Sources of gravitational radiation

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1 Introduction

This is an overview of several currently researched objects that should, according to Einstein's theory of general relativity, emit gravitational waves. Discussed are the mechanisms and physical properties of the objects that lead to the emission of gravitational radiation and as so far possible the detection methods of detectors that can be used for detecting gravitational waves. Several currently developed gravitational wave detectors are also discussed and their prospects for the future.

Until now the existance of gravitational waves has been verified only indirect in the form of binary pulsars which behaviour fits perfectly with Einstein's theory of general relativity and the occurance of gravitational waves. An other way is to find relics of the gravitational waves from objects from the far past. Most other objects don't possess such a measurable mechanism effect due to the fact that its emission of gravitational waves is only very short. The longer emitting objects are rarer to find. The best way to prove and use the gravitational wave theory is to actually try to detect these waves directly.

2 The creation of gravitational waves

Gravitational radiation is mechanism used by stellar objects to prevent distortion or other negative effects. You could almost see it as sweat from a working or sporting person. In this case it is a way to lose heat because else the person will faint or become unconscious. For a stellar object the effects would be far worse.

Gravitational waves are emitted because the stellar object needs to lose some form of gravitional effects. A typical reason is the need to lose angular momentum that is increasing (accelerating masses). There are several cases in which the angular momentum can increase, but stellar objects can only sustain a certain amount until they would break apart or be distorted. The angular momentum energy is converted into gravitational radiation.

The second typical reason is the collapse of an object. All such events involve large gravitational fields that need to be controlled, because the collapse creates huge amounts of energy for the creation of a new object.

The magnetic field of the object is involved in the creation of the gravitational radiation. The gravitational radiation depends on the quadrupole moment, because a dipole moment can't because of conservation of momentum. Only a rotating non-axisymmetric configuration of the magnetic field can create gravitational radiation. The amount of radiation depends sensitively upon the rotation rate of the collapsing object.

The maximum energy gravitational wave power any system can emit is almost 10^{60} ergs/s. This is the case for the merging of a black hole binary.

The specific mechanisms that cause gravitational radiation will be treated per object. The division in the different sections is in some way arbitrary because many sources are related, but I did in some way follow the later mentioned three classes. The three divisions are the sections 3.1-3.2, 3.3-3.6 and section 3.7.

3 Sources of gravitational waves

There are three classes: bursts, continuous emitters and stochastic background. Burst sources produce signals which last for times considerably shorter than available observation times. The chirp signals from compact coalescing binaries belong to this class. Continuous emitters are objects that can remain in a radiation capable state for a longer time thanks to the emission of gravitational waves. The stochastic background is the relic gravitational waves of events in the very early history of the universe. Their remains could still be detected.

It is hard to give a complete overview of all sources and the mechanisms and physical properties involved, so a selection has been made for the most common ones. Some types of sources are hard to place in a certain section, but else it would become to chaotic.

The typical generation of gravitational waves in the case of losing angular momentum is caused by collapsing objects, mainly massive stars, and deformations of stars, by spinning effects or companions. Studies have concentrated on the gravitational wave emission during collapse or the emission from barlike instabilities shortly after bounce. A bar-mode instability is one of the more promising mechanisms by which a significant fraction of the collapsing system's energy can be emitted in gravitational waves. They occur in objects whose rotational energy exceeds some fraction of their potential energy. This number lies at a least 10 percent to suffice the generation of gravitational waves.

The sources include rapidly rotating astrophysical objects that encounter dynamical instabilities. A dynamical instability is driven by gravitational and hydrodynamical forces and develops on the order of the rotation period of the system. A secular instability is driven by a dissipative mechanism, such as viscosity or gravitational radiation, and develops on the timescale of that mechanism (which can be many rotation periods).

Another plausible mechanism for the emission of gravitational radiation in very rapidly spinning stars is the Chandrasekhar-Friedman-Schultz instability, which is driven by gravitational radiation reaction. It may be possible that newly-formed neutron stars may go through this instability spontaneously as they cool soon after formation. The radiation is emitted at a frequency determined by the frequency of the unstable normal mode, which may be less than the spin frequency.

Another possibility for the emission of gravitational waves is a head-on collision between a supermassive blackhole with a compact stellar object, or the capture of such an object into a relativistic orbit.

3.1 Supernovae (the collapse of a core)

The only supernova events that can lead to the emission of gravitational radiation come from rotating cores. This is not the case for non-rotating cores. It is possible that rotating cores may stop the collapse before nuclear matter density is reached, but there is still a bounce to create a shock wave due to centrifugal forces which increase during collapse because of the angular momentum conservation and bring the collapse to a halt. A rotating core can be caused by magnetic fields or shear viscosity which are able to reduce the angular momentum in the interior of the star sufficiently and thus make the core rotate. A star can collapse if it remains spherical - no change in the external gravitational field.

After bounce a rotating core oscillates with a superposition of various radial and surface modes (the r- and f-modes). The frequency of these modes is determined by the average density of the inner core. A certain fraction of the kinetic infall energy of the rotating core will be converted into oscillations, which are damped by non-spherical pressure waves. These oscillations strongly contribute to the gravitational wave signal of the bouncing core.

Above 20-25 $M_\odot$ the supernova falls partially back due to lack of force and the neutron mass becomes a black hole. The fallback can cause the proto-neutron star to spin up fast enough to emit a second burst of gravitational waves. In all cases the total energy emitted exceed 10^{52} ergs, with a maximum power of over 10^{50} ergs/s. Above 40-50 $M_\odot$ there is no supernova and a black hole is formed immediately. These are called collapsars and are likely to accrete at rates a high as 1-10 $M_\odot$ s^{-1}.

There are two types of "standard" gravitational wave signals. Type I exhibit a large wave amplitude at bounce, which is followed by a ring-down of the signal, i.e., by postbounce oscillations with decreasing amplitude. The ring-down is due to damped volume and surface oscillations of the inner core after bounce. They are produced by cores bouncing at nuclear density or at low central densities when the rato of (radial) kinetic energy to rotational energy is small. Signals of Type II are characterized by several pronounced spikes which areis if the core bounces more than once. Between the spikes the signal varies smoothly.

Before bounce the collapse and the flattening of the rotating core leads to a monotonically increasing featureless positive wave amplitude. The abrupt end of the collapse and the subsequent expansion of the core during the bounce gives rise to a rapidly changing quadrupole moment. Hence, the quadrupole wave amplitude rapidly rises shortly before bounce reaching a local maximum. Subsequently the wave amplitude drops rapidly, becomes negative and exhibits a pronounced minimum. During post-bounce evolution the Type I wave signal is most typical.

Cores that remain axisymmetric during collapse produce much weaker gravitational wave signals than cores that do not. In this case the core will be transformed into a bar-like configuration that spins end-over-end like an American football. It is further speculated whether the core might even break up into two or more massive pieces. In that case the resulting graviational radiation could be almost as strong as that from coalescing neutron star binaries. The strength of the gravitational signal sensitively depends on (i) the radius at which the centrifugal hang-up occurs and (ii) what fraction of the angular momentum of the non-axisymmetric core goes into gravitational waves, and what fraction into hydrodynamic waves. These sound and shock waves are produced as the bar or lumps, acting like a twirling-stick, plow through the surrounding matter.

A normal nova in which the white dwarf is vibrating, causes a explosion of the surroundig envelope and an increase in luminosity. The gravitational radiation will of course be small and not really considered, but it is still a source of gravitational radiation. The luminosity can be about 10^{42} ergs/s and lasts about 1.6 sec. The efficiency would be very small, about 10^{-12}.

3.1.1 Collapse into a neutron star

A core collapsed supernova can result in the birth of a hot rapidly rotating neutron star. To become a neutron star, the star has to have a mass between 8-20 $M_\odot$ or a core > 1.4 $M_\odot$. During the first years of its life (while it cools from $\sim 10^{10}$ to 10^9 K) the neutron star will be unstable to the emission of gravitational radiation due to the Chandrasekhar-Friedman-Schultz (CFS) non-axisymmetric instability. In a rotating star, the spherical symmetry is broken. Within a short time the star will have slowed down enough that the bar mode will become stable again. The instability will only operate while the star is rotating more rapidly than some critical angular velocity. Via the instability, gravitational waves carry away a significant amount of the star's angular momentum. The gravitational radiation emitted may be detectable by the planned gravitational wave detectors. It may be possible to indirectly observe the critical angular velocity through the detection of young rapidly rotating pulsars in supernova remnants.

Gravitational radiation drives a polar or axial mode of oscillation unstable whenever the star rotates fast enough that a perturbation that counterrotates in the star's rest frame appears to corotate with respect to a distant inertial observer. Conservation of angular momentum dictates that the mode's angular momentum must decrease; however, the angular momentum of a counterrotating perturbation is negative so that gravitational radiation causes a negative angular momentum perturbation to become more negative.

The quadrupole l=m=2 (bar) f-mode is unstable for stars with gravitational mass as low as 1.0-1.2 $M_\odot$, depending on the equations of state. It has the fastest growth time and will be the most efficient mode for the emission of gravitational radiation.

Recent observations of the fastest rotating young pulsar, in a supernova remnant, suggests that a fraction of neutron stars born in supernovae are born with very large initial rotational energy. If some neutron stars are born in accretion-induced collapse (AIC) of white dwarfs, they are also expected to have a large initial spin. Since it is initially very hot and differentially roatating, a proto-neutron star can even be born with an angular velocity exceeding the mass-shedding limit for uniformly rotating stars.

The frequency of the gravitational waves sweeps downward from a few hundred to 0 Hz, passing through the ideal sensitivity band of LIGO. A rough estimate of the wave amplitude shows that at ~ 100 Hz the gravitational waves from the CFS instability could be detected out to the distance of 30 Mpc by LIGO or VIRGO, and to 140 Mpc by the advanced LIGO detector. An energy equivalent to roughly 1% of a solar mass is radiated as gravitational waves. The luminosity emitted is about 10^{55} ergs/s with a burst time of 10^{-4} sec.

3.1.2 Collapse of an accreting white dwarf

Not only normal stars of a certain mass collapse into a neutron star. This is also possible with an accreting white dwarf in binary system where the white dwarf's gravitation attracts matter from its companion. It can build up sufficient mass to push it beyond the Chandrasekhar limit (1.4 $M_\odot$). As it collapses it contracts and its temperature increases adiabatically. Neutrino cooling limits the rise in temperature, but if this is small there can be ignition of nuclear burning. The entire white dwarf explodes in a thermonuclear explosion known as the Type 1a Supernova. But if ignition is prevented due to neutron cooling it will collapse more and more quickly as electrons capture onto protons, and the white dwarf will ultimately form a neutron star. This is very similar to the core-collapse supernovae. The largest potential source of gravitational waves during the explosion is likely to be from bar formation. The addition of mass is not perfectly symmetric because the white dwarf is rotating and it will not be symmetrical when the Chandrasekhar limit is reached. When the white dwarf starts to collapse it will become more bar-like. The evolution of highly compact binary stars is driven to a large extent by the interplay between loss of angular momentum from gravitational radiation and mass transfer between the components.

The shortest period cataclysmic variables are the most compact binaries known, with orbital periodes < 40 minutes. Many may be double-degenerate systems. Such systems likely begin as a pair of main sequence stars, each of 3-5 $M_\odot$. After perhaps two episodes of common envelope evolution a pair of white dwarfs seperated by only a few $R_\odot$ remain. Gravitational radiation losses eventually bring the pair closer until the smaller mass star begin to fill its Roche lobe. The minimum period of such a system could be as short as 5-6 minutes. The period will be slowly increasing until it is necessary to lose angular momentum in the form of gravitational waves to drive the orbital evolution. The companion of the white dwarf could also be a non-degenerate helium burning star.

About 10^8 double-degenerate systems may populate the Galaxy. Because of their compact nature, these objects are ideal targets for space based gravitational wave detection with the LISA mission. They are likely to be the progenitors of at least some type Ia supernovae and may also represent a substantial fraction of supersoft X-ray sources. The upper limit on the rate of accretion induced collapse in the Galaxy is about 10^{-5} $M_\odot$ per year. The event of the collapse is of course similar to that of the normal formation of a neutron star, only the mechanism is a little different. Accretion can in principle produce relatively strong radiation since the amplitude is related to the accretion rate rather than to structure effects in the star.

3.1.3 Collapse into a black hole

The collapse into a black hole involves the largest contribution of gravity into the process because in the case of massive black holes about all of its rest mass is converted into gravitational energy. In all cases, a significant fraction of the rest-mass energy could be released during the formation of the black hole, if it involves a non-axisymmetric collapse or rotational phase, but efficiencies are probably small, no more than 10 per cent..

If the stellar collapse forms a black hole instead of a neutron star, a different mechanism produces gravitational waves. The properties of the black hole during collapse rapidly change as material from the star falls into it, increasing its mass and possibly its spin. The infalling matter also perturbs the hole's geometry. This distortion causes the hole to "ring" in distinct harmonics as gravitational radiation carries away the perturbation and the settles into a quiescent, stationary Kerr state.

A bar-mode instability is likely to develop shortly after the launce of the supernova shock, similar to the case of the accretion induced collapse. The event rate is about 10^{-2} year^{-1} per galaxy.

Luminosity of the gravitational wave emission is about 10^{59} ergs/s at frequencies up to 10^5 Hz for normal black holes and with a burst time of about 10^{-5} sec. The efficiency is not more than 10 per cent of its rest mass.

Bursts from supermassive black holes are - apart from periodic gravitational waves from known binary stars - the major possible source of low-frequency gravitational waves in the frequency range 10^{-5}-1 Hz, on a mass range of 10^6-10^9 $M_\odot$ that is believed to exist. The event rate lies at 0.1 yr^{-1} for a typical galaxy.

This source of gravitational waves is a probable transient source of gravitational waves for LIGO/VIRGO. A gravitational wave detector with the sensitivity of LISA/SAGITTARIUS would see most prossible gravitational wave events involving supermassive black holes above 10^4 $M_\odot$ back to very high redshifts, thus maximizing the possible event rates.

3.1.4 Collapse of an accreting neutron star

Like in the case of the white dwarf the neutron star is also capable of acquiring new mass by accretion and in this way the capability to collapse into a black hole. If the neutron star acquires sufficient mass to become a black hole the pre-supernova process will be restarted: the new mass will be converted to neutrons, gravity will increase and attract them to the neutron star to extend it. The pressure and temperature will increase until enough mass is converted to make the neutron star collapse to a black hole.

Binary evolution models indicate that neutron stars accreting mass from a companion can be spun up, or 'recycled' to millisecond periods. The spin frequencies of the neutron stars span a relatively narrow range from 300-600 Hz. This is significantly less than the maximum neutron star spin rates. In principle, accretion should drive the spin frequencies close to break-up, unless some other mechanism intervenes to remove the accreted angular momentum. Misaligned quadrupole moment in the neutron star crust make gravitational radiation possible that halts the angular momentum gain. The accretion induced spin up torque could be in equilibrium with gravitational radiation losses.

The physical properties are, like the accreted white dwarf, similar to the normal formation of a black hole.

3.2 Magnetars

Magnetars are propably soft gamma-ray repeaters (SGR) and anomalous X-ray pulsar (AXP). This are neutron stars whose dipole magnetic field is greater than the critical value 4.4×10^{13} G. Magnetic energy, instead of rotational energy, is the main source of free energy. Soon after the formation of the proto-neutron star a large magnetic field of the order of 10^{14} to 10^{16} G can be produced. The strong magnetic field can induce large deformations in the star, which could be, then, a copious source of gravitational waves.

After the collapse of a massive star ($M > 9\ M_{\odot}$) the proto-neutron star has a radius of 100 km and is very hot ($T \sim 10^{12}$ K), and is differentially rotating. It cools and contracts to normal neutron star properties. It spins down due to the action of the electromagnetic and gravitational torques. This action results in the emission of gravitational waves which last a few seconds during the early phases of evolution. One minute after the the birth of the magnetar the solid crust begins to form, so there are two phases. This formation perturbs the gravitational wave signal after one year when it already starts breaking up again and forming glitches, due to magnetic stresses. The frequency of the signals emitted is outside the sensitivity band of interferometers.

For increasing magnetic fields more and more of the gravitational radiation is emitted in the short "fluid" phase, even if its length is much shorter than that of the "solid" phase.

Signals emitted by newborn magnetars in the Virgo cluster could be detected by VIRGO for high distortions and $B \sim 10^{16}$ and by advanced interferometers for moderate distortions and $B > 10^{15}$ G. The levels of distortion could occur in neutron stars, at least in principle.

3.3 Binary systems

In the case of binary systems gravitational radiation is produced when the two objects are spiralling-in together and merge. Of course this merging process can fail but than you get accretion. This section could also have contained the accreting white dwarfs and neutron stars because both mostly exist with a secondary companion from which they acrete matter, but most gravitational radiation emission processes have resembling physical properties so the division is in some way arbitrary. These binary systems stay complete until the moment of merging. How that happens is still not clear.

50 per cent of the stars in our galaxy are thought to be binary stars, so there is a very large number of sources. Many of the X-ray sources have been discovered to be binary star systems. The difference between these types of binaries and normal binaries is that the distance between the objects becomes smaller and that the rotation period becomes higher during that process. This change in period can be measured an it is the way to find objects predicted in gravitatation wave theory that emit gravitational radiation. It has been measured that eccentric systems emit more gravitational radiation than circular ones.

3.3.1 Neutron star binaries

The first neutron star binary discovered, PSR1913+16, had a extremely stable period. It has no glitches or sudden change in spin rate, so the pulsar arrival time can be measured to an accuracy of a few microseconds. In its tiny orbit, the pulsar travels at 0.1 per cent of the speed of light. This made it a perfect object to test general relativity. It was discovered that is precessed in a fast rate.

At times in its orbit, the radio beam from the pulsar passes closer to its companion star than at others. The companion star has a similar mass to the pulsar. When the pulsar beam passes the companion, it must follow the local curvature of space-time. The large deflection means there is a delay in the arrival of the signal. This small delay, due to the changing sampling of the companion's local space-time curvature, adds to the delay due to the orbital motion. Although the radio beam takes the shortest possible route, it is still longer than if there were no deflection of space time due to its companion.

Another effect arises because of the eccentricity of the pulsar's orbit. When the pulsar is close to the companion, its pulsed beam has to climb out of the gravitational well created by both stars. At these times the gravitational redshift is large compared to periodes when the stars are farther apart;that is, the pulses arrive less frequently.

The binary pulsar has allowed all these tiny effects to be measured with great precision and in the process other information can be gathered. It is amazing that the small, subtle effects of general relativity allow us to measure the grossest and most fundamental properties of these stars to high accuracy.

The binary pulsar, like any other binary system, must give off gravitational waves. The gravitational wave energy emitted by an object increases dramatically with orbital speed. When they approach each other, the orbital speeds gets higher. In this system, there should be bursts of gravitational waves of about one-thousandth of a cycle per second, lasting for a half an hour each orbit.

Detection of these gravitational waves from the Earth would be very difficult; our detectors are not sensitive enough. However, the system should lose a substantial amount of energy in gravitational radiation. As the system loses energy, the two neutron stars should spiral closer together, the orbital period shrinking as they do. The change in velocity caused by the emission of gravitational waves can be easily calculated.

As time passes, the binary pulsar will orbit faster and faster. As it speeds up, it will emit stronger and stronger gravitational waves, causing it to lose energy at a faster rate and hence speed up even more. Eventually the two neutron stars will coalescence. This will happen in about 300 million years. Three years before they finally merge, their orbit will have contracted so they are orbiting every three seconds and will they be only a 1000 km apart.

A minute before coalescence the stars will be whipping around each other 15 times a second, but the final merger will occur only in the last few milliseconds, when the stars are spinning around each other hundreds of times per seconds.

Here we have an immensely powerful and distinctive source of gravitational waves. It is distinctive because of a "chirrup": a note rising steadily in frequency and amplitude. It can be accurately predicted throughout the coalescence stage.

Just before coalescence, the binary pulsar emits gravitational waves with a "luminosity" of a hundred thousand galaxies. As they merge, the gravitational wave luminosity continues to increase. Just how bright these gravitational waves become depends on the physical properties of the neutron stars: will they tear each other apart, or remain contact to the bitter end? The answer is unknown. The last few milliseconds of the gravitational wave signal carries details of the neutron star matter; its viscosity, compressibility and density. The gravitational wave signal contains details of the fragmentation and re-coalescence, the disk of bar modes which form, and the way the neutron stars oscillate.

Most neutron star binaries are not so stable as PSR1913+16 and both stars may posses instabilities in the form of glitches or sudden changes in spin rate. The instabilities may have the opportunity to grow after the merger of two neutron stars in a binary coalescence. The merged neutron star is unstable to collapse but has more angular momentum than required to collapse to a Kerr black hole. The neutrino emission is inefficient for shedding the excess angular momentum of the neutron star, and it is suggested that this can happen through the growth of the gravitational-radiation-driven bar quadrupole f-mode. The gravitational waves from the instability in these high-mass ($M > 2.8\ M_{\odot}$) merged neutron stars is expected to be especially strong.

It is not easy to detect relativistic neutron star binary systems: pulsars have very narrow beams, so have to be lucky enough to be in the line of sight in order to see one. Pulsars don't shine forever, and slowly fade from view. Binary pulsars are even harder to find because the pulse period is not constant, but varies as they orbit.

These objects will be prime targets for ground-based detectors as LIGO which because of seismic noise are only sensitive in the high frequency range above ∼100 Hz, which lies in the same frequency as the gravity wave signal produced during binary inspiral and ring down of black hole and neutron star binaries.

The event rate for neutron star-neutron star mergers within 20 Mpc is $\sim 10^{-4}$ year^{-1} or one per million years per galaxy.

3.3.2 Black hole binaries

Black hole binaries are most probably created by the merging of the merging of two galaxies or similar events which involve a large concentration of massive stars.. When reorganizing its structure the central black holes are drawn to the new center of the merged galaxy, on the dynamical timescale of $\sim 10^6$ years until they become bound to one another, forming a massive black hole binary. If the binary loses enough energy and angular momentum to the field stars, which is by no means certain, it will enter a regime where gravitational radiation alone can bring about inspiral and coalescence within the Hubble time.

In a black hole binary the first black hole is gradually spun down by interaction with the stellar wind of its companion, and will likely be a slow rotator even it began with maximal spin. The second hole should not experience this and should retain its high spin.

During black hole binary inspiral, the gravity waves generated sweep through a range of frequencies. In the final merger of two 10^9 $M_\odot$ black holes, a ”chirp” of gravitational radiation with periods as small as 10^4 s will be emitted. It has been suggested that this radiation might be detected through the Doppler tracking of spacecraft and by using space-based interferometers.

At binary frequencies $\sim$ 0.01-1 μHz, the black hole binary persists for many orbits. The strain amplitudes of the ultra-low frequency gravity waves generated by sufficiently massive black hole binaries may be detected out to cosmological distances as perturbations in the pulse arrival times of quiet pulsars.

When they merge the gravitational wave power produced can be 10^{59} ergs/s. This energy levels can only be sustained for a millisecond.

The efficiency of the produced gravitational waves cannot be higher than about 40 per cent, because once a gravitational wave has been created, it then has to escape the influence of the black hole. Gravitational waves are gravitational redshifted, just as light would be and how closer to the center how more redshifted. More than half of the gravitational wave energy is lost this way, while more ends up inside the black hole, adding up to its mass. The intense gravitational waves can only be emitted in very short bursts.

There is a chance of ∼0.001 of detecting a merging black hole binary. Only a small fraction of binary systems can merge within a Hubble time via unassisted stellar dynamics.

Black hole binaries are probably much more common than neutron star binaries of black hole-neutron star hybrids. Only a small fraction of these will merge in a Hubble time, as the larger mass permits the system to remain bound at higher separations.

3.3.3 Thorne-Zytkow objects

If there is a coalesence of two objects with large mass ratios (>2.5) it is possible that there is only little mass ejection. This object is called a Thorne-Zytkow object and an example is a neutron star orbiting a massive red (super)giant forming a neutron star inside a supergiant core. While spiralling-in gravitational radiation is emitted. The event rate for the formation of Thorne-Zytkow object from a high-mass X-ray binary (HMXB) has a lower limit of $\sim 10^{-3}$ per year per a 10^{11} $M_\odot$ Milky-Way-type galaxy. A normal estimate gives the possibility of over 30 formations of TZ objects within a distance of 30 Mpc.

The gravitationale wave frequency lies between between 10^{-5} and 10^{-1} Hz, just capable for the LISA detector to detect.

3.4 Deformations by rotational instabilities

Rotational instabilities come from several types of astrophysical objects, like a centrifugally hung stellar core or ”fizzler”. The formation of a fizzler begins when the core of a massive star depletes its nuclear fuel and begins to collapse to neutron star densities. If the core was rotating initially, conservation of angular momentum requires that the core spin up as it collapses. The spin up could actually halt the collapse if the centrifugal force increases to the point where it overcomes the inward gravitational push. The results would be a rapidly rotating, partially collapsed stellar core. Another example is a cooling supermassive star (mass $> 10^6$ $M_\odot$) that also spins up as it contracts. The radiation could be detectable by LISA.

Rapidly rotating neutron stars (pulsars) tend to be axisymmetric; however, they must break this symmetry in order to radiate gravitationally. Deformation of the star or precession of its rotation axis, leads to gravitational radiation. Rotational energy can be lost by gravitational radiation to slow the pulsar down.

A large magnetic field trapped inside the superfluid interior of a pulsar may also induce deformations of the star. This mechanism has probably extremly small effect for standard neutron star models.

3.4.1 Freely precessing neutron stars

Freely precessing neutron stars have long been recognized as a potential source of gravitational waves. For this to occur the star is modelled as a partly elastic, partly fluid body with quadrupolar deformations of its moment of inertia tensor. A key feature is the the decay of free precession due to dissipative processes internal to the star. The source of deformation in a neutron star is likely to be strains in its solid crust.

Neutron stars are not rigid bodies - they consist of a thin elastic shell containing a superfluid core. The neutron star does not collapse symmetrically and can start to precess. A real neutron star, once set into free precession, wil not precess forever - energy will be dissipated wihtin the star, converting the kinetic energy of the wobble into thermal energy. Also, gravitational wave energy and angular momentum will be radiated to infinity, which must be subtracted of the star's motion.

The amplitude of the wave is limited by the strain the crust of the neutron star can take. So there is and upper bound to the wobble angle of a precessing star. More rapidly spinning neutron stars are better capable to maintain a smaller wobble angle to prohibit fracture, but slowly spinning neutron stars have no limits on the wobble angles by crustal strain.

If there is a torque that is fixed with respect to the reference plane, it would lead to a linear variation in the wobble angle, which is called linear pumping. It will always give a finite precession angle.

Accretion torques are an obvious place to start when looking for mechanisms to pump precession. Not only are they capable of exciting wobble, but they can also maintain the spin frequency of the system, leading to the possibility of long-lived, constant wave amplitude sources.

The torque on the central star is the sum of two parts. The first is simply the material torque, i.e., that due to the accretion of angular momentum from matter detaching from the disc and falling on to the star. The second torque is due to the coupling of the star's magnetic field with the disc. The net effect of these torques is to spin-up slowly rotating stars, but to impose a maximum spin frequency for fast stars where the accretion torque vanishes. Timescales for this are typically 10^4 years.

The accretion rate and therefore also the torque depend upon the balance of gravitational, centrifugal and magnetic forces. The torque is therefore a function of the plasma angular velocity, stellar angular velocity and stellar magnetic moment vectors.

Models of the electromagnetic torque on a spinning neutron star have split into two classes. The first is the Goldreich and Julian model where a dipolar magnetic field embedded in the star generates a strong electric field at the stellar surface which rips out charged particles. These then propagate along the magnetic field lines, forming a magnetosphere. This applies even when the dipole and rotation axes coincide. The radiation the charged particles emit then carries energy away from the star, implying the existence of a braking torque.

The second class does not have a magnetosphere, and instead models the star as a perfect conductor with a magnetic dipole embedded, surrounded by vacuum. If the dipole is inclinded to the rotations axis, electromagnetic radiation at the spin frequency is emitted. This provides the braking torque.

The torque consists of two parts: (i) A part that produces secular variation in the free precession angle and spin rate on the electromagnetic spin-down time-scale, (ii) a part that produces no such secular variation. Instead, it causes oscillations in the spin frequency and wobble angle on the (much shorter) free precession time-scale. Neither of them are likely to lead to detectable levels of gravitational radiation.

The amplitude of the wave-field increases as the electromagnetic spin-down time-scale decreases, so we should focus attention on fast spinning strongly magnetized stars, i.e., stars very soon after birth in supernovae, with temperatures of 10^{11} K. Electromagnetic radiation reaction could provide a way of setting young neutron stars into free precession.

It is possible that secular electromagnetic pumping remains active even in an accreting system: the accretion torque could then maintain the star's spin frequency, while the electromagnetic torque maintains the free precession.

Three phenomena can be used to obtain an upper bound on the gravitational wave signal, independent of the mechanism producing deformation: The accretion spin-up torque, the electromagnetic pumping torque, and internal dissipation.

Glitches in young pulsars are of interest as candidates for isolated impulsive pumping, while nearbody encounters in dense environments are of interest as candidates for non-isolated impulsive pumping. Glitching - the sudden increase of frequency of a pulsar due to cooling - is most common in young pulsars and requires a solid crust, because after its formation the neutron star cools down. Free precession following collisions with other stars can happen in high stellar densities of globular clusters. Interesting levels of gravitational wave emission would occur. It is important in terms of the population evolution of globular clusters, but they are not of use as a mechanism for free precession gravitational wave production, as it is impossible to identify a way in which the collision would set the star into free precession.

For neutron star-neutron star encounters relativistic effects will be important, e.g., Lense-Thirring precession. The event rate for neutron star-star encounters is very small, and the rate for neutron star-neutron star encounters will be extremely low. It lies at rate of 10^{-11} years.

It is almost impossible to find astrophysical pumping mechanisms capable of giving steady gravitational wave amplitudes detectable by an Advanced LIGO. But this conclusion has been reached for stars with oblate deformations and the pumping mechanisms involved an externally generated torque being exerted on the star.

3.5 Black holes

Black holes themselves are are also sources of gravitational waves. If an objects falls into a black hole, it sets up a vibration, which is very strongly damped by gravitational wave emission, except in the case of very rapidly spinning black holes. The vibrations are the vibrations of space, not of the matter inside it. Much of the energy of the black hole is that of the curved space-time that makes it and surrounds it. The singularity is not involved.

Catastrophic events from high-angular-momentum compact sources such as hypernovae and black hole-neutron star coalescence are expected to result in black hole plus disk or torus systems that are powered by the spin energy of the black hole and create gravitational waves. This represents a major fraction of the black hole luminosity, presently emitted as "unseen" emissions, whenever the torus becomes axisymmetric.The fluence of these gravitational wave emissions may give the possibility to obtain true calorimetry of gamma ray bursts. The

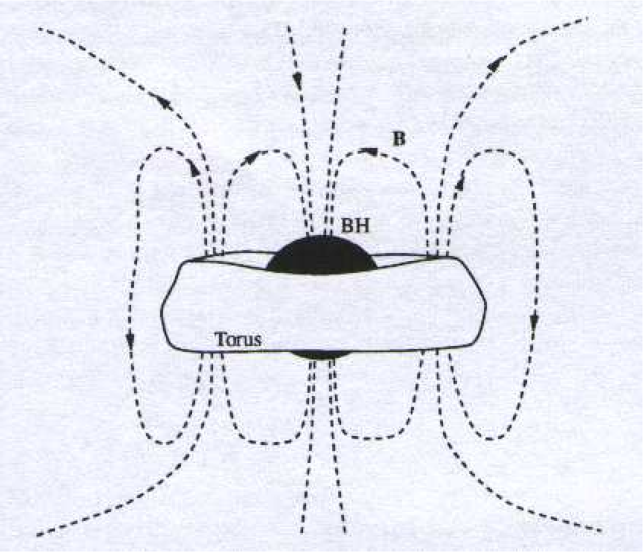

Figure 1: Cartoon of a rapidly rotating black-hole-torus system in suspended accretion. The black hole assumes a equilibrium magnetic moment in its lowest energy state. The torus around the black hole supports a similarly shaped magnetosphere. Equivalence in poloidal topology to pulsar magnetospheres indicates a high incidence of the black-hole luminosity on the inner face of the torus. The torus reradiates this input into gravitational radiation, Poynting flux winds and, possibly, neutrino emission (Figure from ref. 19).

torus is strongly coupled to the spin energy of the black hole; lumpiness in the torus will produce gravitational radiation at twice the Keplerian angular frequency, i.e., in the range of 1-2 kHz; the emission in gravitational radiation should dominate over emissions in radio waves at the same frequency. This process is distinct from emissions in neutron star-neutron star mergers or by fragmentation in collapse towards supernovae.

The torus is likely to possess dynamical and, potentially, radiative instabilities, especially a thick torus. If the torus shows violent behavior, the gravitational waves may be episodical. The stability of the gravitational wave frequency is somewhat uncertain, as it may be variable by the magnetohydrodynamical turbulence in the torus.

3.6 Population III stars

Population III stars are the first generation of stars formed in the early universe when virtually no metals existed. They have masses of 100-500 $M_\odot$. They suffer two fates: Explosion in a giant thermonuclear explosion (”hypernova”) or they collapse to form black holes if their mass is higher than 260 $M_\odot$. However, if the star is rotating, rotational (plus thermal) support prevents the star from undergoing immediate collapse into a black hole. Formed is a proto-black hole of 50-70 $M_\odot$ with a radius of 1000-2000 km. This rotating proto-black hole is susceptible to bar instabilities and may produce a strong gravitational wave signal.

The Population III stars are found at redshifts higher than 5 and collapse in less than a few million years. Thus they are hard to detect, because the redshift moves the peak of the source waves out of the band of LIGO detectors.

3.7 The cosmological stochastic gravitational wave background

It is also possible to detect the gravitational wave backgroud, waves from the far past, produced by mildly nonlinear evolution of density fluctuations, i.e., galaxy clusters. The estimation of this emission is currently not available with the present techniques. The question is if the clusters have produced a significant amount of gravitational radiation, because the emissions appear to be weak.

The gravitational radiation from a galaxy cluster produces progressive deformations on some material systems, called *the secular effect*. For distances smaller than 600 Mpc it could be detected.

The gravitational radiation from a cluster is the superposition of the radiation produced by the motion of many particles of dark and baryonic matter inside the cluster. The efficieny is very low, $\sim 10^{-16}$. This means that during all the age of the universe a single cluster would radiate gravitational energy of $\sim 10^{-16}$ time the cluster mass.

The gravitational waves produce anisotropies one the Cosmic Microwave Background (CMB). Other gravitational waves generated during inflation or in another early process would lead to ”primary” CMB anisotropies because they were present at recombination time; however, the gravitational waves coming from galaxy clusters were emitted after recombination and they can only produce ”secondary” anistropies, which are due to the motion of the CMB photons in the time varying gravitational field associated to these waves. These anisotropies are expected to be too small for detection because their contribution of their energy to the present density is very low: about 10^{-17}-10^{-18}. This means that observations of the CMB seems not to appropriate for detecting the gravitational background from galaxy clusters. It could be done with interferometry, but not yet with the current techniques.

The variation of the background geometry produces graviton pairs which are stochastically distributed and whose logarithmic energy spectra represent a faithful snapshot of the (time) evolution of the curvature scale at very early times. Their energy spectra of the backgrounds extend of a hue frequency of (present) frequencies.

The universe is transparent to gravitational waves back to the Planck epoch (T $\sim 10^{19}$ GeV, $t \sim 10^{-43}$ sec), the stochastic gravitational wave background should contain an unrivaled fossil record of cosmological events, including the 0.9-K gravitational analog of the microwave background and gravitational radiation from cosmic strings, soliton stars, inflation and cosmological phase transitions. Only the last two will be treated in this section.

3.7.1 First-order cosmological phase transition

The production of gravitational waves in a first-order cosmological transition proceeds through the nucleation of true-vacuum bubbles. Candidates include grand-unified-theory-symmetry breaking or first-order inflation (T $\sim 10^{15}$ GeV, $t \sim 10^{-36}$ sec), electroweak symmetry breaking (T $\sim$ 200 GeV, $t \sim 10^{-11}$ sec), and phase transitions.

The frequency of the gravitational waves produced in a phase transition depends on the temperature at which it occurs. The spectrum of the gravity-wave background could well contain the thermodynamic history of the universe. The radiation is produced by the collision of two scalar-field vacuum bubbles. In a first-order cosmological phase transition the universe get "hung-up" in a metastable, false-vacuum state; if the energy barrier between the false- and true-vacuum states is sufficiently large, significant supercooling occurs and the transition to the true vacuum proceeds through the nucleation and percolation of bubbles of true vaccum. Once nucleated, a vacuum bubble expands outward with constant acceleration and quickly approaches the speed of light, being dirven by the pressure difference between its true-vacuum interior and its false-vacuum exterior. The false-vacuum energy liberated as the bubble expands exists in the form of bubble-wall kinetic energy and is eventually transformed into particles (and thermalized) when bubble collide. The false-vacuum energy released is substantial: much greater than that in the ambient thermal bath of radiation, so the the entropy of the universe is increased significantly. For all these reasons, a strongly first-order cosmological phase transition is expected to be a potent source of gravity waves.

3.7.2 Extended inflation

In extended inflation the transition from an inflationary to a radiation-dominated universe is accomplished by bubble-nucleation. Bubble collisions supply a potent - and potentially detectable - source of gravitational waves. If black holes are produced by bubble collisions, they will evaporate producing short-wavelength gravitons.

The gravitational waves just entering the horizon today ($\lambda \sim 10^{28}$ cm) lead to a quadrupole anisotropy in the temperature of the CMBR of magnitude comparable to their dimensionless amplitude.

In models of extended inflation there is an additional and probably much more important source of gravitational waves. The origins of these gravitational waves traces the fundamental difference between slow-rollover inflation and extended inflation: the mechanism for terminating the inflationary phase. In extended inflation the transition occurs through bubble nucleation and percolation. Bubble collisions result in significant production of gravitational waves. It is also possible that mini black holes are produces at the collision sites. These hole evaporate through the Hawking process and produce comparable amounts of gravitational radiation, but at shorter wavelengths.

The prospects for their detection depend upon their wavelength and therfore the reheat temperature (caused by the collisions). If detected, their characteristic wavelength would provide a measure of the reheat temperature and a way of distinguishing between inflation and other cosmological transitions, e.g., the electroweak or QCD phase transitions.

4 Detectors of gravitational waves

General relativity predicts that gravitational waves cause a distortion of spacetime transverse to their direction propagation. The distortions effects of gravitational waves are extremely small, so to measure something you have to have a very large detector; how larger the distance between the measurement point how bigger the distortion becomes to be measured. Space-based detectors offer a solution for this problem, but also Earth-based detectors are capable to perform the task.

All earlier detectors have failed to detect gravitational waves. Currently several different types of gravitational wave detectors are being built, with capability to be improved in later years, to overcome this failure. So these new detectors are the ones presented, because it is not the intention to present possible detection methods that have failed or were not advanced enough to the needed sensistivity. The new detectors are the ones to be available in the next decade and the only one considered. Why would the other ones have been abandoned otherwise?

The direct measurent of gravitational radiation will yield otherwise unobtainable information about massive physical sources. High-sensitivity detection methods include resonant bars, Doppler tracking of spacecraft, and broadband interferometers. Ground-based equal-arm-length interferometric gravitational wave detectors will search for high-frequency (~10-1000 Hz) gravitational waves. Because of the arm-lentgh equality, laser light experiences the same delay in each arm and thus phase or frequency noise from the laser itself precisely cancels at the photodetector. This cancellation is crucial. Space-borne interferometers have been proposed to detect and study low-frequency (~0.1-100 mHz) waves. The equal-arm noise cancellation does not work in the same way and unequal-arm-lengths could be used.

Earth-based interferometers operate in the long-wavelength limit. By contrast, the Doppler tracking technique and space-borne interferometers involve much longer arm-lengths and, over much of the low-frequency band where they are sensitive, are not in the long-wavelength limit. When the physical scale of a free mass optical interferometer intended to detect gravitational waves is comparable to or larger than the gravitational wave wavelength, time delays in the response of the instrument to the waves, and travel times along beams in the instrument, must be allowed for in the theory of the detector response used for data interpretation. It is convenient to formulate the instrumental responses in terms of observed differential frequency shift - for short, Doppler shifts - rather than in terms of phase shifts usually used in interferometry, although of course these data, as functions of time, are interconvertible. Detection is complicated by the rotation of the Earth and its rotation around the sun. These effects on detection must be removed. This can be done by space-based detectors.

A coherent microwave link between the Earth and a distant spacecraft (three-pulse gravitational wave response), the response of an equi-arm Michelson interferometer (four-pulse) and unequal arm interferometers (eight-pulse) have been proposed as detectors of the Doppler response to gravitational waves. The LISA detector is the detector to be constructed.

I will discuss the three most promising projects in which gravitational wave detectors are being built.

4.1 LIGO

The Laser Interferometer Gravitational-Wave Observatory is one of several ground-based interferometers currently planned or under contruction. Tthe detection of gravitational waves happens through the construction of large Michelson interferometers, in which light is passes along two perpendicular paths, reflected at the end of each arm, and recombined to create fringes. Movement of the fringes measures a relative change in length of the two arms. The length of the arm should be as long as possible to increase the fractional strain that can be measured, but the signal will become incoherent if the light travel time is comparable to the period of the gravitational waves. Since the typical frequency of interest may be in the kHz region, the maximum arm length may need to be a few hundred km. A practical means of attaining this is to have a smaller baseline (currently ~10 m, likely to increase 100-fold in a few years) with multiple reflections, using a Fabry-Perot etalon.

There are two observatories seperated by 3002 km that will be operated in coincidence. At each site laser beams propagate in 4 km long evacuated beam lines 1.2 m in diameter. The distance correpsonds to a gravitational wave travel time of 10 ms.

LIGO detects the gravitational waves by comparing the time of propagation of light in mutually orthogonal paths in the distorted space between freely suspended test masses seperated by 4 km using laser interferometry, The distortion that is expected is not larger than a strain of 10^{-21}. The beam tubes need to be aligned along the propagation direction

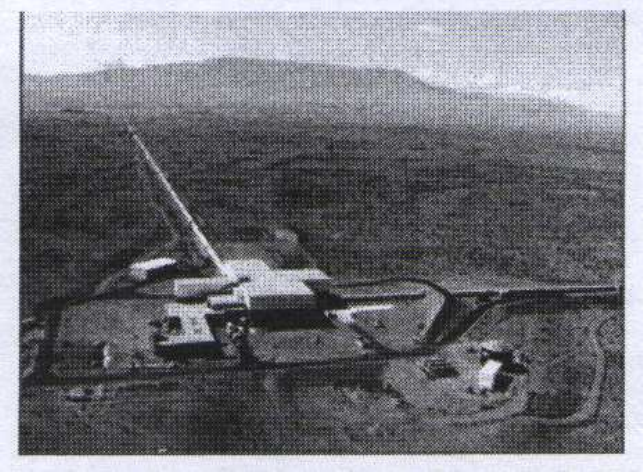

Figure 2: Aerial view of one of the LIGO sites toward the SW along the Y arm. The arm is 4 km long and has a midstation located at 2 km (Figure from ref. 1).

of light in vacuum and not along the direction perpendicular to local gravity on the surface of the Earth.

The direct detection of gravitational waves can provide fundamenal evidence for the behavior of spacetime in strong gravitational fields where Newtonian gravity is no longer a good approximation. Detection may also yield a new view of the universe since gravitational waves emerge from the densest regions in astrophysical processes without attenuation or scattering.

LIGO is developed to improve the detectability of gravitational waves. The Advanced LIGO, often also called LIGO-II and LIGO-III, will be available in the coming years. New active seismic isolation systems, new test masses and supensions, and more powerful lasers will all be installed in the existing infrastructure, with the goal of increasing the broadband phase sensitivity (hence gravitational wave strain sensitivity) of the instrument by at least a factor of 10.

One of the problems is power absorption in LIGO optics. A solution is "thermal compensation": one may attempt to homogenize the absorption-induced temperature fields by radiatively depositing additional heat on the surface of the optic in a tailored pattern, thus compensating the original distortion. A method for this is an active wavefront correction via direct thermal actuation on optical elements of the interferometer. A simple nichrome heating element suspended off the face of an affected optic will, through radiative heating, remove the gross axisymmetric part of the original thermal distortion. A scanning heating laser will then be used to remove any remaining non-axisymmetric wavefront distortion, generated by inhomogeneities in the substrate's absorption, thermal conductivity, etc..

LIGO will be the first of the detectors to take its shot at the first detection of gravitational waves.

4.2 VIRGO

The French-Italian VIRGO, the competitor to the American LIGO, is 3 km long and looks a lot like LIGO but uses a very sophisticated seismic isolation system that promises to move the low-frequency noise "wall" from about 10 Hz (LIGO) to 3 or 4 Hz.

In order to achieve full detection sensitivity at low frequencies, the mirrors of interferometric gravitational wave detectors must be isolated from seismic noise. The VIRGO vibration isolater, called the *superattenuator*, is fully effective at frequencies above 4 Hz. But the residual motion of the mirror at the mechanical resonant frequencies of the system is too large for the interferometer locking system and must be damped. A multidimensional feedback system, using inertial sensors and digital processing, has been designed for the purpose.

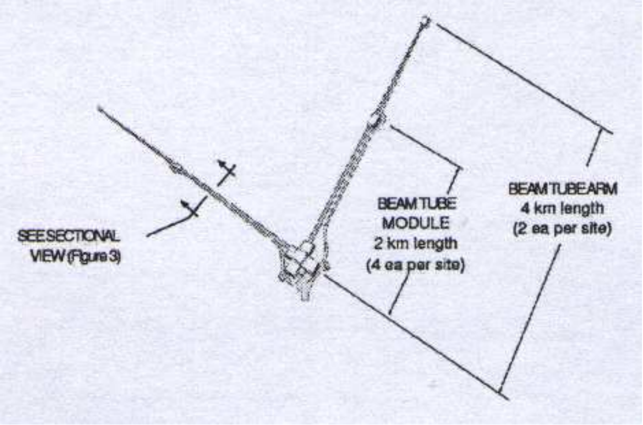

Figure 3: Perspective schematic view of one of the LIGO sites showing the beam tube arms and the 2 km modules of which they are composed (Figure from ref. 1).

A pair of VIRGO detectors could be sensitive enough to stochastic and isotropic gravitational wave background. In the near future the currently built detector might be complemented by another interferometer of even better performances very close (at a distance ¡ 1000 km) to it. The two interferometers of the pair should also be sufficiently far apart in order to decorrelate the local seismic and electromagnetic noises. The graviton spectra will be increasing in frequency instead of decreasing as it happens in ordinary inflationary models.

4.3 LISA

The Laser Interferometer Space Antenna is a spaceborne interferometer. The gravitational wave observatory will use three spacecraft orbiting the Sun. Each spacecraft would be equipped with a laser sending beams to the other two (~0.03 AU away) while simultaneously detecting (using the same laser) the frequencies of the laser beams received from the other two. In a symmetrical way, LISA can be thought of as a closed array of six

one-arm delay lines between the test-masses. Each spacecraft has a laser which is used both to transmit a narrowband beam to the other two spacecraft and (as a local oscillator) to produce Doppler time series from the beams received from the other two spacecraft. Thus, there are six Doppler time series produced. The armlength is about 5×10^6 km.
If developments go according to planning LISA will be operable between 2007 and 2010.

4.4 Other detectors

There are currently three other detectors being or to be constructed. I will metion them only briefly, since they are less important or information is hardly available.
SAGITTARIUS is a similar space-borne interferometer as LISA but is instead orbiting the Earth with similar armlength. The sensitivity will be limited to frequencies below 10^{-3} Hz. Little information is available about this project.
The GEO600 interferometers in Germany is 600 meters long, but will be used mainly to test the newest interferometer techniques and technologies, because of its length. The same counts for the 300 meter long TAMA in Japan, which is the first one already operational.

5 Conclusion

There is quite a large number of sources of gravitational radiation available and it is still possible that there will be added more in the future. Gravitational waves are hard to detect but their bursts do also belong to the most brightest events in the universe. The strongest emitters of gravitational radiation include black holes and neutron stars and binaries of them. A wide range of different sources are being researched, thus increasing the chance of detecting gravitational waves. Until now no gravitational waves have been detected directly, but the currently developed Earth-based and space-based detectors should have a good chance of finally detecting gravitational waves.
On the last page a table from the article by Fryer, Holz & Hughes (2002), ref. 7, had been added and a little bit adjusted to give an overview of the typical features of sources of gravitational radiation. Not all data has been found and I don't want to try to give answers myself by doing calculations of possible numbers.

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Object[a]	Emission mechanism	Rate[b] (yr^{-1})	Typical distance	f (Hz)	Maximum power (ergs/s)
AIC	r-modes	$<10^{-5}$	100 Mpc	$\sim$1000	10^{50}
SN	Bar modes	$<10^{-2}$	10 Mpc	$\sim$1000	10^{53}
	Binary	$<10^{-2}$	10 Mpc	$\sim$2000	10^{54}
	r-modes	$<10^{-2}$	10 Mpc	$\sim$1000	10^{50}
	BH ringing	$<10^{-2}$	10 Mpc	$\sim$2000	10^{55}
Pop III	Bar modes	$<10^{7}$	z=5, z=20	$\sim$10	10^{54}
	Binary	$<10^{7}$	z=5, z=20	$\sim$30	10^{56}
	BH rRinging	$<10^{7}$	z=5, z=20	<70, <20	10^{57}
Nova	-	$<10^{-5}$	20 kpc	50-100	10^{42}
NS	-	$<10^{-2}$	-	$\sim$200-0	10^{55}
SMBH	Binary	<0.1	-	10^{-5}-1	10^{59}
TZO	Binary	10^{-3}	-	10^{-5}-10^{-1}	-

[a] AIC = accretion induced collapse, SN = core collapse supernova, Pop III = Population III stars of 300 $M_{\odot}$, NS = Neutron star, SMBH = supermassive black hole, mostly from black hole binaries, TZO = Thorne-Zytkow Objects..

[b] For AIC and SN, the rate in number per year for a Milky Way-massed galaxy. The number given for the Pop III stars is the rate in the universe per year. These numbers are extremely uncertain.