Black Holes, Gravitational Waves and Warp Drive

Since will not be covering formation of galaxies and stars in class, start by assuming that stars exist.

The fuel of a star

Hydrogen and Helium provide “fuel” that both:

1. Creates light we see. 2. Keeps star stable

During normal processes light atoms are converted into heavy atoms.

The life of a star

Star starts as “ball” of mostly hydrogen, with fusion in core.

Ask: What happens when runs out of fuel? What happens when Hydrogen runs out?

Without hydrogen fuel to make things “expand”, i.e., exert outward pressure, gravity crushes atoms closer and closer together. Takes temperature of 100 million Kelvin to fuse Helium - may never happen for many stars. What happens next depends on “mass” of star.

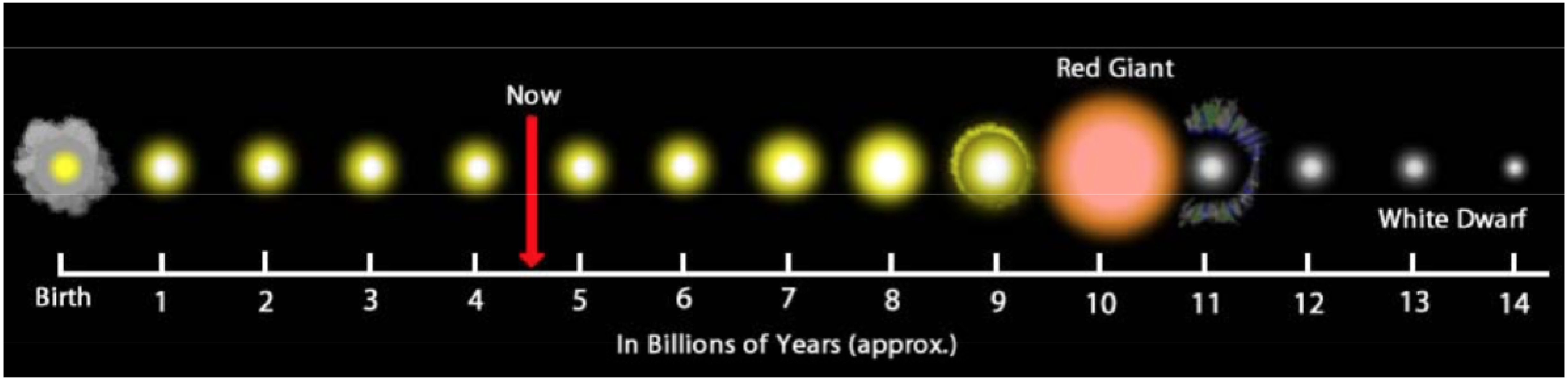
Start with stars like our Sun

Mid-sized stars (between 8% and 8 times mass of our Sun) all typically have similar life.

Smaller than 8% of Sun → won’t get hot enough to fuse hydrogen in first place. Isn’t really star at all - called brown dwarf.

More than 8 times mass of our Sun → complicated things can happen (later...).

The life and death of our Sun



Sun using hydrogen to create light. Helium produced falls to center (core). As of today: core about 15 million Kelvin → not hot enough to convert helium into Carbon.

In future will become white dwarf.

When most of hydrogen used up, core gets crushed. Eventually atoms get REALLY close to each other and strength of repulsion between electrons from quantum mechanics is so big that it balances out gravity. Outer part becomes Red Giant and then diffuses into space while Inner part stabilizes → white dwarf.

Hot core creates heavy elements . It can shine for quite awhile - why call it “white”. Really dense: object with mass of Sun shrunk to size of Earth - why call it a “dwarf”. How dense? Marble would weigh about 2 tons!

The life of a heavy star

For heavy stars 1st part of life same as lighter stars: after hydrogen runs out, gravity crushes core. Different -> heavy stars have so much mass that gravity continues to crush core, and temperature rises significantly. For stars with more than 8 times mass of Sun, core can reach temperature of 100 million Kelvin, and helium fusion can start - makes heavier elements.

Death of very massive stars

If star much more massive than our Sun runs out of fuel quickly

- 1 x Sun → 10 billion years
- 10 x Sun → 30 million years
- 100 x Sun → ≈ 100,000 years

Different things happen as runs out of fuel → gravity so strong can REALLY crush star. More crushing → Neutron Star

After fuel runs out, if mass of star large enough, things change quickly! Gravity quickly crushes atoms into each other. Electrons are pushed so close to protons -> start to interact and turn into neutrons. Star crushes itself into ball of neutrons about size of Manhattan. Neutrons don't like to be "too close" to each other because of Quantum Mechanics → core can stabilize. In this process core collapsed from size of Earth into ball of neutrons just few kilometers across. Incredibly dense! - Billions of tons per cubic inch. Marble made from neutron star material would weigh same as Earth.

Inner part of star quickly crushed into neutron star. What happens to outer part? Atoms fall towards center! Hits dense neutron core and bounces back into space as giant explosion = Supernova. Explosion so big -> can shine as bright as 10 billion suns for couple of weeks. Temperatures in explosion so high and atoms are densely packed that really heavy atoms can be created and then blown into space. How get stuff like uranium on Earth.

Moving towards black holes

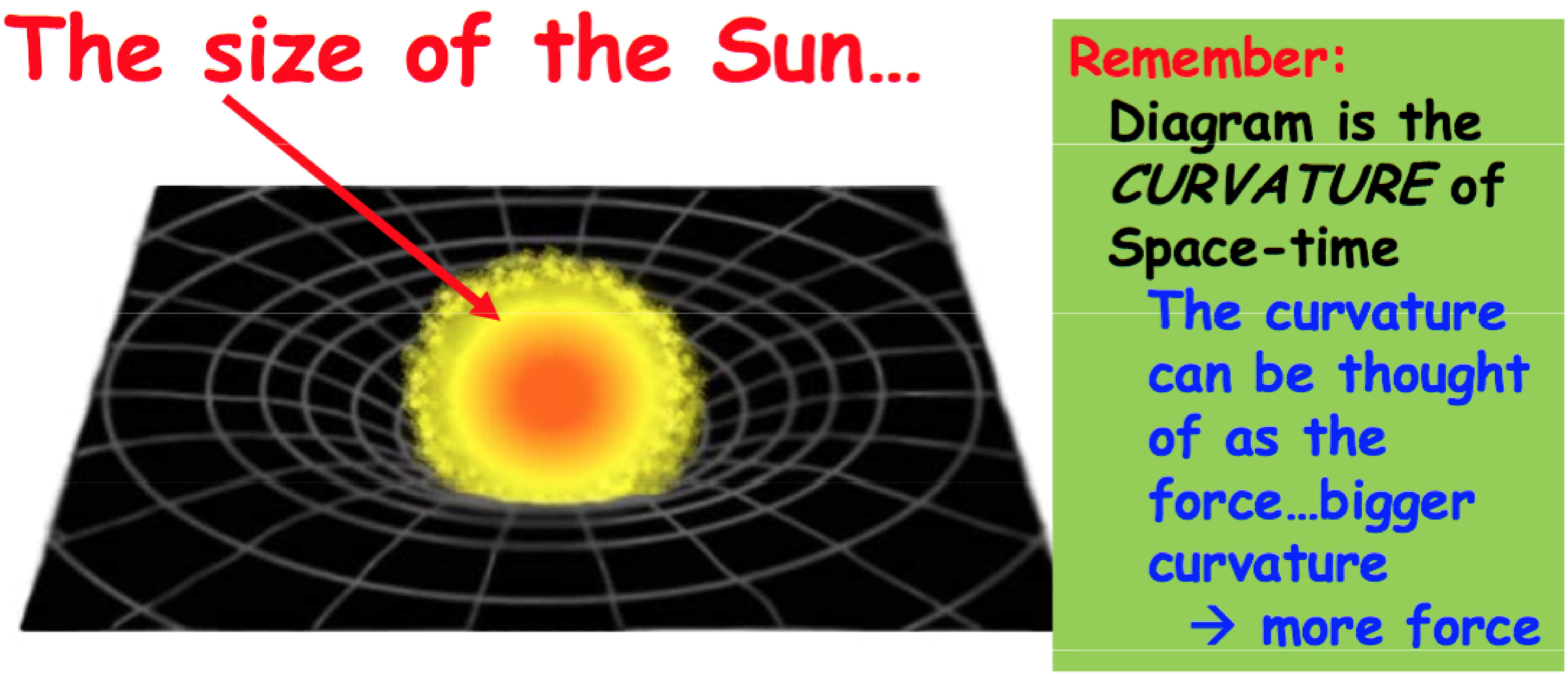
If remaining neutron star (what was core of star) has "critical mass" ($3 \times M_{Sun}$) can continue to collapse under its own gravity. Nothing left to oppose crush of gravity! → continues to collapse until becomes Black Hole.

Black Holes

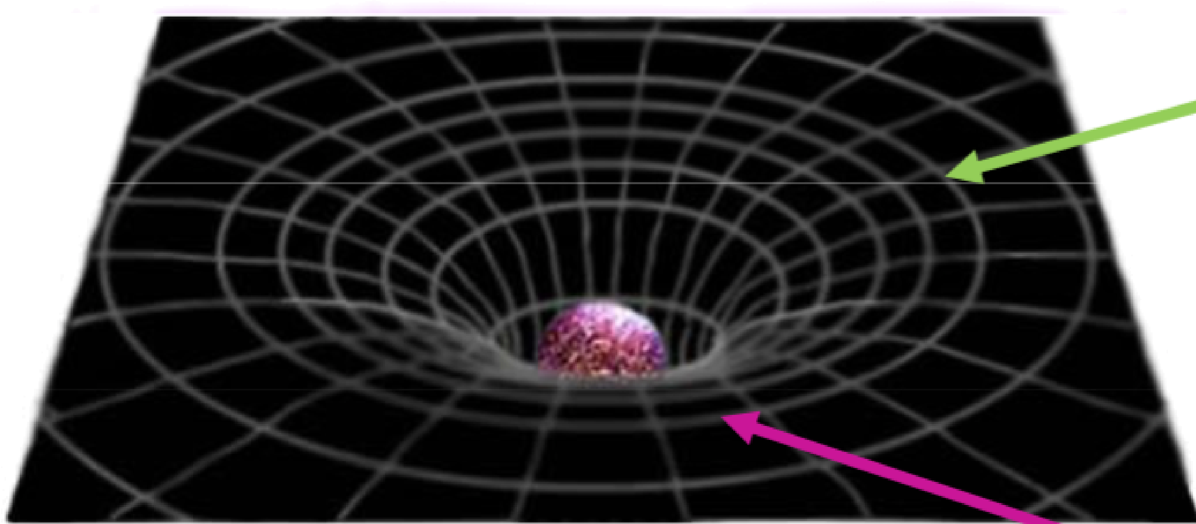
What they are... and aren't

- Black holes aren't demonic, sucking power holes.
- A black hole is just another thing a star can turn into when it runs out of fuel.
- It is basically a really massive, non- shining, ex-star.
- Then again, something with that much mass but a size smaller than a proton does have some unusual properties.
- No dent in space... Just a small object.

Space looks same, but let's look at curvature of spacetime near Sun



How does curvature change as compress Sun into Neutron Star?



Far outside the Sun you can't really tell the difference

- Force is the same

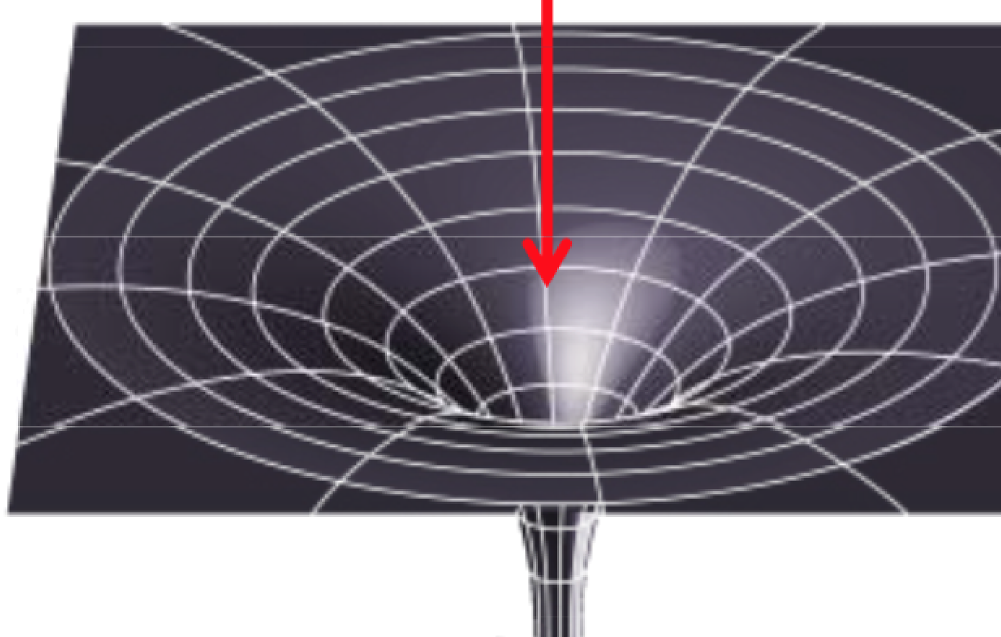
You can tell the difference if you are very close to the Sun itself

- Force is bigger

The sun is now a few kilometers across

Compressing Sun into Black Hole have:

Black hole is just a point in space



Infinite curvature

Curvature is VERY different really close to where the mass is

What does this have to do with light being able to escape? Gravitational force exerted on all massive objects means that massive objects require minimum velocity(called escape velocity) to leave massive body.

Moon - escape velocity = 2.4 km/sec and photons can escape

Earth - escape velocity = 11.2 km/sec and photons can escape

Sun - escape velocity = 620 km/sec and photons can escape

Neutron Star - escape velocity = ≈ 100,000 km/sec and photons can escape

Black Hole - escape velocity > speed of light - nothing can escape; since light cannot escape → name!

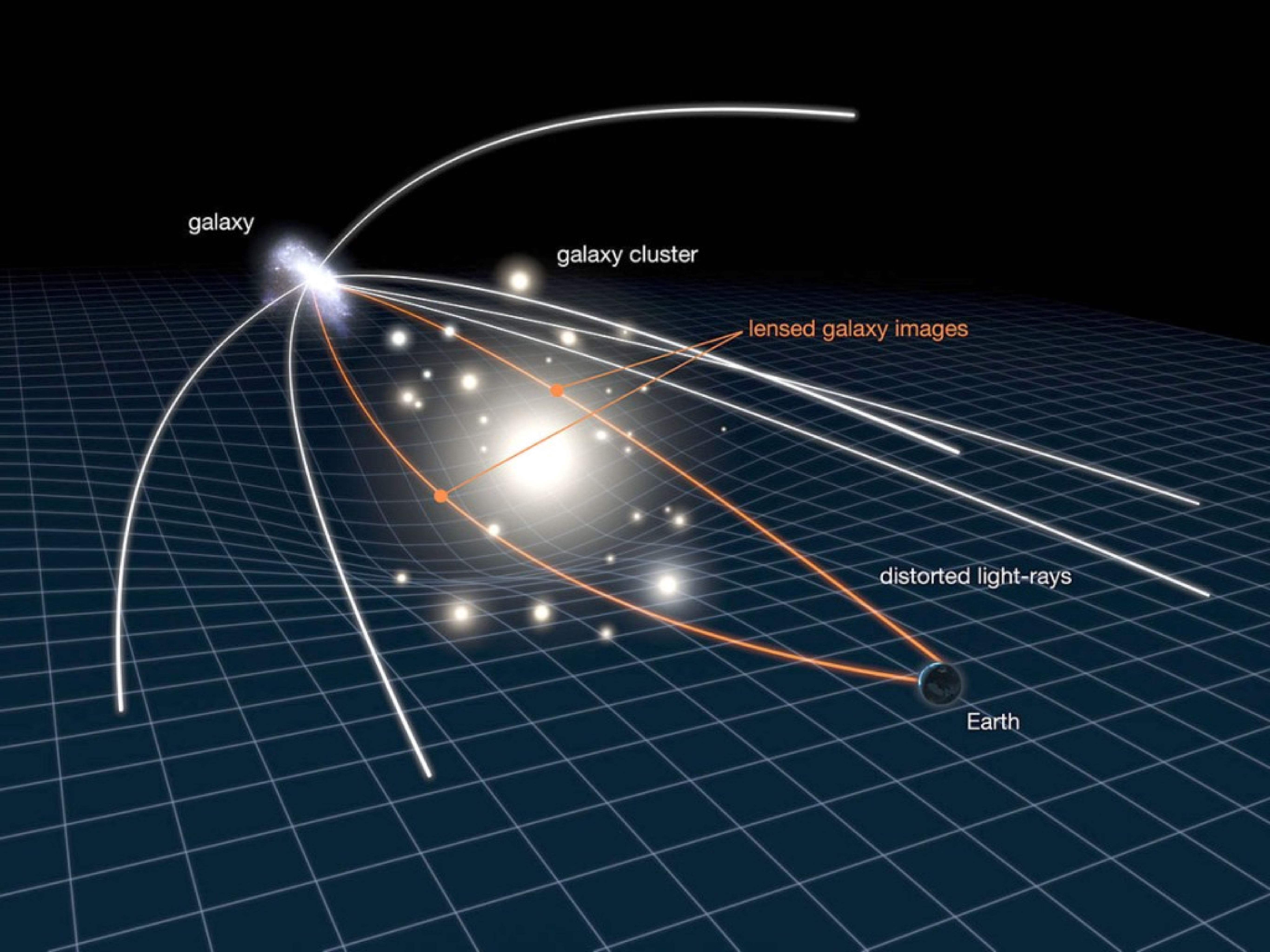
Remember that GR as theory of gravity says that no objects - massive or not - experience any forces. Gravity via energy density causes spacetime to become curved. All objects are free and move along path corresponding to shortest possible distance in spacetime - this path called a “geodesic”.

Parabolic path of thrown object near surface of earth actually geodesic in 4-dimensional spacetime! Elliptical orbits of planets around sun are actually geodesics in 4-dimensional spacetime!

Spacetime near a Black Hole

Gravity of Black Hole curves spacetime SO MUCH that light simply can’t leave - its path of motion or geodesic cannot pass outwards through “event horizon”. If light can’t escape then can’t “see” light from it and “appears” black. Since light could fall in, and never come back out -> “Black Hole”. Path of light passing nearby gets bent (bending first experimentally verified by observing light passing Sun in 1919).

Dramatic example of bending is phenomenon of gravitational lensing.


galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth

Blackholes are foundation for strange objects called “wormholes’ - discuss later.

Gravitational Waves

Since gravitational waves now experimentally observed, let me say a few words about them.

As have seen, in Einstein’s theory of general relativity, gravity treated as phenomenon resulting from curvature of spacetime. Curvature caused by presence of mass(energy). Generally, more mass contained within given volume of space, greater the curvature of spacetime will be at boundary of volume. As objects with mass move around in space-time, curvature changes to reflect changed locations of those objects. In certain circumstances, accelerating objects generate changes in this curvature, which propagate outwards at speed of light in wave-like manner. These propagating phenomena are known as gravitational waves.

As gravitational wave passes observer, observer will find spacetime distorted by effects of strain. Distances between objects increase and decrease rhythmically as wave passes, at frequency corresponding to that of wave. Occurs despite such free objects never being subjected to an unbalanced force.

Magnitude of effect decreases proportional to inverse distance from source. Inspiraling binary neutron stars are predicted to be powerful source of gravitational waves as they coalesce, due to very large acceleration of their masses as they orbit close to one another. However, due to astronomical distances to these sources, effects when measured on Earth are predicted to be very small, having strains of less than 1 part in 10^{20}. Scientists have demonstrated existence of these waves with ever more sensitive detectors. Most sensitive detector accomplished the task possessing a sensitivity measurement of about one part in 5×10^{22} (as of 2012) provided by the LIGO and VIRGO observatories. A space based observatory, the Laser Interferometer Space Antenna, is currently under development by ESA.

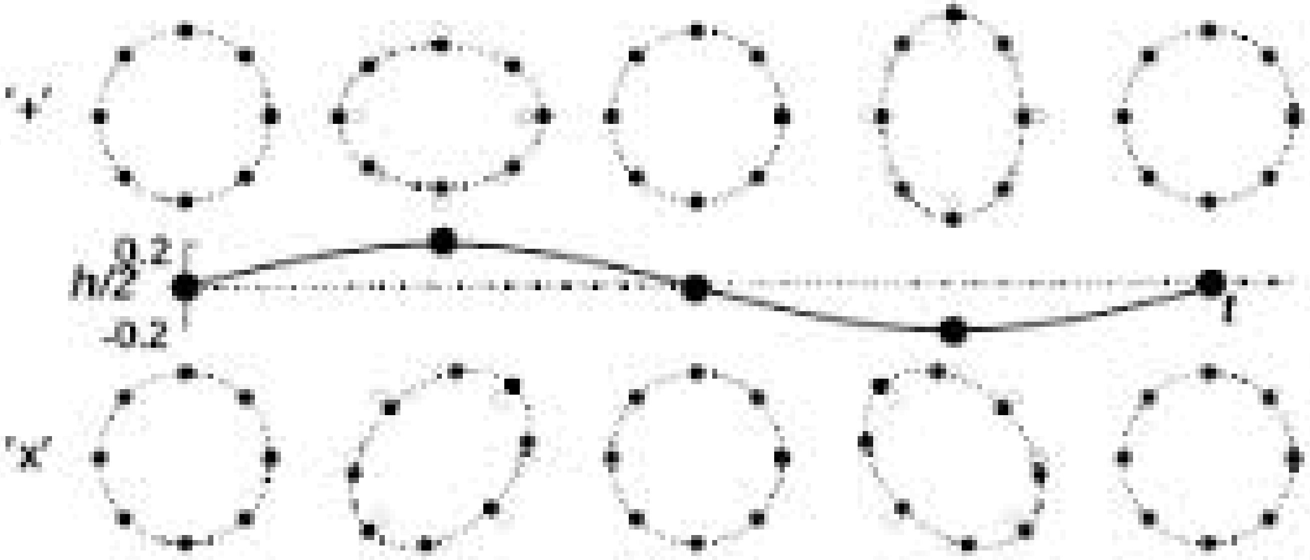
Gravitational waves can penetrate regions of space that electromagnetic waves cannot. They are able to allow observation of merger of black holes and possibly other exotic objects in distant Universe. Such systems cannot be observed with more traditional means such as optical telescopes or radio telescopes, and so gravitational-wave astronomy gives new insights into working of Universe. In particular, gravitational waves could be of interest to cosmologists as they offer a possible way of observing very early Universe. Not possible with conventional astronomy, since before recombination Universe was opaque to electromagnetic radiation. Precise measurements of gravitational waves will also allow scientists to more thoroughly test general theory of relativity. In principle, gravitational waves could exist at any frequency. However, very low frequency waves would be impossible to detect and there is no credible source for detectable waves of very high frequency.

Effects of passing

Gravitational waves are constantly passing Earth; however, even strongest have minuscule effect and their sources are generally at great distance. For example, waves given off by cataclysmic final merger of GW150914 reached Earth after traveling over a billion light-years, as a ripple in spacetime that changed length of 4-km LIGO arm by a ten thousandth of width of a proton, proportionally equivalent to changing distance to nearest star outside Solar System by one hair’s width. This tiny effect from even extreme gravitational waves makes them undetectable on Earth by any means other than the most sophisticated detectors.

Effects of passing gravitational wave, in an extremely exaggerated form, can be visualized by imagining a perfectly flat region of spacetime with a group of motionless test particles lying in a plane (e.g., surface of computer screen).

As gravitational wave passes through particles along line perpendicular to plane of particles (i.e., following observer's line of vision into screen), particles will follow distortion in spacetime, oscillating in "octopole" manner, as shown.

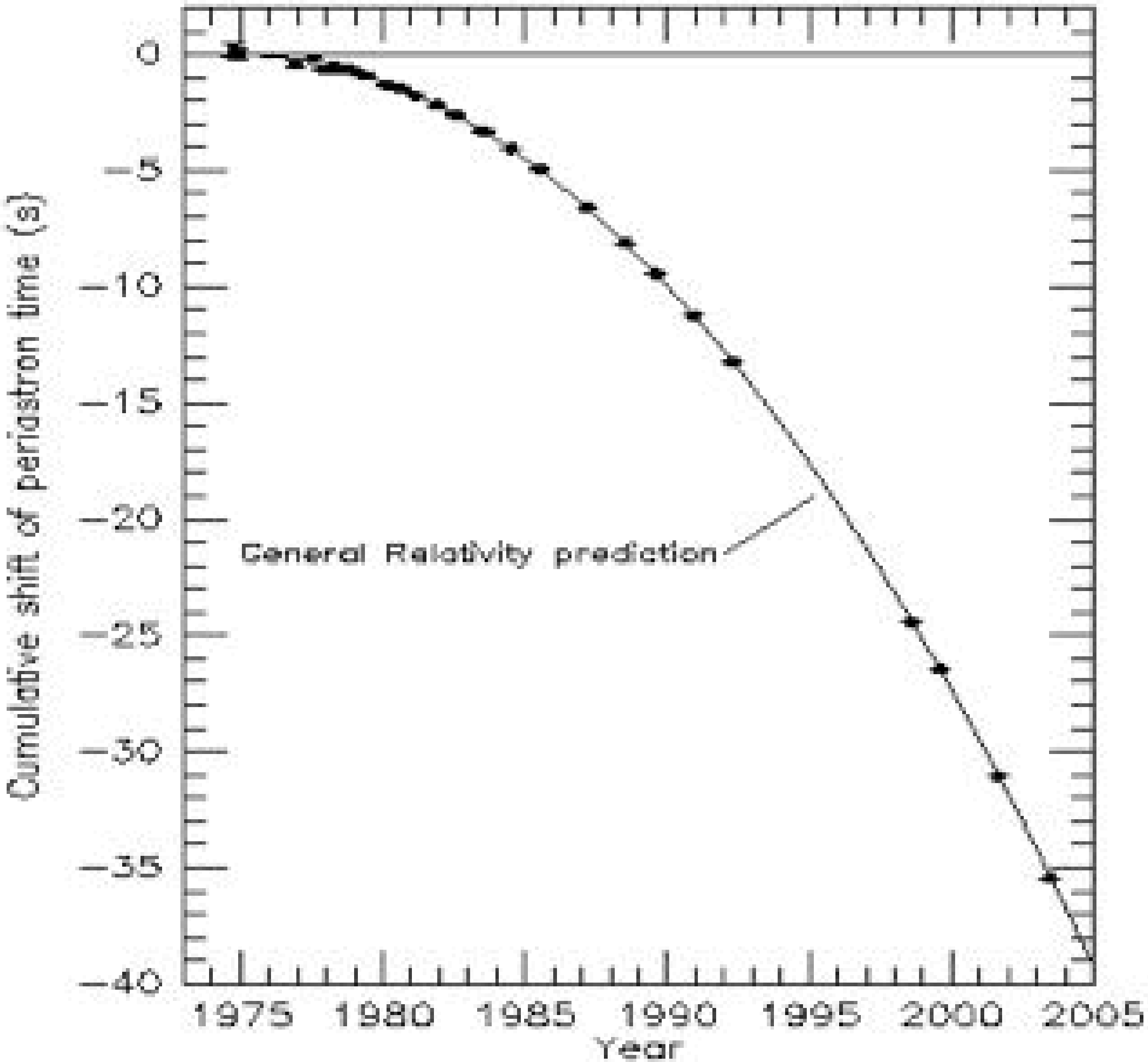


Area enclosed by test particles does not change and there is no motion along direction of propagation.

Oscillations from a gravitational wave have very small amplitude. They illustrate kind of oscillations associated with gravitational waves as produced, for example, by pair of masses in circular orbit. In this case amplitude of gravitational wave is constant, but plane of polarization changes or rotates at twice orbital rate and so time-varying gravitational wave size (or 'periodic spacetime strain') exhibits variation. If orbit of masses is elliptical then gravitational wave's amplitude also varies with according to Einstein's quadrupole formula.

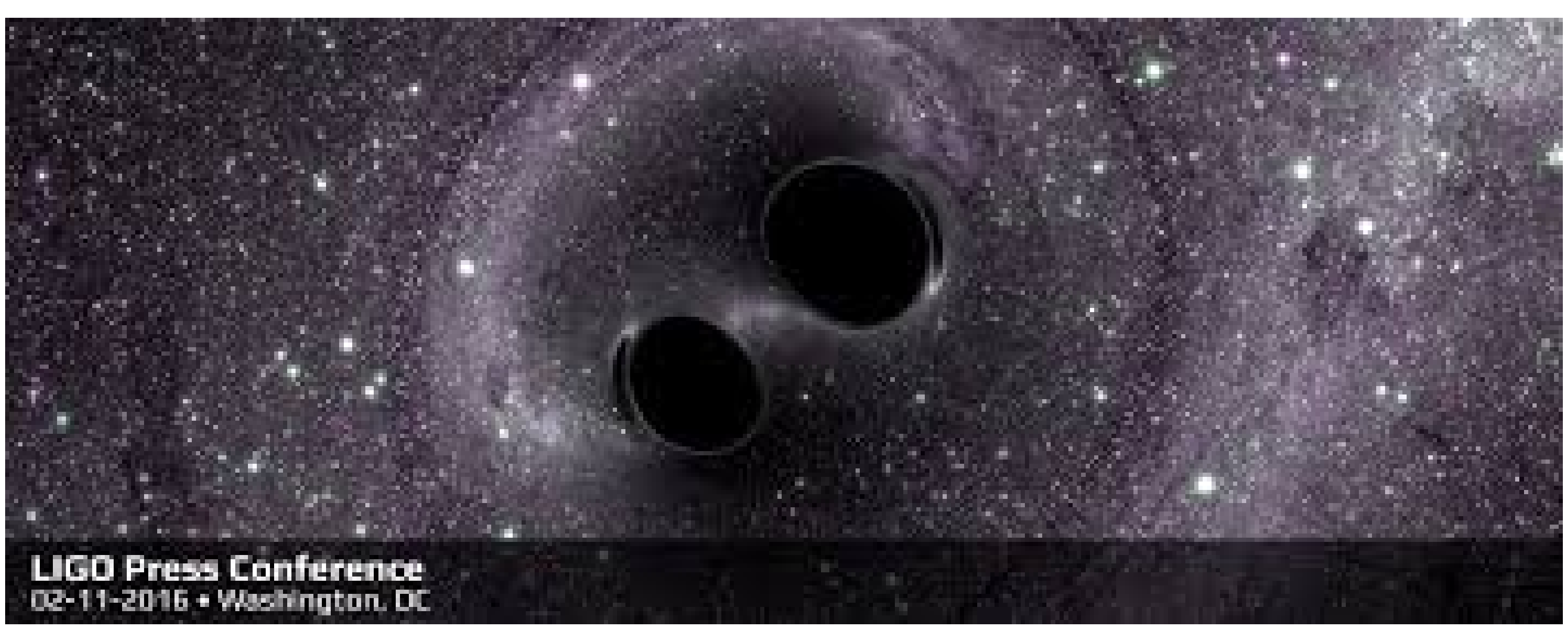
Existence of gravitational waves first demonstrated in 1970s and 80s by Joseph Taylor, Jr., and colleagues. Taylor and Russell Hulse discovered in 1974 a binary system composed of a pulsar in orbit around a neutron star. Taylor and Joel M. Weisberg in 1982 found that orbit of pulsar was slowly shrinking over time because of release of energy in form of gravitational waves. For discovering pulsar and showing that it would make possible this particular gravitational wave measurement, Hulse and Taylor were awarded Nobel Prize in Physics in 1993.

Their data versus GR predictions is shown below



-> spectacular confirmation of existence of gravitational waves exactly as Einstein predicted.

According to general relativity, a pair of black holes orbiting around each other lose energy through emission of gravitational waves, causing them to gradually approach each other over billions of years, and then much more quickly in final minutes. During final fraction of second, two black holes collide into each other at nearly one-half speed of light and form single more massive black hole, converting portion of combined black holes' mass to energy, according to Einstein's formula $E = mc^2$.



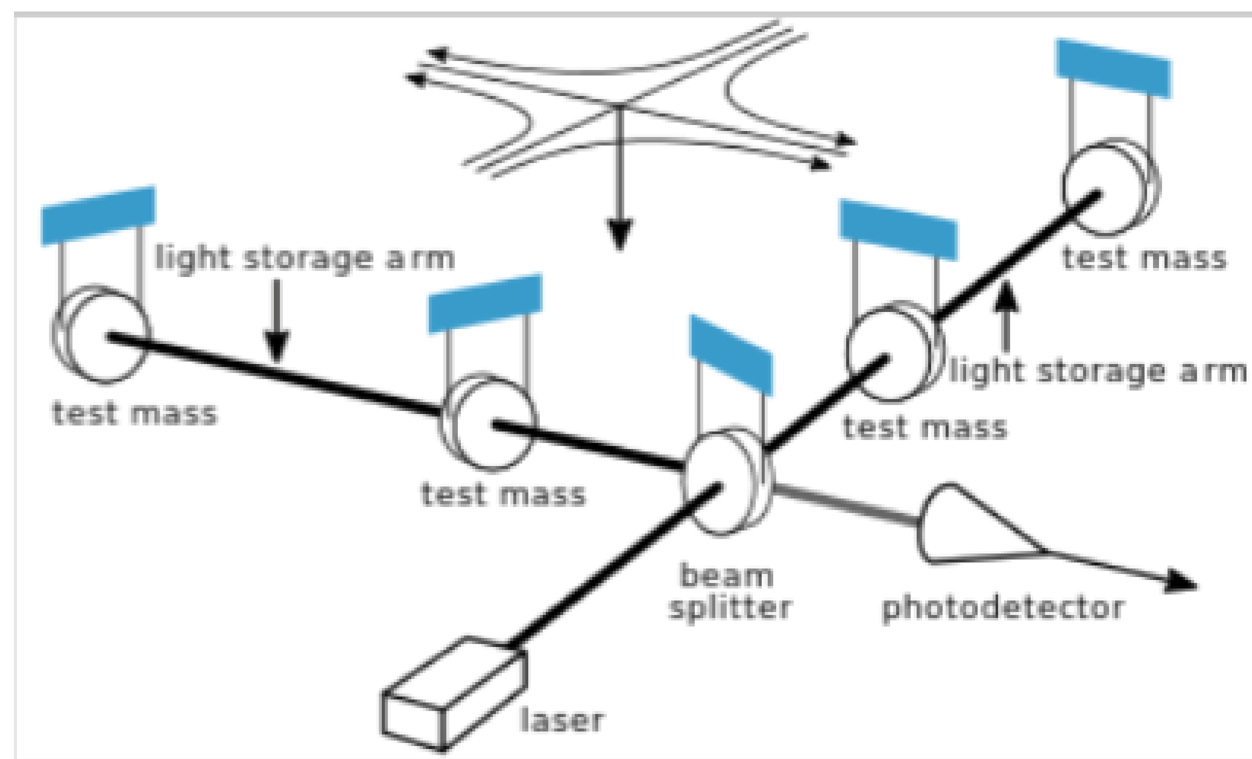
Energy emitted as final strong burst of gravitational waves. It is these gravitational waves that LIGO has observed. New LIGO discovery is first observation of gravitational waves themselves, made by measuring tiny disturbances waves make to space and time as they pass through earth.

Discovery was made possible by enhanced capabilities of Advanced LIGO, a major upgrade that increases sensitivity of instruments compared to first generation LIGO detectors, enabling a large increase in volume of universe probed -> discovery of gravitational waves during first observation run. Advanced LIGO detectors are tour de force of science and technology. At each observatory, two-and-a-half-mile (4-km) long L-shaped LIGO interferometer uses laser light split into two beams that travel back and forth down arms (four-foot diameter tubes kept under a near-perfect vacuum).

Beams are used to monitor distance between mirrors precisely positioned at ends of arms. According to Einstein's theory, distance between mirrors will change by an infinitesimal amount when gravitational wave passes by detector.

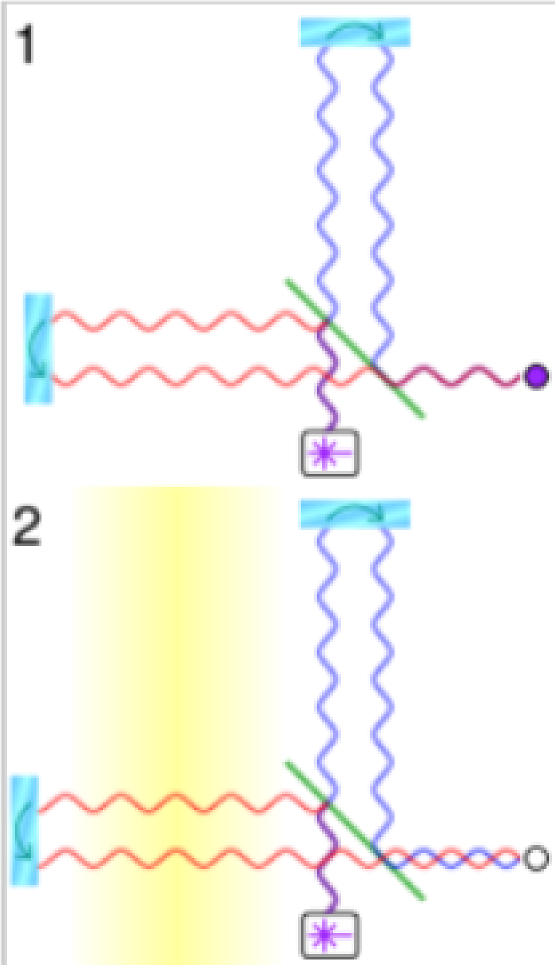
A change in lengths of arms smaller than one-ten-thousandth the diameter of a proton (10^{-19} meter) can be detected. A schematic diagram of a laser interferometer is shown.

This allows masses to be separated by large distances (increasing signal size); further advantage is that it is sensitive to a wide range of frequencies (not just those near resonance as for Weber bars).



Even with such long arms, strongest gravitational waves will only change distance between ends of the arms by at most roughly 10^{-18} meters. LIGO should be able to detect gravitational waves as small as $h \sim 5 \times 10^{-22}$. Upgrades to LIGO and other detectors such as Virgo, GEO 600, and TAMA 300 increase the sensitivity still further; the next generation of instruments (Advanced LIGO and Advanced Virgo) will be more than ten times more sensitive. Another highly sensitive interferometer, KAGRA, is under construction in Kamiokande mine in Japan. Key point is that a tenfold increase in sensitivity (radius of 'reach') increases volume of space accessible to instrument by one thousand times. This increases rate at which detectable signals might be seen from one per tens of years of observation, to tens per year. Interferometric detectors are limited at high frequencies by shot noise, which occurs because the lasers produce photons randomly; one analogy is to rainfall - rate of rainfall, like laser intensity, is measurable, but raindrops, like photons, fall at random times, causing fluctuations around average value. This leads to noise at output of detector, much like radio static. In addition, for sufficiently high laser power, random momentum transferred to test masses by laser photons shakes mirrors, masking signals of low frequencies. Thermal noise (e.g., Brownian motion) is another limit to sensitivity. In addition to these 'stationary' (constant) noise sources, all ground-based detectors are also limited at low frequencies by seismic noise and other forms of environmental vibration, and other 'non-stationary' noise sources; creaks in mechanical structures, lightning or other large electrical disturbances, etc. may also create noise masking an event or may even imitate an event. All these must be taken into account and excluded by analysis before a detection may be considered a true gravitational wave event. That is why there are two detection sites - they see coincidences and help eliminate stray noises.

A simple description of how a gravitational wave observatory works is shown below.



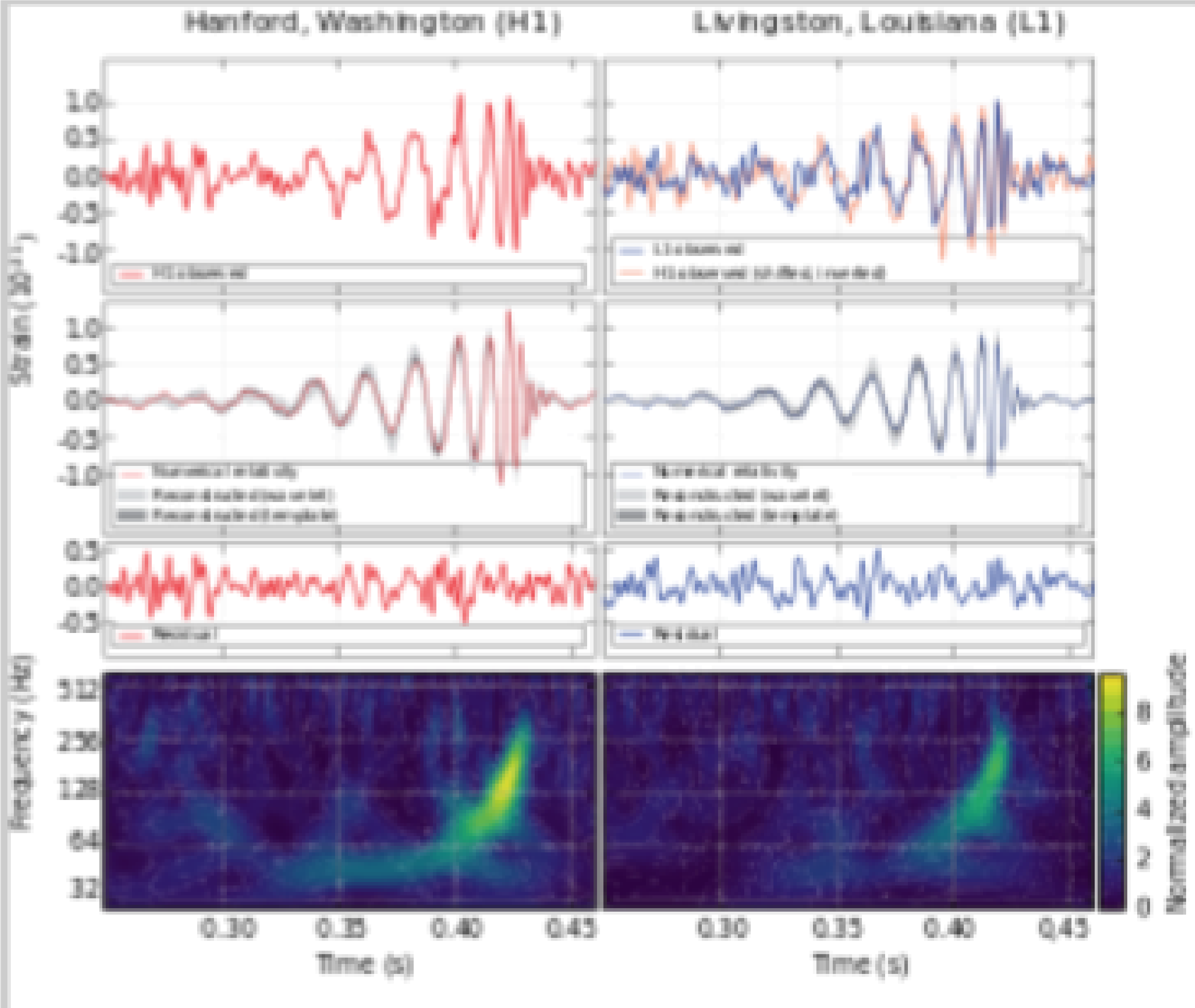
In part 1 of figure, a beamsplitter (green line) splits coherent light (from white box) into two beams which reflect off mirrors (cyan oblongs); only one outgoing and reflected beam in each arm is show, and separated for clarity. Reflected beams recombine and an interference pattern is detected (purple circle). In part 2 of figure, gravitational wave passing over left arm (yellow) changes its length and thus interference pattern.

LIGO gravitational wave observation, 2015, 2016

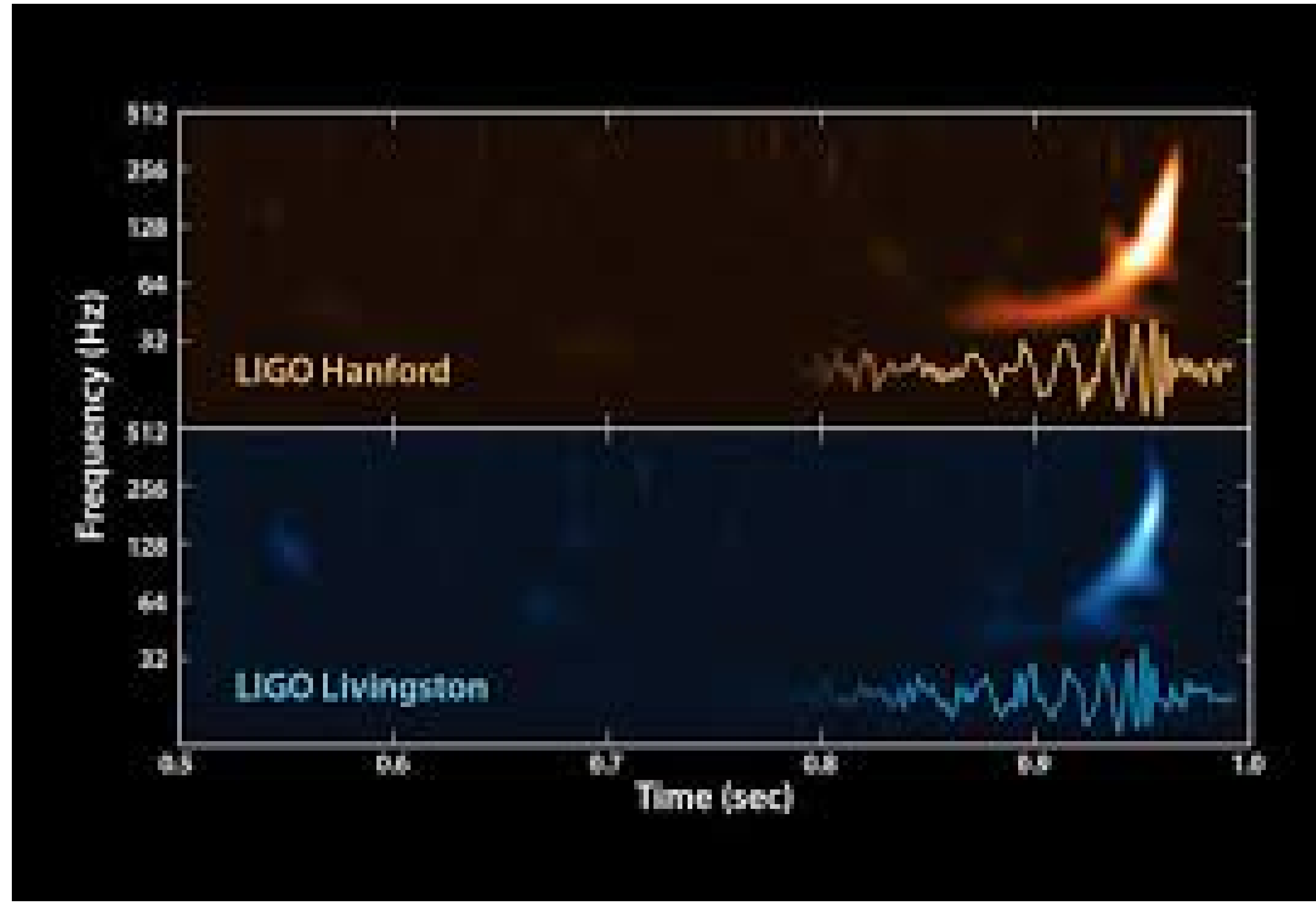
On 11 February 2016, LIGO collaboration announced detection of gravitational waves, from signal detected at 09:50:45 GMT on 14 September 2015 of two black holes with masses of 29 and 36 solar masses merging about 1.3 billion light years away.

A second observation was recorded in May 2016 of a different pair of black holes merging.

During final fraction of second of merge, it released more power than 50 times that of all stars in observable universe combined.[62] The signal increases in frequency from 35 to 250 Hz as it rises in strength. Mass of new black hole obtained from merging two was 62 solar masses. Energy equivalent to three solar masses was emitted as gravitational waves. Signal was seen by both LIGO detectors, in Livingston and Hanford, with time difference of 7 milliseconds due to angle between two detectors and source. Signal came from Southern Celestial Hemisphere, in rough direction of (but much further away than) the Magellanic Clouds. Confidence level of this being an observation of gravitational waves was 99.99994%. Data is shown in two figures below.



LIGO measurement of the gravitational waves at the Hanford (left) and Livingston (right) detectors, compared to the theoretical predicted values.

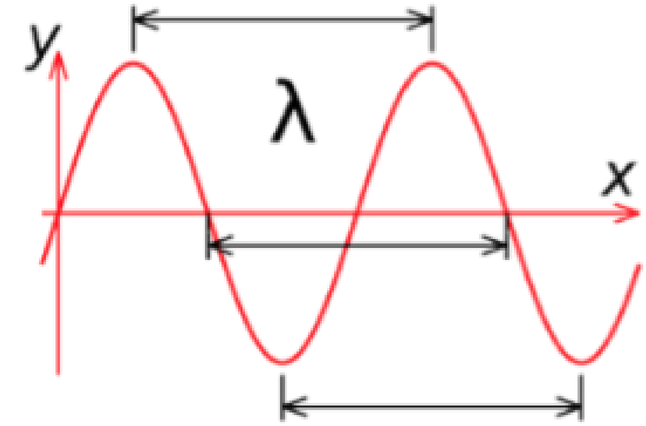


A question that arises many times is the following:

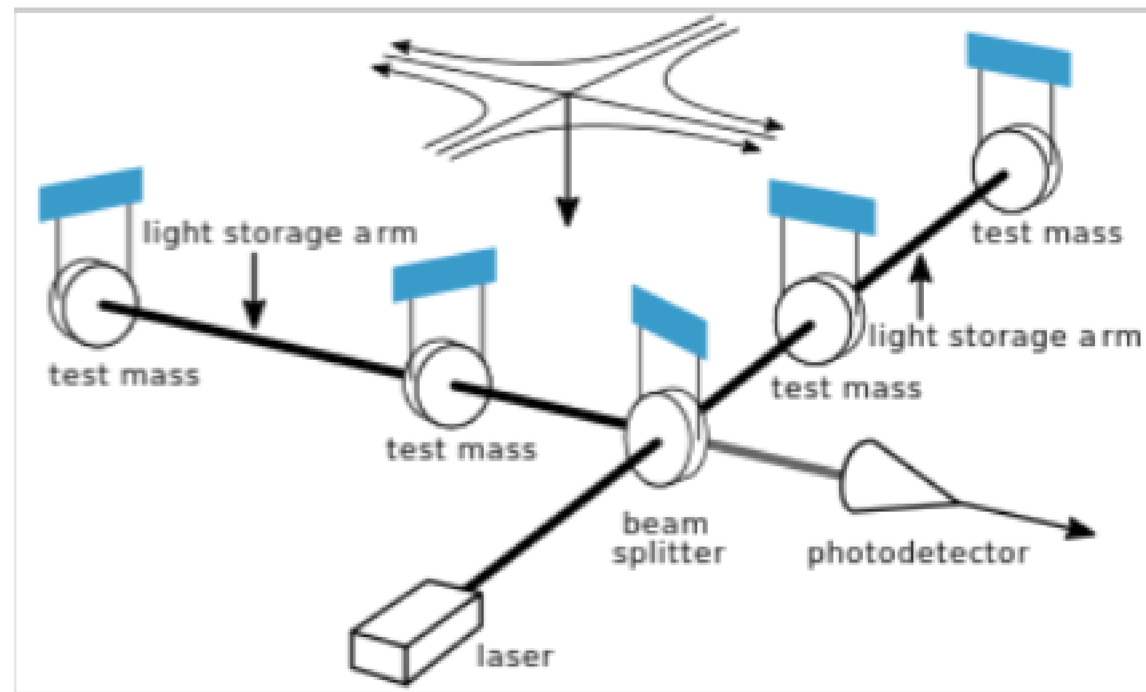
If light is stretched/compressed by gravitational wave, why use light inside LIGO?

Let us address this question that many professional physicists fully don't understand! Wrote earlier about how light and gravitational waves will stretch out as Universe expands (called redshift). If object is coming towards us, light is compressed (called blueshift). Basically, if objects are moving, light and gravitational waves will experience Doppler effect. Also wrote about how a passing gravitational wave will stretch and compress space in perpendicular directions. When put these two facts together, come to conclusion that light inside arms of LIGO is also stretched and compressed by a gravitational wave. So, how can we use this light to measure gravitational waves when light itself is affected by gravitational wave?

This is not obvious upon first inspection. Apparent paradox arises from thinking of laser light as ruler. When you think of light, you usually think of it as a wave (which it is, but light is also a particle - not relevant to this discussion). Waves have wavelength – distance between each successive wave peak:



A passing gravitational wave will expand and compress space-time and wavelength of light using to measure gravitational waves is itself affected by gravitational wave. Since LIGO and detectors like it effectively measure length of its arms and compares them to each other, how can we rely on light to measure any length changes from passing gravitational wave? Solution begins to become clear when start thinking of laser light as clock instead of ruler. When light comes out of laser, there is fixed time between each crest of wave (called the period of wave). Let's label each crest as 'tick' (like clock). Our laser (labeled 'Laser' in image below) is very stable in that it produces very consistent wavelength of 1064 nm (near-infrared light). Because speed of light is constant no matter how you measure it, that means that there are almost 282 trillion ($2.817 x 10^{14}$) 'ticks' every second. This light is then split into two equal parts (at 'Beam Splitter')



Since different things can happen to light once it is in arms, let’s reference beam splitter for making length measurements (i.e., let beam splitter stay in same place while gravitational wave alternates squishing and stretching arms). A real gravitational wave will cause one arm to shorten and other to lengthen. This will also cause laser wavelength in shortened arm to decrease (blueshift) and wavelength in lengthened arm to increase (redshift). But there is nothing in detector that measures wavelength. What it really measures is shift in arrival time of each ‘tick’ of wavelength crests. If arms stay same length (no gravitational wave), then ‘ticks’ of laser light come back to beam splitter at same time and produces destructive interference where we measure light (labeled ‘Photodetector’ in image above). If gravitational wave causes length of arms to change and shifts where ‘ticks’ of laser light occur, two light beams will no longer return to beam splitter at same time. It is this “out of sync” arrival time of crests of laser light that produces interference pattern we utilize to detect gravitational waves - couldn’t care less about actual wavelength of light (other than it was consistent going into detector).

Alcubierre (warp) drive

Now for discussion that probably should be classified as science fiction, but who knows!!!!

Alcubierre drive or Alcubierre warp drive (or Alcubierre metric, referring to metric tensor in GR) is speculative idea based on solution of Einstein’s field equations in general relativity as proposed by theoretical physicist Miguel Alcubierre, by which spacecraft could achieve apparent faster-than-light travel if configurable energy-density field lower than that of vacuum (that is, negative energy - similar to requirement need later for a wormhole) could be created.

Rather than exceeding speed of light within local reference frame, spacecraft would traverse distances by contracting space in front of it and expanding space behind it, resulting in effective faster-than-light travel. Objects cannot accelerate to speed of light within normal spacetime; instead, Alcubierre drive shifts space around an object so that object would arrive at destination faster than light would in normal space.

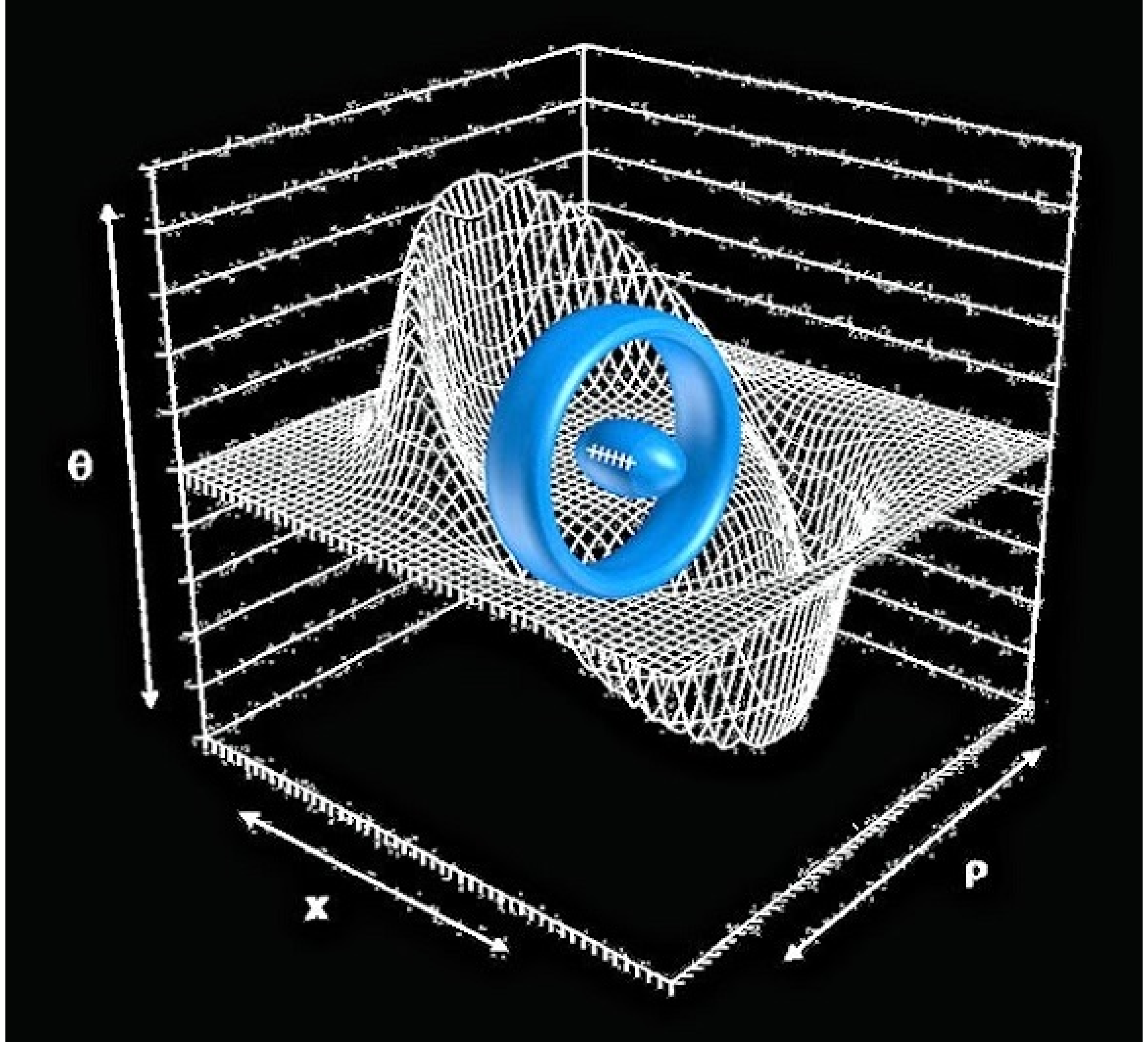
Although metric proposed by Alcubierre is mathematically valid (proposal consistent with Einstein field equations), may not be physically meaningful, in which case drive will not be possible. Even if physically meaningful, its possibility would not necessarily mean that drive can be constructed. Proposed mechanism of Alcubierre drive implies negative energy density and therefore requires exotic matter. So if exotic matter with correct properties does not exist then drive could not be constructed. However, at close of original paper Alcubierre argued (following argument developed by physicists analyzing traversable wormholes) that Casimir vacuum between parallel plates could fulfill negative-energy requirement for Alcubierre drive.

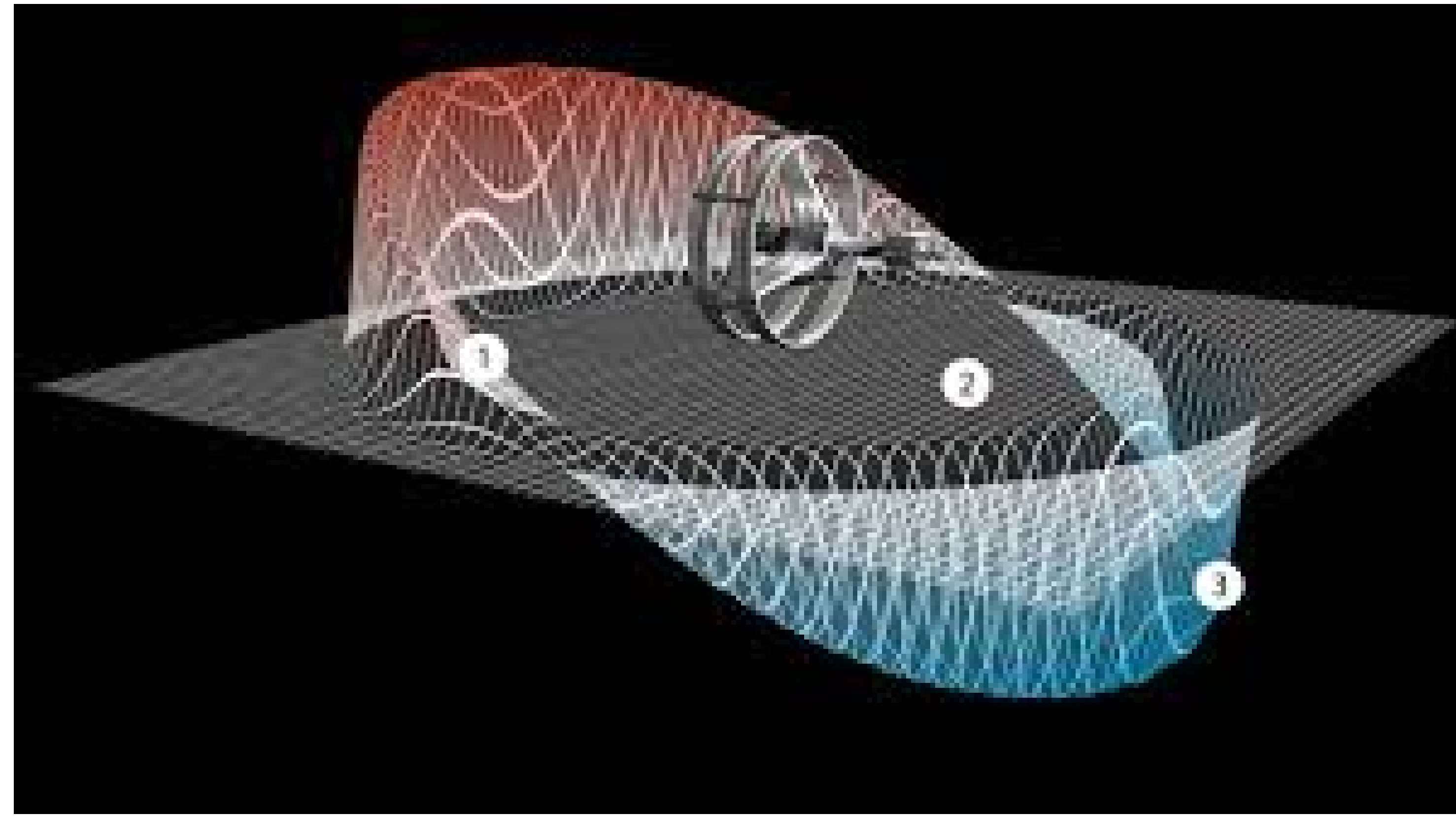
Another possible issue is that, although Alcubierre metric is consistent with Einstein's equations, general relativity does not incorporate quantum mechanics. Some physicists have presented arguments to suggest that theory of quantum gravity (which would incorporate both theories) would eliminate those solutions in general relativity that allow for backwards time travel and thus make Alcubierre drive invalid.

History

In 1994, Alcubierre proposed a method for changing geometry of space by creating wave that would cause fabric of space ahead of spacecraft to contract and space behind it to expand. Ship would then ride wave inside region of flat space, known as warp bubble, and would not move within this bubble but instead be carried along as region itself moves due to actions of drive. Was thought to use too much negative energy until Harold White showed that amount of energy required could be reduced if warp bubble were changed into a warp ring

Two possible images are:





Alcubierre metric

Alcubierre metric defines warp-drive spacetime.

It is spacetime structure that, if interpreted in context of general relativity, allows warp bubble to appear in previously flat spacetime and move away at effectively superluminal speed. Interior of bubble is standard reference frame and inhabitants suffer no proper acceleration. This method of transport does not involve objects in motion at speeds faster than light with respect to contents of warp bubble; that is, a light beam within warp bubble would still always move faster than ship. Because objects within bubble are not moving (locally) faster than light, mathematical formulation of Alcubierre metric is consistent with conventional claims of laws of relativity (namely, that an object with mass cannot attain or exceed speed of light) and conventional relativistic effects such as time dilation would not apply as they would with conventional motion at near-light speeds. Alcubierre drive, however, remains a hypothetical concept with seemingly difficult problems, though amount of energy required is no longer thought to be unobtainably large.

For those familiar with effects of special relativity, such as Lorentz contraction and time dilation, Alcubierre metric has some apparently peculiar aspects. In particular, Alcubierre has shown that ship using an Alcubierre drive travels on free-particle geodesic even while warp bubble is accelerating: crew would be in free fall while accelerating without experiencing accelerational g-forces. Enormous tidal forces, however, would be present near edges of flat-space volume because of large space curvature there, but suitable specification of metric would keep them very small within volume occupied by ship.

In general relativity, one often first specifies a plausible distribution of matter and energy, and then finds geometry of spacetime associated with it; but is also possible to run Einstein field equations in other direction, first specifying metric and then finding energy-momentum distribution associated with it -> what Alcubierre did in building his metric. This practice means that solution can violate various energy conditions and require exotic matter. Need for exotic matter raises questions about whether one can distribute matter in an initial spacetime that lacks warp bubble in such a way that bubble is created at later time, although some physicists have proposed models of dynamical warp-drive spacetimes in which warp bubble is formed in previously flat space. Moreover, according to Krasnikov, generating bubble in previously flat space for one-way FTL trip requires forcing exotic matter to move at local faster-than-light speeds, something that would require existence of tachyons, although Krasnikov also notes that when spacetime is not flat from outset, similar result could be achieved without tachyons by placing in advance some devices along travel path and programming them to come into operation at preassigned moments and to operate in preassigned manner. Some suggested methods avoid problem of tachyonic motion, but would probably generate naked singularity(no horizon) at front of bubble. Allen Everett and Thomas Roman comment that Krasnikov's finding "does not mean that Alcubierre bubbles, if it were possible to create them, could not be used as a means of superluminal travel.

It only means that actions required to change metric and create bubble must be taken beforehand by some observer whose forward light cone contains entire trajectory of bubble". For example, if one wanted to travel to Deneb (2,600 light years away) and arrive less than 2,600 years in the future according to external clocks, would be required that someone had already begun work on warping space from Earth to Deneb at least 2,600 years ago, in which case "A spaceship appropriately located with respect to bubble trajectory could then choose to enter bubble, rather like passenger catching passing trolley car, and thus make superluminal journey". Everett and Roman also write that "as Krasnikov points out, causality considerations do not prevent crew of spaceship from arranging, by their own actions, to complete round trip from Earth to distant star and back in an arbitrarily short time, as measured by clocks on Earth, by altering metric along path of their outbound trip".

Difficulties

Metric of this form has significant difficulties because all known warp-drive spacetime theories violate various energy conditions. Nevertheless, Alcubierre type warp might be realized by exploiting certain experimentally verified quantum phenomena, such as Casimir effect, that lead to stress-energy distributions that also violate energy conditions, such as negative mass-energy, when described in context of quantum field theories.

Mass-energy requirement

If certain quantum inequalities conjectured by Ford and Roman hold, then energy requirements for some warp drives may be unfeasibly large as well as negative. For example, energy equivalent of 10^{64} kg might be required to transport small spaceship across Milky Way - an amount orders of magnitude greater than estimated mass of observable universe. Counterarguments to these apparent problems have also been offered.

Chris Van den Broeck, tried to address potential issues. By contracting 3+1-dimensional surface area of bubble being transported by drive, while at same time expanding three-dimensional volume contained inside, Van den Broeck was able to reduce total energy needed to transport small atoms to less than three solar masses. Later, by slightly modifying Van den Broeck metric, Serguei Krasnikov reduced necessary total amount of negative mass to few milligrams. Van den Broeck detailed this by saying that total energy can be reduced dramatically by keeping surface area of warp bubble itself microscopically small, while at same time expanding spatial volume inside bubble. However, Van den Broeck concludes that energy densities required are still unachievable, as are small size (few orders of magnitude above Planck scale (10^{-35} m)) of spacetime structures needed.

In 2012, physicist Harold White and collaborators announced that modifying geometry of exotic matter could reduce mass-energy requirements for a macroscopic space ship from equivalent of planet Jupiter to that of Voyager 1 spacecraft (700 kg) or less, and stated their intent to perform small-scale experiments in constructing warp fields. White proposed changing shape of warp bubble from sphere to torus. Furthermore, if intensity of space warp can be oscillated over time, energy required is reduced even more.

Placement of matter

Krasnikov proposed that if tachyonic matter cannot be found or used, then solution might be to arrange for masses along path of vessel to be set in motion in such a way that required field was produced. But in this case, Alcubierre drive vessel can only travel routes that, like railroad, have first been equipped with necessary infrastructure. Pilot inside the bubble is causally disconnected with its walls and cannot carry out any action outside bubble: bubble cannot be used for first trip to distant star because pilot cannot place infrastructure ahead of bubble while “in transit”.

For example, traveling to Vega (25 light-years from Earth) requires arranging everything so that bubble moving toward Vega with superluminal velocity would appear; such arrangements will always take more than 25 years.

Coule has argued that schemes, such as one proposed by Alcubierre, are infeasible because matter placed en route of intended path of craft must be placed at superluminal speed - that constructing an Alcubierre drive requires an Alcubierre drive even if metric that allows it is physically meaningful. Coule further argues that an analogous objection will apply to any proposed method of constructing an Alcubierre drive.

Survivability inside the bubble

Paper by José Natario argues that crew members could not control, steer or stop ship because ship could not send signals to front of bubble. More recent paper by Carlos Barcel, Stefano Finazzi, and Stefano Liberati uses quantum theory to argue that Alcubierre drive at faster-than-light velocities is impossible mostly because extremely high temperatures caused by Hawking radiation would destroy anything inside bubble at superluminal velocities and destabilize bubble itself; paper also argues that these problems are absent if bubble velocity is subluminal, although drive still requires exotic matter.

Damaging effect on destination

Brendan McMonigal, Geraint F. Lewis, and Philip O'Byrne have argued that when an Alcubierre-driven ship decelerates from superluminal speed, particles that its bubble has gathered in transit would be released in energetic outbursts akin to sonic boom shockwave; in case of forward-facing particles, energetic enough to destroy anything at destination directly in front of ship.

Wall thickness

Amount of negative energy required for such a propulsion is not yet known. Pfenning and Allen Everett of Tufts hold that warp bubble traveling at 10 times light-speed must have wall thickness of no more than 10^{-32} meters - close to limiting Planck length, 1.6×10^{-35} meters. In Miguel Alcubierre's original calculations, bubble macroscopically large enough to enclose ship of 200 meters would require total amount of exotic matter greater than mass of observable universe, and straining exotic matter to extremely thin band of 10^{-32} meters considered impractical. Similar constraints apply to Krasnikov's superluminal subway. Chris Van den Broeck recently constructed a modification of Alcubierre's model that requires much less exotic matter but places ship in a curved space-time "bottle" whose neck is about 10^{-32} meters.

Causality violation and semiclassical instability

Calculations by physicist Allen Everett show that warp bubbles could be used to create closed timelike curves in general relativity, meaning that theory predicts that they could be used for backwards time travel. While it is possible fundamental laws of physics might allow closed timelike curves, chronology protection conjecture hypothesizes that in all cases where the classical theory of general relativity allows them, quantum effects would intervene to eliminate possibility, making these spacetimes impossible to realize (possible type of effect that would accomplish this is buildup of vacuum fluctuations on border of region of spacetime where time travel would first become possible, causing energy density to become high enough to destroy system that would otherwise become time machine). Some results in semiclassical gravity appear to support conjecture, including calculation dealing specifically with quantum effects in warp-drive spacetimes that suggested that warp bubbles would be semiclassically unstable, but ultimately conjecture can only be decided by a full theory of quantum gravity.

Miguel Alcubierre briefly discusses some of these issues. He writes “beware: in relativity, any method to travel faster than light can in principle be used to travel back in time (a time machine).” He then brings up chronology protection conjecture, and writes “The conjecture has not been proven (it wouldn’t be a conjecture if it had), but there are good arguments in its favor based on quantum field theory. The conjecture does not prohibit faster-than-light travel. It just states that if a method to travel faster than light exists, and one tries to use it to build a time machine, something will go wrong: the energy accumulated will explode, or it will create a black hole.”

Experiments

In 2012, a NASA laboratory announced that they had constructed an interferometer that they claim will detect spatial distortions produced by expanding and contracting spacetime of Alcubierre metric. Work has been described in Warp Field Mechanics 101, a NASA paper by Harold Sonny White. Alcubierre has expressed skepticism about experiment, saying “from my understanding there is no way it can be done, probably not for centuries if at all”. In 2013, Jet Propulsion Laboratory published results of a 19.6-second warp field from early Alcubierre-drive tests under vacuum conditions. Results have been reported as “inconclusive”.

Relation to Star Trek warp drive

The Star Trek television series used term “warp drive” to describe their method of faster-than-light travel. Neither Alcubierre theory, nor anything similar, existed when series was conceived, but Alcubierre stated in an email to William Shatner that his theory was directly inspired by term used in how, and references it in his 1994 paper.