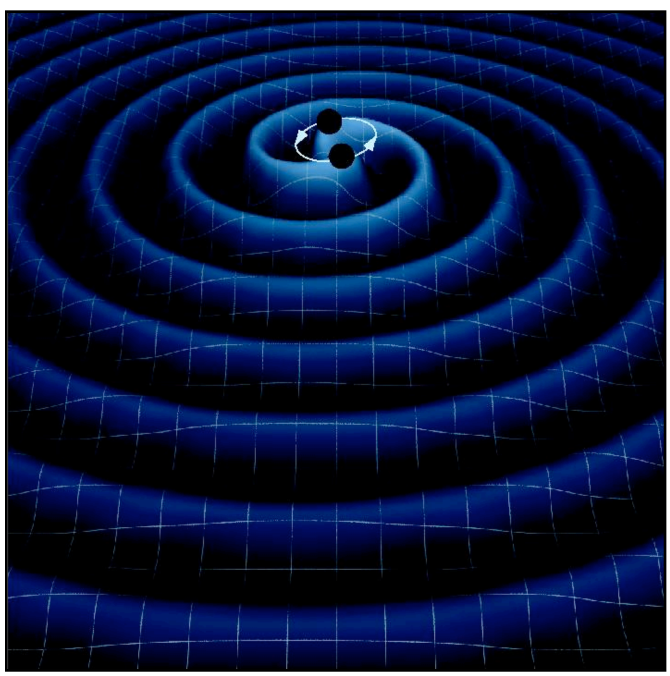
Precision Cosmology with Gravitational Waves

Craig J. Hogan
University of Chicago and Fermilab, +1 630 840 5523, craighogan@uchicago.edu

Bernard F. Schutz, Curt J. Cutler, Scott A. Hughes, and Daniel E. Holz



Measurement of distance underlies much of astronomy and cosmology. An important example is the Hubble constant, which has had a long history of steady refinement (for example, as an HST Key Project) but still has calibration errors of order ten percent. A low frequency gravitational wave detector, such as LISA, has the potential to measure absolutely calibrated distances to individual black hole binary sources with absolute precision better than one percent. Although the number of detected sources is uncertain, the best estimates indicate that a large number of precise distances will be available from LISA--- enough to bring a transformative new tool to precision cosmology.

Precision cosmology characterizes the structure and behavior of the Universe as a whole: its global curvature, its expansion with time, and the behavior of perturbations. The global curvature of space is a relic of the earliest moments of inflation and carries information about the initial conditions of the Universe; cosmic expansion history tests models of the new physics of dark energy; and cosmological perturbations test the dynamical predictions of general relativity on the largest scales. More than simply mapping our Universe, precision cosmology explores in detail the physics of space, time, matter and energy at the opposite extremes to black holes: the lowest density, the largest scales, and the earliest times.

For the most powerful tests we seek not only high precision, but also a variety of different techniques that measure global spacetime in different ways. Precision measurements of cosmic microwave background (CMB) anisotropies (from COBE, balloon- and ground-based experiments, WMAP, and soon, Planck Surveyor), currently set the highest standard of quality: CMB now reliably determines certain combinations of cosmological parameters with precision at a level of a few percent. Combining other types of measurements with the CMB data breaks degeneracies in fundamental quantities, increases reliability by controlling systematic errors, probes recent expansion where dark energy dominates, and allows deeper questions to be asked: for example, whether dark energy varies with time or reflects a need to modify the theory of gravity on large scales (rather than a new form of energy).

Improved precision in measurements of cosmological quantities, such as absolute and relative distances, the power spectrum of density fluctuations, and the growth of structure, have thus emerged as a top priority of cosmological research. Over the next decade several large programs are being carried forward with this goal (Albrecht *et al.* 2006). Each of the proposed techniques has complementary strengths, weaknesses, sources of systematic errors and physical and astronomical assumptions, and thus it is prudent to pursue a balanced program of many approaches.

Science questions

- What is the nature of dark energy?
- What other forms of energy exist?
- How did the Universe begin?
- What is size and shape of the Universe?

A special challenge is calibration of the large-scale cosmos to absolute (ultimately, laboratory) standards of length or time. Such measurements allow globally-measured quantities, such as CMB angles and galaxy redshifts, to be connected to locally-measured quantities, such as the temperature of the cosmic microwave background, cosmic chronometers, and element abundances. Traditionally this absolute calibration employs a cosmic distance ladder: Direct geometrical parallax measurements of nearby stars calibrate indirect measures for larger distances, in a series of steps extending to cosmological scales. This indirect approach adds substantial errors even to the best distance indicators at large distances, such as Type Ia supernovae. Other more direct absolute calibrators (such as geometrical distances to distant megamaser sources) are now being developed but still present major challenges in systematic reliability and precision, and require a variety of assumptions — again, requiring multiple approaches for a robust result.

LISA will add a unique and complementary new tool: absolutely calibrated distances determined by measuring the waves generated by binary black hole inspiral and mergers. Measurement of these inspiral waves makes it possible to directly determine the luminosity distance to a single source with an intrinsic precision that in favorable cases can be as good as 0.1%. (This is the "raw" value we would achieve given only instrumental limitations, if the waves could propagate with no disturbance from source to observer. In reality, effects such as weak gravitational lensing will degrade this precision, by an order of magnitude at large distances.) The intrinsic precision may be higher than any other technique, in some respects even better than the CMB, and it brings an absolute physical calibration, tied directly to laboratory time standards, based on gravity alone, unlike any other technique.

Precise and absolute distances from gravitational waves

Waveforms from black hole binary (BHB) merger inspirals yield absolute distances to high redshift. The individual raw absolute precision for a single event depends on signal-to-noise and other factors, but often is better than one percent. The absolute physical calibration, high per-event precision, and large redshift range all represent new and unique capabilities. A redshift-distance relation with this approach requires an independent electromagnetic estimate of the host galaxy redshift, either statistically or by identifying the host directly. Additional errors are added by weak lensing noise at high z. It is estimated that LISA will measure the Hubble constant and other parameters to better than 1% accuracy, and will probe global curvature and cosmic dark energy with a precision comparable to other methods. The technique complements other methods: their combination provides unique information about the new physics of dark energy, and new tests of concordance cosmology.

Since the BHB technique yields independent and physically calibrated absolute distances it complements other techniques of precision cosmology, many of which yield relative distances only, and all of which use different assumptions with radically different systematic errors and biases from BHBs. Calibration of the absolute distance scale, in combination with CMB measurements alone, and a definite scaling law for the dark energy power-law parameter $w(a)$, allows a determination of w with high precision (Hu 2005, Eisenstein & White 2004). Similarly, a one percent constraint on absolute distance, combined with the CMB data, yields $\sim 10^{-3}$ error on global curvature Ω_k (Knox 2006); in this respect the constraints are similar to those obtainable in the future from Baryon Acoustic Oscillations (Eisenstein *et al.* 2005). With both techniques (that is, BHB and BAO together), fewer assumptions are needed about unknown physics; for example, a new tight constraint can be derived on the density of any invisible relativistic species or "dark radiation" that affects the BAO calibration.

Unique features of black hole binary distances compared with other techniques

LISA's distance measurements to black hole binary (BHB) mergers will independently and precisely measure absolute distances in an entirely new way. Among all the techniques used for cosmological measurement, BHB is unique in several ways, being:

- Physically calibrated assuming only general relativity (no astronomical assumptions about system configuration or environment);
- Absolutely calibrated (a true physical distance in laboratory time units– not a distance ratio to an astronomically defined reference);
- Of very high intrinsic precision (up to 0.1%) for a single event; and
- Useful over a very wide range of redshift (merger events from $z << 1$ to $z \approx 20$).

Even though they are macroscopic systems, black hole binaries are completely characterised by a well understood mathematical model: their gravitational waveforms as they spiral together are known from first principles even better than the properties of atoms in a laboratory experiment. Everything about a detected source can be characterised by seventeen parameters (including distance, direction, and time of merger), and these can be measured directly from the detected waveform. Even with a small number of events, the unique features of black hole binary inspirals – their reliable absolute calibration, inherent precision, and large range in redshifts – introduce a new capability that promises to make all other precision measurements more robust and informative.

The basic principle of estimating distances from measured waveforms is elegantly simple (Schutz 1986): the chirping time τ of inspiral/merger waveform, together with its orbital frequency ω and strain h, gives an absolute luminosity distance $D \approx c/\omega^2\tau h$, with a numerical factor depending on details of the configuration that are precisely determined by the details of the measured waveform. Roughly speaking, the directly measured wave period tells the redshifted final absolute Schwarzschild radius, and the ratio of that length to the luminosity distance is the directly measured metric strain, h.

Note that at cosmological distances, waveform measurements cannot independently determine the redshift of a source. In gravitational wave measurements, the source's intrinsic frequency and chirp time are always measured in combination with cosmic redshift: $\omega = \omega_{int}/(1+z)$, $\tau = (1+z)\tau_{int}$. The redshift is always degenerate with the source's intrinsic parameters, and cannot be determined from the GW data alone. An independent measurement of redshift is therefore needed. This may be accomplished by getting the optical redshift to the host galaxy, for instance by identifying an electromagnetic radiation counterpart to the event (Bloom et al. 2009). Without an identification, it may also be accomplished statistically, by surveying redshifts of galaxies correlated with the host. In reality this promising tool will have limitations. The number and redshift distribution of events that can provide useful distances is uncertain. At large distances, weak gravitational lensing by intervening clustered matter between us and the source introduces significant errors in distance. And depending on the other material present in the vicinity of the merging holes, it may be difficult to identify the host galaxy electromagnetically.

For these reasons, massive black hole binaries, although they are likely to yield the most precise probes of black hole physics and general relativity, may not be the best population to study for precision cosmology. These events work best as cosmic distance measures if we can gather a statistical sample at z less than or of order 1. It is expected however that they are relatively rare and distant, perhaps as rare as about one event per year at z<1, so their distance estimates are significantly affected by gravitational lensing, which adds an error of a few percent at z=1. In addition, their great distance may make the identification of an optical counterpart less certain.

> Precision cosmology with gravitational waves requires electromagnetic data. LISA waveforms provide precise distances, and independent redshift information will be supplied from galaxy surveys in the direction of the sources.

For precision cosmology, less risk attaches to the more numerous population of inspiral events consisting of a compact stellar mass or intermediate mass black hole, or some other compact remnant captured by a massive black hole in a galactic nucleus. For these extremely large mass ratio inspirals (EMRIs), the signal-to-noise ratio and per-event precision are not as good as for binaries with two massive holes. On the other hand these events are likely to be numerous, with many sources at z<0.5. At such a low redshift the errors introduced by gravitational lensing are less than one percent per object.

It has also been demonstrated that at z<0.5, precise and unbiased statistical information about host redshifts can be obtained from galaxy catalogs in the vicinity of the events, so specific individual host galaxy identifications are not needed. The technique is based on the assumption that the BHB host galaxies are correlated with other galaxies. The direction and distance information from a BHB waveform fit provides a 3D ``error box'' for the location of the host galaxy. Depending on the redshift and the fit, there are typically hundreds or even thousands of candidate hosts in this region of space. A galaxy redshift survey in the angular error box allows identification of candidate host galaxies and a 3D map of their distribution. These galaxies are then allowed to “vote” on where the true host redshift is. Because the galaxies are significantly clustered in the cosmic web, the distribution of their redshifts is highly nonuniform within the box. The error in the estimated source redshift is not eliminated, but is significantly reduced by adding this information from the actual spatial galaxy distribution in the direction of a source. A simple version of the technique was shown to yield a high precision estimate of Hubble’s constant using mock catalogs based on Sloan Digital Sky Survey redshift data (MacLeod & Hogan 2008).

The rate of EMRIs is highly uncertain, because of required extrapolation to nuclear stellar populations in galaxies where we have very limited information at present. Studies however estimate that LISA will measure thousands of EMRI events to z of the order of unity (Gair et al. 2004), enough to enable extensive statistical use of gravitational wave distances.

Gravitational waves from black hole inspirals, in conjunction with electromagnetic observations, may profoundly transform precision cosmology.

Albrecht A, *et al*. 2006 "Report of the dark energy task force" astro-ph/0609591

Bloom, J S *et al*. 2009, "Coordinated Science in the Gravitational and Electromagnetic Skies", arXiv:0902.1527

Dalal N, *et al.* 2006 "Short GRB and binary black hole standard sirens as a probe of dark energy" *Phys Rev D* **74**, 063006

Eisenstein D, White M 2004 "Theoretical uncertainty in baryon oscillations" *Phys Rev D* **70**, 103523

Eisenstein D, *et al*. 2005 "Detection of the baryon acoustic peak in the large-scale correlation function of the SDSS luminous red galaxies" *ApJ* **633**, 560–574

Freedman W, *et al.* 2001 "Final results from the Hubble Space Telescope key project to measure the Hubble constant" *ApJ* **553**, 47–72

Gair J R, Barack L, Creighton T, Cutler C, Larson S L, Phinney E S & Vallisneri M, *Class. Quantum Grav.* **21**, S1595 (2004)

Holz D E, Hughes S A 2005 "Using gravitational-wave standard sirens" *ApJ* **629**, 15–22

Hu W 2005 "Dark energy probes in light of the CMB" in Observing Dark Energy, Eds Wolff S, Lauer T, ASP Conf Ser **399***,* 215

Knox L 2006 "On precision measurement of the mean curvature" *Phys Rev D* **73,** 023503

Kocsis B, Frei Z, Haiman Z, Menou K, 2006, "Finding the Electromagnetic Counterparts of Cosmological Standard Sirens," *ApJ* 637, 27

Lang R, Hughes S 2006 "Measuring coalescing massive binary black holes with gravitational waves: The impact of spin-induced precession" *Phys Rev D* **74**, 122001

MacCleod C L, Hogan C J 2008, "Precision of Hubble constant derived using black hole binary absolute distances and statistical redshift information," *Phys. Rev. D* 77, 043512 (2008)

Schutz B 1986 "Determining the Hubble constant from gravitational wave observations" *Nature* **323**, 310–311