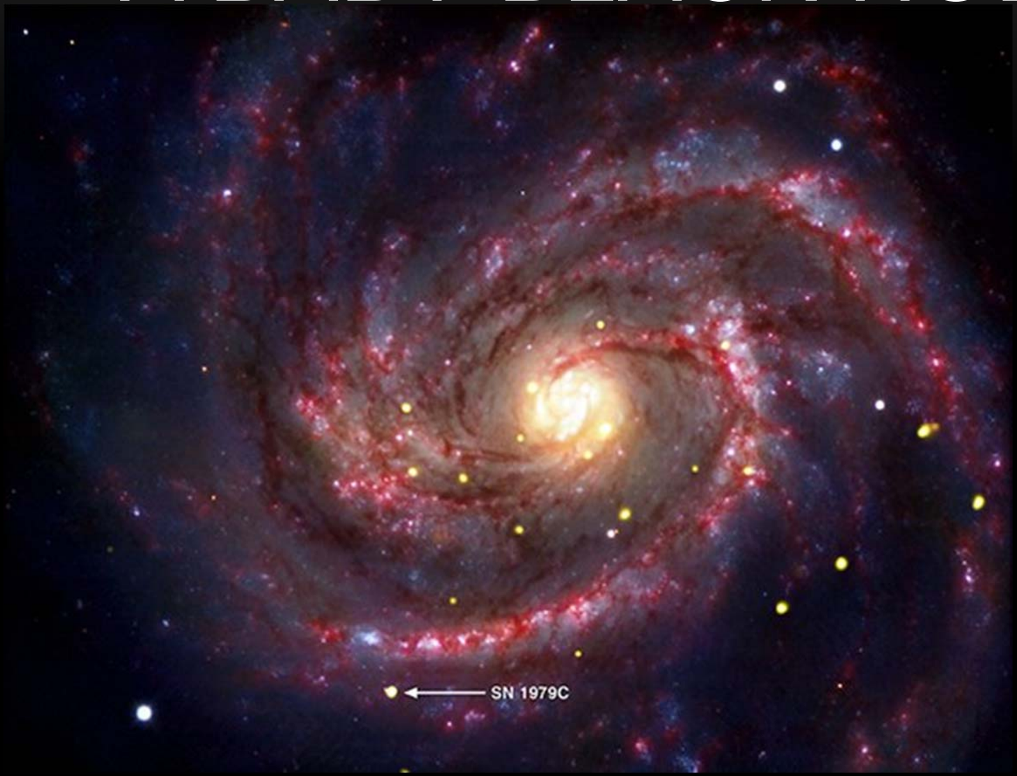


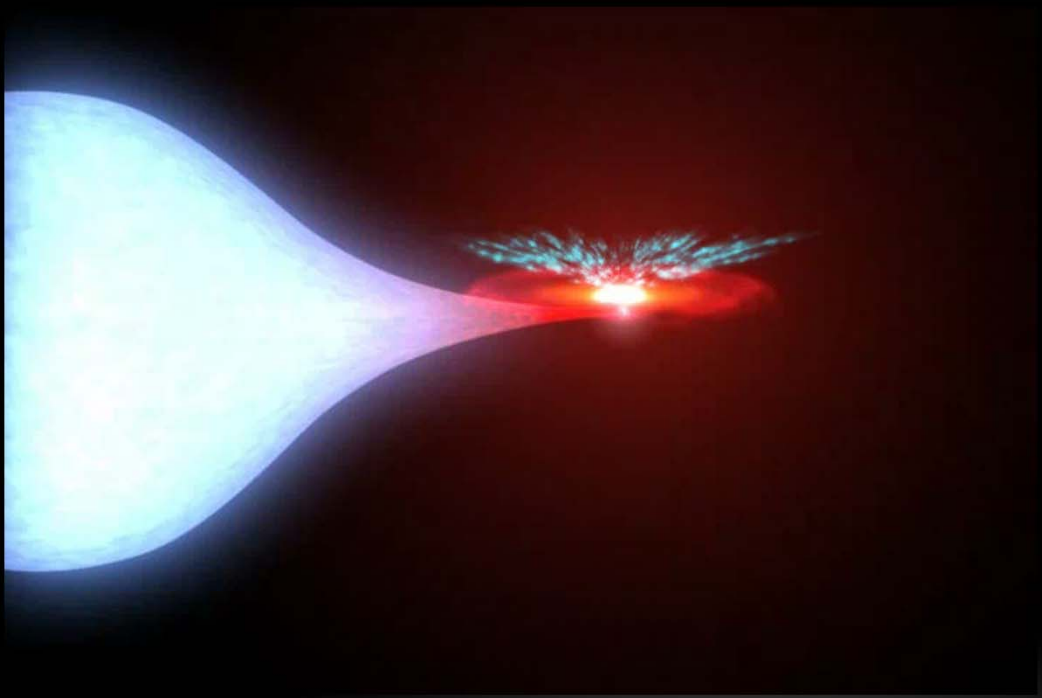
Image of M100
X-ray: NASA/CXC/SAO/D.Patnaude et al,
Optical: ESO/VLT, Infrared: NASA/JPL/Caltech

- X-ray observations of a recent SN show a steady X-ray light curve characteristic of stuff falling into a BH

DO WE SEE BLACK HOLES?

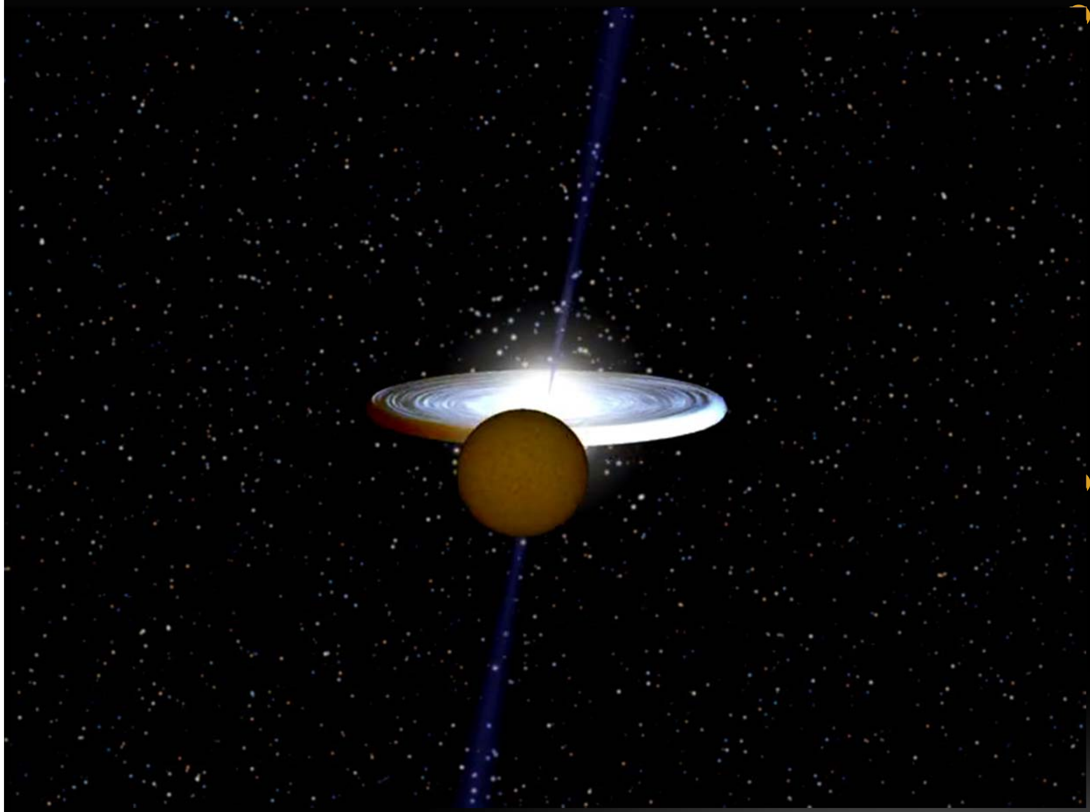
- There are many objects out there that appear to be black holes
  - Most everyone expects that they are
  - But extraordinary claims require extraordinary evidence
  - One could concoct other (often wild) scenarios to explain these objects
- So – yes we probably see them, but we haven't caught the culprit with the smoking gun red handed yet

IN BINARY STARS



- Especially if it's a nova-like situation, where a companion star is feeding stuff to the Black Hole

X-RAY BINARIES

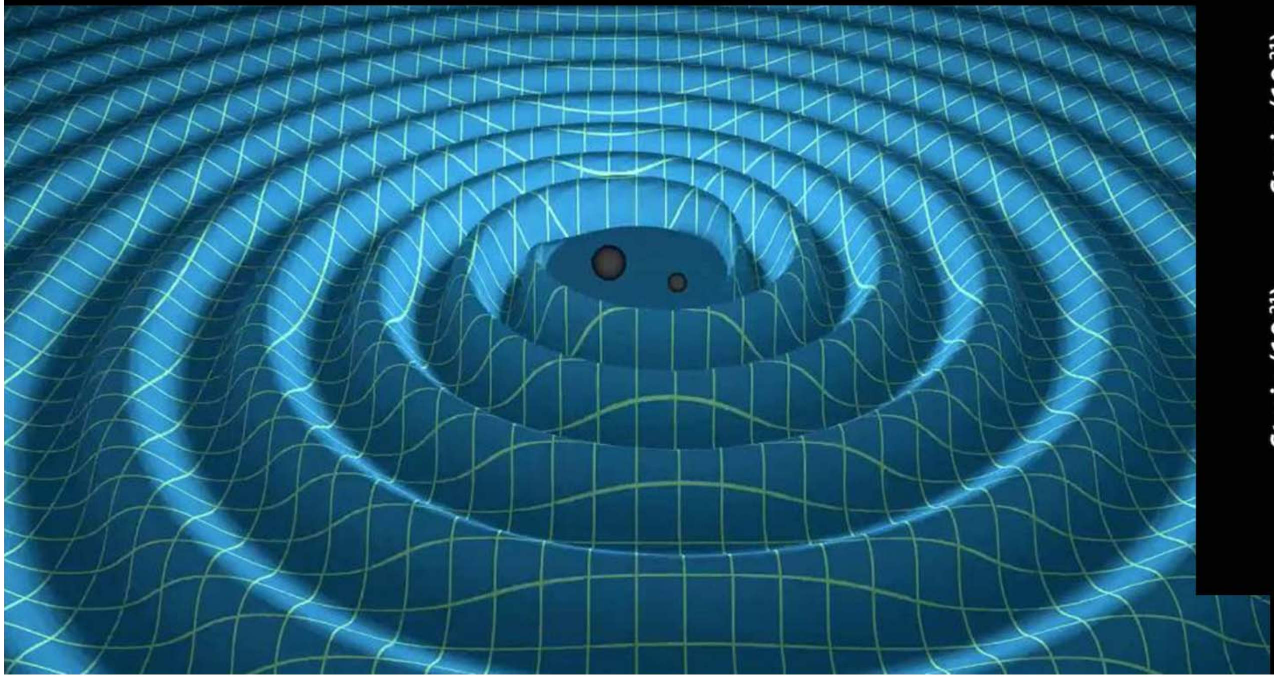


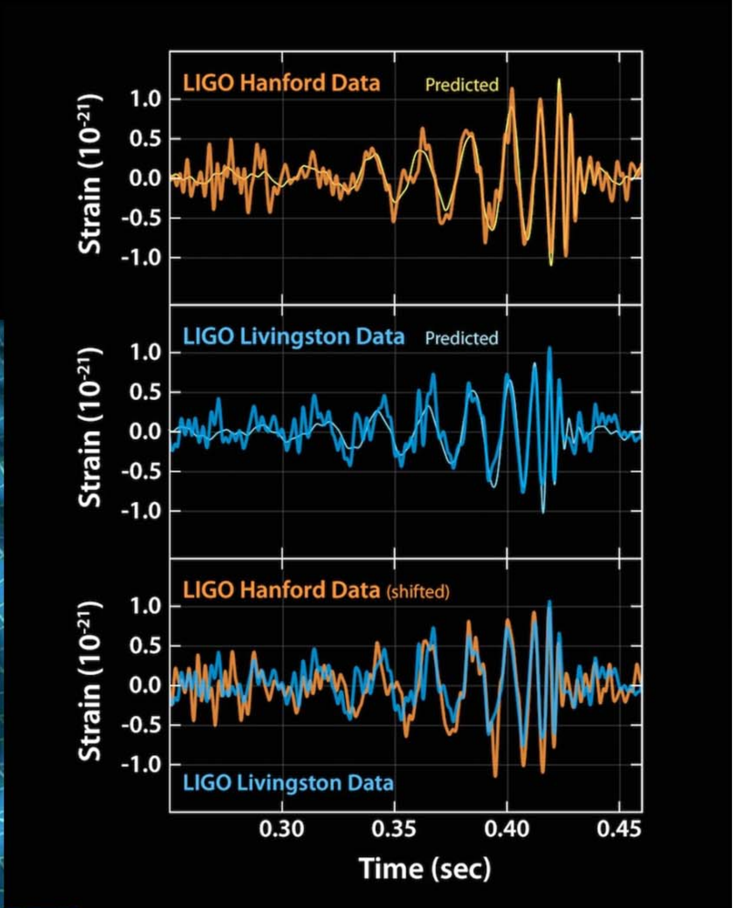
- All that stuff falling onto the accretion disk is very hot
  - therefore X-rays
- Makes jets too
  - Particle accelerators

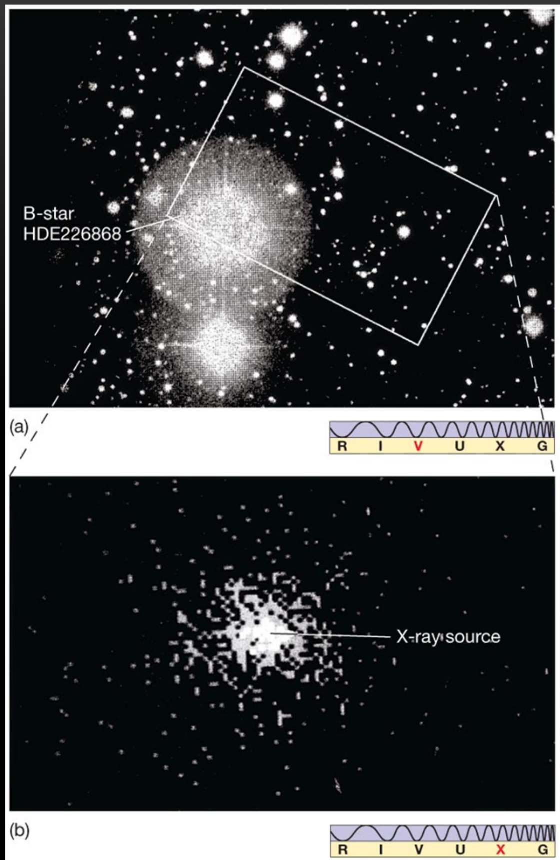
Animation from Rob Hynes and
Marc van der Sluys

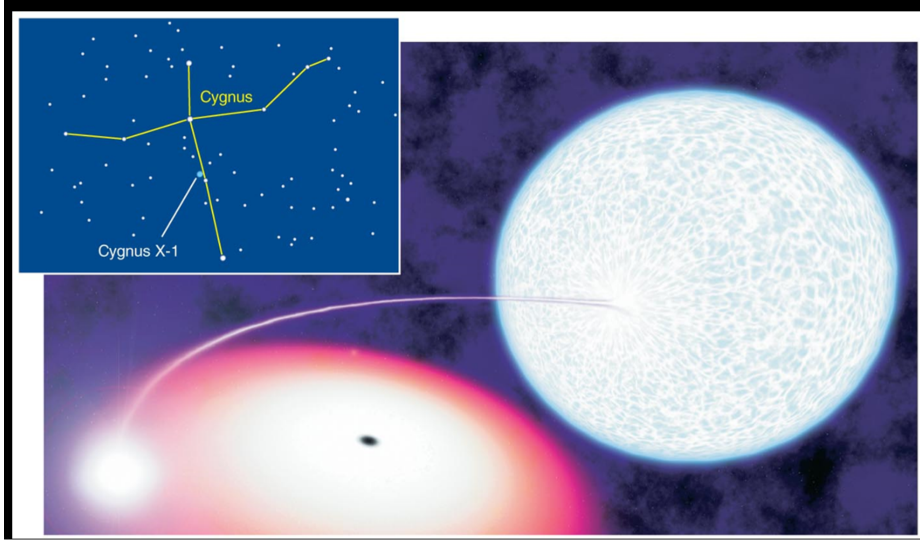
COLLIDING BLACK HOLES

- LIGO saw the gravitational waves from this:









CYGNUS X-1

- One of the most powerful X-ray sources in the sky seems to be a black hole and a blue giant star in a binary pair
  - Also a very good song by Rush, which includes some of the radio sounds from space

Fig.14.15

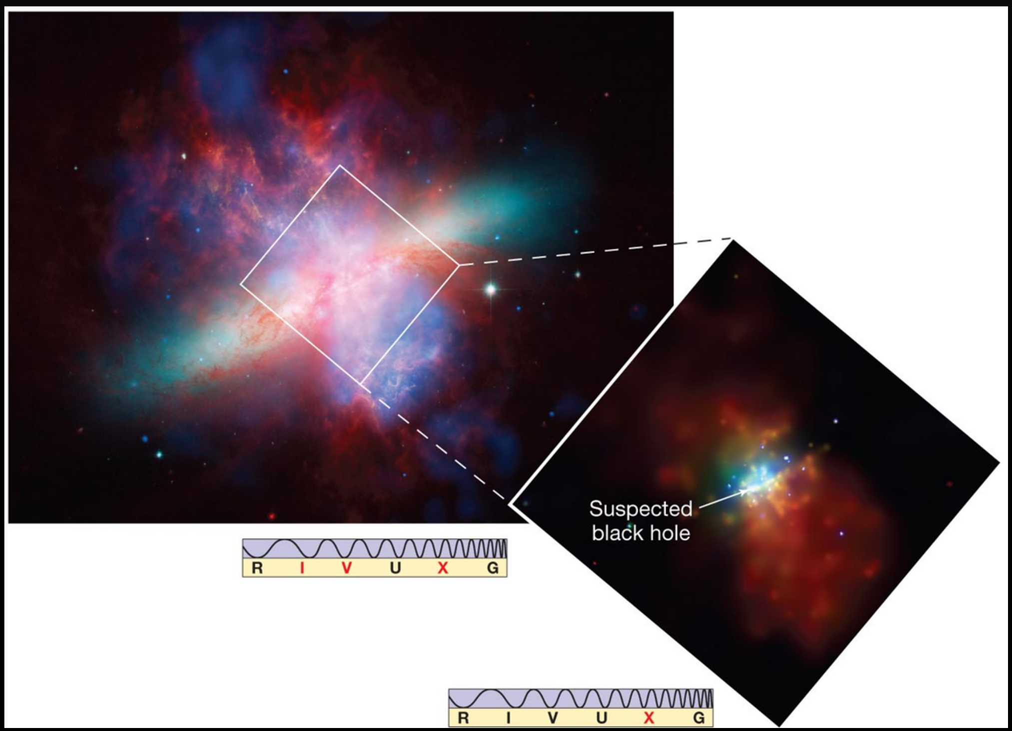
ORBITS

- Play same orbit game with Kepler's Laws as we've done may times before
  - If mass of second thing is more than a neutron star can be (~3 $M_{\odot}$), it's likely a black hole
- Also, can look at gas swirling around accretion disk in X-rays
  - Measure mass
  - Measure radius: if the orbit is very small, a black hole is the only way you can fit in enough mass in that small of a volume

SUPERMASSIVE BLACK HOLES

- The centers of most galaxies show evidence of really big (millions of $M_{\odot}$) Black Holes
  - More on these in the Galaxies chapter

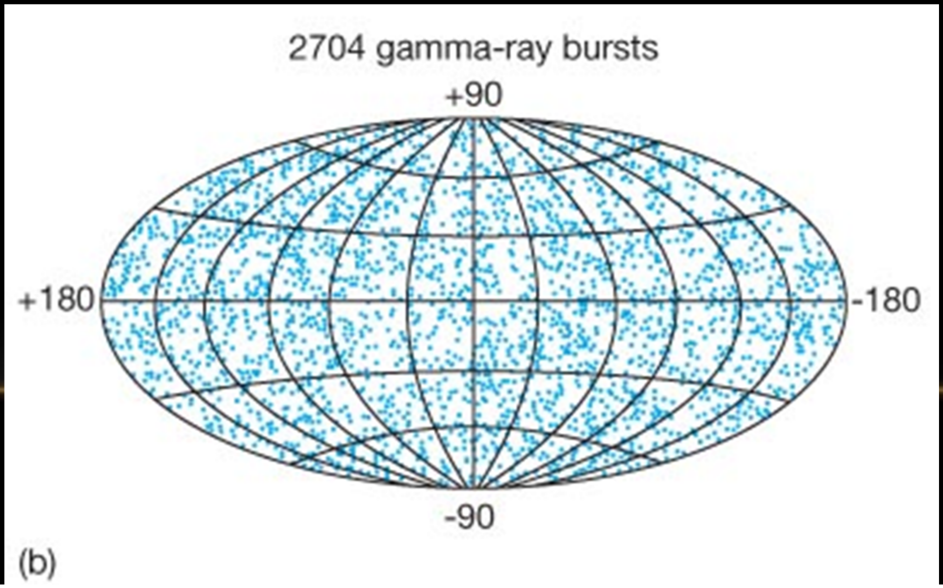
NEW STUFF:



- Intermediate mass black holes
  - $100\ M_\odot - 1000\ M_\odot$
  - Where do they come from?
    - Dunno
  - LIGO's colliding black holes were $\sim 30\ M_\odot$

GAMMA RAY BURSTS

- In the 60's, nuclear test verification satellites see what look like bomb bursts, coming from space!
- These happen about once per day
- From all over the sky

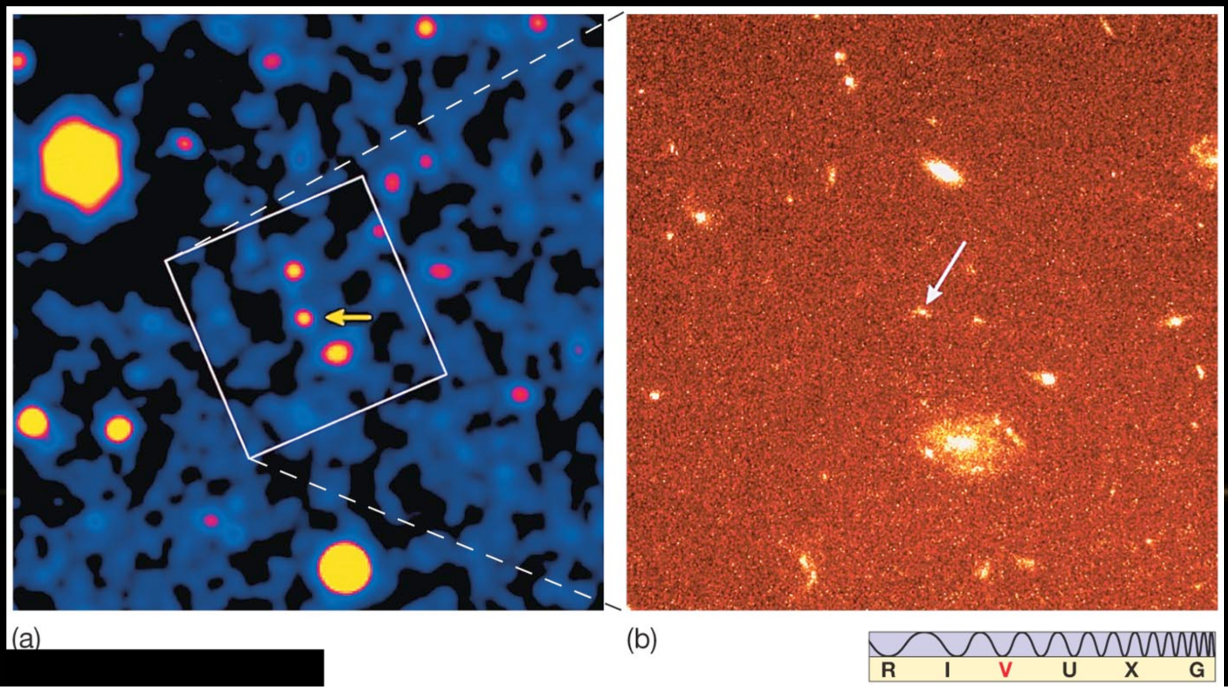


WHERE ARE THEY?

- Evenly spread out, so
  - Either really close by
  - Or really far away
- At an in-between distance, they would be galaxy-shaped, or appear to come from other galaxies
- If really far away, they msut be the most energetic things in the universe to appear so bright

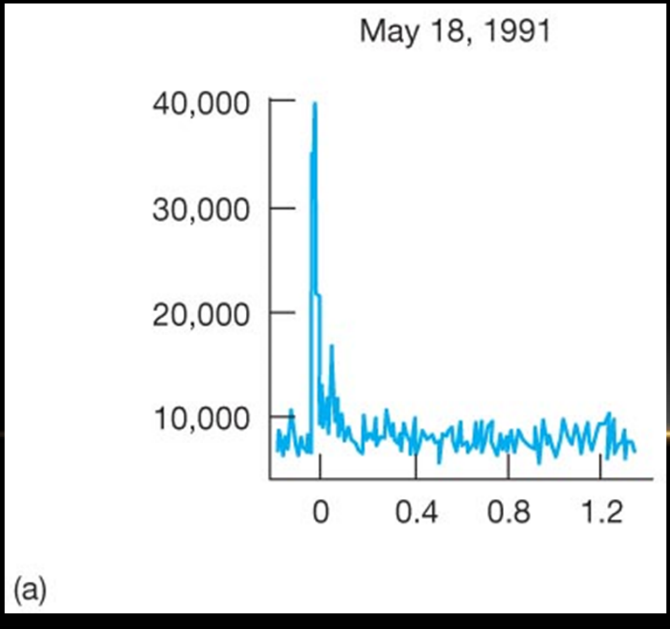
CONFIRMED: WAY OUT THERE!

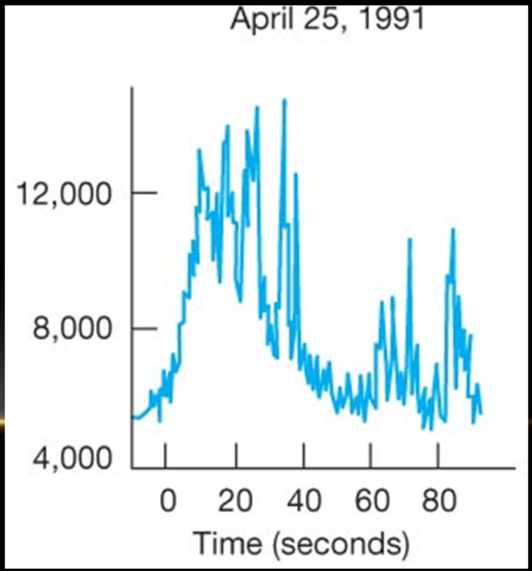
- Years of work trying to follow up the gamma ray blasts with more precise pictures and spectra succeed!
  - First one measured: 2 billion parsecs



WHAT ARE THEY?

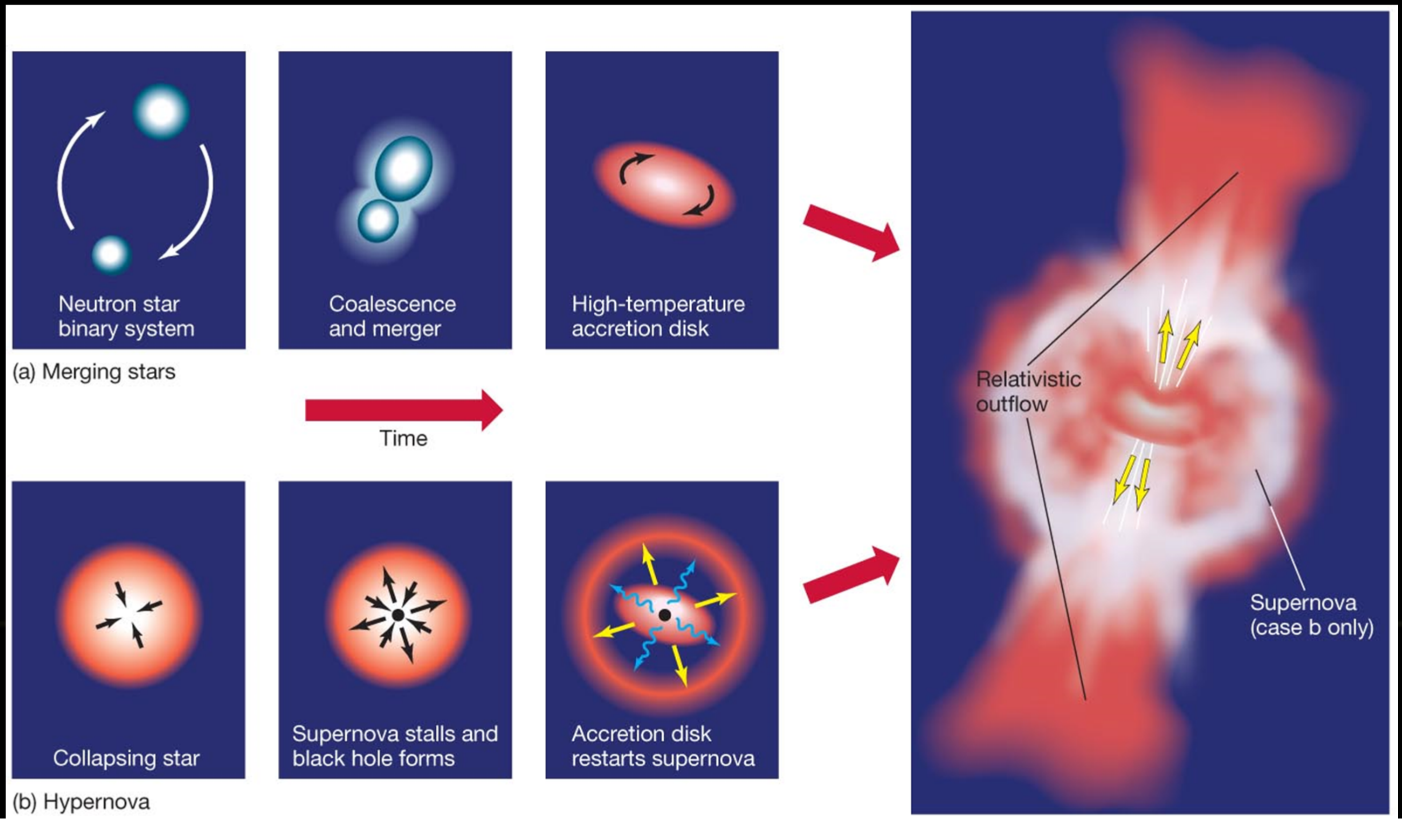
- GRB's come in two different sorts,
  - Hard (*spectrum is more energetic*) + Fast (less than a second)
  - Soft (*spectrum is less energetic*) + Slow (10's of seconds)





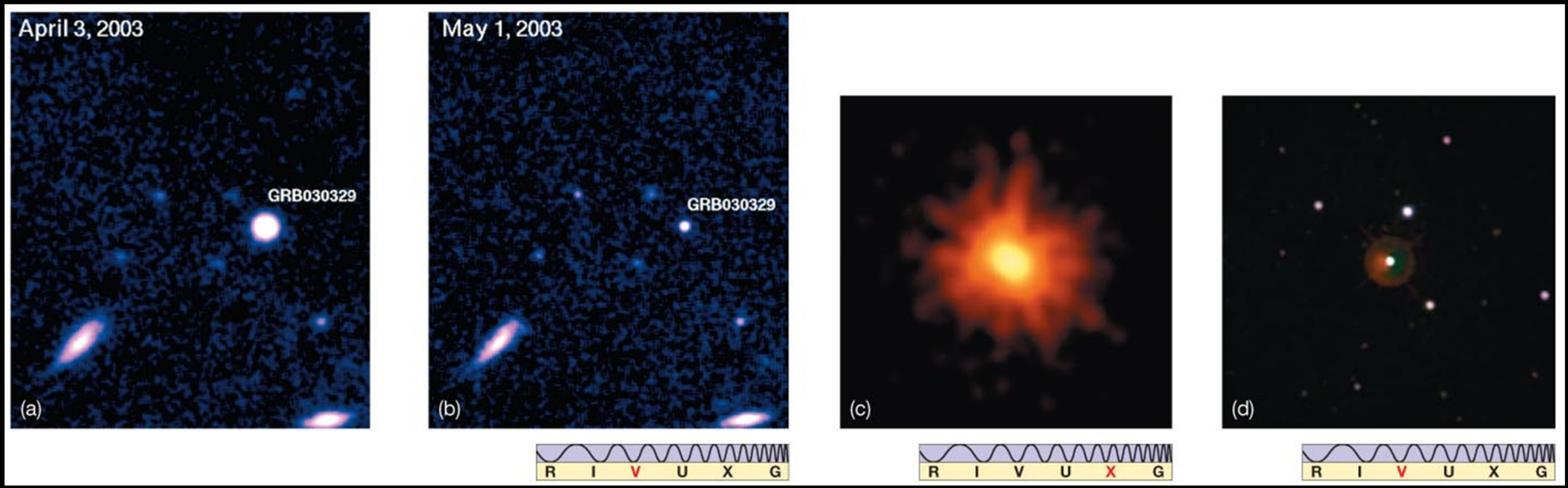
TWO MODELS:

- Colliding neutron stars
- Hypernovae



SOME LOOK LIKE HYPERNOVAE

- More recently, good follow-up pictures catch what look like SN ejecta near Soft-Slow GRB's



AND JUST ON AUG 17 2017:

- LIGO and VIRGO saw gravitational waves from colliding neutron stars at the same time and place as a “short” gamma ray burst happened 130 million ly away