

## Overview of Stellar Evolution

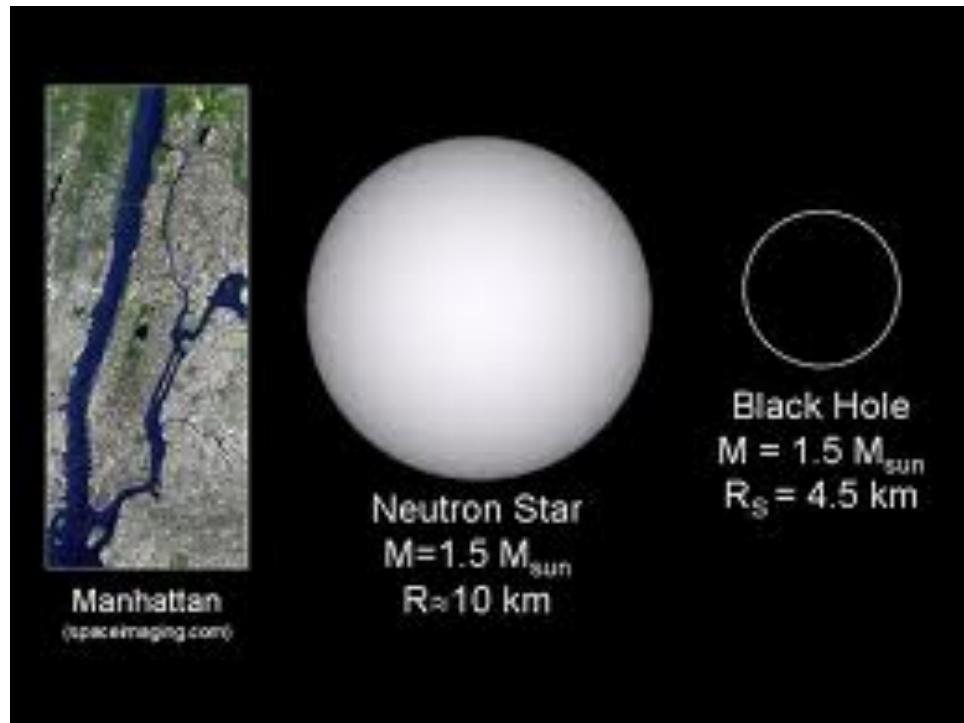
# Walter Baade 1893-1960



- With Fritz Zwicky first proposed that neutron stars could be formed by supernovae in 1934
- Iron core collapse
- Electron+proton → neutron+neutrino( $\nu$ )

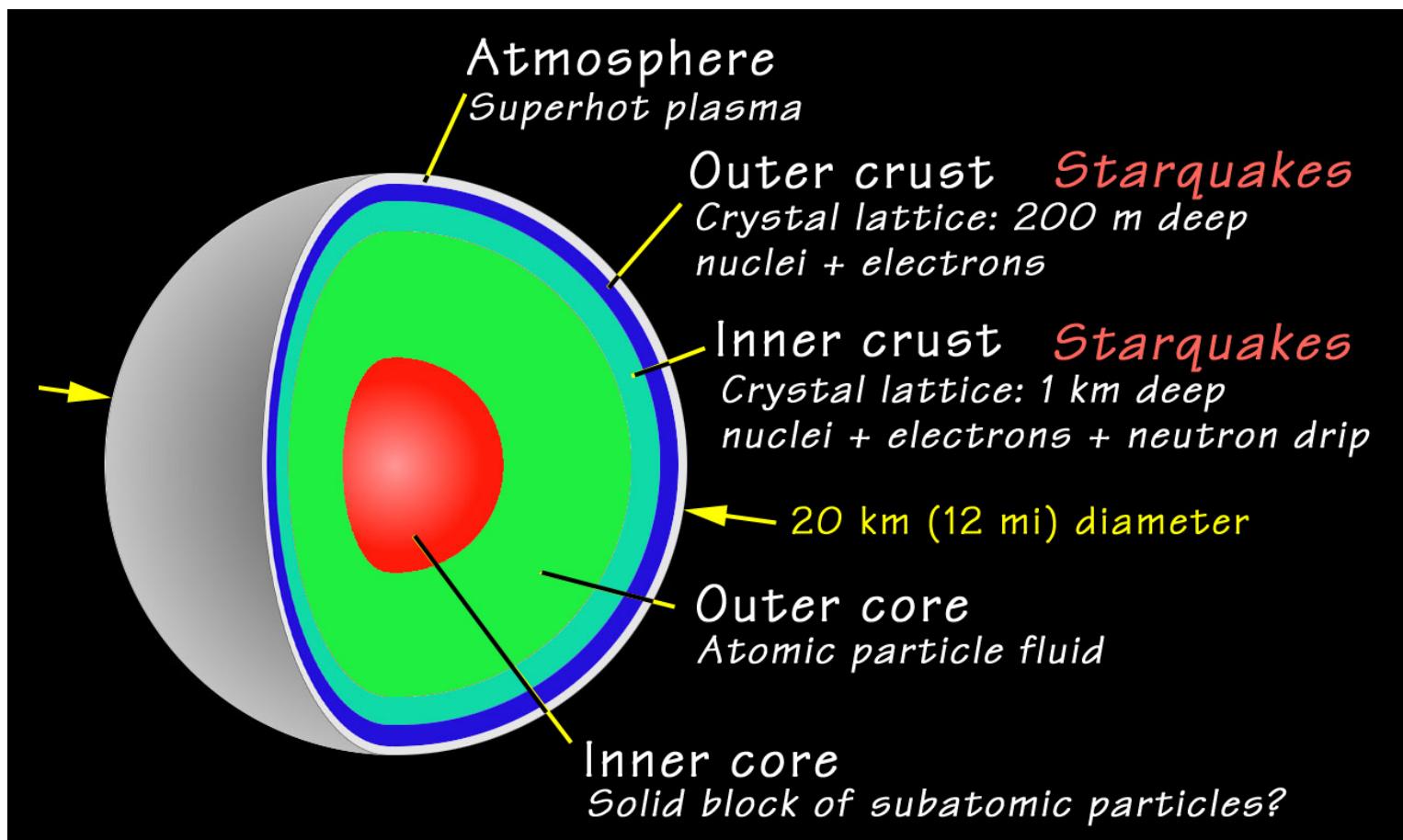
# Size of stellar Remnants

- White dwarf=size of Earth 10,000km
- Neutron star=size of Victoria 10km
- Black Hole= size of UVic ~3km

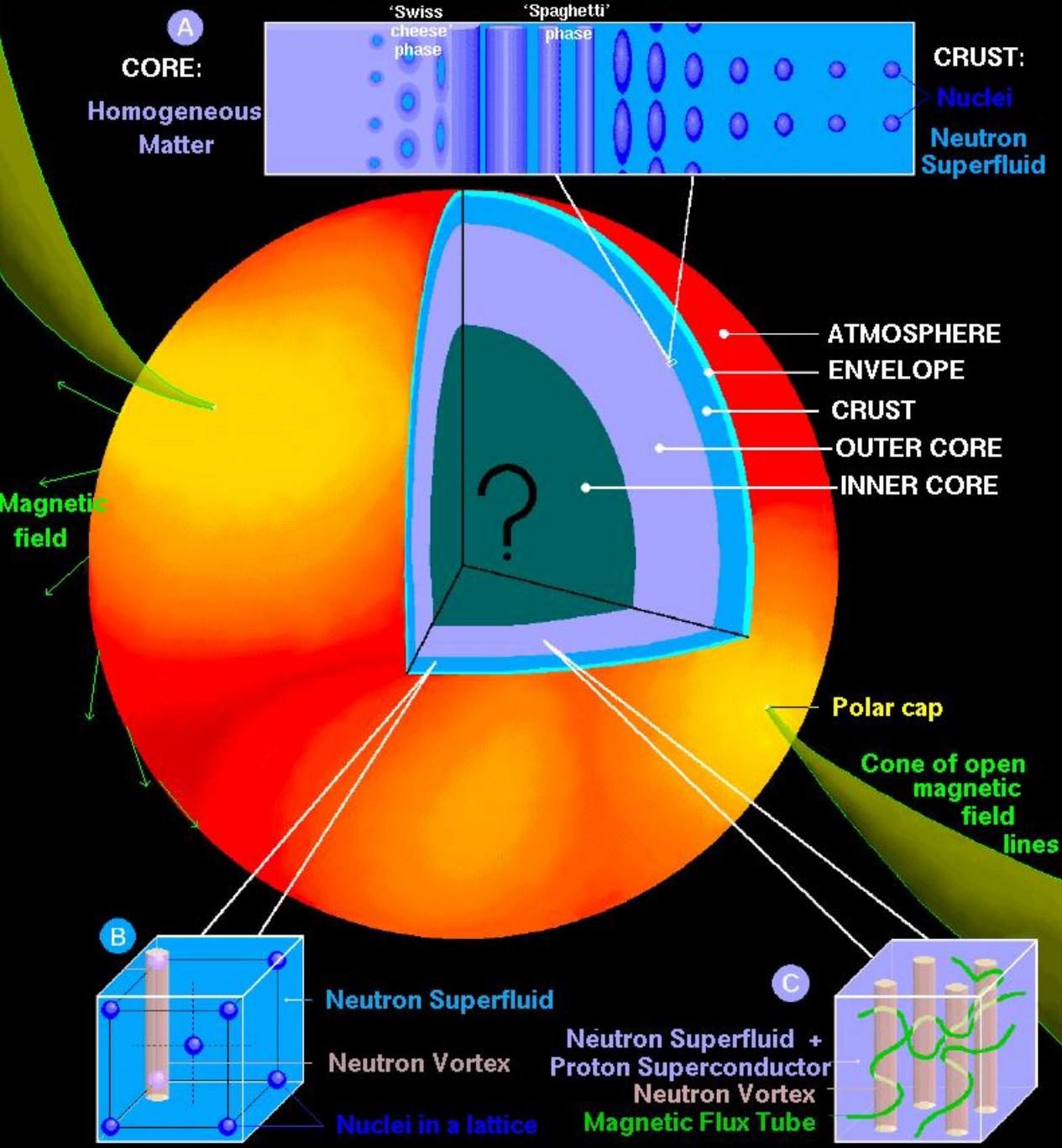


# Neutron Star: core Type II Supernova

- Over Chandrasekhar limit of  $1.4M_{\text{sun}}$  & less than  $\sim 3M_{\text{sun}}$
- Radius decreases by  $10^5$  to 10km so density increases  $10^{15}$
- Spin increases  $10^{10}$  times so rotation from 25d to millisec



## A NEUTRON STAR: SURFACE and INTERIOR



# Degenerate Neutrons

- Temperature of Millions K
- Magnetic field increases  $10^{10}$  to  $10^{13}$  gauss (Fridge magnet  $\sim 100$  g)
- Neutrons form Superconducting Superfluid core
- Convection currents turnover in millisecs

# Jocelyn Bell 1943-

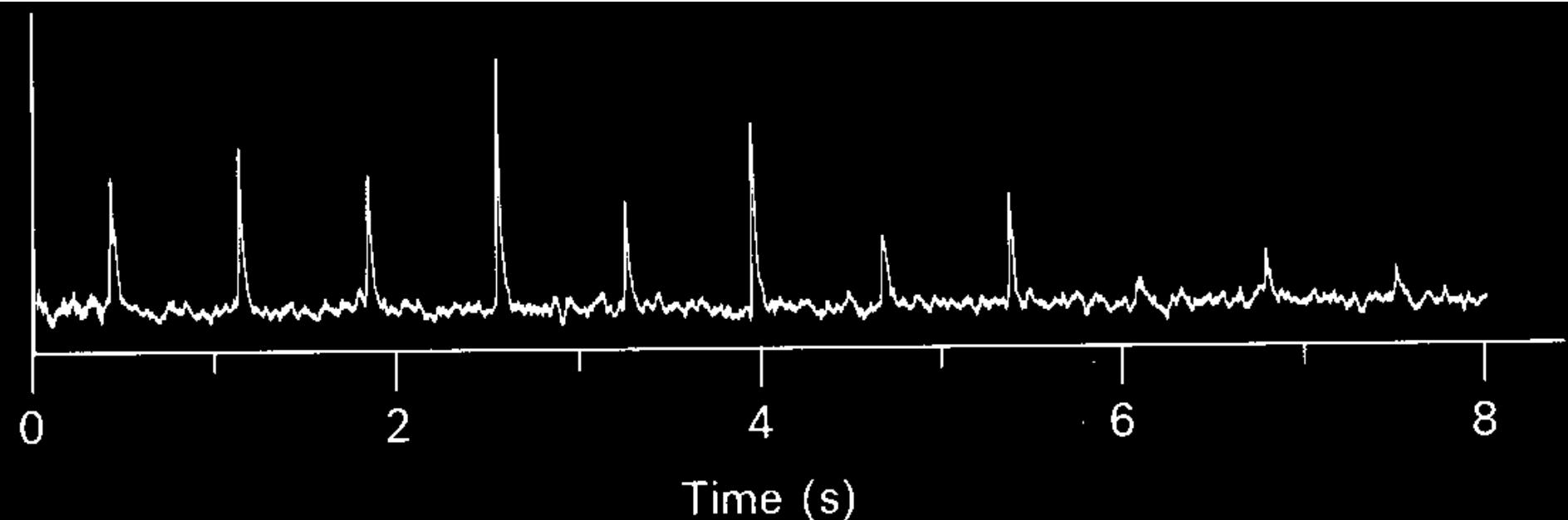
- Discovered first pulsar in 1967 (now ~1500)
- While using new radio telescope in Cambridge UK
- Discovered Crab pulsar 1968 showing link to Supernovae





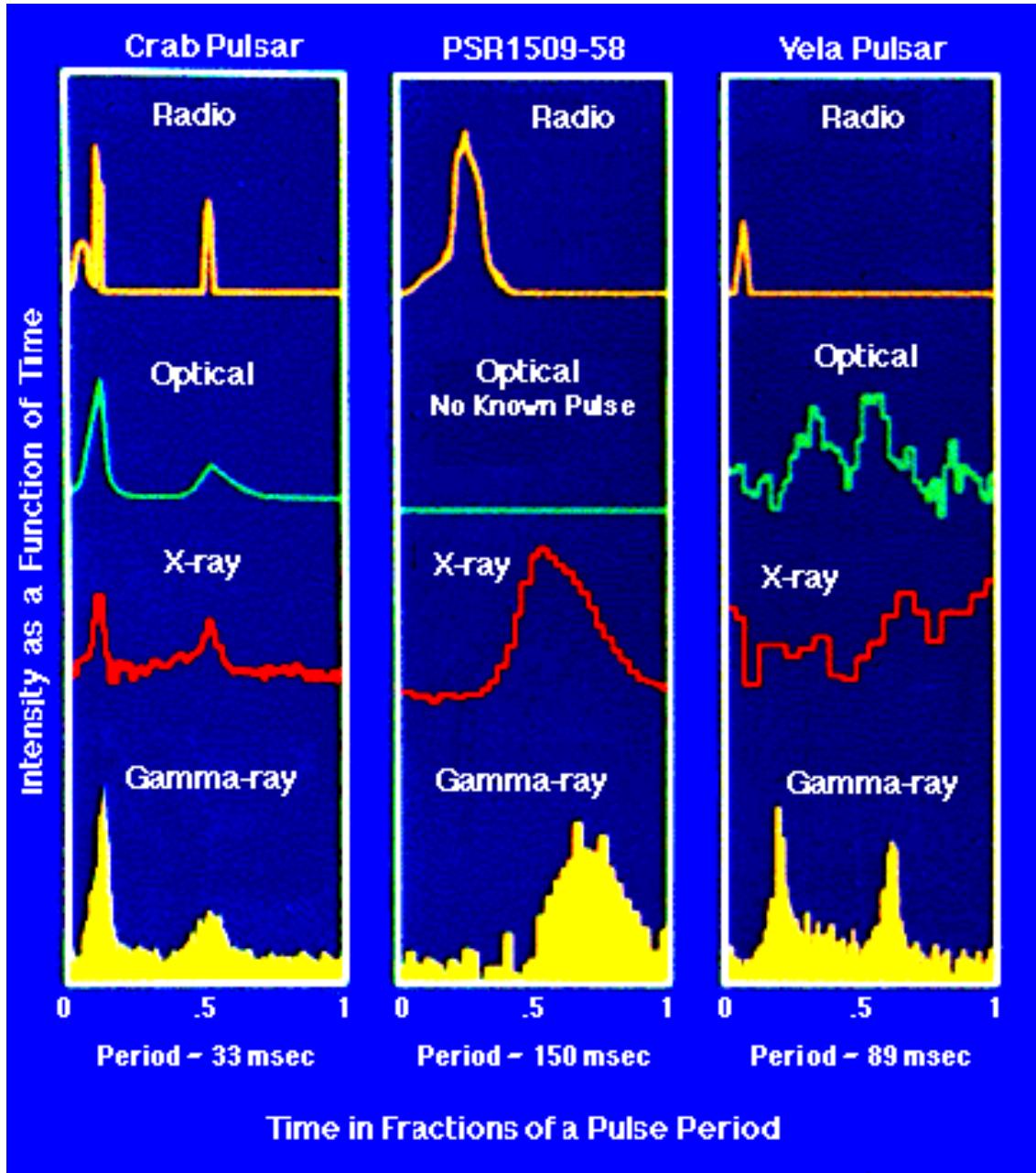
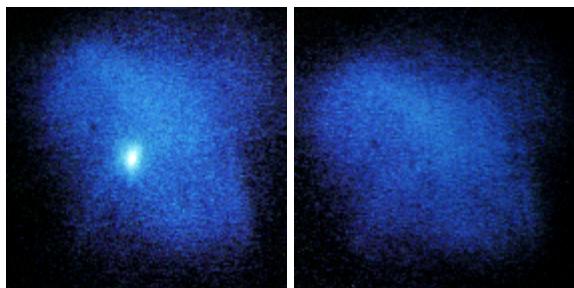
# Pulsar Pulses

- Spin rate = pulse periods from 0.033 to 3.75 seconds
- White Dwarf would fly apart if spun this fast
- Precision equal to atomic clock implies rotating massive object



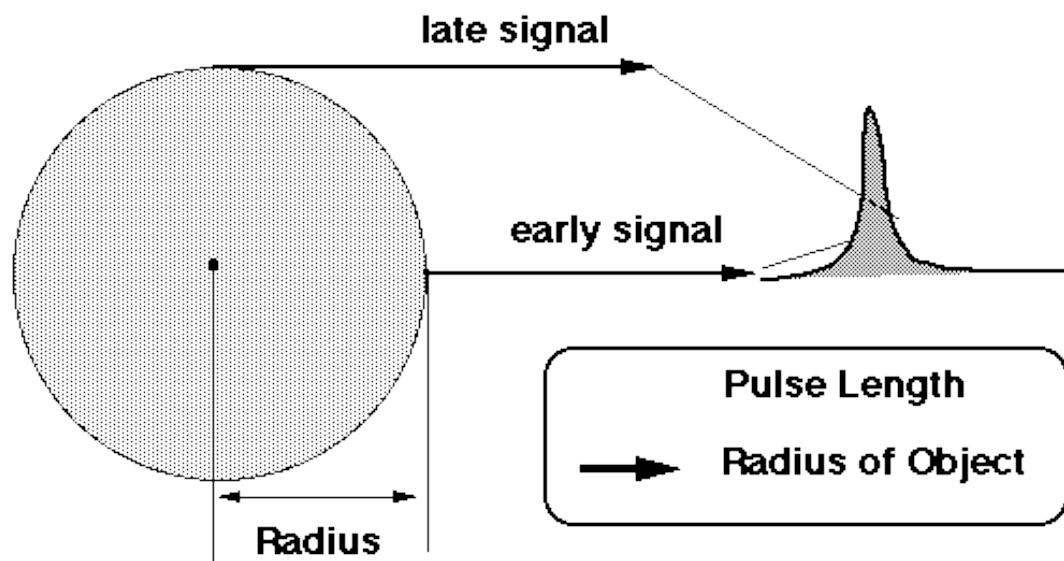
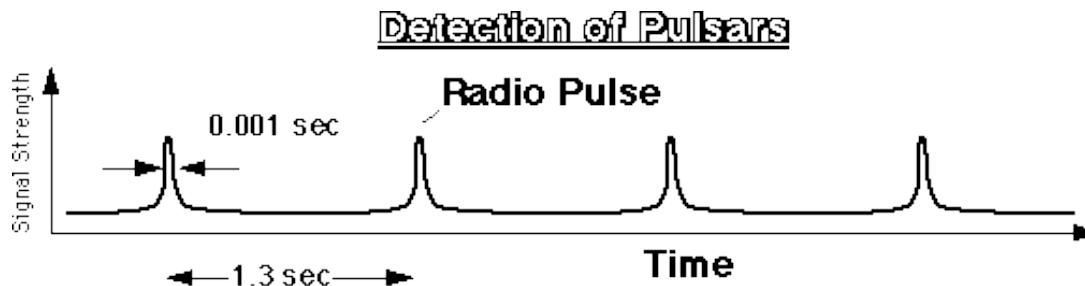
# Pulsar Profiles

- Pulses seen at all wavelengths but most easily at radio
- Sometimes strong and weak pulses
- Crab pulsar on/off

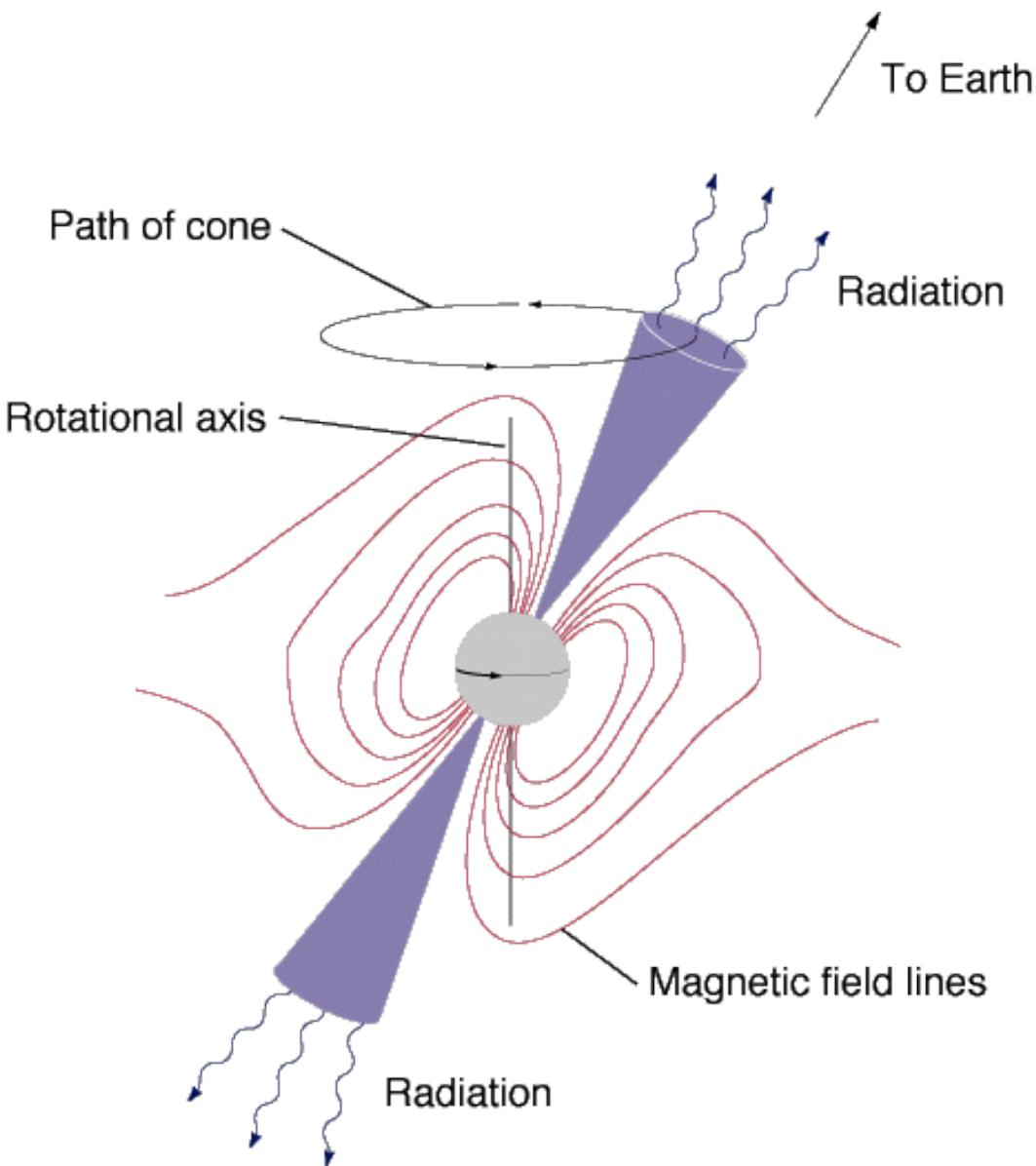


# Size of Emitting Region

- Duration of pulse must be less than light time across object so from pulse width of 0.001sec; emitter must be less than  $0.001\text{ sec} \times 300,000 \frac{\text{km}}{\text{sec}} \leq \sim 300 \text{ km}$  diameter



# Lighthouse Model



- Rapidly rotating neutron star
- Magnetic field inclined to rotation axis
- Light beam points along magnetic field axis
- If beam shines at Earth we see pulses

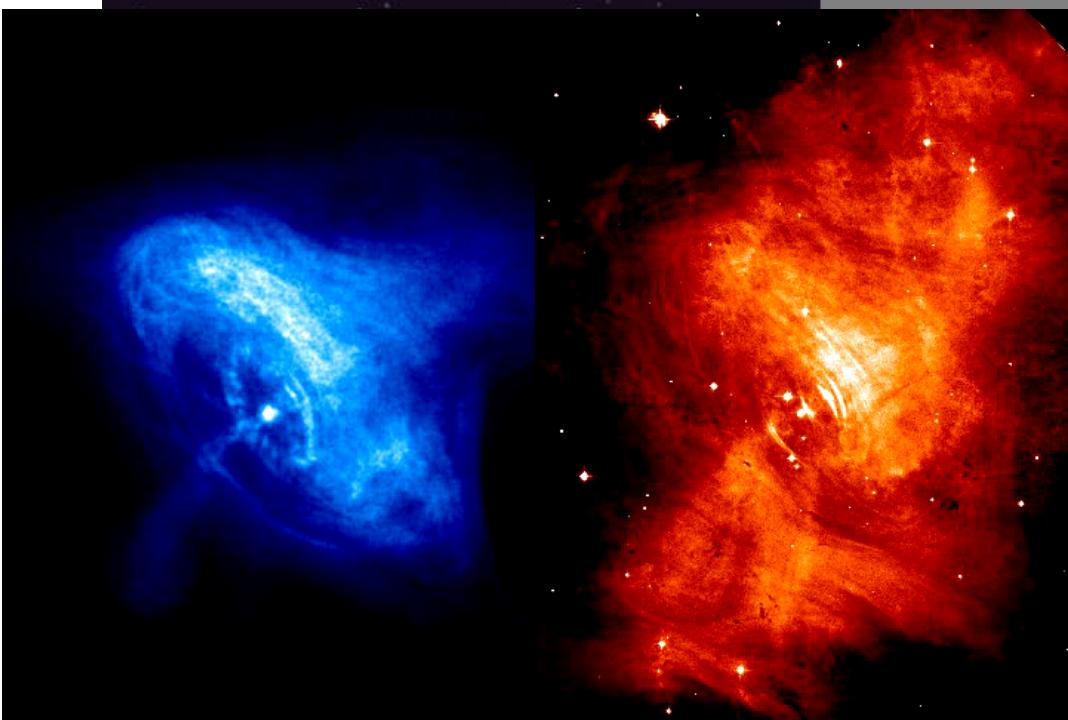
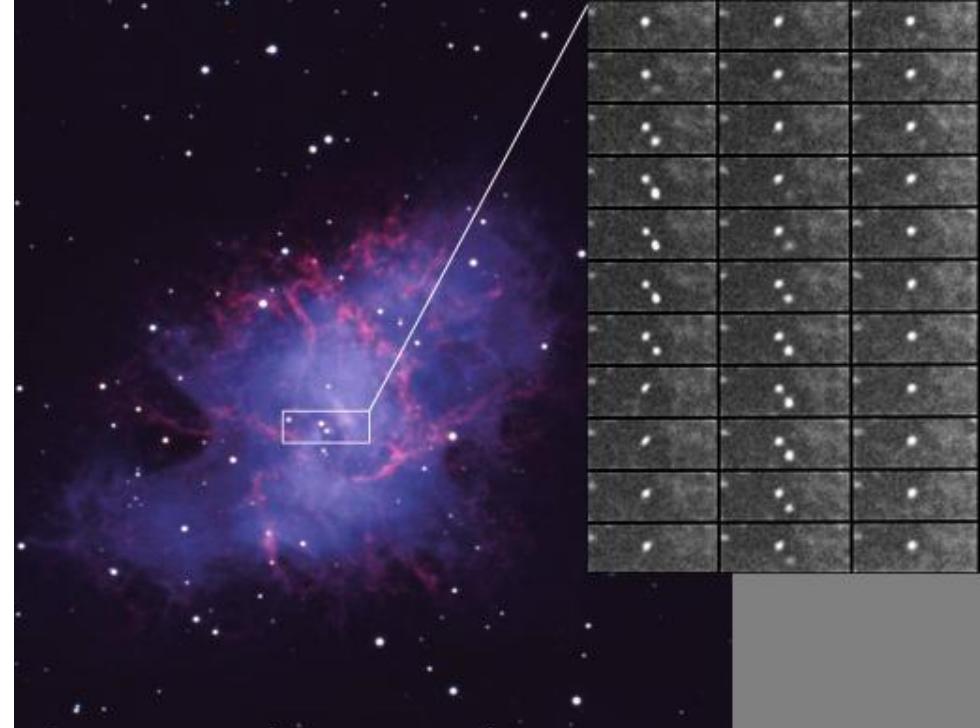
# Parks' Movie of Lighthouse Model

- At 1000km magnetic field rotating at speed of light
- Spinning magnetic field generates electric field accelerating charged particles = pulsar wind



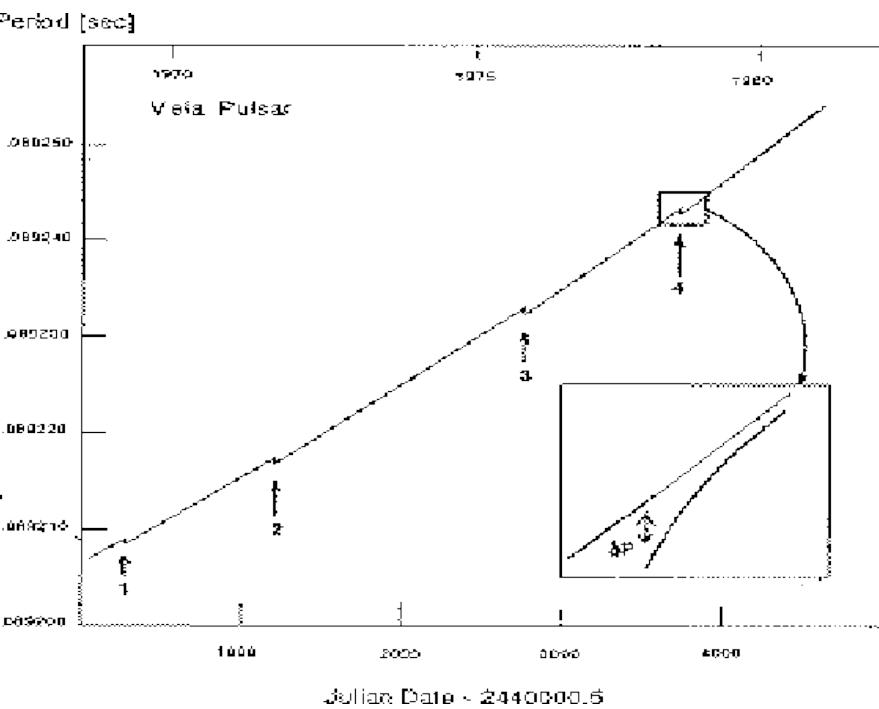
# Crab Movie: X-Ray &Visible

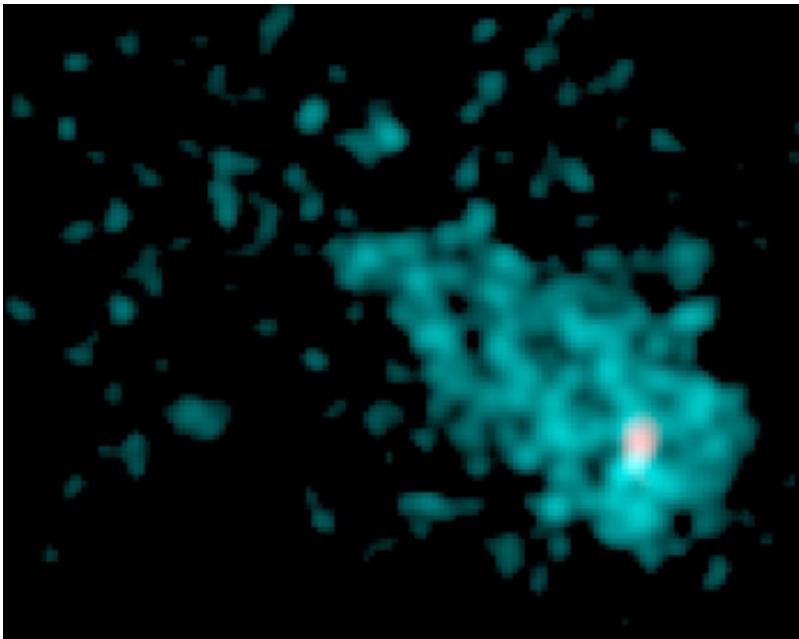
- Pulsar wind (like solar wind) energizes the nebula by carrying away the rotational energy of the pulsar



# Pulsars Spin Down

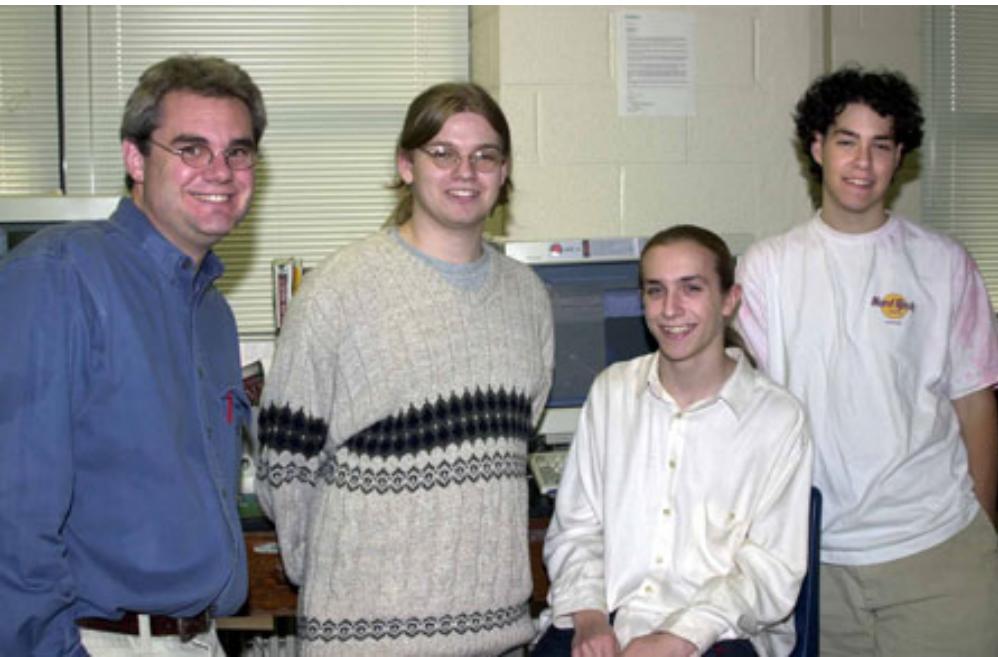
- Lose of rotational energy causes rotation period to increase
- Glitch is abrupt period decrease (Vela shown in graph)
- Pulsars spin down in millions of years
- Many more neutron stars than pulsars since: 1. Spun down & 2. Beams do not point at Earth





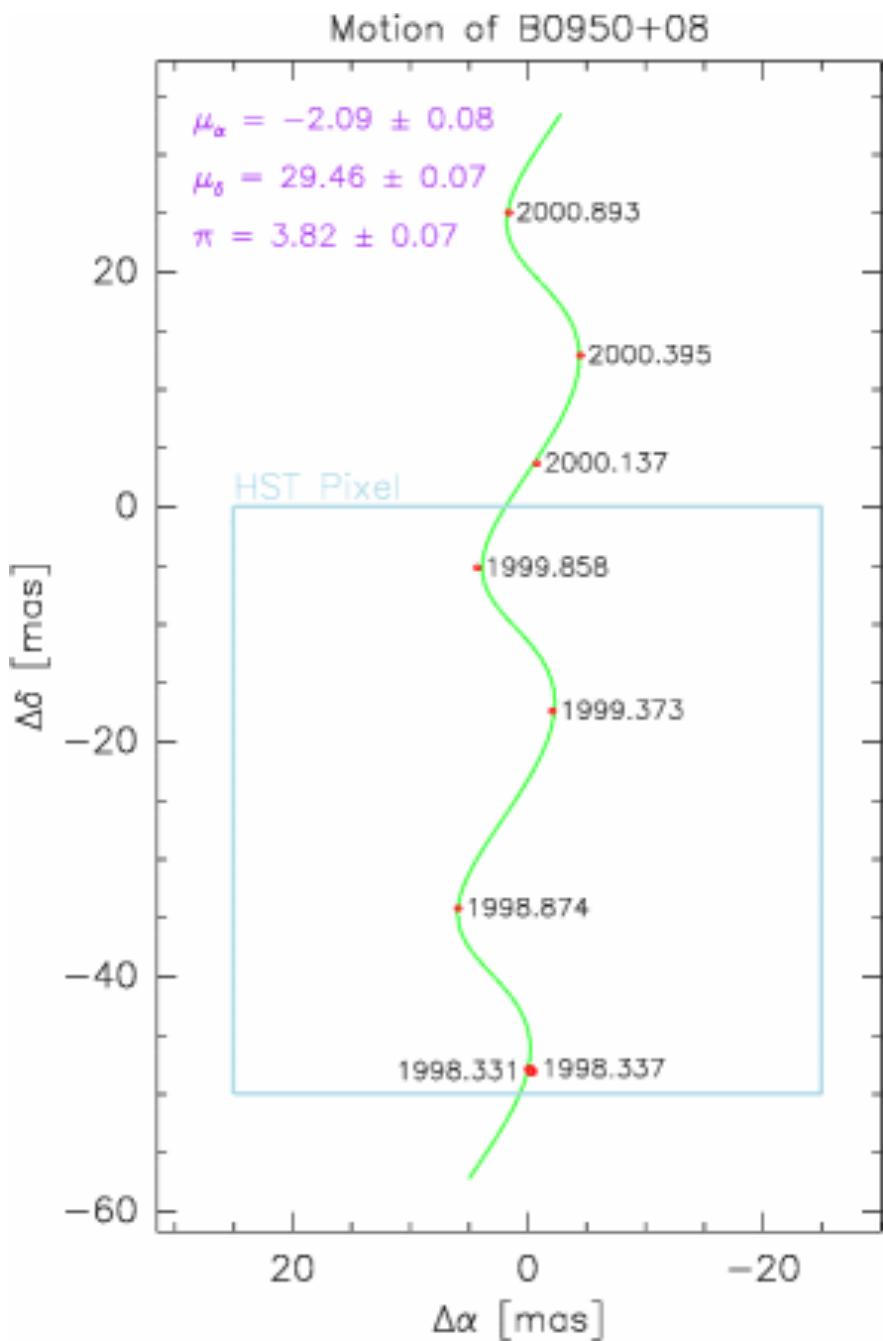
# Neutron Star in IC443

- Summer High School students
- Using Chandra X-ray data
- Found neutron star offset from center of SNR
- Most pulsars not in Supernova Remnants and lots of SN remnants have no pulsar.  
Why????



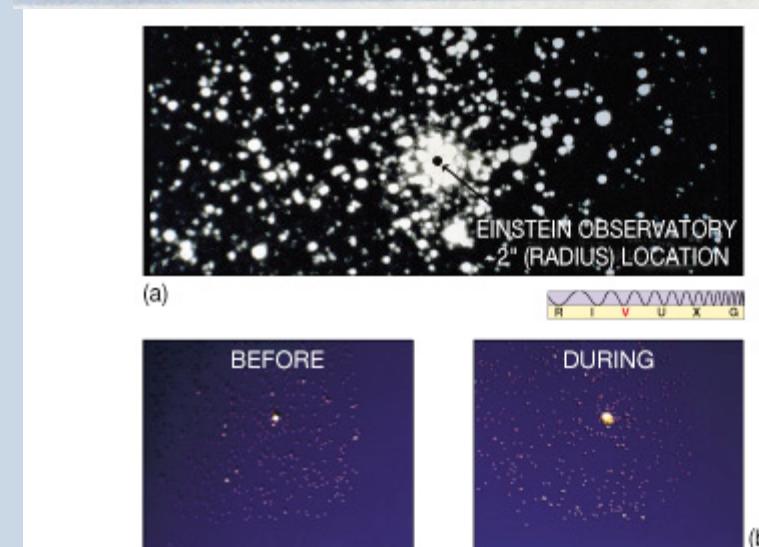
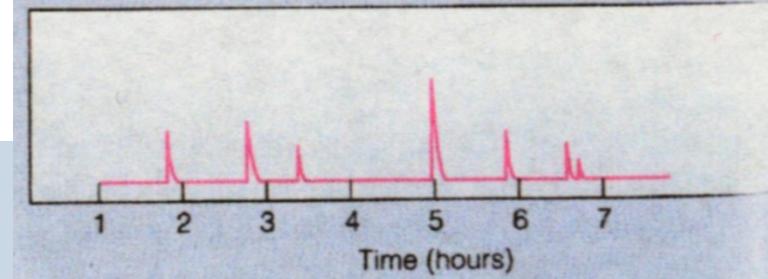
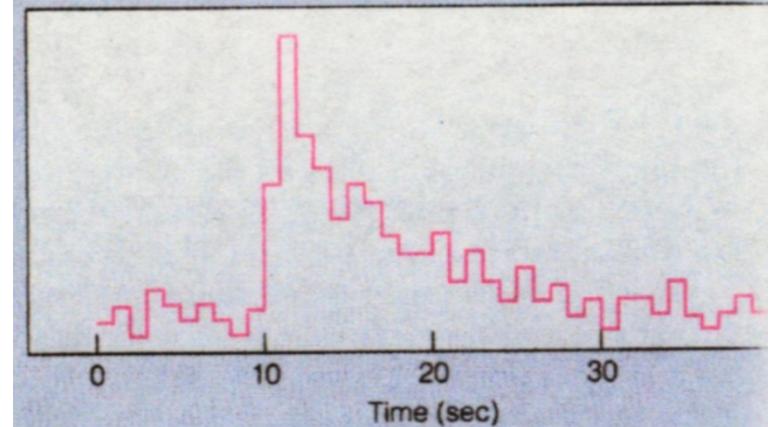
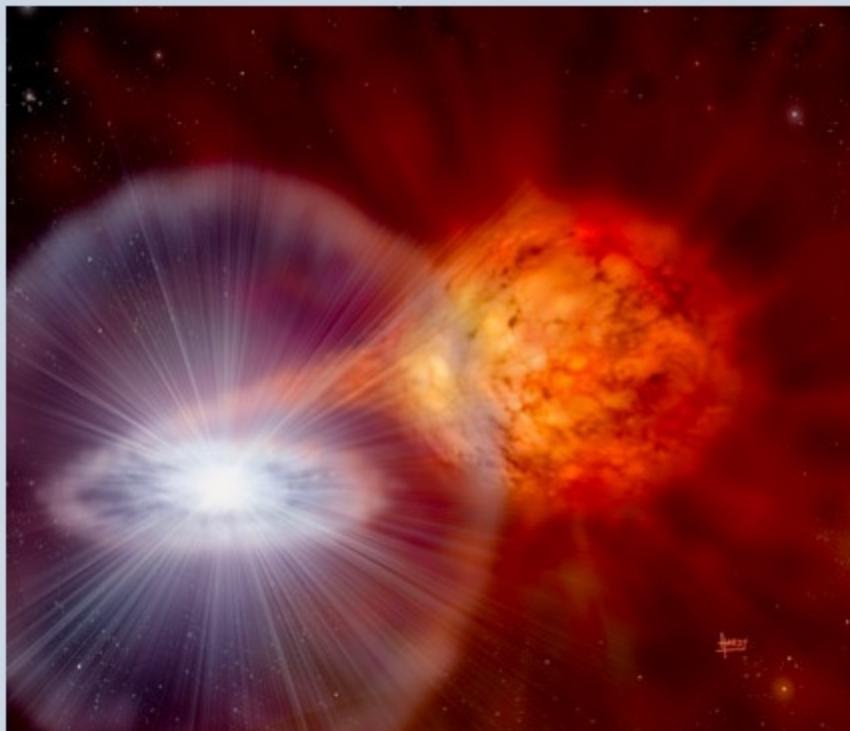
# Why are Pulsars NOT Found in SNR?

- Large proper motions
- Asymmetric explosions
- Disrupted binary stars
- SNR last  $\sim 50,000$  years
- Pulsars spin down in  $\sim 10$  Million years



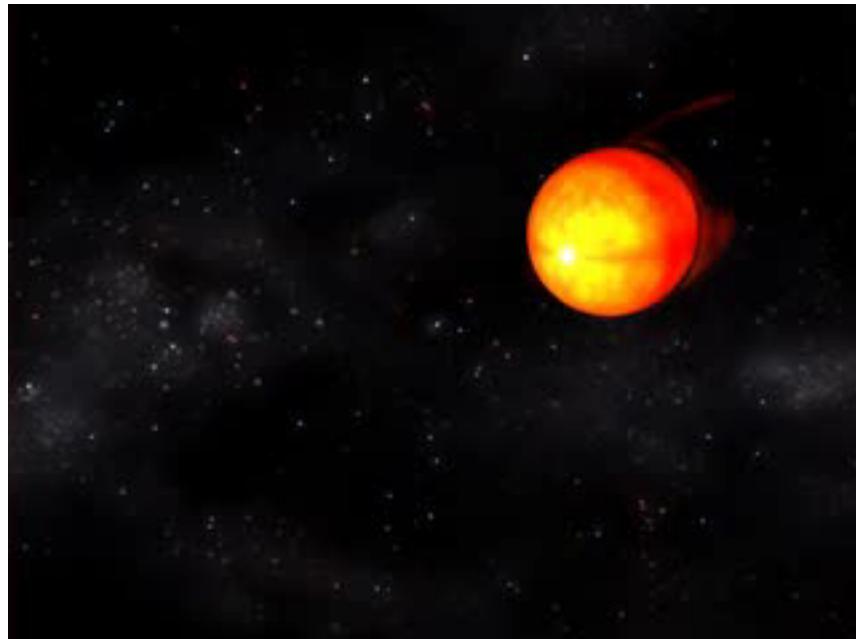
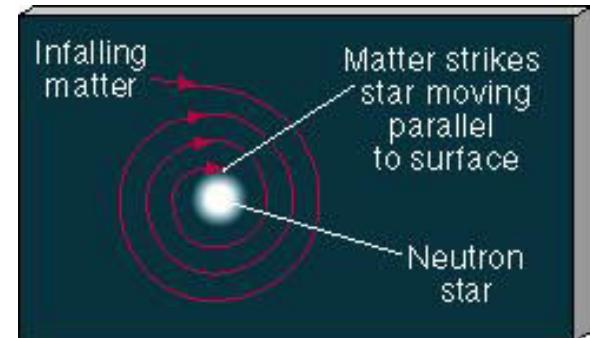
# X-ray Burster

- Carbon (or helium) builds up on surface of neutron star
- Which explodes – like a nova
- Lasting a few seconds;
- Repeats in hours or days



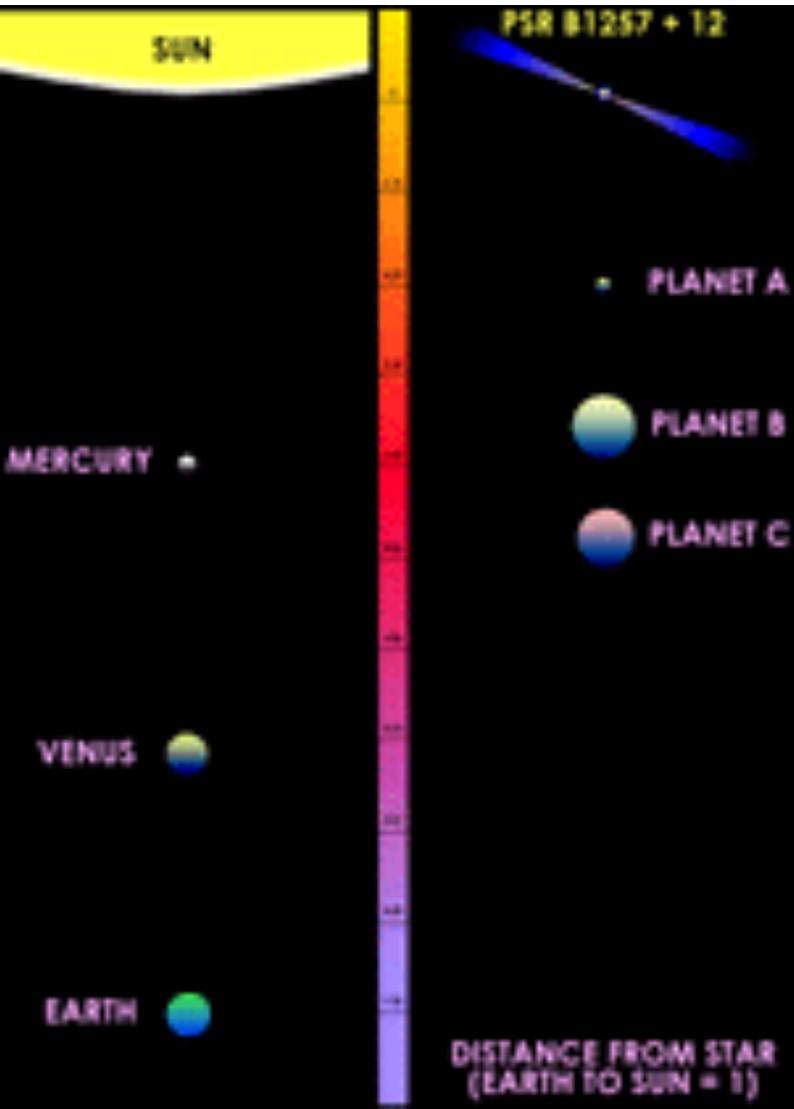
# Fastest Millisecond Pulsar

- Spun up by mass from companion
- Discovered by J. Hessels McGill
- Rotates at 716Hz=a blender~40000rpm
- Less than 16 km radius.
- Found in Globular Cluster= old star
- Spun up by companion



# Pulsar PSR 1257+12's Planets

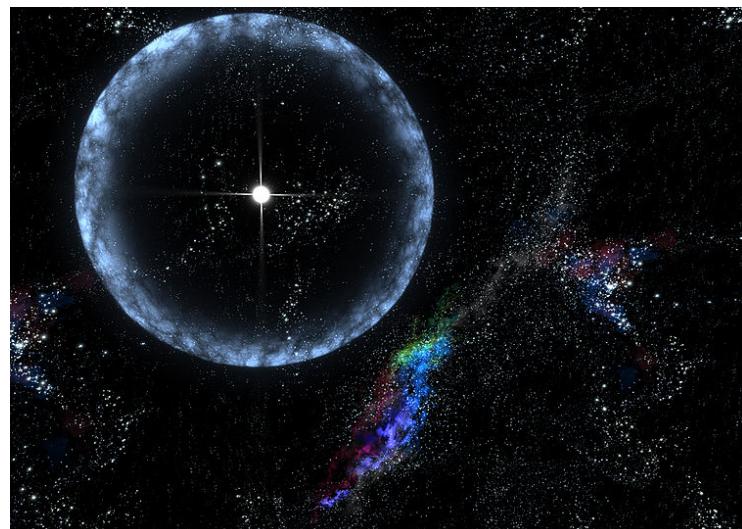
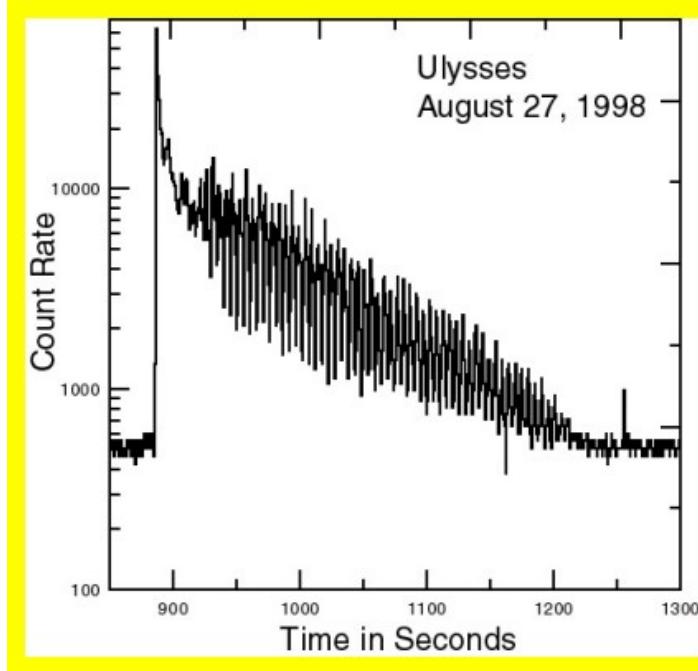
- Planet masses from mutual interactions:  
2 ~Earths, 1 ~moon mass
- Orbit so close to pulsar they should have been destroyed in explosion
- High energy jets may make surface of planet fluoresce





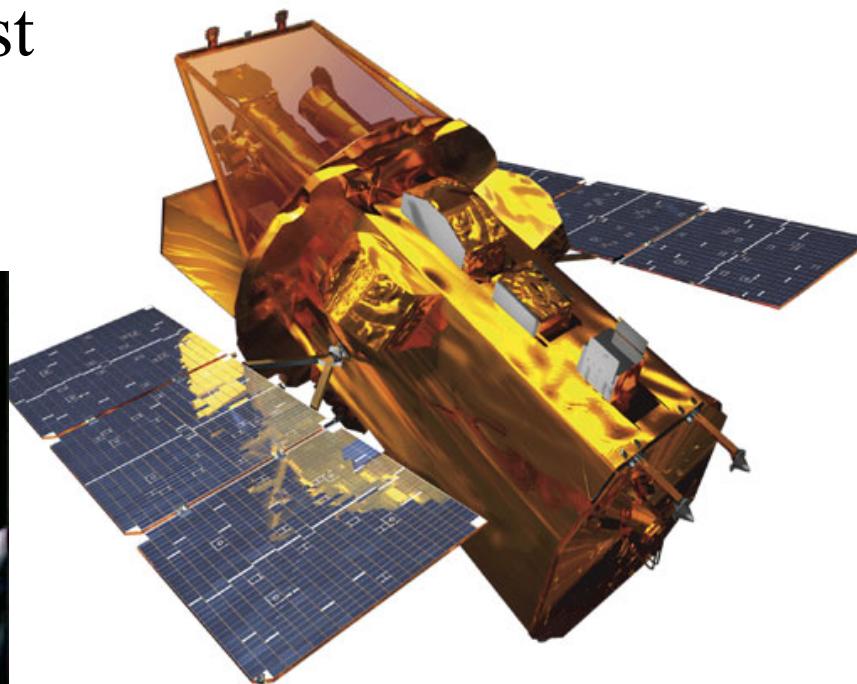
# Magnetar

- Pulsar with 1000 times the already enormous magnetic field strength of “normal” pulsars
- Energy stored in magnetic field can be liberated by starquake? as flashes of gamma rays seen across the galaxy
- Dangerous within 10 light years
- SGR1806-20 @50,000 light yrs, affected Earth’s atmosphere 2004



# Gamma-Ray Bursts

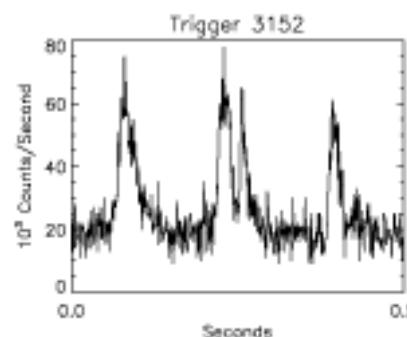
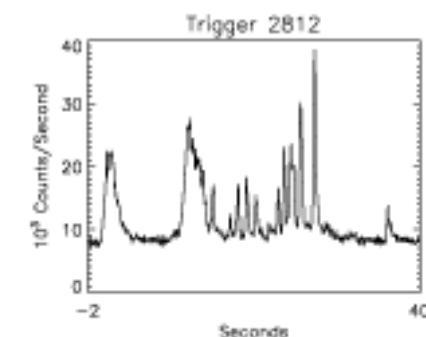
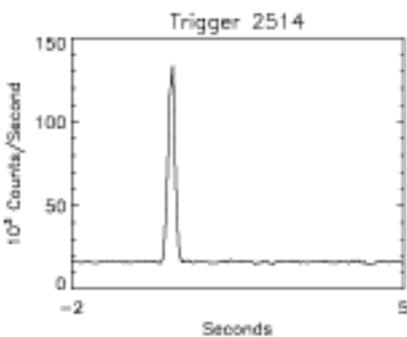
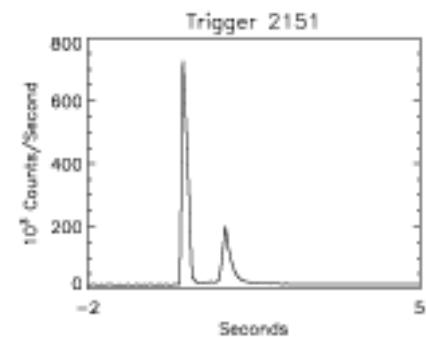
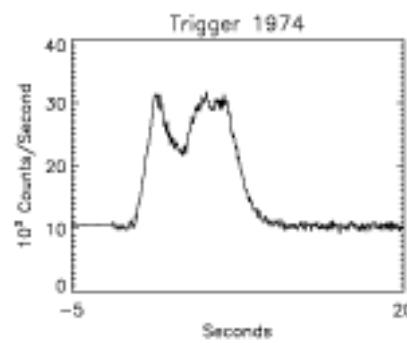
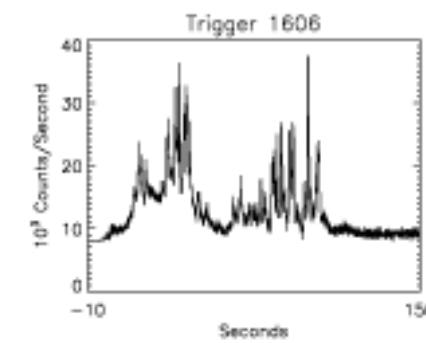
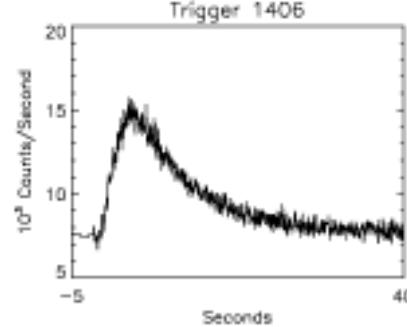
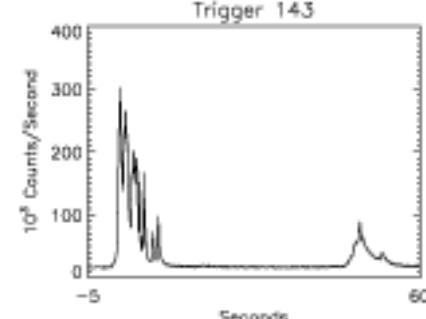
- Bright irregular flashes of gamma-rays
- Vela 1968 designed to detect nuclear bomb tests
- Beppo-Sax 1997 pinpointed burst
- SWIFT detects about 1 a day



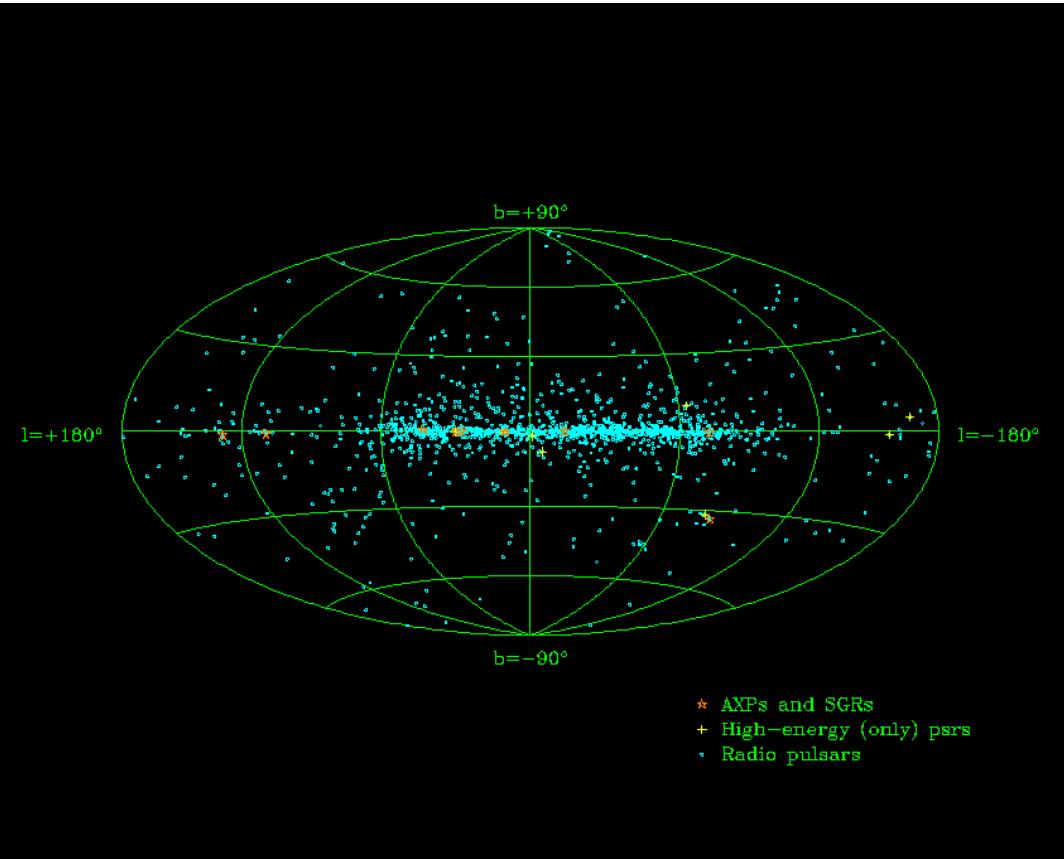
# Gamma Ray Burst =GRB

## Light Curves

- Long & short bursts
- Duration of seconds sets upper limit of size to ~million kilometers
- Same as pulsar pulse limits size of neutron star



# Pulsar Distribution

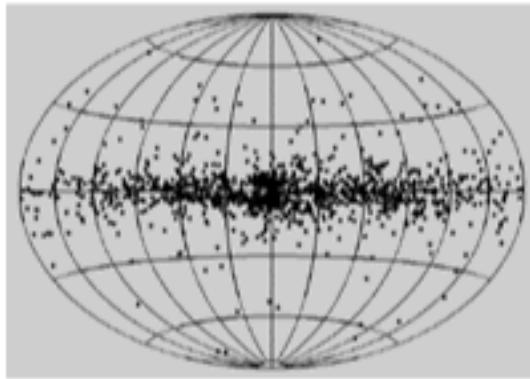


- GRB's expected to be some sort of explosion on/of Neutron stars but
- Thousand discovered
- Most neutron stars not pulsars - spun down or wrong tilt
- Millions in galaxy
- Mostly in galactic plane =Milky Way

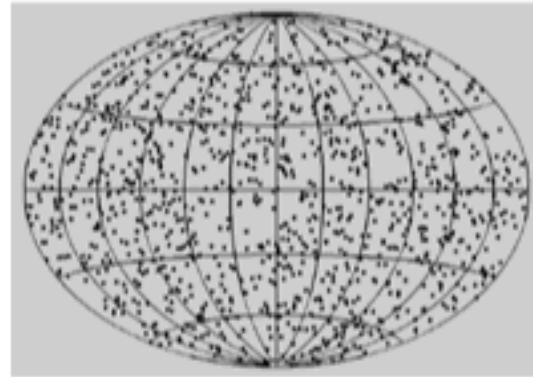
# Gamma-Ray Burst Distribution

- No concentration to: Sun, Sirius, Crab, galactic plane, galactic center, Andromeda galaxy, Virgo Cluster
- Isotropic (Same-Direction) distribution so beyond galaxy

Distribution of Gamma-Ray Bursts on the Sky



Expected



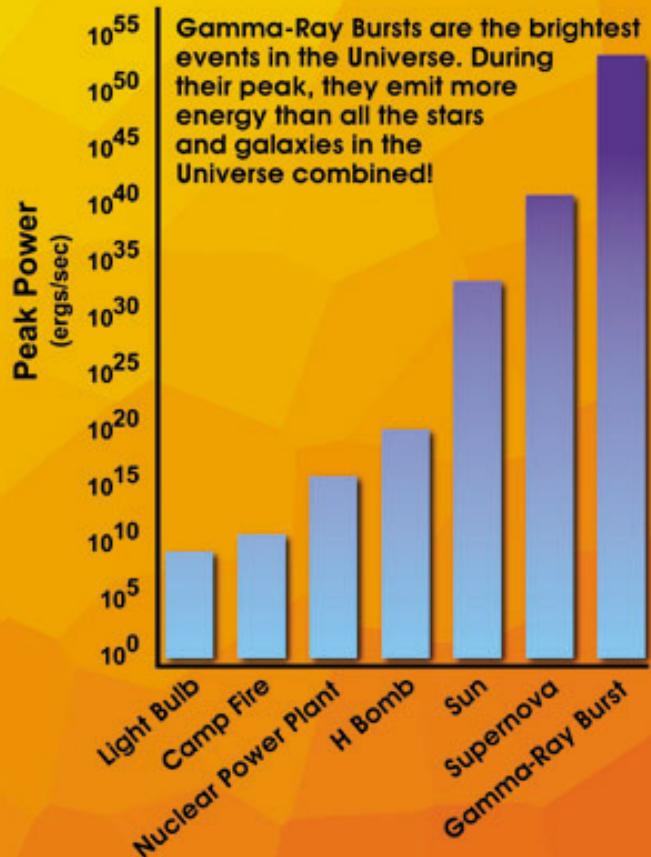
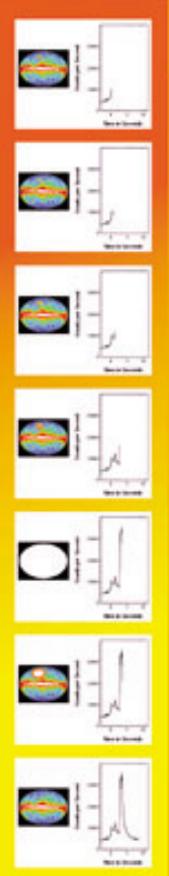
Observed



# Gamma-Ray Bursts



The Most Powerful Events  
in the Universe



IMAGINE THE UNIVERSE!

<http://imagine.gsfc.nasa.gov/>

NASA  
Goddard Space Flight Center

EW-1999-06-015-GSFC

# Power of Gamma Ray Bursts

If isotropic: Brighter than all the stars in the universe for a second

$10^{53}$  ergs is the mass of sun totally converted to energy

Beaming reduces energy but increases frequency

# Long GRB's Collapsar = Hypernova?

- 30 Solar Mass star's core collapses forming Black Hole, accretion disc forms, jets form, eventually blast through surface of star, hit surrounding material, creates gamma rays

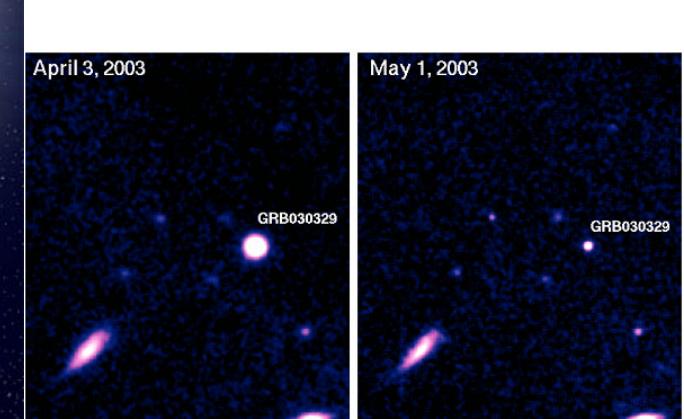
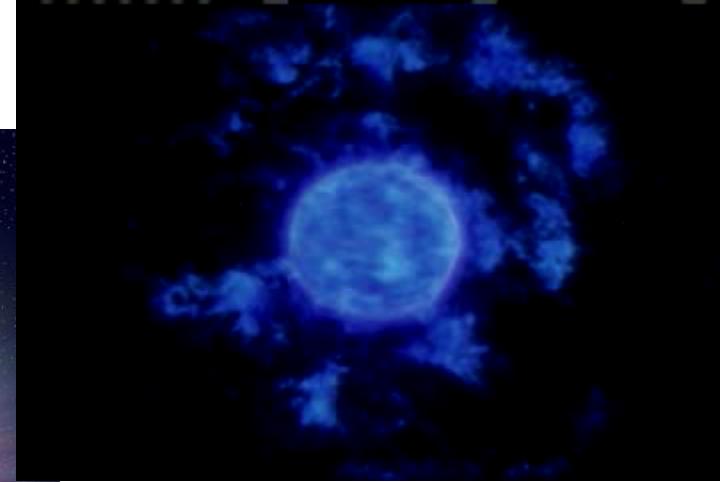
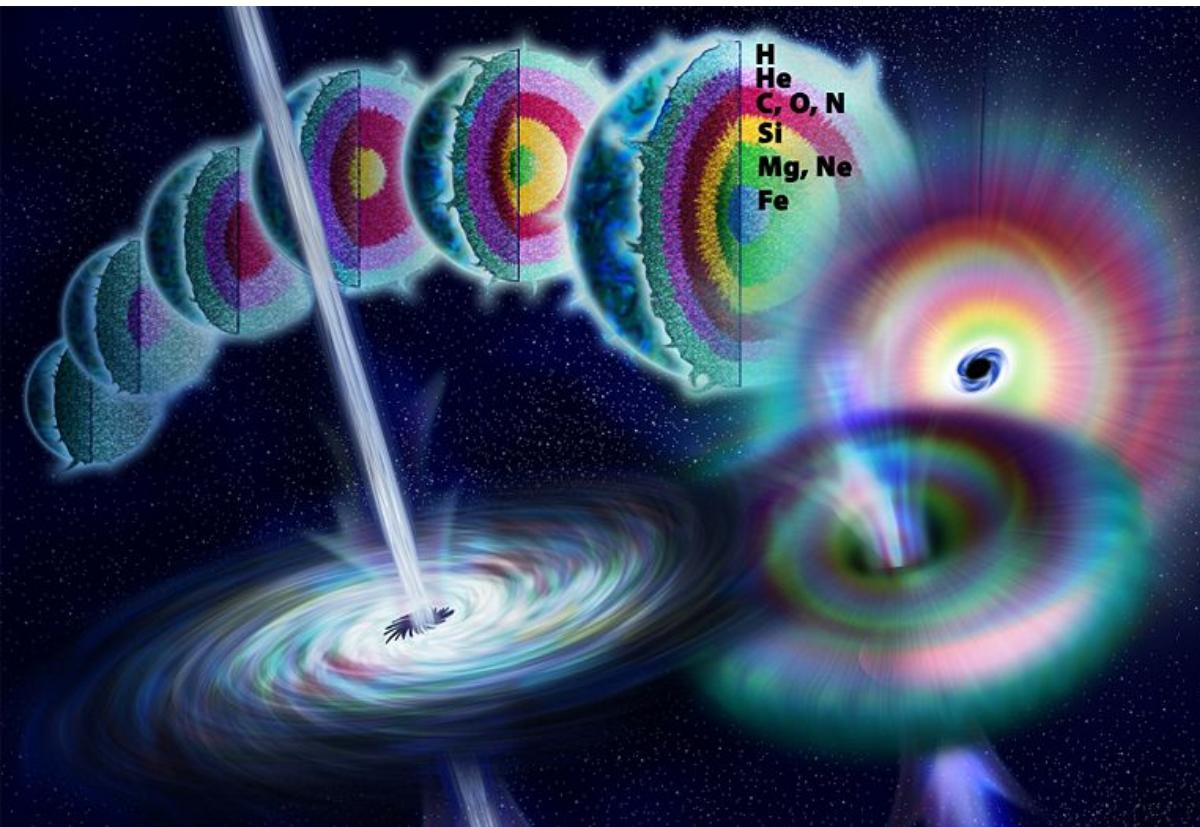
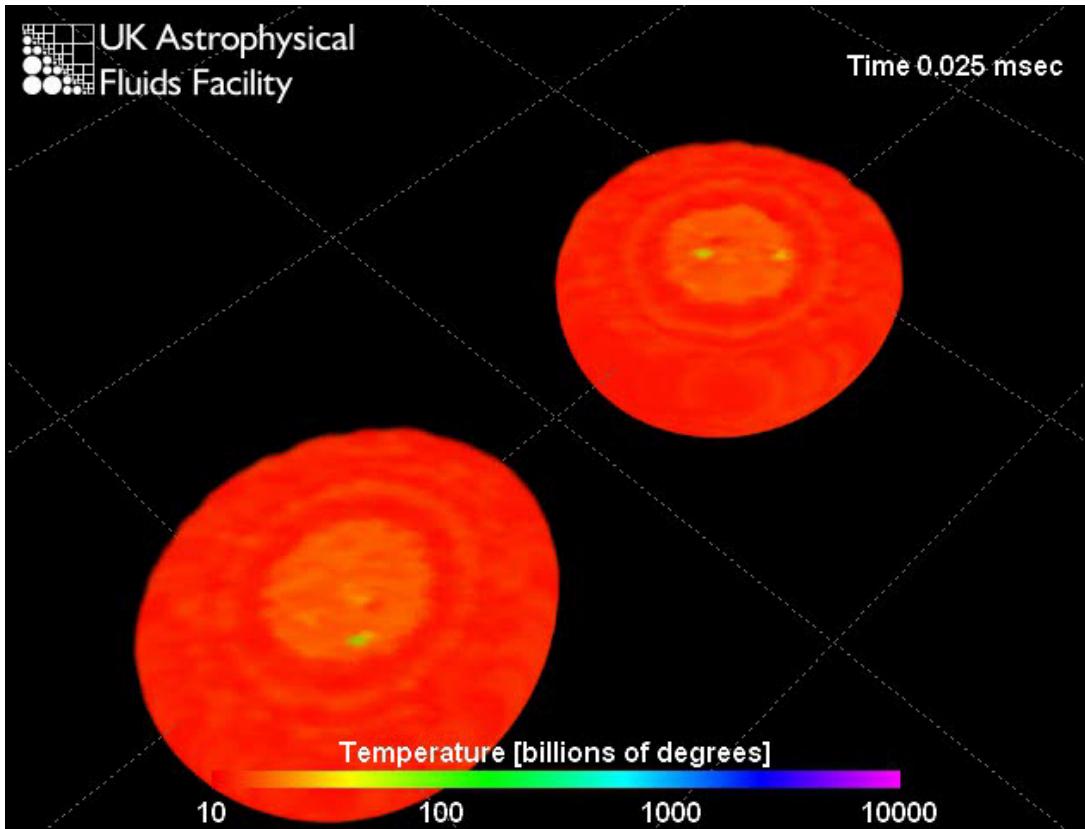


Image of Afterglow of GRB 030329  
(VLT + FORS)

ESO PR Photo 17a/05 (18 June 2005)

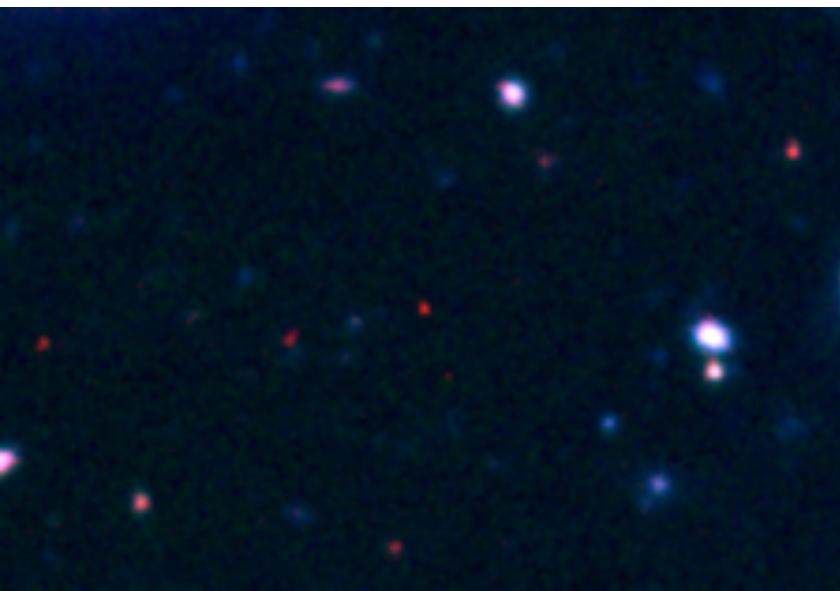
# Short GRB's: Merging Neutron Stars?

- ~30,000 binary neutron stars and 300 black hole binaries
- 2 stars 1.4 solar masses are 30km diameter and 10km apart
- This is a cut-away showing the insides



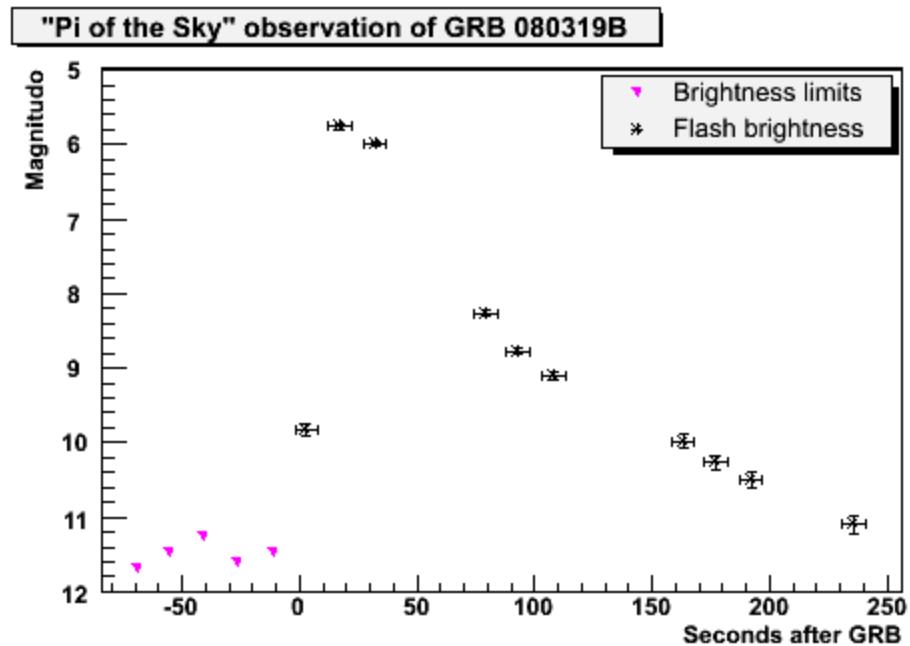
# Most Distant GRB Known to Man

- GRB090429B. Red shift of  $z=9.4$
- Progenitor star formed 500million years after Big Bang
- Light has been traveling 13.14 Billion years



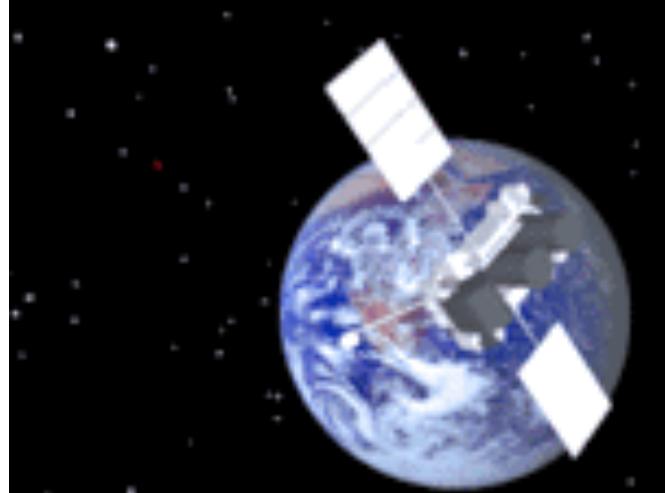
# GRB 080319B

- 7.5billion light years = half way to Big Bang
- Most intrinsically luminous object visible to eye =sun @6000ly



# GRB Effects on Earth

- Nearest binary pulsar  $\sim 1600\text{ly} = 10^4$  megaTon
- Occur every few hundred(?) million years

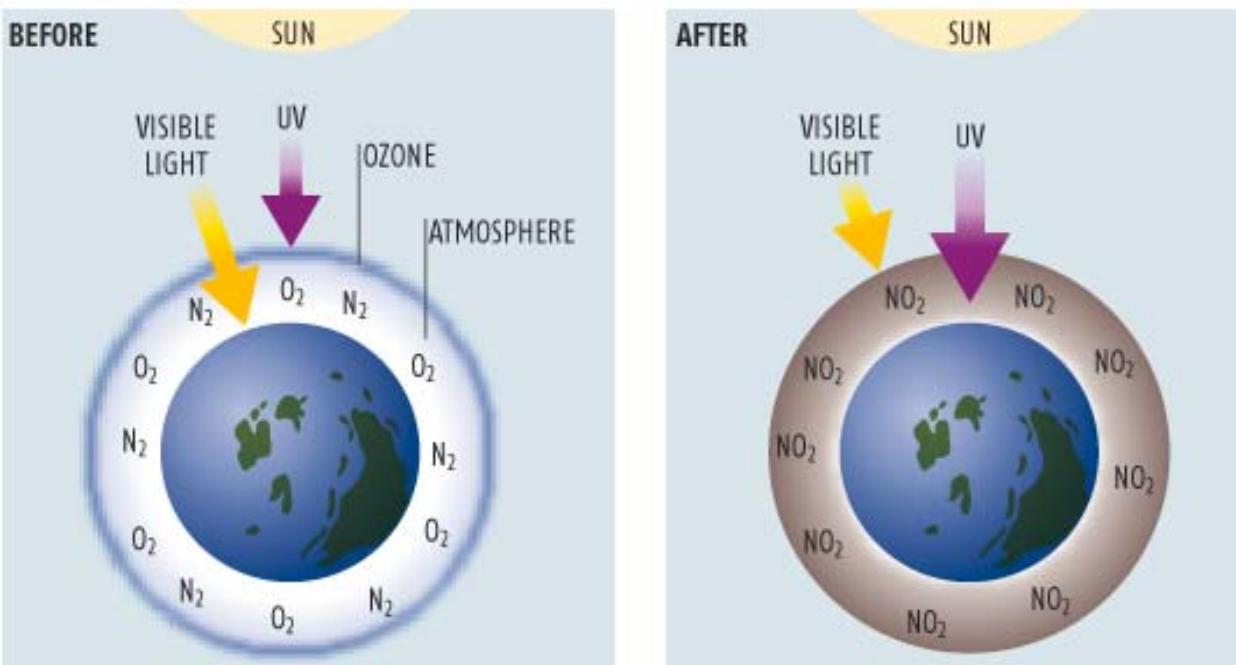


## DOOMSDAY SCENARIO

Is this what caused the Ordovician extinction?

A nearby gamma-ray burst splits nitrogen and oxygen molecules in the atmosphere, forming nitrogen dioxide.  $\text{NO}_2$  is a toxic brown gas, and it blocks out visible light from the sun. It also destroys the ozone layer, letting through dangerous levels of ultraviolet light.

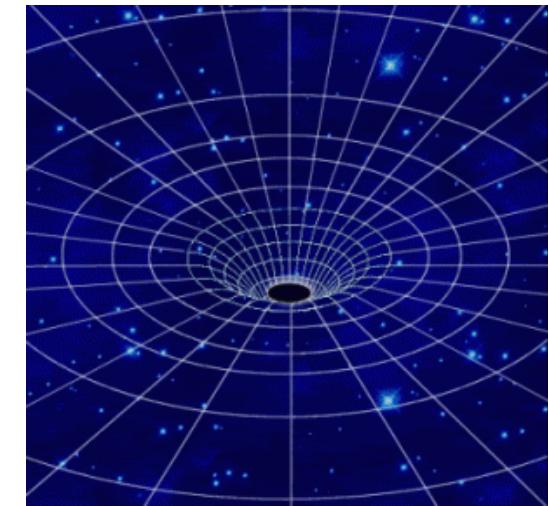
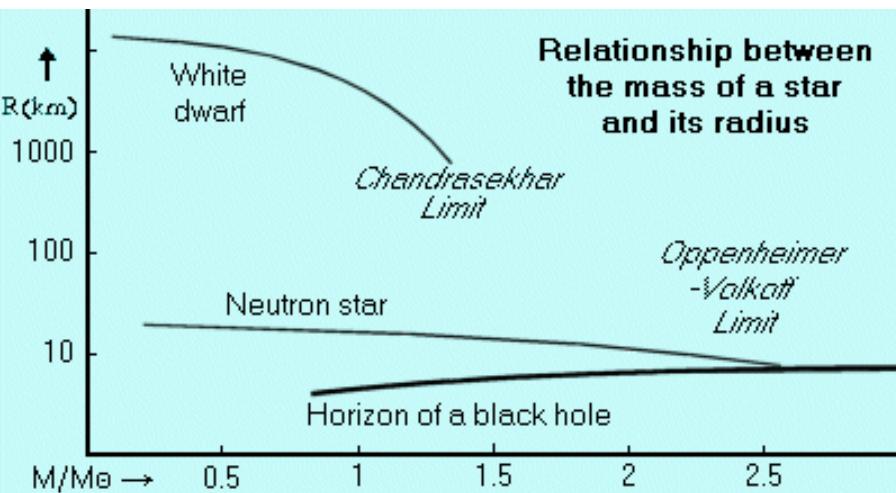
Life on land and in shallow water is devastated, while deep-sea creatures are relatively unharmed



# Karl Schwarzschild 1873-1916



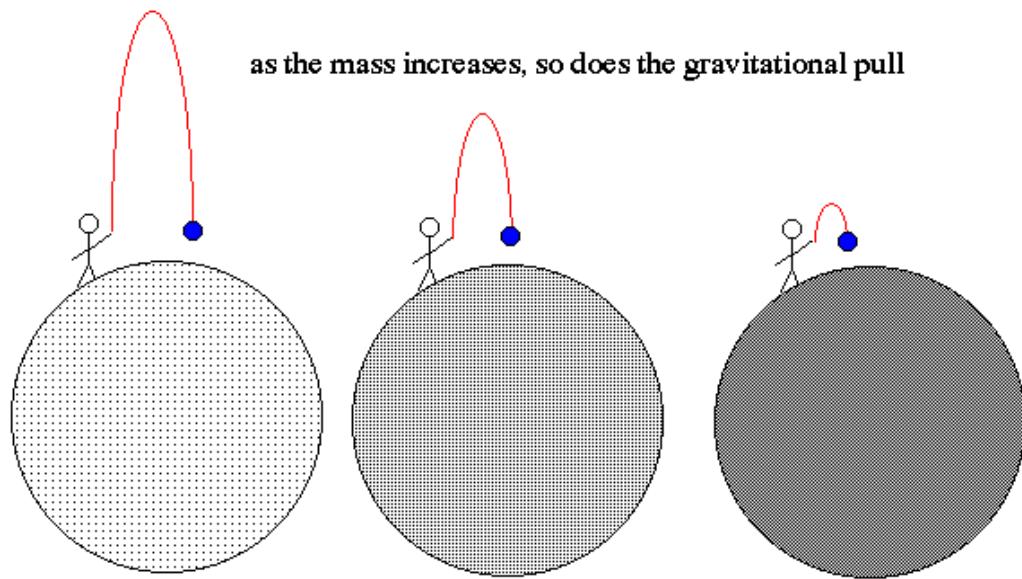
- First solution to General Relativity equations for Black Hole
- **Schwarzschild Radius**  $R_s=2GM/c^2$
- = Event Horizon
- 1 Solar Mass  $\rightarrow$  3km,  $2M_{\text{sun}} \rightarrow$  6km
- 10 Solar Mass  $\rightarrow$  30km
- Radius in km  $R_s=3 M$  in solar masses



# Black Holes

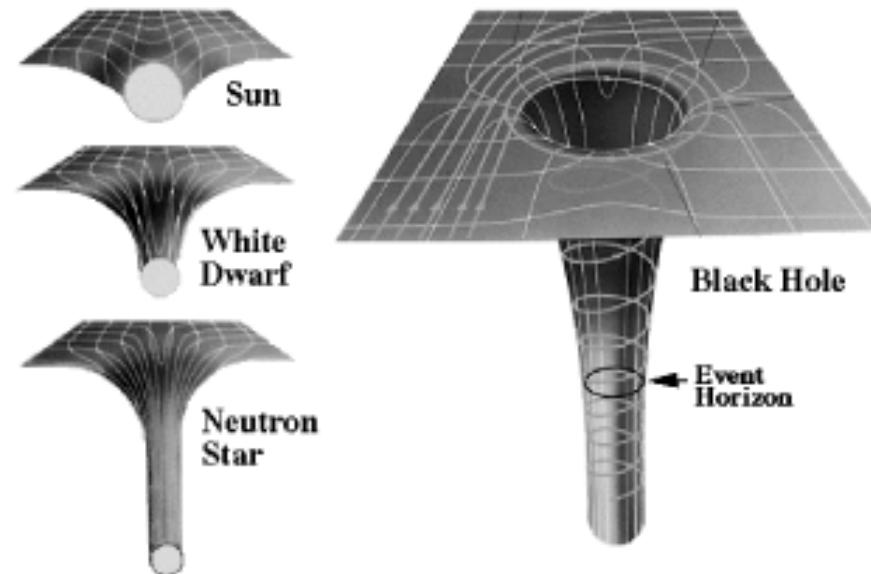
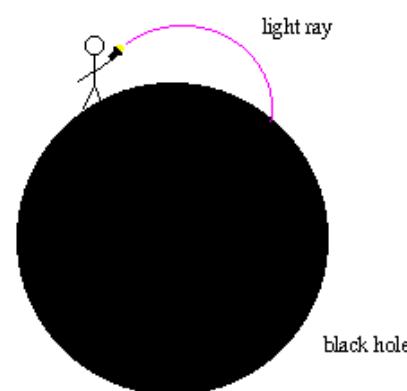
Black Hole

as the mass increases, so does the gravitational pull

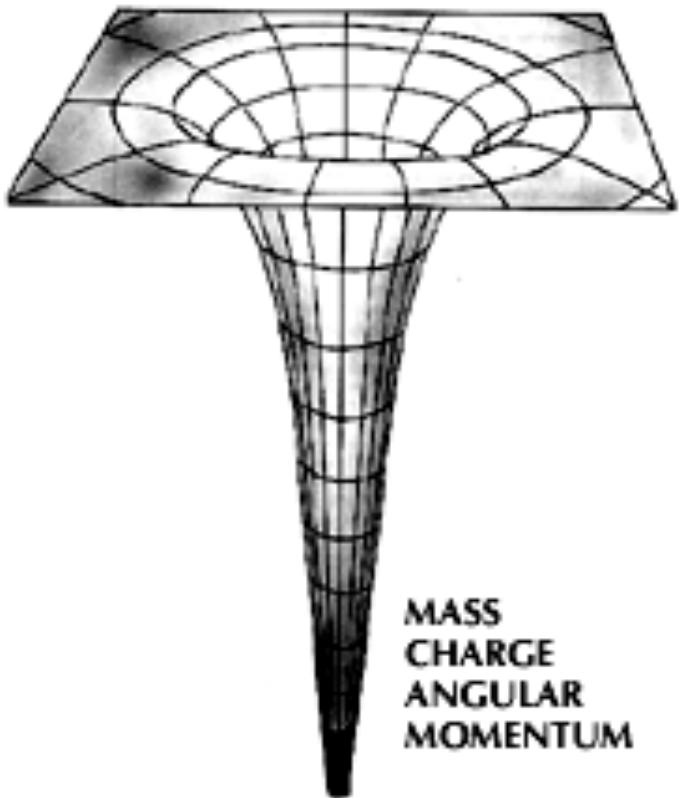
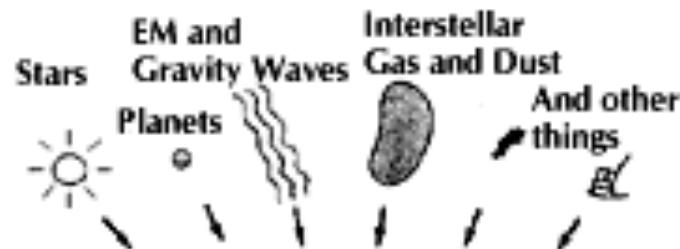


- Escape velocity of :
  - Earth=11km/sec,
  - Sun=600km/sec,
  - white dwarf= 10,000km/sec,
  - neutron star= 100,000km/sec
- At **Event Horizon** escape velocity = speed of light

if the gravitational pull is such that even light cannot escape, then a black hole forms



# Event Horizon: Law of Cosmic Censorship

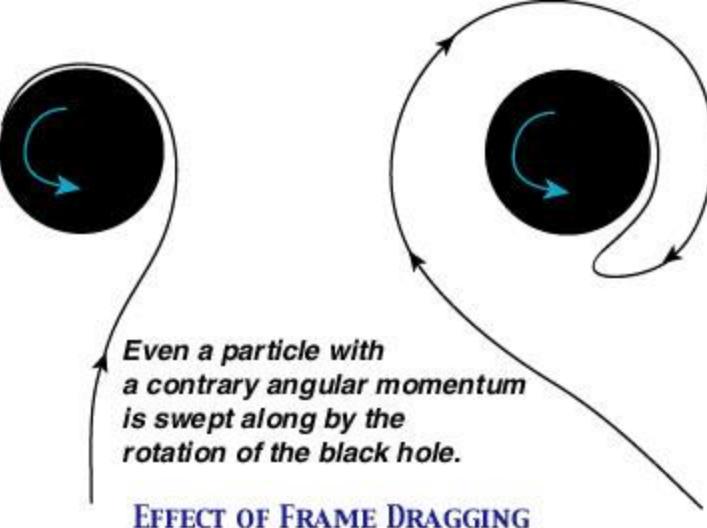


- What happens in a Black Hole stays in the Black Hole
- Only observable properties are: **Mass, Charge, Rotation**
- Information seems to be destroyed??

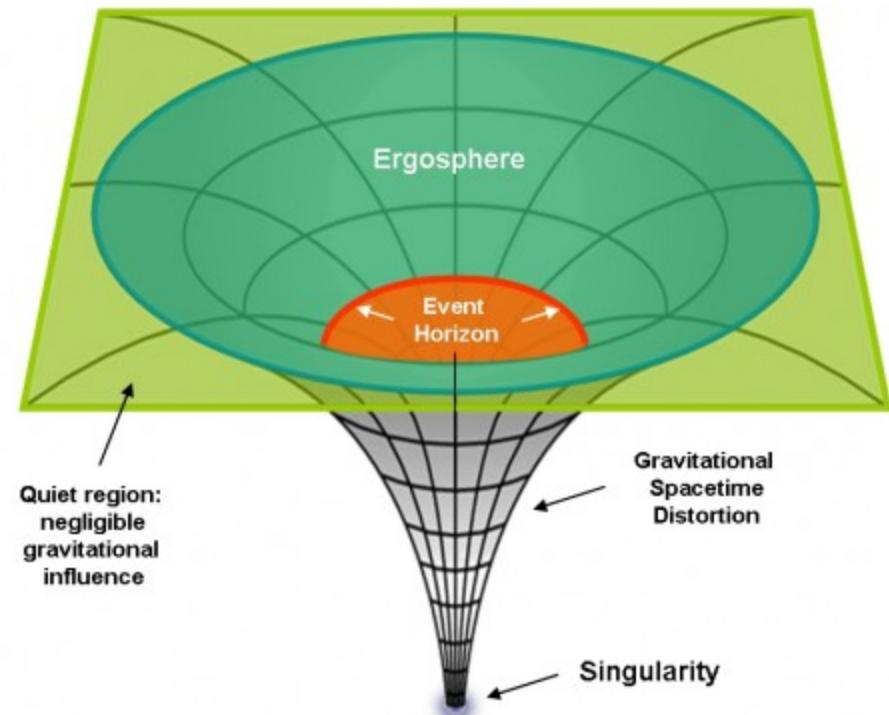
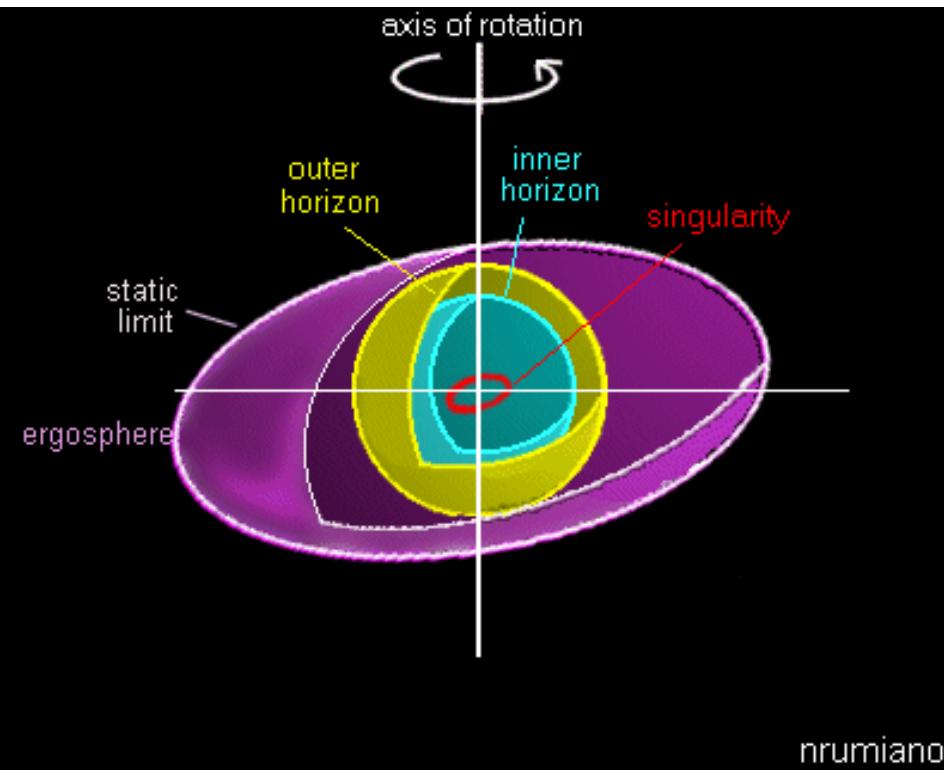


# Kerr Black Hole

- When stars collapse they are rotating so remnant black hole spins fast
- Event horizon- oblate spheroid
- Ergosphere- area where space-time rotates with black hole

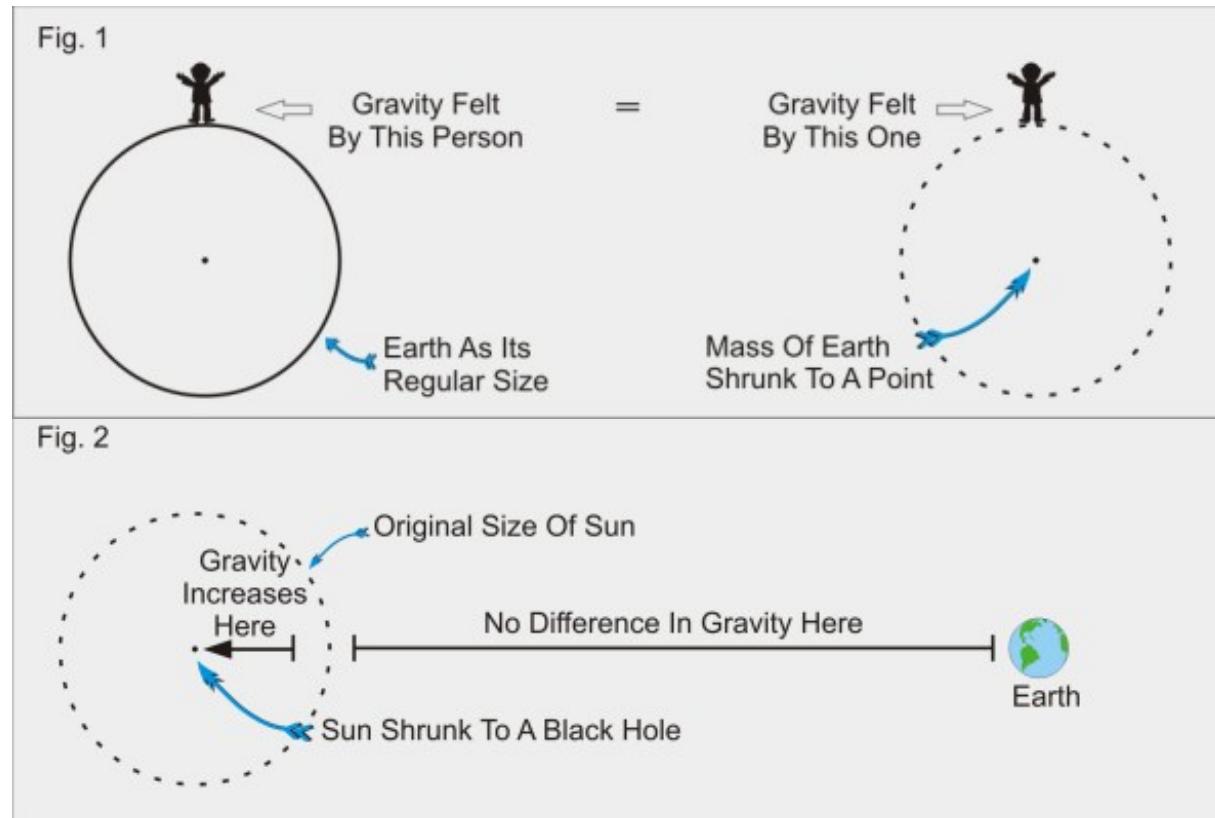


Black Hole Regions



# Black Holes are NOT Cosmic Vacuum Cleaners

- Earth replaced by Black Hole of same mass
- Sun replaced by Black Hole of same mass



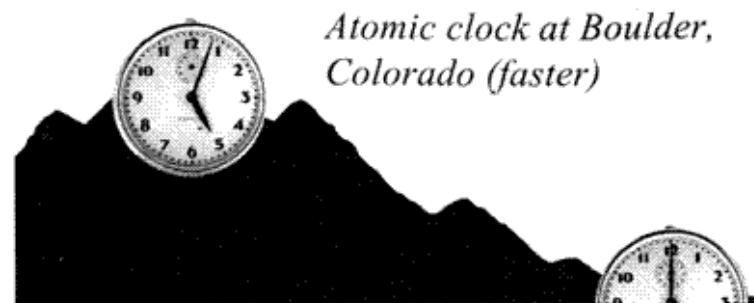
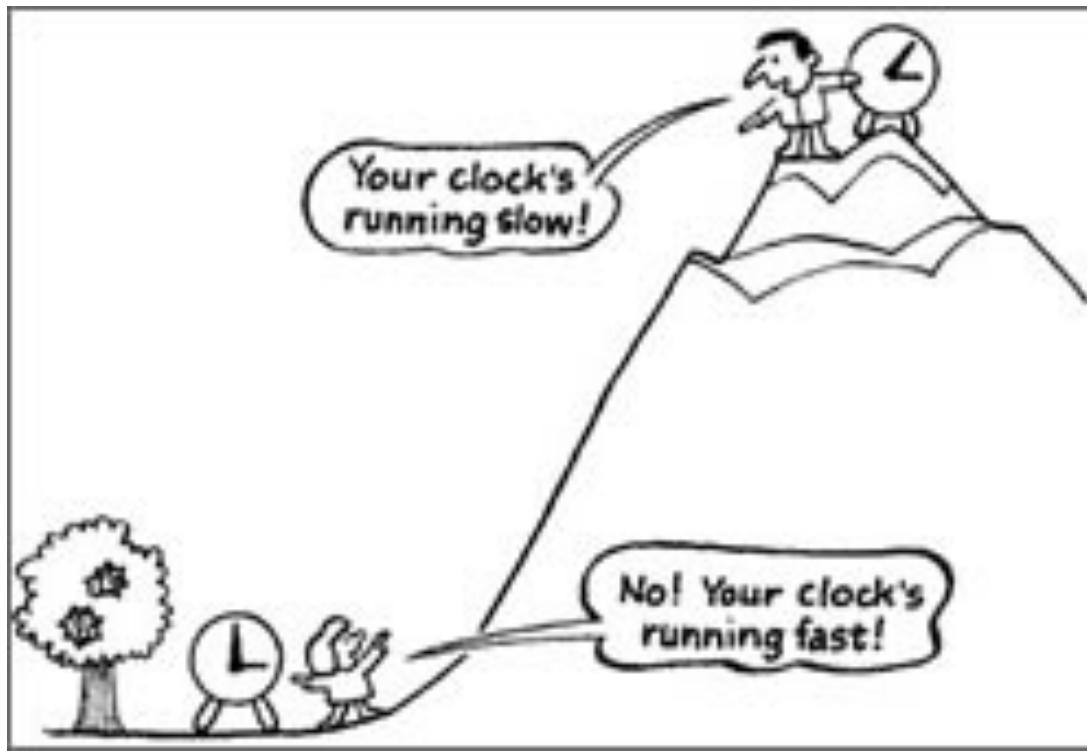
# Tidal Effects

- The part of an object closest to a Black Hole will feel the greatest force = stretched
- The sides will get squeezed
- Heats the object
- Called Spaghettification



# Time Dilation in GR

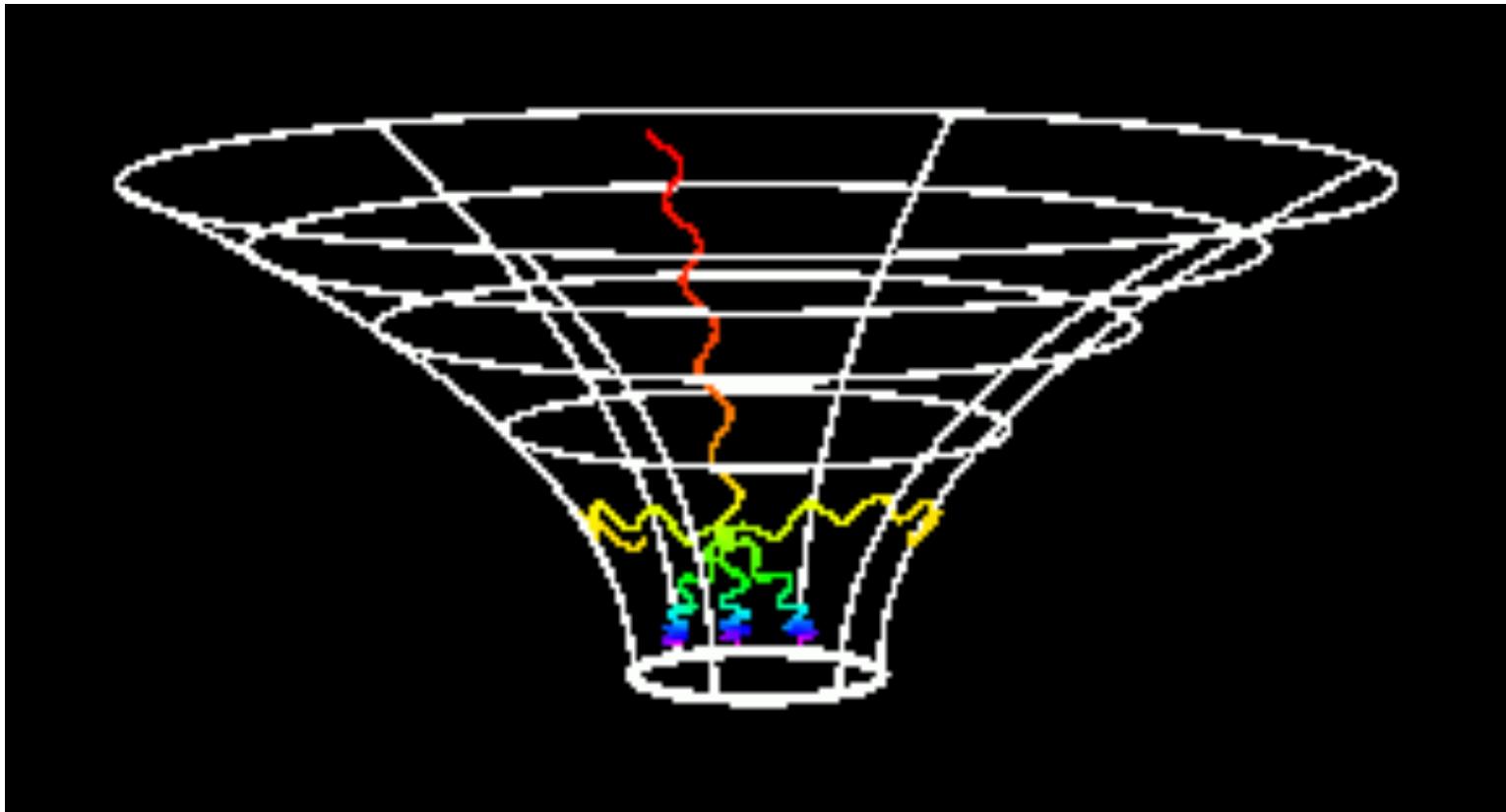
- General Relativity predicts that
- Gravity makes a clock run more slowly – seen in GPS
- As seen by distant observer time stops at event horizon of Black Hole



**Gravitational Time Dilation:** The rate at which an atomic clock records time is diminished as gravity increases.

# Gravitational Redshift

- As light comes out of a Black Hole it loses energy & thus redshifted
- At Event Horizon light infinitely redshifted



# Falling into a Black Hole



Person A falling into BH



Person outside BH sees

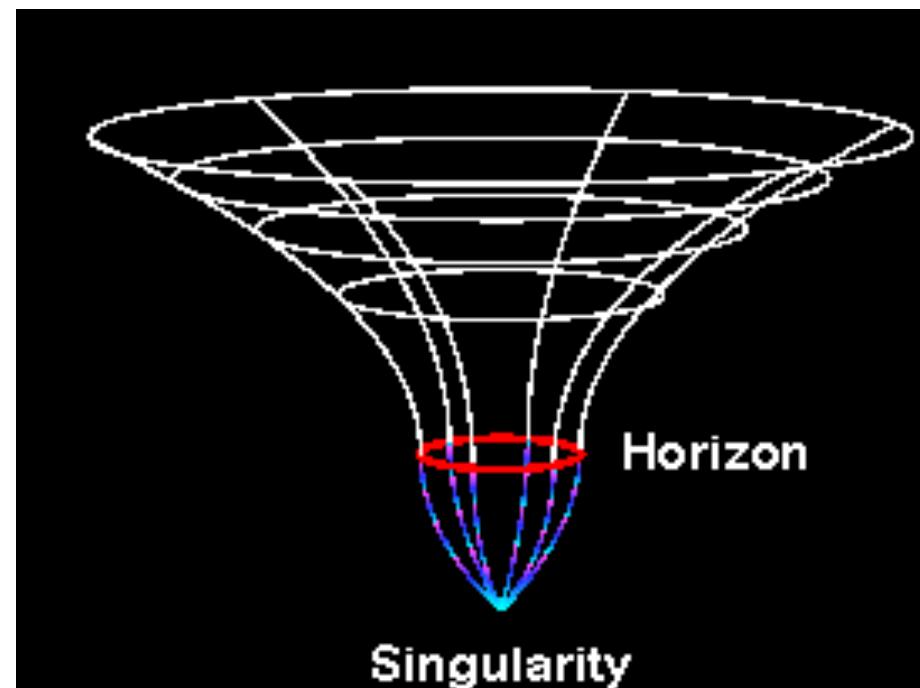
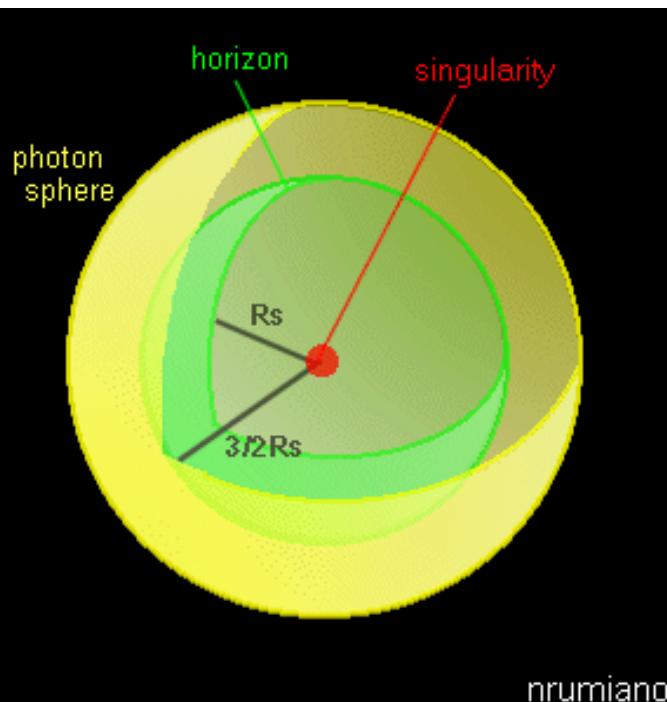
1. Photons from A redshifted.
2. Clock A slow down.
3. Person A stretched and ripped apart by tidal forces.
4. Tides heat him to millions K
5. Clock A would stop as he reached event horizon
6. Person A would notice nothing unusual at event horizon



Black Hole

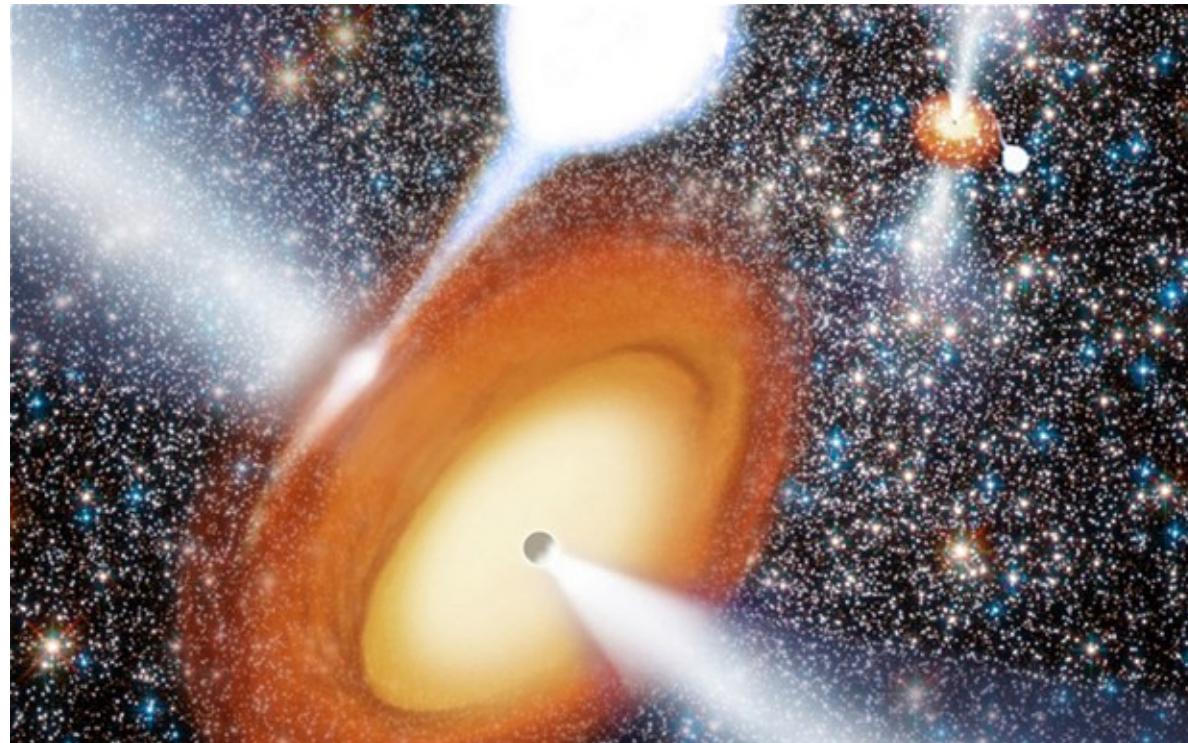
# Inside the Event Horizon

- **Singularity** is where  $R=0$        $F=GMm/R^2$  becomes infinite
- Density becomes infinite
- General Relativity breaks down and Quantum Mechanics does not include gravity so we have no theory to describe the singularity



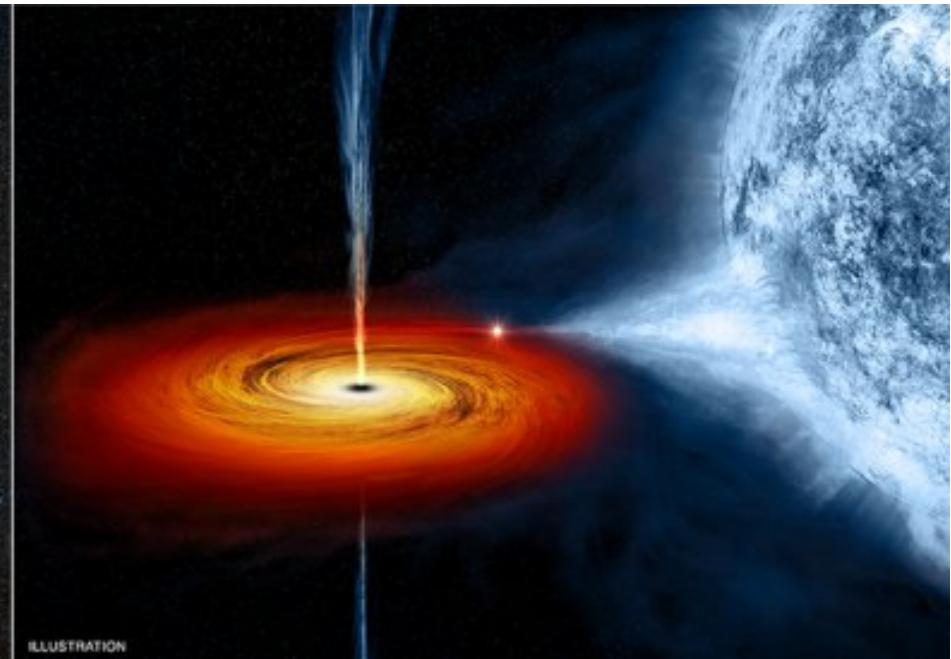
# How Many Black Holes?

- A supernova every hundred years and galaxy is 10 billion years old so 100million remnants so millions of stellar mass Black Holes
- Chances of running into one – close to zero



# Evidence for Black Holes: Cygnus X-1

- O-type Supergiant
- 6070 light years
- $14.8M_{\text{sun}}$  Black Hole
- 5.600d orbital period
- X-rays flicker in 0.01sec = 3,000km size
- Spins at 800 times per second



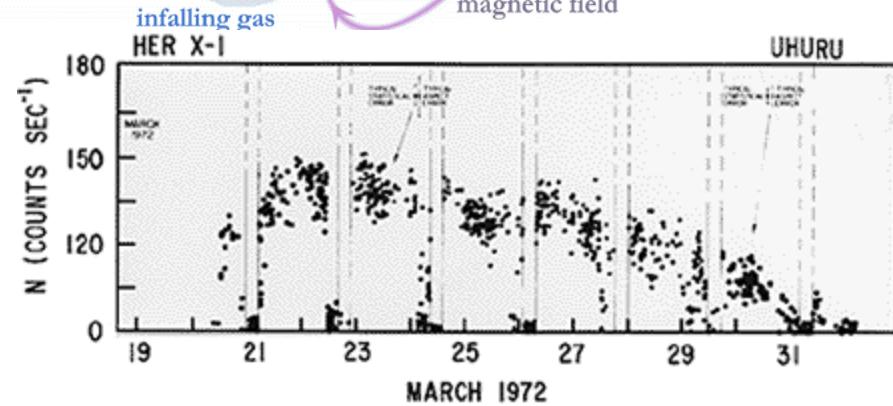
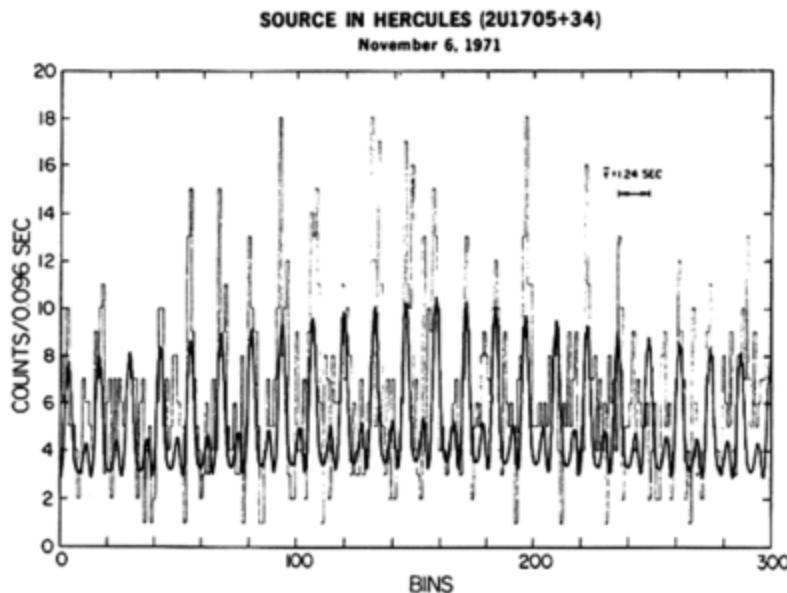
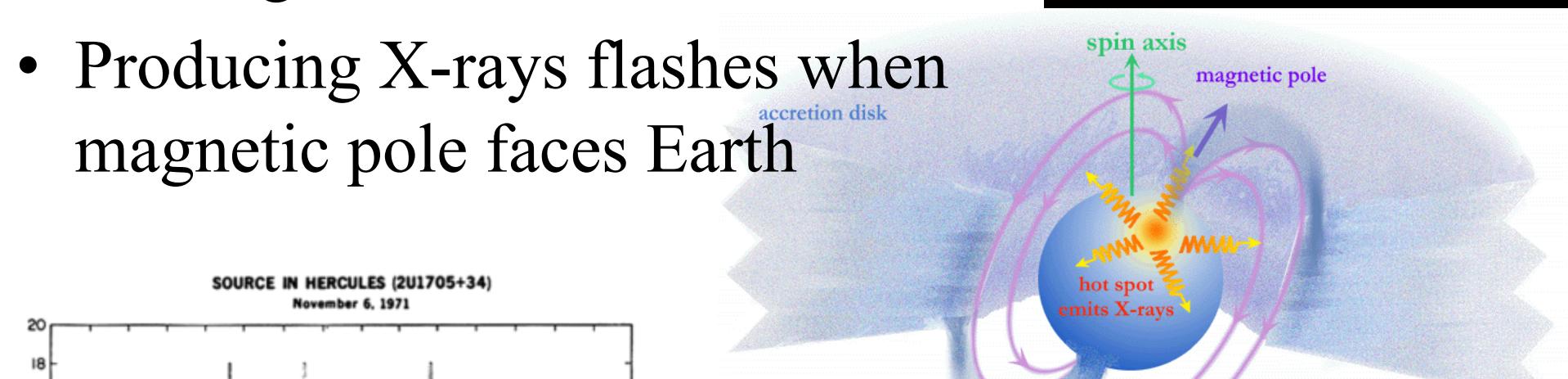
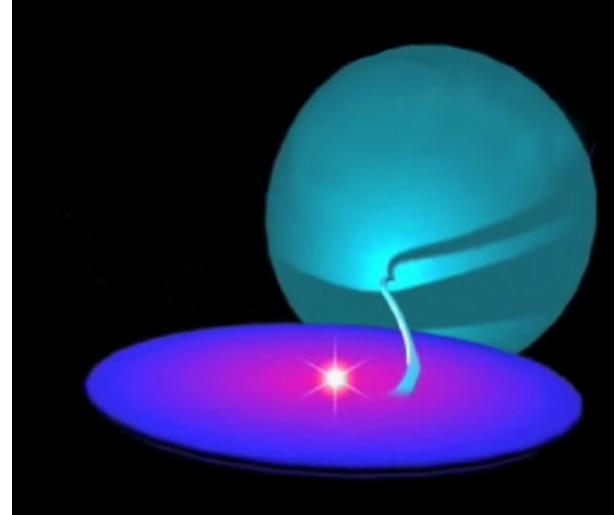
Which of the following statements is FALSE:

- a. Pulsars are neutron stars that have light beams like a light house
- b. Millisecond pulsars are neutron stars spun up by mass transfer from a companion
- c. Gamma Ray Bursters are very powerful distance sources of Gamma Rays
- d. Black holes have an event horizon where the velocity of escape equals the speed of light
- e. All of these are correct



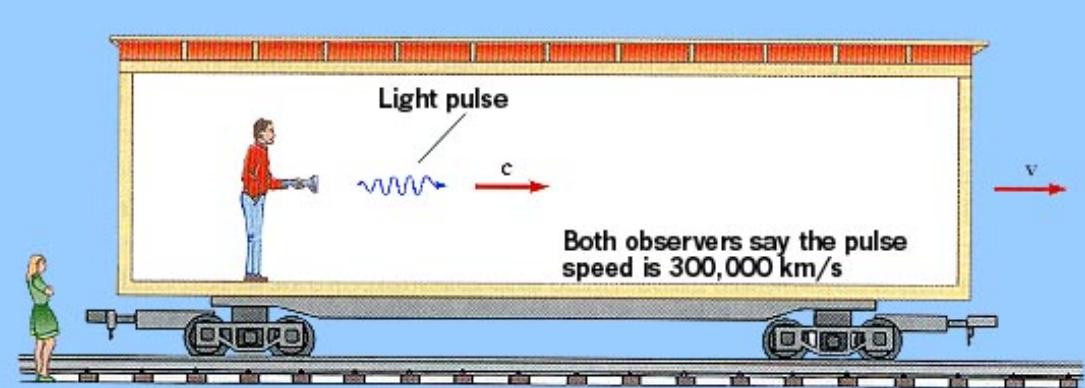
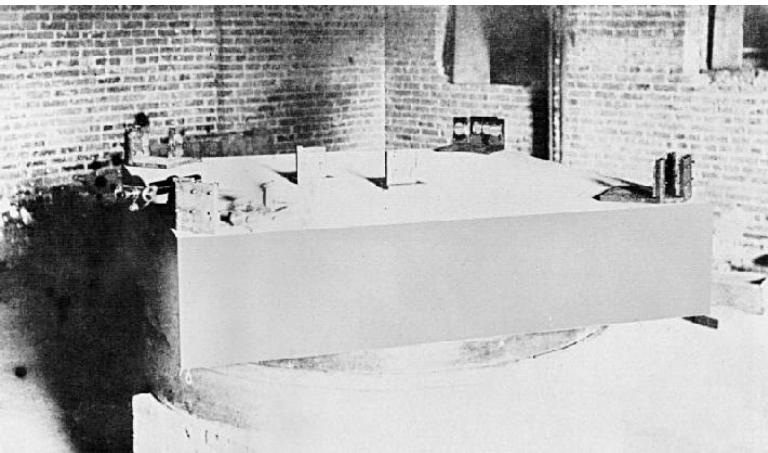
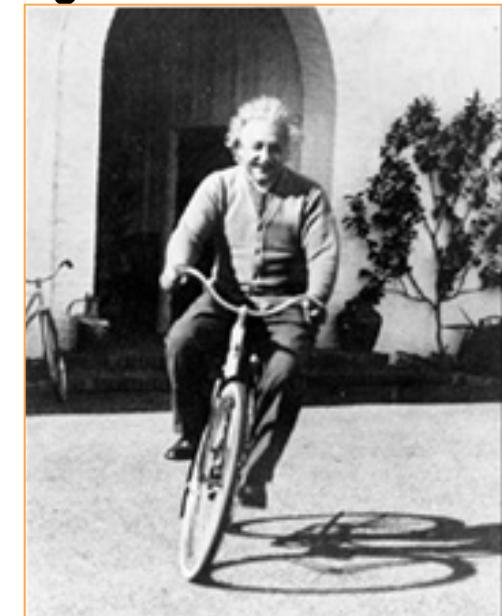
# Neutron Star Binaries

- Hydrogen falls from companion (Her X-1 is eclipsing)
- Heating accretion disk and
- Producing X-rays flashes when magnetic pole faces Earth



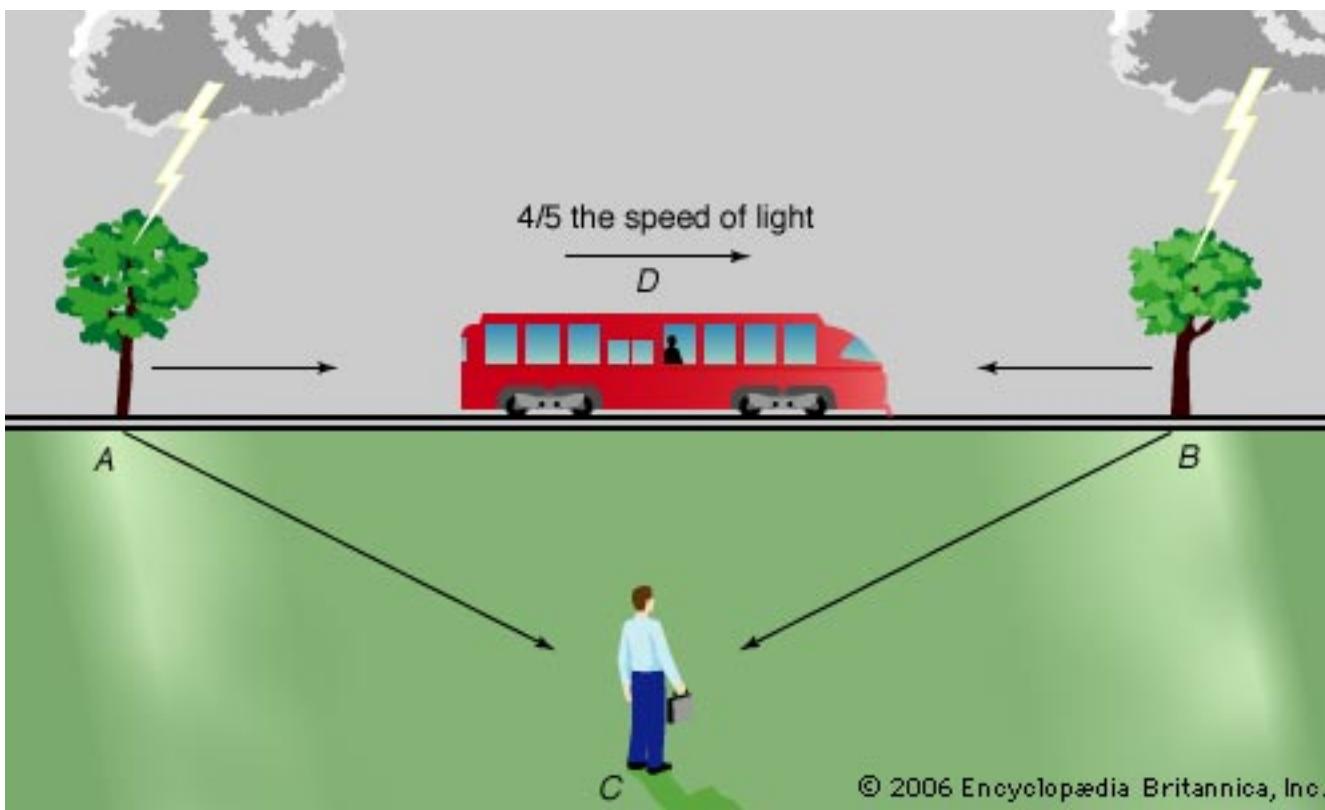
# Special Theory of Relativity 1905

- 1<sup>st</sup> Principle – Physical laws are the same for all observers (not accelerated)
- 2<sup>nd</sup> Principle of Invariant Light Speed – The velocity of light is a constant and will be the same for all observers. Can Not tell who is moving.
- $E=Mc^2$  Mass is Energy & Energy is Mass



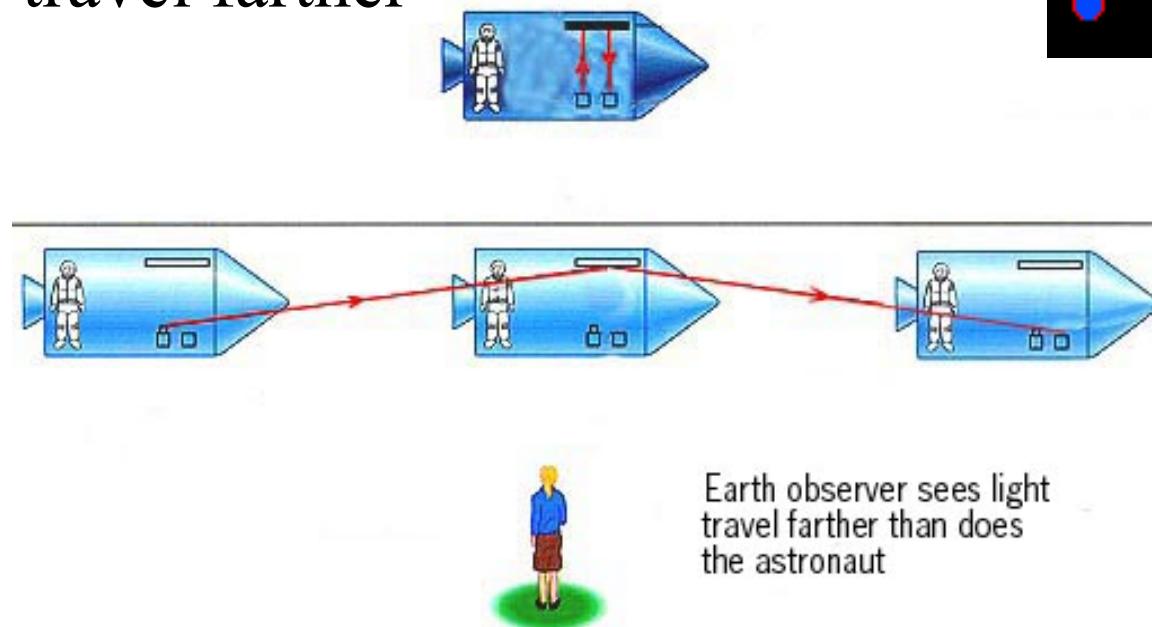
# Simultaneity

- The observer on the ground sees the lightning bolts hit simultaneously BUT the moving observer on the bus sees lightning bolt B before A --- Not simultaneous



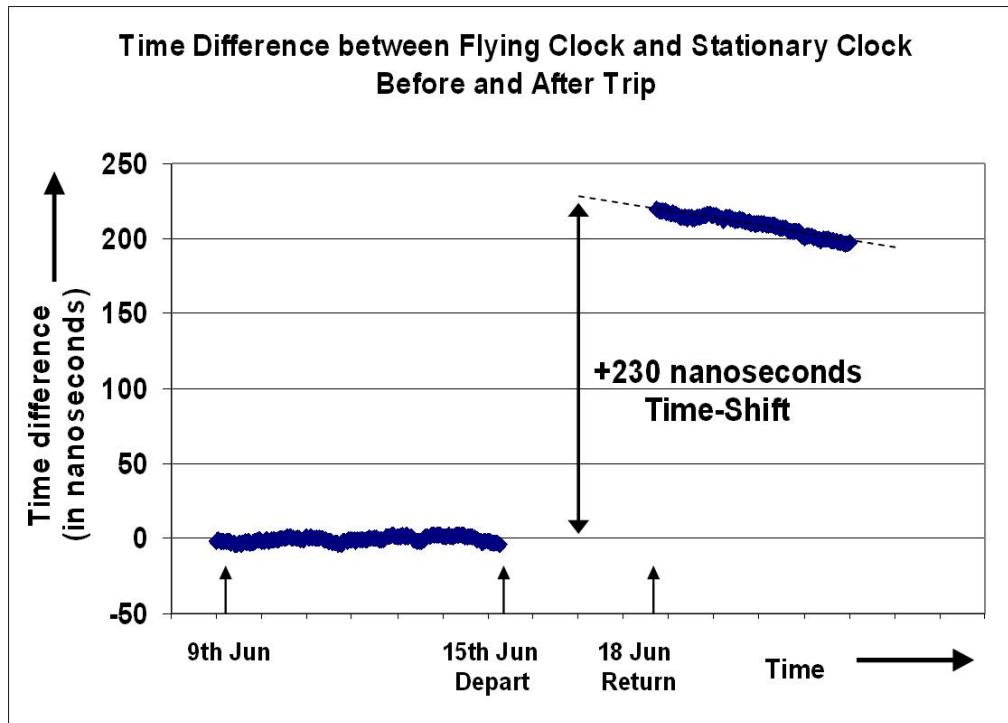
# Special Relativity: Time Dilation

- Red&Blue make identical clocks with light pulses & mirrors – simultaneous pulses
- If Blue moves near the speed of light his clock runs slower relative to Red's because his light pulses need to travel farther



# Time Dilation Observation

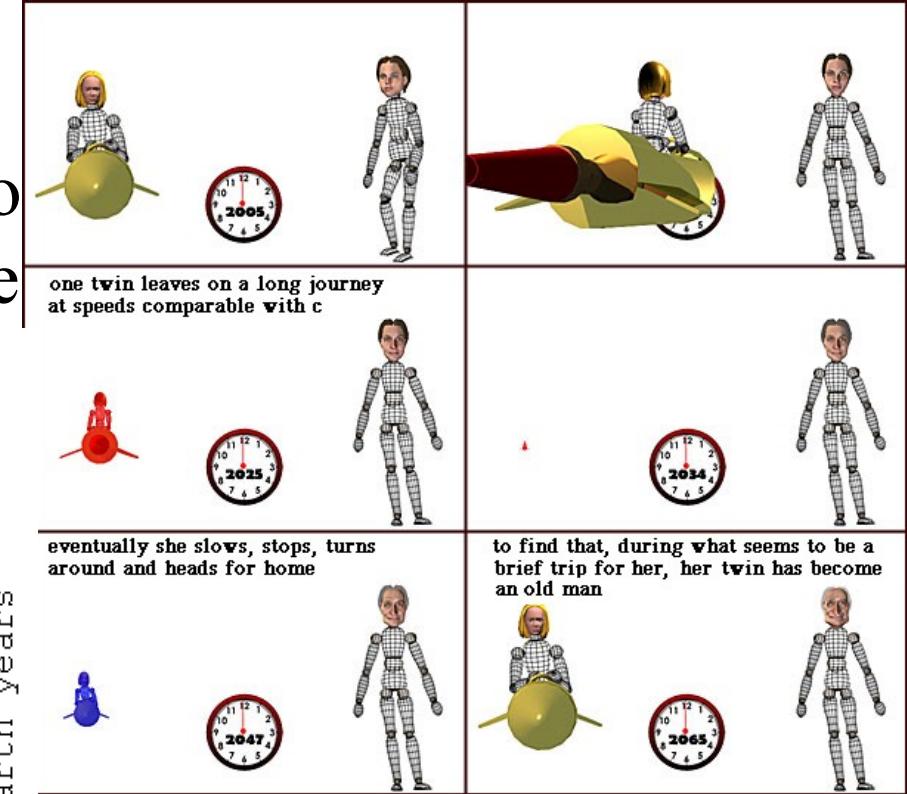
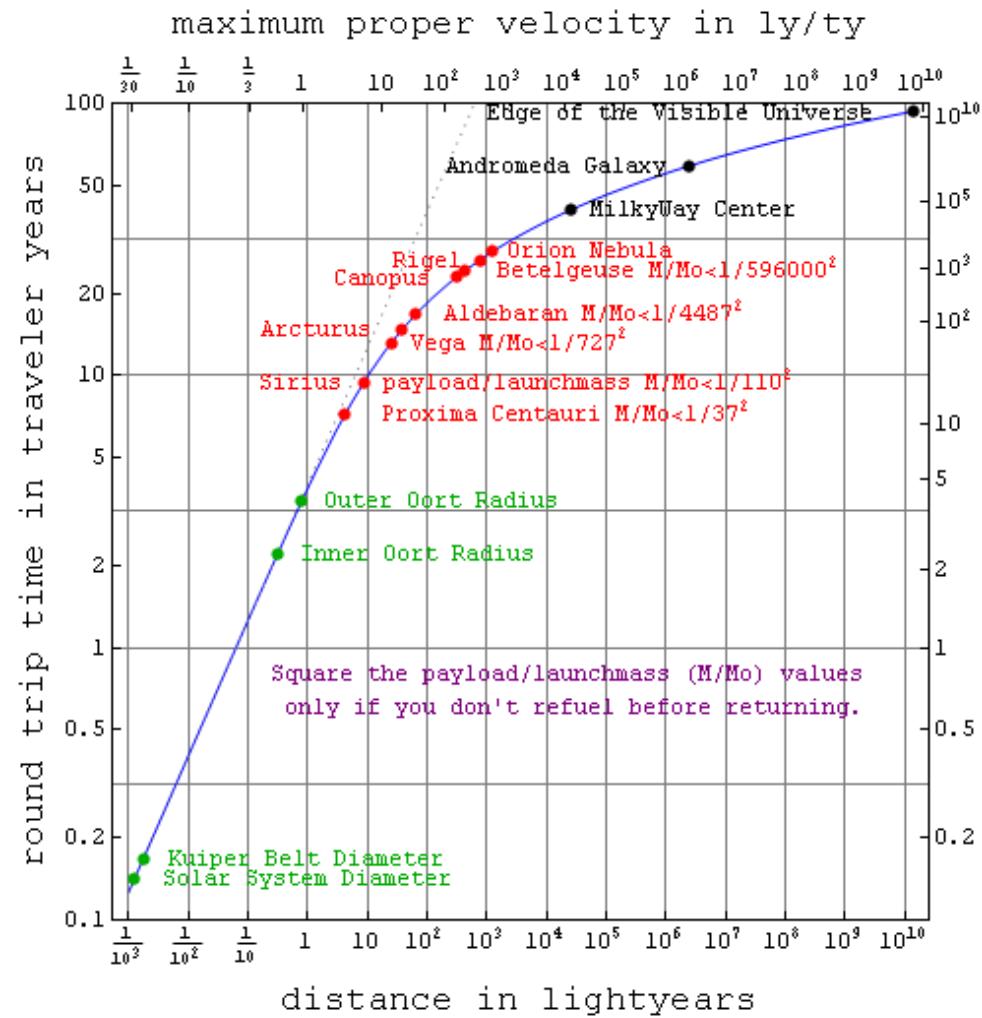
- BBC1 took atomic clock around world on airplane
- Moving clock predicted to be 246nanoseconds slow
- Measured to be  $230 \pm 20$ nanoseconds



# Twin Paradox

- Speed makes a time machine to slow time & travel to the future

## 1-Gee Accelerated-Twin Round Trips

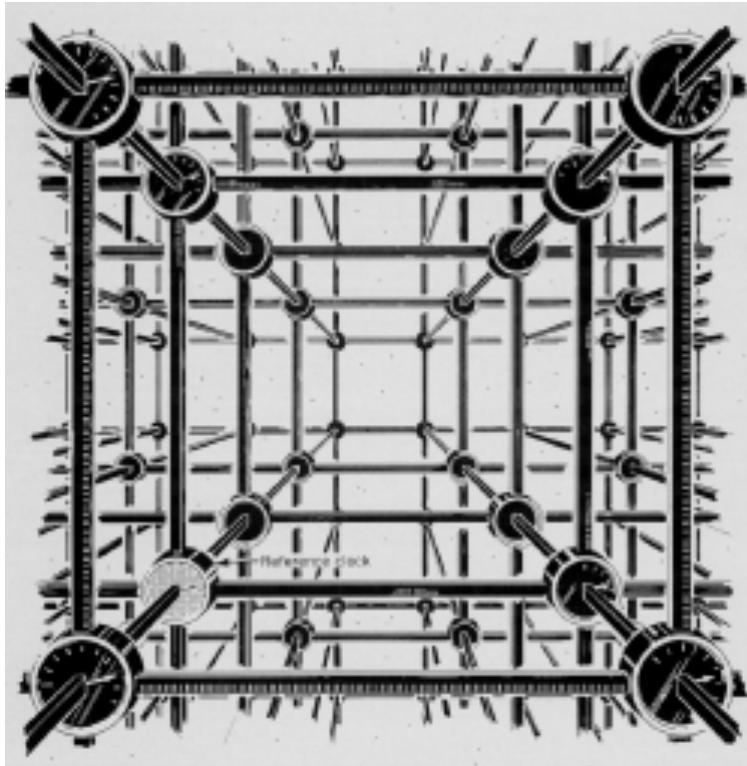


# Time Travel

- Special Relativity: speeds near light slow your clock
- GR: Strong gravitational fields slow your clock
- So you can slow your clock as much as you want BUT you can not make it run backward



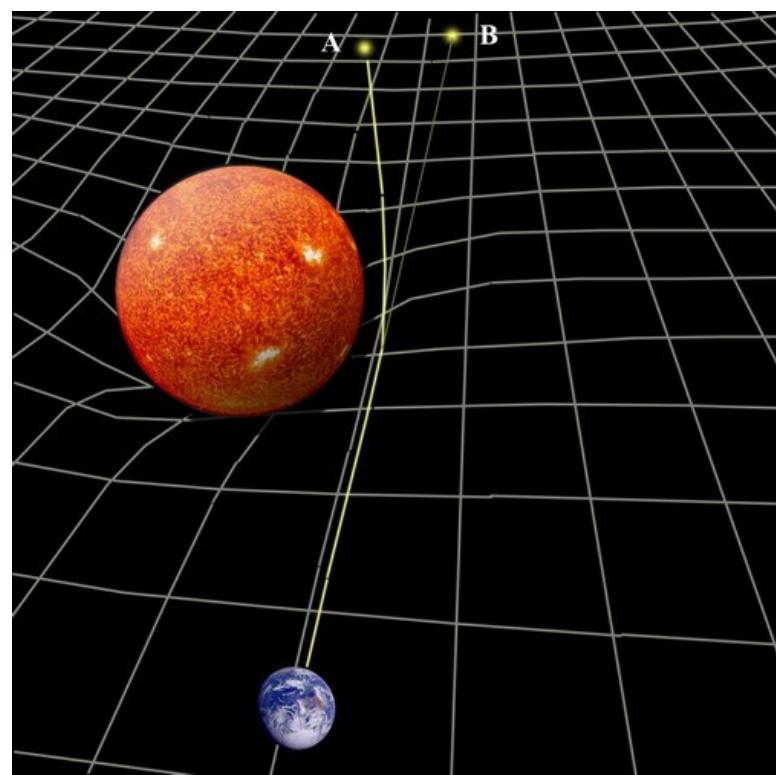
# Spacetime



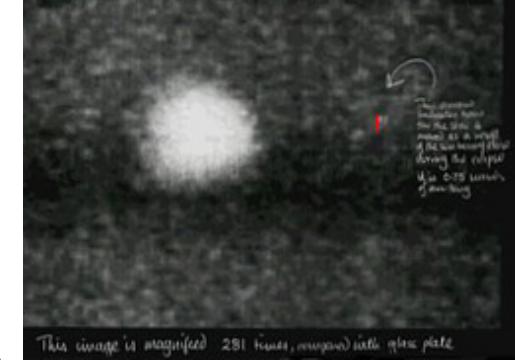
- Because each observer has his/her own clock
- Everything has a position in space and time so **Spacetime** is  $x,y,z$  and  $t$

# General Theory of Relativity 1915

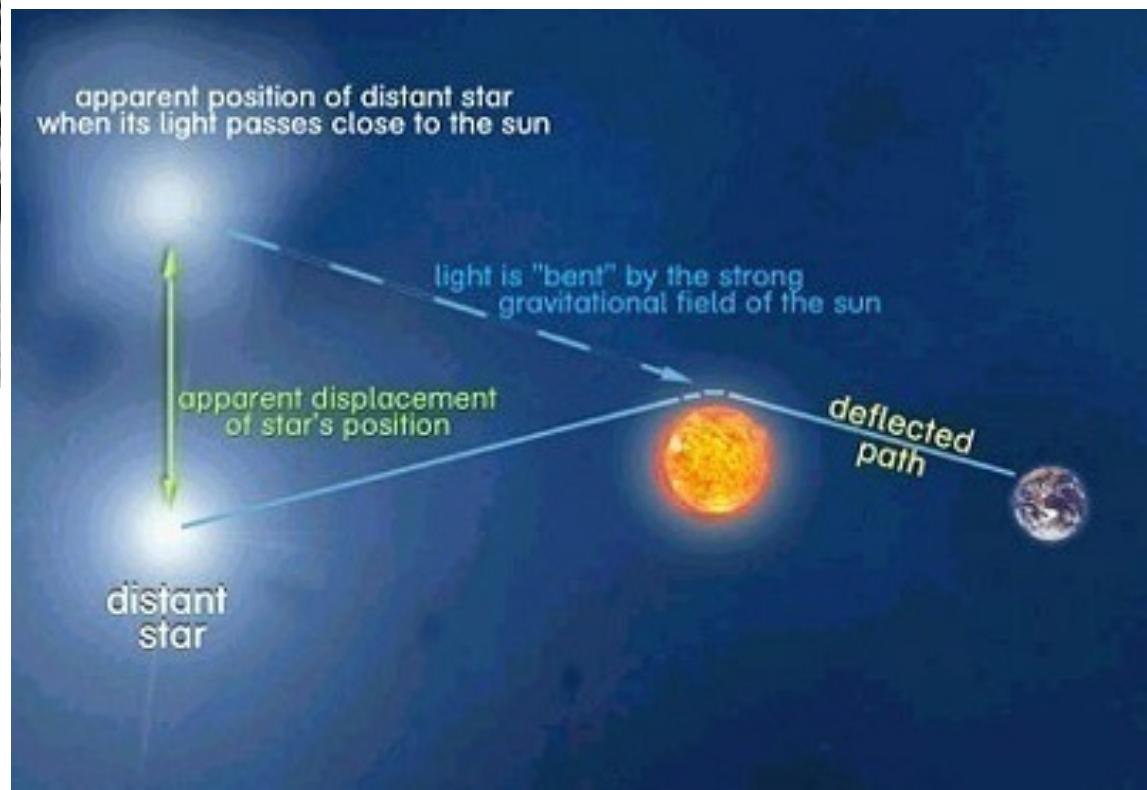
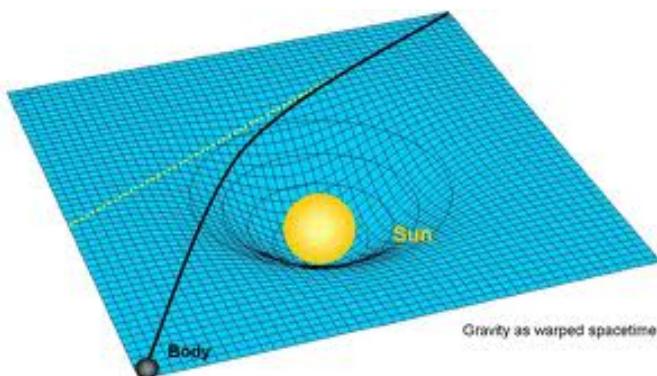
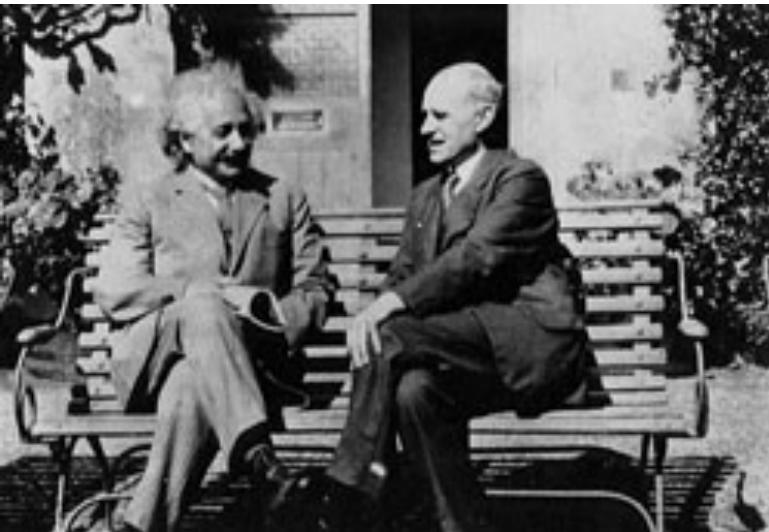
- Applies to accelerated motion not just constant velocity
- Spacetime tells matter how to move, and matter tells spacetime how to curve.”
- Describes Gravity, Black holes, the Universe      BUT
- Incompatible with Quantum Theory



# 1<sup>st</sup> Test of GR: Gravitational Bending of Light

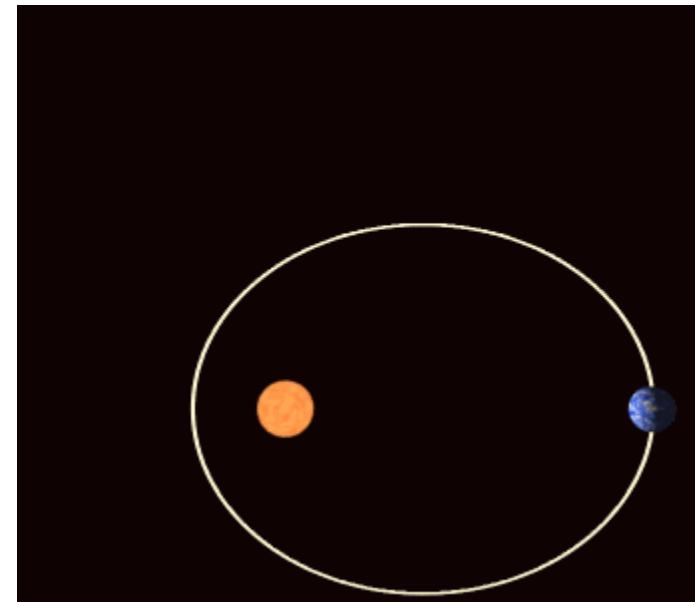
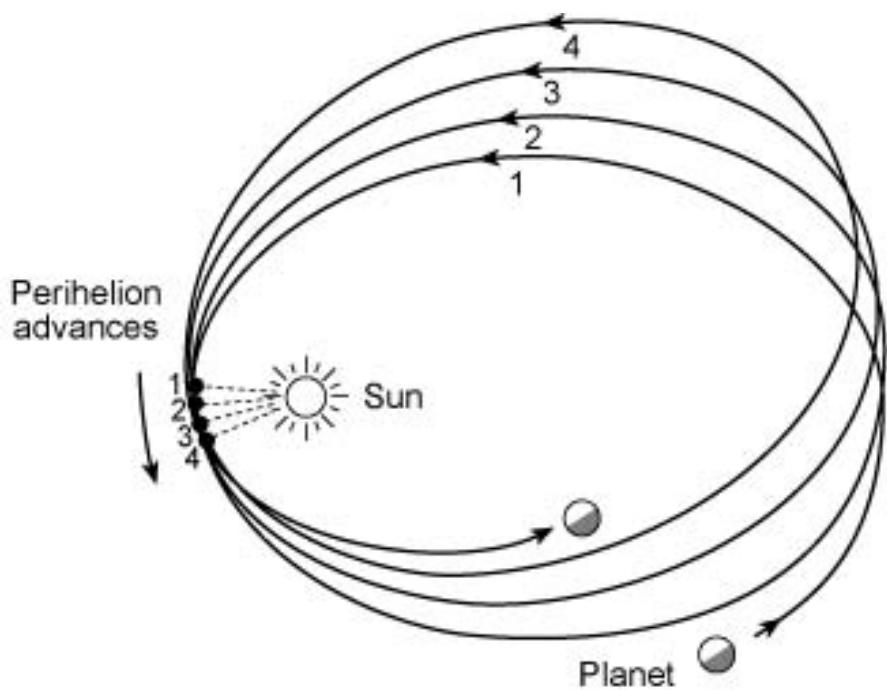


- Positions of stars seen during a solar eclipse displaced as predicted by General Relativity;



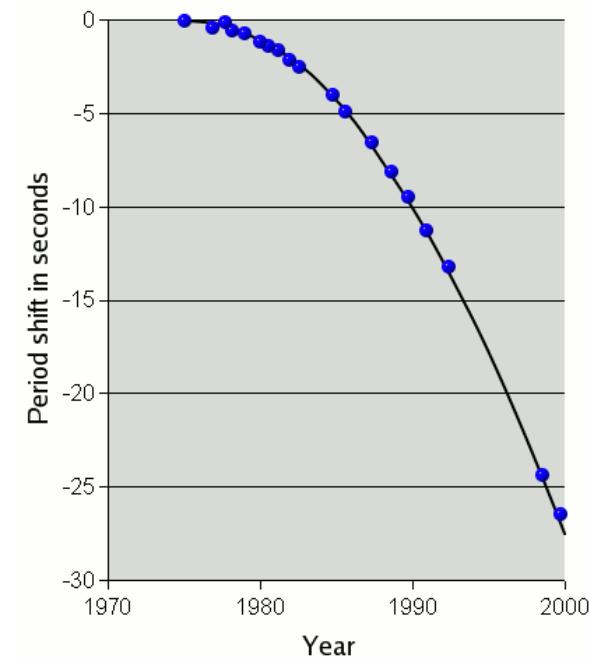
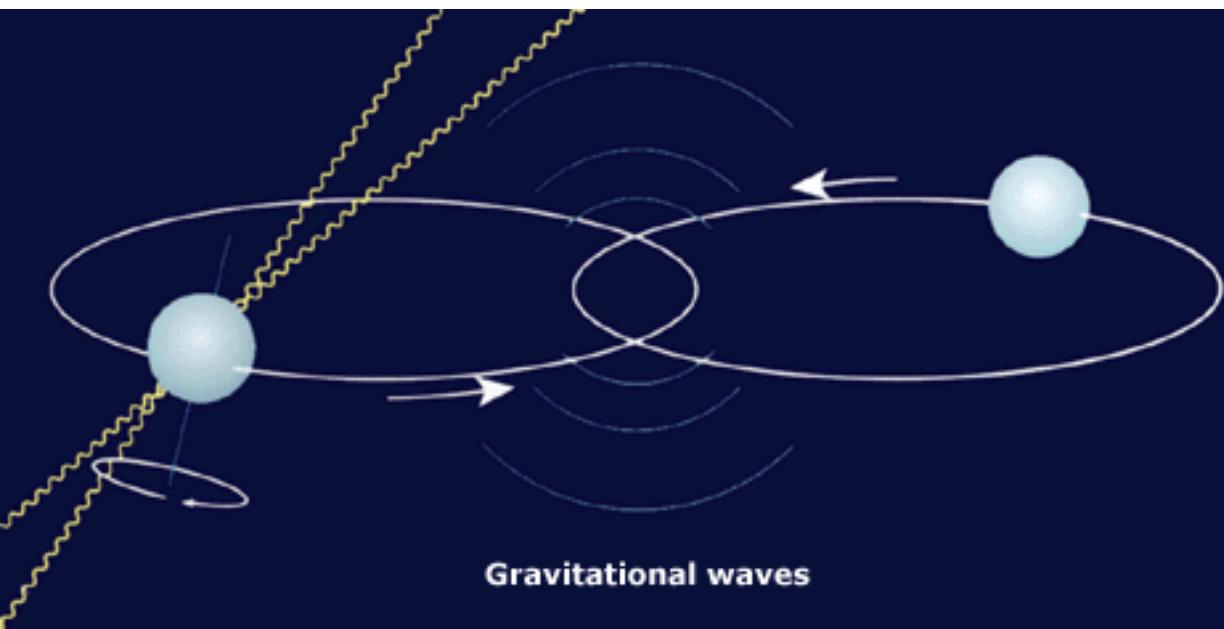
# 2<sup>nd</sup> Test of General Relativity : Precession of Mercury's Orbit

- General Theory of Relativity correctly predicts the precession of Mercury's orbit
- Evidence can support theory or disprove --- never prove theory correct



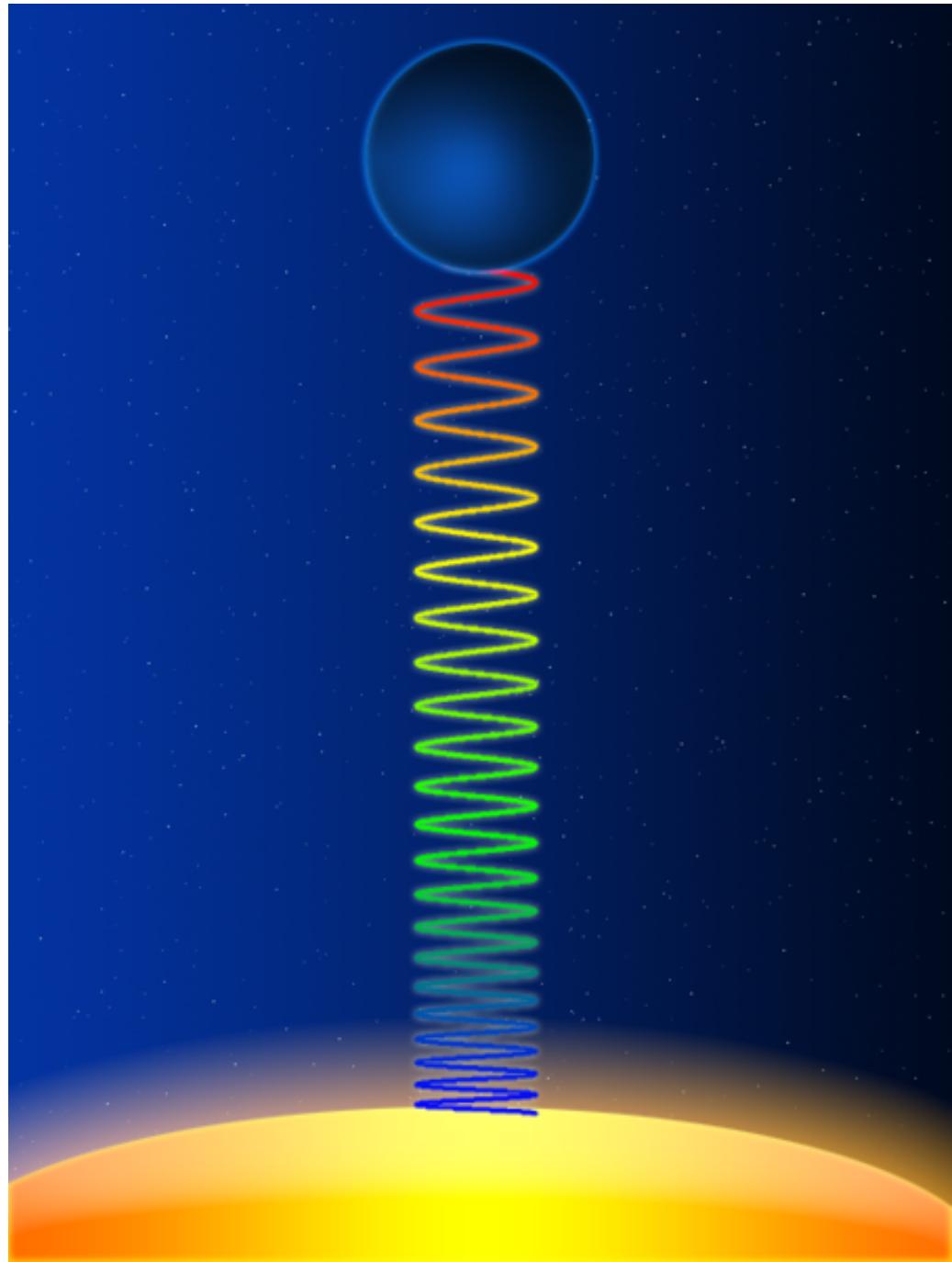
# 3<sup>rd</sup> Evidence Supporting GR: Binary Pulsar PSR1913+16

- Discovered 1974; Nobel prize for Taylor&Hulse 1993
- Orbital Period ~8 hours: Separation =solar radius
- One pulsar & the other a neutron star= 1.35 solar mass
- Slows due to **Gravitational Radiation** predicted by General Relativity
- Orbit shrinks 3mm/year so they will merge in 300 million years



# 4<sup>th</sup> evidence supporting GR: **Gravitational Redshift**

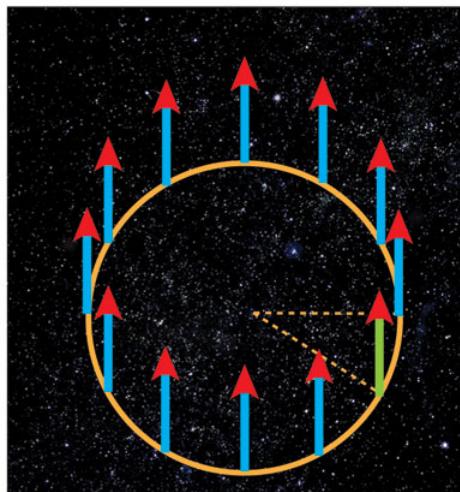
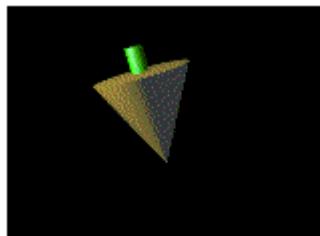
- As light climbs out of gravitational potential well it loses energy
- It can not slow down so it must redshift
- Has been observed for Sun, White Dwarfs and on Earth



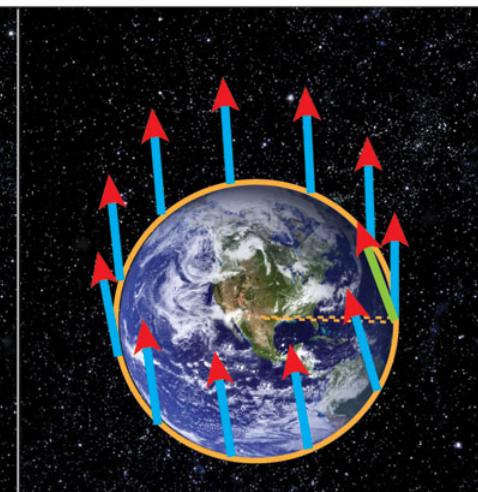
# 5<sup>th</sup> Test of GR:

## Frame Dragging

- Inclusion of Earth shrinks orbit 1 inch
- Gyroscope precesses

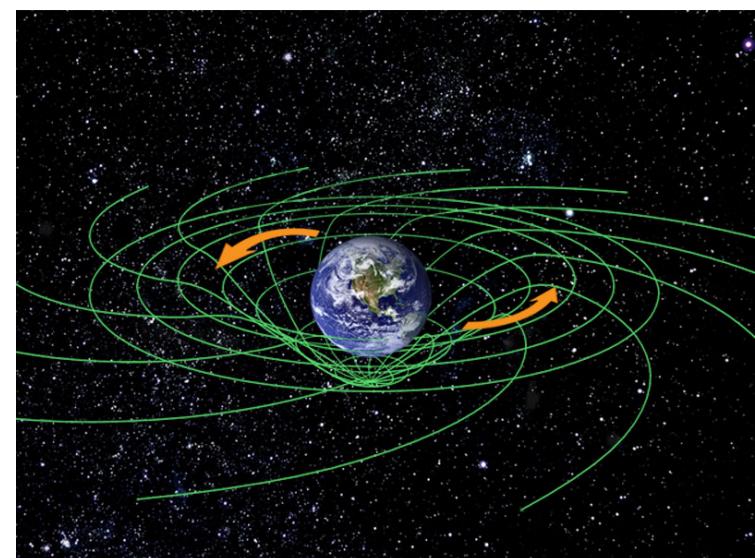
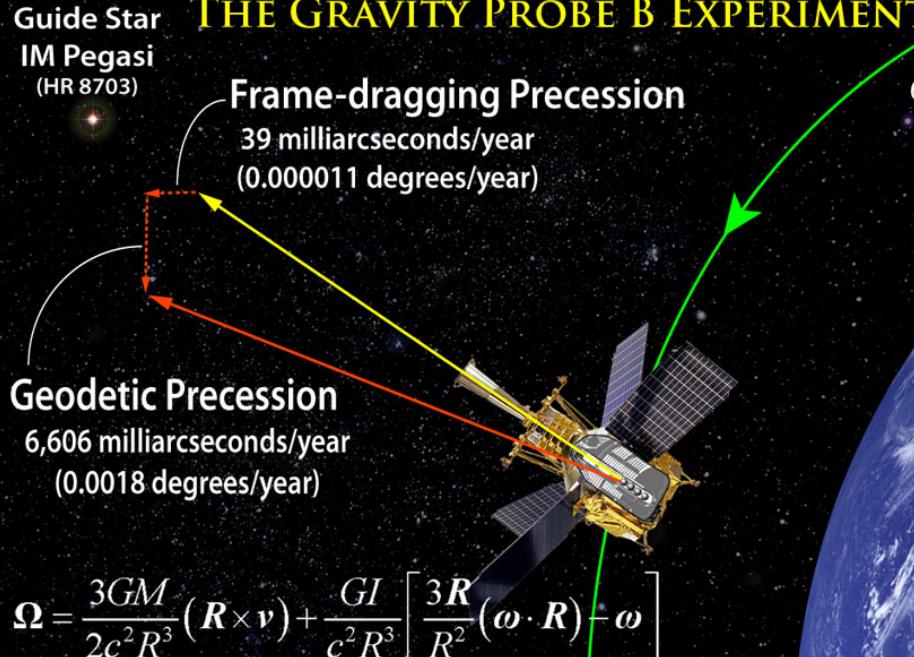


A circle with Earth's equatorial diameter (~7,926 mi) in empty space has a circumference of  $\pi D$  (~24,901 mi). A gyroscope following this circular path in empty space will always point in the same direction, as indicated by the arrows above.



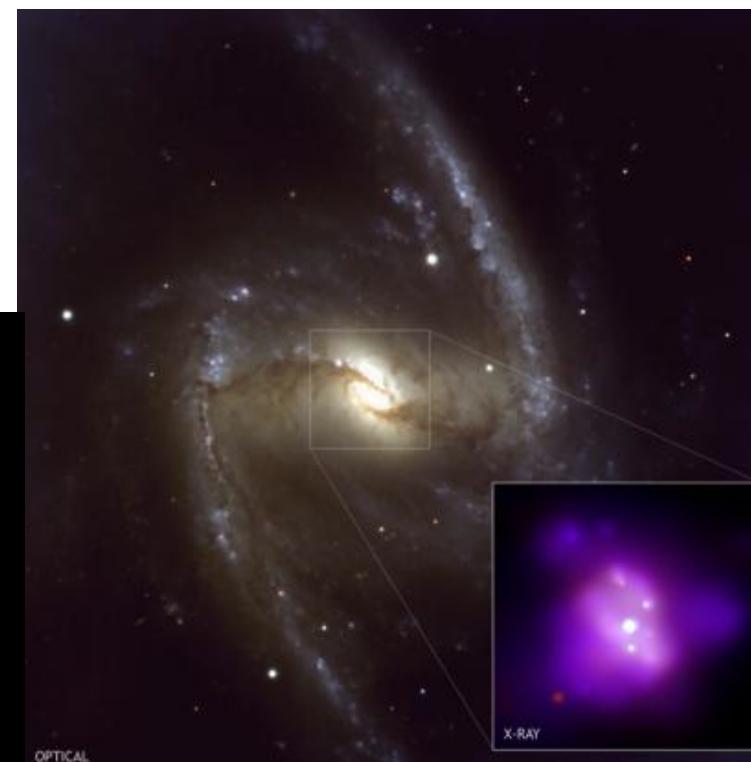
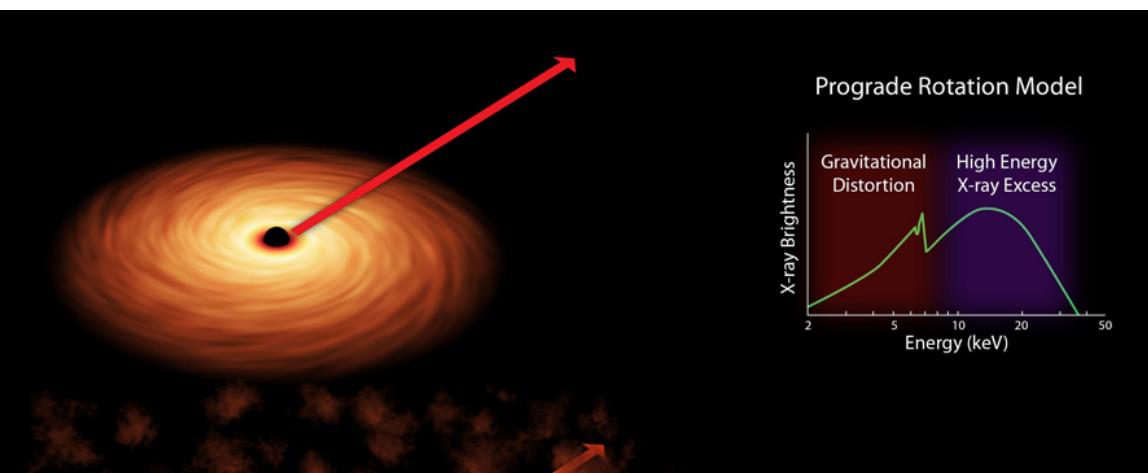
Earth's mass warps spacetime inside the circle into a cone, formed by removing a pie-shaped wedge (dotted lines). This reduces the circle's circumference by 1.1 inches. A gyroscope will now change its orientation while tracing the conical path, as shown in the drawing above.

### THE GRAVITY PROBE B EXPERIMENT

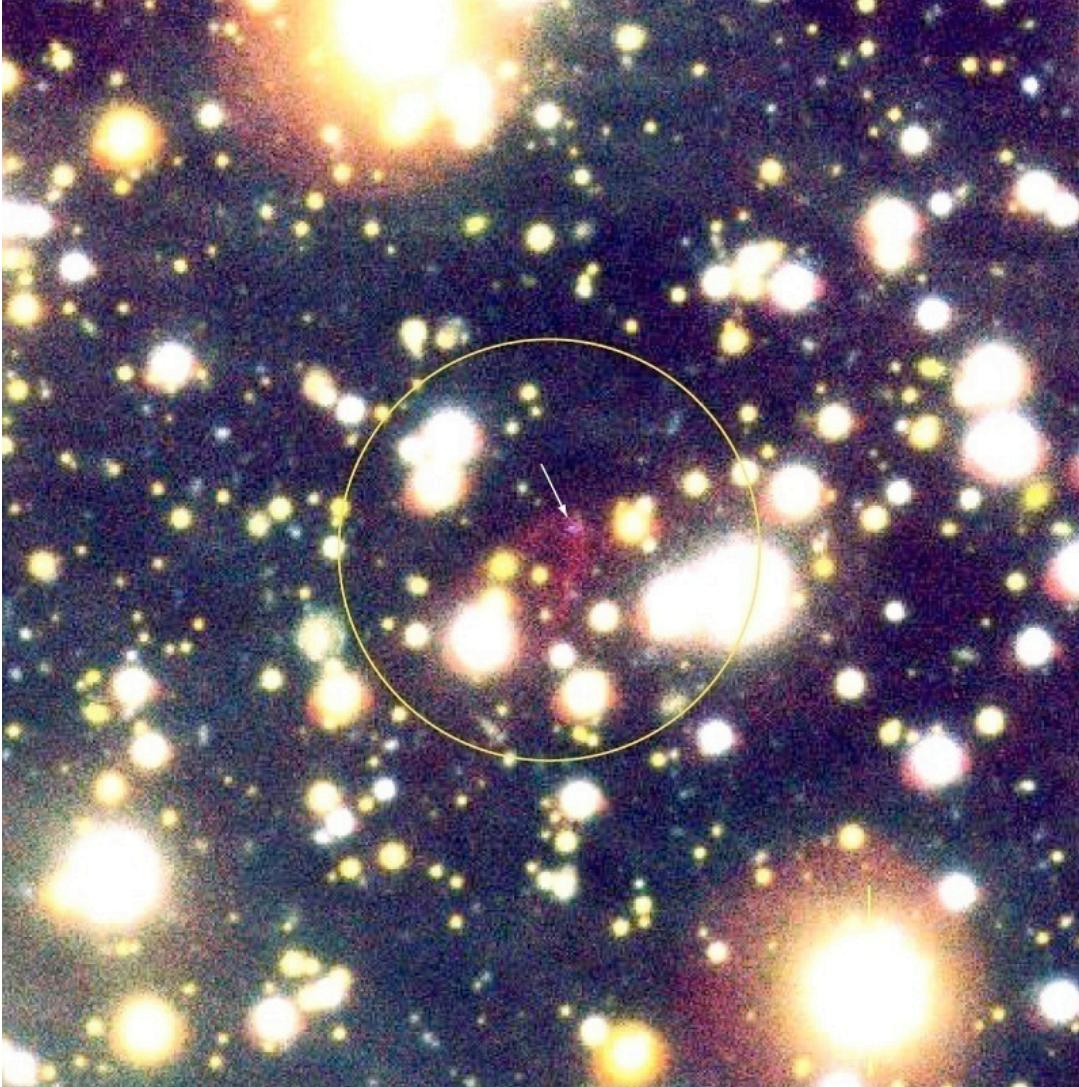


# Supermassive Black Holes

- NGC1365 eclipse of x-rays/accretion disk gives size
- Doppler shift of X-ray observations gives rotation speed of disk thus mass of Black Hole ~million suns
- Black Hole spins at 84% speed of light at equator so it grew from gas not mergers



# Hard to Detect Nearest Neutron Star



A Bowshock Nebula Near the Neutron Star RX J1856.5-3754 (Detail)  
(VLT KUEYEN + FORS2)

ESO PR Photo 23b/00 (11 September 2000)

© European Southern Observatory



- 180 light years
- 700,000K
- 20km diameter
- Small luminosity
- Plowing through ISM
- At 200km/sec forming
- A bow shock of recombining hydrogen

# X-Ray Burster Movie

RXTE PUFFED ACCRETION DISK  
VERSION 2 WITH NO Wobble



ANIMATION BY

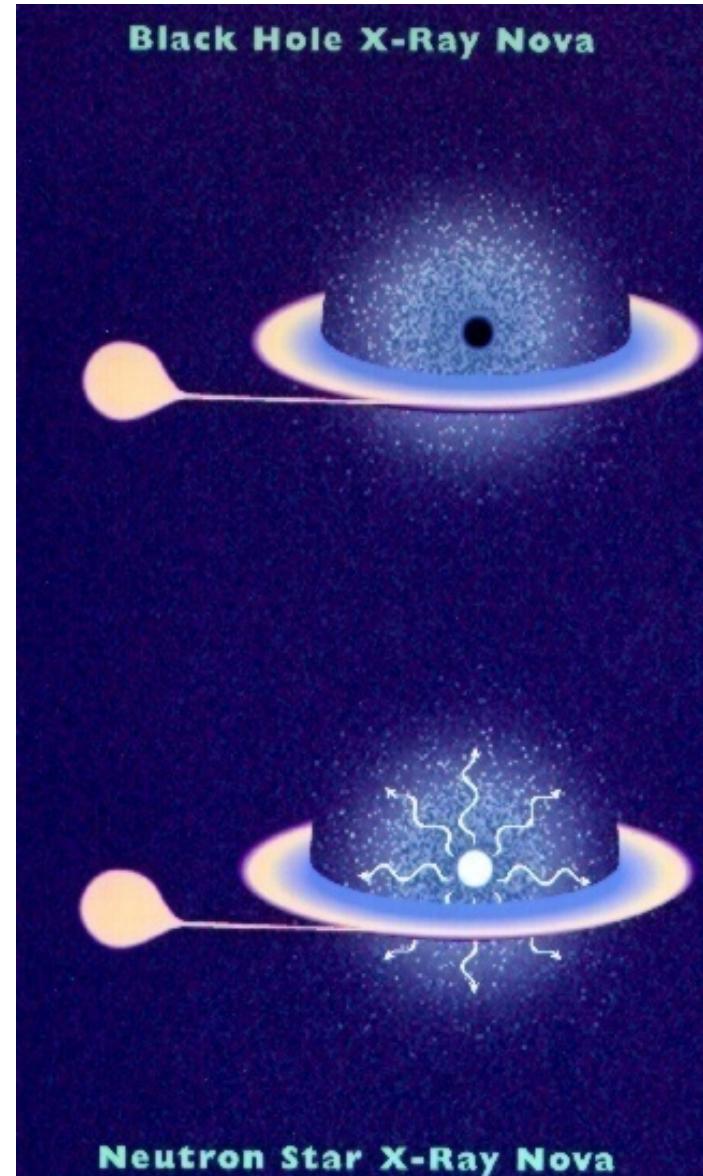
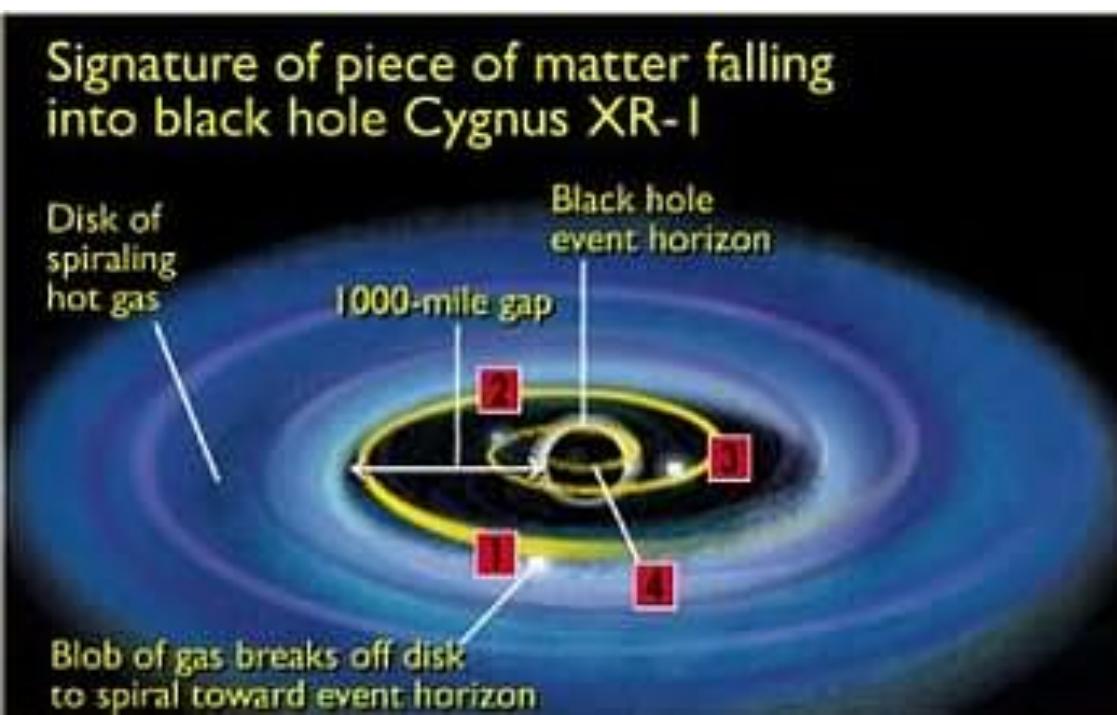
DANA BERRY

SKYWORKS DIGITAL ANIMATION

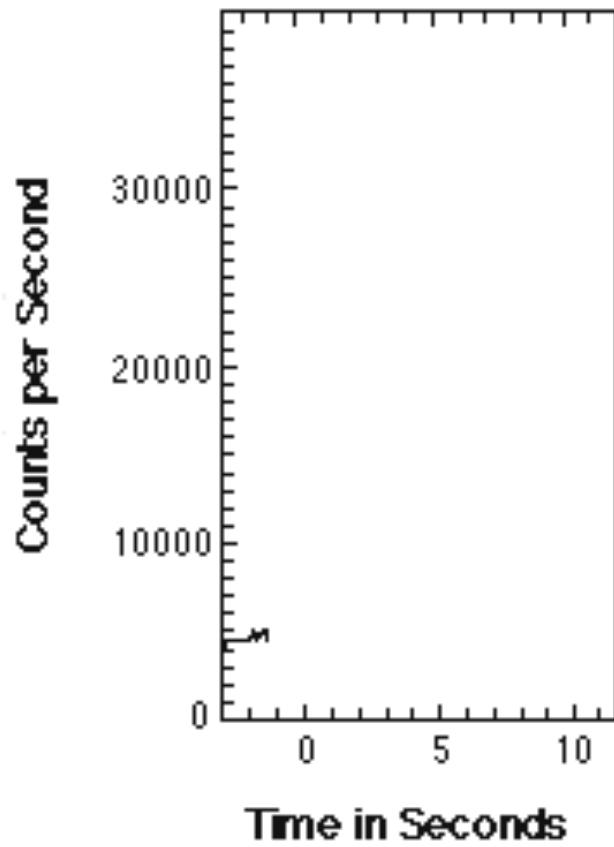
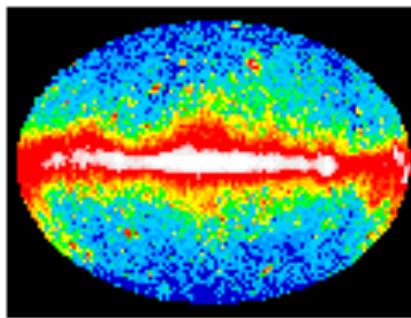
310-441-1735

# Quasi-Periodic Oscillations

- A mass falling into a black hole will release 100 times as much energy as could be obtained from fusion
- Will orbit faster & faster until it hits
- Terminal burst on Neutron star and nothing on black hole

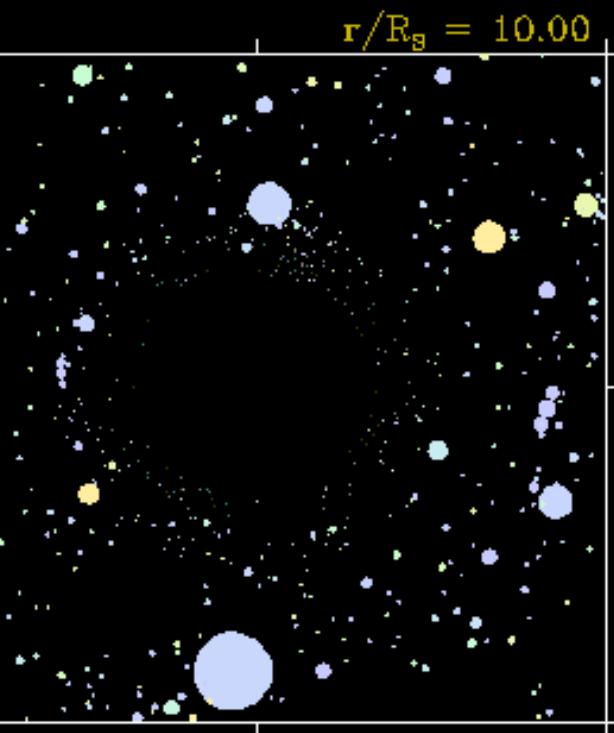
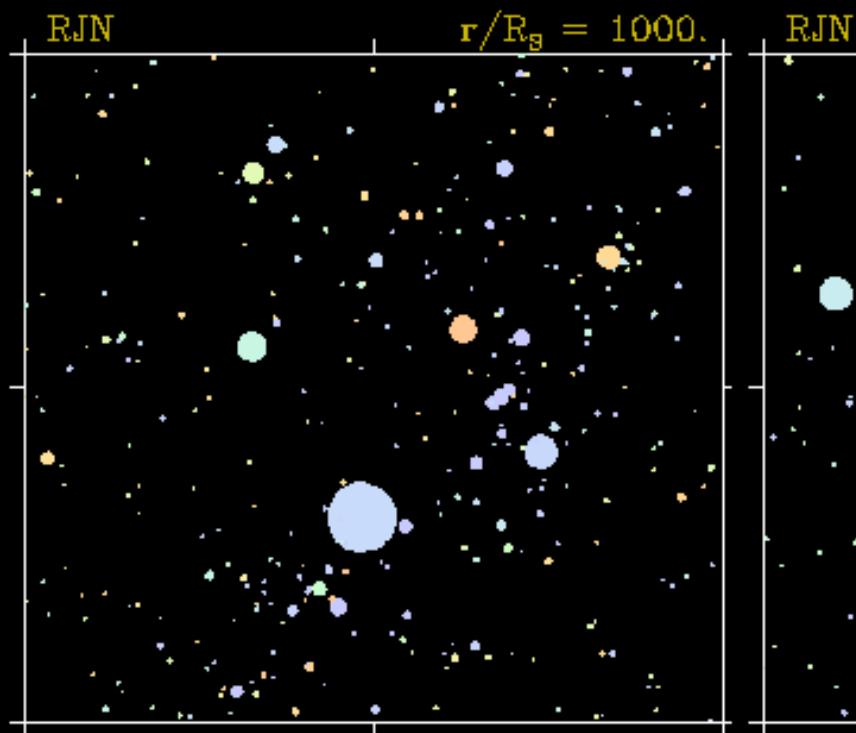
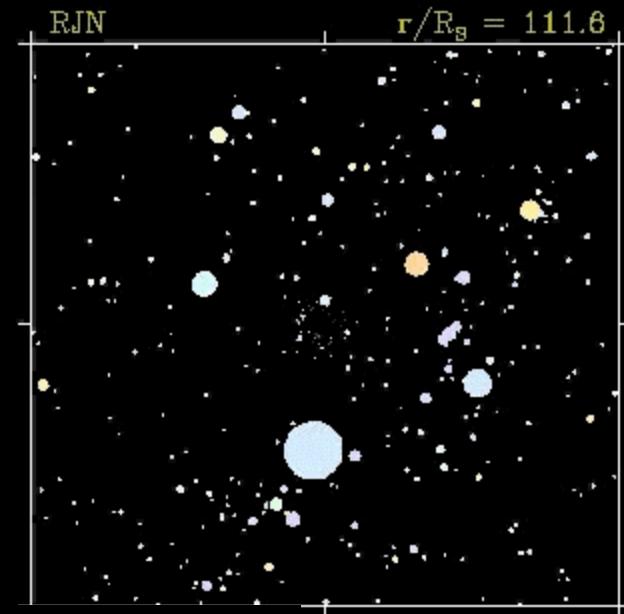


# Gamma Ray Burst Animation



# Black Hole Lens in Orion

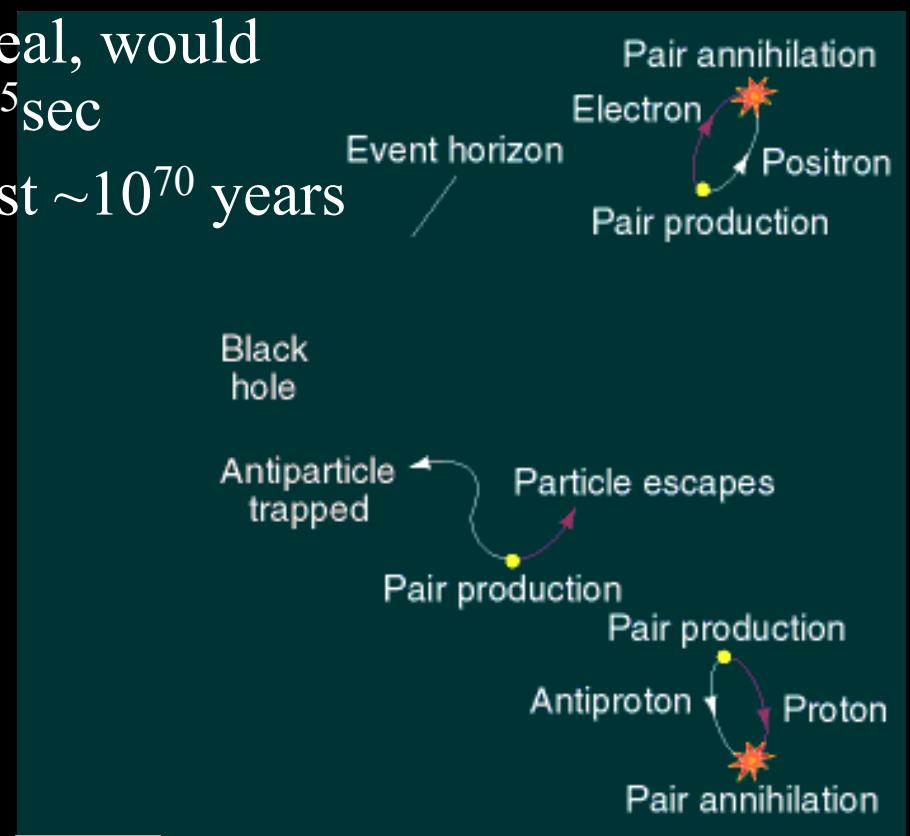
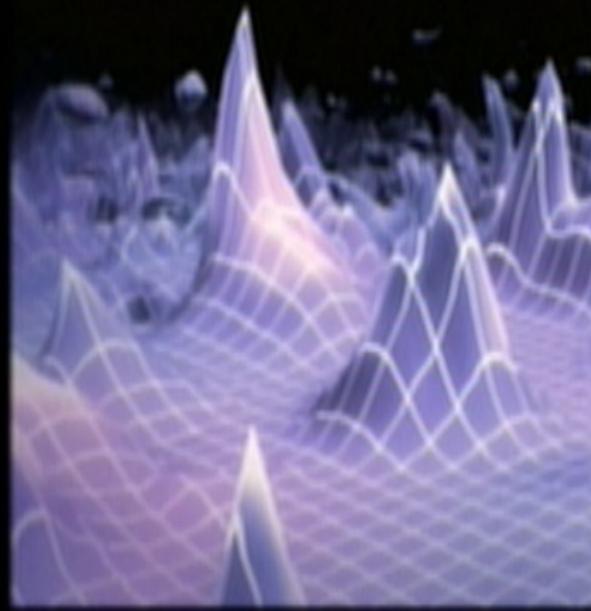
- Black hole bends light
- Two images appear, one on either side



# Black Hole Evaporation

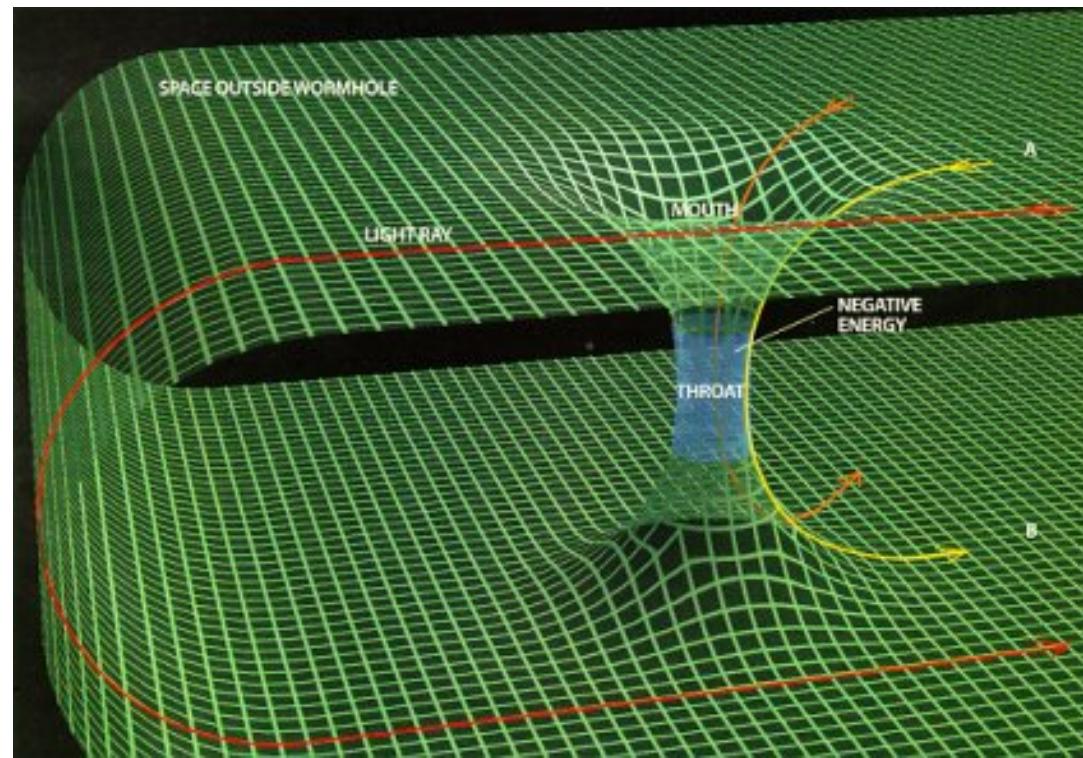


- Black Holes do seem to radiate energy by
- **Heisenberg Uncertainty Principle** which implies **Virtual Pair Production**
- The smaller the hole the hotter it seems – **primordial black holes?**
- Black Holes made in CERN, if real, would evaporate before they grow  $\sim 10^{-25}$  sec
- A 1 Solar mass black hole will last  $\sim 10^{70}$  years



# Wormholes

- Solutions to General Relativity Eqns include connected black holes = wormholes
- A few people speculate that this is a means of faster than light communication



- Jan 2012

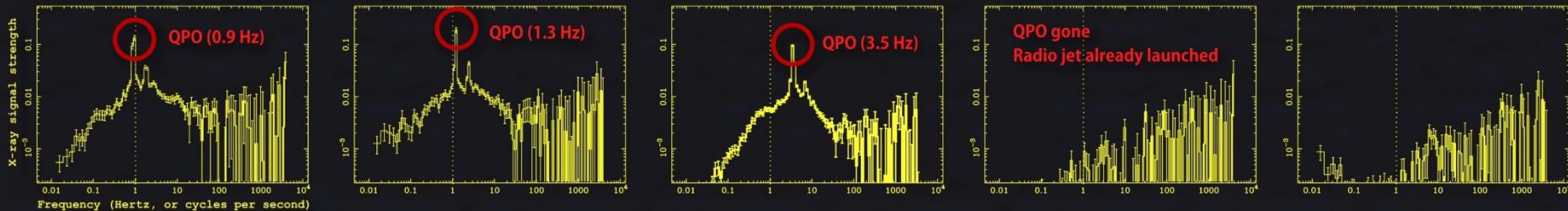
# Black Hole Ejects Blob

## Caught in the Act: Black Hole H1743–322 Launches a Jet

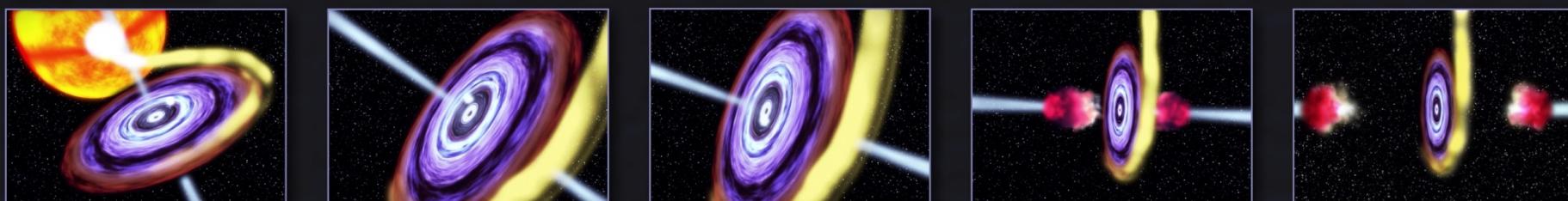
Very Long Baseline Array radio images



Rossi X-ray Timing Explorer power spectra



Artist's rendition



# Inside a Black Hole

- Can not see in front because light is falling away
- Can see stars behind
- Trip from Event Horizon to singularity takes 20 seconds for Black Hole at center of galaxy



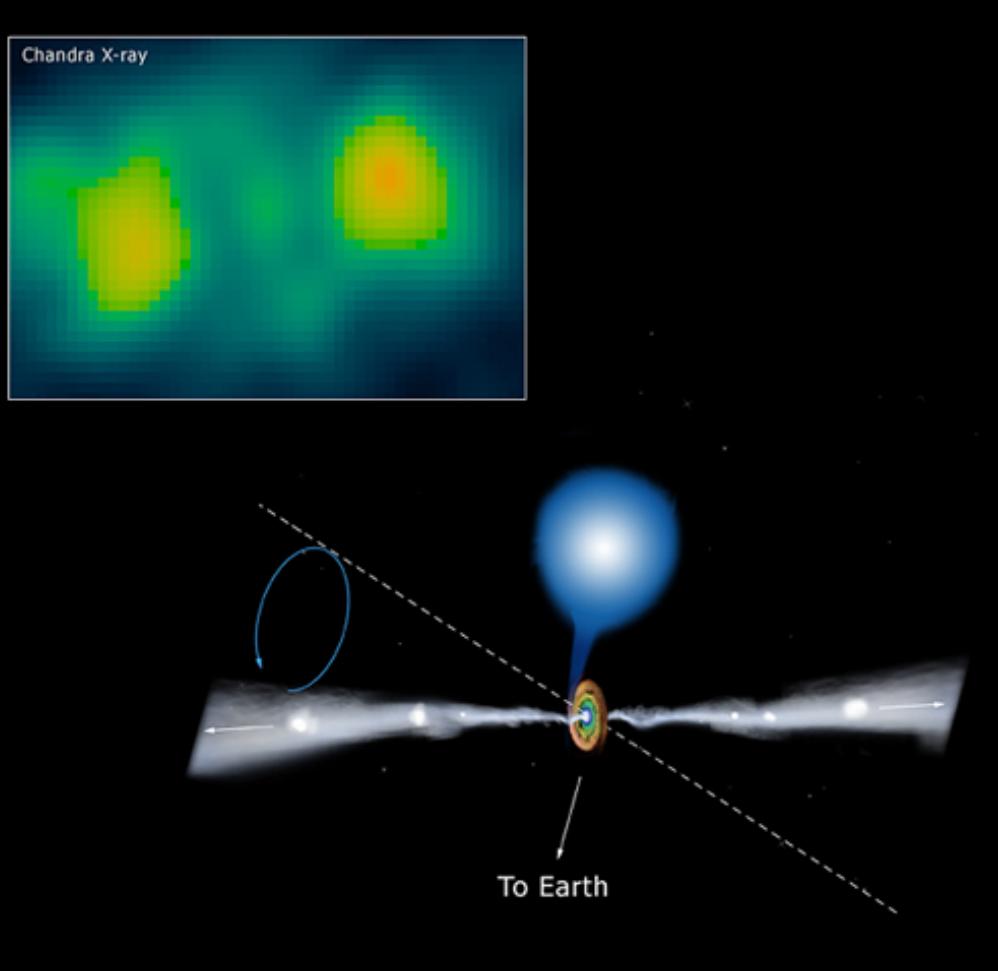
# Man Falling Into a Black Hole

- Personal point of view  
= spaghettification



- Distant observer point of view: redshift, never crosses event horizon

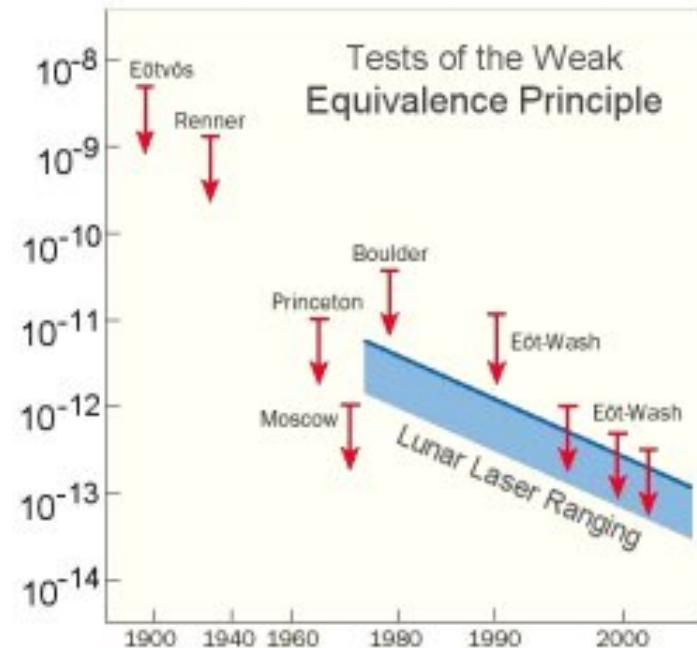
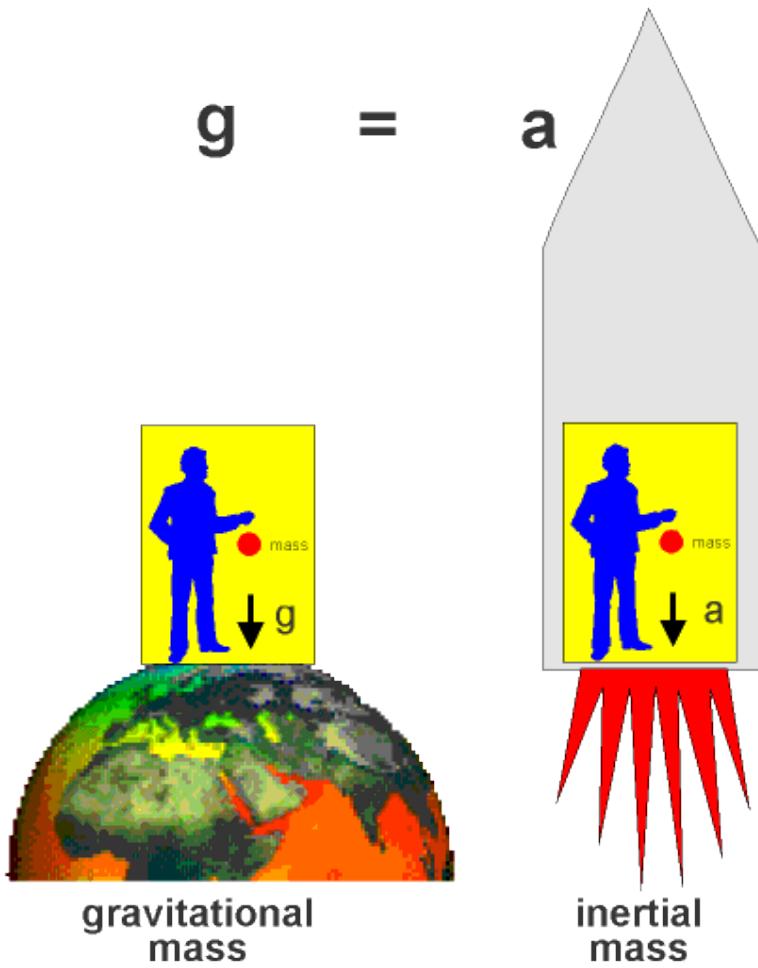
# SS433's Jets; Black Holes are Messy Eaters



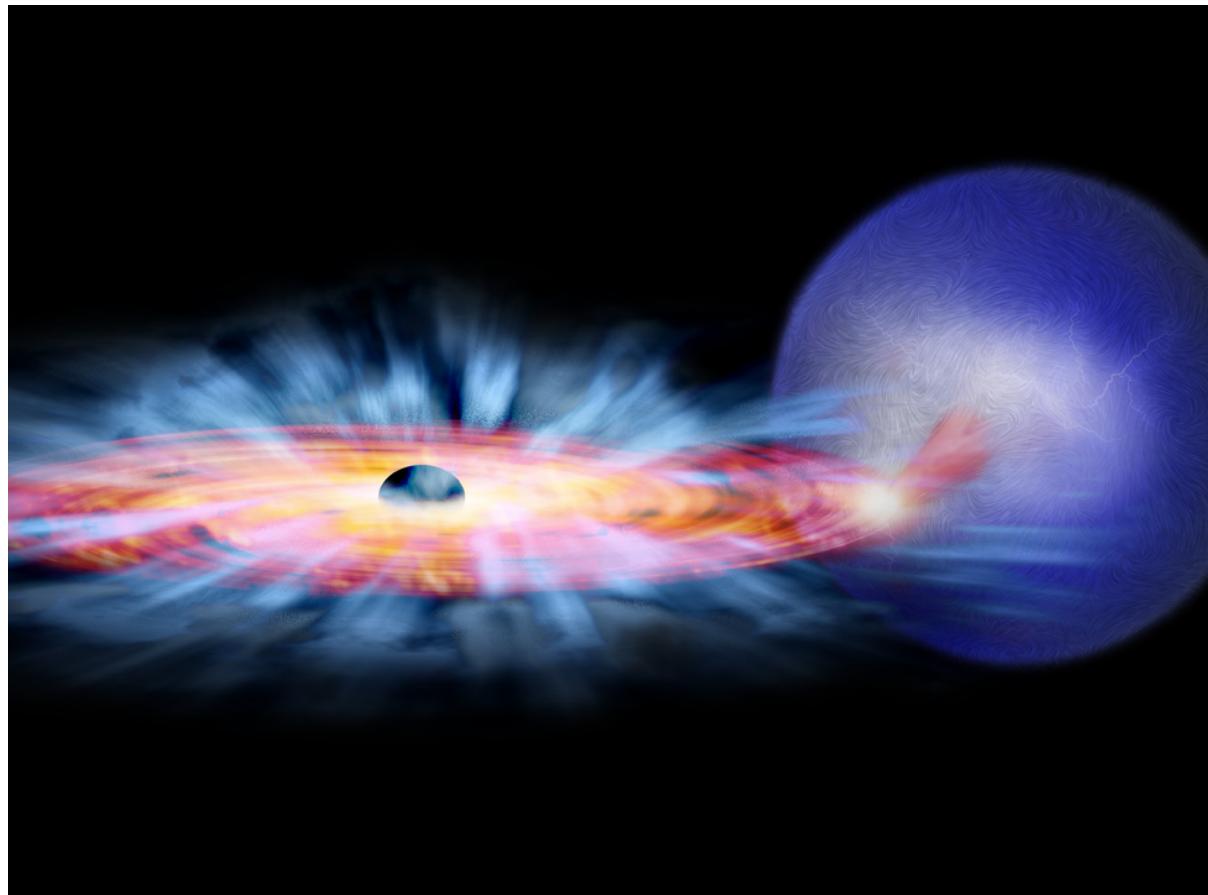
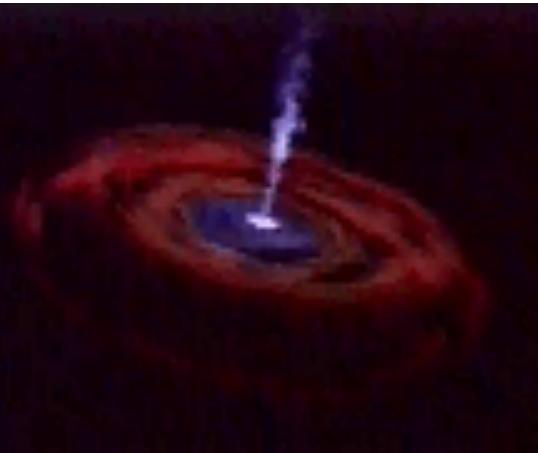
- 16,000ly distant
- Eclipses every 13 days
- Star is  $13 M_{\text{sun}}$
- Interaction of magnetic fields of accretion disk and compact object ejects jets at  $0.25 c$
- Precesses in 164 days
- Seen in X-rays and radio
- Black hole is  $3-8 M_{\text{sun}}$

# Equivalence Principle

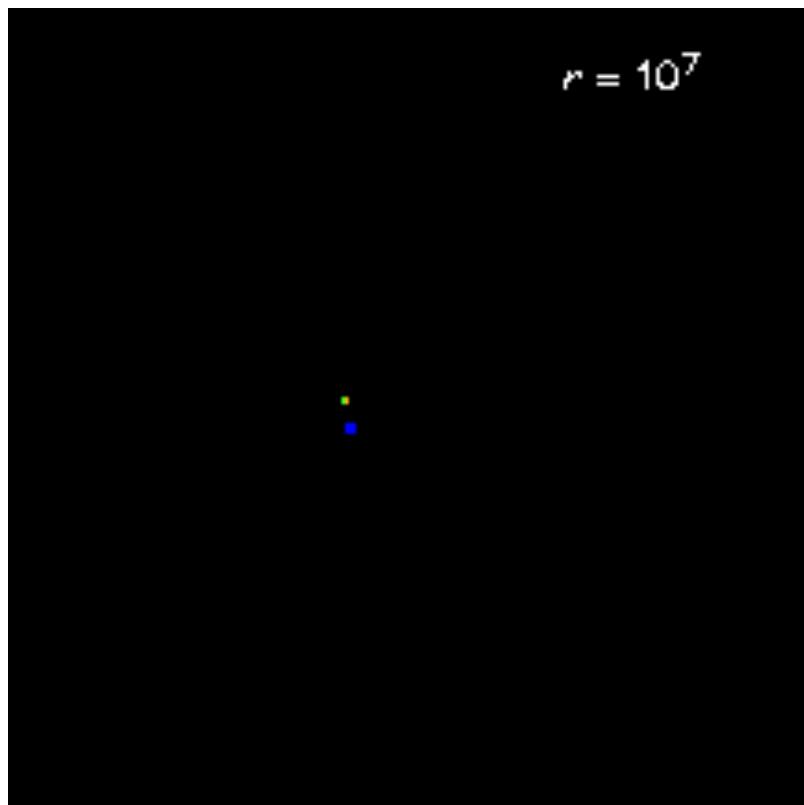
- Downward pull of gravity can be duplicated by upward acceleration of observer
- Gravitational Mass Equals Inertial Mass



# Painting of Black Hole



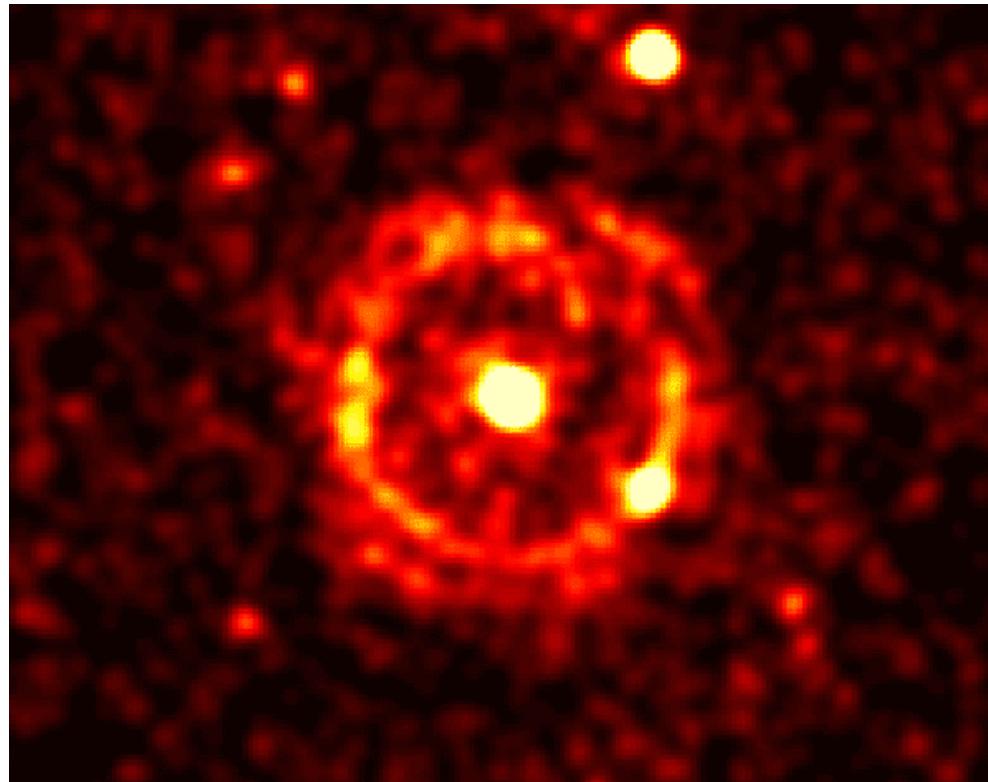
# Falling into BH Movie



- 30 Solar Mass BH
- Done by Andrew Hamilton
- From 1 AU takes 65 days
- No redshift

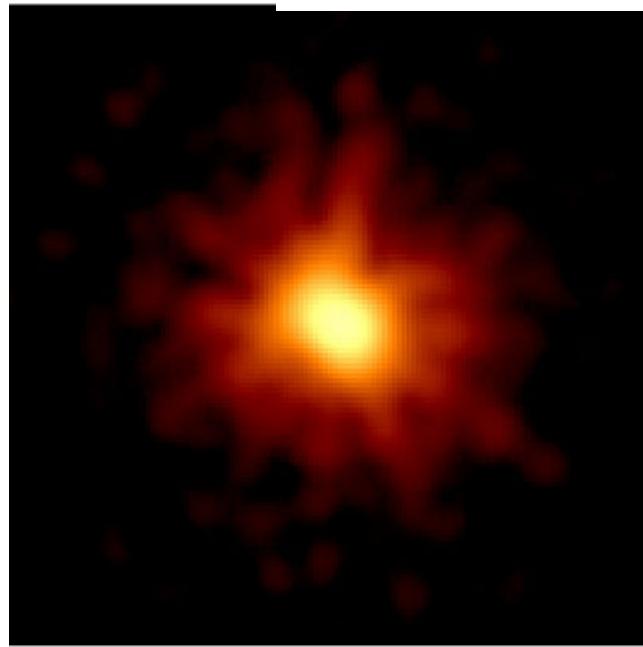
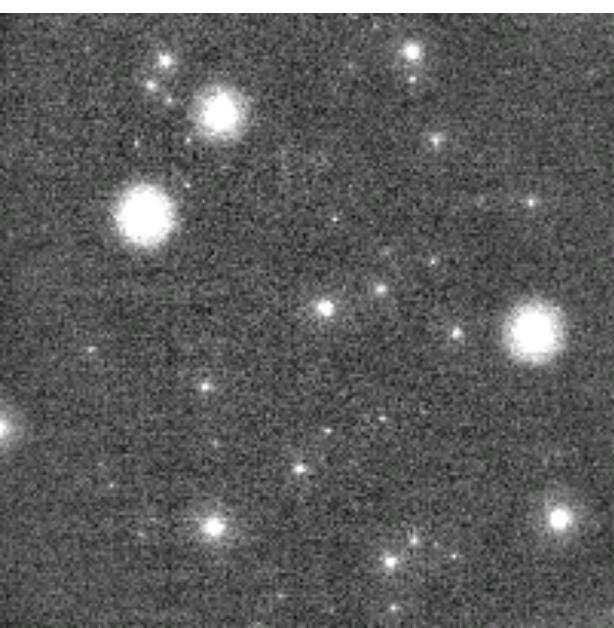
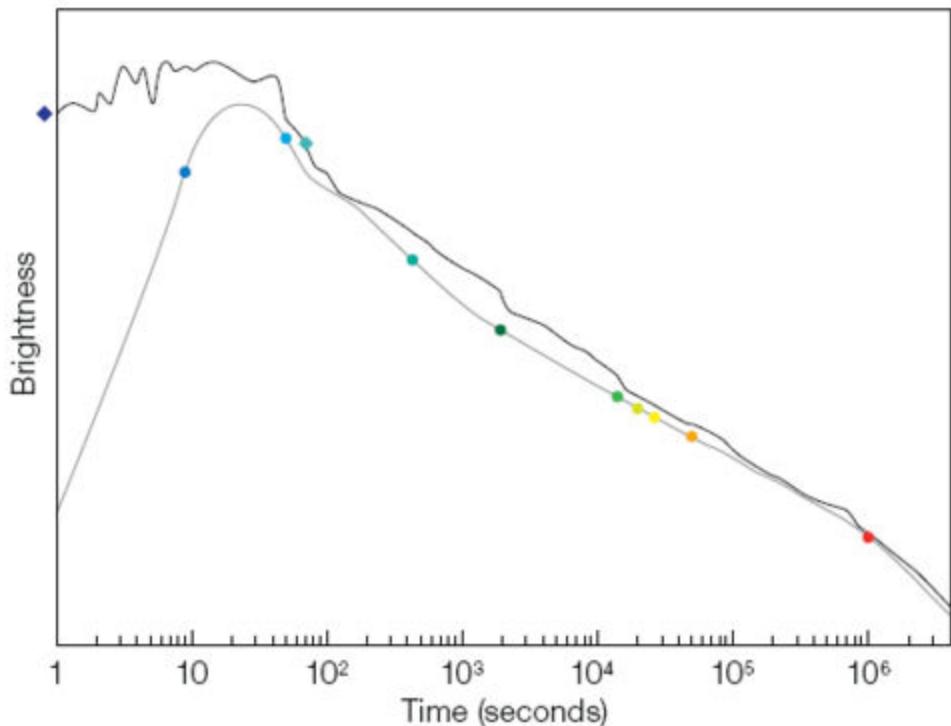
# GRB Light Echo in X-Rays

- X-Rays emitted during a GRB reflect off a dust cloud 3500ly from Earth in our Galaxy
- So it is beyond the dust cloud



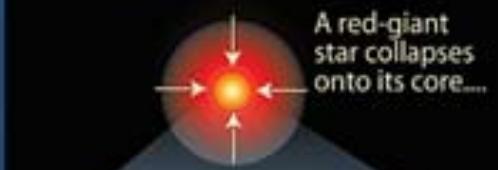
# GRB080319B

- Naked eye visible  
 $V_{max}=5.8$  for 30 sec
- X-Ray and UV images
- Distance is 7.5 billion light years



# Gamma-Ray Bursts (GRBs): The Long and Short of It

## Long gamma-ray burst (>2 seconds' duration)



Torus

Jet

Gamma rays

## Short gamma-ray burst (<2 seconds' duration)

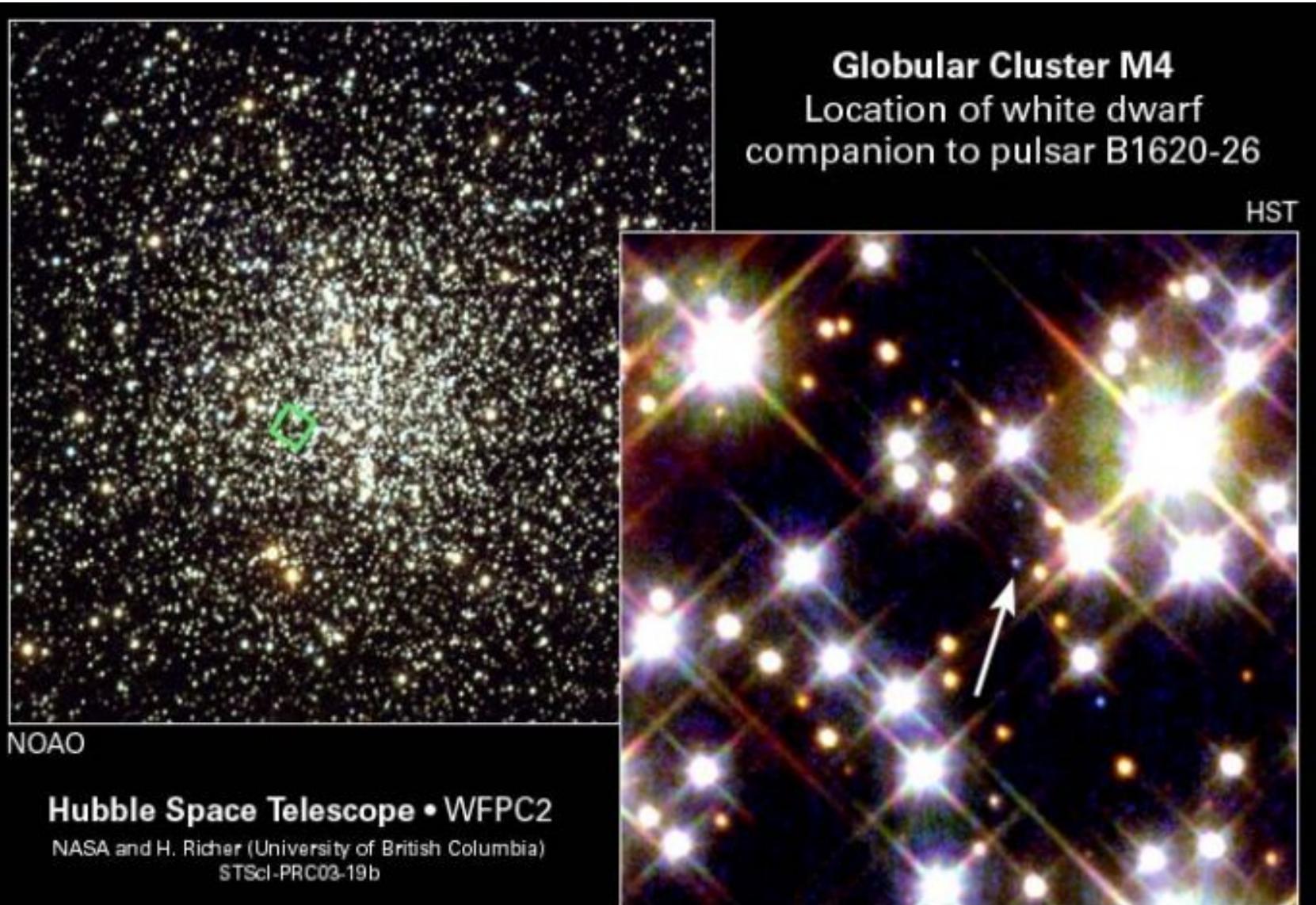
Stars\* in a compact binary system begin to spiral inward....

...eventually colliding.

The resulting torus has at its center a powerful black hole.

\*Possibly neutron stars.

# Oldest Planet and White Dwarf Orbit Millisecond Pulsar



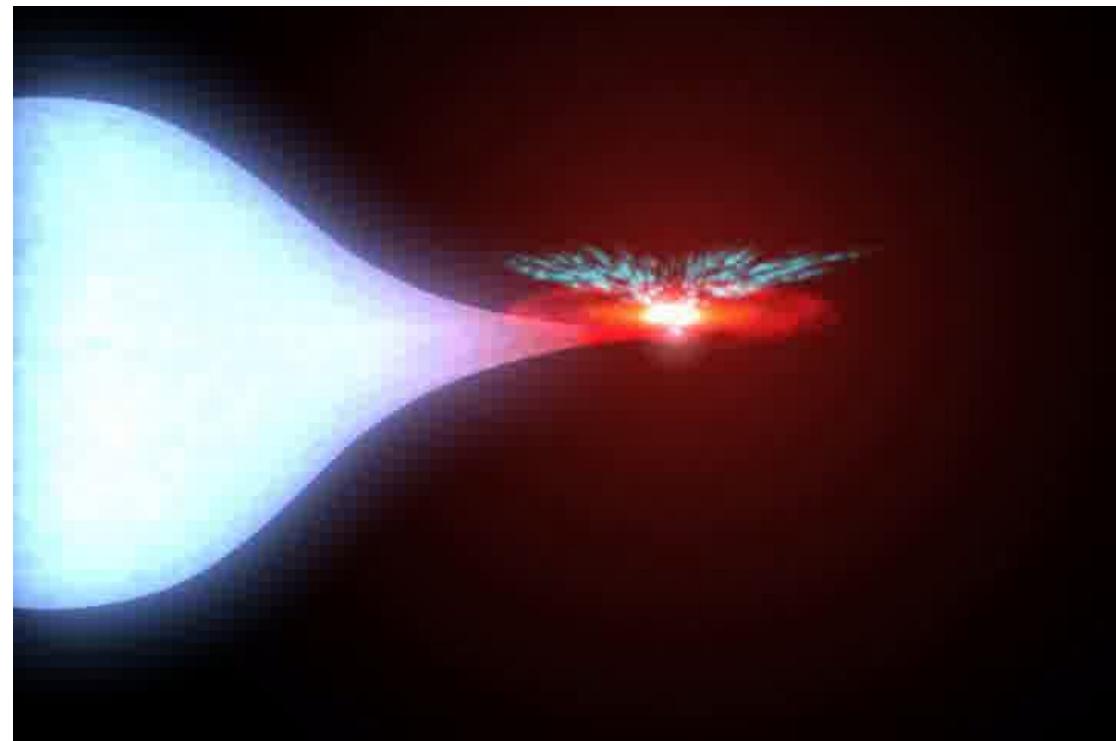
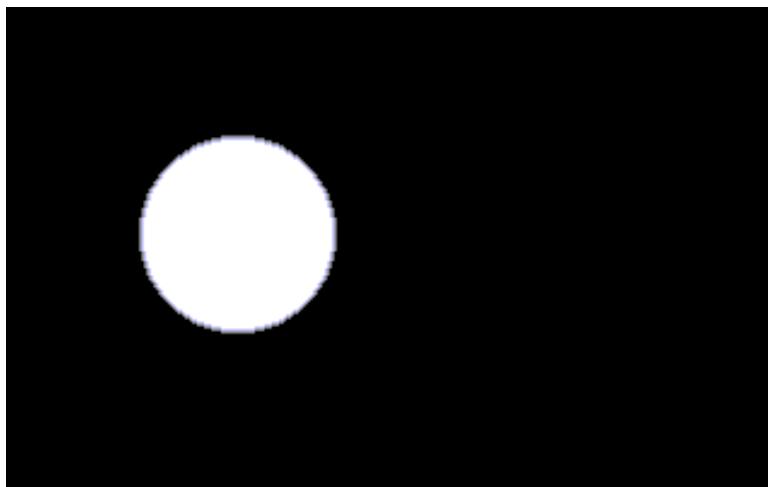
# XTE 1550-56

## Black Hole & Solar Mass Star

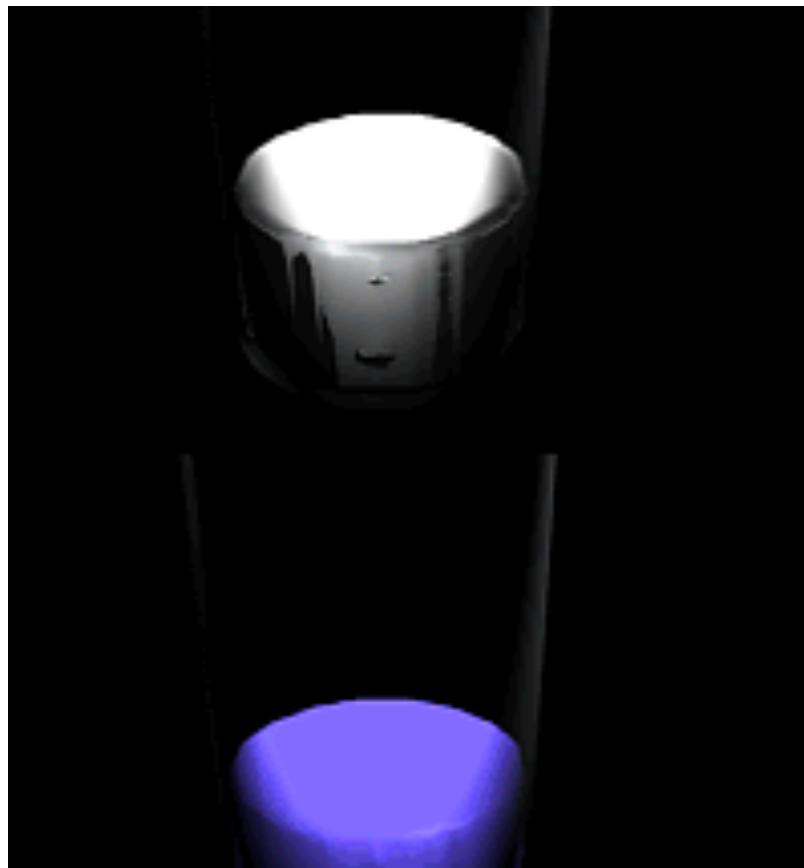


# X-Ray Binary

- X-ray binary containing a Black Hole will be fainter than one containing a neutron star
- No terminal burst



# Viscosity of Liquids



# Cosmic Rays

- FERMI results confirm belief that high energy Cosmic Rays come from Supernova Remnants

