GENERAL RELATIVITY & the UNIVERSE

It was realised almost immediately after Einstein published his theory that it possessed solutions for the configuration of spacetime, in the presence of a homogeneous distribution of matter (like that seen in telescopes), that had a ‘closed geometry’, and which moreover were expanding in time. The existence of a closed geometry meant that the solution was describing the whole universe!

Einstein did not at first believe this, and so he added an extra term to his equations (the ‘cosmological term’) to stop this ‘Big Bang’ solution. He later withdrew this in the face of the incontrovertible evidence (from Hubble’s observations) that the universe was indeed expanding uniformly.

Worse was to come. In 1938 Oppenheimer & co-workers found a ‘black hole’ solution to the equations, after extending work of Chandrasekhar and Landau. Again this was too much for Einstein, but in the 1960’s, pioneering work by Zeldovich et al, Hawking, and Penrose, showed the inevitability of these solutions and their importance for real astrophysical phenomena. This theoretical framework has since then led to a complete re-writing of astrophysics: the modern picture is discussed later in this course.

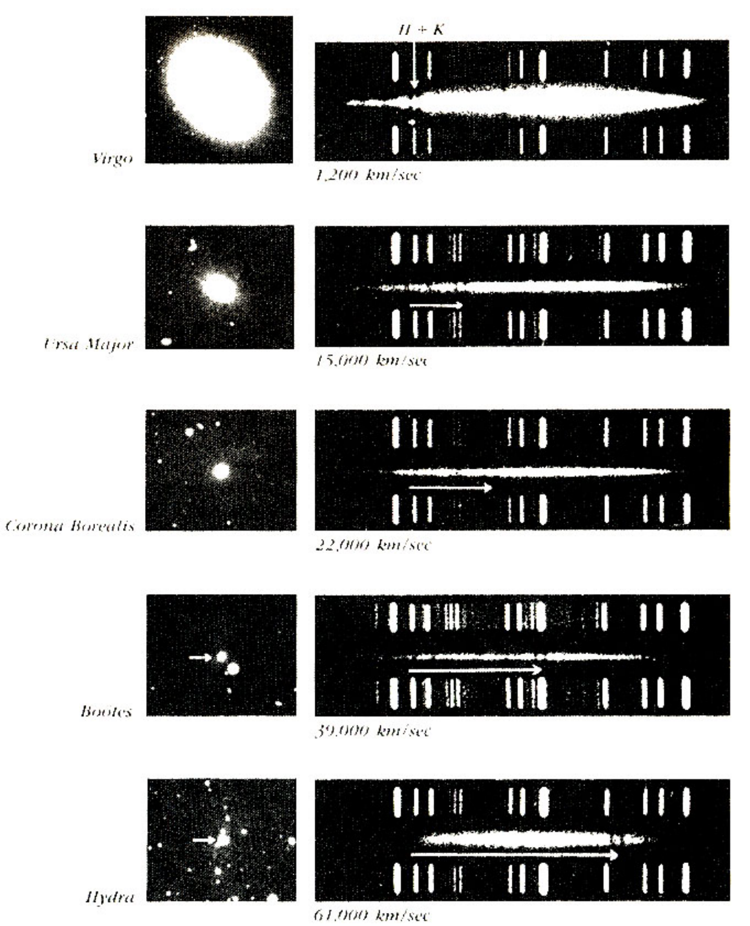
In what follows I outline the most radical consequences of strong gravitational fields.

The EXPANDING UNIVERSE

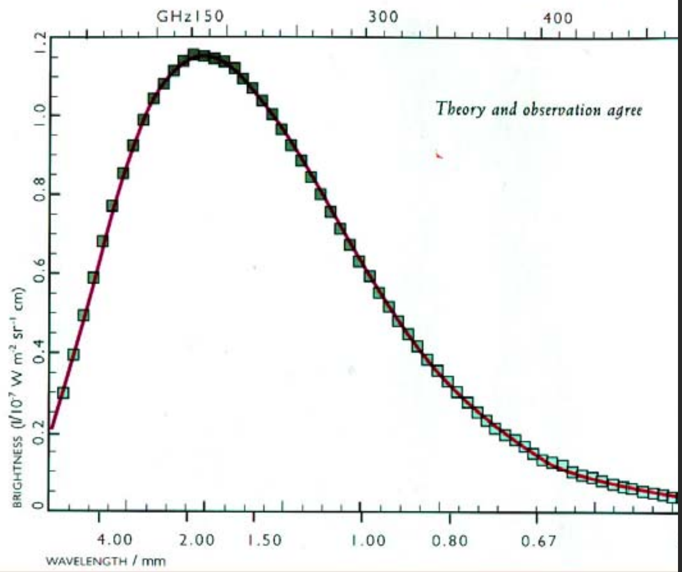
It was very quickly realized that one simple solution of the Einstein field equations was a universe beginning with zero volume and then rapidly expanding- a “big bang”. Einstein himself really disliked this and so added an extra “cosmological term” to the equations, to prevent this solution.

However in 1928 E. Hubble used the newly built 100-inch “Hooker” telescope to look farther then ever out into the universe- and discovered the famous “Hubble law”. This says that the galaxies recede from us at a velocity proportional to their distance from us. This was basically what Einstein’s theory had predicted in the 1st place.

Confirmation of the big bang model came with the discovery of the microwave background in 1964- the universe is full of thermal radiation, left over from the original explosion (see left).

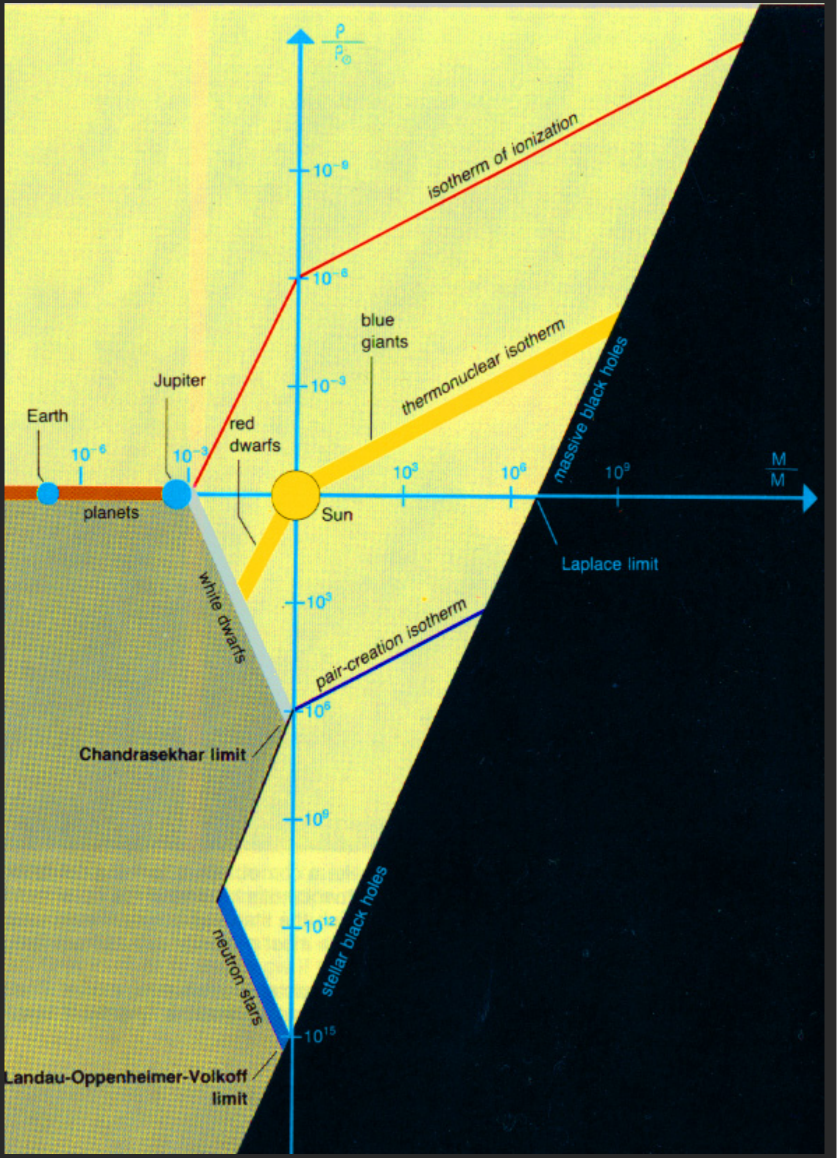


The galactic spectra obtained by Hubble (1928), for different clusters.



GRAVITATIONAL COLLAPSE

Landau and Chandrasekhar first realised the importance of General Relativity for Stars (1930). If we increase their mass and/or density, the effects of gravitation become increasingly important. If a star of Solar mass runs out of nuclear fuel, it will collapse to a white dwarf, the size of the earth but with density a million times that of water (1 ton per cubic centimetre). Above the Chandrasekhar limit of 1.4 solar masses it will collapse to a neutron star, made of nuclear matter, with a density of 10^{15} times that of water- a billion tons (the mass of Grouse mountain) per cubic centimetre). The gravitational fields are then enormous, with severe spacetime curvature. Another increase by a factor of 2 or 3 and no force can prevent the collapse to a singularity of spacetime (shown by Oppenheimer and his students Volkoff & Snyder, in 1938-39). 30 yrs later these singularities received a name… black holes.

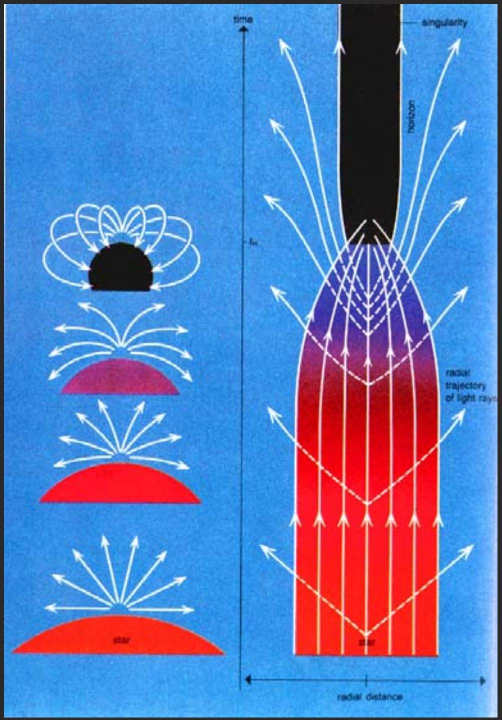


The state of massive bodies as a function of their mass (increasing to right) and their mean density (increasing downwards).

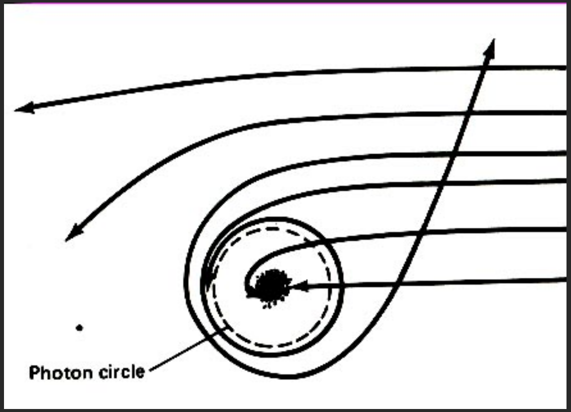
BLACK HOLES

Above the critical mass, nothing can stop collapse to a black hole. Inside a critical sphere (the event horizon) not even light can escape- just outside it, only light travelling nearly directly away can escape (see left). The distortion of light paths leads to very odd light images near a black hole. Black holes are compact- one with the mass of the sun has an event horizon only 6 km in diameter (this diameter is proportional to the black hole mass). Although a non-rotating black hole has only 2 defining properties (mass and charge), they are usually surrounded by a rotating "accretion disc" of matter.

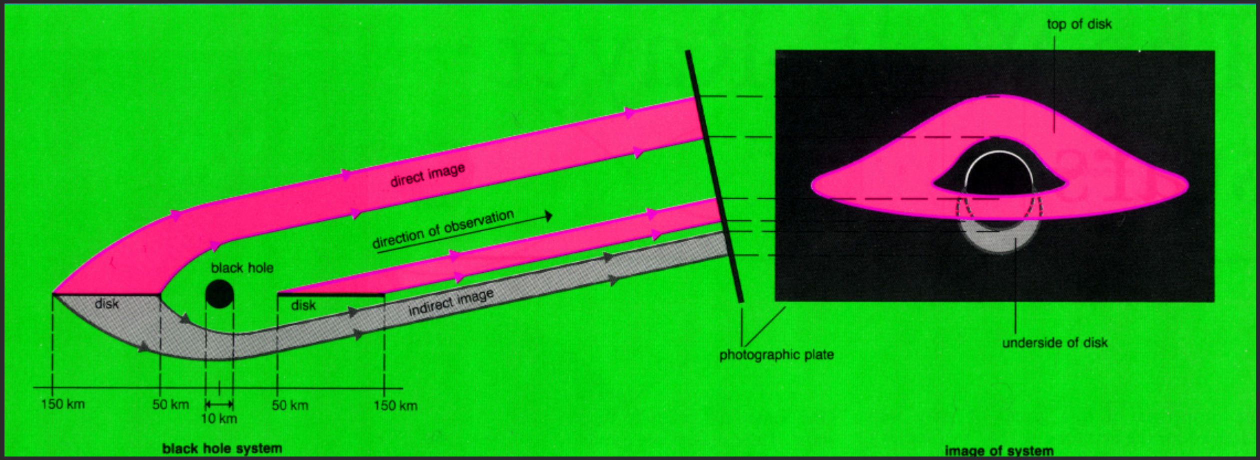
Below: successive stages of black hole formation



Below: light paths near a black hole

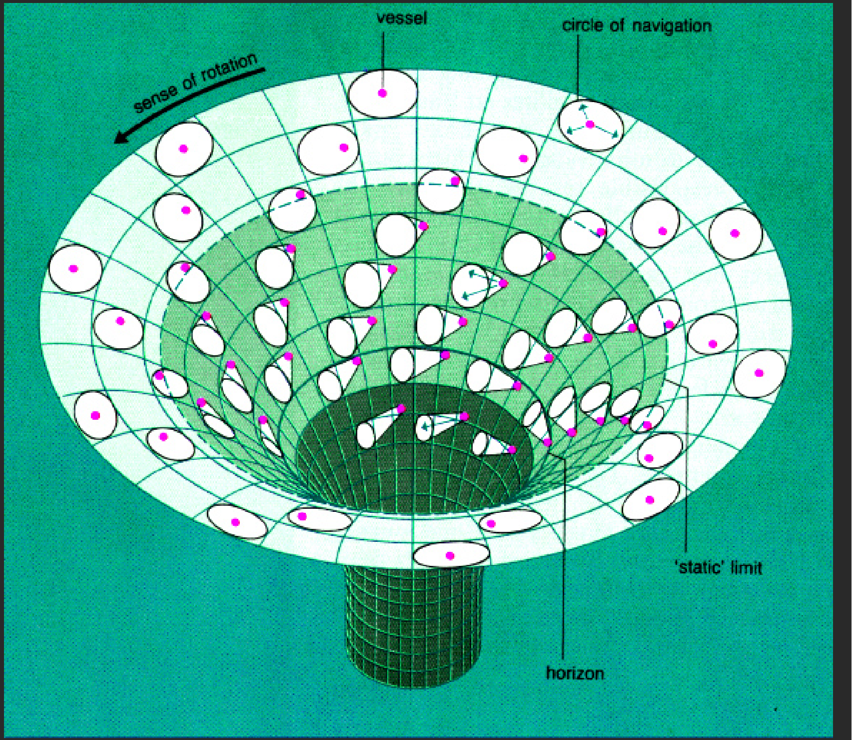


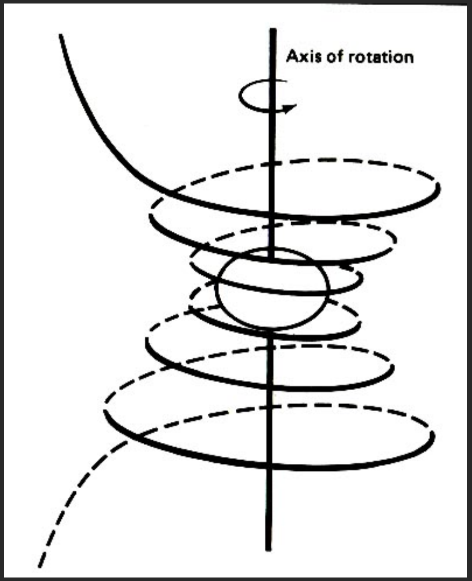
Below: how the accretion disc of a black hole would appear on a photo. Light coming directly to the plate is shown in mauve, that coming around (underneath) is shown in grey



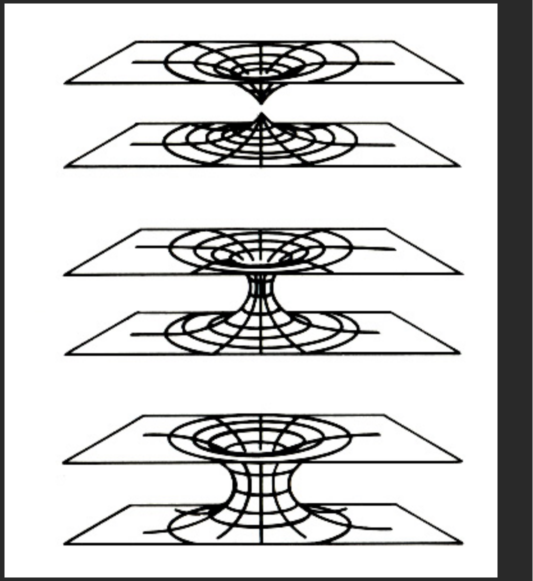
ROTATING BLACK HOLES

If the black hole has angular momentum (it is "spinning") then the spacetime metric does not become singular- instead, a more complex configuration results (the "Kerr metric"), shown schematically here. The black hole "twists" the spacetime near to it, and light can follow a spiral path through this region (see below). The light cones of light emitted in this region get "dragged" by the distorted spacetime, as shown at right. Light passing close to a rotating black hole can follow a pretty peculiar path in this spacetime (see left).





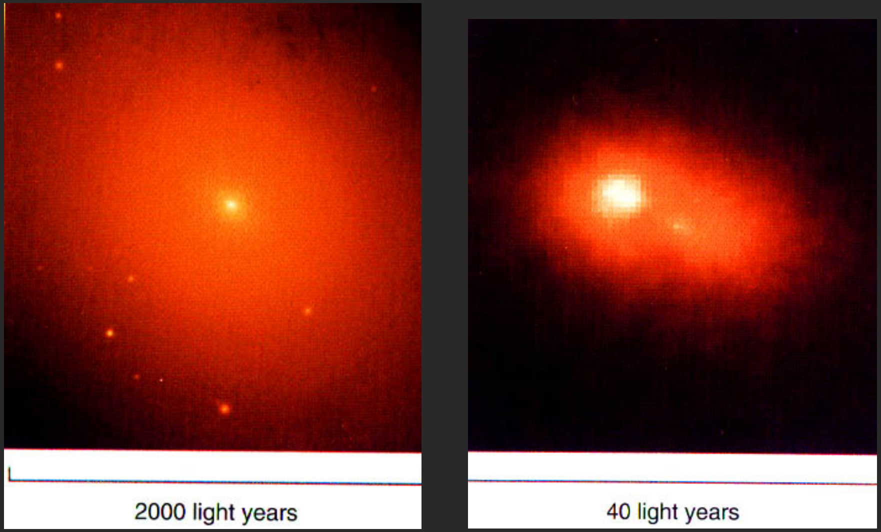
It has been known since the 1930's that one can have "Einstein-Rosen bridges" between 2 regions of spacetime (now called "wormholes"); their formation is shown at right. If there is also rotation, once can theoretically get a black hole joined to a "white hole", although this is not now believed to be stable.



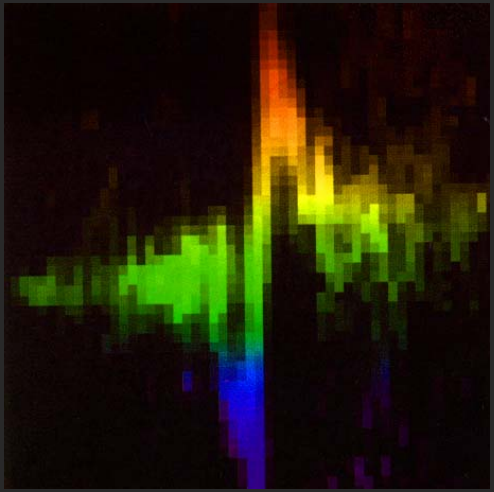
BLACK HOLES in GALACTIC CORES

The gravitational potential well near the centre of a galaxy favours a high concentration of stars and gas there. But in most galaxies a central black hole has formed, which is slowly eating its surroundings. The mass is often several billion solar masses.

At right: the galaxy **M31**, in our "Local Group": diameter ~ 130,000 ly. Below, the central portions (scale indicated).

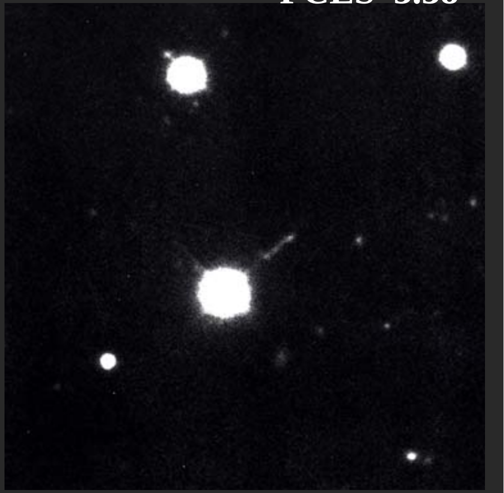


At right: the spectra of stars on a line passing through the centre of **M84**. The Doppler shift yields the mass distribution, showing a central black hole of mass ~ 1.5 billion suns.

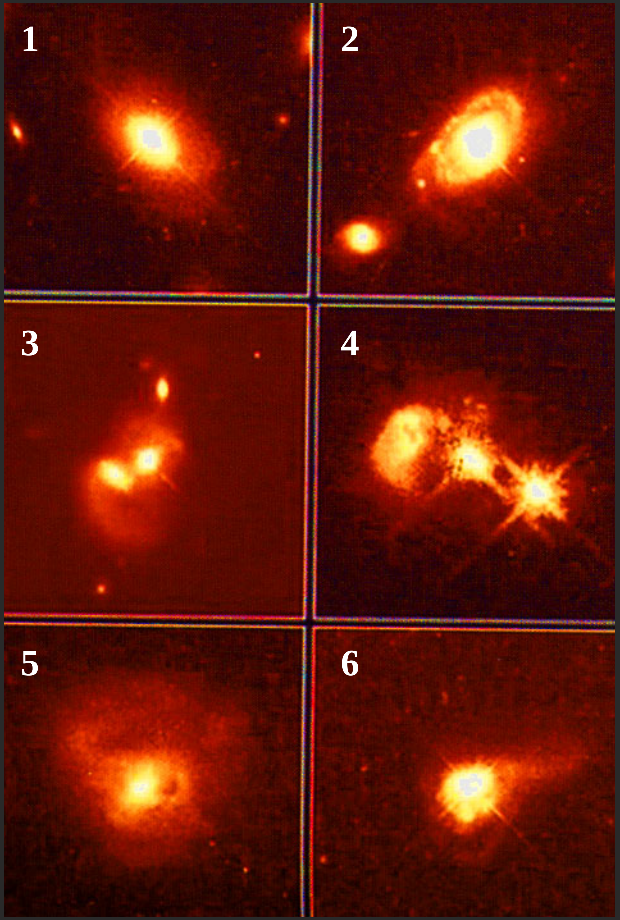


BLACK HOLES in QUASARS

Astronomers were shocked in 1963 when M. Schmidt showed that quasars ("quasi-stellar radio sources") are actually *billions* of light years from us- and thus can be hundreds of times more luminous than entire galaxies! This seemed impossible- their power output sometimes fluctuated in a matter of DAYS, showing they could only be a light day or so across (the size of the solar system)! The mystery was resolved when it was realised that these were supermassive black holes, with output powered by the accretion of large amounts of gas, dust, and even whole stars, whose mass was being converted to energy upon being swallowed. Often huge jets are seen emerging from these regions near galactic centres, at relativistic velocities.

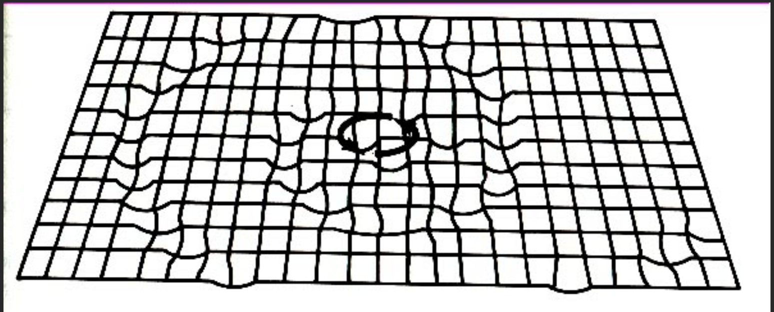


The quasar 3C273, the 1st one found by Schmidt- notice the jet emerging from it, 120,000 ly long. The galaxy is invisible.



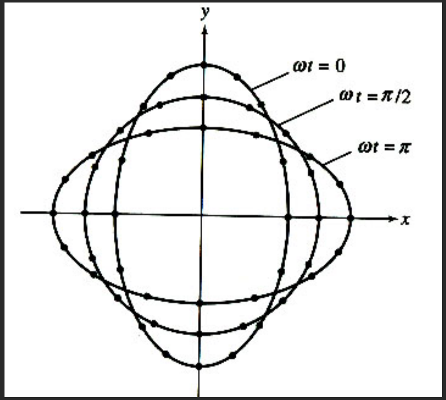
At LEFT…(1) PHL909, in an elliptical galaxy; (2) PG 0052+251, in a spiral galaxy; (3) PG 1012+008, in a binary galaxy; (4) 2 colliding galaxies, with the quasar IRAS 04505-2958; (5) quasar IRAS 13218+0552; and (6) quasar 0316-346, trailing gas from a previous galactic collision.

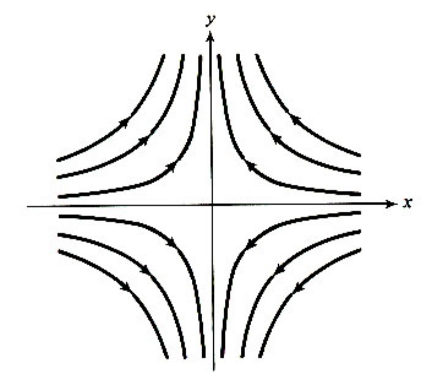
GRAVITATIONAL WAVES



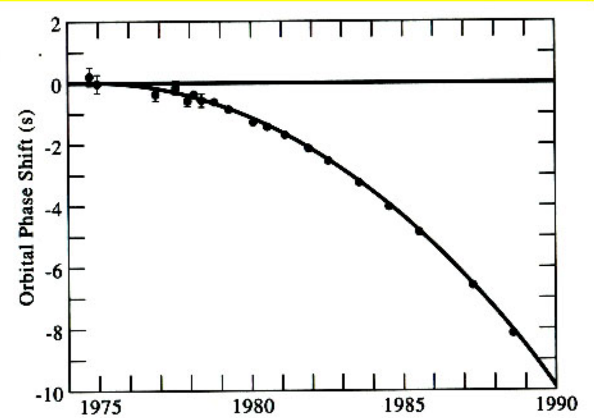
Spacetime distortion by a sudden perturbation (eg., a back hole collision).

Like any other field, the spacetime metric supports wavelike disturbances. These have a “quadrupolar” form, in which space transverse to the wave direction is alternately squeezed and stretched (along with any body in that region of space). This means that any disturbance of spacetime having the same quadrupolar character will create gravity waves. To have effects of reasonable magnitude we need very massive objects. This means collisions between black holes, or similar catastrophic events.





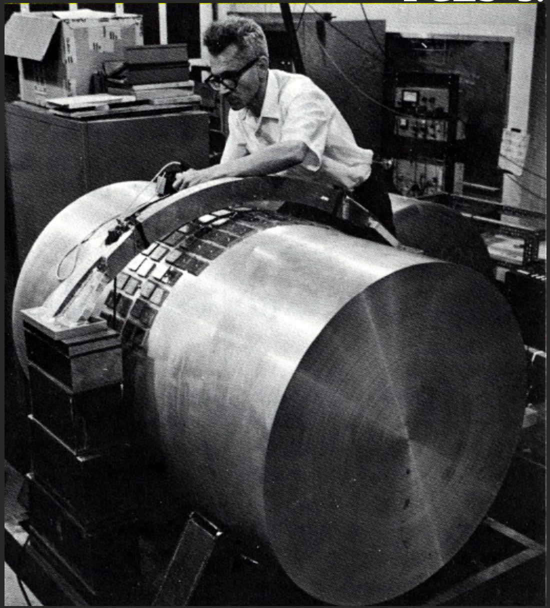
Top: distortion of a body by a gravity wave.
Bottom: force lines



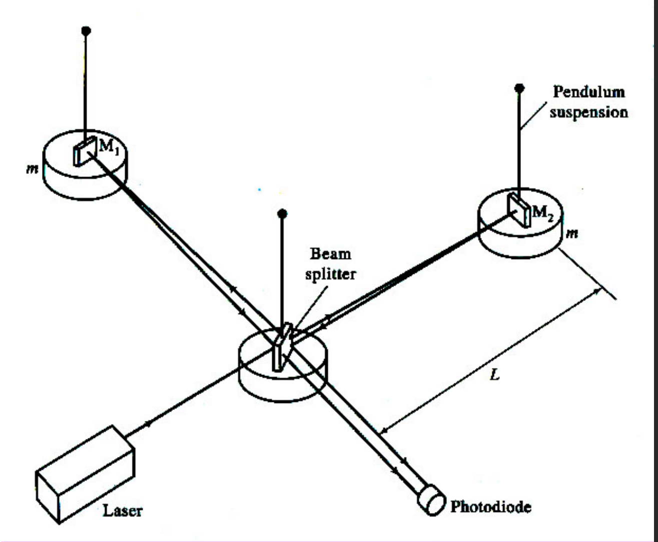
The best indirect evidence for gravity waves is the decay of the orbit of the “binary pulsar” PSR1913+16. Here 2 neutron starts orbit each other every 7 hrs- the periodic distortion of spacetime causes emission of gravity waves from the system. The energy loss causes the orbital period to slowly change (at left). Comparison with theory has so far given agreement.

GRAVITATIONAL WAVES II

The attempt to detect gravity waves has been going on for over 40 years. What is needed is an object that will respond to very small distortions in spacetime. The first experiments, by J. Weber in the 1960's, used huge Aluminium bars, designed to resonate if distorted by a gravity wave. Later designs are much more sensitive. At present very large detectors called LIGO's (Laser Interferometer Gravity wave Observatory) are being perfected. These work by looking at the interference of 2 light beams as shown. If gravity waves pass they change the path lengths, thus changing the interference. The long-term aim is to allow observation of gravitational radiation, as we observe EM radiation now.

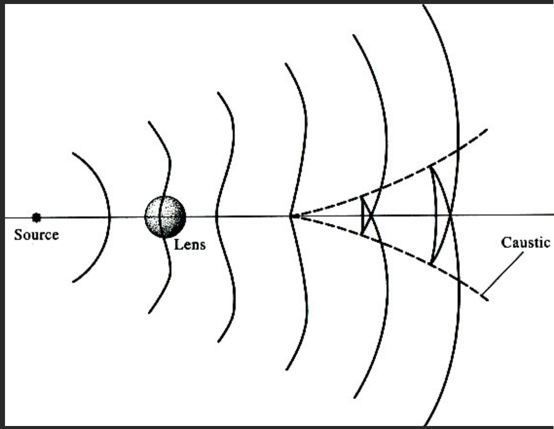


J. Weber with one of his gravity wave detectors



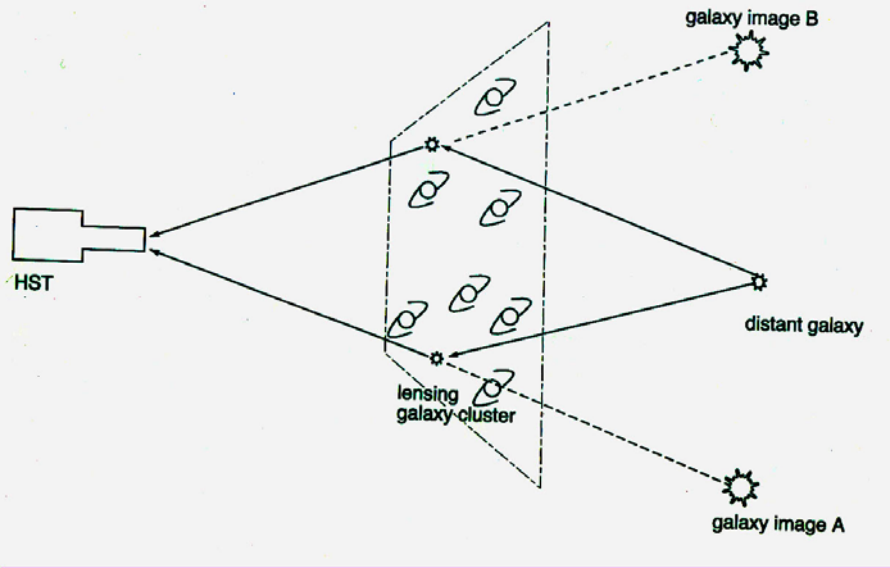
In a LIGO, the laser light along the 2 paths both converge in the diode detector- and thus interfere.

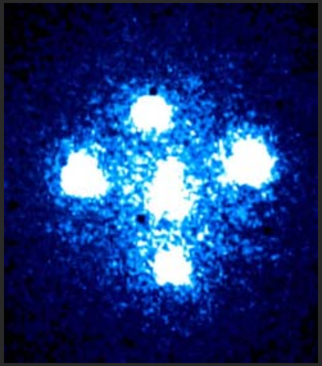
Gravity waves (and EM radiation) can be focused when passing a massive body- this is called gravitational lensing (see right)



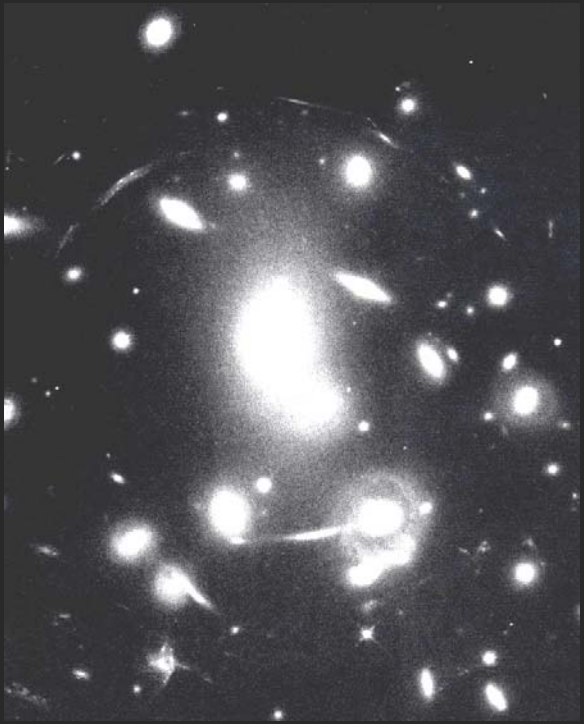
GRAVITATIONAL LENSING

In the same way that the sun slightly bends the path of light, so can a galaxy or cluster of galaxies. If another galaxy lies directly behind, as seen from earth, a distorted image of this further galaxy will be seen, with shape depending on the distribution of mass in the cluster, and the exact line to the farther galaxy. One gets multiple images, stretched in peculiar ways which can be calculated. The lensed galaxies can be very far- the blue galaxy lensed by 0024 +1654 is ~ 10 billion l.y. away- we are seeing back to the very young universe (full of blue galaxies).

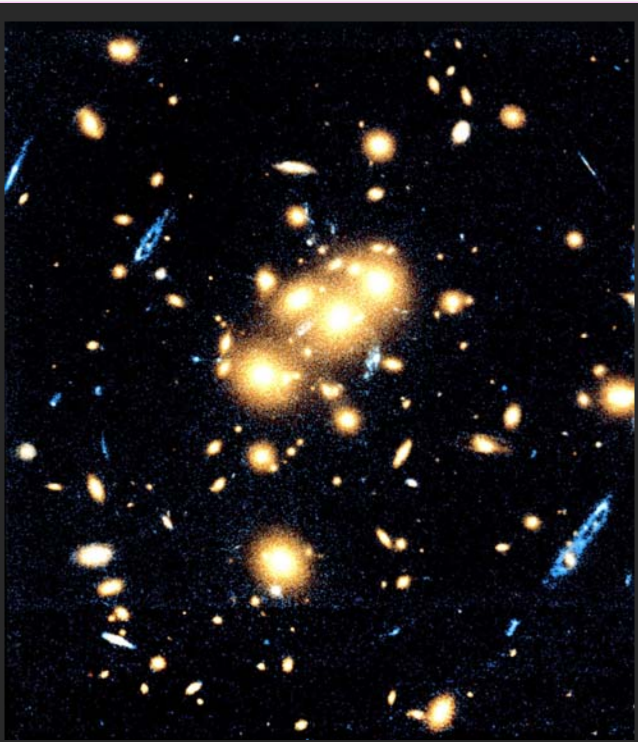




“Einstein’s cross”



Lensing by cluster Abell 2218



Galaxy lensed by cluster 0024+1654