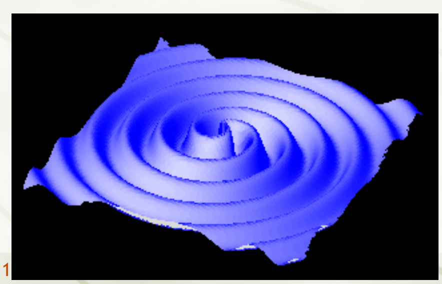
Testing of GR

- The metric of GR (the set of equations describing space-time) is mathematically complex.
- However one can express it approximately as a algebraic series where the first time is 'Newtonian' and the higher order terms represent deviations from Newtons laws.
- $ds^2 = (1 + 2\phi_N + 2\beta\phi_N^2 + . .)c^2dt^2 - (1 - 2\gamma\phi_N + . . .)dx^2$.
- (Remember back in Special relativity we defined ds^2 as the space time distance)
- In GR $\beta,\gamma = 1$ and different values would represent a deviation from GR.
- β,γ have been measured in the solar system and elsewhere and deviate by $<3\times10^{-5}$ from 1.

GRAVITATIONAL WAVES-Another Prediction of GR and a Test

- Accelerating masses produce continual changes in space-time geometry
- Periodically-moving bodies (e.g. orbiting stars) create ripples in space-time curvature
- Ripples travel at speed of light through space-time (how do we know this if we've never found one?)
- These are called **gravitational waves**.



From LISA2 movie

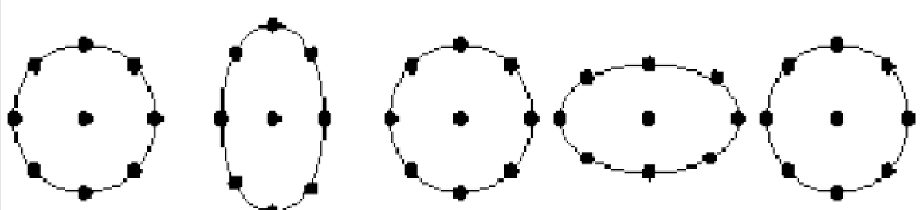
Gravitational waves

- Features of gravitational waves…are radiated by objects whose motion involves *acceleration,* if it is not perfectly spherically symmetric (like an expanding or contracting sphere) or cylindrically symmetric (like a spinning disk or sphere).
  - Usually extremely weak!
  - Only become strong when massive objects are orbiting close to each other*.
  - Gravitational waves carry energy away from orbiting objects… this causes objects to spiral toward each other
  - The grand challenge – to compute the spiralling together of two black holes
- How do we know that these waves exist?

*Power in grav wave $P \sim (G^4/c^5)\ (m_1 m_2)^2 (m_1+m_2)/r^5$ if $m_1 \sim m_2$ $P \sim (G^4/c^5)\ m^5/r^5$ for earth-sun system this is about **200 watts-** **this energy loss shrinks the earths orbit by 3.5×10^{-13} m/yr about 1/300 the size of a hydrogen atom**

Gravitational Waves

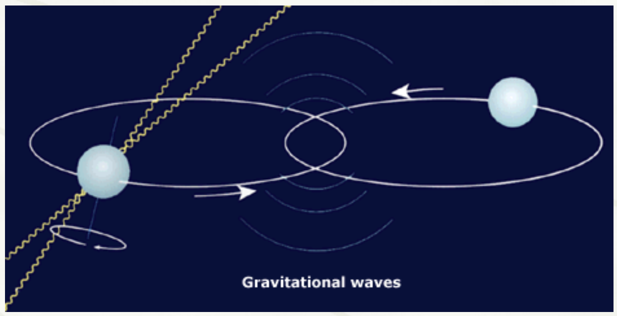
- The waves are 'quadripolar'-motion of a test particle as the wave goes by
- The effect is extremely small- the motion $h=\Delta x/x=$ due the wave is expected to be $<10^{-21}$ dimensionless



Motion of test particle as grav wave goes by

The binary pulsar (PSR1913+16)

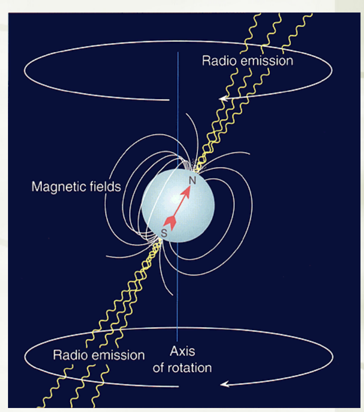
- Russell Hulse & Joseph Taylor (1974)
  - Discovered remarkable double star system
  - Nobel prize in 1993



From Nobel Prize website

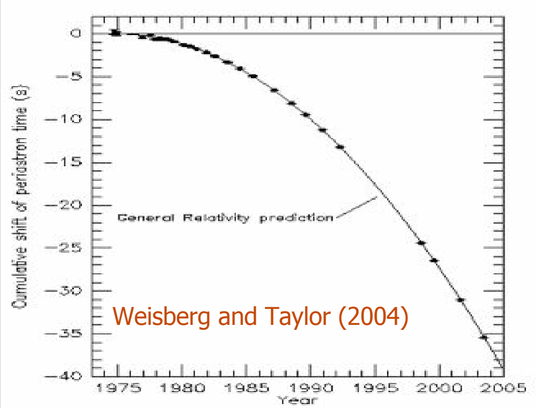
Hulse-Taylor system

- Two neutron stars orbiting each other
- One neutron star is a pulsar –
  - Neutron star is spinning on its axis (period of 59ms)
  - Emits pulse of radio towards Earth with each revolution
  - Acts as a very accurate clock!
- Strong gravity- good place to test GR
  - Orbit precesses by 4 degree per year!
  - Orbit is shrinking due to gravitational waves

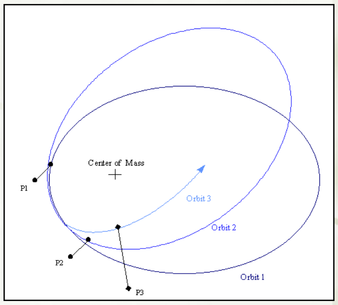


Precise test of certain aspects of GR

- When pulsar is approaching Earth, pulse frequency increases (Doppler shift); when pulsar is receding, pulse frequency decreases -- orbit of pulsar can therefore be "mapped"
- Orbit is observed to be precessing (same physics as for Mercury) and shrinking (loss of energy due to gravitational waves) at exactly the rate predicted by Einstein's theory



Weisberg and Taylor (2004)



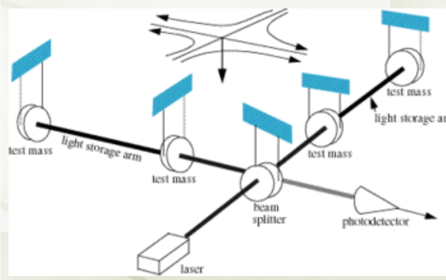
Direct detection of gravitational waves

- How do you search for gravitational waves?
- Look for tidal forces as gravitational wave passes: local compression or expansion of space
- Pioneered by Joseph Weber (UMD Professor)
  - Estimated wave frequency (10000Hz)
  - Looked for "ringing" in a metal bar caused by passage of gravitational wave
  - Insufficient technology in the 1970's for detection


AIP archives

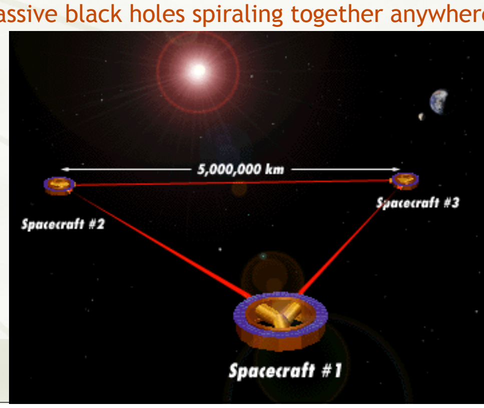
Modern experiments : LIGO

- **L**aser **I**nterferometer **G**ravitational Wave **O**bservatory
- Two L-shaped 4km components: Hanford, Washington, & Livington, Louisiana
- Recently became operational!
- Can detect gravitational waves with frequencies of about 10-1000Hz.
- VERY sensitive… need to account for
  - Earthquakes and Geological movement
  - Traffic and people!
- What mightlit detect?- Predicted rates are very uncertain
  - Stellar mass black holes spiraling together
  - Neutron stars spiraling together



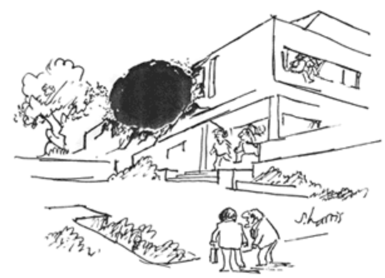
LISA

- **L**aser **I**nterferometer **S**pace **A**ntenna
- Space-based version of LIGO (planned launch date >>2020, used to be 2011)
- Sensitive to lower-frequency waves (0.0001 – 0.1Hz)
- Might be able to see
  - Normal binary stars in the Galaxy
  - Stars spiraling into large black holes in the nearby Universe.
  - Massive black holes spiraling together anywhere in the universe!



Lecture 12: Black Holes

- Old ideas for black holes
- Theory of black holes
- Real-life black holes
  - Stellar mass
  - Supermassive
- Speculative stuff



I : OLD IDEAS FOR BLACK HOLES

- "What goes up must come down"… or must it?
- **Escape velocity**, V_{esc}
  - Critical velocity object must have to just escape the gravitational field of the Earth
    - $V<V_{esc}$: object falls back to Earth
    - $V>V_{esc}$: object never falls back to Earth
- In fact, escape velocity given in general by

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

when the mass of an object is M and the distance from the center is R
- Starting from Earth's surface, V_{esc}=11 km/s
- Starting from Sun's surface, V_{esc}= 616 km/s

18^{th} Century ideas

- By making M larger and R smaller, V_{esc} increases
- Idea of an object with gravity so strong that light cannot escape first suggested by Rev. John Mitchell in 1783
- Laplace (1798) – "*A luminous star, of the same density as the Earth, and whose diameter should be two hundred and fifty times larger than that of the Sun, would not, in consequence of its attraction, allow any of its rays to arrive at us; it is therefore possible that the largest luminous bodies in the universe may, through this cause, be invisible.*"

II : MODERN IDEAS

- Karl Schwarzschild (1916)
  - First solution of Einstein's equations of GR
  - Describes gravitational field in (empty) space around a point mass
- Space-time interval in Schwarzschild's solution (radial displacements only) is rather complex- see text book
- Features of Schwarzschild's solution:
  - Yields Newton's law of gravity, with flat space, at large R
  - Space-time curvature becomes infinite at center (R=0; this is called a **space-time singularity**)
  - Gravitational time-dilation effect becomes infinite on a spherical surface known as the **event horizon**, where coefficient of Δt is zero
  - Radius of the sphere representing the event horizon is called the **Schwarzschild radius,** $R_s = 2GM/c^2$

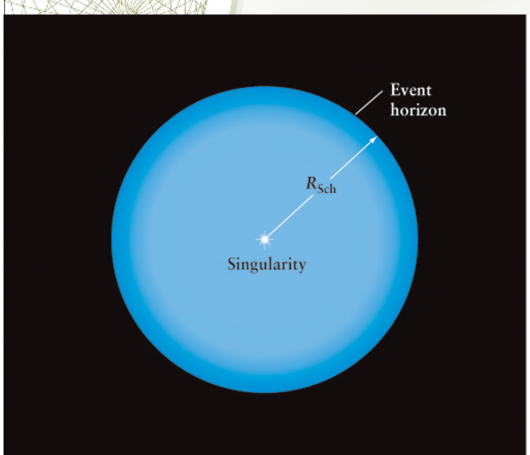
- Event horizon
  - **Point of no-return…** the location where the escape velocity equals the speed of light
  - The **gravitational redshift becomes infinite** here (as seen by an outside static observer)
  - Nothing occurring inside can be seen from outside (or have any causal effect on the external Universe!)
  - So… as a practical matter, astrophysics never need concern themselves with the Universe interior to the event horizon
  - Radius corresponding to event horizon for a non-spinning black hole is known as the Schwarzschild radius

$$R_{Sch} = \frac{2GM}{c^2} \approx 3 \left(\frac{M}{M_\odot} \right) \text{ km}$$

$\odot$ symbol for sun, $M_\odot$ =solar mass

Derived from GR treatment of problem… but same formula results from using Newtonian treatment of escape velocity

II : Modern (GR) ideas of black holes



Gravitational redshift outside of a spherical object with mass M is

$$\nu_{obs} = \left(1 - \frac{2GM}{rc^2}\right)^{1/2} \nu_{emit}$$

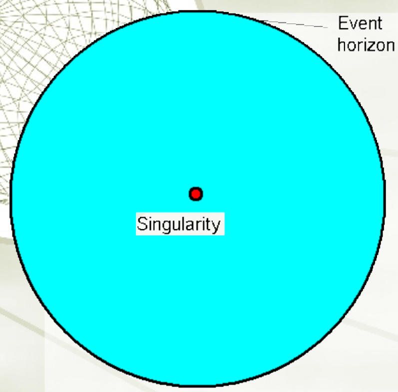
Gravitational length contraction

L'=Lsqrt (1-R_s/R)

Gravitational time dilation
t'=t/sqrt (1-R_s/R_s)

$R_{s=}$ 2GM/c^2

As R→ R_s time goes to ∞
length goes to zero, wavelength of emitted radiation goes to zero



Schwarschild radius is NOT the singularity

At the Schwarzschild radius the gravitational time dilation goes to infinity and lengths are contracted to zero

- For a body of the Sun's mass, **Schwarzschild radius**

$$R_S = \frac{2GM}{c^2} \rightarrow 3\text{km}$$

- **Singularity** – spacetime curvature is infinite. Everything destroyed. Laws of GR break down.
- **Event horizon** – gravitational time-dilation is infinite as observed from large distance.
- Any light emitted at R_s would be infinitely redshifted - hence could not be observed from outside

More features of Schwarzschild black hole

- Events inside the event horizon are causally-disconnected from events outside of the event horizon (i.e. no information can be sent from inside to outside the horizon)
- Observer who enters event horizon would only "feel" "strange" gravitational effects if the black hole mass is small, so that R_s is comparable to observer's size
- Once inside the event horizon, future light cone always points toward singularity (any motion must be inward)
- Stable, circular orbits are not possible inside $3R_s$: inside this radius, orbit must either be inward or outward but not steady
- Light ray passing BH tangentially at distance $1.5R_s$ would be bent around into a circle
- Thus black hole would produce "shadow" on sky

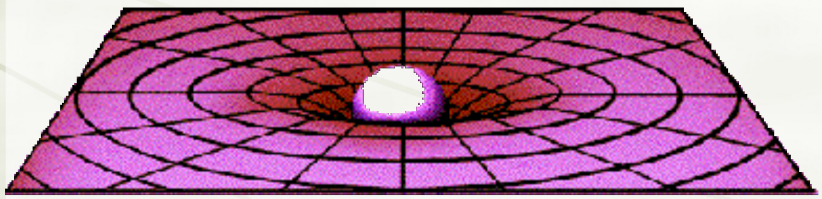
Falling Into A Black Hole

NOVA

Singularity

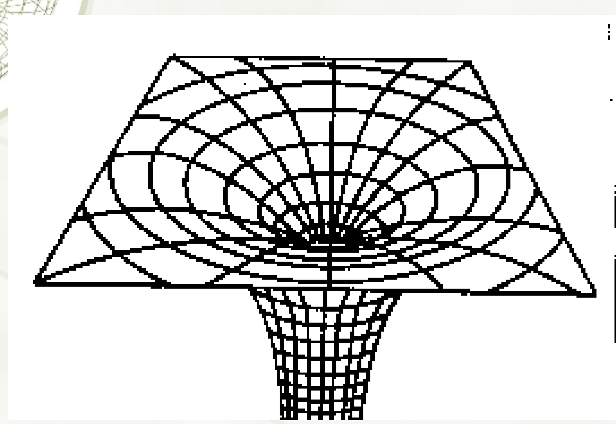
- The center of the black hole… the place into which all of the matter making the black hole has been crushed
- General Relativity gives nonsense answers here (infinite density, infinite spacetime curvature)… **so GR must break down here**
- Some new theory of **quantum gravity** is needed

Curved space around a star…



From web site of UCSD

… and around a black hole

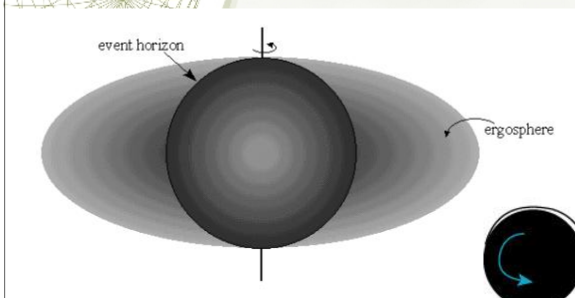


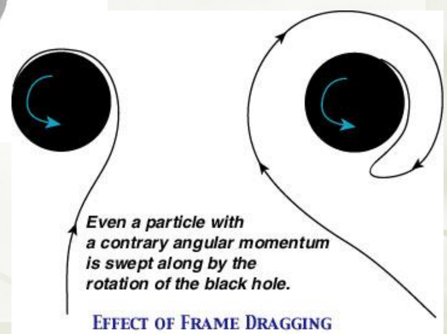
Rotating black holes- remember the extra special nature of accelerated frames

- Roy Kerr (1963)
  - Discovered solution to Einstein's equations corresponding to a *rotating* black hole
  - Kerr solution describes all black holes found in nature
- Features of the Kerr solution
  - Black Hole completely characterized by its mass and spin rate (no other features [except charge]; **no-hair theorem**)
  - Has space-time **singularity** and **event horizon** (like Schwarzschild solution)
  - Also has "**static surface**" inside of which nothing can remain motionless with respect to distant fixed coordinates
  - Space-time near rotating black hole is dragged around in the direction of rotation: "**frame dragging**".
  - **Ergosphere** – region where space-time dragging is so intense that its impossible to resist rotation of black hole.

- For spinning black holes…
  - Spacetime is twisted by rotation… objects close to black hole are "dragged" into rotation with it (frame-dragging)
  - Within **ergoregion**, it becomes impossible to stand-still… you have to rotate in same sense as black holes-
- Called the Lense–Thirring effect ：
  - Think of a satellite rotating around the Earth. According to Newtonian Mechanics, if there are no external forces applied to the satellite but the gravitation force exerted by the Earth, it will keep rotating in the same plane forever (this will be the case whether the Earth rotates around its axis or not). With General Relativity, we find that the rotation of the Earth exerts a force to the satellite, so that the rotation plane of the satellite precesses, at a very small rate, in the same direction as the rotation of the Earth
- Turns out that ergoregion is where the rotational energy of the black hole is stored
- Nature can tap this energy store… can energize accretion disk or power jets

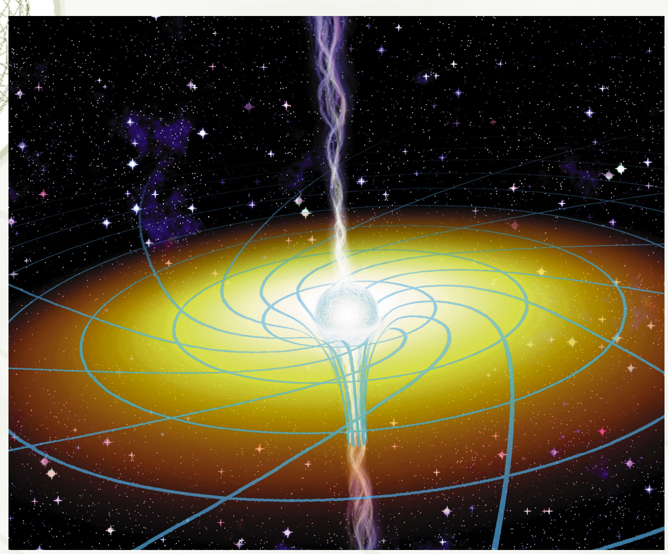
Frame dragging by rotating black hole





Graphics: University of Winnipeg, Physics Dept.

Artist's conception of rotating black hole



III : Real-life black holes

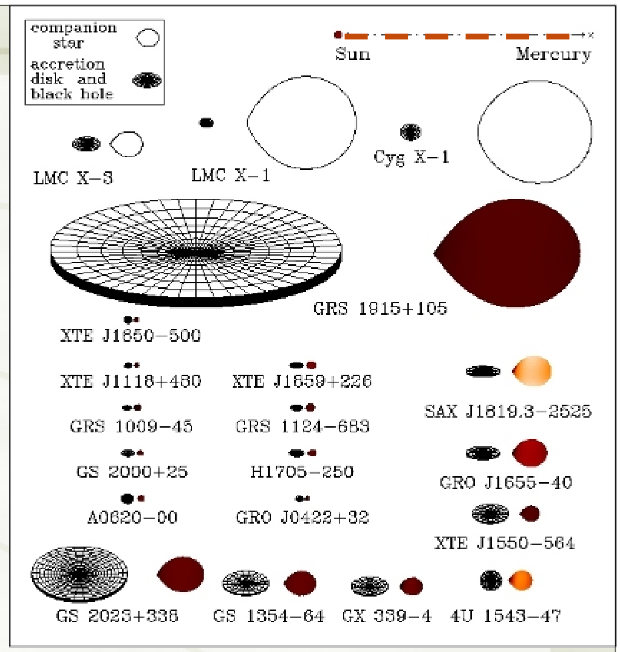
- So much for theory – what about reality
- Thought to be two (maybe three?) classes of black hole in nature
  - **"Stellar mass black holes"** – left over from the collapse/implosion of a massive star (about 10 solar masses)
  - **"Supermassive black holes"** – giants that currently sit at the centers of galaxies (range from millions to billions of solar masses)
  - **"Intermediate-mass black holes"** – suggested by very recent observations (hundreds to thousand of solar masses)

Why Do We Think Black Holes are Real

- In binary stars can determine the mass of the stars by measuring their orbits- Keplers laws
- In x-ray binaries one of the stars is 'normal' the other has strange properties (emits lots of x-rays and is very small and other things)
- Mass of the the 'strange' star is larger than a neutron star can be (maximum mass of a neutron star is set by quantum mechanics (!))
- So lots of mass and very small leads to the idea of a black hole

The Known Galactic Black holes

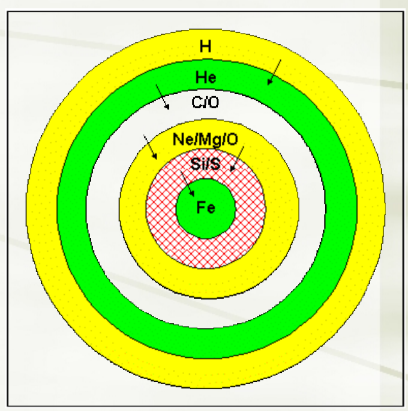
- About 20 black holes known in the Milkyway Way
- Mass between 5-16$M_{\odot}$



(Figure by Jerome Arthur Orosz)

Stellar mass black holes

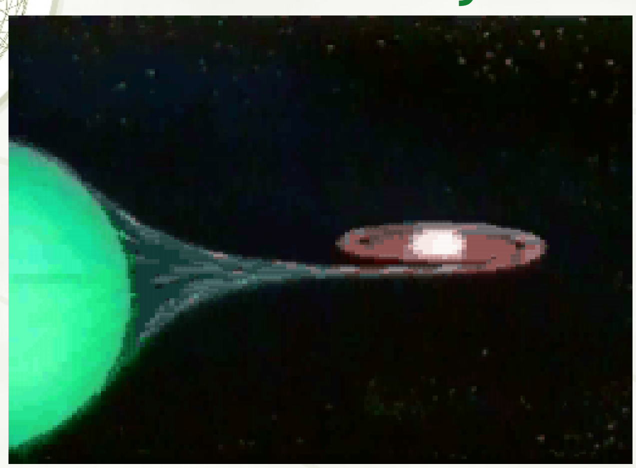
- End of massive star's life…
  - In core, fusion converts hydrogen to heavier elements (eventually, core converted to iron Fe).
  - Core collapses under its own weight
  - Huge energy release: Rest of star ejected – **Type II Supernova**
- Either a black hole or neutron star remains



Black holes in binary systems

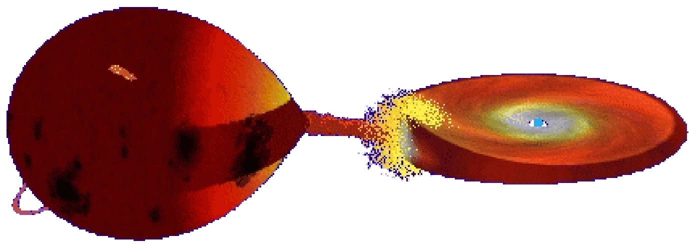
- If black hole is formed in binary star system,
  - Tidal forces can rip matter of the other star
  - Matter goes into orbit around black hole – forms an **accretion disk**
  - As matter flows in towards the black hole, it gives up huge amount of energy
    - analogy to hydroelectric power derived when water falls over a dam
  - Energy is first converted to heat, raising gas temperature in accretion disk to millions of degrees
  - Hot accretion disk radiates away energy, emitted as X-rays
  - These systems are called **X-ray binaries**

"X-ray" binary



Outer layers of a nearby star are pulled off by tides, crash into accretion disk around BH

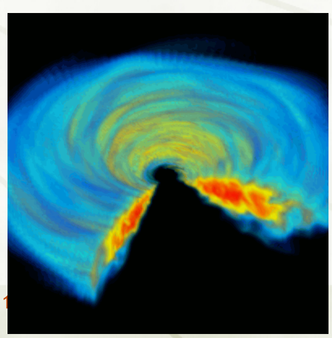
Accretion Onto A Compact Object

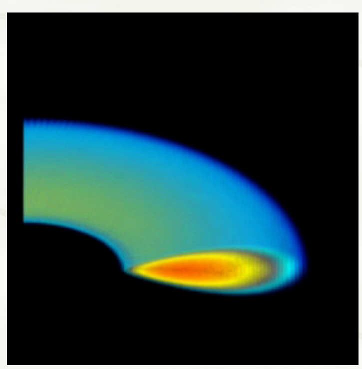


- http://physics.technion.ac.il/~astrogr/research/animation_cv_disc.gif

Accretion disk from numerical simulation

- Turbulence develops and causes gas to accrete (flow inward) onto the black hole

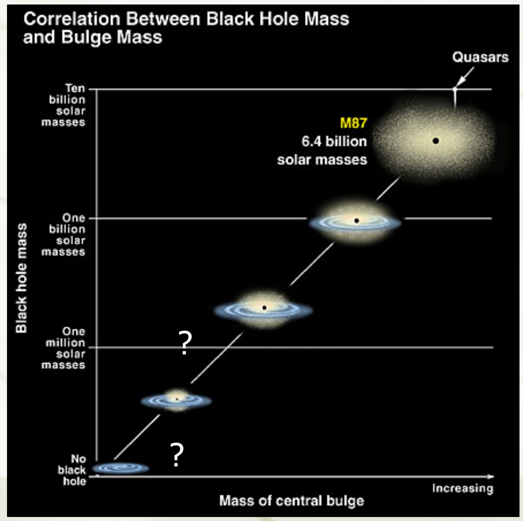




J. Hawley, U. Virginia

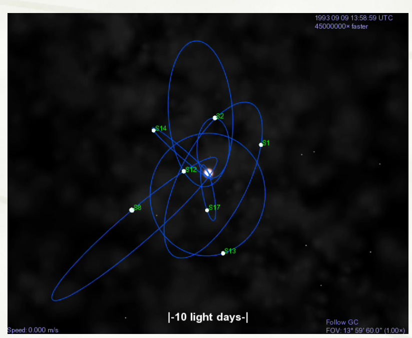
Supermassive black holes (SMBHs)

- Found in the centers of most big galaxies
- Mass of black hole and galaxy are correlated



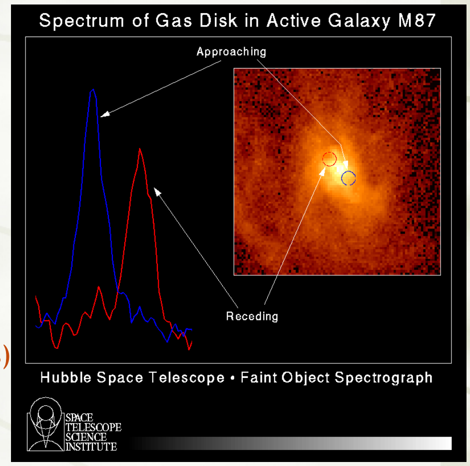
*Center of the Milky Way: Sgr A**

- The center of our own Galaxy
  - Can directly observe stars orbiting an unseen object
  - Need a black hole with mass of 3.7 million solar masses to explain stellar orbits
  - Best case yet of a black hole.



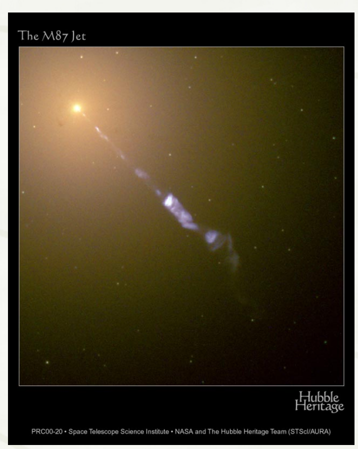
M87

- Another example – the SMBH in the galaxy M87
  - Can see a gas disk orbiting galaxy's center
  - Measure velocities using the Doppler effect (red and blue shift of light from gas)
  - Need a 3 **b**illion solar mass SMBH (Keplers Laws) to explain gas disk velocities

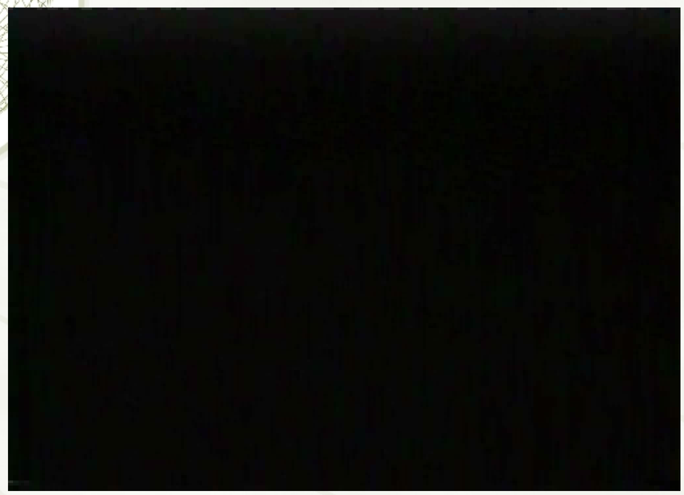


Active Galactic Nuclei

- M87 shows signs of "central activity"
- The Jet
  - Jet of material "squirted" from vicinity of SMBH
  - Lorentz factor of >6
  - Powerful (probably as powerful as galaxy itself)
- What powers the jet?
  - Accretion power
  - Extraction of spin-energy of the black hole



Artist's conception of M87 system



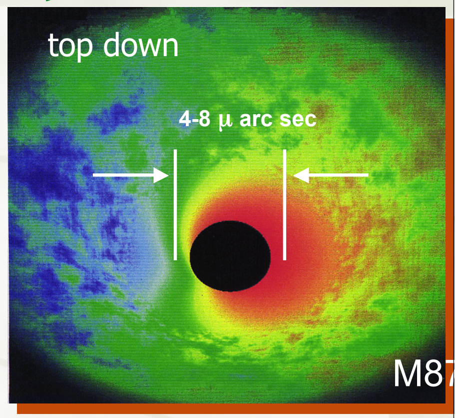
MUSE: Supermassive Black Hole
("Black Holes and Revelations" 2009)

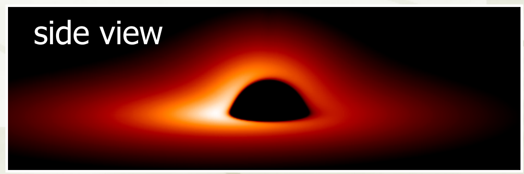
Active Galaxies

- M87 is example of an "active galactic nucleus"
  - Material flows (accretes) into black hole
  - Energy released by accretion of matter powers energetic phenomena
    - Emission from radio to gamma-rays
    - Jets
  - More numerous in the young universe than today
- Particularly powerful active galactic nuclei are sometimes called **Quasars- can be up to 10^{14} x more luminous that the sun**

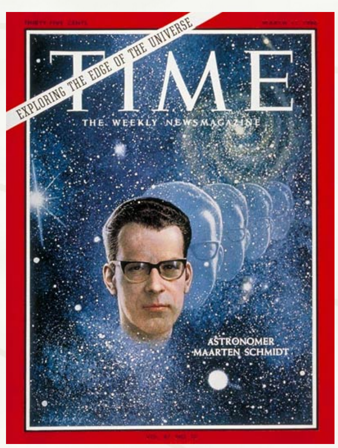
Images of a Black Hole

- A theoretical calculation of what the region near a black hole might look like
- The red/blue represent the Doppler shift and the asymmetries the effect of GR



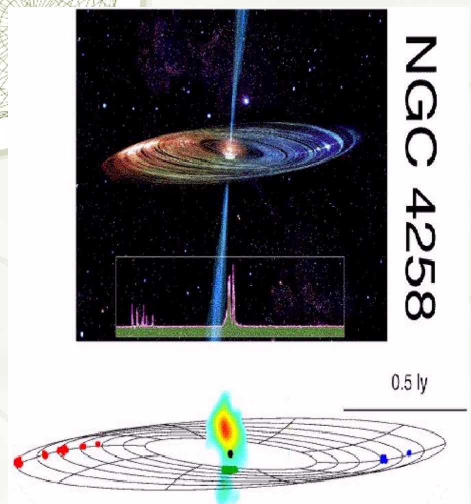


1966 Cover, discovery of QSOs



quasars can be seen at redshifts >6

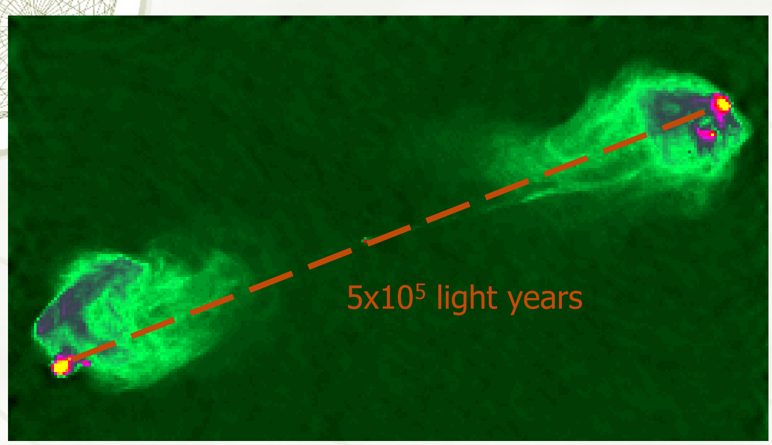
Water masers and dynamics in NGC 4258



Masers reveal a tiny warped disk around a massive black hole
Use Kepler's Laws to get mass (need velocities and distances from BH)

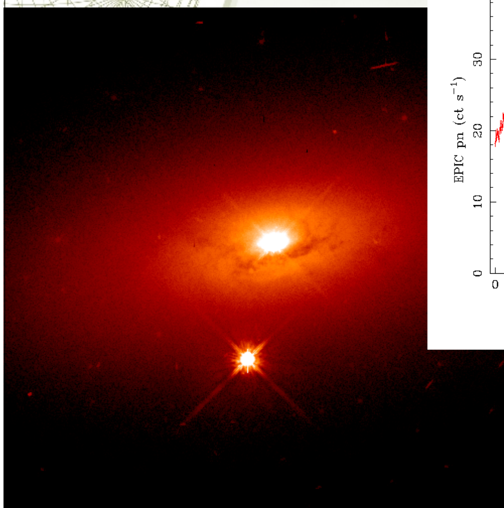
Miyoshi et al 1995;
Greenhill et al 1996;
Herrnstein et al. 1998

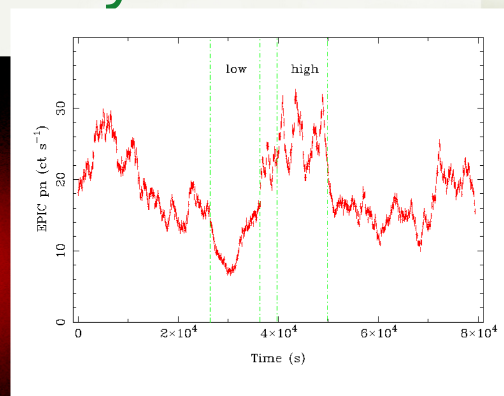
The powerful radio-galaxy Cygnus-A



Radio image with the
Very Large Array in New Mexico

Another example… the "Seyfert galaxy" MCG-6-30-15



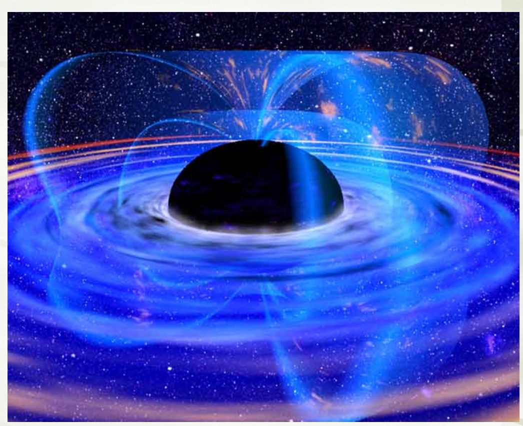


time variability of source luminosity ~10^{10} Suns- intensity changing on timescales of minutes

Active galaxies (e.g. radiating supermassive black holes) emit radio, IR, optical, UV, x-ray and γ-ray radiation !

Broad band spectrum very different than stars

In the x-ray band there is a signature of the physics very close to the event horizon



*What can come **out** of black hole?*

…more than you might think!

- Magnetic fields threading ergosphere can attach to and drag surrounding matter, reducing the black hole's spin and energy
- "Hawking Radiation": black hole slowly evaporates due to quantum mechanics effects
  - Particle/antiparticle pair is created near BH
  - One particle falls into horizon; the other escapes
  - Energy to create particles comes from gravity outside horizon

$$t_{evap} = 10^{10} yrs \times \left(\frac{M}{10^{12} kg} \right)^3$$

  - Solar-mass black hole would take 10^{65} years to evaporate!
  - Mini-black holes that could evaporate are not known to exist now, but possibly existed in early Universe

Next Lecture-Last before Exam

- The expanding universe- ch 10

and

Any pressing questions about the semester up till now