Gravitational waves

Testing Einstein:

- with gravitational waves
- with observations of the Universe
- with thought experiments inside the horizon

Gravitational waves

Recap: prediction of general relativity, masses in non-uniform motion close to the speed of light excite waves in space time

No waves from spherical or axisymmetric sources

Strong waves from binaries involving compact objects: neutron stars and black holes

Gravitational waves

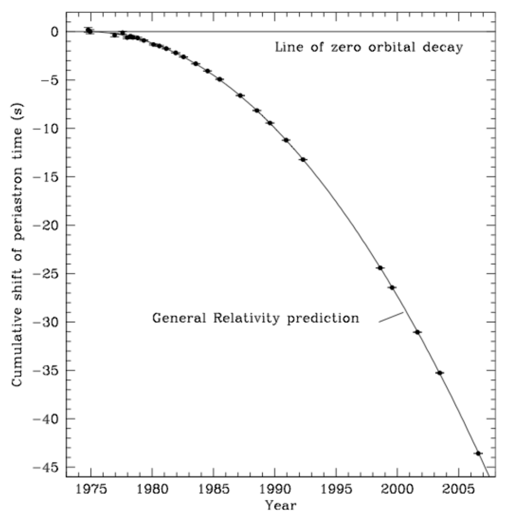
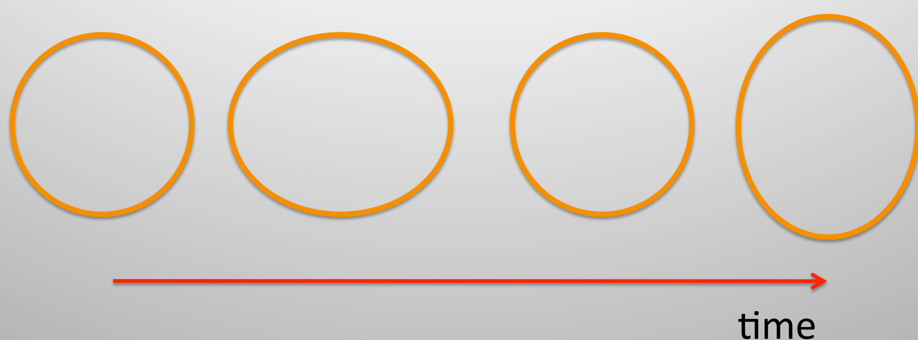


Figure 2. Orbital decay caused by the loss of energy by gravitational radiation. The parabola depicts the expected shift of periastron time relative to an unchanging orbit, according to general relativity. Data points represent our measurements, with error bars mostly too small to see.

Know these waves exist from binary pulsar, but have not detected them directly

Existing observations probe velocities $v \ll c$

Gravitational waves

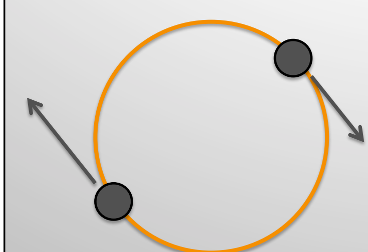


- travel at the speed of light
- alternately compress and stretch space as they pass – key to their direct detection

Gravitational waves

Key properties:

- strength – expressed as fractional distortion of space caused by wave: e.g. if the wave caused a 1cm distortion to a 1m rod, h = 0.01. Depends on source, distance
- frequency – number of crests of the wave that pass each second… depends on the source



e.g. two neutron stars with an orbital separation of 100 km

Orbital period: $P = \frac{2\pi}{\Omega} = 2\pi\sqrt{\frac{d^3}{G(M_1 + M_2)}}$

About 0.01 s

Neutron star mergers produce waves with f ~ 100 Hz – kHz in final stages

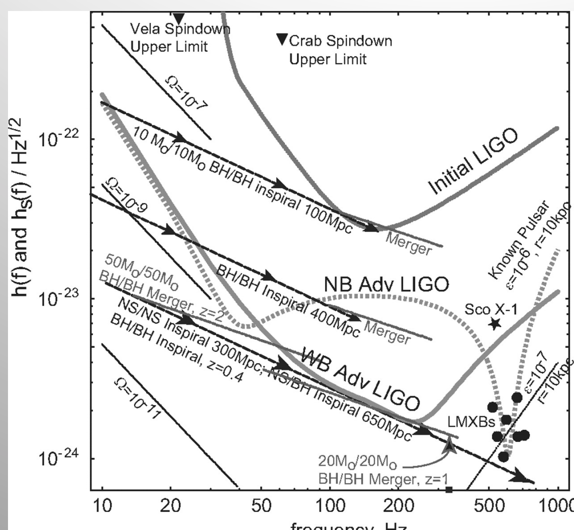
How close is the nearest neutron star binary that will merge this year?

Closest separation *Galactic* binaries will merge via gravitational radiation in about 100 Myr

Estimate the rate per galaxy as ~10 per Myr, i.e. need to see 100,000 galaxies to catch 1 each year

There are about 0.01 galaxies per cubic Mpc

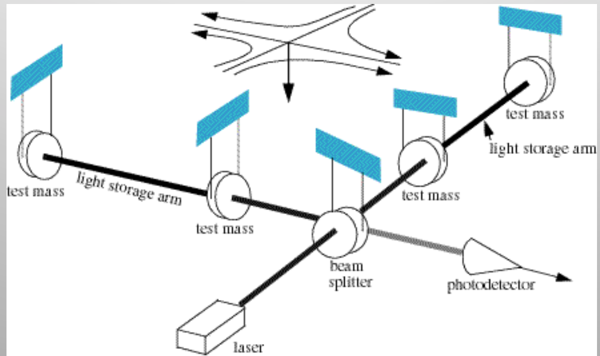
Want volume ~10 million Mpc^3, d ~ 200 Mpc



Distortion of space at Earth from NS-NS merger at few hundred Mpc is very weak

Fractional displacement at 100 Hz: h ~ 10^{-23}
Much less than diameter of proton over many km

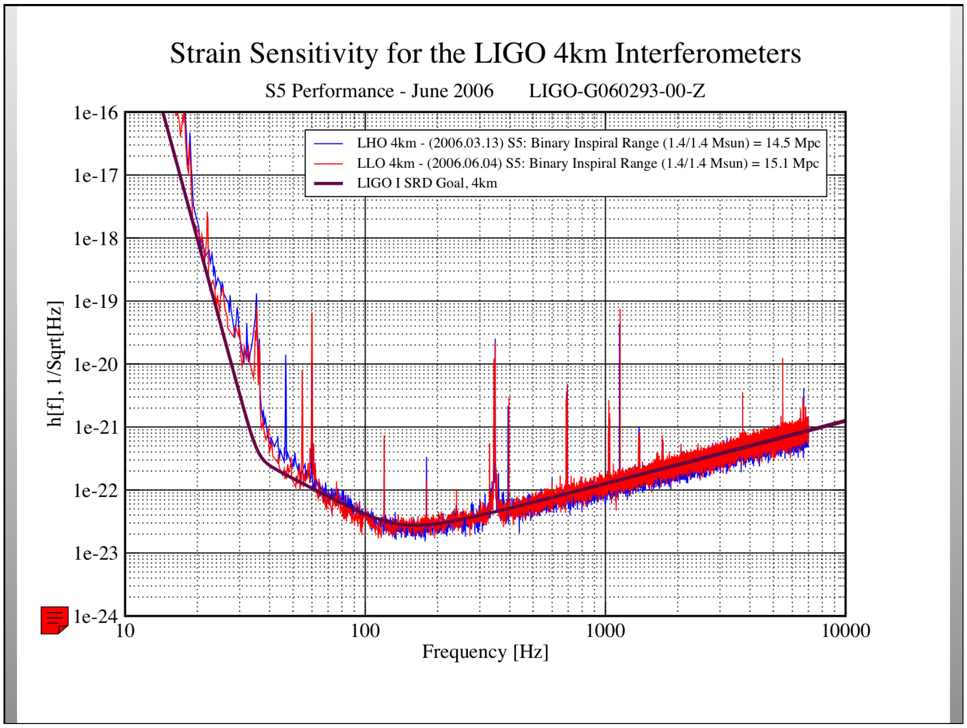
But measureable – we think! Use lasers to measure shifts in the length of two arms at right angles with time:



Laser interferometer: can approach the ultimate sensitivity set by quantum uncertainty principle

LIGO – Laser Interferometer Gravitational Wave Observatory

Two instruments in Washington and Louisiana



Sensitivity achieved in initial operations reached design goal, but only good enough to see NS-NS mergers out to ~15 Mpc… not enough

No signals seen

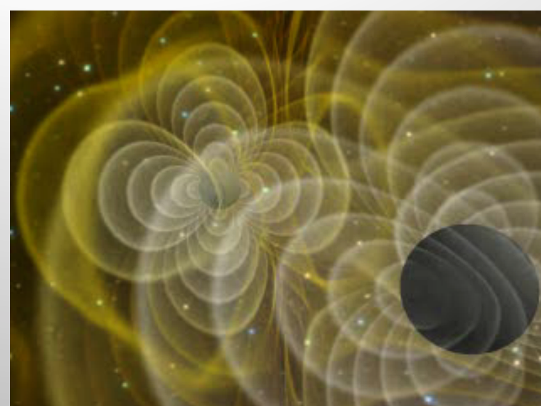
Currently being upgraded: *Advanced LIGO* expected to start operating within next couple of years

Expect first direct detection of gravitational waves

Sources:

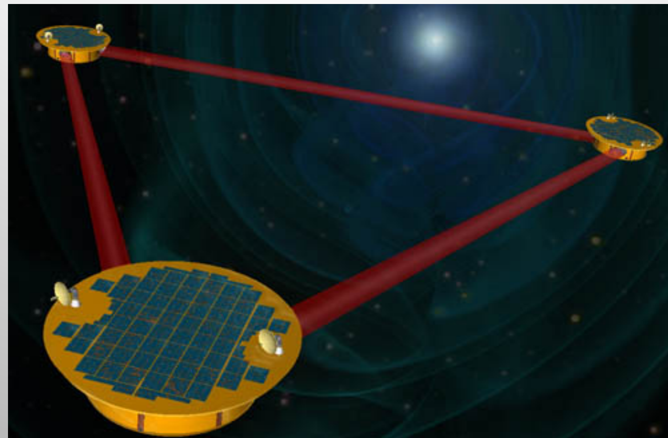
- neutron star binaries
- neutron star – black hole binaries
- supernova explosions (?)
- asymmetric rotating neutron stars (?)
- new classes of sources!

Mergers of supermassive black holes would also emit gravitational waves

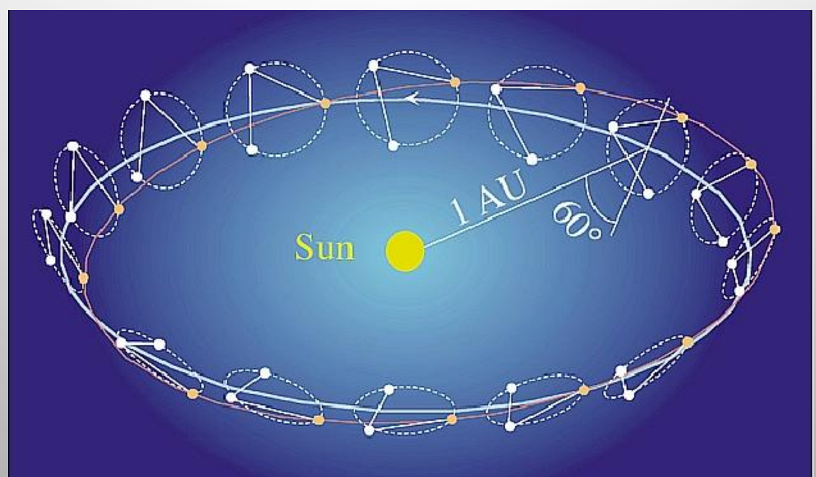


Final orbital periods ~hour, so much lower frequency

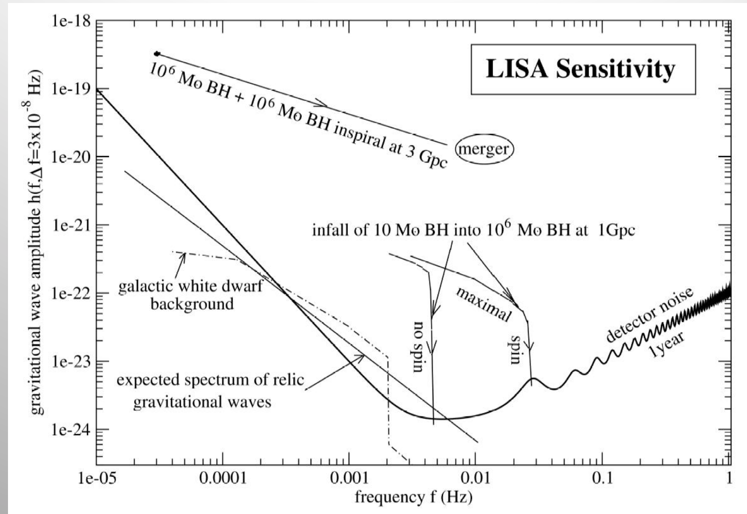
Not accessible from the ground



LISA – proposed mission to detect gravitational waves in space using laser interferometry between three free-flying spacecraft



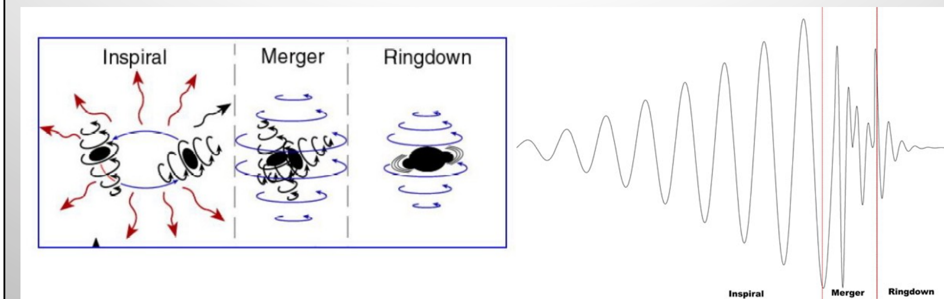
Spacecraft would orbit in a rotating triangular configuration about the Sun



Look for: supermassive BN binary mergers, inspiral of stellar mass BHs into supermassive ones

Status:

- "LISA Pathfinder" mission to demonstrate technology due to launch in 2015
- No decision to proceed on full LISA



Goal: observe the inspiral, merger and ringdown as two black holes merge

- can predict waveform accurately
- ringdown is when the new hole loses its "hair"
- test No-Hair theorem for GR, GR in the regime of strong fields