Probing Gravity and Cosmology with Ground-based Gravitational Wave Detectors

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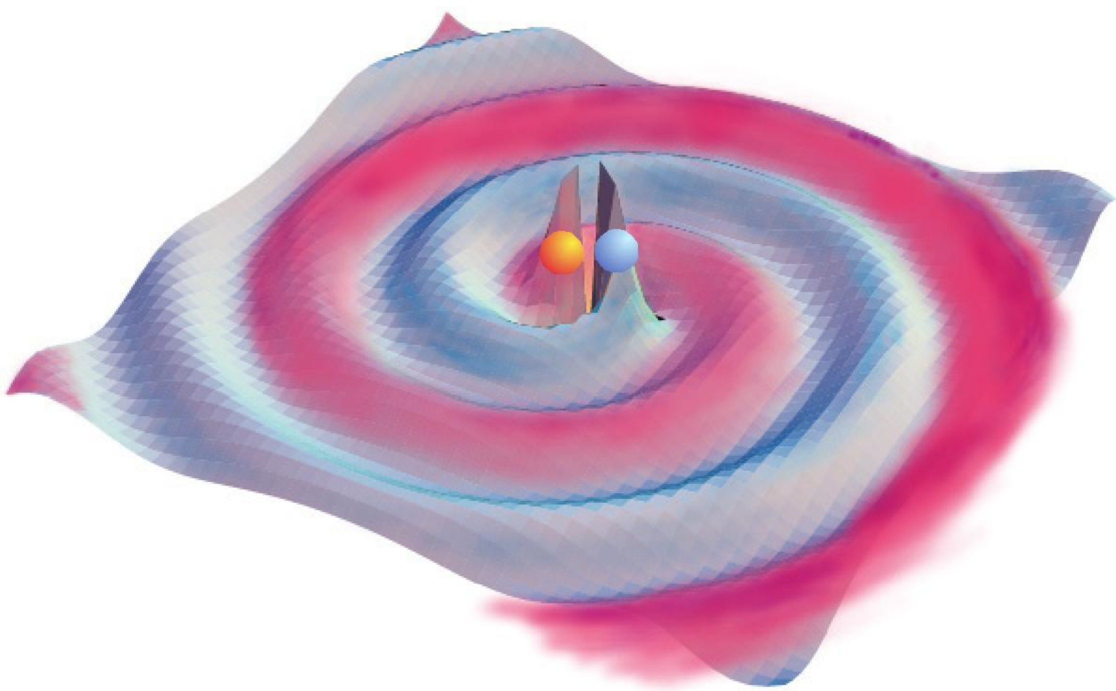

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Gravity and astronomy have been inseparably intertwined since the time of Kepler, and the interplay of new astronomical observations confirming and constraining our most fundamental physics theories continues through to the present day. General relativity received its first experimental support through Eddington's expedition to observe the bending of starlight during the 1919 eclipse, while Hulse and Taylor's discovery of the binary pulsar PSR B1913+16 gave the first observational evidence for the existence of gravitational waves [Weisberg & Taylor, 2004].

The next decade will see the operation of an international network of ground-based gravitational-wave interferometers (Advanced LIGO in the US, Advanced Virgo and GEO HF in Europe, and LCGT in Japan) which will use gravitational-wave observations to probe fundamental questions in gravitation and cosmology. Measurements of the properties of gravitational waves and the waveforms from compact binary systems will probe the dynamical nature of gravity in the same way that Hertz's experiments probed the dynamics of electricity and magnetism. General relativity has been remarkably successful in explaining all observations to date, but attempts to quantize gravity or to unify it with other forces strongly suggest that there is new physics to be found.

At the same time, the most direct way of observing the primeval Universe is via the gravitational-wave window. Theoretical considerations based on fairly general assumptions predict the production of gravitational waves in the early Universe which have been traveling to us unscathed since the inflationary era as a consequence of their weak coupling to matter and other forms of radiation. The same weak interaction with matter that makes gravitational waves so hard to detect means that they travel nearly unchanged (except for the cosmological redshift and gravitational lensing) since their production.

Important Questions in Gravitation

What are the properties of gravitational waves?

General relativity makes two firm predictions for gravitational waves, that their speed is identical to the speed of light, and that their force pattern is transverse and quadrupolar in shape. From the perspective of elementary particle physics, the prediction that the speed of gravitational waves is the same as that of light goes hand-in-hand with the concept that the "graviton", the hypothetical carrier of the gravitational interaction, has zero rest mass. The transverse, quadrupolar polarization properties are a consequence of the tensor nature of general relativity (corresponding to a spin 2 graviton) combined with the zero rest mass of the graviton. In alternative theories of gravity, violations of either property could take place; gravitons might have a non-zero rest mass and/or might include a spin 0 component (scalar field) in addition to the spin 2 component. To date, there is no direct observational evidence that addresses either of these fundamental properties.

Extremely accurate comparisons between the speed of gravitational waves and the speed of light are possible if even a single gravitational wave burst can be correlated with an electromagnetic counterpart [Will, 2006]. Simultaneous observations of a burst of gravitational waves accompanying a gamma-ray burst from the same source will give an immediate, high-precision measurement of the speed of gravitational waves relative to that of light. For example, if ground-based interferometers detect a signal from a source at 200 Mpc (well within the range of Advanced LIGO and Advanced Virgo) whose arrival is within minutes of the arrival of an electromagnetic pulse from the same source, then a bound of parts in 10^{15} on any difference in speed between the two waves could be achieved.

If the graviton were massive, then the speed of gravitational waves would depend on wavelength, and the detected chirp-like signal from inspiraling compact binaries (such as neutron star-neutron star binaries) would be distorted compared to the zero mass prediction[Will, 2006]. By searching for such distortions in the signal, one can place stringent bounds on the graviton mass. Advanced LIGO and its partners can place bounds comparable to existing bounds derived from examinations of the orbits of the outer planets in our solar system; LISA, observing the waves from inspirals of massive black hole binaries at much lower frequencies, can follow up and do much more precise checks. Such bounds could constrain a variety of theories of gravity designed to go beyond general relativity, including theories where the non-gravitational interactions reside on a four-dimensional “brane” in a higher dimensional spacetime, while gravity extends to all the dimensions.

Polarization tests of gravitational waves require observations with detectors in a variety of orientations. If a gravitational wave burst is detected simultaneously in three independent detectors of the ground-based array, and the source direction is determined by other means (for example via correlation with a gamma ray burst), then it will be possible for the first time to test whether the waves are composed of only the expected spin-two polarization states [Will, 2006]. Alternatively, detection of the continuous waves from a pulsar can provide an even more stringent test of the polarization properties. The long-lived nature of the source means that a single detector will be sensitive to varying mixtures of the polarization as the earth rotates on its axis. Any confirmed evidence of a third mode of polarization would cast doubt on the validity of general relativity.

Is general relativity the correct theory of gravity?

Despite decades of experimental tests supporting general relativity, numerous alternative theories or extensions of general relativity exist. Some are motivated by attempts to unify gravitation with the other interactions of physics, such as string theory, while others are motivated by a desire to avoid dark matter or dark energy by modifying general relativity at large distance scales. Experimental tests of gravity, as well those afforded by the data from the Hulse-Taylor binary, are consistent with both Einstein’s theory and various scalar-tensor (spin-2 plus spin-0) alternatives, including the Brans-Dicke theory. Gravitational waves provide entirely new ways to test general relativity, beyond the mass of the graviton and the polarizations of the waves, as described above.

The inspiral of a binary system of compact objects (either neutron stars or black holes) is governed by a relatively small number of parameters: the masses and spins of the two bodies, an initial orbital eccentricity, and initial orientations of the spins and orbit. Much of the inspiral phase, characterized by slow motions and weak gravitational fields, can be described with exquisite precision by analytic solutions to general relativity that make use of the so-called "post-Newtonian" approximation. Specifically, the evolution of the phase of the gravitational-wave signal can be calculated to extremely high precision. A precise comparison between the observed gravitational-wave phasing and the predicted phasing using such techniques as matched filtering can search for failure of general relativity [Arun et al, 2006]. For example, there is now evidence from numerical solutions of Einstein's equations that, depending on the magnitude and alignment of the spins, the mergers could be very rapid or could experience a temporary "hang-up," with significant consequences for the observed waveform. Such tests can be made using both ground and space-based observations.

In black hole - black hole inspirals, it will also be possible to measure with rather high precision the effects of the dragging of inertial frames, an important general relativistic effect hinted at in observations of accretion onto neutron stars and black holes. This has only recently been observed directly in the solar system by tracking LAGEOS satellites and results soon expected from the Gravity Probe B mission. This effect likely plays a central role in producing relativistic jets observed in quasars, for example. In inspiraling binaries, when the two bodies have significant spin, there can be precessions of the spins as well as of the orbital plane, and modifications of the rate of inspiral. These phenomena result in modulations of the gravitational waveform and alterations in the phase evolution that can be measured with high precision using interferometric detectors, both on the ground and in space. Observing the effects of frame dragging in such an extreme environment would be a stunning test of general relativity.

In some alternative theories of gravity, there is the additional possibility that systems could emit "dipole" gravitational radiation, in addition to the uniquely "quadrupolar" radiation that general relativity predicts. For inspiraling binary systems, this additional form of radiation can modify the decay of the orbit and thus distort the gravitational waveform compared to what general relativity would predict. Observations by ground based detectors could strongly constrain such alternative theories.

Motivated by the success of the holographic principle in explaining the black hole information paradox, in the 1990s, theories [Susskind, 1995; 't Hooft, 1993] have been proposed in which our three spatial dimensions are in effect a holographic projection of physical processes that take place on a distant 2D surface, the horizon of the observable Universe. One consequence of this is that the scale of quantum structure of spacetime could be far larger than the Planck length [Hogan, 2008]. In fact, it has recently been suggested that ground-based interferometer technology is capable of measuring positions with such precision that they might actually be sensitive enough to probe the quantum structure of spacetime [Hogan, 2008]. It is likely that certain classes of holographic theories of quantum gravity can be tested by direct experiment. While such theories are far from universally accepted, the ability to test any plausible theory of quantum gravity is tantalizing.

Is general relativity still valid under strong-gravity conditions?

Most tests of general relativity have taken place under the relatively weak-gravity conditions of the solar system or of binary pulsars. Although there is some evidence of strong-field general relativistic phenomena, notably from observations of the inner regions of accretion disks near neutron stars or black holes, the evidence is not conclusive. The final merger of two black holes is a quintessentially strong-field phenomenon. Recent breakthroughs in numerical relativity have led to increasingly robust theoretical predictions for the shape of the merger waveform. The comparison of such predictions with observed merger waveforms would provide unique tests of general relativity in the highly dynamical, highly nonlinear,strong-gravity regime. Ground-based interferometers, operating as a network in the coming decade, will provide the initial tests of such strong-gravity behavior, while the larger SNRs expected for future underground interferometers (like the Einstein Telescope currently undergoing a design study in Europe) and LISA will yield higher precision tests of strong-field general relativity.

Are Nature's black holes the black holes of general relativity?

Although black holes are widely accepted in astronomy, observational hints of their existence consist entirely of evidence that a large amount of mass is confined to a small region of space, too small to be compatible with any other stable, long-lived object governed by general relativity and the normal laws of matter. Gravitational waves, by contrast, will bring us high-precision studies of the central objects, be they black holes or something else.

General relativity predicts that black holes have a unique property, sometimes called the "no-hair" theorem. The external spacetime of a black hole is completely characterized by its mass and angular momentum; for example the multipole moments of its external gravitational field are all determined by these two parameters. Specifically, according to general relativity, all undisturbed black holes are described by the Kerr metric. This is in complete contrast to normal gravitating bodies, whose external gravity field may depend on their internal structure, on whether they are partly solid and partly liquid, and on surface deformations such as mountains. Black holes have no such "hair". Gravitational waves provide a number of ways to test this prediction of general relativity.

An unambiguous signature of black holes could be provided by the detection of their quasi-normal modes – through gravitational radiation that has a mode's characteristic frequency and decay time. Failure to detect such radiation from, for example, a newly formed black hole would mean that gravity is more exotic than what we currently believe (e.g., gravitational collapse might lead to entities called naked singularities) and reveal new phases of matter at extremely high densities.

Observations of the merger of two stellar mass black holes will be carried out in the next decade by Advanced LIGO and Advanced Virgo, followed by high-SNR observations with future underground detectors. The merger of a binary black hole will conclude with the so-called "ringdown" gravitational waves emitted by a distorted final black hole. Since the frequencies and damping times of each of the individual quasi-normal modes of oscillation of the black hole depend uniquely on the mass and spin of the hole, it will be possible to measure the final mass and spin with the observation of each mode. If no ringdown waves are seen, the final object cannot be a black hole – in violation of general relativity. If ringdown waves *are* seen, then general relativity insists that the frequency and damping time of each of the final hole's observed quasi-normal modes depend uniquely on the hole's mass and spin, so it will be possible to measure the final mass and spin from the observation of each mode. If the mass and spin inferred from the several observed normal modes are not the same, to within experimental accuracy, then general relativity must be wrong.

The inspiral phase can be used to determine the masses and spins of the initial inspiralling black holes. If general relativity is correct, then the final hole's mass and spin must be related to the initial masses and spins in a manner that will be computed with high precision by numerical relativity, and in a manner that can be used to test the black-hole "no-hair" and "area increase" theorems. LISA can perform even more precise tests by observing more massive black hole mergers with correspondingly higher SNR.

The most precise no-hair tests of black holes will come from extreme mass-ratio inspirals (EMRI). These involve a stellar-mass compact object (black hole, neutron star or white dwarf) spiraling into a massive or intermediate mass black hole. Over the 10^4–10^5 eccentric, precessing orbits traced out by the smaller mass during the observation time, the emitted waves encode details about the spacetime structure of the larger hole with a variety of distinct signatures. In addition to providing determinations of the black hole's mass and angular momentum to fractions of a percent, the observations can also be used to test whether the spacetime that governs the orbits is the unique Kerr geometry. These sources are one of the key targets for LISA. However, future underground detectors might also detect and measure them if intermediate black holes of one to ten thousand solar masses exist at cores of globular clusters and smaller galaxies.

Important Questions in Cosmology

What is the history of the accelerating expansion of the Universe?

Because compact binary inspirals are controlled by a relatively small number of parameters, such as mass, spin, and orbital eccentricity, they are near perfect candidates for standard candles. This is because the frequency and frequency evolution of the waves are determined only by the system's parameters, while the amplitudes of the waves' two polarizations depend on orbital inclination and the luminosity distance to the source. No additional calibrations are needed to extract the inclination and distance.

The network of ground-based gravitational wave interferometers (Advanced LIGO and Advanced Virgo) will observe neutron star mergers to distances of a few hundred Mpc and black hole mergers to distances greater than a gigaparsec (depending on total mass), facilitating an independent check on the local value of the Hubble constant if electromagnetic observations determine the redshift to go along with the gravitationally determined distance. Subsequent underground detectors will be able to measure the luminosity distance to a gamma-ray burst source at a red-shift z =1 to an accuracy of 2-5%, with the host galaxy of the burst providing the red-shift. These detectors will enable precision cosmology avoiding all the lower rungs of the cosmic distance ladder. With all-sky coverage to cosmological distances, these detectors will accumulate enough statistics to measure the Hubble parameter, the dark energy and dark matter content of the Universe and the dark energy equation of state to a good accuracy within their first years of operation.

Gravitational wave measurements have the potential to measure the parameter *w,* which characterizes the 'dark energy' supposedly responsible for the acceleration of the Universe, to an accuracy better than 10%, for future underground detectors, and around 4%, for LISA.

Were there phase transitions in the early Universe?

The early history of the Universe must have witnessed several phase transitions during the process of its evolution. First-order phase transitions in the early Universe, if they occurred, would begin with bubbles of the new phase that collide producing cavitation, turbulence and a detectable background of gravitational waves. A detectable background could also arise from vibrations of our universe as a brane in higher dimensions. Gravitational waves from such events in the era between an attosecond (10^{-18} seconds) and a nanosecond after the big bang would be redshifted into the LIGO or LISA frequency bands. This is an epoch not directly accessible by any other technique. Detectable background radiation could also arise from a network of vibrating cosmic strings, produced by phase transitions in the very early universe, and from vibrations and collapses of "boson stars," stars made of hypothetical scalar-type matter.

Background radiation due to any of these hypothetical early-universe phenomena could be detected by using a pair of detectors and looking for a correlated component of their "noise" output, on the assumption that their instrumental noise is not correlated. With its data analyzed this way, the LIGO detectors have already set an upper limit on the effective energy density in background waves as a fraction of the critical density of $\Omega_{GW} < 5.9 \times 10^{-6}$ at 100 Hz [Abbott et al 2009]. This limit improves on the previous best limit (from the constraint provided by Big Bang Nucleosynthesis [Kolb & Turner, 1990; Cyburt et al, 2005] by a factor of 2, and already constrains early Universe cosmological models and cosmic (super)string parameters. In the next decade, Advanced LIGO and Advanced Virgo should reach 10^{-10} at around 40 Hz, and a future underground detector could reach 10^{-12} at 100 Hz[1]. Detection of a cosmic background, though uncertain, would have major

[1] Since the gravitational wave spectrum may spread across the entire available frequency range, with multiple sources, searches in different bands complement each other. LISA should also approach a limit of 10^{-10} at about 1 mHz. Pulsar timing with the Square Kilometer Array could push the limits on a background at 3 nHz to $\Omega_{GW} \sim 10^{-13}$. The gravitational wave background with time scales of megayears may also be encoded into the cosmic microwave background through the structure of the fluctuations in the polarization spectrum.

ramifications for understanding the early Universe.

Do relics from the earliest moments of the Universe persist to this day?

There is a tentative prediction from string theory that during the early inflationary era of our universe some fundamental strings were inflated to cosmic size, becoming cosmic strings [Polchinski, 2004]. Therefore, searching for cosmic strings may provide a unique and powerful window into string theory and into particle physics at the highest energy scales. Although a stochastic background from a network of cosmic strings might be confused with other stochastic backgrounds, cosmic strings produce another type of waveform that is unique. When two cosmic strings pass through each other, there is a substantial probability that they will reconnect producing kinks that travel down the strings at the speed of light, emitting a beam of gravitational waves. If the cusp motion points nearly toward Earth a detectable burst with unique waveform will be seen. This waveform is robust to classical perturbations [Siemens & Olum, 2003] as well as quantum effects [Chialva & Damour, 2006], and is so distinctive as to make possible the identification of a detected signal as originating from a cosmic string cusp. The large mass per unit length of cosmic strings combined with the large Lorentz boost makes these bursts powerful enough that, if this scenario is correct, both LIGO and LISA have a possibility to detect them [Damour & Vilenkin, 2000, 2005; Berezinsky et al, 2000; Siemens et al, 2006]. Theoretical predictions of rates of such events are quite uncertain, but the implications for such a discovery are certainly profound.

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