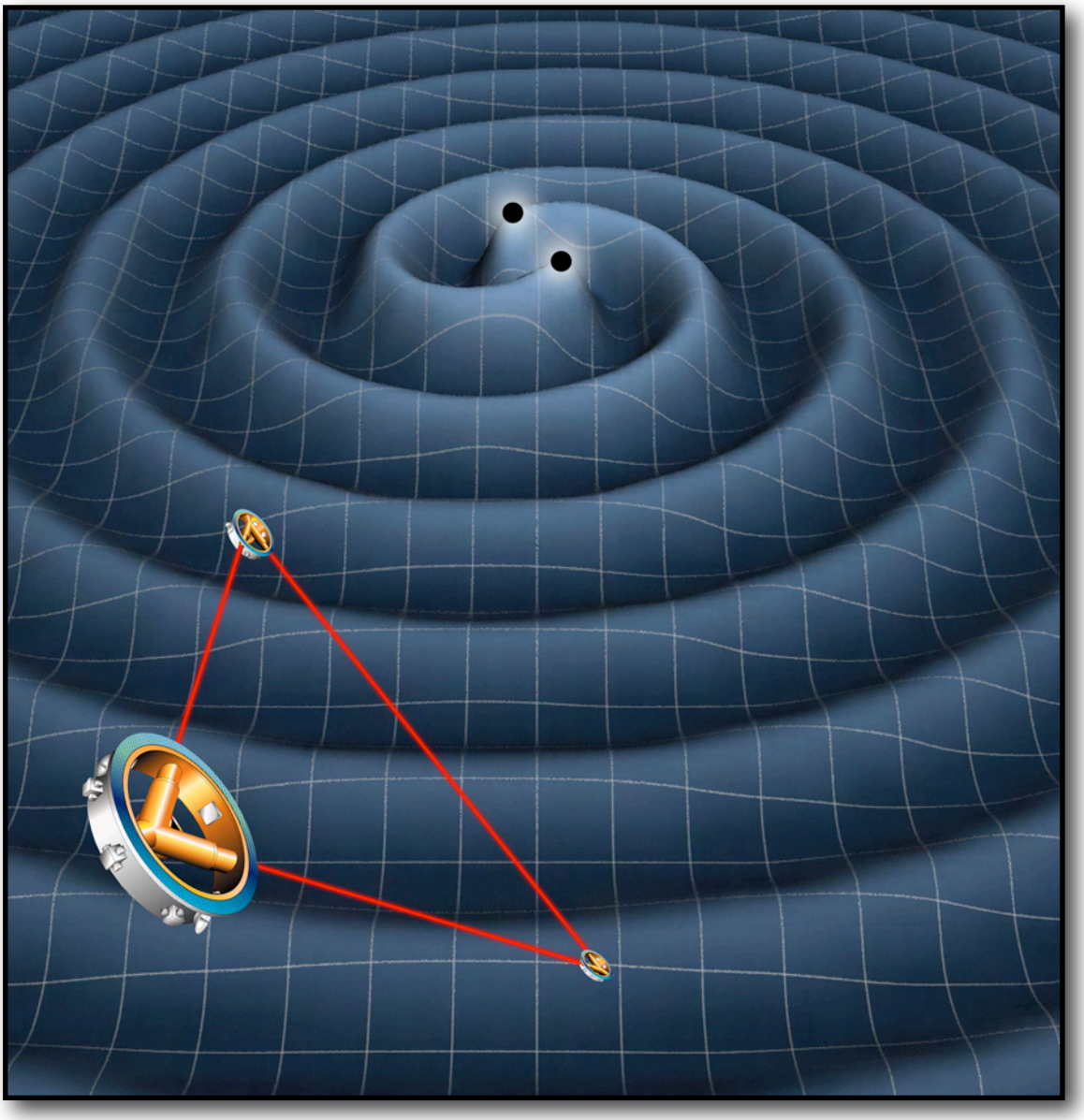
LISA: Probing the Universe with Gravitational Waves



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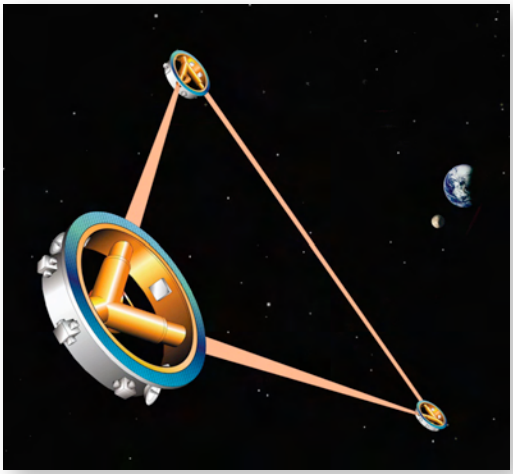
Executive Summary

The New Science of Gravitational Waves

Einstein's theory of spacetime and gravity, general relativity, predicts that motions of mass produce propagating vibrations that travel through spacetime at the speed of light. These gravitational waves (as the vibrations are called) are produced abundantly in the Universe and permeate all of space[1]. Measuring them will add an altogether new way to explore what is happening in the Universe: rather than studying the propagation and transformation of conventional particles and fields in spacetime, as all science has done up to now, we will sense vibrations of the fabric of spacetime itself. Studying this new form of energy will convey rich new information about the behavior, structure, and history of the physical universe, and about physics itself. When gravitational waves become observable they will provide a new and uniquely powerful probe of the extremes of spacetime, from the Big Bang to black holes, to address the deep questions that have emerged in Einstein's vision of the cosmos: what powered the Big Bang, what happens to space and time in black holes and what is the mysterious dark energy accelerating the expansion of the Universe?

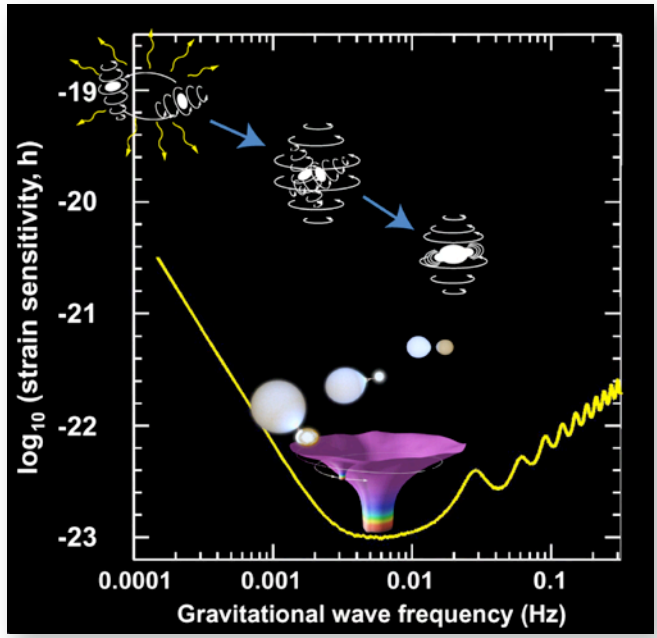


LISA is a space mission designed to measure gravitational radiation over a broad band at low frequencies, from about 0.1 to 100 millihertz, a band where the Universe is richly populated in strong sources of gravitational waves. It measures signals from a wide range of different sources: massive black holes merging in galaxies at all distances; massive black holes consuming smaller compact objects; known binary compact stars and stellar remnants; members of known populations of more distant binaries; and probably other sources, possibly including relics of the extremely early Big Bang, which are as yet unknown. These strong signals convey detailed information addressing a wide range of science: the history of galaxies and black holes in the Universe; general relativity itself and the behavior of spacetime; precision measurements of the Universe as a whole; the physics of dense

[1] Gravitational waves have never been directly detected. Nevertheless, the existence of gravitational waves is in little doubt as their effects have been measured precisely, if indirectly. Any theory of gravity consistent with special relativity will exhibit gravitational waves, and the predictions of general relativity should be quantitatively reliable for LISA because the long standing best evidence for of gravitational waves is the orbital decay of the Hulse-Taylor binary pulsar, which radiates at frequencies only marginally below LISA's operating band. Moreover, LISA is sensitive to any time-dependent tidal gravitational force, even to those of Newtonian theory produced by, say, the Sun. Therefore LISA will be able to detect the gravitational waves predicted by any reasonable theory of gravity.

matter and stellar remnants; and possibly new physics associated with events in the early Universe or relics predicted in string theory.

In the same way that electromagnetic radiation accompanies acceleration of electric charges, gravitational radiation accompanies quadrupolar acceleration of any kind of mass or energy. Quadrupolar motion in a system with mass M and size R at a distance D typically perturbs spacetime with a dimensionless metric-strain amplitude (fractional variation in proper spatial separations) of about $h \approx \left(GM/(Rc^2)\right)^2 (R/D)$. LISA senses this by monitoring the changes in the distances between inertial proof masses. LISA uses precision laser interferometry across a vast distance of space to compare separations among proof masses that are protected by the spacecraft from non-gravitational disturbances. Over a separation of $L \approx 5$ million kilometers, LISA's ability to measure variations of $\Delta L \approx 0.05$ picometers (rms over one year observation) corresponds to a strain amplitude sensitivity of about $h \approx \Delta L/L \approx 10^{-23}$. LISA *coherently* measures spacetime strain variations, including frequency, phase, and polarization, all of which reflect large-scale properties of the systems that produce them and are therefore direct traces of the motions of distant matter.



The LISA strain sensitivity curve showing approximate frequency range and strain amplitude of three categories of sources: massive black hole inspiral, ringdown, and merger (uppermost source); ultra-compact Galactic binaries (middle source); capture of stellar mass compact object by massive black holes (lower source).

LISA is an astronomical observatory of unprecedented versatility and range. Its all-sky field of view ensures that it misses nothing. Its coherent mode of observing allows it to resolve and distinguish overlapping signals and locate them on the sky. Its dynamic range of 10^5 or more in amplitude (10^{10} in energy) allows it to study sources within the Galaxy and out to the edge of the Universe. Finally, LISA's wide frequency band (more than three decades) allows it to study similar sources of widely different masses and cosmological redshifts. Because gravitational waves penetrate all regions of time and space with almost no attenuation, LISA can sense waves from the densest regions of matter, the earliest stages of the Big Bang, and the most extreme warpings of spacetime near black holes.

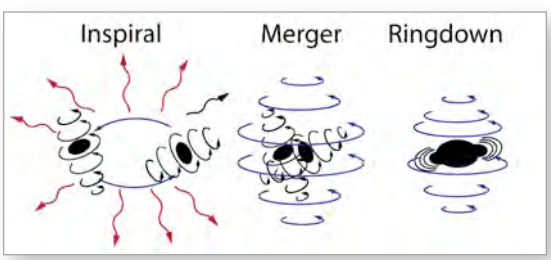
Survey of LISA Science

We now provide a brief survey of the key scientific measurements that LISA will perform. These measurements address the basic scientific goals of the LISA mission, which are captured formally in the LISA Science Objectives listed in the first appendix. The scientific background for the LISA science measurements and objectives is discussed extensively in the various sections of this document.

LISA records the inspirals and mergers of binary black holes, the most powerful transformations of energy in the Universe, allowing precision measurements of systems composed only of pure dynamical spacetime.

The strongest gravitational waves are generated by systems with the largest gravitational fields GM/R, hence large masses and small sizes. The strongest of all are generated by interactions of black holes, dense knots of pure spacetime energy with $GM/Rc^2 \approx 1$. At LISA frequencies the strongest sources are massive black hole binaries with about 10^4 to 10^7 times the mass of the sun. Two black holes orbit each other, spiral together as they lose energy by radiation, and finally merge. The waves from these events — many cycles over a long inspiral, climaxing in a brief series of powerful waves during a violent merger, and a final ringdown to a quiescent single black hole — record dynamical general relativity not only in its purest form but also in its most violent, nonlinear behavior: a maximally warped vacuum spacetime interacting with itself.

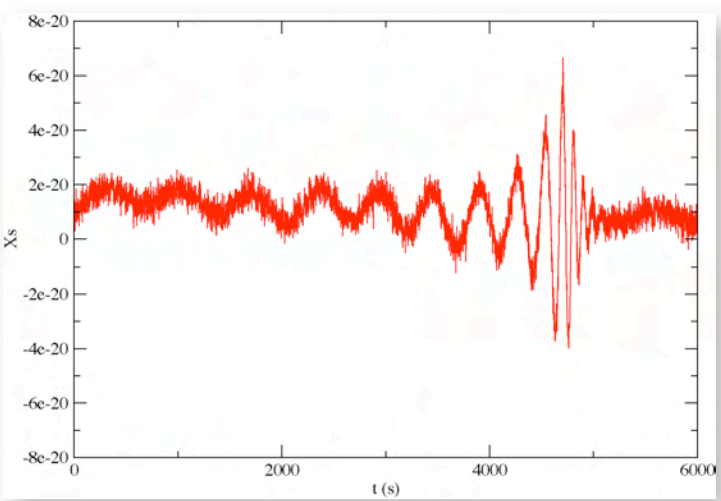
The black hole binaries start with wide orbits at low frequencies. As they lose energy their frequency increases and their radiation strengthens. A typical source enters the LISA band a year or more before the final merger so many orbits are recorded, encoding details of the system properties and behavior, position on the sky, and absolute distance. The coherent phase and polarization information obtained over LISA's solar-orbit baseline (and variable inclination) can often pinpoint where a source is in the sky to better than a degree. In the last hours or minutes the signal-to-noise ratio grows very high, often into the hundreds to thousands depending on distance. At its peak luminosity, around the moment of merger, a black hole binary is the most extreme transformation of mass-energy of any kind in the Universe, radiating a power $\approx 10^{-3}c^5/G$ (or ~10^{49} watts), in a few wave cycles, for a time of about 100 GM/c^3. This peak radiated power is about 1000 times more than all the stars in the visible Universe. The merger throes of a million solar mass binary black hole merger last about 500 seconds. Massive black hole binary inspiral and merger events are such powerful radiators that LISA can detect them anywhere, out to the largest redshifts where galaxies might exist.



The detailed study of waveforms from black hole binaries provides a rich testbed for general relativity. Recent breakthroughs now allow numerical computation of Einstein's field equations throughout the entire inspiral and merger event, yielding a detailed map of the predicted gravitational waveform that will be the first detailed test of dynamical, strong-field general relativity. Waveforms coherently correlated over many orbits (from ≈ 10 to ≈ 1000 depending on mass and redshift) recorded in the LISA signal stream, and detection of events with a signal to noise of a thousand or more, allow precise tests of the theory as well as precise measurements of system parameters to a precision of order 10^{-2} to 10^{-3}. Comparison with the computed details of the inspiral and merger waveform will provide a powerful test of the binary black hole model assumed for these systems.

LISA will map isolated black holes with high precision, verifying whether they are the stationary "no hair" spacetime configurations described by the Kerr metric, completely specified by four numbers: the mass and three components of spin.

In general relativity the final isolated spinning black hole is described mathematically as a particular, precisely specified spacetime shape called a Kerr metric, that depends only on the physics of gravity and not at all on the history or environment of the black hole. Comparison of the ringdown waveform with theory can verify that the final black hole which arises from a merger is indeed described by the Kerr solution, and satisfies the "no hair" theorem of general relativity that states that an isolated, stationary black hole is completely specified by its mass, charge and angular momentum. The LISA signals during the merger phase are so strong that the signal-to-noise ratio is often greater than 100 even in one oscillation cycle: signal waveforms are visible on an oscilloscope type display of raw data even to the naked eye, so even if general relativity were to be wrong at the levels allowed by our existing tests (*e.g.* the double binary pulsar J07037-3039) we would be able to use LISA data to make sense of what is happening.



Gravitational wave signal for the final few orbits, plunge, merger and ringdown of a massive black hole binary. The signal is the sum of the gravitational waveform and simulated LISA noise. Note that the waveform stands up well above the noise and is visible in fine detail. A merger event such as that shown here can have a total signal to noise of 200 even at a redshift, z = 15.

LISA also uses a second type of source to explore the spacetime near a massive black hole. Driven by chance encounters, a much smaller mass compact objects — such as a degenerate dwarf, neutron star or stellar-mass black hole — sometimes finds itself captured by the massive black hole, after which it orbits many times until it

finally plunges into the horizon and disappears. The gravitational waves from these extreme mass ratio inspirals (EMRIs) encode a detailed map of a relatively unperturbed massive black hole, predicted to be a pure Kerr knot of highly curved, spinning spacetime. About 10^5 wave cycles are measured for each source, emitted from orbital paths exploring deep into different parts of the relativistic region near the massive black hole. The specific mass quadrupole and higher moments predicted by the Kerr solution are measured with a precision of about 10^{-4}, and precision tests of small variations about the equilibrium Kerr solution — the small amounts of "hair" added by the perturbing object — are measured at the one percent level. Gravitational waves from these events map in exquisite detail the cleanest and most accurately predicted structures in all of astrophysics, whose mathematical elegance Chandrasekhar once likened to that of atoms.

A small compact object orbiting a spinning massive black hole.

LISA directly observes how massive black holes form, grow, and interact over the entire history of galaxy formation.

Optical, radio and x-ray astronomy have produced abundant evidence that nearly all galaxies have massive black holes in their central nuclei (and indeed that some recently merged galaxies even have two black holes). These nuclear black holes have a profound effect on galaxy formation; the influence of black hole powered jets on the intergalactic gas out of which galaxies form is in some cases directly observed. There is a circumstantial case, but no direct evidence, that the formation of this population of black holes was associated with a multistage process of binary inspiral and merger, together with accretion. LISA will obtain direct and conclusive evidence and study details of this process via gravitational radiation.

In standard concordance cosmology, the first massive black holes naturally arise from the very first, supermassive stars. In this scenario, black hole binaries begin to form from a high redshift, $z \approx 20$, when galaxies start to assemble by a series of (hundreds to thousands of) hierarchical mergers of smaller protogalaxies. When two galaxies merge into one, their central black holes sink to the center of the new galaxy, find each other, inspiral and merge. There are so many galaxies forming in the Universe observed by LISA that mergers happen quite frequently: estimates based on standard galaxy formation theory suggest that if black holes indeed grew by hierarchical merging, LISA detects a merger event about once or twice every week on average, from a wide range of redshifts extending back to massive binaries in early protogalaxies at $z \approx 15$. At any given time, in addition to the actual mergers, these models predict that LISA observes inspiral signals from hundreds of binaries in the final years before their merger. LISA digs directly and intimately into the detailed evolution of galactic nuclei: the large sample of binaries provides a direct record of the whole history of galaxy formation in the observable Universe, and of the processes that grew their central black holes and shaped their nuclei.

In addition to mergers of massive black holes, LISA will also observe the inspiral of stellar mass black holes into the massive black holes in the centers of normal galaxies. These are the extreme mass ratio inspiral events (EMRIs) mentioned earlier. The parameters measured from extreme mass ratio events yield a census of isolated massive black hole spins and masses in many galaxies today, a revealing relic of black hole history. The local universe also produces observable inspirals of less compact stars and stellar remnants that probe the rich astrophysics near the massive central black holes as they consume piecemeal the various stellar populations in their vicinity.

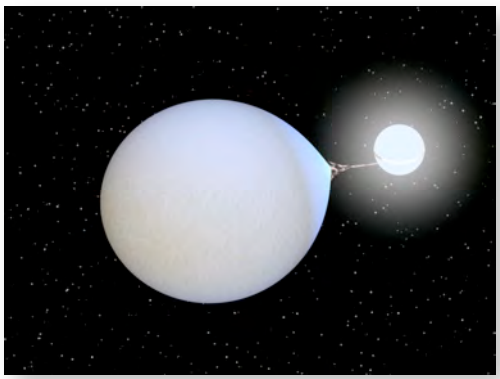
LISA measures precise, gravitationally-calibrated absolute luminosity distances to high redshift, with the potential of contributing uniquely to measurement of the Hubble constant and dark energy.

Because the inspiral leading up to the merger is a clean, pure vacuum spacetime system of two black holes, properties of the radiation can be computed exactly in general relativity, so that the black hole masses, spins, orientations and even the exact distance can be reconstructed from LISA data. (Roughly speaking, the final wave cycle period tells the final absolute Schwarzschild radius, and the ratio of that length to the distance is the metric strain, h.) These inspiral distances are both individually precise and absolutely calibrated, using only pure gravitational physics, and they cover a wide range of redshift. In the absence of lensing effects the absolute physical luminosity distance to a single LISA inspiral event is typically estimated from the waveform alone with on the order of one percent precision, and in some cases with as good as 0.1% precision. If identification of the host galaxy[2] allows an independent redshift determination, the redshift-distance relation is also measured with high precision. Black hole binaries thus represent a unique and independent new capability for precision cosmology that complements other techniques. Even a small number of sources at moderate redshift calibrates the distance scale and Hubble constant an order of magnitude better than any current method — a powerful constraint on dark energy models in combination with microwave background data. The expected large sample of high redshift inspiral events may lead to measurements of dark energy parameters comparable in precision to other methods, but with independent calibration and completely different systematic errors. The main source of error, especially at high redshift, is the noise induced by cosmic weak gravitational lensing along the line of sight, but in a statistical sample this is controllable, and indeed provides unique new information about the nature and clustering of dark matter over time.

[2] LISA's waveform fitting can often pinpoint the direction of a source to much better than a degree, and the distance estimate also narrows the redshift range considerably; nevertheless there may be many thousands of galaxies in the LISA "error box" for a given source. Models suggest that the host may be identified from a telltale nuclear starburst associated with the merger, or from variability associated with the disrupted disks around the merging holes, but galaxy nuclei are too little understood to make a firm prediction. Study of LISA electromagnetic counterparts may provide an exploratory bonanza for wide field synoptic imaging and spectroscopy across the electromagnetic spectrum, but it is also possible that identification of hosts will prove elusive.

LISA studies in detail thousands of compact binary stars in the Galaxy, providing a new window into matter at the extreme endpoints of stellar evolution.

In addition to mergers and meals of distant black holes, LISA detects many lower mass binary systems in our galaxy, mostly very compact remnants of normal stars, called white dwarfs. Very soon after turning on, LISA will quickly detect a handful of nearby binary compact stars already studied and named. These "verification binaries" provide sources with known positions and periods ensuring particular, predictable LISA signals. Signals are also certain to appear from populations in our galaxy of numerous and various remnants, including white dwarfs and neutron stars, which are known to exist from some that emit electromagnetically. Simple extrapolation of known nearby samples to the whole Galaxy predicts that LISA will detect thousands of binaries. The most compact binaries (those at high frequency) will be measured in detail as individual sources from across the Galaxy, while at lower frequencies only the nearby ones will be individually distinguished; millions of others from across the Galaxy will blend together into a confusion background. LISA provides distances and detailed orbital and mass parameters for hundreds of the most compact binaries, a rich trove of information for detailed mapping and reconstruction of the history of stars in our galaxy, and a source of information about tidal and other non-gravitational influences on orbits associated with the internal physics of the compact remnants themselves. LISA may also detect at high frequencies the background signal from compact binaries in all the other galaxies.



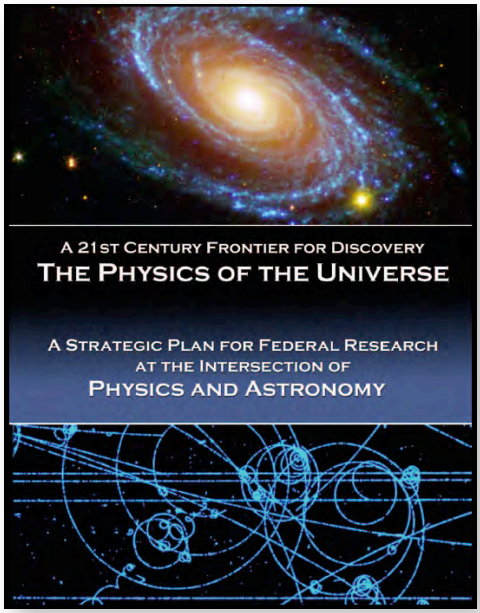
LISA may find entirely new phenomena of nature not detected using light or other particles.

Given that all forms of mass and energy couple to gravity, other sources of gravitational waves may exist that are not known from extrapolating current electromagnetic observations. LISA's frequency band can indeed be extrapolated to very high redshift where we do not yet have any direct observations, and to a regime where LISA itself will be our first information of any kind about the nonlinear behavior and motion of matter. For example, the LISA frequency band in the relativistic early Universe corresponds to horizon scales at the Terascale frontier, where phase transitions of new forces of nature or extra dimensions of space may have caused catastrophic, explosive bubble growth and efficient gravitational wave production. LISA is capable of detecting a stochastic background from such events from about 100 GeV to about 1000 TeV, if gravitational waves in the LISA band were produced with an overall efficiency more than about 10^{-7}, a typical estimate from a moderately strong relativistic first-order phase transition. This corresponds to times about 3×10^{-18} to 3×10^{-10} seconds after the start of the Big Bang, a period not directly accessible with any other technique. Reaching much further still beyond the range of any particle accelerator, LISA also deeply probes possible new forms of energy such as cosmic superstrings, relics of the early Universe predicted in some versions of string theory, that

are invisible in all ways except by the gravitational waves they emit. In principle, their signature could provide direct evidence for new ideas unifying all forms of mass and energy, and possibly even spacetime itself.

LISA and the Key Questions of Astronomy and Physics

LISA addresses forcefully and directly a broad cross-section of the research priorities and key questions raised by recent astronomy and physics decadal, community, agency and White House reports. These include National Research Council reports such as *Astronomy and Astrophysics in the New Millenium* and *Connecting Quarks with the Cosmos*, as well as the National Science and Technology Council report *A 21st Century Frontier of Discovery: The Physics of the Universe*.



LISA approaches many deep questions set forth in these documents in a new and unique way not possible with any other space- or ground-based observatory. Indeed, LISA has the potential to transform much of physics and astronomy: it senses the remote Universe in an entirely new way, and explores many new kinds of phenomena that can be explored in no other way. Its discoveries are likely to expand the scope of both astronomy and physics significantly and to reshape the science questions of the future. By directly sensing the dynamical activity of spacetime, LISA feels the beating heart of Einstein's cosmos. The new science of gravitational waves provides the most direct way to advance the goals of NASA's Beyond Einstein program.

1. Gravitational Waves: An Overview

Most everything we know about the Universe we have learned from *light*: since ancient times, electromagnetic waves have been messengers from the cosmos to our eyes, and later to our telescopes and our antennas. More recently, we have begun to parse the messages of more exotic carriers like the elusive neutrinos from the Sun and beyond. We are now ready to add an altogether new modality to science: sensing vibrations of the very fabric of spacetime. *Gravitational waves* will add a many-voiced soundtrack to the rich imagery of the cosmos (see Hogan 2006).

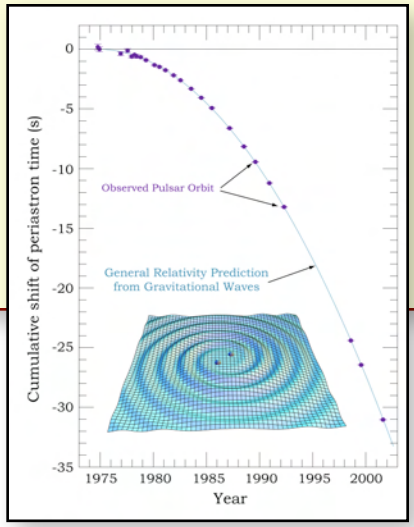
In 1967, the first radio pulsar was discovered by Jocelyn Bell and Anthony Hewish (for which Hewish received the Nobel Prize in 1974). Pulsars were quickly identified as neutron stars, the incredibly compressed remnants of the supernova explosions of main-sequence stars.

In 1974, Russel Hulse and Joseph Taylor discovered the first binary pulsar, PSR 1913+16. This system consists of two neutron stars (of which only one emits as a pulsar) with an orbital period of eight hours. The general theory of relativity predicts that the orbiting stars stir spacetime around them, losing energy by emitting gravitational waves and therefore spiraling closer together.

In 1993, Taylor and Hulse received the Nobel prize for showing that the orbital period of PSR 1913+16 is decreasing at exactly the rate predicted by Einstein's "quadrupole formula" for the emission of gravitational waves in binaries.

In 2004, an international team of astronomers announced the discovery of PSR J0737-3039A/B, a *double* binary pulsar of two neutron stars, both of which emit detectable radiation. This system is a unique general-relativistic laboratory: timing studies of its emissions over 2.5 years have already improved on some of the most stringent tests of general relativity from other binary pulsars and from Solar-system dynamics (Kramer *et al.* 2006).

The gravitational waves from neutron binary stars await direct detection by LISA and by ground-based detectors.



Precession of periastron in PSR 1913+16 as measured in 27 years of radio data and as predicted by general relativity.

In Einstein's 1915 theory of general relativity, the geometry of spacetime is not a passive setting for the dynamics of matter and energy, but an equally dynamic player. Matter and energy cause spacetime curvature, which in its turn guides the free fall of matter and energy. Remarkably, spacetime can support curvature without any matter: *black holes*, the densest masses in the Universe, are objects of pure spacetime wrapped around itself; *gravitational waves* are self-sustaining, undulatory excitations of spacetime, carrying energy and traveling at the speed of light. Unlike electromagnetic radiation (but much like neutrinos) gravitational waves interact very weakly with matter, and can penetrate anything without losing intensity. This makes them powerful probes of faraway regions and extreme conditions, but it also makes them very hard to detect. Only recently has technology advanced to the point of building apparatus sensitive enough to measure the minute effects of gravitational waves on matter.

Gravitational waves will reveal the most violent events in the Universe, the collision and coalescence of two black holes. In the final minutes before the merger, the power radiated in gravitational waves reaches 10^{49} W, a thousand times more luminous than all the stars in all the galaxies in the visible Universe put together. These mergers will allow us to test how well Einstein's equations work in such extreme conditions, offering us insight into the strongest and most violently dynamic spacetimes Nature has produced since the Big Bang.

Gravitational waves produce tiny oscillations in the distance between *freely-floating* masses isolated from all forces other than gravity; these oscillations can be monitored using laser interferometry. This principle is implemented in the ground-based Laser Interferometer Gravity-wave Observatory (LIGO), funded by NSF. LIGO and similar observatories worldwide will likely make the first detection of gravitational waves at relatively high frequencies, between 1 and 1000 Hz. The *Beyond Einstein* Great Observatory LISA will be sensitive in a broad band at much lower frequencies, between 0.1 and 100 mHz. It will detect entirely different sources, in great numbers, and with exquisite precision.

With LISA we will observe the coalescence of the massive black holes at the centers of merging galaxies; the radiation from thousands of individual ultra-compact binaries in our galaxy; the infall of small black holes, neutrons stars, and white dwarfs into the massive black holes at galactic centers. These sources will provide rich astrophysical information about the evolution of galaxies and stars, and they will serve as unique laboratories for precision measurements that may lead to new insights into fundamental physics and cosmology. In addition to these well-known astrophysical sources, LISA will search for gravitational waves from the very early Universe, as well as Big Bang remnants such as cosmic superstrings.

What are gravitational waves?

Electromagnetic (EM) waves are self-sustaining oscillations of the electric and magnetic fields, propagating through spacetime. By contrast, gravitational waves (GWs) are oscillations of spacetime itself (see Thorne 1987 and Flanagan & Hughes 2005 for reviews). Einstein predicted GWs shortly after developing his theory of general relativity (GR), but the first experimental verification of their existence had to wait over 60 years, until the binary pulsar observations by Hulse and Taylor starting in 1974 (see sidebar on the previous page).

According to GR, GWs propagate at the speed of light, acting *tidally* by stretching and squeezing any extended distribution of matter or energy through which they pass. This warping action is transverse to the direction of wave propagation. GWs contain two dynamical degrees of freedom, which can be identified in the "+" (plus) and "×" (cross) polarizations, corresponding to the axes associated with the stretching and squeezing. For instance, as depicted in Figure 1-1, a pure "+" polarization squeezes along the x axis and stretches along the y axis, and then vice-versa one half-cycle later.

Just as EM waves are generated by accelerated charges, GWs are generated by accelerated masses. Because of charge conservation, an oscillating charge dipole is the lowest-order time-

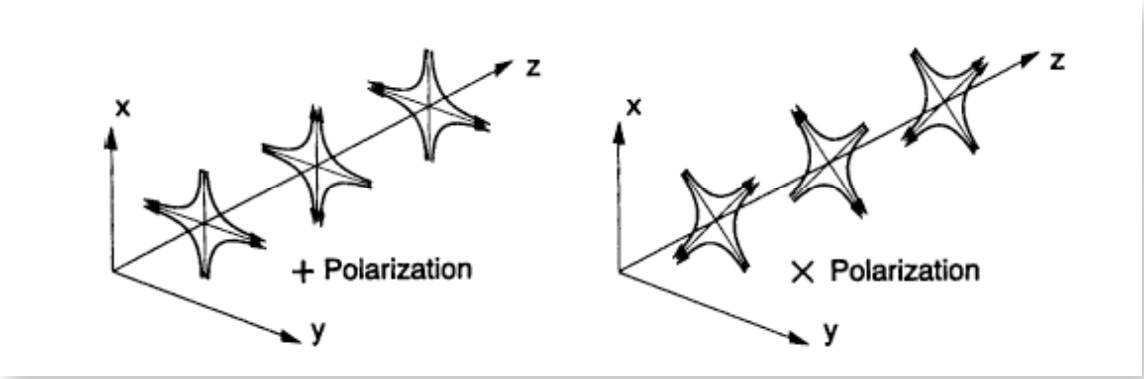
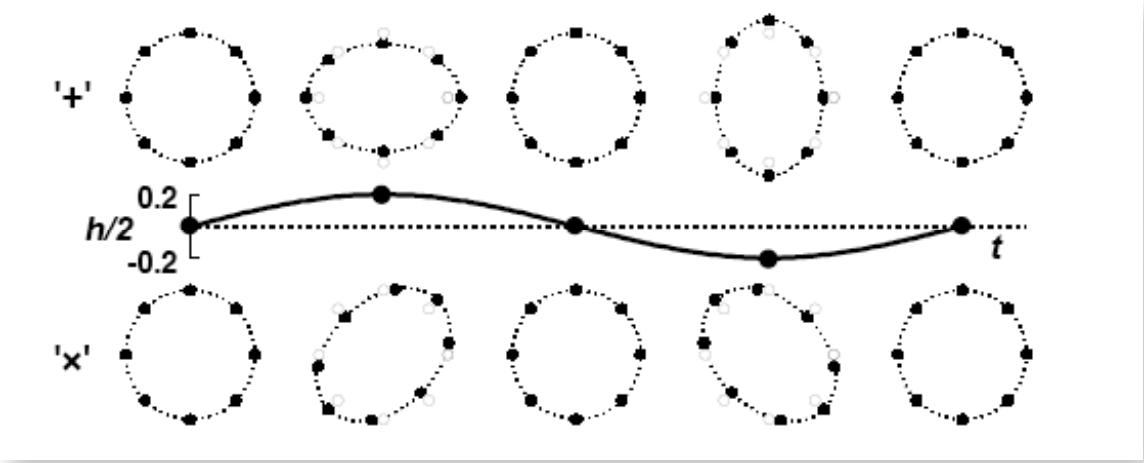


Figure 1-1: The effect of linearly polarized gravitational waves is to alternately stretch and squeeze the intervening matter and energy in perpendicular directions, as visualized here by the motions of a set of freely-floating *test* particles (*i.e.*, bodies small enough that their own gravitational field is negligible).



dependent distribution that can produce EM waves; because of mass and momentum (*i.e.*, mass dipole) conservation, a variable mass *quadrupole* is needed to produce GWs. (Technically it is the second time derivative of the transverse-traceless part of the quadrupole moment that generates GWs.)

EM waves arise from the interactions of atoms, nuclei, or other particles within astrophysical sources and they are typically generated in numerous individual emitting volumes, much smaller than the astrophysical object of interest, so the wavelength of radiation is also much smaller than the object. For this reason, EM waves permit us to image the object if it is close enough or big enough. But the short wavelength has a disadvantage: we typically receive an incoherent superposition of radiation from many independent regions in the source, and if the source is not close enough to resolve, then it is often a difficult and uncertain job to model the emission process well enough to go from the information we get about many different wavelength-scale regions up to the much larger scale of the entire astrophysical system.

By contrast, GWs are generated by the bulk mass distribution of the objects, so the wavelength of GW radiation is typically comparable to or larger than the size of the entire emitting

region. (For instance, for two black holes orbiting each other and losing energy by gravitational radiation, the wavelength of the GW radiation is 10 or 20 times the radius of the orbit.) Thus, GW observations do not generally allow imaging, and the extraction of information from waveforms proceeds with audio-like methods such as time–frequency analysis. Because GW radiation is emitted coherently from the entirety of the astrophysical object, it provides *direct* information about the object's large-scale structure. Moreover, GW observations allow us to extract information from the *phase* of the wave as well as its amplitude or intensity. The phase evolution often carries more information about the detailed dynamics of the emitter than the amplitude does.

An astronomical observatory for GWs has very different characteristics from observatories of EM radiation. It will help to understand the range and versatility of LISA's observations as described in this document if we make some of these differences explicit.

First, LISA has a large intrinsic dynamic range: it could in principle measure accurately signals over an amplitude range of 10^5 or an energy range of 10^{10}. This is because it measures tiny changes in separations between the proof masses and therefore always operates in a linear regime. LISA is designed to study sources well below its mean noise level (extracting them by matched filtering) up to the strongest expected sources in the Universe.

Second, LISA has a very large frequency range, spanning four decades, limited by its size and by the difficulty of isolating the proof masses at low frequencies. This means that, unlike optical, ultraviolet, or infrared observatories, LISA is less likely to miss distant sources because they are cosmologically redshifted to lower frequencies: indeed, it will be able to study homogeneously populations of objects out to the highest redshifts.

Third, LISA has all-sky acceptance of signals; it sweeps three different quadrupolar antenna patterns across the sky as it orbits the Sun, so that its sensitivity for all but the shortest transient sources is fairly isotropic. Unlike any imaging EM observatory, LISA is not pointed, so it does not miss any signals if they are above its noise level. This is particularly important because it allows LISA to detect strong transient events like black hole coalescences without having to point at the source; the strongest events in the Universe are necessarily transient, because they radiate far too much energy to be sustained in a steady state. Although LISA is an all-sky detector, it can nevertheless reconstruct event positions through its data analysis, by using phase modulation (Doppler effects) and amplitude modulation, which are available to it because it makes coherent observations. LISA can also separate thousands of simultaneously superimposed signals because it uses phase information to resolve them, so its all-sky acceptance does not lead to confusion except where there are really huge numbers of sources.

Finally, because GWs interact very weakly with matter, LISA is not troubled by absorption, scattering, or obscuration in any of its observations. The best illustration of this is in its search for a cosmological background of radiation from inflation: LISA can in principle see right back to the end of the inflationary epoch, through all stages of decoupling, symmetry breaking, and particle creation. GWs will also give us our deepest views of the interiors of very dense environments, our only direct information about black holes, leading to their unequivocal identifica-

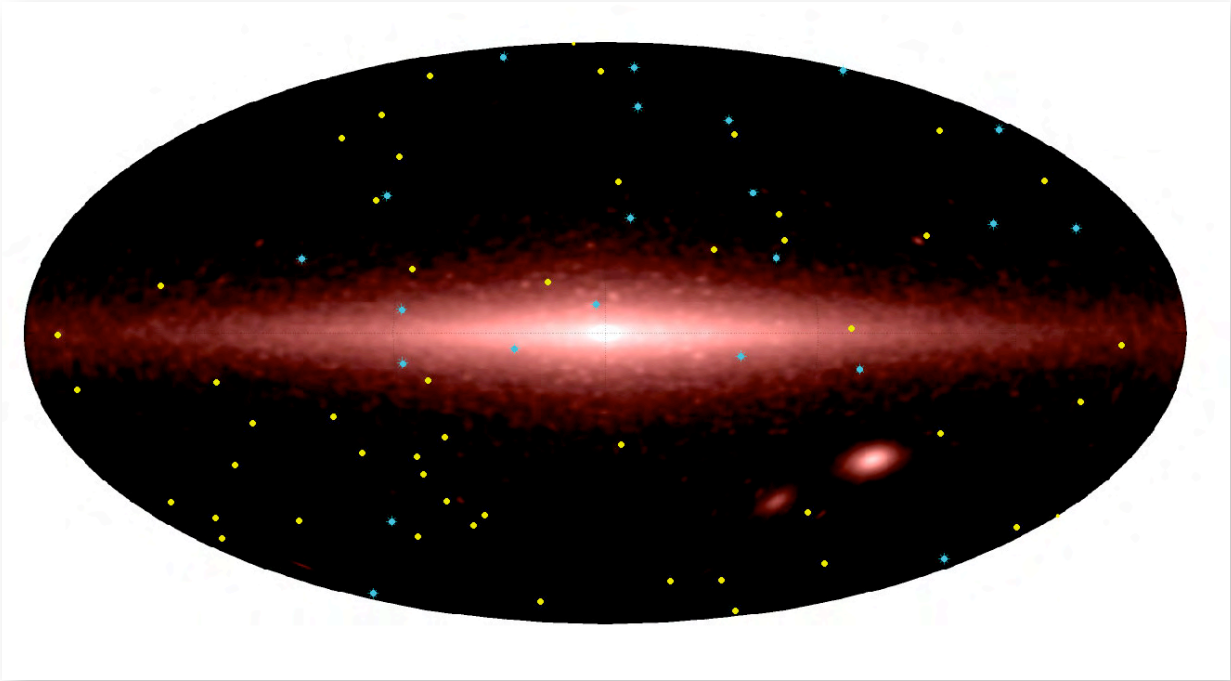


Figure 1-2: Simulation of the gravitational wave sky in the LISA band. The plane of the Galaxy is clearly visible as a horizontal band of emission from the population of compact white dwarf binaries. Also visible are the Magellanic clouds. Massive black hole mergers and the capture of compact objects by massive black holes, which are temporary events, are indicated by yellow and blue symbols.

tion, and to our first possibility to observe any possible structures in the electrically uncharged dark matter in the Universe.

We also note that the GW observable is the amplitude of the wave (or *wave strain*) h, the fractional amount of the stretching and squeezing discussed above. The amplitude h falls off only as $1/r$. A consequence is that strong sources of GWs (such as the binary inspirals of massive black holes, which LISA will see with amplitude signal-to-noise ratios ~ 1000 at a redshift $z = 1$), can essentially be detected out to arbitrarily large redshifts.

The distinctive characteristics of GWs ensure that they will provide a unique new channel to study the Universe, complementing information gathered over decades from EM channels, and probing previously inaccessible dense and dark regions of the Universe. The potential for discovery and surprise is great.

The gravitational wave Universe in the LISA band

Although GWs have not been detected yet, we know enough about the contents of the Universe to make reasonably accurate guesses about some of the GW sources that LISA will observe (see Hughes 2003 & 2006 for reviews). As discussed earlier, in the same way that accelerated electric charges generate EM radiation, accelerated mass and energy of any kind generate gravi-

tational radiation. The periodic motion of a system of mass M and size R creates GWs at a distance D with a strain amplitude of about $h \approx \left(GM/(Rc^2)\right)^2 (R/D)$, with frequency determined by the frequency of the motion. The shapes and strengths of the observed waves give us details about the structure and behavior of the system that produced them.

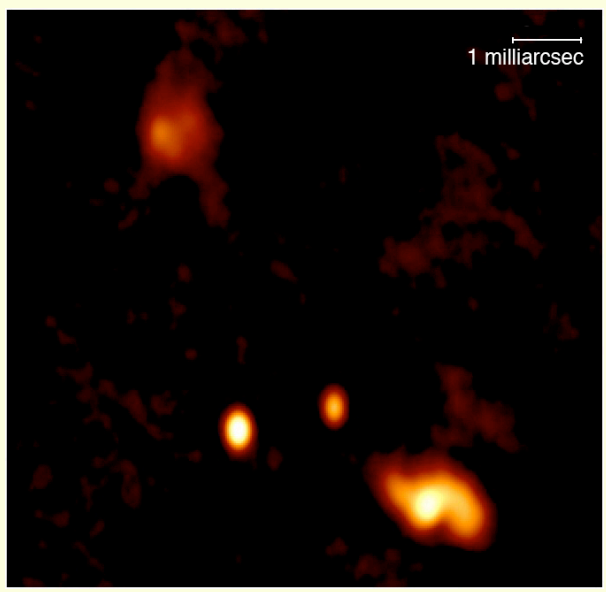
The strongest waves are generated by the systems with the largest gravitational fields GM/R, which correspond to large masses and small sizes. The strongest of all are generated by the interactions of black holes, which have $GM/Rc^2 \approx 1$. The lightest black holes (remnants of single stars, with about ten times the mass of the Sun) emit at the highest frequencies, in the 100-Hz band accessible to ground-based detectors.

By contrast, the strongest sources in the far lower LISA band (between 0.1 to 100 mHz) are the massive black holes (MBHs) at the centers of galaxies; these are the remnants of the process of galaxy formation, with about 10^4 to 10^7 times the mass of the Sun. Optical, radio, and X-ray astronomy have produced abundant evidence that nearly all galaxies have massive black holes in their central nucleus, and that some of them even have two (see sidebar on the previous page).

Mergers of MBHs happen frequently: galaxies are continually forming, in a hierarchical fashion, from the mergers of smaller galaxies, and whenever two galaxies merge their central black holes

A supermassive black hole binary with parsec-scale orbital separation

Massive black hole binaries with parsec-scale orbital separation are expected to be quite common in the Universe. Since however the corresponding angular separations are very small, it is hard to image the binary components separately, and until recently the only known massive black-hole binaries had kiloparsec-scale separation. Recently, radio imaging with the Very Long Baseline Array has revealed a supermassive black-hole binary (0402+379) with an angular separation of just 7 milliarcseconds, corresponding to a projected spatial separation of 7.3 parsecs (Rodriguez *et al.* 2006). The binary sits in an elliptical galaxy, and its total mass is estimated to be about 10^8 Solar masses. The radio map of this amazing system is shown in the figure, and it consists of two compact cores associated with the two supermassive black holes, as well as two extended radio lobes. The radio lobes are estimated to be only about 1000 years old, indicating very recent activity associated with one of the two black holes. While this particular system is not necessarily expected to coalesce in a Hubble time because of its large mass, it demonstrates the existence of binary black holes resembling the progenitors of the coalescing systems that will be observed by LISA. There are so many galaxies in the observable volume that mergers are estimated to occur about once or twice a week, and signals from multiple binaries will be observed at any given time.



15 GHz VLBA image of 0402+379 (courtesy of Greg Taylor)

sink to the center and find each other. MBH mergers are so powerful that LISA can see them out to a wide range of redshifts, extending back to the first protogalaxies at $z \approx 15$. Estimates from standard galaxy formation theory suggest that LISA will detect MBH mergers about once or twice every week (Volonteri 2006), but predictions are very uncertain at the high-redshift end, which sits beyond the reach of EM observations. LISA will lift the veil of these cosmic "dark ages", providing a direct record of the history of galaxy formation and central black hole growth in the observable Universe.

Smaller galactic objects can also be captured (and eventually consumed) by the central black hole. Compact objects such as degenerate dwarfs, neutron stars, and black holes will sometimes be driven by chance encounters into a close orbit around the MBH: a dance of death that they will repeat many times until they finally plunge into the black hole's event horizon. The GWs from these extreme-mass-ratio inspirals (EMRIs) encode a detailed map of spacetime geometry around the MBH. The history and environment of the black hole leave no imprint on this geometry, which is a very pure and beautiful solution (the *Kerr metric*) of the equations of GR. Thus, EMRI signals will test Einstein's theory by probing the most accurately predicted structures in all of astrophysics.

In addition to black holes, many other known systems in our Universe can produce GWs in LISA's frequency band. Soon after it is turned on, LISA will quickly detect a handful of nearby *verification* binary stars, which have known periods and positions (and even assigned names), and which will appear in the LISA data with predictable, distinctive signatures.

A numerous Galactic population of *undiscovered* degenerate-dwarf binaries will be observed all across the LISA band; we know that such objects exists from EM observations in our vicinity, but LISA will detect thousands of individual binaries throughout the Galaxy. At low frequencies millions more binaries from across the Galaxy will blend together into a confusion background in the LISA data, which will nevertheless teach us about the statistics of their population. At higher frequencies, the binaries have more powerful signals, and are farther apart in frequency space, allowing LISA to characterize each individually. At high frequencies, LISA may also detect the background signal from the degenerate binaries in other distant galaxies, allowing us to place constraints on cosmic star formation rates.

Given that all forms of matter and energy couple to gravity, it seems likely that the Universe will treat LISA to yet other GW sources that we cannot anticipate on the basis of our EM observations. This is especially true for observations at very high redshifts, where LISA may give us the very first clues to the unknown conditions of matter and energy in the very early Universe.

In the relativistic early Universe, the LISA frequency band corresponds to the *Terascale frontier*, where the phase transitions of exotic fields or extra spatial dimensions may have caused catastrophic and explosive bubble growth, with efficient GW production. LISA will also probe *superstrings*, relics of the early Universe predicted in some versions of string theory. These exotic structures, which are completely invisible except for the GWs they emit, could produce strong, distinctive LISA signatures; they could provide direct evidence that all forms of matter and energy, and possibly even spacetime itself, are ultimately made of quantum strings.

How are gravitational waves detected?

Einstein's great epiphany was that gravity is the manifestation of the curvature of spacetime, the background for all the interactions of matter and energy. Freely-falling *test* bodies (small compared to spacetime curvature and undisturbed by other forces) thread spacetime along *geodesics*, the straightest paths possible through this curved arena. Nearby, approximately parallel geodesics are pushed together and pulled apart by spacetime curvature. Indeed, GWs are waves of spacetime curvature, experienced by test bodies as an oscillating change in their relative distance.

To understand how this principle is used to detect GWs, it is useful to visualize an idealized Michelson laser interferometer (see Figure 1-3) whose components are floating freely in space, at rest with each other, and far removed from any gravitating bodies. The power measured by a photodetector at the exit port of the interferometer is a simple function of the phase difference of the two light beams that are divided at the beamsplitter, propagated across the two arms, and recombined at the exit port. Incoming GWs (consider for simplicity a plane GW, propagating perpendicularly to the plane of the interferometer, with "+" polarization aligned with the two arms) alternately increase the distance experienced by light traveling along one arm and decrease the distance along the other, creating oscillations in the power measured at the exit port.

The currently operating ground-based GW detectors such as LIGO (Abramovici *et al.* 1992) implement much more sophisticated versions of this setup (for instance, in LIGO light is

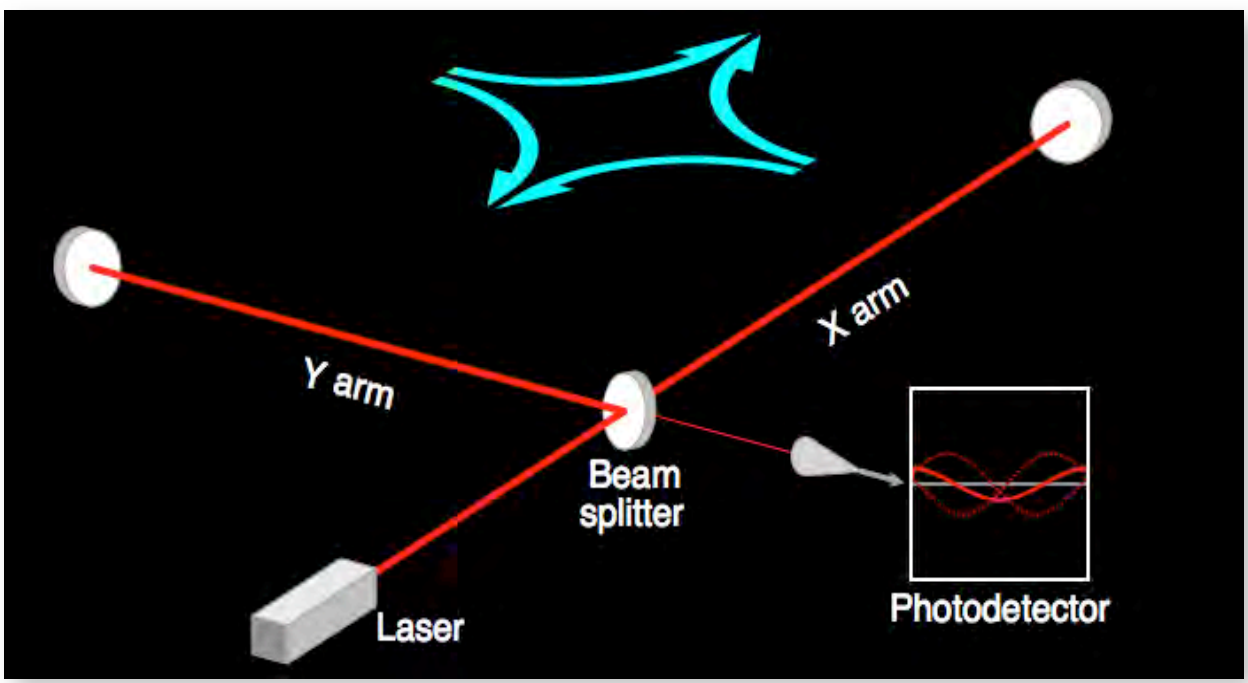
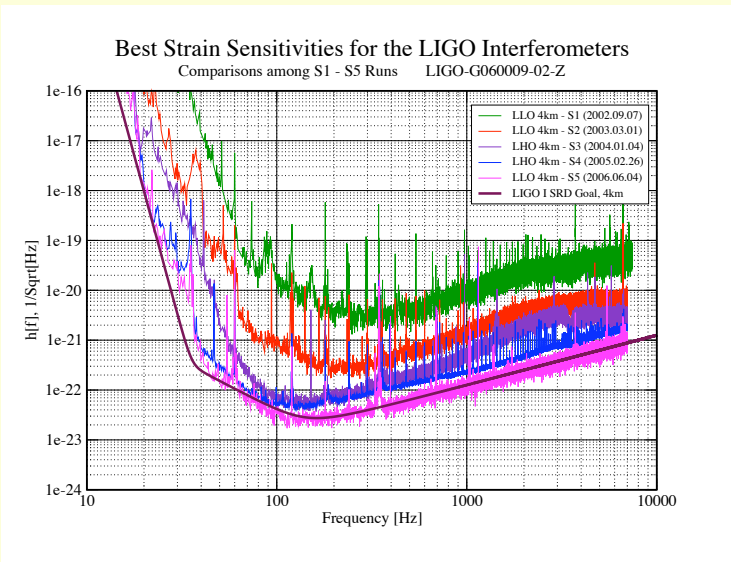


Figure 1-3: Idealized Michelson interferometer with laser, beam splitter, end mirrors, and photodetector at the exit port. the blue arrows represent a perpendicularly propagating, linearly polarized gravitational wave.

LIGO reaches its design sensitivity

The absolute accuracies required by GW observations may at first seem unachievable. The LIGO design sensitivity (black line) implies measurements of the change in distance between interferometer mirrors that are accurate to better than one part in 10^{22} in the relevant frequency band. Yet, as shown in this figure by the progression of experimental noise curves for the LIGO Hanford 4 km interferometer (colored lines), the dedication and ingenuity of countless scientists and engineers has made these measurements possible.

Because of LISA's much longer armlength, the metrology accuracy required locally at each spacecraft is much less exacting than the LIGO requirement, by a factor of about one half million .



made to bounce several times along cavities in each arm, enhancing the phase-accumulation effect). The free fall of interferometer components is approximated, along the "sensitive" axes, by suspending them from pendulums that are carefully isolated from the environment.

The sensitivity and frequency range of ground-based interferometers is set by their size (with armlengths ranging from a few hundred meters to 4 km for LIGO), and by various noise sources, including photon shot noise in the phase-difference measurement, and thermal noise in the suspensions and optical components. To detect an amplitude of $h \approx 10^{-22}$, LIGO must measure displacements of the order of 10^{-19}m, an extremely challenging target. At frequencies below 10 Hz, seismic noise from terrestrial sources is especially challenging to the mechanical isolation systems. Below about 1 Hz, another terrestrial noise begins to be larger than expected astronomical signals: gravity-gradient noise from time-dependent changes in the local Newtonian gravitational field. No GW detector can be isolated from these tidal gravitational fields, so that detection in the LISA frequency band requires a detector far from the Earth.

LISA brings the Michelson measurement concept to the grander scale and much quieter environment of space. While ground-based detectors are naturally limited by the Earth's curvature to km armlengths, LISA can be more than a million times larger. Longer arms magnify the effect of GWs, so LISA can achieve 10^{-22} strain accuracy by measuring displacements of the order of fractions of a picometer, a million times larger than those LIGO has to cope with. When this is combined with the absence of seismic and gravity-gradient noise, LISA can achieve remarkable sensitivity to the lower-frequency GWs emitted by larger, more massive systems. Thus, while advanced ground-based detectors may observe neutron stars or stellar-mass black holes coalesc-

ing out to distances of hundreds of megaparsecs, LISA will be sensitive to MBH coalescences out to redshifts greater than 10, allowing it to plumb the earliest stages of galaxy formation.

While LISA can be thought of as a "Michelson interferometer in space", its actual implementation is quite different from a conventional Michelson interferometer. The experimental approach is closer to that of spacecraft Doppler tracking, in which the observed quantity is the frequency change in the signal from a distant spacecraft. In LISA, each spacecraft sends a beam of laser light to each of the other two distant spacecraft, and in turn receives a beam from each of them. The received laser light is coherently combined at a photodetector with the light from an onboard reference laser, and the frequency difference is recorded as a beat signal. The beat signals recorded at each of the three spacecraft are delayed in time and recombined in a technique called "Time Delay Interferometry" (Tinto 2005), which essentially creates three virtual Michelson interferometers whose output signals represent the basic LISA science data stream.

2. LISA Mission Overview

The LISA mission uses three identical spacecraft whose positions mark the vertices of an equilateral triangle five million km on a side, in orbit around the Sun. LISA can be thought of as a giant Michelson interferometer in space, with a third arm that provides independent information on the two gravitational wave (GW) polarizations, as well as redundancy. The spacecraft separation – the interferometer armlength – sets the range of GW frequencies LISA can observe (from about 0.1 mHz to above 0.1 Hz). This range was chosen to reveal some of the most interesting sources: mergers of massive black holes, ultra-compact binaries, and the inspirals of stellar-mass black holes into massive black holes. The center of the LISA triangle traces an orbit in the ecliptic plane, 1 AU from the Sun and 20º behind Earth, and the plane of the triangle is inclined at 60º to the ecliptic (see Figures 2-1 and 2-2). The natural free-fall orbits of the three spacecraft around the Sun maintain this triangular formation throughout the year, with the triangle appearing to rotate about its center once per year.

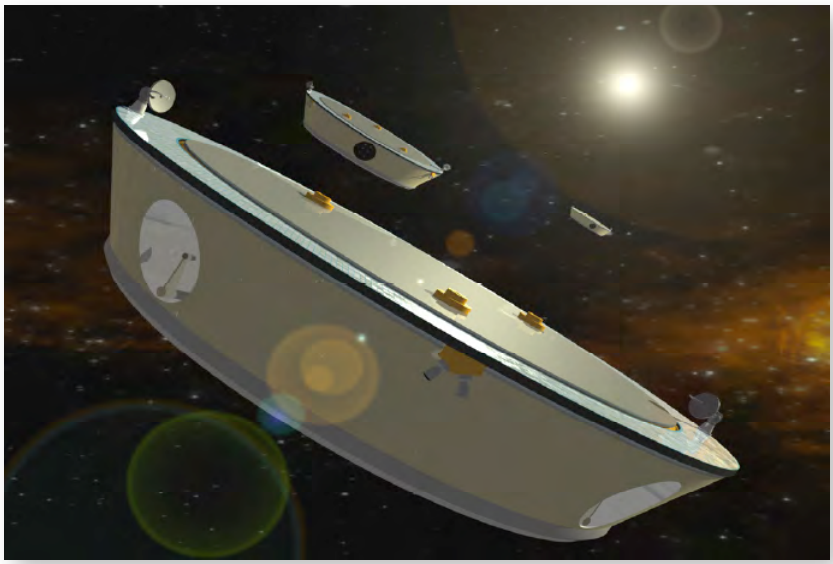


Figure 2-1: The LISA constellation of three spacecraft separated from one another by five million km (0.03 AU), with the Sun visible in the distance at 1 AU.

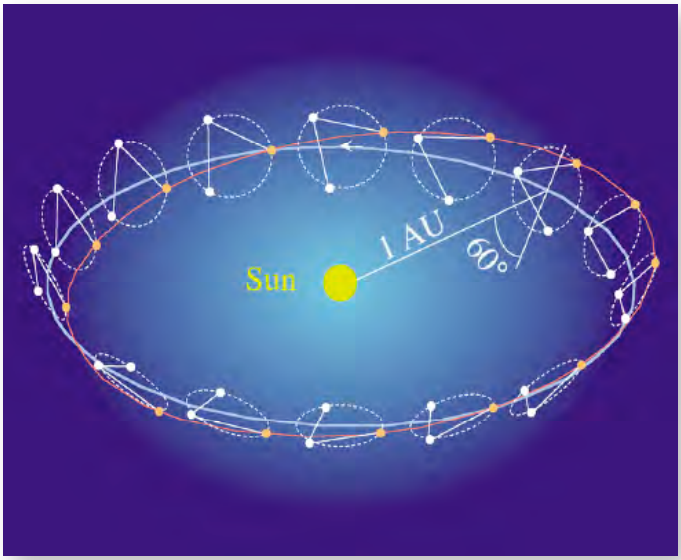


Figure 2-2: The LISA constellation's heliocentric 1-AU–radius orbit, with the plane of the triangle inclined at 60º to the ecliptic. The triangle appears to rotate once around its center in the course of a year's revolution around the Sun.

As mentioned above, the actual implementation used for LISA resembles the technique known as spacecraft Doppler tracking, but realized with infrared laser light instead of radio waves. The laser light going out from one spacecraft to the

other corners is not reflected back directly, because diffraction losses over such long distances would be too great. Instead, in analogy with an RF-transponder scheme, the laser on the distant spacecraft is phase-locked to the incoming light and transmitted back at full intensity. When the transponded laser light arrives back at the original spacecraft, it is superposed with a portion of the original laser beam, which serves as the local oscillator in a standard heterodyne detection scheme. This relative phase measurement gives information about the length of that interferometer arm, modulo an integer number of wavelengths of the laser light. The difference between the phase measurements for the two arms gives information about the relative changes in the two arms—the GW signal.

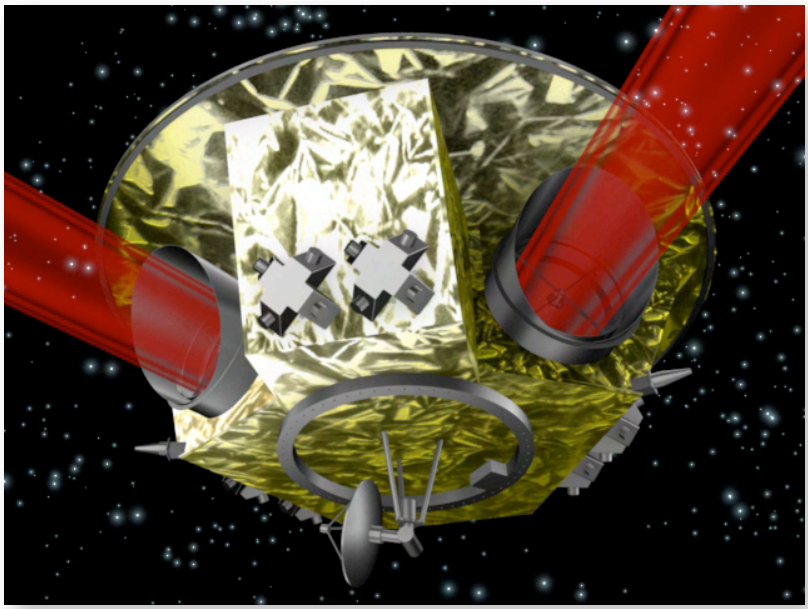


Figure 2-3: View of the exterior of one LISA spacecraft, showing the two telescope assemblies, two of the six thruster packages, and the telemetry antenna.

A two-arm interferometer can be prone to phase errors due to laser frequency fluctuations. If the arms were exactly equal in length, then laser frequency fluctuations would cancel perfectly in the armlength difference measurement. Unfortunately, annual variations in the LISA spacecraft orbits prevent perfect cancellation of laser noise. To minimize the measurement error from laser phase noise the lasers are frequency stabilized—first to an optical cavity, and then to the 5 million km interferometer arm (Sheard *et al.* 2003, Herz 2005). Any residual laser frequency noise in the LISA measurements will be removed by post-processing on the ground using a technique called Time Delay Interferometry (TDI; Tinto *et al*. 2003, Tinto & Dhurandar 2005).

Each spacecraft contains a pair of optical assemblies oriented at roughly 60º to each other (see Figure 2-3). Each assembly is pointing toward a similar one on the corresponding distant spacecraft, to form a (non-orthogonal) Michelson interferometer. Through a 40 cm aperture telescope on each assembly, a laser beam from a 1.064 μm Nd:YAG master laser and 1 W Yb-doped fiber amplifier is transmitted to the corresponding remote spacecraft. The same telescope is used to collect the very weak incoming beam (around 100 pW) from the distant spacecraft, and direct it to a sensitive photodetector, where it is combined with a local-oscillator beam derived from the original local laser light. At the heart of each assembly is a vacuum enclosure containing a free-flying polished platinum-gold cube, 4 cm in size – the *proof mass* that serves as an inertial reference for the local optical assembly (see Figure 2-4). A passing gravitational wave will produce a relative strain in this large optical truss, causing an increase in the optical path length between the proof masses forming one arm while causing a decrease for the other arm. These length

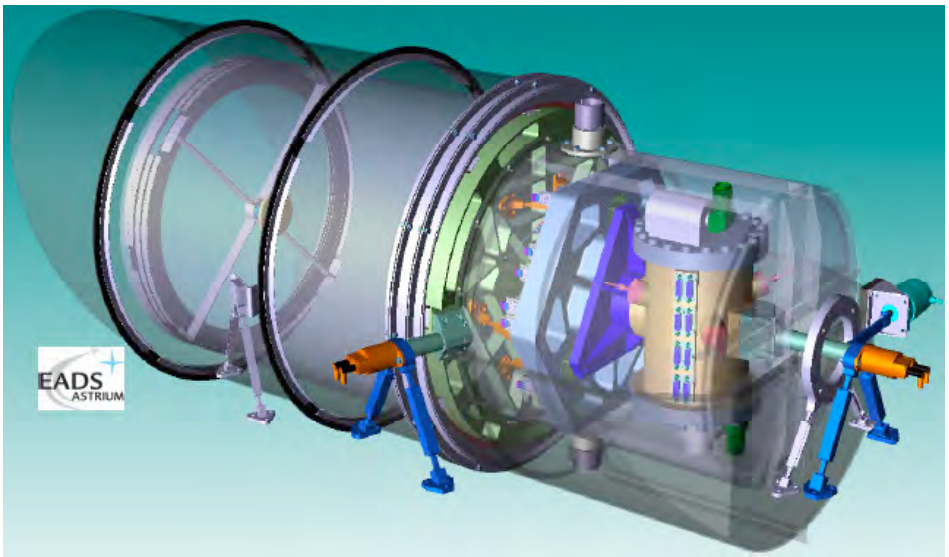


Figure 2-4: Optical assembly, containing (from left to right) the telescope assembly, the optical bench, and the proof mass vacuum enclosure.

changes are measured interferometrically with sub-Angstrom precision. In this way, LISA will be sensitive enough to detect GW induced strains of amplitude $h = \Delta l / l \sim 10^{-23}$ in one year of observation, with a signal-to-noise ratio of 5.

The spacecraft surrounding each pair of optical assemblies serves primarily to shield the proof masses from the adverse effects of solar radiation pressure fluctuations; the spacecraft positions do not enter directly into the measurements. Nevertheless, in order to minimize disturbances to the proof masses from fluctuating forces in their vicinities, each spacecraft must be kept moderately centered around the proof masses (to about 10 nm/$\sqrt{\text{Hz}}$ in the measurement band). This is achieved by a *drag-free* control system based on small electric thrusters and displacement sensors. Specifically, both capacitive and optical sensors are used to measure the displacements and rotations of the proof masses relative to the spacecraft. These offset signals are then fed back to control micro-Newton thrusters, which force the spacecraft to follow its proof masses. The thrusters are also used to control the attitude of the spacecraft relative to the incoming optical wavefronts, using signals derived from quadrant photodiodes. Capacitive actuation is used to adjust the positions or orientations of the proof masses when needed.

Each of the three LISA spacecraft has a launch mass allocation of about 575 kg (with margin) including the payload, propulsion module, and the spacecraft adapter. The propulsion modules use a chemical propulsion system to transfer each spacecraft from the Earth orbit to the final position in interplanetary orbit. All three spacecraft can be launched together by a single Atlas V (531). Each spacecraft carries a small, steerable antenna used for transmitting the science and engineering data in the Ka-band to the NASA Deep Space Network. The nominal mission lifetime is five years. Additional information about the LISA mission can be found in Hammesfahr (2001) and Cramer *et al.* (2003).

LISA capabilities

Sensitivity

The sensitivity of LISA is shown in Figure 2-5 together with a comparable sensitivity curve for the future ground-based Advanced LIGO. Sensitivity over a logarithmic frequency interval is shown here in terms of the dimensionless strain $\sqrt{f}\sqrt{S_h(f)}$ (where $\sqrt{S_h(f)}$ is the 1-σ level of strain noise spectral amplitude), in order to facilitate comparison with the much higher measurement frequencies of LIGO. The LISA sensitivity curve divides into three regions: a low-frequency region where proof-mass acceleration noise dominates, a mid-frequency region where shot noise and optical-path measurement errors dominate, and a high-frequency region where the sensitivity curve rises as the wavelength of the GW becomes shorter than the LISA armlength. Additionally, a diffuse background of unresolved galactic binaries is expected to contribute to the measured strain level in the frequency range from 0.1 - 1 mHz; this component is indicated in Figure 2-5.

Figure 2-5 illustrates also the different astrophysical sources that LISA will study, contrasted with those studied by ground-based interferometers such as LIGO. In general, a ground-based

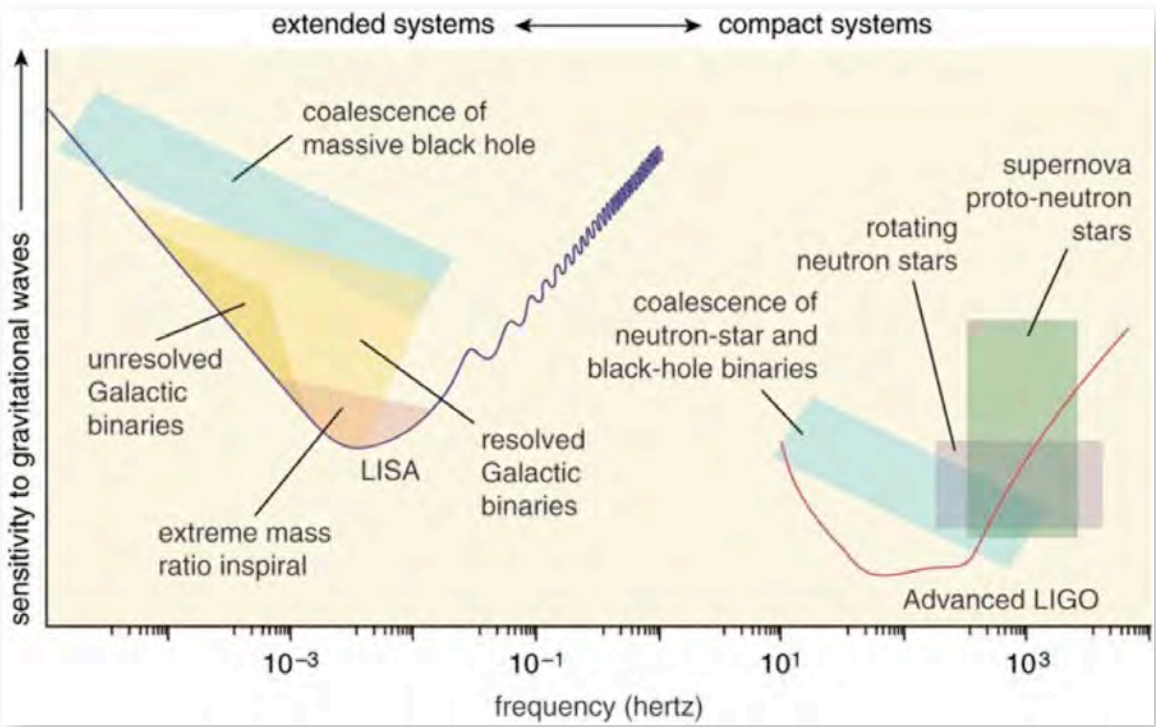


Figure 2-5: Strain sensitivities predicted for LISA and Advanced LIGO. The curve is plotted in units of ($\sqrt{fS_h(f)}$), where $S_h(f)$ is the LISA noise power spectrum with $\sqrt{S_h(f)}$ representing the 1-σ noise level. The units of ($\sqrt{fS_h(f)}$) are the natural units for plotting sensitivity per logarithmic frequency interval.

interferometer is limited to frequencies above about 10 Hz because of seismic noise, corresponding to wavelengths less than about 30,000 km. The sources it studies will therefore generally be very compact sources with orbital separations comparable to the wavelength. Such sources include neutron-star binaries and stellar-mass black hole binaries just before merger. In contrast, LISA will see most of its sources in the frequency range below about 10 mHz, corresponding to wavelengths greater than about 30 million km. This is the characteristic size of systems involving massive black holes, as well as most of the compact white-dwarf binaries in our Galaxy.

Sky position determination

LISA can determine a source's position in the sky using techniques that are similar to those used in the radio frequency domain, namely AM and FM modulation. For higher frequencies, above about 1 mHz, LISA will use a technique similar to the localization of pulsars *via* pulsar timing: that is observing the phase or Doppler shifts of the GW signal as a function of the position of LISA in its orbit about the Sun. At low frequencies the wavelengths are too long to do positioning using frequency modulation. Consequently, the position is determined from the modulation of the amplitude of the GW signal as the LISA constellation changes aspect in its orbit about the Sun. Both of these methods can provide sub-degree location accuracy for strong GW sources.

Distance determination

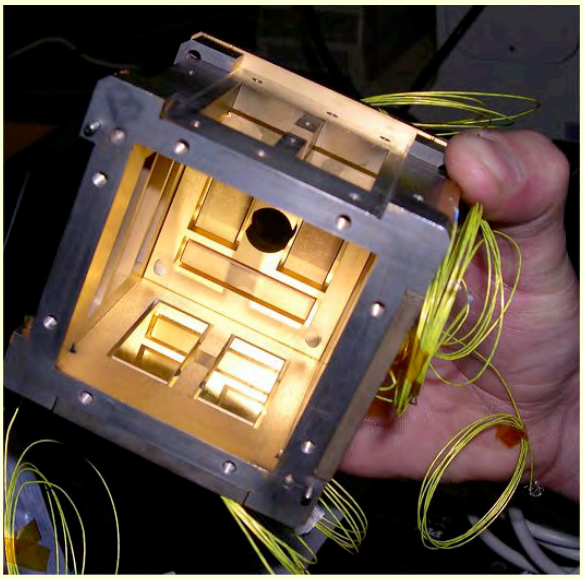
A unique feature of GW measurements of astrophysical systems is the capability of determining precise distances for many GW sources. A coalescing binary has a characteristic frequency of emission, which is twice the orbital frequency, and which increases in time due to the loss of energy to GW emission. The rate of increase of the frequency, *df/dt*, depends on the so-called "chirp mass", $M_{\rm chirp} = (1+z)(M_1 M_2)^{3/5}(M_1+M_2)^{1/5}$, where z is the redshift and M_1 and M_2 are the masses of the two members of the binary. The amplitude of the GW signal at the detector depends both on the chirp mass and on the distance. By determining the chirp mass from the rate of increase of the frequency the signal amplitude can then be used to determine the distance. LISA will typically be able to measure the distance to a coalescing massive black hole binary to a few-percent accuracy. In contrast, the redshift z is not independently determined from GW observations. Dimensionful system parameters such as mass and spin enter the system's dynamical evolution as timescales. For distant sources, these timescales acquire a redshift factor $(1 + z)$; as a consequence, the inferred system parameters likewise acquire factors of $(1 + z)$. Redshift is always degenerate with a measured system's intrinsic parameters; it must be determined by associating a merging system with a host galaxy. We thus have the situation that for electromagnetic (EM) observations distance determination is typically difficult, but redshift determination reasonable straightforward, while the opposite is true for GW observations. The excellent distance determination capability of LISA is extremely important for determining the number density of

LISA Pathfinder: Flight test of key LISA technologies

The European Space Agency is preparing a flight validation of the LISA drag-free and interferometry systems on the LISA Pathfinder (LPF) mission, planned for 2009. LPF will provide validation and risk reduction for key LISA technologies by carrying two drag-free proof masses and an interferometer to measure their relative displacements using heterodyne techniques as planned for LISA. Essentially, LPF shrinks one LISA arm down to fit inside a single spacecraft; it thereby loses its sensitivity to GWs but tests the LISA sensitivity to relative proof-mass displacements.

The picometer displacement sensitivity required of LISA's interferometer is not particularly challenging: it is about one-million times more relaxed than LIGO currently achieves on the ground, and it is only a thousand times more stringent than Albert Michelson achieved in his original interferometer 125 years ago. LPF will demonstrate that this can be achieved in space, but the primary reason for launching LPF is to validate the drag-free system. LPF will demonstrate a proof-mass assembly that can survive launch vibration and still provide the required degree of isolation from external disturbances in space. LPF will also carry two independent microthruster hardware and control systems, one supplied by ESA and the other by NASA. It will provide an opportunity to compare the stability, reliability, and precision of these key components of the drag-free system.

The LPF design, incorporating any lessons learned from the mission, will form the basis of the LISA drag-free and interferometry systems. ESA plans to give LISA the final go-ahead for Phase C/D once the results of LPF have been evaluated.



The LISA pathfinder engineering model of the drag-free sensor housing, showing the capacitive sensors.

BH mergers versus epoch, for possible H_0 and dark energy measurements, and for determining the distribution of ultra-compact binaries in the Galaxy.

Science operations

LISA will deliver a rich and diverse scientific data set, providing numerous opportunities for guest investigations associated with LISA observations. Opportunities will include: complementary EM observations during flight and pre- and post-flight, development of analysis techniques for LISA data, analysis of the LISA data for detection and characterization of sources of GWs, and use of LISA-generated source lists, waveforms, catalogues for physics and astrophysics research investigations and theoretical investigations. These are discussed further in later sections.

The starting point for most science analysis of LISA data will be the construction of three science data channels, the so-called "Time-Delay Interferometry (TDI) variables". A full discussion of the TDI data is beyond the scope of this document; further information can be found in Tinto & Dhurandar (2005). Basically, the three TDI data channels can be thought of as containing the in-

formation about the "+" and "×" GW polarizations, as well as a third channel of information, the "Symmetrized Sagnac" channel, which is relatively insensitive to GWs and can be used as a monitor of LISA instrumental noise, very important for LISA measurements of the diffuse GW background.

LISA data are expected to contain the signals from many sources simultaneously. Well-developed techniques exist to detect and characterize multiple sources. Thus, in addition to the calibrated TDI channels, a data product will be released that will be a "model" for the LISA data, providing at any time the best estimate for its source content (including waveform estimates), effectively providing three source-subtracted LISA data channels for use by researchers interested in searching for new sources.

In addition to the actual scientific data channels, LISA will provide "alerts" of specific events, such as predictions of merger times and locations of massive black hole binaries, as well as catalogues and ephemerides for detected sources: extra-galactic black hole binaries, ultra-compact galactic binaries, inspirals of stellar-mass compact objects into massive black holes in external galaxies, *etc*. These data products will provide a wealth of opportunities for follow-up ground- and space-based astronomical facilities, as well as opportunities for theoretical research.

Status of LISA data analysis

There is already a robust community effort in the development, simulation and demonstration of LISA data analysis, which has resulted in the publication of over 200 papers (see the bibliographic database at www.srl.caltech.edu/lisa). LISA has an active program of data simulation and "mock data challenges" to refine the understanding of the science capabilities of LISA (Arnaud *et al.* 2006). Techniques have been developed for detection and parameter estimation for all classes of LISA sources: massive binary black hole coalescences, galactic white-dwarf binaries, extreme mass-ratio inspirals, and stochastic backgrounds. These techniques have a rich heritage, not only from ground-based GW detectors, but also from related analysis fields such as sonar, radar, seismology, radio astronomy, and voice recognition.

LISA mission quick facts

LISA Pathfinder: The joint ESA-NASA LISA Pathfinder/ST-7 mission will demonstrate the core technologies needed for both LISA's interferometers and for the "drag-free" spacecraft control that protects LISA's proof masses from disturbance.

LISA: The Laser Interferometer Space Antenna is a joint mission of NASA and ESA. Specifications below are per the baseline of design of 2006 but are subject to change.

Launch and cruise: A single Atlas-V rocket lifts all three spacecraft, each with its own propulsion module. They reach their final solar orbits after a 13-month cruise.

Orbits: Each drag-free spacecraft is in an independent heliocentric orbit, trailing Earth by about 20 degrees.

Station-keeping: There is no station-keeping. The orbits are chosen to keep the spacecraft at the corners of a nearly equilateral triangle throughout the mission life.

Inter-spacecraft separation: About 5 million kilometers (0.03 Earth-Sun distance, or 17 light-seconds).

Spacecraft:
Size: 2.7-m diameter, 0.7-m thick
Mass: 575 kg
Orientation: 60 degrees to the Sun, constant.
Power: 820W per spacecraft, from solar cells.
Attitude and drag-free control: six micro-Newton thrusters, 4 to 30 μN each.
Telemetry: Ka-band, DSN, under 10 kbps.

Payload (per spacecraft):
Lasers (two): 1-W diode-pumped 1064-nm Nd:YAG lasers, frequency-stabilized to an onboard reference cavity and also to the inter-spacecraft arms.

Proof masses (two): 2-kg Au-Pt cubical proof masses. Electrostatic actuation perpendicular to the measurement axes. Charge control by UV illumination.

Telescopes (two): 40-cm diameter, f/12, used both to transmit and receive.

Measurement and error budget:
Measurement: Optical heterodyne: The received laser beam (about 10^{-10} W) is mixed with about 1mW of local laser light on a quadrant photodiode. Measurements from all three pairs of spacecraft are combined using time-delay interferometry to synthesize two independent Michelson interferometers and a third independent Sagnac interferometer.

Optical-path errors: Caused by detector shot noise, pointing jitter *etc*., total not to exceed 2×10^{-11} m/√(Hz) over the LISA bandwidth.
Acceleration errors: Caused by unmeasured residual forces on proof masses. Total not to exceed 3×10^{-15} $(m/s^2)/\sqrt{(Hz)}$ from 0.1 to 1 mHz. Divide by $(2\pi f)^2$ for resulting displacement error.

Strain sensitivity: Primary sensitivity to gravitational waves of frequency 0.0001 – 0.1 Hz.

Source localization in space: Below 1 mHz, or lifetime < months: degrees.
Above 10 mHz, lifetime > months: arcminutes.

3. Black Hole Astrophysics: Massive Black Holes in Galactic Nuclei

There is now abundant evidence that nearly all galaxies have massive black holes in their central nuclei. These nuclear black holes can have profound effects on galaxy formation, releasing huge amounts of energy into the galaxy via accretion-powered jets. The formation of this population of massive black holes is thought to be associated with a multistage process of binary inspiral and merger, together with accretion. LISA will detect the merger events directly, thus tracing the growth and merger history of massive black holes and their host galaxies. LISA will search for a population of seed black holes at early epochs and use precision measurements of black hole spins to help determine the relative importance of black-hole growth mechanisms. LISA will also probe the rich astrophysics in the nuclei of normal galaxies by observing the inspiral of compact objects into the massive black holes in their centers.

Key science questions

- When did the massive black holes in galactic nuclei form, and how did they grow?
- What fraction of proto-galaxies contained massive black holes in their cores, as a function of redshift?
- What are the mass and spin distributions of the massive black holes in galactic nuclei?
- What is the role of black hole mergers in early hierarchical structure assembly?
- What are dynamics of stars near massive black holes in galactic nuclei?

Evidence for supermassive black holes in galactic nuclei

Supermassive black holes accreting gas in galactic nuclei were first proposed in the 1960s (Salpeter 1964; Zel'dovich & Novikov 1964) to explain the enormous luminosities of the newly discovered quasars. Refinements of this idea have become the generally accepted explanation for the electromagnetic and kinetic emissions from all active galactic nuclei (AGN; see, *e.g.*, Krolik 1999).

The disks of gas around accreting black holes (mass $M_\bullet$) in active galaxies are inferred to have luminosities approaching the Eddington limit (at which radiation pressure on the Thomson cross section σ_T of electrons balances the gravitational attraction on them and the protons from which they were stripped):

$$L_{\rm Edd} = 4GcM_\bullet m_p/\sigma_T = 10^{46}\ {\rm erg\ s^{-1}}(M_\bullet/10^8 M_\odot)\ .$$

Thus, the black holes in AGN, producing radiation from accreted rest-mass with efficiency $\varepsilon \equiv 0.1\varepsilon_{0.1}$ must be increasing in mass by accretion with an e-folding time known as the Salpeter time,

$$t_S = \varepsilon M_\bullet c^2/L_{\rm Edd} = 4\times 10^7 \varepsilon_{0.1}\ {\rm yr}\ .$$

Since t_s is about one percent of the age of the Universe at redshift $z = 1$, at most about one percent of black holes can be radiating at near the Eddington limit; the rest must be quiescent. This crude estimate is consistent with observations: the deepest images from the Hubble Space Telescope (HST) show nearly 10^6 galaxies per square degree. Only about one percent have the variable nuclei characteristic of AGN (Cohen *et al.* 2006). In its longest exposures, the Chandra X-ray observatory also detects about 10^4 active galactic nuclei in each square degree of sky (Brandt & Hasinger 2005). We might expect, then, that the deep Universe is populated by billions of invisible black holes, representing 99% of the total population. Gravitational wave observatories such as LISA can reveal these hidden objects.

As Lynden-Bell pointed out, another consequence of the ~ 1% "duty cycle" is that a large fraction of local galaxies must have been quasars in their youth, and must today harbor relic black holes in their nuclei (Lynden-Bell 1969). A 1% duty cycle could mean that 1% of galaxies host a black hole that is active for most of its life or, at the other extreme, that most galaxies host black holes that are active only 1% of the time. The latter interpretation has recently been confirmed spectacularly by the discovery that in the centers of almost all bright nearby galaxies (including our own Milky Way) the velocities of stars and gas begin to rise in the Keplerian fashion expected if there were a central point mass dominating the central potential (Ferrarese & Ford 2005; see Figure 3-1).

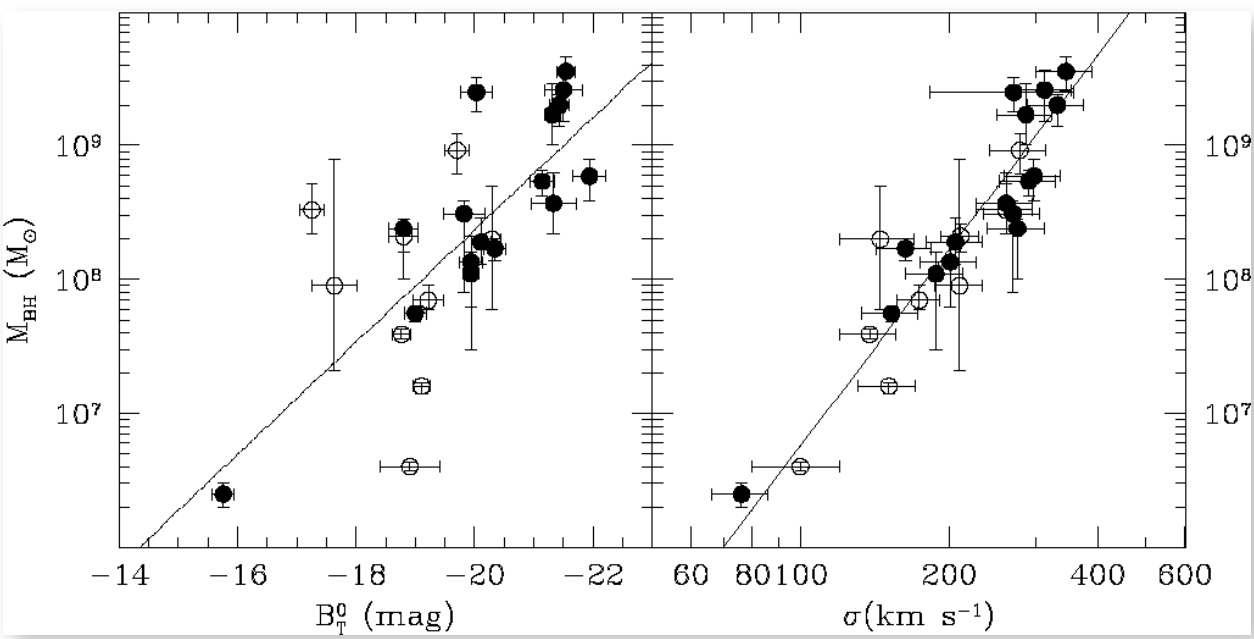


Figure 3-1: The correlation between black hole mass $M_\bullet$ and the luminosity of the host galaxy's stellar bulge (left) and between $M_\bullet$ and the host galaxy's bulge velocity dispersion σ (right) for all detections in galaxies near enough that current instruments resolve the region in which the black hole dominates the dynamics. Filled symbols show elliptical galaxies; open symbols show spiral and lenticular galaxies (from Ferrarese & Ford 2005; see also Gebhardt *et al.* 2000).

Hubble Space Telescope press releases consistently call these central masses black holes, and we follow that practice here. But one of the most important questions LISA will address is whether these masses are actually the Kerr black holes of Einstein's relativity. In almost all cases, current measurements cannot probe regions closer than $\sim 10^5$ times the Schwarzschild radius of the inferred black hole, so other astrophysical models (*e.g.*, dense clusters of stellar-mass black holes) are not conclusively ruled out. But in the notable case of our own Milky Way, one can measure the orbits of stars passing as close as 1300 Schwarzschild radii from the $4 \times 10^6 M_\odot$ central mass (Ghez *et al.* 2005; Eisenhauer *et al.* 2005), and one can rule out even contrived astrophysical alternatives to black holes

Massive or supermassive?

The terms "massive black hole" and "supermassive black hole" often are used almost interchangeably to refer to the massive objects in the centers of galaxies. In this document we generally use the following definitions:

Supermassive Black Hole (SMBH):	$10^7 M_\odot < M_{BH}$
Massive Black Hole (MBH):	$10^4 M_\odot < M_{BH} < 10^7 M_\odot$
Intermediate Mass Black Hole (IMBH):	$10^2 M\odot < M_{BH} < 10^4 M_\odot$

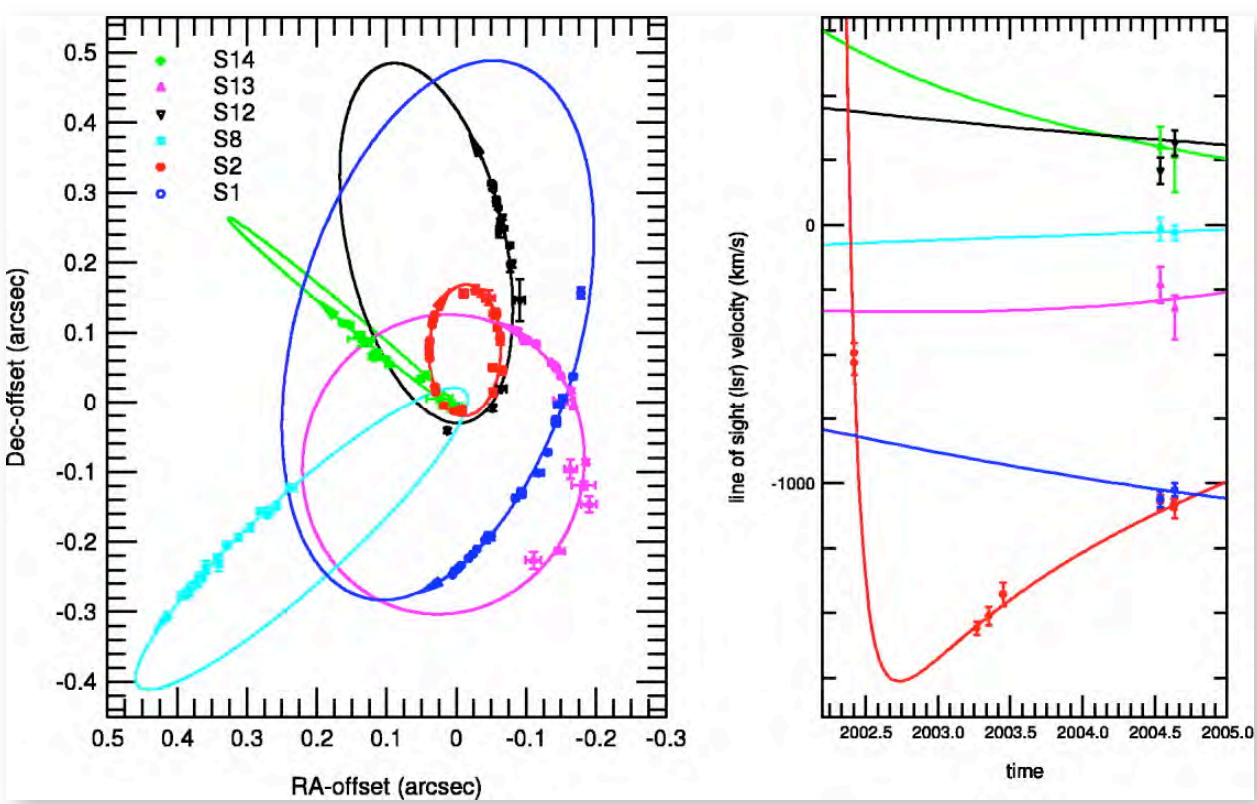


Figure 3-2: The orbits on the sky, and radial velocity measurements of six stars close to the central point mass in the Milky Way. At their peribothrons, stars S2 and S14 pass within 5×10^{-4} pc = 100 AU = 1300 Schwarzschild radii of the central black hole, of mass $4 \times 10^6 M_\odot$ (from Eisenhauer *et al.* 2005).

(Maoz 1998), though not exotic models invoking new physics such as soliton stars with radii of less than a few Schwarzschild radii. See Figure 3-2.

The black hole mass estimates derived from the kinematics of stars and gas in the nuclei of nearby representative galaxies also allow one to estimate the space density of local black holes (Figure 3-1). These estimates give

$$\rho_\bullet = 2\text{-}5 \times 10^5 M_\odot \text{ Mpc}^{-3}$$

(for $H_0 = 70$ km s^{-1} Mpc^{-1}; Aller & Richstone 2002; Marconi *et al.* 2004). The uncertainty in $\rho_\bullet$ results principally from uncertainties and dispersion in the correlations between black hole mass and galaxy luminosity or between black hole mass and velocity dispersion (*c.f.* Lauer *et al.* 2006, Tundo *et al.* 2006).

One can compare $\rho_\bullet$ to the total increase in the mass density of black holes derived from the total radiation density emitted by AGN, an argument suggested by Soltan in 1982. If the total radiation density emitted by AGN were produced by accretion onto black holes with an efficiency ε of converting accreted rest-mass to radiation, then it must have increased the mass-density of supermassive black holes by

$$\Delta\rho_\bullet \approx 3.5 \times 10^5 \varepsilon_{0.1}^{-1} M_\odot \text{ Mpc}^{-3}$$

where $\varepsilon_{0.1} \equiv \varepsilon/0.1$ (Marconi *et al.* 2004; Soltan 1982). Most of this radiation comes from AGN with redshifts between 0.5 and 3. There is probably a 50% uncertainty in $\Delta\rho_\bullet$ due to uncertainties in the bolometric corrections and in corrections for obscured AGN and faint high-redshift AGN.

The striking correlation shown in Figure 3-1 between the mass of a galaxy's nuclear black hole and the galaxy's stellar mass and velocity dispersion (and hence the depth of its gravitational potential well) has convinced astronomers that throughout

Figure 3-3: Snapshots from a simulation of a collision of two spiral galaxies, similar to the Milky Way, containing $10^5 M_\odot$ seed black holes at their centers. The images show only the gas in the galaxies. Color indicates temperature and brightness gas density. The collision drives both star formation in the galaxy and gas accretion onto the black holes, causing them to merge. The resulting quasar expels most of the gas from the galaxy, leaving a gas-poor galaxy containing a $\sim 10^8 M_\odot$ black hole (from Di Matteo *et al.* 2005).

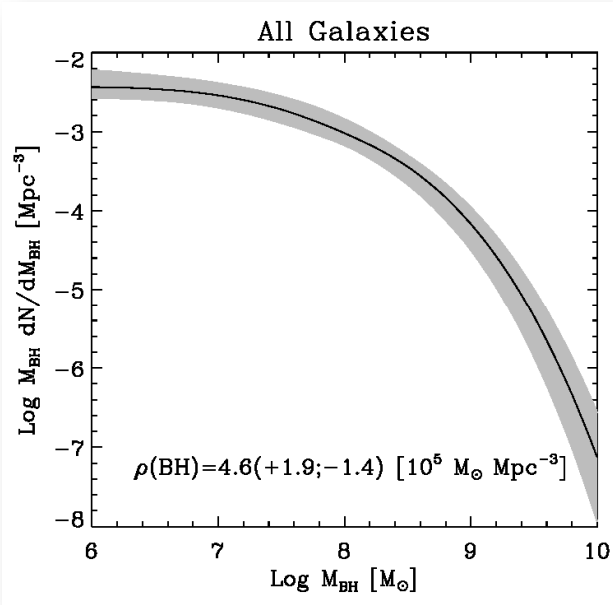


Figure 3-4: The local space density of black holes in galactic nuclei as a function of black hole mass, inferred from measurements of the kinematics of stars and gas in the nuclei of nearby galaxies (from Marconi *et al*. 2004).

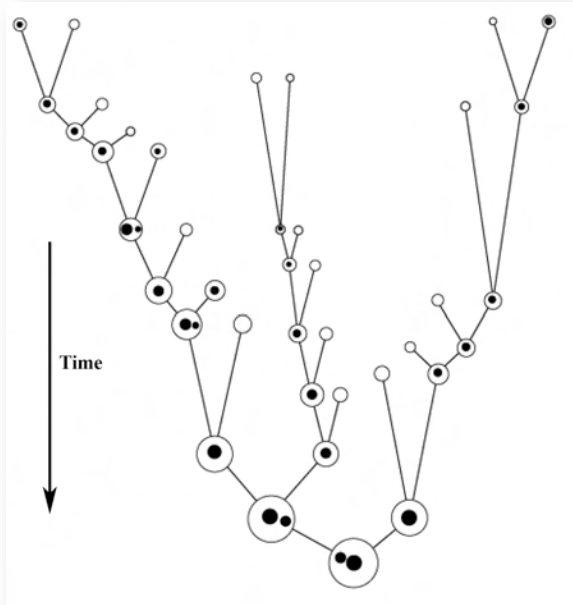


Figure 3-5: A cartoon of the merger-tree history of the assembly of a galaxy and its central black hole in cold-dark matter cosmology. Time increases from top to bottom, and the horizontal axis is a spatial direction. In this case the final galaxy is assembled from the merger of twenty smaller galaxies, containing a total of four seed black holes, and results in four mergers of binary black holes.

cosmic history, the growths of galaxies and their nuclear black holes have been tightly coupled (Gebhardt *et al.* 2000; Tremaine *et al.* 2002). Events in the galaxy decide the rates of the black hole's accretion, stellar capture, and merger; and jets and radiation from the black hole's accretion disk can remove gas from the galaxy and its surroundings (Figure 3-3).

The estimates for the growth in black hole mass, $\Delta\rho_\bullet$, can be compared to the estimate for the local density of black holes. Most of the contribution to the local black hole mass density comes from black holes with masses between 10^8 and 10^9 $M_\odot$ (Figure 3-4). Similarly, the main contribution to $\Delta\rho_\bullet$ comes from black holes in the same mass range at z = 2 - 3 (Merloni 2004). Since these billion-solar-mass black holes have grown in mass mainly through accretion, by a few orders of magnitude from z = 3 to now, the high-redshift Universe must have been dominated by black holes of a smaller variety, $10^6 - 10^7 M_\odot$. Were the smaller black holes quietly growing by mergers, while the supermassive ones were growing by accretion? Here lies a great potential for discovery by LISA, which will detect mergers of mass 10^5 - 10^7 $M_\odot$ with high signal-to-noise out to redshift $z \sim 20$ or higher.

Growth and merger history of massive black holes

Expected merger rates

There is a simple argument bounding the number of mergers of massive black holes that LISA is likely to see. Hubble Space Telescope observes more than 10^{10} galaxies. Most bright local galaxies contain central supermassive black holes. Fossil evidence for mergers among local galaxies implies that about 70% of these have undergone a merger during the 0.8×10^{10} years since redshift $z = 1$ (Toomre 1977; Bell *et al.* 2006). Therefore, the galaxy merger rate at $z < 1$ must be close to one per year, and if the black holes in merging galaxies merge in turn, the merger rate of massive and supermassive black holes should also be at least one per year.

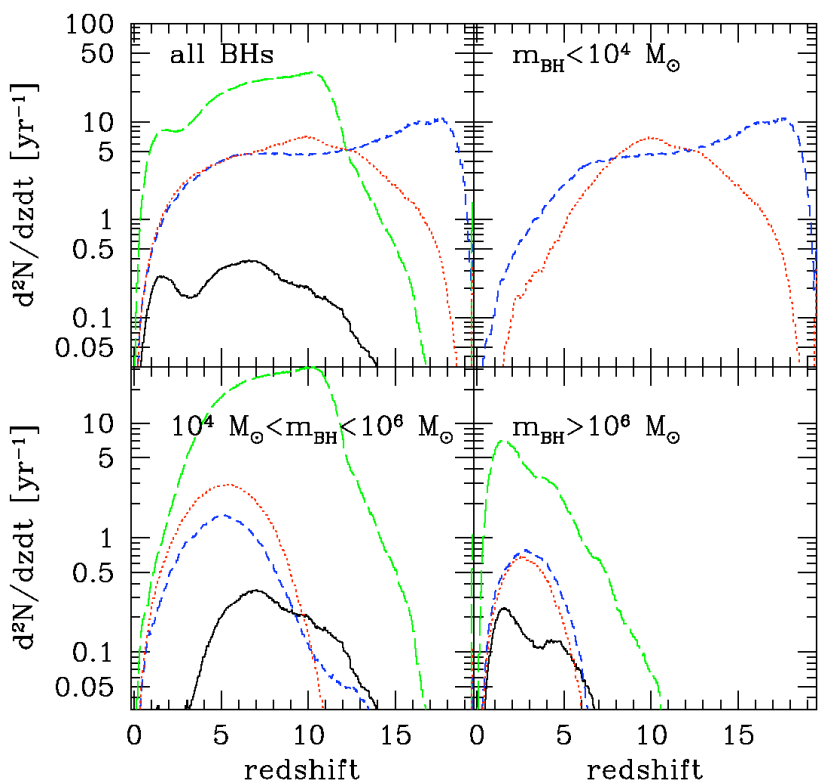


Figure 3-6: Predicted rates of massive black hole binary coalescences observable by LISA. Red, blue curves: scenarios with 150 $M_\odot$ black hole seeds resulting from the collapse of the first stars formed at $z > 20$, with black hole growth occurring by gas accretion during galaxy mergers. The black hole mergers are assumed to be driven initially by spherical stellar dynamics alone (red) or to be prompt (blue, *e.g.*, driven by gas drag). Black, green curves: scenarios with heavy seed black holes ~ 10^4-10^5 $M_\odot$. The green curve assumes the heavy seeds were produced in all dark halos with masses > 10^8 $M_\odot$ by $z = 15$. These merge to produce today's black holes (Koushiappas *et al.* 2004) The black curve assumes a much smaller number of similarly substantial seeds only in dark halos of > 10^{10} $M_\odot$, and requires that today's black holes grew mainly by gas accretion (from Volonteri 2006).

Observations show that our Universe is dominated by cold dark matter, and that its initial spectrum of perturbations was such that the first objects to collapse under their self-gravity were tiny systems the size of dwarf galaxies. These then fell into each other to create larger ones (see Figure 3-5). Present-day galaxies like our Milky Way grew by the merger of more than 1000 subunits, which started forming already at redshift higher than 20. If each of these subunits initially contained a seed black hole of $10^4 M_\odot$, the merger rate

seen by LISA could be as high as one thousand per year!

These elementary arguments suggest strongly that the merger rate of binary black holes that LISA will see lies in the range 1 - 1000 yr^{-1} (see Figure 3-6). The actual rate is proportional to: (1) the fraction of proto-galactic fragments that contain seed black holes massive enough for LISA to detect their mergers, multiplied by (2) the fraction of galaxy mergers that lead to black hole mergers. Our theoretical understanding of these fractions is limited and neither is well constrained observationally. LISA's measurements offer our best hope of determining them.

Seed black holes

The number densities and masses of the seed black holes largely determine their merger history. The similarity between $\rho_\bullet$ (the current best estimate for the mass density in black holes) and $\Delta\rho_\bullet$ (the density of rest mass that must have been accreted in order to produce the observed AGN) suggests that accretion does play a large part in the building of supermassive black holes. However, the estimates are also consistent with a significant fraction of the present black hole mass density being already present as black hole "seeds" by z = 10 - 20 (Koushiappas *et al.* 2004). In this scenario only a few of the seeds have grown through accretion to a billion solar masses, and these make up most of the mass we detect in supermassive black holes today and explain most of the accretion luminosity. The majority of seeds did not grow to high mass by accretion, so their presence and evolution is best traced by observing their mergers di-

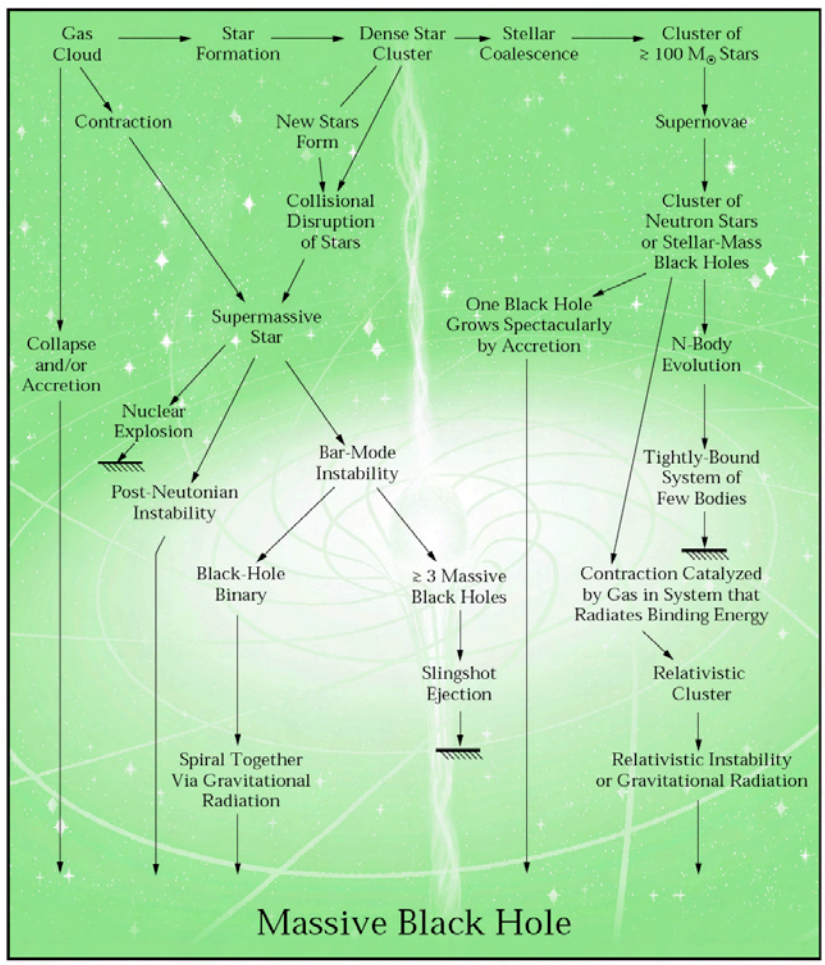


Figure 3-7: Scenarios for the formation of a massive black hole out of dense gas in the center of galaxies. From http://www.slac.stanford.edu/pubs/beamline/31/1/31-1-trimble.pdf (after Rees 1978).

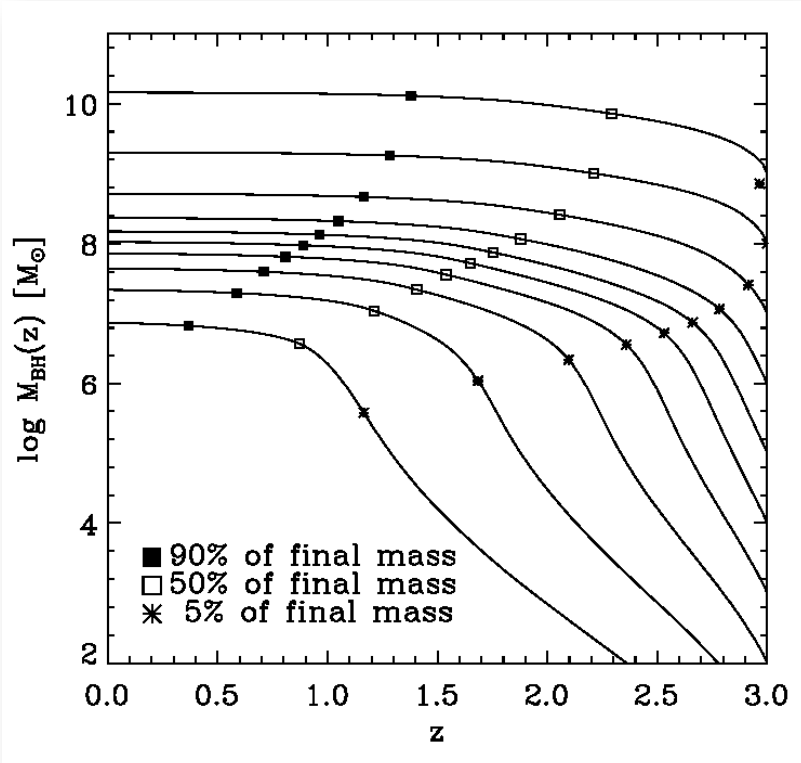


Figure 3-8: One possible growth history of black holes in active galaxies due to gas accretion, as a function of redshift and black hole mass, inferred from an X-ray selected sample of active galactic nuclei, assuming near-Eddington accretion (from Marconi *et al.* 2004).

rectly through gravitational radiation.

Broadly, there are two currently popular scenarios for these "seeds". The first supposes that they are the ~100 $M_\odot$ black hole remnants of the first stars to form from primordial gas in the Universe (so-called Population III stars: Abel *et al*. 2002; Bromm *et al.* 2002; Bromm & Larson 2004; Madau & Rees 2001).

The second scenario is motivated in part by the existence of quasars at z = 5 - 6 (when the Universe was not even one billion years old) so luminous as to require black holes $> 10^9 M_\odot$ even at that early time. This second scenario supposes that much more massive seeds (10^4-$10^5 M_\odot$) could grow either by direct collapse of radiation-dominated massive star-like objects (Rees 1978; Bond *et al.* 1984), or by rapid accretion at super-Eddington rates (Begelman *et al.* 2006). See Figures 3-7 and 3-8.

Understanding how black hole seeds formed is a challenging observational task. There may be a population of "mini-quasars" at high redshift powered by accretion onto seed black holes, but if the mass of the seeds is below $\sim 10^6 M_\odot$ their flux, diluted by the large distance light has to travel from the formation redshifts ($z \sim 10$ - 30), is too weak for single sources to be detected electromagnetically. There is however evidence for a nearby population of low-mass AGN at $z < 0.2$ (Barth *et al*. 2005). Seeds of mass $\sim 10^4 M_\odot$ can nevertheless be identified at high redshift during their mergers by observing their emission of gravitational radiation with LISA. Mergers may in fact play a much more important role in the higher-redshift Universe, because at $z > 5$ the merger rate is not limited by the Soltan-type argument that constrains the number of mergers at $z < 3$. Furthermore, constraints derived from the X-ray background actually limit the overall growth by accretion for black holes at $z > 6$.

The role of massive black holes in the evolution of early cosmic structure.

Active galactic nuclei powered by supermassive black holes keep the Universe ionized at $z < 4$, structure the intergalactic medium (IGM), and probably regulate star formation in their host galaxies. Intermediate mass black holes accreting gas from the surrounding medium may shine as "miniquasars" at redshifts as high as $z \sim 20$, with dramatic effects on the thermodynamics of the IGM (Kuhlen & Madau 2005). There are significant uncertainties about this key period in structure formation, from the fate of first stars (Abel, Bryan, & Norman 2002; Bromm *et al*. 2002; Bromm & Larson 2004) to the growth of $M > 10^9\ M_\odot$ black holes from seed black hole precursors in redshift $z > 6$ quasars (Madau & Rees 2001; Bromm & Loeb 2003) to the role of black holes in the reheating and reionization of the Universe (Madau *et al.* 2004) to the establishment at early epochs of the currently observed tight correlation between black hole mass and galactic bulge properties (Ferrarese & Merritt 2000; Gebhardt *et al.* 2000; Tremaine *et al*. 2002; Ferrarese & Ford 2005).

Models of hierarchical structure assembly predict that galaxy-sized dark matter halos will start to be common at redshifts $z \sim 10$ - 20 (see, *e.g.,* Mo & White (2002) for a pedagogical summary). This is also the epoch in which stars and galaxies first form in abundance, hence it is the beginning of the nonlinear phase of the Universe. However, electromagnetic observations of the properties and interactions of these early galaxies will be extremely challenging, because the first ones will be under-luminous dwarfs and because the surface brightness decreases as $(1 + z)^{-4}$.

In contrast, LISA observations of massive black hole coalescences from this epoch will be uniquely powerful in probing the halo mergers required in current models. The central black holes in many early halos are expected to have masses $M \sim 10^4$ - $10^6\ M_\odot$, corresponding to the redshifted mass range $10^5\ M_\odot < M(1+z) < 10^7\ M_\odot$ to which LISA will be most sensitive. The best current models predict tens of detected mergers per year at redshifts $z > 10$ (*e.g.,* Sesana *et al.* 2004). This is enough to characterize the redshift and mass distributions and discriminate between classes of structure formation models, in a crucial realm that is otherwise inaccessible to observation.

What happens when black holes collide and merge?

When two galaxies collide, the gravitational interactions between their stars and dark matter merge them into a ball of stars in $\sim 10^8$ yr. If both galaxies contain nuclear black holes, the black holes orbit within the ball of stars, and lose energy by deflecting the orbits of stars that pass near them. Within several orbital periods, the two black holes eject all the stars in their vicinity, and the rate of subsequent shrinking of their orbits is controlled by whatever stars and gas dribble in from larger radii, plus gravitational radiation (Merritt & Milosavljevic 2005). For black holes with mass $< 10^7 M_\odot$ (the ones to which LISA is sensitive), which live in galaxies with bulges

smaller than the Milky Way's, gravitational radiation alone will merge the black holes in less than 10^{10} yr (Yu 2002). In more massive galaxies, the larger pair of black holes can eject all their surrounding stars before the pair is close enough for gravitational radiation to merge them. Then, without a further dribble of stars or gas, the black holes could be left orbiting each other for longer than the age of the Universe, at orbital separations of 0.1 - 1 pc and orbital periods of 10^2 - 10^4 yr. However, it appears that many galaxies have sufficiently flattened or tri-axial bulges of stars, or enough gas that the continuing supply of material for the pair to eject continues to cause the pair's orbit to shrink. The black holes are eventually driven close enough together that gravitational radiation takes over and merges them on a fairly short timescale. Observational evidence, too, favors prompt mergers even among the massive black holes. If the close pairs were long lived, a third merger would frequently lead to a third black hole interacting with the pair, leading to ejection of all three black holes from the nucleus of the galaxy, contrary to observation (Haehnelt & Kauffmann 2002). Furthermore, the most compelling explanation for X-shaped and double-double radio galaxies is that they result from reorientation of the black hole spin following a merger (Zier 2006 and references therein).

Black Hole Spins

No hair and no naked singularities

In general relativity, astrophysical black holes are predicted to be completely described by exactly two parameters: mass and *spin* (vacuum relativity also allows an electric charge, but this is quickly shorted out to gravitationally insignificant levels in the real world). This is the famous theorem that "black holes have no hair " (Thorne 1995). The total spin angular momentum S is usually specified in terms of the angular momentum per unit mass $a = S/M$ or the dimensionless $a_\bullet = S/(GM^2/c) = S/M^2 = a/M$ (the last two equalities being true only in relativists' units where $G = c = 1$). For a specified mass M, a black hole described by relativity cannot have $a_* > 1$ without showing a naked *singularity i.e.* one uncloaked by an event horizon (and this would generally be forbidden by the Cosmic Censorship conjecture). The simple non-rotating Schwarzschild black hole has $a_* = 0$.

Predicted spins from formation and growth

So what values $0 < a_* < 1$ do astronomers now expect for astrophysical black holes? Rotating gas clouds and stars have $a_* > 1$, so black holes that form from their collapse have high spin ($a_* = 0.75$), and leave much of their angular momentum in a residual disk that could accrete and raise a_* still more (Shibata & Shapiro 2002; Gammie *et al.* 2004). However, as discussed above in the context of seed black holes, most of the black holes in galactic nuclei have masses well

above likely seed masses. Doubling the mass of a black hole is also enough to change a_* by of order unity, so the values of a_* probably depend more on the growth history than on the original spins of the seeds (Hughes & Blandford 2003, Gammie *et al.* 2004, Volonteri *et al.* 2005). One possible evolutionary path involves rapid disk accretion of interstellar gas onto the black hole. Evidently this was the dominant path for the rare quasar black holes, which are too large to be probed by LISA. Another possible path involves a combination of gas accretion with many generations of black hole mergers. A third possibility for the growth of black holes is the random accretion of small packets of less dense material, such as material from tidally disrupted individual stars.

Merging binary black holes of comparable masses also have orbital angular momentum much larger than the maximum allowed for the merged black hole. However, recent numerical relativity simulations of the merger of equal mass, non-spinning black holes show that enough angular momentum is radiated to avoid a naked singularity, and the final steady-state merged black hole has $a_* = 0.7$ (Pretorius 2005). Simulations of the mergers of equal-mass rapidly rotating Kerr holes suggest it is unlikely to create a maximally rotating hole in this way; a maximum final value of $a/M = 0.89$ was produced from two holes with individual spin parameters $S/M^2 = 0.757$ aligned with the orbit (Campanelli *et al.* 2006).

By contrast, growing a black hole by accreting small companions (*e.g.*, stars or stellar mass black holes of mass M_c) which fall in on isotropically distributed orbits causes a secular decrease $a_\bullet$. If $M \gg M_c$, the angular momentum is essentially determined by a random walk, and $a_* \sim (M_c/M)^{1/2} \sim 10^{-3}$. This mechanism of black hole growth is most plausible for lower luminosity AGN and black holes of $< 10^7 M_\odot$ (Milosavljevic *et al.* 2006). In nuclear clusters dense and massive enough to supply enough stars to grow black holes of 10^8-$10^9 M_\odot$, stars collide (Figure 3-7; Rauch 1999). The subsequent evolution is hard to model, and there is no compelling evidence for the existence of such massive clusters.

Accreting unmagnetized gas in a thin disk with a steady direction of angular momentum drives a black hole to $a_* = 0.998$ after the accretion has increased its mass by a factor of 2.5 (Thorne 1974). Magnetized accretion disks are less effective at spinning up black holes, since they also lose angular momentum electromagnetically through disk winds, torques in the region where the gas begins to plunge into the black hole, and through magnetically-mediated extraction directly from the black hole. Simulations suggest that these effects may limit the final spins to $a_* \sim 0.9$, in contrast to the $a_* = 0.998$ of an unmagnetized thin disk (Krolik *et al.* 2005; Hawley & Krolik 2006). These results are summarized Table 3-1.

Although massive black holes could form by any combination of these processes, numerical astrophysics and relativity have show that these different mechanisms can produce very different distributions of black hole spins, skewing the distribution to high or low spins or spreading it evenly over a wide range of spins. No other astronomical observable can provide such a direct probe into the history of a key structural constituent of the Universe, and LISA will be able to measure such spins to better than 1% accuracy.

Table 3-1 Black hole spin characteristics for different growth scenarios (a-e), and representative efficiencies in converting accreted mass into radiation. Here efficiencies are calculated assuming no torque inside the innermost circular orbit, and corrected for the radiation emitted by the disk and swallowed by the hole (Thorne 1974).

black hole spin a_*	thin disk radiation efficiency (corrected for capture by hole) $\epsilon = L_{\rm disk}/(\dot{M}c^2)$
0^a	0.057
0.7^b	0.133
0.9^c	0.151
0.998^d	0.308
1^e	0.400

[a] result of isotropic accretion of small bodies.
[b] result of collapse or equal mass merger.
[c] approx equilibrium spin in magnetised disk accretion.
[d] equilibrium spin in unmagnetised disk accretion.
[e] maximal rotation before naked singularity appears.

Merging massive black holes: Open questions and LISA's answers

There is strong evidence from electromagnetic observations that the many diverse phenomena of active galactic nuclei, ranging from giant radio jets to quasars, ultra-luminous infrared galaxies, the X-ray background and gamma-rays from blazars are all caused by accretion onto black holes. There is also strong evidence that galaxies grow by mergers, and that those mergers cause inflow of gas into the nuclear regions, exciting starbursts and feeding the central black holes. The winds and radiation from the stars and accreting black holes in turn expel the remaining gas, and determine the structure of the galaxy (Begelman 2003; Murray *et al*. 2005; Hopkins *et al*. 2006). While this evidence from electromagnetic observations is compelling, it is incomplete. Many fundamental questions about black holes and the galaxies they inhabit remain, which LISA will address:

- Except in a very small number of cases, the masses of the black holes in both quiescent and active galaxies are uncertain by factors of at least a few (due to the difficulty of constraining observationally the complications of stellar and gas dynamics). This prevents us from improving our understanding of accretion disk structure and dynamics. LISA observations of merging MBHs will reveal both their masses to typically less than 1% (Lang & Hughes 2006).
- Today, almost nothing is known observationally about the high-redshift merger tree that led to the galaxies we see today (see Figure 3-7). LISA observations of merging MBHs represent one of our best chances of observing this complex history. LISA can determine the binary's

luminosity distance, typically to within a several percent. Assuming the standard concordance cosmology, this distance gives us the binary's redshift. Thus one can deduce the MBH merger rate as a function of z, and so trace the early history of galaxy mergers and the build-up of MBH masses over time (at least for those of solar masses). Today, the fraction of low-luminosity galaxies with black holes at $< 10^6 M_\odot$ is unknown at all redshifts.

- The spins of both quiescent and active black holes are poorly known. The distribution of spins will be strongly diagnostic of the mechanism of black hole growth (see discussion above on predicted spins). And the spins themselves are vital to many models of electromagnetic phenomena: jet formation, jet twists, accretion efficiency, tidal disruption events. LISA observations of MBH mergers will reveal the spin parameters a_* of the merging BHs to within 1% (Lang & Hughes 2006). EMRI detections (see below) should typically reveal the MBH spin a_* to within ~ 0.01% (Barack & Cutler 2004).

Direct gravitational wave observations of these objects, which we now assume to be black holes, whether through their mergers or their capture of compact stellar-mass companions, should resolve these questions with a precision and certainty unachievable by other modes of observation.

Stellar captures and the dynamics of galactic nuclei

Some of the most exciting astrophysics with LISA will come from observing the gravitational waves produced by inspirals of stellar-mass compact objects into massive black holes. There is compelling indirect evidence that these inspirals are common throughout the Universe and occur about once per million years in galaxies like the Milky Way (Freitag 2003, Hopman & Alexander 2006). Because the mass ratio for these binaries is typically ~ 10^{-5}, these sources are commonly referred to as extreme mass ratio inspirals, or EMRIs.

White dwarfs, neutron stars, and stellar-mass black holes all share the property that they reach the last stable orbit around the massive black hole (MBH) before they are tidally disrupted; hence all three types of compact stars can in principle lead to observable EMRI signals. However, black holes (BHs), being more massive, are expected to dominate the observed rate for LISA, for two reasons: mass segregation tends to concentrate the heavier compact stars nearer the MBH, and BH inspirals have higher signal-to-noise, and so can be seen within a much larger volume.

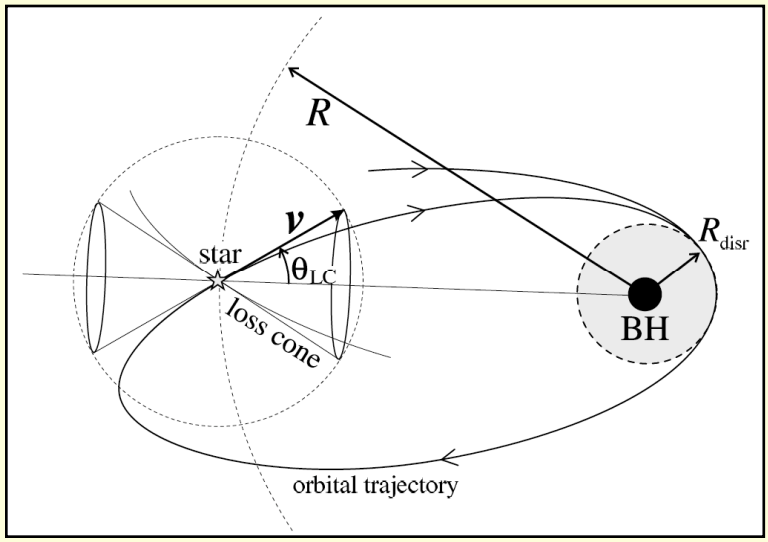
There are currently about 20 confirmed stellar-mass black holes, with estimated masses in the range ~ 5 - 15 $M_\odot$. However, it is generally believed that there are tens of millions of them in our galaxy, since they are expected to be produced in the deaths of massive (greater than ~ 20 - 25 $M_\odot$) stars (Woosley *et al.* 2002). The mechanism of mass segregation insures that the fraction of stars that are black holes is much higher very near the central MBH than at a random spot in the galaxy. In the Milky Way, near Sgr A*, it is estimated that there are several thousand stellar-mass BHs in the innermost parsec (Miralda-Escudé & Gould 2000; Freitag *et al.* 2006)

and that stellar-mass BHs dominate the total stellar mass within 0.01 parsec.

The oldest and best understood mechanism for creating EMRIs is that two-body encounters between stars in a dense stellar cluster near the MBH result in diffusion in each one's specific angular momentum, J. For non-rotating (Schwarzschild) MBHs, if J is reduced below about $4M$ (where M is the MBH mass), then the star plunges directly into the MBH. More interesting for LISA are the compact stars that diffuse into very high-eccentricity orbits, but that do not plunge directly. If the changes in J bring the value down to roughly $6M$, substantial energy starts to be lost due to gravitational radiation. The apocenter of the orbit shrinks as energy is radiated, and it is possible for the apocenter to shrink enough that the compact star essentially ceases to interact with the other stars near the center of the galaxy, and gravitational radiation reaction completely drives the final evolution of the orbit.

Mechanisms for creating extreme mass ratio inspiral (EMRI) events

Three different mechanisms for the production of EMRIs have been explored in the literature. The oldest and best-understood mechanism is the diffusion of stars in angular-momentum space, due to two-body scattering. Compact stars in the inner ~ 0.01 pc will sometimes diffuse onto very high eccentricity orbits, such that gravitational radiation will then shrink the orbit's semi-major axis and eventually drive the compact star into the MBH. This diffusion of stars into the "loss cone" is illustrated in the figure below.



Important physical effects setting the overall rate for this mechanism are mass segregation, which concentrates heavy, ~ 10 solar mass BHs close to the MBH, and resonant relaxation (the stars in the inner cusp are on nearly periodic orbits around the MBH, so the same two stars will interact with each other repeatedly), which increases the rate of diffusion (Hopman & Alexander 2006). The other two proposed mechanisms for producing EMRIs are tidal disruption of binaries that pass close to the MBH (Miller *et al*. 2005) and the creation of massive stars (and their rapid evolution into compact objects) in accretion disks surrounding MBHs (Levin 2006). It is not clear which mechanism will actually dominate the rate; indeed, all three could be roughly comparable.

Unfortunately, other scenarios can occur also. If J random-walks away from near zero before the BH-MBH system becomes substantially more tightly bound, then the losses due to gravitational radiation become negligible. Or, if J decreases to about $4M$ before much energy is radiated away, the black hole will plunge into the MBH rather than spiral in gradually. The gravitational wave signal then would not last long enough to produce a detectable signal-to-noise ratio. For a MBH of ~ 3 - 4 million solar masses (such as the one at the center of our Milky Way), gradual inspirals – the observable LISA sources – arise from the stars that are scattered

towards the MBH from distances within a few times 0.01 parsec (Hopman & Alexander 2006). For such gradual inspirals, the last years of inspiral will typically be observable by LISA. Compact stars that are scattered into low-J orbits start out with orbital eccentricity very close to unity ($1 - e \sim 10^{-4}$), and their orbits remain moderately eccentric until the final plunge; median final eccentricities might be $e \sim 0.2$.

It is estimated that most LISA detections of EMRIs will come from $\sim 10\ M_\odot$ BHs spiraling into MBHs with masses in the range $\sim 10^6$ - $10^{6.5}\ M_\odot$. The space density of MBHs in this mass range is $\sim\ 1.7 \times 10^{-3}\,\mathrm{Mpc}^{-3}$, and LISA can detect such sources out to $z \sim 1$, corresponding to a co-moving volume of $\sim 200\ \mathrm{Gpc}^3$. The two-body scattering mechanism discussed above leads to a rate (of observable inspirals) in Milky Way-type galaxies of $\sim 2.5 \times 10^{-7}\,\mathrm{yr}^{-1}$ (Hopman & Alexander 2006), which then implies a LISA detection rate $\sim$ 85/yr (Gair *et al.* 2004). (The above estimate ignores "edge effects" related to the fact that inspirals ending in the first few months after LISA turns on will generally not be observable, since not enough signal-to-noise will have built up. Also EMRIs with unfavorable orientations will not be observable to $z = 1$, so a more conservative estimate would be $\sim$ 50/yr.) The uncertainty in this rate is perhaps a factor of ~ 20.

In addition to the two-body scattering mechanism, other proposed channels for EMRIs are tidal disruption of binaries that pass close to the MBH (Miller *et al.* 2005) and creation of massive stars (and their rapid evolution into black holes) in the accretion disks surrounding MBHs (Levin 2006). Either of these channels could lead to a rate of the same order of magnitude as quoted above for two-body scattering, and this multiplicity of channels gives added confidence that at least one of them will produce a significant detection rate for LISA. Given a reasonable sample of detections, it should also be possible to infer the relative contributions from the different EMRI channels listed above. That is because two-body scattering leads to EMRIs that are moderately eccentric and have arbitrary inclination with respect to the MBH spin. In contrast, tidal disruptions of binaries lead to EMRIs that also have arbitrary inclination, but whose eccentricities are very close to zero; this is because tidal disruption results in orbits with (initially) much larger pericenter than for two body scattering, giving more time for radiation reaction to circularize the orbit before it becomes visible to LISA. Disk formation of EMRIs leads to sources with zero eccentricity and zero inclination (*i.e.*, orbital angular momentum parallel to the MBH's spin angular momentum). The orbital inclination and eccentricity can both be measured with very high accuracy from the LISA data (Barack & Cutler 2004).

During the last years before merger, the motion is highly relativistic, with speeds typically a third the speed of light. The period for precession of periapsis is comparable with the period for radial motion, and the orbital plane precesses just a few times less rapidly if the MBH has large spin. Thus the motion is quite complex, and correspondingly, the number of templates needed to do a brute force search for the signal is extremely high. Indeed, a brute force search for the signal over a year or more of data will not be possible, even with the computer power available in 2016.

Fortunately, Gair *et al.* (2004) were able to show that the search problem can be overcome by using shorter time intervals for the initial searches, and then combining the results incoherently.

For three-week initial intervals, the computational resources required are reduced to reasonable levels. The main penalty of this approach is that the signal-to-noise ratio required for a successful search is increased from roughly 15 to 30-35. (That is, the source strength must be such that the combined, matched-filtering signal-to-noise using two independent LISA channels is 30-35.) Whether other search methods can be found that will avoid this increase in the required signal-to-noise ratio is now under investigation.

Recently, much more detailed simulations of EMRI events and of the stellar and compact object populations in galactic nuclei have been carried out by several different groups (Alexander & Hopman 2003; Freitag 2004; Hopman & Alexander 2005, 2006). As noted, there are still substantial uncertainties in the rates for EMRI events, because current observations simply do not impose strong constraints on models of the stellar swarms in galactic nuclei. The event rates for black hole EMRIs as a function of MBH mass will give detailed information on conditions in the galactic nuclei that probably cannot be obtained in other ways. The estimated event rates for white dwarf and neutron star EMRIs are considerably lower, but such events also are likely to contribute to clarifying conditions in the galactic nuclei.

Barack & Cutler (2004) showed that EMRI observations will permit measurement of the MBH spin parameter a_* with extremely high accuracy: $\Delta a_* \sim 10^{-4}$. Hence LISA is likely to provide a databank of hundreds or more black hole spins in the low-redshift ($z < 1$) Universe. As noted above, this spin distribution is highly sensitive to the evolutionary paths of the MBHs (Hughes & Blandford 2003, Gammie *et al*. 2004, Volonteri *et al.* 2005). No other astronomical observable provides such a direct probe into the history of MBHs, which chart the history of galaxies themselves.

LISA science objectives and investigations relevant to this section (see Appendix 1)

1. Understand the formation of massive black holes

1.1. Search for a population of seed black holes at early epochs.

1.2. Search for remnants of the first (Pop III) stars through observation of intermediate-mass black hole captures, also at later epochs.

2. Trace the growth and merger history of massive black holes and their host galaxies

2.1. Determine the relative importance of different black hole growth mechanisms as a function of redshift.

2.2. Determine the merger history of 10^4 to 3×10^5 $M_\odot$ black holes before the era of the earliest known quasars ($z \sim 6$).

2.3. Determine the merger history of 3×10^5 to 10^7 $M_\odot$ black holes at later epochs ($z < 6$).

3. Explore stellar populations and dynamics in galactic nuclei

3.1. Characterize the immediate environment of MBHs in $z < 1$ galactic nuclei from EMRI capture signals.

3.2. Study intermediate-mass black holes from their capture signals.

3.3. Improve our understanding of stars and gas in the vicinity of Galactic black holes using coordinated gravitational and electromagnetic observations.

4. Black Hole Physics: Confronting General Relativity with Precision Measurements of Strong Gravity

Setting the stage

Key science questions

- Is the strong field gravity correctly described by GR?
- Are the massive dark central objects in galaxies really black holes?

General relativity (GR) is a theory of gravity, one of the fundamental forces of nature, in which gravitational fields are manifested as curvature of spacetime. GR was put forth by Albert Einstein nearly one hundred years ago as a remarkable marriage of physical insight and mathematical beauty. In its first experimental triumph, GR provided an elegant solution to an outstanding physical conundrum, the missing 43 seconds of arc per century in the precession of Mercury's perihelion that could not be accounted for by Newtonian gravity. The advances in our ability to measure such small effects during the latter part of the 19th century provided this precision probe of the gravitational field near the Sun, and a confrontation with Newtonian gravity. Today, in the early years of the 21st century, LISA provides the means to confront GR with experimental measurements at levels of precision and gravitational field strengths unimaginable a hundred years ago.

GR has no adjustable (or free) parameters and makes solid, specific predictions. While any test can therefore potentially be fatal, any failure of GR can point the way to new physics. Confronting GR with experimental measurements, particularly in strong gravitational fields, is an essential enterprise. And despite its great successes, we know that GR cannot be the final word on gravity, since it is a classical theory and so must break down at the Planck scale. As yet there is no complete, quantum theory of gravity, and gravitation is not yet unified with the other fundamental fields

While so far GR has passed all the tests to which we have subjected it (Will 2006), most of these tests have been in the weak-field regime, which we can define by using the parameter $\varepsilon \sim v^2/c^2 \sim GM/(Rc^2)$. Here v is the typical velocity of the bodies, M their mass, and R their typical separation. In weak gravitational fields, $\varepsilon \ll 1$. For many astrophysical situations, such as Solar System dynamics, a fully general relativistic treatment is beyond our capabilities, but it is both practical and perfectly adequate to describe the dynamics using post-Newtonian (PN) equations, which are derived from the full general relativistic equations by systematically expanding them as a power series in ε. For the tests of GR that have been carried out in our Solar System, second-order corrections are of order $\varepsilon \sim 10^{-16}$, and so to-date it has been sufficient to model Solar System dynamics using first-order PN equations. Solar System tests have been completely consistent with GR, to this order of approximation.

Binary pulsars, which are essentially very stable and accurate clocks with typical orbital velocities $v/c \sim 10^{-3}$, can be seen as Nature's gift to relativists (Lorimer 2005). They have been excellent laboratories for precision tests of GR in gravitational fields considerably stronger than those prevailing in our Solar System. Current observations of several binary pulsars are perfectly consistent with GR predictions, as calculated through first PN order. Observations of the first binary pulsar to be discovered, PSR B1913+16, also provided the first astrophysical evidence for gravitational radiation (earning the Nobel Prize for the binary's discoverers, Hulse and Taylor). Loss of energy due to gravitational-wave emission (radiation reaction) causes the binary's orbit to shrink slowly; its period derivative $\dot{P}$ (an $O(\varepsilon^{2.5})$ effect) agrees with that predicted by GR to within 0.2%, which is within the error bars (Weisberg & Taylor 2004). The double pulsar system, PSR J0737-3039 A and B, discovered three years ago, should in the future provide even better tests of GR, for several reasons: it is the most highly relativistic of the known pulsar binaries; its distance and acceleration (relative to us) are much smaller; and, since both neutron stars are pulsars, it was possible to determine the mass ratio almost immediately from Newtonian-level dynamics, rather than having to infer it from relativistic effects. The last has made possible several additional GR tests that were not available previously (Kramer *et al.* 2006). The orbital period derivative has already been measured (and is consistent with GR at the 1.4% level), and second-order PN effects are expected to be measurable within several years (Kramer *et al.* 2006). (Why is radiation reaction – an $O(\varepsilon^{2.5})$ effect – more measurable than the $O(\varepsilon^{2})$ PN effects? Because radiation reaction drains energy from the system and so causes inspiral, its effect on the orbital phase grows quadratically with time. By contrast, the first- and second-order PN equations are conservative, and so their effect on the orbit grows only linearly in time. For observation times T of order $P/\varepsilon^{-0.5}$, the non-conservative $O(\varepsilon^{2.5})$ effect is more measurable than the second-order PN corrections.) And binary pulsars provide some important tests of truly strong-field gravity—basically because the redshift at the surface of a neutron star is of order 0.2. While the effects of this strong internal gravity on the neutron star orbits is essentially "effaced" within GR (since GR enforces the strong equivalence principle) this is not true in all potential rivals to GR. In particular, binary pulsars can provide important limits on some scalar-tensor theories, where internal gravity as strong as that in neutrons stars can produce order unity departures from GR predictions for the orbital motions (Damour 2000).

Nevertheless, LISA observations of coalescing massive black hole (MBH) binaries, or of stellar-mass compact objects spiraling into MBHs, will allow us to confront GR with precision measurements of physical regimes and phenomena that are clearly not accessible to Solar System or binary pulsar measurements. The merger of comparable-mass MBH binaries at cosmological distances produces an enormously powerful burst of gravitational radiation, which LISA will be able to measure with amplitude signal-to-noise as high as several thousand. In the months prior to merger, LISA will detect the gravitational waveform due to the binary's inspiral and, from that inspiral waveform, the masses and spins of the two MBHs can be determined to high accuracy. Given these physical parameters, numerical relativity will be able to predict the exact shape of the burst waveform, and this can be compared directly to the observed burst – providing an ideal test of the pure GR, in the highly dynamical, strong-field regime.

Stellar-mass compact objects spiraling into MBHs will provide a qualitatively different sort of test, but an equally exquisite one. The compact object travels on a near-geodesic of the spacetime of the MBH, and as it spirals in, it effectively maps out the spacetime surrounding the MBH. For these extreme-mass-ratio inspirals (EMRIs), LISA will typically observe of order 10^5 cycles of inspiral waveform, all of which are emitted as the compact object spirals from 10 horizon radii down to a few horizon radii. Encoded in these waves is an extremely high precision map of the spacetime metric, just outside a rapidly rotating, MBH. Better opportunities than these for confronting GR with actual strong-field observations could hardly be hoped for. (One caveat, however, is that LISA observations of black hole (BH) binaries cannot discriminate between GR and scalar-tensor theories of gravity. The reason is that black holes do not support scalar fields; *i.e.*, they have no scalar "hair". Even after LISA flies, the best limits on scalar-tensor theories will come from Solar System and binary pulsar measurements; see Esposito-Farese 2004)

Did Einstein have the last word on gravity?

At the dawn of the 20th century, Newton's theory of gravity was astonishingly successful. It provided a compelling and beautiful explanation of gravitational effects throughout the known cosmos. Newtonian gravity successfully predicted the existence of a previously unknown planet in the Solar System. The theory passed every known experimental test, except one. Precision measurements of the precession of the perihelion of Mercury's orbit about the Sun revealed a small discrepancy of 43 seconds of arc per century. Newtonian gravity was unable to account for this anomalous precession, which was seen only in the orbital motion of the planet closest to the Sun – the planet where the Sun's gravity is strongest. GRs first triumph was to account naturally for this anomalous 43 seconds of arc per century.

At the dawn of the 21st century, Einstein's theory of gravity is astonishingly successful. It also provides a compelling and beautiful explanation of gravitational effects through the cosmos as we know it today. GR successfully predicted phenomena such as gravitational lensing, black holes, and gravitational waves, and provides a natural framework for the expansion of the Universe. GR has passed every experimental test to date. But there is no well established quantum theory of gravity, and gravity is not yet unified with the other fundamental fields.

LISA provides unparalleled opportunities for making precision measurements in the regime of very strong and dynamical gravitational fields. Will such measurements unveil any flaws in the otherwise solid and successful edifice of GR? Even on macroscopic scales Newton did not have the last word on gravity.... did Einstein?

Now, this strong-field regime will quite likely be observed by ground-based gravitational-wave detectors several years before LISA flies (*e.g.*, the Advanced LIGO detectors should come online ~ 2014 and LIGO is expected by that point to have observed stellar mass BH mergers where the components are of roughly comparable mass). However, even the brightest BH mergers that LIGO will likely observe will still have amplitude signal-to-noise ratio ~100 times smaller than the brightest MBH mergers that LISA will observe. The precision with which LISA can measure the merger and ringdown waveforms will correspondingly be ~100 times better than for ground-based detectors. Similarly for extreme mass ratio inspirals: while the ground-based detectors may detect binaries with mass ratios ~ 10^{-2} (*e.g.*, a neutron star spiraling into a 100 $M_\odot$ BH), in observations lasting ~10^2 – 10^3 cycles, the precision with which the spacetime can be mapped in such cases is at least two orders of magnitude worse than what is achievable with

LISA's EMRI sources. Thus LISA will test our understanding of gravity in the most extreme conditions of strong and dynamical fields, and with a precision that is two orders of magnitude better than attainable from the ground.

GR has been extraordinarily fruitful in correctly predicting new physics, including the gravitational bending of light (or gravitational lensing), the gravitational redshift, black holes and gravitational waves. GR also provided the overall framework for modern cosmology, including the expansion of the Universe. Even if GR is fully correct (on length scales of astrophysical interest), LISA may reveal more new physics from strong-field GR. The famous singularity theorems of Penrose and Hawking assert that sufficiently compact objects must collapse, resulting in some spacetime singularity, but it is only a conjecture that the singularity is generically clothed by a black hole's event horizon. Might LISA reveal naked singularities or some other object formed of strongly warped spacetime? Could some central objects in galactic nuclei represent some other form of matter, such as massive boson or soliton stars? Since our understanding today of the nonlinear, strong gravity regime of GR is quite limited, using LISA to explore gravitational fields in the dynamical, strong-field regime could reveal new objects that are unexpected, but perfectly consistent with GR.

The inspiral, merger, and ringdown of MBH binaries

LISA's strongest sources are expected to be coalescing MBH binaries where the components have roughly comparable masses, $0.1 \lesssim M_2/M_1 < 1$. The coalescence waveforms will be visible by eye in the data stream, standing up well above the noise, as illustrated in Figure 4-1.

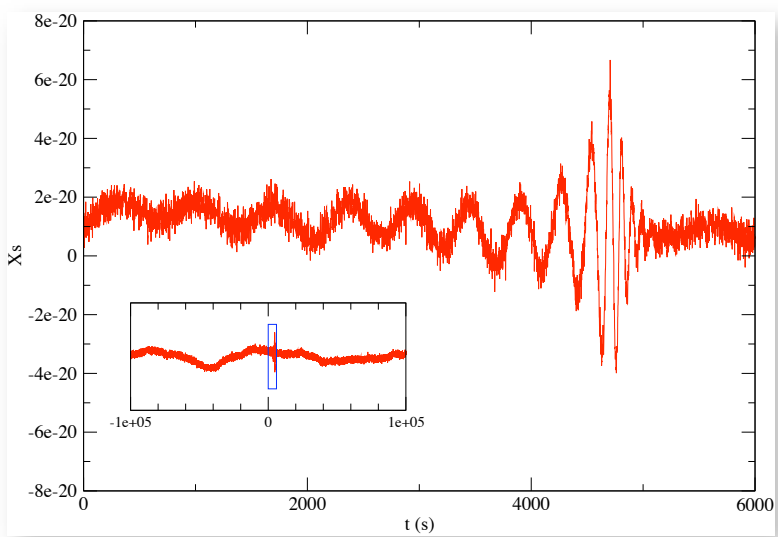


Figure 4-1: Gravitational wave signal for the final few orbits, plunge, merger and ringdown of an MBH-MBH binary. Here both MBHs have mass $2 \times 10^5 M_\odot$, and are not spinning, the binary is at *z* = 5, and is seen face-on. The signal is the sum of the gravitational waveform and simulated LISA noise. Note that even at *z* = 5, the waveform stands up well above the noise and is visible in fine detail. The inset shows a longer stretch of data, containing the merger waveform. The large-amplitude, low-frequency "wiggles" are due to LISA's acceleration noise, which rises at lower frequencies.

As depicted in Figure 4-2, the coalescence can be described in three stages: inspiral, merger, and ringdown (Flanagan & Hughes 1998), all of which will typically be observable by LISA. The inspiral stage is a relatively slow, adiabatic process in which the BHs spiral together on quasi-

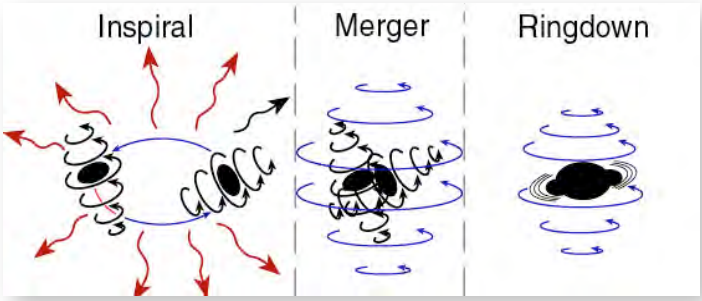


Figure 4-2: Schematic drawing of the three stages of the final coalescence of a comparable mass black hole binary, with spinning holes.

circular orbits. The BHs have wide enough separations that they can be treated as point particles within the PN approximation; consequently, this stage can be computed analytically, with high-order PN expansions. The inspiral is followed by the dynamical merger, in which the BHs leave their quasi-circular orbits and plunge together, forming a highly distorted remnant BH. Here, the BH velocities approach v/c ~1/3, the PN approximation breaks down, and the system can only be analyzed using numerical relativity simulations of the full Einstein equations. The distorted remnant settles into a stationary Kerr BH as it "rings down" by emitting gravitational radiation. While numerical relativity is required to tell us the initial state of the distorted BH, the evolution of that distortion—its "ringing down"—can be interpreted in terms of BH perturbation theory. At the end of the ringdown the final black hole is left in a quiescent state, with no residual structure besides its Kerr geometry. Its spacetime metric is then determined fully by its mass and spin, as required by the BH "no-hair" theorem.

For equal-mass MBH binaries with total mass in the range $3 \times 10^5 < M(1+z) < 3 \times 10^7 M_\odot$ where z is the cosmological redshift, the three stages all have comparable signal-to-noise; *i.e.*, within an order of magnitude of each other (see Figure 6 of Flanagan & Hughes 1998). From a typical LISA observation of the inspiral part of the signal, it should be possible to determine the physical parameters of the binary to extremely high accuracy. Using these parameters, numerical relativity should be able to predict precisely the merger and ringdown waves. The merger and ringdown waveforms will typically stand out well above the noise (by a factor $\sim 10^2 - 10^3$ after the noise has been band-passed to remove the large noise contribution from very low- and high-frequencies), so an extremely clean comparison will be possible between the observed waveforms and the predictions of GR.

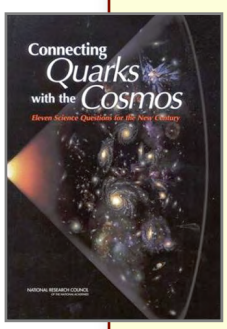
We will now discuss the three stages of binary coalescence in greater detail, taking them in turn.

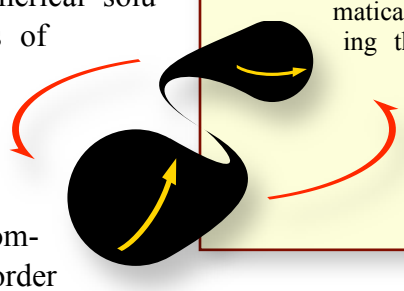
The inspiral stage: inferring the binary's masses and spins

With orbital velocities typically in the range $v/c \sim 0.05$ - 0.5, most of the inspiral stage can be well described using high-order PN equations. The inspiral waveform is a chirp: a sinusoid that increases in frequency and amplitude as the BHs spiral together. The part of the inspiral stage that is observable to LISA lasts of order months to years. (More precisely, when the gravitational-wave frequency sweeps past 10^{-4} Hz, the time remaining until merger is approxi-

mately $1.7 \times 10^8 s(0.25/\eta)[M(1+z)/2 \times 10^5 M_\odot]^{-5/3}$ where $M \equiv M_1 + M_2$ is the total mass of the binary and $\eta \equiv M_1 M_2 / M^2$ is the symmetric mass ratio. LISA will observe the last $10^4 - 10^5$ GW cycles from the inspiral. Since the inspiral signal is quite well understood theoretically, matched filtering can be used to dig these inspiral waveforms out of the noise, starting more than a year before the final merger, when the waves do not yet stick up above the noise as in Figure 4-1. And because the inspiral waveforms are strong, long-lived, and well-understood, it should be possible from the inspiral alone to determine the system parameters to amazingly high accuracy. Both masses should be determined to within fractional error $\sim 10^{-3}$, and their spins should be measured to within $\sim$ 0.1 - 1% (Lang & Hughes 2006).

These are the size of random errors due to instrumental noise and confusion noise from white-dwarf (WD) binaries. Although the waveforms available today are completely adequate for detection of waves, there will be some systematic errors in measured parameters due to the fact that the inspiral "template" waveforms, necessary for parameter estimation, will not be perfectly known theoretically. Highly accurate numerical solutions for tens of thousands of orbits are well beyond our current abilities, and will likely remain so for some time. However, great advances have been made in computing the inspiral to high order in PN theory. For non-spinning bodies on nearly circular orbits, the PN dynamics have been completely solved up through order $O(\varepsilon^{3.5})$ and the radiation reaction effects have been solved up through $O(\varepsilon^6)$: three-and-a-half orders beyond the order where radiation reaction effects first enters (Nissanke & Blanchet 2005). The influence of BH spin on the waveform phase has al-





Numerical relativity: Meeting the theory challenge

Recent dramatic advances in numerical techniques for simulating BH mergers and computing their waveforms have boosted opportunities for confronting GR with LISA observations. The importance—and difficulty—of calculating the gravitational waveforms from black hole mergers had been recognized by the AANM, Q2C, and Gravitational Physics decadal reports as a major theory challenge in this field. In the words of the Q2C report (page 118):

> "Nearly as difficult as building these (gravitational wave) observatories, however, is the task of computing the gravitational waveforms that are expected when two black holes merge. This is a major challenge in computational general relativity and one that will stretch computational hardware and software to the limits. However, a bonus is that the waveforms will be quite unique to general relativity, and if they are reproduced observationally, scientists will have performed a highly sensitive test of gravity in the strong-field regime."

Numerical relativists have attempted to calculate gravitational waveforms from black hole mergers for over 30 years. The first full orbit of an equal mass, non-spinning black hole binary was finally achieved in late 2003. Roughly 1½ years later the field exploded, as several groups developed the means to simulate the final few orbits, plunge, merger and ringdown using dramatically different methodologies and achieving the same resulting gravitational waveforms. The first simulations with non-equal masses, and with spins, followed quickly. Numerical relativity is currently in an era of much activity and rapid progress, on a broad front

ready been calculated to 2.5 orders beyond the lowest-order radiation reaction terms (Blanchet *et al.* 2006). And for binaries with very small mass ratio, the PN expansion is known to still much higher order. Additionally, it should also be possible to use numerical solutions to the late stages of inspiral to check and refine proposed methods for accelerating the convergence of the PN expansion, such as Pade approximants. Therefore it seems very likely that well before LISA flies, theorists will be able to reduce to a very low level any systematic parameter estimation errors due to inaccurate theoretical inspiral waveforms.

The merger stage: Spectacular bursts

The inspiral is followed by a dynamical merger that produces a burst of gravitational waves. This is a brief event, comprising several cycles $\sim 10^3$ s $M/(10^6 M_\odot)$. However, it is fantastically energetic: during merger the gravitational-wave luminosity is $L_{GW} \sim 10^{23} L_\odot$, in that time producing more power than all the stars in the observable Universe. The final merger of MBH-MBH binaries occurs in the very strong-field, highly non-linear and highly dynamical regime of GR and is the strongest gravitational wave source that LISA is clearly predicted to see. LISA will be able to see the merger of two $10^4 M_\odot$ BHs out to redshift $z \sim 20$, and for mergers of $\sim 10^6 M_\odot$ BHs at $z \sim 1$ the LISA signal-to-noise will be in the thousands; see Figure 4-3. As mentioned above, LISA observations of the inspiral should give the masses and spins of the MBH components to ~0.1%. With these in hand, numerical relativity will make a very specific prediction for the merger and ringdown radiation from the system. Comparison with the waveform that LISA actually observes will allow us to confront the predictions of GR with an ultra-high precision measurement in the fully nonlinear and dynamical regime of strong gravity.

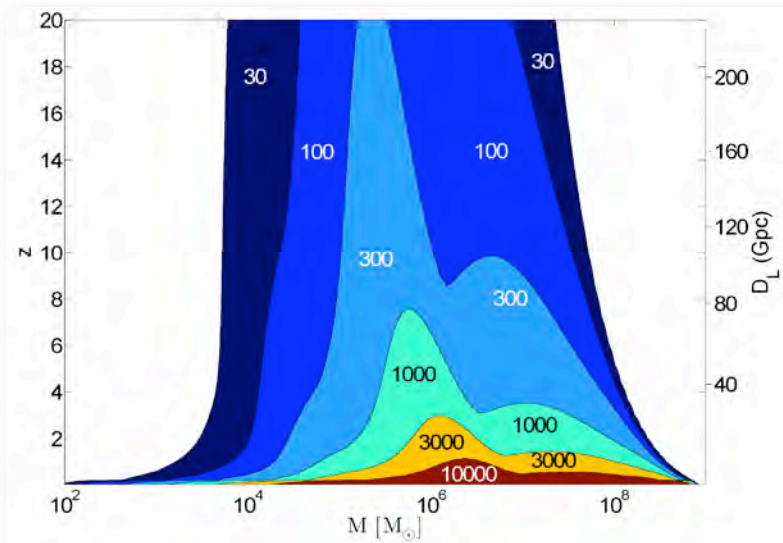


Figure 4-3: Plot of total signal-to-noise (in one synthetic Michelson) for all three stages of merger, for equal-mass binaries, as a function their total mass and redshift (Baker *et al.* 2006).

To carry out this test, we must be able to compute the burst from merger and ringdown by solving Einstein's equations numerically. Such numerical simulations should start with the final few orbits of the black holes and then proceed into their plunge and merger, signaled by the for-

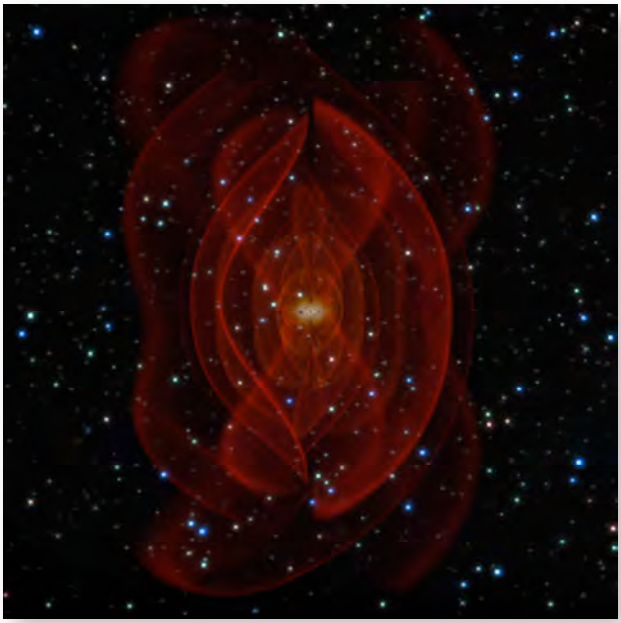


Figure 4-4: Gravitational waves from a numerical simulation of a binary black hole merger. The black holes are still separated in this frame and the gravitational waves are shown as the reddish contours.

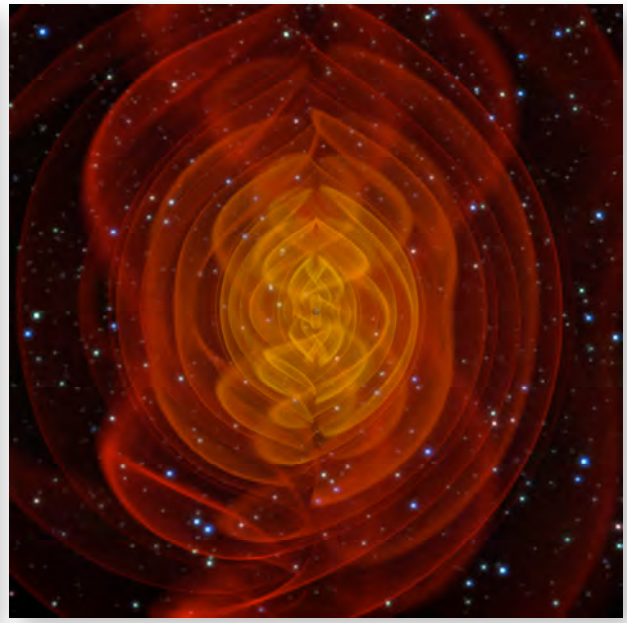


Figure 4-5: Here the black holes have merged and the resulting gravitational waves have increased in intensity, shown by the yellow and orange contours.

mation of a single horizon, and continue through the ringdown of the remnant black hole. This has proved to be a very difficult undertaking, with attempts going back more than 30 years. For many years, the simulation codes were beset with many difficulties, including instabilities that caused the codes to crash before the evolution reached even one orbital period. Fortunately, a series of remarkable breakthroughs has occurred recently; see sidebar. With the development of new methods for evolving black holes on numerical grids, several groups can now evolve black hole binaries for several orbits and then through plunge, merger, and ringdown. So far, three groups have compared their numerical relativity waveforms from the merger of two equal-mass, non-spinning BHs, and they all get the same simple shape shown in Figure 4-1 (Baker *et al.* 2007). In addition, there is consensus that the merger of two equal-mass Schwarzschild BHs produces a final remnant BH with spin $J \sim 0.7GM/c$ (Centrella 2006). Figures 4-4 and 4-5 are visualizations of the merger and emitted waves; Figure 4-1 is the waveform with superposed LISA noise.

Simulations of binaries in which the black holes have equal masses and spins, and non-equal masses but no spins, have also been carried out. Numerical relativity is now in an era of rapid progress, and it seems reasonable to expect that BH mergers with unequal masses and generic spins will be amenable to numerical solution well before LISA flies. In short, recent theoretical breakthroughs in numerical relativity expand the science that LISA can do, making LISA especially timely.

The ringdown stage: Black hole spectroscopy

Though numerical relativity waveforms from colliding holes naturally include the ringdown waves, those waves are also well understood analytically. GR predicts are that every "excited" BH settles down to a stationary state, characterized entirely by its mass and spin[3], through the emission of gravitational radiation. These ringdown waves consist of a superposed set of BH quasi-normal modes (QNMs), waves with exponentially damped sinusoidal time dependence, plus a far weaker "tail" that decreases as $(1/\text{time})^6$. The modes are strongly damped as the mode energy is radiated away to infinity, so the final ringdown stage will be brief, lasting a few cycles.

The QNMs of Kerr BHs can be solved for using perturbation theory. That is, the spacetime metric is written as the Kerr metric plus a small perturbation, and Einstein's equations are expanded to first-order in that perturbation. The solutions can be decomposed into a sum of eigenmodes with complex eigenfrequencies. It was discovered in the 1970s that the partial differential equations for the eigenmodes/frequencies of Kerr BHs can be fully separated (*i.e.*, reduced to ordinary differential equations), so they are known to essentially arbitrary accuracy. While there are a countable infinity of these modes (corresponding to the angular order and overtone of the perturbation from the stationary state), the lowest order modes are the most readily excited and the most weakly damped; in practice only a few modes are likely to be observed. The frequencies and damping times of these ringdown QNMs are completely determined by the mass and spin angular momentum of the final, merged MBH.

We note that if two different QNMs are detected in a ringdown, then the ringdown radiation itself provides a test of strong-field GR and the hypothesis that the central massive objects in galactic nuclei are really Kerr BHs. The reason is that from two modes one measures four parameters (the frequencies and damping times of both modes), which must all be consistent with the SAME mass and spin values (Dreyer 2003). Thus, in the same way that we can identify chemical elements through their spectroscopic fingerprint, so we can uniquely identify a BH (*i.e.*, determine its mass and spin) from the spectrum of its ringdown radiation. On the other hand, if the observed radiation arises from a different source (*e.g.*, a boson star), or if GR does not correctly describe gravity in the extremes of strong fields and dynamical spacetimes, the spectrum would very likely be inconsistent with that predicted by GR for BHs.

Extreme mass ratio inspirals: Precision probes of Kerr spacetime

Introduction

Observational evidence for the existence of MBHs at the centers of galaxies is currently based on modeling the gravitational potentials of these objects using the motions of stars and gas,

[3] And electric charge, though for astrophysical black holes the charge has a negligible effect on the spacetime structure.

and comparing the results with those expected if the central object were a black hole. The best case today comes from stellar motions near the center of our galaxy, which reveal the presence of a compact dark object of mass $M \sim 4 \times 10^6 M_\odot$; stellar orbits show the central mass to be point-like down to a scale of ~100 AU. LISA will map the structure of MBH spacetimes on length scales ~10^4 times smaller – the size of the horizon.

An inspiraling binary with one body much less massive than the other is referred to as an extreme-mass-ratio inspiral (EMRI). In the LISA context, the larger body is a ~10^5 – 10^7 $M_\odot$ MBH and the smaller one a stellar-mass compact object (white dwarf, neutron star, or stellar-mass BH) or perhaps an intermediate-mass BH, with mass ~10^3 $M_\odot$. Thus LISA EMRIs will have mass ratios $10^{-7} \lesssim m_2/m_1 \lesssim 10^{-2}$. While white dwarfs, neutron stars and BHs should all reach the event horizon of a MBH before being tidally shredded, the best current estimates are that inspirals of ~10 $M_\odot$ BHs will dominate the LISA detection rate (both because mass segregation concentrates them more strongly near the MBH, and because, being more massive, they produce a stronger signal and so can be seen to greater distance). Therefore in this section we concentrate on the ~10 $M_\odot$ BH case, shown in Figure 4-6 (but with the small hole enlarged in size for easy visualization).

Even the closest EMRI will yield a signal too weak to be immediately visible above the LISA noise, so matched filtering will be necessary to dig EMRI signals out of that noise. Fortunately, the matched filtering signal-to-noise scales like the square root of the number of observed GW cycles, and LISA will observe each EMRI for a timescale of order years, or equivalently for of order 10^5 cycles, so the matched filtering signal-to-noise will be a factor ~300 higher than the instantaneous signal-to-noise. Unfortunately the number of independent year-long templates is so vast that straightforward matched-filtering, using a grid of templates densely covering the entire parameter space, will not be feasible

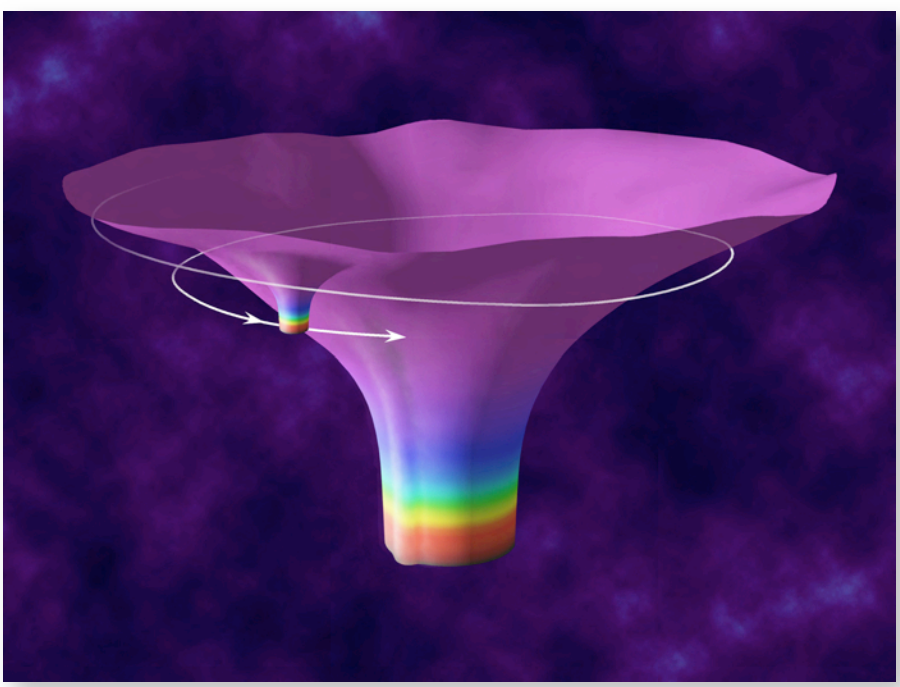


Figure 4-6: Embedding diagram of an EMRI, with the smaller black hole orbiting in the spacetime of the larger black hole. The colors depict the slowing of time (the "lapse" function) as one nears the horizons and the shape depicts the geometry of space in the orbital plane.

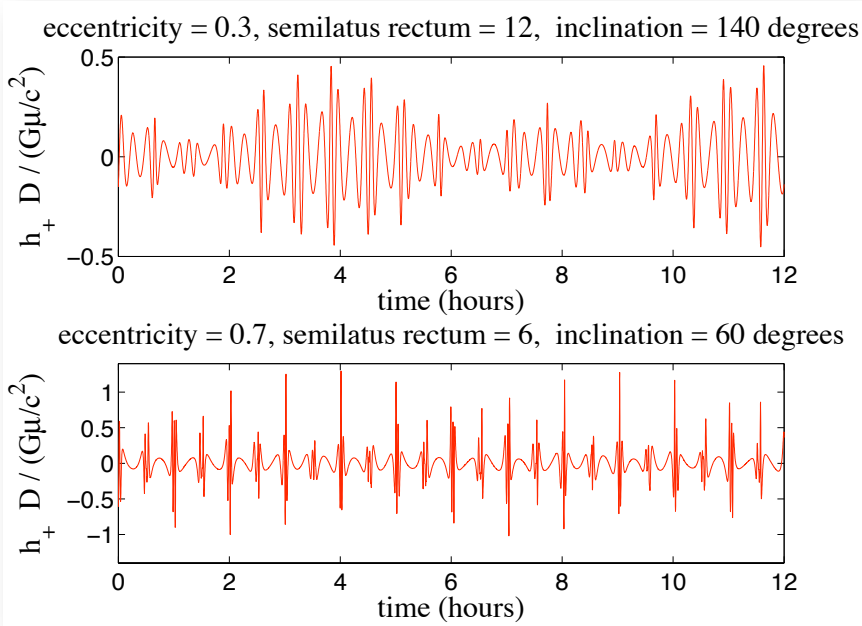


Figure 4-7: Segments of generic EMRI waveforms (Drasco & Hughes 2006); These are the plus-polarized waves produced by a test mass μ orbiting a $10^6 M_\odot$ black hole that is spinning at 90% of the maximal rate allowed by general relativity, a distance D from the observer. The two panels correspond to different configurations of the test mass' orbit, characterized by the shown parameters. The top panel assumes a slightly eccentric and inclined retrograde orbit modestly far from the horizon. The bottom panel assumes a highly eccentric and inclined prograde orbit much closer to the horizon. The amplitude modulation visible in the top panel is mostly due to Lense-Thirring precession of the orbital plane. The bottom panel's more eccentric orbit produces sharp spikes at each pericenter passage.

computationally, and one will likely have to resort to filtering that is suboptimal (compared to straightforward Wiener filtering), but more computationally efficient. The best current estimate is that EMRIs with (total, matched-filtering) signal-to-noise > 30-35 will be detectable with such methods (Gair *et al.* 2004). Then a 10 $M_\odot$ BH spiraling into an MBH will be observable by LISA out to $z \sim 1$. Given the current best estimate for the rate of BH inspirals in the Milky Way ($\sim 2.5 \times 10^{-7}$/yr; Hopman 2006), and extrapolating this rate to the rest of the Universe, leads to a LISA detection rate of ~ 50 - 100/yr, with the strongest sources having (matched-filtering) signal-to-noise > 100 (Gair *et al.* 2004).

The EMRIs are expected to be very clean astrophysical systems (except perhaps in the few percent of galaxies containing active galactic nuclei, where interactions with the accretion disk could possibly affect the dynamics). Over timescales of order a day, the orbits of the smaller body are essentially geodesics in the spacetime of the MBH. On longer timescales, the loss of energy and angular momentum due to gravitational-wave emission causes the smaller body to spiral in; *i.e.*, the geodesic's "constants" of integration change slowly over time. For LISA's entire observation time (of order years), the orbits are highly relativistic (radius < 10 Schwarzchild radii) and display extreme forms of perihelion precession and precession of the orbital plane due to dragging of inertial frames by the MBH's spin. Figure 4-7 shows two sample waveforms, corresponding to short stretches of time.

To correctly model the orbit over timescales longer than ~ 1 day, one must include gravitational radiation reaction, which causes the small body to lose energy and angular momentum. The natural approach to this problem is to take advantage of the tiny mass ratio m_2/m_1 and use

perturbation theory; *i.e.,* treat the small body as producing a metric perturbation on the spacetime of the MBH. It is simplest to model the small body as a point particle, so one can ignore its internal structure [as was justified by the work of Mino *et al.* (1997)], but the cost of this simplification is that the perturbed metric diverges at the location of the particle, and so the radiation reaction force must be regularized. A general (and quite beautiful) regularization prescription was given independently by Mino *et al.* (1997) and Quinn & Wald (1997), but implementing their prescription numerically has been a challenge. How to do so is at once a fascinating question in pure GR and a practical requirement for deriving the maximum science possible from LISA. It is therefore a very attractive problem for a relativist to work on, and a highly talented community of ~ 25 relativists is now heavily engaged in this sub-field. Recently, Mino (2005) has suggested a relatively simple and practical solution to this problem, based on calculating the average effect of radiation reaction over many orbits rather than the instantaneous self-force. It is not yet clear whether Mino's proposal will yield waveforms that are sufficiently accurate for LISA's purposes, but, if not, there is also a well-developed alternative: Barack & Ori (2003) have developed a mode-sum numerical procedure for regularizing the self-force, and its effectiveness has been demonstrated for circular orbits in Schwarzschild, where the results can be checked using simpler methods (Barack & Lousto 2005). Therefore it seems very likely that theorists will provide extremely accurate EMRI template waveforms well before LISA flies.

Given the very large number of EMRI GW cycles that accumulate over a year of LISA observations (~100,000), a fit of the observed gravitational waves to theoretically calculated templates will be very sensitive to small changes in the templates physical parameters. As mentioned above, this sensitivity makes the search computationally challenging, but it allows extremely accurate determination of the source's parameters, once an EMRI signal is identified. For example (assuming that GR is correct and the central massive object is a Kerr BH), LISA should be able to determine the mass and spin of the MBH to fractional accuracy $\sim 10^{-5} - 10^{-3}$ (Barack & Cutler 2004).

EMRI tests of the Kerr-ness of the central massive object in galactic nuclei

This level of precision suggests that we can do more – use the EMRIs as a highly precise observational test of the "Kerr-ness" of the central massive object. That is, if we do NOT assume that the larger object is a BH, we can use gravitational waves from an EMRI to map the spacetime of that object. The spacetime outside a stationary axisymmetric object is fully determined by its mass moments M_l and current multipole moments S_l. The mass moments tell us about the distribution of mass and energy in the source; they are analogous to electric charge moments in classical electricity and magnetism. The current multipole moments tell us about the *motions* of mass and energy; they are analogous to magnetic moments. Since these moments fully characterize the spacetime, the orbits of the smaller object, and the gravitational waves it emits, are therefore determined by the spacetime multipolar structure. By observing these gravitational waves with LISA we can characterize the spacetime of the central object.

Indeed, Ryan (1995) showed that for inspiraling trajectories that are slightly eccentric and slightly non-equatorial, *in principle* all the multipole moments are redundantly encoded in the emitted gravitational waves, through the time-evolution of the orbit's three fundamental frequencies. Basically, these are the fundamental frequencies associated with the r, θ, and ϕ motions (Drasco & Hughes 2004), or, equivalently, the radial frequency and the two precession frequencies. Extracting the moments from EMRI waves is analogous to geodesy, in which the distribution of the earth's mass is determined by studying the orbits of satellites. Black hole geodesy—also known as holiodesy—is very powerful because Kerr BHs have a very special multipolar structure. A Kerr BH with mass M and spin parameter a (in units with G=c=1) has multipole moments given by $M_l + iS_l = M(ia)^l$. Thus, $M_0 = M$, $S_1 = aM$, $M_2 = -a^2 M$, and similarly for all other multipole moments; they are all completely determined by the first two moments, the BH mass and spin. This is nothing more than the "no hair" theorem for BHs: a BH's properties are entirely determined by its mass and spin.

How accurately can M_2 be extracted from an observed EMRI signal, independently of M and S_1? It was recently estimated that M_2 could be measured to within $\Delta M_2 \sim 10^{-2} - 10^{-4} M^3$ (Barack & Cutler 2006), along with $\Delta M/M$ and $\Delta S_1/M^2$ to $10^{-5} - 10^{-3}$. Thus the standard picture for the central massive object—a Kerr BH described by GR—makes a definite prediction regarding M_2, which can be checked to very high precision using EMRI data. Any inconsistency with the Kerr relation could signal a failure of GR, or the discovery of a new type of compact object, or a surpisingly strong perturbation from some other material or object.

Other tests of the Kerr-ness of the central massive object have also been proposed. For example, Kesden *et al.* (2005) have argued persuasively that one can use EMRI waves to distinguish definitively between a central MBH and a boson star. In the BH case the GW signal "shuts off" shortly after the inspiraling body reaches the last stable orbit (and then plunges through the event horizon), while for a massive boson star, the signal gets prolonged, and its frequency derivative changes sign, as the body enters the boson star and spirals toward its center.

The above tests take the standard model of the central object (a Kerr BH described by GR) and either 1) compare it with a different model (*e.g.*, a boson star) or 2) embed that model in a larger one with extra free parameters (*e.g.*, Kerr, but with arbitrary quadrupole moment), and ask whether the best fit to the data is consistent with Kerr values for the extra parameters. These are all essentially comparison tests. There seems to be no unique or optimum way of constructing such tests – basically because today there is no compelling alternative to GR to compare against it. Nevertheless, tests of this sort would be very useful in either cementing confidence in the standard picture, or homing in on discrepancies.

But precisely because there is no compelling alternative to GR today, it is important to also consider other ways of "confronting GR" with EMRI data, which do not involve comparison with (perhaps somewhat *ad hoc*) alternatives. For instance, one could break an observed EMRI signal into, say, four consecutive pieces (each piece with signal-to-noise $\sim 100/\sqrt{4} = 50$), and estimate the binary's physical parameters from each piece separately. It is clear that very precise estimates of both BH masses and the MBH spin could be obtained from each segment, and all

four segments must yield the same parameters, within the error bars. It is clear that inter-segment comparison would yield a quite precise test of the null hypothesis that the central massive object is indeed a Kerr BH. Other tests of a similar nature could easily be formulated.

Measuring the speed of gravitational waves

From LISA observations, it should be possible to improve significantly on the current Solar System bound on the graviton mass: $m_g < 4 \times 10^{-22}$ eV.

Within GR, gravitational waves travel at the speed of light; *i.e.*, at the same speed as electromagnetic waves. Two different methods for testing this prediction, using LISA, have been proposed. The first method is based on LISA observations of WD binaries. A large fraction of the gravitationally strongest WD binaries will be eclipsing, so optical observations will tell us the instant when, as seen from Earth, one body is (almost) directly behind the other. This is also the instant, when the (square of) the gravitational-wave strain field goes through a minimum, assuming that the gravitons and photons propagate at the same speed. However if gravitons and photons travel at different speeds, there will be a phase shift between the optical and gravitational signals. It is convenient to parameterize the difference between the two propagation speeds by assuming that gravitons have some some non-zero mass, which one bounds by bounding the optical/gravitational phase delay. A single binary should be sufficient to set a limit of $m_g < 10^{-22}$ eV. With N such sources, the bound should decrease like $N^{-1/2}$, and N should be of order 100, so a bound of $m_g < 10^{-23}$ eV could be achieved this way (Cooray & Seto 2004). (Note the bound from any binary is independent of its distance, D; doubling D would double the delay for any m_g but the error bar on the phase delay also doubles, since the signal-to-noise is halved.) This would be a significant improvement on the current Solar System bound on the graviton mass: $m_g < 4 \times 10^{-22}$ eV.

The second method is based on measuring the phase evolution of MBH inspiral signals. This phase evolution is predicted rather precisely by high-order PN calculations. However if $m_g > 0$, the higher-frequency gravitational waves emitted late in the inspiral travel faster than the lower-frequency waves emitted earlier, and to some extent "catch up" with them. Since MBH inspirals are much stronger GW emitters than WD binaries, this leads to a correspondingly stronger bound: $m_g < 10^{-25}$ eV (Berti *et al.* 2006).

LISA science objectives and investigations relevant to this section (see Appendix 1)

5. Confront general relativity with observations

5.1. Detect gravitational waves directly and measure their properties precisely.

5.2. Test whether the central massive objects in galactic nuclei are the black holes of general relativity.

5.3. Make precision tests of dynamical strong-field gravity.

5. Precision Cosmometry and Cosmology

Precision cosmometry is defined as the art of making precision measurements of the world or the Universe. The measurement of distance forms the foundation for much of astronomy and cosmology. An example is the Hubble constant, which has had a history of refinement spanning decades. LISA has the potential to make fundamental contributions to precision cosmometry with its ability to provide gravitationally calibrated distances to sources with a 1% accuracy or better.

Using precision cosmometry for cosmology

LISA measurements of waveforms from black hole binary merger inspirals yield gravitationally calibrated, absolute distances to high redshift. The individual raw absolute precision for a single event ranges from typically about 0.2% to 0.4% at a redshift $z = 1$ to 1% to 3% at $z \approx 3$ to 5. 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 identification of the host galaxy to obtain a redshift independently, and additional errors are added by weak lensing noise at high z. Even a small number of events at $z < 1$ may allow LISA to measure the Hubble constant to better than 1% accuracy, and together with events at higher redshifts may 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.

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 behavior 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 cosmometric techniques that measure global spacetime in different ways (see "Cosmology Primer" box). Precision measurements of cosmic microwave background (CMB) anisotropies (from COBE, balloon- and ground-based experiments, WMAP (Spergel *et al.* 2006), and in the future, Planck) 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 ex-

Key science questions

- What is the nature of dark energy?
- What is the global geometry of the Universe?
- What is the Hubble constant?
- Can we identify electromagnetic counterparts, or the host galaxies, of massive black hole mergers, and thus measure their redshift?

A cosmology primer

Precision cosmology aims to measure the global properties of our spacetime: the geometry (and statistical fluctuations) of the temporally evolving, nearly spatially uniform 4-dimensional manifold that best represents all of the Universe that we can see. This geometry contains information about the curvature of 3-space, thought to be a relic of how the Universe began, and about the character of the average mass-energy content of the Universe over time.

Abundant evidence indicates that the Universe on the largest scales is nearly homogeneous and isotropic: on a large scale average, it is statistically the same everywhere and in all directions. Such a smooth, symmetric universe can be visualized as a uniform 3D space (which may have a uniform positive, flat, or negative spatial scalar curvature k/a^2, as specified by a curvature parameter k=1,0,−1), that uniformly changes size with time according to a cosmic scale factor $a(t)$. Points "at rest" in this space appear to recede at a speed cz that is proportional to their distance: z is called the (dimensionless) redshift and the physical rate of recession per unit separation is given by the Hubble parameter $H(t) = \dot{a}/a$.

Einstein's equations relate the evolution of a to the mass-energy density and curvature:

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\sum_i \rho_i - \frac{kc^2}{a^2}$$

where the mass-energy is divided here into components i with density ρ_i . As the Universe expands, the matter and energy spread out. Furthermore, if a component has a significant pressure (momentum flux) p_i, the work done during the expansion changes its internal energy. Local energy conservation gives:

$$\dot{\rho}_i = -3H(1+w_i)\rho_i,$$

where $w_i \equiv p_i/\rho_i c^2$ is the equation of state parameter for each component. For discrete components with constant w_i, the evolution of the scale factor can be written

$$H(a)^2 = H_0^2 \sum_i \Omega_i \left(\frac{a_0}{a}\right)^{3(1+w_i)}$$

where H_0 denotes the present-day Hubble constant, and the Ω_i represent the present-day densities of mass-energy components in units of the so-called critical density,

$$\rho_c = (3/8\pi G)H_0^2.$$

The history of the expansion of the Universe reflects both its geometry and composition. The sum includes a term Ω_k (with w_k=−1/3) representing the dynamical effect of spatial curvature, components describing radiation (with w_k=1/3), and nonrelativistic (baryonic and cold dark) matter (with w_m=0). Of particular interest is the value of w_{DE} (or more generally, $w_{DE}(t)$), which reflects the physical character of mysterious cosmic dark energy. Current data suggest that the Universe is dominated by dark energy ($\Omega_{DE} \sim 0.74$), and w_{DE} is constrained at about the ten percent level by relative supernova distances (Astier *et al.* 2006), $w_{DE} = -1.023 \pm 0.090$(random) ± 0.054(systematic). Einstein's cosmological constant Λ, corresponding to the gravitation of a uniform physical vacuum, has w_Λ=−1, with no t dependence. Precise data are capable of discovering whether the dark energy is consistent with an Einstein Λ or other models of $w_{DE}(t)$, estimating the other parameters including Ω_k, and testing whether general relativity is an accurate description of global behavior. Some techniques (such as relative distance distances from Type Ia supernovae or other standard candles, or gravitational lenses with time delays) measure the global spacetime metric directly via photon propagation. Others (such as weak gravitational lensing by intergalactic dark matter perturbations, or surveys of high redshift galaxy clusters) also measure the response of the smooth metric to mass density perturbations via the growth of structure. A few techniques offer absolute physical calibration of distances; these include Sunyaev-Zeldovich mapping of plasma in galaxy clusters, and, more precisely, mapping of the galaxy correlations imprinted by acoustic oscillations of baryons in the baryon/radiation plasma before recombination. The most precise data at present, the anisotropy spectrum of the microwave background, constrains most directly the behavior of the plasma/dark matter system at high redshift, and is most powerful when combined with one or more other techniques that probe the nearby Universe.

LISA will use gravitational wave propagation to obtain absolute, gravitationally calibrated luminosity distances, a combination of attributes not shared by any other technique. Even a small number of absolute distances yeilds a value for H_0, a measurement of central importance. LISA/BHB constraints are similar to the absolute calibration provided by the Baryon Acoustic Oscillation technique, but provide a pure-physics calibration not reliant on cosmological models; by combining these two techniques, new constraints can be placed on "dark radiation" such as new types of relativistic particles.

pansion where dark energy dominates, and allows deeper questions to be asked: for example, whether dark energy varies with time or reflects a pathology in 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 (NRC Committee on the Physics of the Universe 2003, 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 all of them.

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 units based only on gravity – not a distance ratio to an astronomically defined reference);
- Of very high intrinsic precision (ranging from 0.2% to 3% for a single event at $1 < z < 5$); and
- Useful over a very wide range of redshift (detectable BHB merger events are expected from $z < 1$ to $z \approx 20$).

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, using direct geometrical parallax measurements of nearby stars to calibrate indirect measures for larger distances, in a series of steps extending to cosmological scales. Other absolute calibrators are now becoming competitive but present major challenges in systematic reliability and precision, and require a variety of assumptions — again, requiring multiple approaches for a robust result (see box on “Absolute Distance Calibration”).

LISA will add a unique and complementary new tool: absolutely calibrated distances determined by measuring the waves generated by massive binary black hole inspiral. Previous sections provide detailed discussion of these waves; for our purpose here, the main point to note is that measurement of these inspiral waves makes it possible to directly determine the luminosity distance to a source with a precision that can be as good as 0.1%. The main weakness of this tool relative to other techniques is the still uncertain number and redshift distribution of events that can provide useful distances, as discussed below. For several applications, the need to identify a host galaxy and corresponding redshift may limit the applicability of this technique. On the other hand the intrinsic precision may be higher than any other technique, possibly in some respects even better than the CMB, and it brings an absolute physical calibration based on gravity alone, unlike any other technique. 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.

Absolute cosmometry with black hole binaries

The principle of estimating distances from measured waveforms is elegantly simple (Schutz 1986): the chirping time τ of an inspiral/merger event, 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 measured waveform. (As explained in previous sections, roughly speaking, the directly measured redshifted chirp mass tells the redshifted final absolute Schwarzschild radius, and the ratio of that length to the luminosity distance is the metric strain, h.)

> LISA is synergistic with deep multiband imaging, synoptic monitoring, and deep multiobject spectroscopy. LISA data and electromagnetic data will rely on each other and will be used iteratively to create a more powerful probe than either on its own, both of precision cosmology and of the behavior of galactic stars and gas surrounding massive black holes. LISA waveforms provide a final level of precision better than any other technique but require supporting electromagnetic data to get there.

However, as discussed in detail in Section 2, *LISA Mission Overview*, LISA 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.

If a cosmological model is assumed, then a redshift can be inferred self-consistently by requiring agreement between the estimated distance and that predicted from the cosmology. Thus to the extent that cosmological parameters are roughly known, only a certain narrow range of redshift is allowed for the host. Once a host is identified, the precise direction allows a still more precise estimate of distance from LISA. Thus LISA data will be used iteratively and synergistically with electromagnetic data where these are available, to achieve maximal precision.

Identification of the host galaxy to a merger event can occur in many different ways. For an unusually nearby ($z < 1$) event with large black hole mass and signal-to-noise ratio, the LISA error box in angle and redshift might contain fewer than a thousand candidate galaxies, and the host might be easily identified from large scale optical morphology (such as tidal tails) as the site of a recent galaxy merger. More typically, the error box contains of order ten thousand galaxies, and the merger event may not be associated with a major visible disruption; in many cases the redshift is also very high, making optical identification difficult. On the other hand, models suggest that the same galaxy merger that creates a black hole binary often sends interstellar gas rain-

Fig 5-1: HST image of the Antennae, a famous pair of tidally interacting galaxies. Tidal interactions, stripping and disruption accompany the mergers of galaxies that preced mergers of their nuclei and massive black holes. (Credit: B. Whitmore (STScI) and NASA.)

ing into the new galaxy nucleus, and the same gas that helps the two holes dissipate energy and momentum as they sink towards each other also forms a bright infrared nuclear starburst. For large binary mass ratios, and total binary masses at the upper end of the range of expected LISA BHB events (more than about $10^6 M_\odot$), the starburst is expected to still be active when the merger event occurs (Dotti *et al.* 2006). Such starbursts will be visible to very high redshift with JWST, and observations in the infrared penetrate deeply even into highly obscured nuclei.

An even more distinctive signature to identify the host galaxy may come from responses of the material near the black holes' horizons to the merger event, which can lead to observable time-variable X-ray/UV emission from the galactic nucleus, modulated by the evolution of the potential as the inspiral progresses. (In the case of obscured nuclei, the time variations may appear in reprocessed infrared emission.) For most LISA-observable holes (less than a few million $M_\odot$), gas accretion disks are evacuated during the merger process but then reestablish emission within a few years, causing an "afterglow" — a newly observable X-ray source (Milosavljevic & Phinney 2005). For higher mass holes, the interaction of accretion discs as the holes approach each other can lead to observable, variable X-ray precursors to the merger event (Dotti *et al.* 2006). If the two holes have disks and/or black-hole-spin-powered jet emission, the disrupted disks and jets can show nonthermal signatures that may appear from radio to gamma rays. Recent observations of low power AGN (presumably from low mass holes) suggest that such evidence may not be at all rare or unusual. Only a tiny fraction (much smaller than $\sim 10^{-10}$) of the variable gravitational energy of the system needs to appear as a variable electromagnetic signal to be clearly visible.

At redshifts significantly less than unity, the relevant inspiral events consist of a compact stellar mass or intermediate mass black hole (IMBH) captured by a massive black hole in a galactic nucleus. These events will be extremely large mass ratio inspirals (see section on EMRIs). The signal-to-noise ratio and per-event precision are not as high for these as for binaries of comparable mass, but are still possibly good enough (a few percent per event, possibly for hundreds of events) for precision measurement of H_0. Even if electromagnetic counterparts for EMRIs are not found, adequate redshift calibration for a large sample might be obtained statistically from galaxy surveys in the LISA error boxes.

Absolute distance calibration

One of the most important sources of error in constraining global parameters at present is the determination of the absolute cosmic distance scale at low redshift, the Hubble constant H_0. This is not well constrained by CMB measurements, which provide an absolute ruler at high redshift, the sound horizon size at recombination r_S=147.8 ± 2.6 Mpc. The CMB data confine models to a narrow degeneracy line, well approximated by $\Omega_k = -0.3040 + 0.4067\ \Omega_\Lambda$ (Spergel *et al.* 2006) but do not distinguish well between points along this line. A precise measure of absolute distance, even at low redshift, narrows the allowed region to a small interval on this line. With the HST Key Project estimates of H_0, WMAP yields $\Omega_k = -0.003 \pm 0.015$, with the error dominated by H_0.

The best distance ladder estimate, the HST Key Project value for the Hubble constant H_0 = 72 ± 8 km/s/Mpc (Freedman *et al.* 2001), still has an uncertainty of more than ten percent. The possibility of systematic errors in this value cannot be completely ruled out, as perhaps suggested by other different HST estimates (Sandage *et al.* 2006) [H_0 = 62.3 ± 1.3 (random) ± 5.0 (systematic) km/s/Mpc] and by recent evidence of a low value ≈ 61 km/s/Mpc from independent Cepheid calibration via eclipsing binaries (Bonanos *et al.* 2006). Other absolute calibration techniques include gravitational lens time delays, and Sunyaev-Zeldovich observations of hot gas in galaxy clusters. So far the systematic errors in these techniques have prevented reliable precision at better than the ten percent level.

A new promising technique now emerging uses very long baseline radio observations of proper motions of distant megamasers in disk galaxies; this method is essentially geometrical, with some assumptions about orbit configuration and motions. Currently the formal error from this method [H_0 = 74 ± 3 (random) ± 6 (systematic) km/s/Mpc based on one object still tied to Cepheids rather than distant Hubble flow (Macri *et al.* 2006)] is comparable to the Key Project error. As more objects are observed in the coming decade, the megamaser technique may achieve a precision at the few percent level at sufficiently large distances that Cepheids or other secondary calibrators will be unnecessary.

The Baryon Acoustic Oscillation (BAO) technique also provides an absolute calibration, based on the known physics of the dark matter/baryon-radiation plasma system around recombination. Currently it offers precision at the 4% level (Eisenstein *et al.* 2005), with prospects for improvement from a larger sample size. This calibration depends on precise understanding of the matter/radiation energy ratio, largely constrained by CMB.

LISA's calibration is based only on the physics of gravitational waves, without reference to cosmological contents, detailed properties of astronomical systems, such as history or environment, or even Standard Model physics. (All of the relevant parameters of the inspiralling black holes can be measured from the waveform and ultimately connect to laboratory measurements of Newton's G and speed of light c). For a single object, the main source of error is noise from gravitational lensing, which can change the measured h and therefore inferred distance by an amount that is unknown for each individual object. This effect is partially correctable using a statistical sample and in any case is small at $z < 1$.

By measuring the inspiral waves, particularly in the case where binaries are of comparable mass, LISA will pinpoint many events to better than a degree (in some cases, much better). LISA will also be able to predict the time of merger well in advance (often, hours to weeks), allowing searches for precursors and afterglows, as well as emission associated with the moment of the merger itself. In general, finding and studying electromagnetic signatures from an active inspiral/merger nucleus requires deep imaging over a wide (~ degree) field, in multiple wavebands. The time variable signatures require sampling on a timescale as long as intervals of years, down to a time resolution scale as short as the ~ 1000 second orbital period. Fortunately, such capability is being created in many bands, including arrays of large aperture infrared telescopes, extremely capable optical systems such as LSST (which will image galaxies to $z > 1$, in a field 4 degrees across, in less than a minute), extremely wide angle radio interferometry (being demon-

strated in systems such as the Allen Telescope Array), and new capabilities in space from the infrared (JWST) to gamma rays (GLAST).

LISA electromagnetic counterpart sources may provide a rich field of study, with many identifiable hosts and counterparts. LISA sources have possible electromagnetic counterparts over a wide variety of wavebands and timescales: potentially, an exploratory bonanza providing access to new phenomena over a huge range of scales. On the other hand given our ignorance about the processes in galactic nuclei associated with massive black holes and their mergers, it is also possible that the observable electromagnetic signatures may be very rare, in which case precision cosmology with these sources will be impractical.

Another important source of uncertainty is the rate of events, as discussed in Section 3, “Black hole astrophysics”. Standard galaxy formation theory suggests that the first black holes formed from the first massive stars, in the first baryonic collapses at redshifts of order 20. Subsequent hierarchical clustering of halos led to mergers of holes on successively larger scales, eventually forming the population of massive black holes found today in galactic nuclei. Detailed models of this process (Sesana *et al.* 2004, Volonteri 2006) predict that LISA will see many dozens of massive black hole merger events per year, spread over a range of masses from 10^4 to 10^7 solar masses and a range of redshifts from 1 to 20. On the other hand a more conservative model for the formation of the massive black holes, based only on observed populations of massive black holes, and allowing them to grow as much as possible via accretion rather than mergers, can produce rates an order of magnitude smaller. The total rate and redshift distribution make a big difference in LISA's capability for precision cosmology. Similarly, the rate of EMRIs is highly uncertain (covering a similar range of possible rates), because of required extrapolation to nuclear stellar populations in galaxies where we have very limited information at present.

The most important practical limit on precision of distance measurements at high redshift comes from gravitational lensing, which can magnify and brighten an object, or demagnify it relative to the mean for a given cosmology, and thus bias its inferred distance. Because high precision is the goal, even small-amplitude modulation by weak lensing is a concern. This effect must be controlled at high redshift by using a statistical sample, as is done for example with supernova distance indicators. The overall precision thus depends on the BHB redshift distribution and event rates.

Impact of LISA/BHB distances: Examples

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.

The potential contribution of BHB to precision cosmology has not yet been evaluated as thoroughly as other tools, and is subject to the above uncertainties, some of which will not be

resolved until LISA flies. Nevertheless it is useful to cite several benchmark examples of potential impact:

- In a homogeneous universe, the BHB technique with realistic LISA capabilities and source parameters yields absolute distances with a raw per-event precision from about 0.2% to 0.4% at $z = 1$, to about 1% to 2% $z = 3$ to $z = 5$ (Holz & Hughes 2005), depending on the source properties; in some cases, even 0.1% precision is possible, as shown in Figure 5-2 (Lang & Hughes 2006).

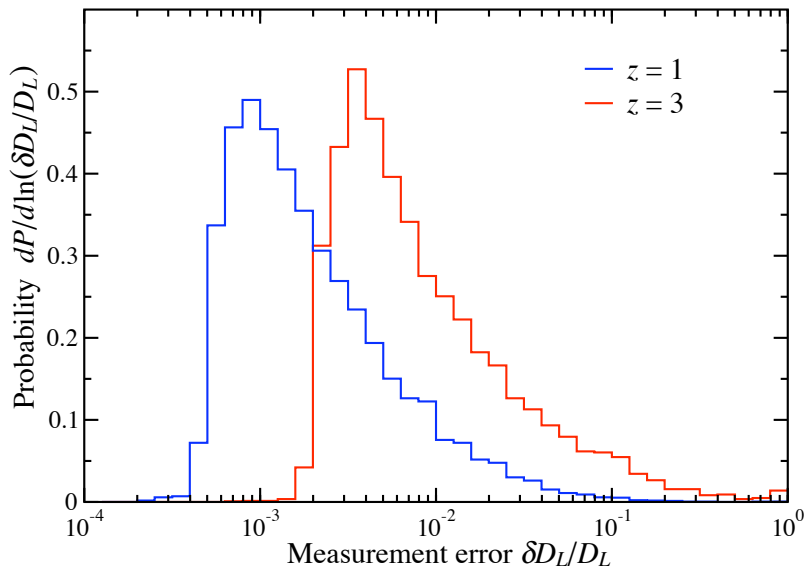


Figure 5-2: Simulated distribution of errors in BHB luminosity distances D_L at $z = 1$ (blue) and $z = 3$ (red), with black hole masses of 10^5 and $6 \times 10^5 M_\odot$, assuming that an electromagnetic counterpart allows precise sky position determination (Holz & Hughes 2005). Even at $z = 3$ most measurement errors are less than 2%.

- Since most lines of sight to $z < 1$ are nearly empty of dark matter, lensing errors are relatively small. A few massive inspiral events, or a large number of EMRI events, at redshift less than or of order unity may lead to a reliable measurement of the Hubble constant H_0 to better than 1%, an order of magnitude improvement over current techniques. Absolute gravitational calibration adds unique information even if other techniques attain comparable formal precision with different assumptions.

- Calibration of the absolute distance scale, in combination with CMB measurements alone, and a definite scaling law for the dark energy $w(a)$, allows a determination of w with high precision (Hu 2005, Eisenstein & White 2004). With Planck quality CMB data alone, calibration of the Hubble constant at 2% precision achieves w accuracy of better than 3% (Olling 2007). Similarly, a one percent constraint on absolute distance, combined with the CMB data, yields ~ 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, LISA and BAO together), a new tight constraint can be derived on the density of any invisible relativistic species or "dark radiation" that affects the BAO calibration.

- LISA/BHB distances are also useful at moderate z (of order 2 to 3) if the BHB sample is large enough for fitting to a lensing amplification model. Even with conservative assumptions about lensing noise, a sample of 100 LISA/BHB events provides comparable precision to a sample of ≈ 3000 SNIa distances at comparable redshift (Dalal *et al.* 2006).

- The considerable number of events from higher redshift, out to $z \sim 20$, will provide measurements of black hole mergers as a function of distance, and measurements of integrated weak

lensing along multiple lines of sight to high redshift. The galaxy counterparts of these sources will be infrared galaxies, many of them in very early stages of assembly, and many of them potentially observable with JWST. LISA's observations will complement the revolutionary JWST views of early structure and galaxy formation, adding detailed information about the early growth of nuclear regions, massive black holes, and dark matter density fluctuations at high redshift.

LISA science objectives and investigations relevant to this section (see Appendix 1)

6. Probe new physics and cosmology with gravitational waves

6.1. Study cosmic expansion history, geometry and dark energy using precise gravitationally calibrated distances in cases where redshifts are measured.

6. Ultra-Compact Binaries

Summary

Close binary stars are double stars in which two compact objects such as white dwarfs and neutron stars, orbit each other in a short period. Binaries with orbital periods below a few hours emit gravitational radiation in the LISA band and are generally called ultra-compact binaries. They have relatively weak gravitational wave signals in comparison to massive black hole binaries, but are numerous in the Galaxy and even the Solar neighborhood. The prospects for LISA in this area of astrophysics are truly spectacular. Several thousand systems are expected to be detected individually, with their parameters determined to high precision, while the combined signals of the millions of compact binaries in the LISA band will form a well detectable background signal. This should be compared to less than 50 ultra-compact binaries known today. The shear number of detections will allow study of entire populations of binaries in such detail that not only the properties of this particular population can be determined, but through comparison with models, the formation of these binaries and thus many preceding phases in binary evolution can be strongly constrained. This has a strong bearing on our understanding of many high-energy phenomena in the Universe such as supernova explosions, gamma-ray bursts and X-ray sources as they share parts of the evolution history of the binaries detectable by LISA.

The number of sources in the LISA band also ensures that many of them can be detected at high signal-to-noise ratio (often larger than 100), allowing for detailed study of individual binaries. For many the frequency and phase

Key science questions

- Is general relativity the correct theory of gravitation?
- Is there a large population of ultra-compact binaries in the Galaxy?
- How did compact binaries form and what is the outcome of a common-envelope phase?
- What is the nature of the fundamental physical interactions in compact binaries?
- How are the compact binaries distributed in the Galaxy and what does that tell us about the formation and evolution of the Galaxy?

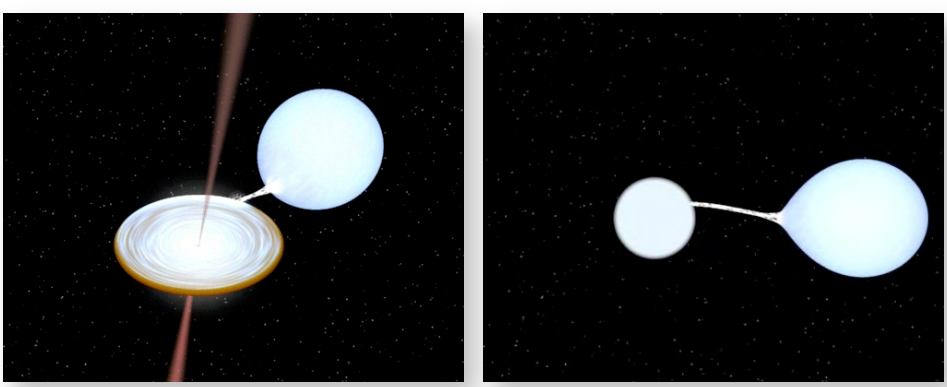


Figure 6-1: Impression of two types of ultra-compact binaries: (left) an ultra-compact X-ray binary in which a neutron star accretes from a compact companion; (right) an AM CVn binary in which a white dwarf accretes from a compact companion.

evolution can be studied. This will enable the study of the physics of tides and mass transfer in unprecedented detail. The extreme conditions of short orbital periods, strong gravitational fields and high mass-transfer rates are unique in astrophysics.

The LISA measurements will provide very different information compared to what can be deduced from electromagnetic detections. In particular LISA's capability to determine distances as well as the fact that the gravitational wave signals are unaffected by interstellar dust provide huge advantages over other detection techniques. Compared to GAIA, LISA will detect a quite different population, with most distance determinations right in the Galactic center – where most ultra-compact binaries are – rather than between the Sun and the Galactic center. The distance determinations will make it possible to map the distribution of many compact binaries in the Galaxy, providing a new method to study Galactic structure. On the other hand, many of the detectable binaries can be studied electromagnetically thus providing a strong complementarity if both techniques are combined. Dedicated complementary observing programs as well as public data releases will ensure simultaneous and follow-up electromagnetic observations.

The importance of electromagnetic observations

The LISA measurements will provide complementary information to what can be deduced from electromagnetic detections. In particular its capability to determine distances as well as the fact that the gravitational wave signals are unaffected by interstellar dust provide huge advantages over other detection techniques. On the other side, the positional accuracy of LISA is quite limited compared to electromagnetic detectors. This highlights the importance of coordinated gravitational wave and electromagnetic observations, a unique possibility when studying gravitational waves at low frequencies. Although the majority of the binaries discovered by LISA will not likely be detected with electromagnetic detectors due to the dust absorption, the shear number of expected gravitational wave detections will ensure that there are still many tens or hundreds for which it is possible to do complementary electromagnetic observations. This will yield not only their position in the sky – thus putting strong priors on the gravitational wave parameter estimation – but also provide additional information, ranging from temperature and age estimates if only broadband colors can be measured, to individual masses and even radii if the system is eclipsing or spectra can be taken.

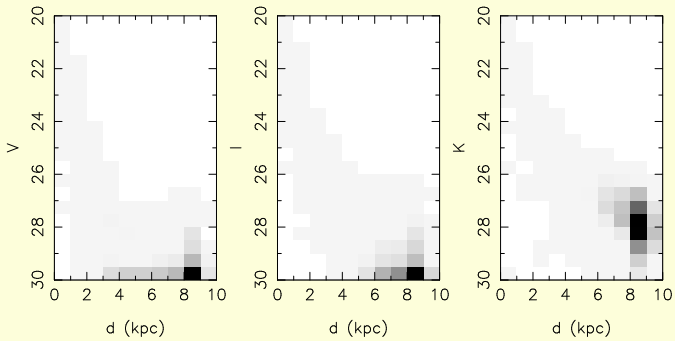


Figure 6-2: Optical and infrared magnitudes of the expected double white dwarf binaries detected by LISA.

A number of guaranteed detectable sources are known to date. Some of these can be used to verify instrument performance by looking for a gravitational signal at twice the orbital period and comparing the signal to expectations. In addition, once LISA has detected several nearby binaries and determined their sky position they can be observed optically thus providing an additional quantitative check on instrument sensitivity. Among the currently identified sources are the two most exotic but controversial binaries known, possibly with ultra-short orbital periods. As LISA will really open a new window to the Universe, arguably the most exciting prospect for

Tutorial: Ultra-compact binaries

At the end of the 1960s, binary stars with periods of less than one hour were discovered, and astrophysicists recognized that the two stars are so close together that an ordinary star like the Sun could not fit in their orbits. The close proximity of the objects suggests that both components are remnants: white dwarfs, helium stars, neutron stars, or even black holes that form after stars exhaust their nuclear fuel. The components of ultra-compact binaries are stars that have evolved beyond hydrogen-core burning.

A useful distinction can be made between systems in which the two components are far apart (detached systems) and systems in which the components are so close together that mass is being transferred from one star to the other (interacting systems). Examples of detached systems are double neutron stars and double white dwarfs. Their existence in the LISA band is inferred from longer period systems that are known and are evolving towards shorter periods, such as the double pulsar PSR J0737-3039 and the double white dwarf WD 0957-666.

Currently some 30 interacting ultra-compact binaries are known. They naturally divide in two classes, based on their observed characteristics (Figure 6-1). In ultra-compact X-ray binaries, gas falls onto a neutron star whose potential well is so deep that the gas heats up to millions of Kelvin and produces abundant X-rays. The second class comprises the AM CVn stars, so named because the first of them was a variable star discovered in the constellation Canes Venatici (hunting dogs). In AM CVn systems gas falls onto a white dwarf, which has a much shallower potential well than a neutron star. The gas is heated to only about 100 000 K, and most radiation is emitted at optical and UV wavelengths in the range of 100–600 nm. The number of known systems is increasing regularly due to new discoveries or period determinations of X-ray sources that turn out to be ultra-compact X-ray binaries.

LISA is the detection of many additional completely unknown and highly exotic sources in the Galaxy.

LISA as a workhorse: thousands of new binaries

Ultra-compact binaries (see Tutorial Box: Ultra-compact binaries) will completely dominate the number of source detections by LISA. Current estimates suggest the number of resolved compact binaries that will be detected by LISA will be counted in thousands, if not ten-thousands. These systems will be dominated by the shortest period systems and most will have periods less than about 20 min (Figure 6-3). If we compare that with the fact that less than 50 ultra-compact binaries[4] are known today – less than a handful with periods shorter than 20 min – it is clear that the knowledge of this population will be revolutionized by LISA. As these systems are relatively short lived and faint, there is no hope to detect these system with any other means than via gravitational radiation. Their detection will allow us to test different models for the common-envelope phase: the dominant uncertainty in our understanding of binary evolution and many high-energy phenomena. The internal statistical accuracy delivered by the shear number of detected sources will ensure that the common-envelope phase will be put to the most critical test that can be expected in the midterm future of astrophysics.

[4] http://www.astro.ru.nl /~nelemans/dokuwiki

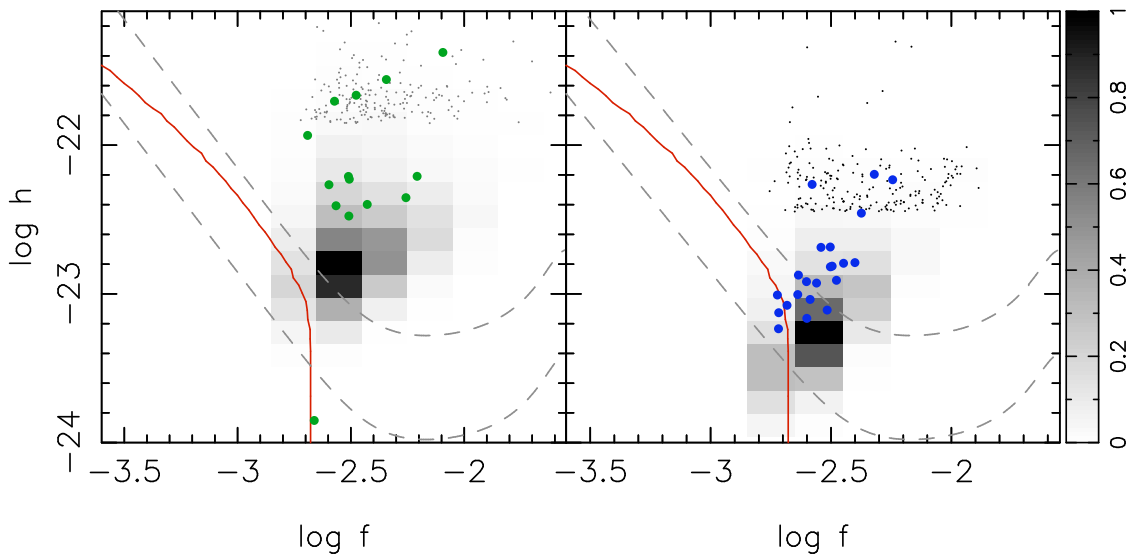


Figure 6-3: GWR wave amplitude *h* as function of the GWR frequency *f* (Hz) for the Galactic binaries that are expected to be detectable by LISA. The left panel shows the (10658) double white dwarf systems as the grey shade, with the 200 strongest sources as points, to increase their visibility. The right panel shows the (9831) resolved AM CVn systems that are expected, again showing the 200 strongest sources as points. Over plotted with the large symbols are the neutron star binaries in the left panel and the ultra-compact X-ray sources in the right panel. The average double white dwarf background is plotted as the solid line, while the dashed curves show the LISA sensitivity for a integration time of 1 year giving S/N of 1 and 5 respectively. Based on Nelemans *et al*. (2004).

Key question: the outcome of the common envelope phase

Less than half of the stars in the Universe are single, the majority being part of a binary, a triple or a higher order system. Of the binaries on the order of half are formed with a sufficiently small orbital separation that during the evolution of the components into giants or super giants the stars will interact. Especially for low-mass stars the majority of interactions are unstable and will lead to runaway mass transfer. Based on the observed short orbital periods of binaries that have passed this stage it is argued that somehow the companion of the giant ends up inside the giant's outer layers. During that common envelope phase, friction reduces the velocity of the companion, leading to orbital shrinkage and transfer of angular momentum from the orbit into the envelope of the giant. Along with angular momentum, orbital energy is deposited in the envelope, whose matter is then unbound from the giant's core, leading to a very compact binary consisting of the core of the giant and the original companion (Paczynski 1976).

Virtually all compact binaries and most of the systems giving rise to high-energy phenomena (such as X-ray binaries, relativistic binary pulsars and possibly gamma-ray bursts) have experienced at least one common-envelope phase. Given the importance of this phase in high-energy astrophysics our understanding of the physics and our ability to predict the outcome of the

Tutorial: Evolution of a star

Based on the fundamental set of structure equations—balancing gravity with pressure and accounting for energy generation and transport—it has been possible to construct stellar models that compare very well to the observed stars in the local Universe. Stars first stay on the main sequence, when they are burning hydrogen in their high pressure and temperature cores just as our Sun is currently doing. The nuclear burning, however, cannot go on forever. In time, no hydrogen remains in the core where the nuclear burning takes place. Once the hydrogen is gone, the pressure in the core cannot be sustained; gravity wins the battle of forces, and so the core contracts. Meanwhile, the outer layers of the star expand, typically by an impressive factor of 10 to 100, and the star becomes a red giant. Stars less massive than about 8 times the mass of the Sun lose their outer layers into space due to a stellar wind. All that remains is a compact degenerate core, about the size of Earth but typically 300 000 times more massive, forever cooling and visible as a small, initially hot star called a white dwarf.

More massive stars will continue nuclear fusion and their core will be burnt into heavier and heavier elements until it is made of iron. But neither fusion nor fission can produce energy from iron, so the iron core has no way of counterbalancing gravity and it collapses. The extreme pressure forces the electrons and protons to combine into a degenerate gas of neutrons that, if the core is not too heavy, generates enough additional pressure to halt the contraction. The resulting neutron star has a radius of about 10 km and a mass of 3×10^{30} kg. If the core is massive enough, even the pressure of the degenerate neutrons cannot offset gravity, and the core collapses into a black hole. Neutron stars are formed from the cores of stars with masses between about 10 and 25 solar masses; black holes, as far as we know, are created from stars with masses greater than about 25 solar masses. During the formation of either a neutron star or a black hole, the outer layers of the star are blown into space in a violent explosion called a supernova.

common-envelope phase are alarmingly poor. Theoretical progress to understand the phase from first physical principles is slow (*e.g.* Taam & Sandquist 2000) and observational tests have led to questioning of the applicability of the standard formalism described above. Comparison of the parameters of the thousands of binaries detected by LISA with model predictions will provide a direct test of the different proposed outcomes of the common-envelope phase and our understanding of the preceding binary evolution in general.

Formation of ultra-compact binaries in globular clusters

Of special interest are globular clusters, dense assemblies of up to a million stars that represent the oldest stellar populations in the Galaxy. The angular resolution that can be achieved with LISA is such that globular clusters can be resolved, so that the cluster sources can be distinguished from the Galactic disc sources (Figure 6-4). Globular clusters have a strong overabundance of bright X-ray sources probably due to dynamical interactions. In particular it seems that the number of ultra-compact X-ray binaries is severely enlarged compared to the other Galactic populations. It is not clear if ultra-compact binaries with white dwarf components are overproduced as well. LISA will directly test this by determining the number of ultra-compact binaries in globular clusters. This will provide unique information, since the details of how these interactions lead to the formation of ultra-compact X-ray binaries are poorly understood (Verbunt & Lewin 2006).

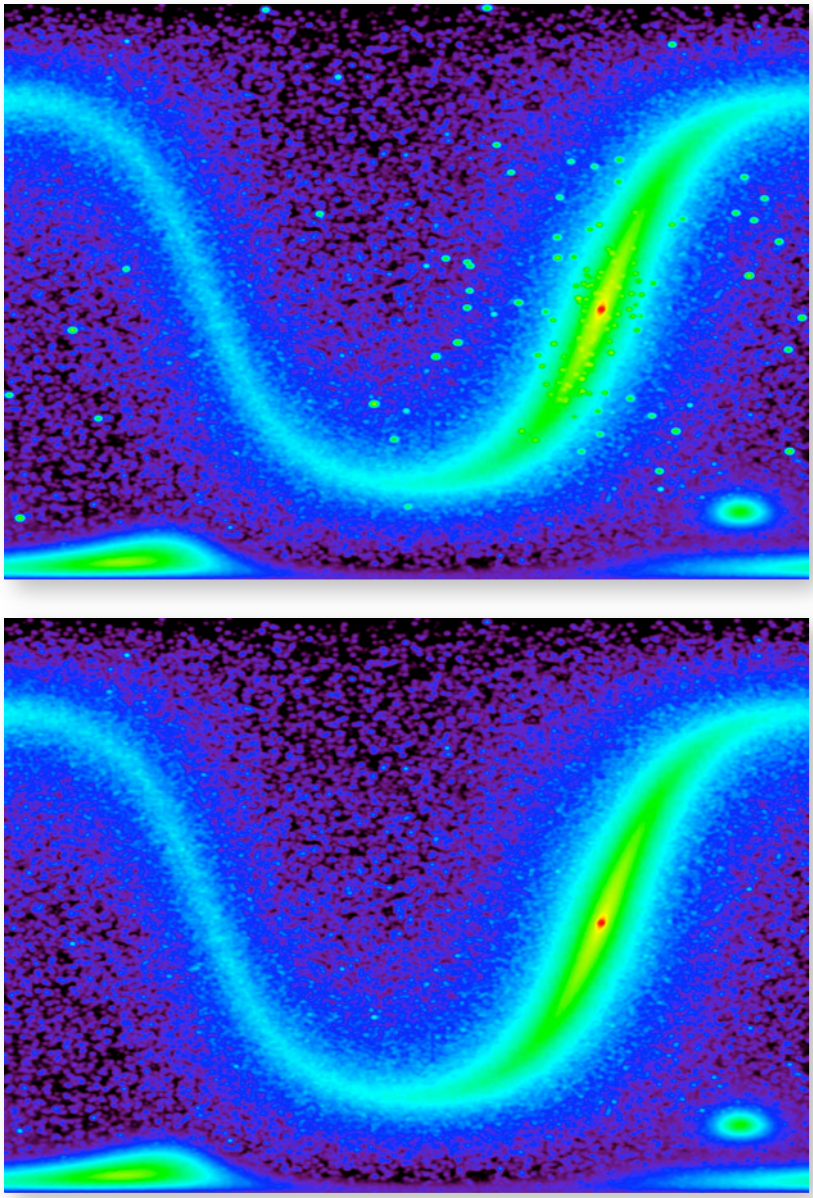


Figure 6-4: Sky brightness in GWR as seen through LISA eyes showing the Galactic disc and bulge, globular clusters, LMC and SMC. In the top plot the number of ultra-compact binaries in globular clusters is assumed to be enhanced compared to the field making the globular clusters stand out, while in the bottom plot the number is not enhanced.

The foreground of Galactic gravitational waves

At frequencies below a few mHz the number of sources in the Galaxy is so large that only a small percentage, the brightest (and closest) sources, will be individually detected. The vast majority will form an unresolved foreground signal in the detector. (We distinguish the Galactic "foreground" from the diffuse extragalactic "background".) This foreground is often described as an additional noise component which is misleading for two reasons. The first is that there is a lot of astrophysical information in the foreground. The overall level of the foreground is a measure of the total number of ultra-compact binaries, which is very valuable information given the current uncertainty levels in the normalization of the population models. The spectral shape of the foreground also contains information about the homogeneity of the sample, as simple models of a steady state with one type of binary predict a very distinct shape. In addition, due to the concentration of sources in the Galactic center the foreground is strongly modulated during the year, with periods in which the foreground is more than a factor 2 lower than during other periods (Figure 6-5). The cyclo-stationary character of the foreground allows for further tests of the population models and thus the uncertainties in binary evolution theory *e.g.* Edlund *et al.* (2005)

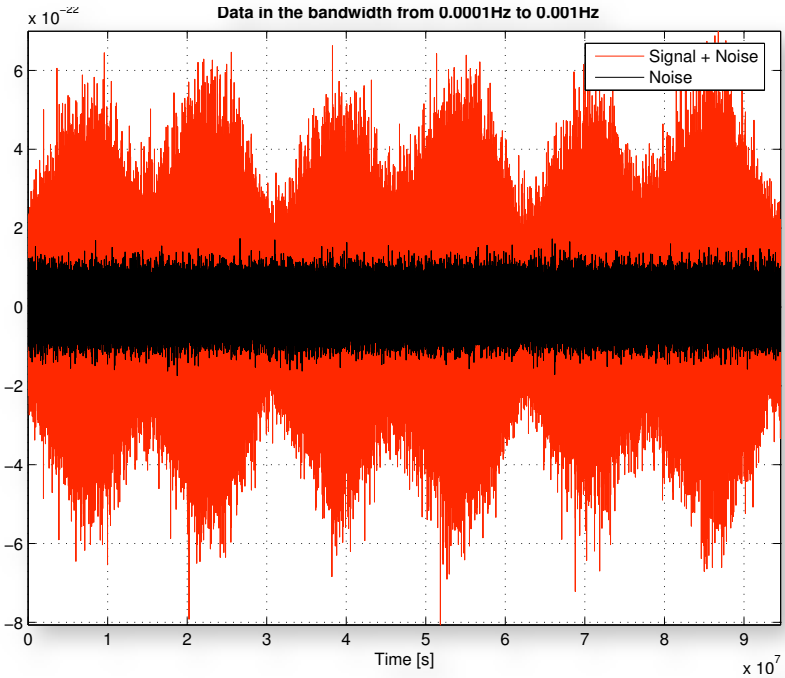


Figure 6-5: Level of the Galactic gravitational wave background as function of time, showing the yearly change. From Edlund *et al.* (2005)

The extragalactic ultra-compact binary background

The masses of white dwarfs and their minimal separation set a maximum to the signal strength of an individual binary, which puts the distance of individual binaries detectable by LISA to less than 100 kpc. This means the LMC and SMC are just within reach, but no individual ultra-compact binaries can be detected farther away. However, the combined extragalactic signal – dominated by the signals from sources around redshift of 1 – is expected to be just around the limit of the sensitivity of LISA at a few mHz (Farmer & Phinney 2003). So if the resolved binaries in the Galaxy can be effectively removed, (non) detection of this extragalactic compact binary background will provide insight in the cosmic star formation provided that the Galactic binaries have greatly reduced the uncertainties in the binary evolution that also hinder the extragalactic background predictions.

Verifying LISA and testing GR

The first and arguably most fundamental test that LISA will perform is direct measurement of gravitational radiation, although this might well have happened earlier using ground-based detectors. However, LISA is able to test a much simpler and cleaner system than the ground-based detectors by measuring the monochromatic signal of a detached binary. The brightest expected sources have signal-to-noise ratios larger than 100 and will allow detailed tests of the monochromatic and higher order terms. For the most compact high-frequency sources (above a few mHz) the first and second derivative of the frequency also will be measured. In addition, the most exciting possibility and expectation is the unexpected. LISA will likely discover objects and phenomena that are completely unknown and might shed new light on our understanding of the Universe.

Verification binaries

A subset of the known ultra-compact binaries have been recognized as ideal verification sources, as they should be detected in a few weeks to months and thus can be used to verify the performance of the instrument (Stroeer & Vecchio 2006). The reliability of the verification binaries has been improved recently by determinations of distances and systems parameters thus providing predictions of the expected signals with well defined error bars (Figure 6-6). Their expected monochromatic nature within the LISA mission time prevents astrophysical effects (see next section) hampering their detection.

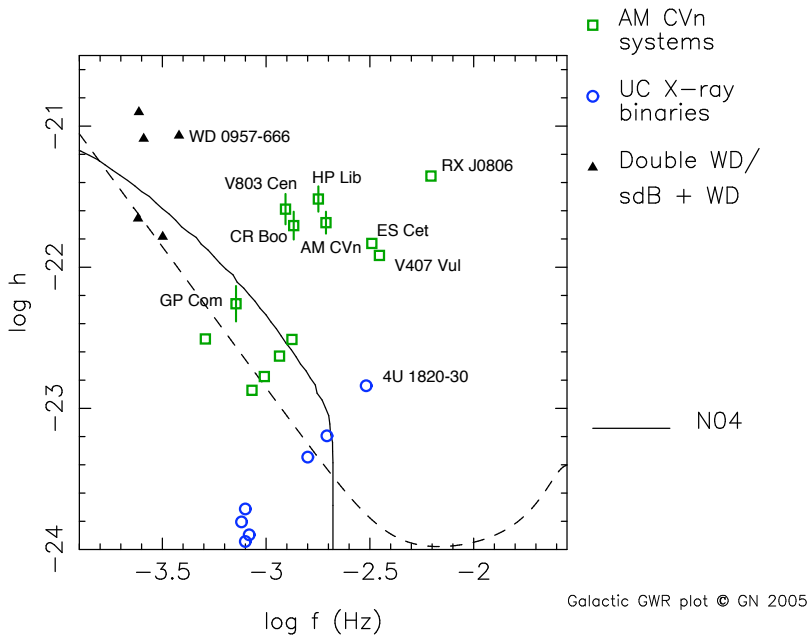


Figure 6-6: Gravitational wave strain versus frequency for the verification binaries. The instrument sensitivity and the average Galactic background are also plotted. Based on Roelofs *et al.* (2006)

The LISA measurements will immediately test the determination of the system parameters and, more importantly, will provide the definitive answers to the debate about the nature of the two shortest period binaries RX J0806.3+1527 and V407 Vul. These have received special attention in the past few years because they show repeating signals with periods of 5.4 and 9.5 minutes. In some interpretations, those times are the remarkably small orbital periods of binaries in which two white dwarfs are separated by about a quarter of the Earth Moon distance. A good deal of debate and uncertainty attends the two systems, and several competing theories purport to explain them, ranging from a detached pair of magnetic white dwarfs in which their X-ray emission is produced by induction and an interacting pair of white dwarfs in the so-called direct impact phase, to models in which the observed periods are not orbital periods at all (see Nelemans 2006). No model is strongly favored, and we might have to wait until LISA is launched before the two objects are understood.

Outlook: expected developments in the next decade

There are a number of initiatives that will improve our knowledge of ultra-compact binaries in the next decade, before LISA will fly. One of the major contributions to the increase in the number of known AM CVn systems in the last years has been the Sloan Digital Sky Survey (SDSS), in which 6 new systems have been found. This number will certainly go up with the ongoing extension of the SDSS to lower Galactic latitudes (the SEGUE survey) and the Euro-

pean Galactic Plane Surveys, two surveys that are particularly well designed for finding compact binaries. However, all SDSS systems have relatively long orbital periods (longer than about 30 minutes). Two surveys capable of finding AM CVn stars with periods less than 30 minutes are underway or will start soon: the Rapid Time Survey (RATS[5]) and OmegaWhite[6].

For the future there are initiatives to find more ultra-compact X-ray binaries both through the continued monitoring of the sky to search for X-ray transients with RXTE and other satellites, as well as through dedicated X-ray and optical surveys of the Galactic Bulge that are currently in development.

With these developments the number of verification sources available for LISA will be several tens allowing detailed tests of the performance of the instrument.

Studying the astrophysics of compact binaries using LISA

Although the effect of gravitational radiation on the orbit will dominate the evolution of the binaries detected by LISA, additional physical processes will cause strong deviations from the simple point mass approximation. The two most important interactions that occur are tides – when at least one of the stars in a binary system is not in co-rotation with the orbital motion or when the orbit is eccentric – and mass exchange. Because many binaries will be easily detected, these interactions do not hamper their detection, but instead will allow for tests of the physics underlying these deviations. Gravitational wave measurements will provide a completely complementary approach to many aspects of astrophysics because they are optimal for the study of short period systems in contrast to the current bias towards bright electromagnetic systems and events.

Physics of tidal interaction

LISA measurements of individual short period binaries will give a wealth of information on the physics of tides and mass transfer (stability). For detached systems with little or no interaction, the frequency evolution is well determined. The strain amplitude h, the frequency f and its derivatives are connected by:

$$h \propto M^{5/3} f^{2/3} d^{-1} \quad (1)$$

$$\dot{f} \propto M^{5/3} f^{11/3} \quad (2)$$

[5] http://www.mssl.ucl.ac.uk/-gtbr/rats.html

[6] http://www.astro.ru.nl /omegawhite/

$$\ddot{f} = \frac{11}{3}\frac{\dot{f}}{f} \qquad (3)$$

where M is the chirp mass and d is the distance. Thus measurement of h, f, $\dot{f}$ provides chirp mass and distance. Additional measurement of $\ddot{f}$ gives a direct test of the dominance of gravitational wave radiation in the frequency evolution (third equation). Tidal interaction between white dwarfs in detached systems before the onset of mass transfer will give rise to distinct deviations of the frequency evolution as compared to systems with no or little tidal interaction. The strength of the tidal interaction is virtually completely unknown, with estimates ranging over many orders of magnitude (Marsh *et al.* 2004). Knowledge of the strength of the tides is not only important for the understanding of the physics of tides in general and the physics of white dwarf interiors, but has important consequences for the tidal heating (and possibly observability) of LISA sources and the stability of mass transfer between white dwarfs (Racine *et al.* 2006).

Physics of mass-transfer stability

Detached ultra-compact binaries will evolve to shorter and shorter periods due to the angular momentum loss through gravitational wave radiation. At sufficiently short orbital period (a few minutes) one of the stars becomes larger than its Roche lobe – the equipotential surface that crosses the minimum of the potential between the two stars – and material "leaks" out of the potential well of one star onto the other star. Depending on the difference between the change of the radius of this star and the Roche lobe upon mass transfer, there may be positive or negative feedback, leading to either limited, stable mass transfer, or a runaway mass-transfer instability.

For double white dwarfs and white dwarf-neutron star binaries the stability of the ensuing mass transfer has important consequences, both for the number of expected mass-transferring LISA sources as well as a number of open astrophysical questions. The stable systems will form detectable interacting binaries (AM CVn systems or ultra-compact X-ray binaries). LISA will detect a number of double white dwarfs and AM CVn systems that are so close to the onset of mass transfer that the stability of the mass transfer can be tested directly by comparing the two numbers. In addition, LISA will detect several ultra-compact X-ray binaries at the very early stages of mass transfer, providing a test of the mass transfer stability in these systems as well.

For AM CVn systems the dominant uncertainty in the mass-transfer stability is again the tidal interaction between the two white dwarfs. Most likely the mass transfer will proceed via the direct impact configuration: due to the proximity of the two stars the mass transfer stream lands directly on the surface of the accreting white dwarf, rather than wrapping around the accreting stars, interacting with itself to form a flat accretion disk in the plane of the orbit (Webbink 1984). It turns out that the stability of the mass transfer depends critically on the tidal interaction between the two white dwarfs (Marsh *et al.* 2004). In absence of any tidal interaction there will be additional angular momentum loss from the orbit due to the transfer of angular momentum from

the orbit to the accreting star which will consequently spin-up. This is different from the cases where the accretion is via a disc for which most of the angular momentum generally is stored in the disc and eventually via very efficient tidal interaction put back into the orbit. However, efficient tidal coupling between the accreting star and the companion might return the angular momentum back to the orbit as well (Racine *et al*. 2006, d'Souza *et al.* 2006; see Figure 6-7), thus reducing the magnitude of the spin-up.

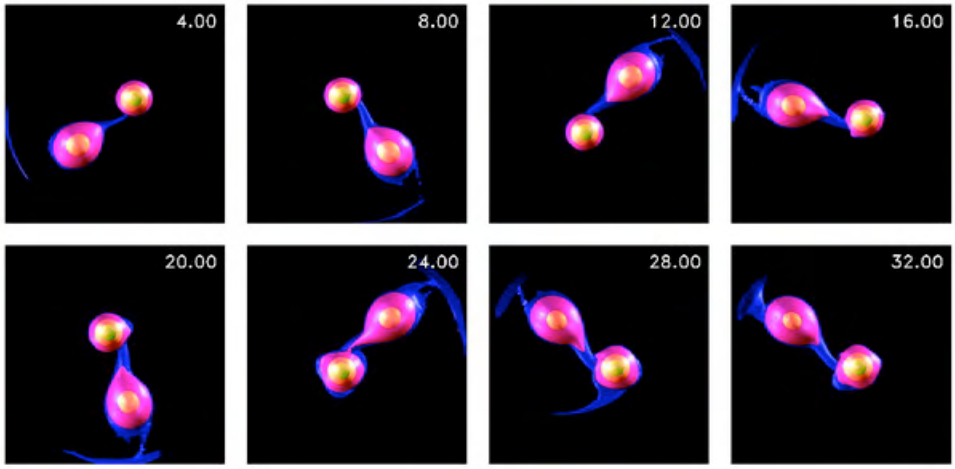


Figure 6-7: Numerical simulation of the stability of mass transfer in a binary with mass ratio 0.5, in which the mass transfer is stable (d'Souza *et al.* 2006).

The difference between efficient and inefficient tidal coupling is rather dramatic: the fraction of double white dwarfs estimated to survive the onset of mass transfer can drop from about 20 percent to 0.2 percent (Nelemans *et al*. 2001) depending on assumptions about the tidal coupling. This difference is very easily measurable with LISA.

For ultra-compact X-ray binaries, the stability issue is completely different. At the onset, the mass transfer is orders of magnitude above the Eddington limit for a neutron star (the mass transfer rate at which the potential energy liberated in the accretion can couple to the infalling gas to blow it away). For normal stars and white dwarfs this would likely lead to complete merger of the system, but the enormous amount of energy liberated when matter is falling into the very deep potential well of a neutron star allows matter to be dumped on it at rates up to a thousand times the Eddington limit. This allows the formation of ultra-compact X-ray binaries from white dwarf-neutron star pairs, if the white dwarf has a low mass (see Yungelson *et al.* 2002). LISA will unambiguously test this prediction, by detecting a several tens of ultra-compact X-ray binaries with periods between 5 and 20 minutes (Figure 6-3).

Double white dwarf mergers

The 80 to 99.8 percent of the double white dwarfs that experience run-away mass transfer and merger likely give rise to quite spectacular phenomena. Although it is not expected that LISA will be able to witness the actual merger of a double white dwarf it will certainly detect the shortest period binary known, expected at a period of about 3 minutes and give an extremely good estimate of their merger rate. Mergers of double white dwarfs have been proposed as pro-

genitors of single subdwarf O and B stars, R Corona Borealis stars and maybe all massive white dwarfs. The merger of a sufficiently massive double white dwarf has been proposed as the trigger for type Ia supernova events, the standard candles that play an important role in our understanding of the expansion of the Universe and the existence of dark energy. Alternatively, if the merger does not lead to an explosion a (rapidly spinning) neutron star will be formed. This is one possible way to form isolated millisecond radio pulsars as well as magnetars, which have been proposed as sites for short gamma-ray bursts *e.g.* Levan *et al.* (2006). LISA will be able to put strong constraints on these hypotheses. By measuring (chirp) masses and coalescence times LISA will directly determine the merger rate for double white dwarfs with different masses which can then be compared with the rates and population of their possible descendants determined by other means.

Neutron star and black hole binaries

In addition to the thousands of white dwarf binaries, several tens of neutron star binaries will be detected by LISA, if the current observational and theoretical estimates of the formation rate of neutron star binaries turn out to be reliable (*e.g.* Nelemans *et al.* 2001). For all these populations, the sample will be complete at the shortest periods as the systems can be seen throughout the Galaxy and thus the sample will be independent of selection effects such as those present in radio pulsar surveys and X-ray surveys that only pick up transient X-ray sources which currently hamper our knowledge about this population in the Galaxy. In addition, by the time LISA will fly, Advanced LIGO will likely have detected a number of double neutron star mergers from far away galaxies, so these measurements together will test our ability to extrapolate our population models from our own galaxy to the rest of the Universe.

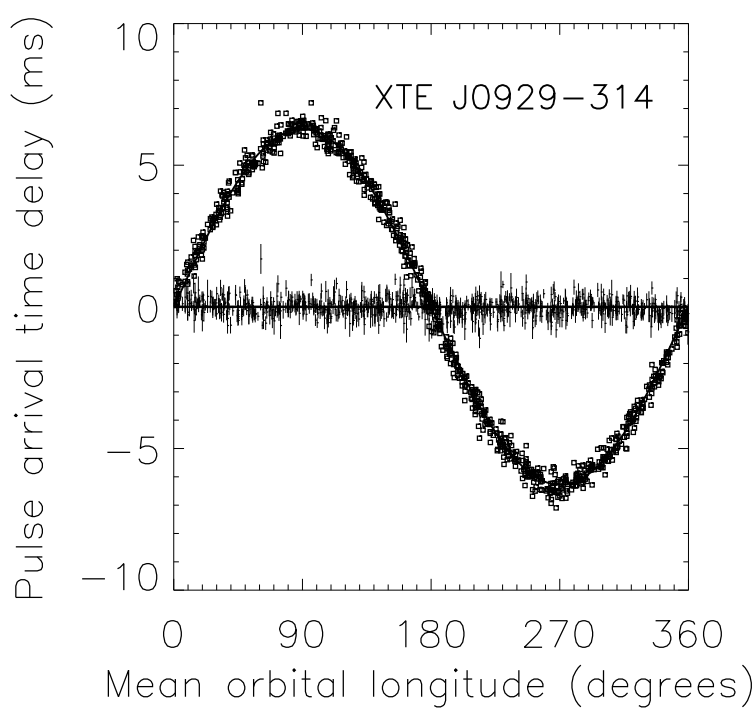


Figure 6-8: Imprint of the 40 min orbital period on the arrival times of the X-ray pulsations in the ultra-compact X-ray binary XTE J0929-314. From Galloway *et al.* (2002)

A very special situation might arise in the millisecond X-ray pulsars in ultra-compact X-ray binaries. In recent years, observations of X-ray pulsations from many ultra-compact X-ray binaries have enabled astrophysicists to determine the rotation rate of the neutron star using the NASA mission RXTE (Figure 6-8). As had been expected on theoretical grounds, the neutron stars are spinning rapidly several hundred times per second due to the angular momentum gained from infalling matter. The measurements give credence to the idea that rapidly spinning neutron stars observed as millisecond radio pulsars are descendants of accreting neutron stars in binary systems (*e.g.* Bhattacharya & van den Heuvel 1991). However, scientists have yet to establish the exact role of ultra-compact binaries in the formation of these pulsars. The distribution of spin periods discovered in X-ray binaries suggests additional neutron star angular momentum loss on top of the plasma physics interaction between the accretion and magnetic field of the spinning neutron stars (Chakrabarty *et al*. 2003). One exciting possibility is that this additional angular momentum loss is due to strong gravitational wave emission (Bildstein 1998). In that case ultra-compact X-ray binaries might be the only sources that could be studied simultaneously with LISA and Advanced LIGO, with LISA detecting the orbital period and LIGO detecting the neutron star period.

If they exist in sufficient quantities, LISA will easily pick up black hole binaries in the Galaxy. There is a lot of uncertainty about the number of ultra-compact stellar mass binary black holes in the Galaxy *e.g.* Belczynski *et al*. (2002) but if they exist they will show up in the LISA band and indeed this is the only way such systems may ever be detected.

New studies of galactic structure with LISA

One of the major advantages of LISA is that it will determine distances for more than 100 compact binaries by measuring their $\dot{f}$ (Equation 2). The exact ability of LISA to determine distances depends critically on the mission lifetime, as larger life times lead to more accurate $\dot{f}$ measurements.

The directional dependence of the Galactic background as well as the directional accuracy for the resolved systems allow for a statistical assessment of the contributions of the different Galactic components such as the Galactic bulge (with its bar), the thin and thick disc and especially the Galactic halo.

Galactic halo

The halo sources will of course be distributed completely differently from the other Galactic components. The LISA directional sensitivity will immediately pick up any strong halo population. The halo population might be enhanced compared to the disc as the formation and evolution of binaries in the halo may have been quite different. Such old and metal poor population can

locally only be studied in globular clusters, where the formation and evolution of binaries is generally completely altered by dynamical effects. There is currently a very interesting suggestion. Two of the 18 known AM CVn systems seem to be most consistent with belonging to the halo. They have very low metal abundances and anomalous velocities. If true this implies a very large number of AM CVn stars in the halo, maybe as many as in the rest of the Galaxy. LISA would certainly pick up the short period systems in this population.

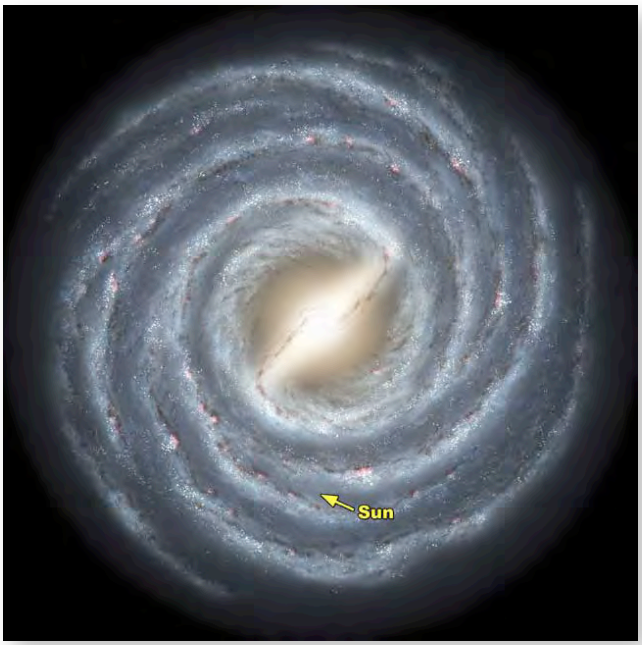
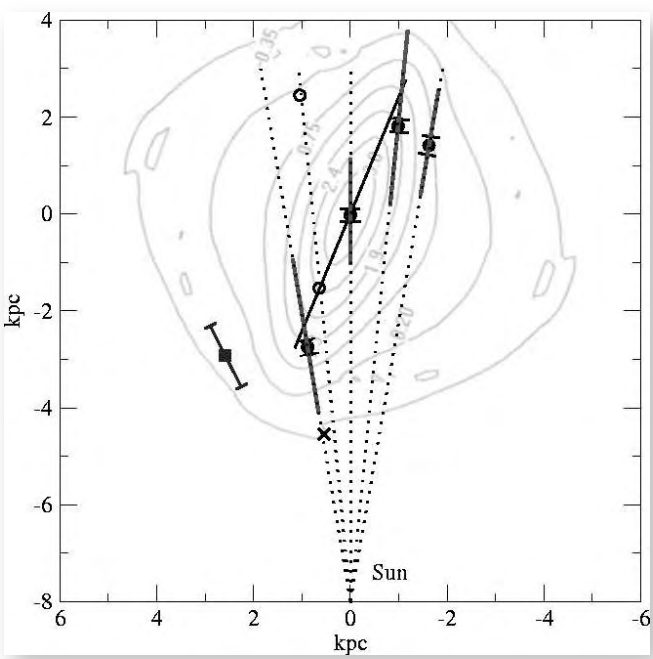


Figure 6-9: Different models for the Galactic bar: above the Spitzer GLIMPSE model, below the model of Bizants and Gerhardt with measured distances to red clump stars (from Babusiaux & Gilmore 2006). Note the difference in the angle of the bar.



Galactic center and bar

The Galactic center is one of the most interesting areas of the Galaxy, with a central massive black hole surrounded by a dense assembly of stars with intriguing properties. Dynamical effects, in particular mass segregation, will lead to many interactions close to the central black hole so that wide binaries will become tighter or will be disrupted (for a review see Alexander 2005). This likely leads to an increase in the number of ultra-compact binaries as well as the possibility of extreme mass-ratio inspirals (see other sections in this volume). However, current observational techniques, fundamental observational limits due to the extreme faintness of these sources as well as severe limitations to theoretical calculations of these processes result in a virtual absence of any constraints on these populations and this will likely remain the situation until LISA will fly.

Another major question about the central region of the Galaxy is the size and orientation of a bar (see Hadamache *et al.* 2006, Gerhard 2002, also Figure 6-9). Because the ultra-compact binaries are expected to closely follow the mass distribution in the Galaxy, direct measurement of distances and directions to hundreds of ultra-compact binaries in

the Bulge will put a constraint on the bar, independent of the interpretation of star counts.

Galactic disc scale height

The level and shape of the double white dwarf background will provide information on the scale height of the ultra-compact binary population (Benacquista & Holley-Bockelmann 2006) in the disc of the Galaxy. For many of the resolved sources the LISA measurements will also provide an estimate of the orbital inclination which for the first time will give hints on the dynamics of the formation of binaries from interstellar clouds because in a statistical way the angular momentum vectors of the binaries can be compared to the overall angular momentum of the Galaxy.

LISA science objectives and investigations relevant to this section (see Appendix 1)

4. Survey compact stellar-mass binaries and study the structure of the Galaxy

4.1. Elucidate the formation and evolution of Galactic stellar-mass binaries: constrain the diffuse extragalactic foreground.

4.2. Determine the spatial distribution of stellar mass binaries in the Milky Way and environs.

4.3. Improve our understanding of white dwarfs, their masses, and their interactions in binaries and enable combined gravitational and electromagnetic observations.

7. New Physics and the Early Universe

Gravitational waves penetrate all of cosmic history, and LISA explores scales, epochs, and new physical effects not accessible in any other way (Figure 7-1). A detectable gravitational wave background in the LISA band is predicted by a number of new physical ideas for early cosmological evolution (Maggiore 2000, Hogan 2006a). Two important mechanisms for generating stochastic backgrounds are relativistic phase transitions and cosmic strings:

Signatures of motions in the early Universe

LISA can detect a broad band stochastic background caused by a first-order phase transition with critical temperature from about 100 GeV to 1000 TeV. Proposed phase transitions include electroweak or supersymmetry breaking, dynamically active submillimeter extra dimensions, and some types of inflationary reheating. LISA may also detect a background, and possibly bursts, from otherwise unobservable cosmic superstrings.

- Many types of new physics predict first-order phase transitions leading to bulk motions from cataclysmic bubble nucleation, cavitation, collisions, and turbulence (Figure 7-2). The cosmic expansion rate at a temperature of about 1TeV, corresponding to an apparent horizon size of about $c/H = ca/\dot{a} \approx 1$ mm at that time, is redshifted now to a frequency

$$f_0 = \dot{a}(t) \approx 10^{-4}\text{Hz}\ [H(t) \times 1\text{mm}/c]^{1/2} \approx 10^{-4}\text{Hz}\ (T/1\text{TeV})\ .$$

Thus, LISA's frequency band of about 0.1 to 100 millihertz today corresponds to the horizon at and beyond the Terascale frontier of fundamental physics. This allows LISA to probe bulk motions at times about 3×10^{-18} to 3×10^{-10} seconds after the Big Bang, a period not directly accessible with any other technique. Taking a typical broad spectrum into account, LISA has the sensitivity to detect cosmological backgrounds caused by new phase transitions from 0.1 to 1000 TeV, if more than a modest fraction $\approx 10^{-7}$ of the energy density is converted to gravitational radiation in LISA's band (Figure 7-3).

- Fundamental string theory, the subject of intense theoretical study as a unified framework for all particles and forces of nature, also predicts the possibility of new fundamental objects called cosmic superstrings, stretched to astronomical size by the cosmic expansion, that lose energy principally through gravitational radiation with a very broad and uniquely identifiable

Key science questions

- Is there a first-order phase transition at or beyond TeV energies?
- Are there extra dimensions at the submillimeter scale?
- Do stable superstrings exist, and can they be blown up to form cosmic strings?
- What was the quantum state of the Universe at or before the Big Bang?
- How did inflation end?
- Were there violent events in the early Universe that left no relic trace in conventional particles and fields?

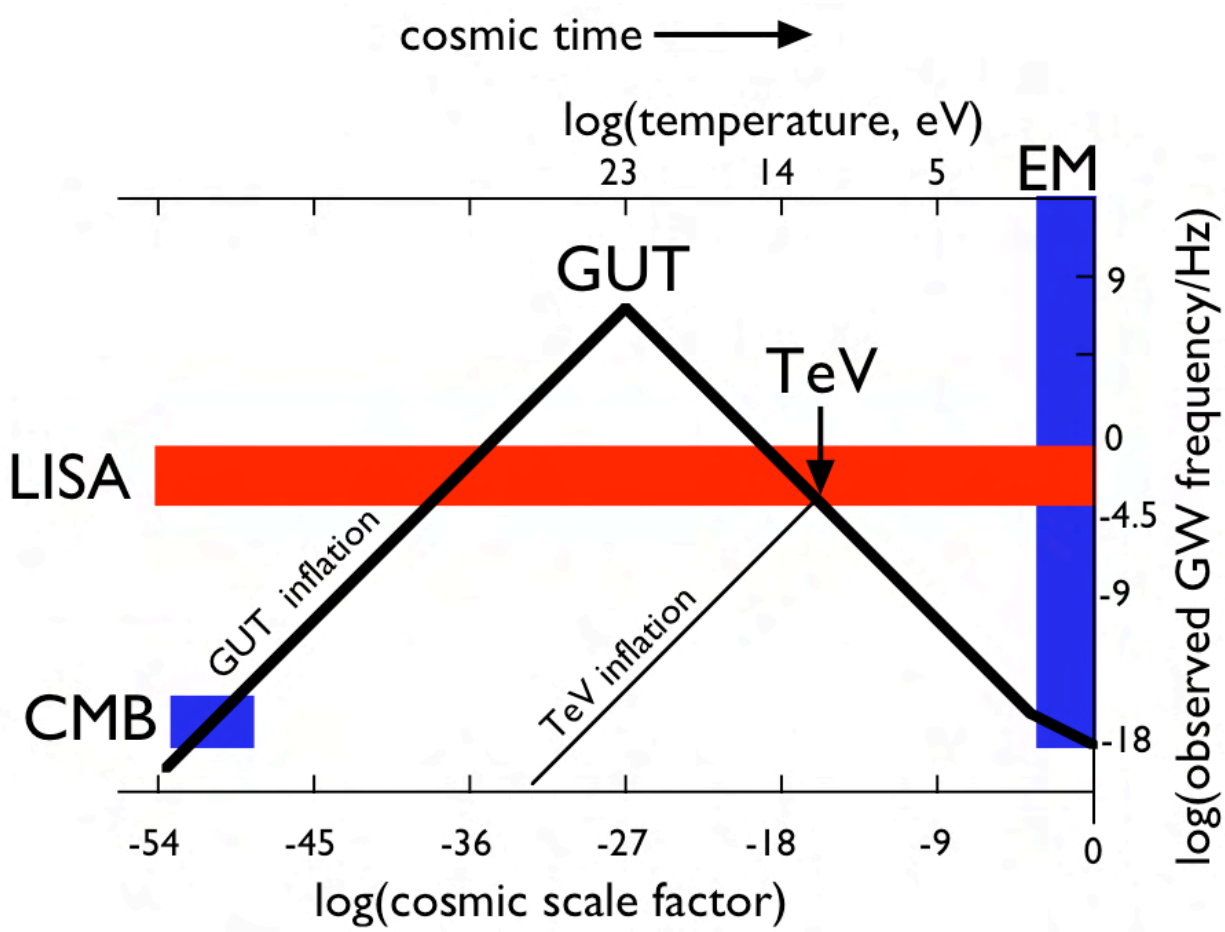


Figure 7-1: The expansion history of the Universe, in units that show the unique penetration power and discovery potential of gravitational waves in cosmology. The observed (redshifted) frequency of wave-generating phenomena is shown as a function of cosmic scale factor *a*, with the present epoch at the right. The solid line shows the redshifted Hubble rate or horizon scale, for a standard Grand Unified Theory (GUT) and a lower temperature Terascale (TeV) inflationary cosmology; the peak represents the epoch of reheating. Regions above these lines correspond to motions smaller (*i.e.*, at higher frequencies) than the cosmological horizon. The red bar shows the range of cosmic history accessed by LISA. Blue regions are accessible to electromagnetic (EM) observations; the bar to the right shows the Universe since recombination (some sources are also seen by LISA, where the two bars overlap), and the box at lower left shows the relic fluctuations imprinted in the CMB at inflation. LISA probes all processes within the horizon up to about 1000 TeV, as well as a regime of cosmic inflation different from CMB observations.

spectrum. LISA will be our most sensitive probe for these objects by many orders of magnitude and so offers the possibility of detecting direct evidence of fundamental strings.

First-order cosmological phase transitions: Bulk motion from bubble nucleation, cavitation, collisions, turbulence

Abundant evidence suggests that the physical vacuum was not always in its current state, but once had a significantly higher free energy. This idea is fundamental and general: it underlies symmetry breaking in theories such as the Standard Model and its supersymmetric extensions, and cosmological models including almost all versions of inflation. Common to all these schemes is the feature that a cold, nearly uniform free energy contained in the original ("false") vacuum is liberated in a phase transition to a final ("true") vacuum, and eventually converted into thermal energy of radiation and hot plasma.

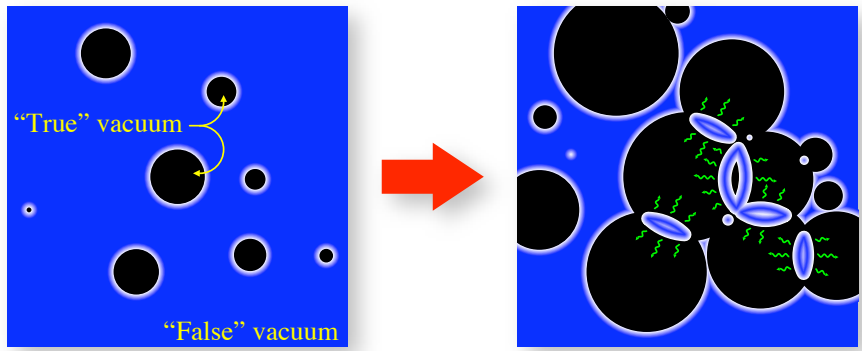


Figure 7-2: First-order phase transition between a "false" and a "true" vacuum. When expanding bubbles of the new phase collide, the latent heat of the old phase is converted into relativistic matter flows, which can produce gravitational radiation.

In many theories the conversion between vacuum states corresponds to a first-order phase transition. In an expanding universe this leads to a cataclysmic process. After supercooling below the critical temperature for the transition, a thermal or quantum jump across an energy barrier leads to the formation of bubbles of the new phase at widely separated nucleation sites. The bubbles rapidly expand and collide (Figure 7-2). The internal energy is thus converted to organized flows of mass-energy, whose bulk kinetic energy eventually dissipates via turbulence and finally thermalizes. The initial bubble collision and subsequent turbulent cascade lead to relativistic flows and acceleration of matter that radiate gravitational waves on a scale not far below the horizon scale (Witten 1984, Hogan 1986, Kosowsky *et al.* 2002, Dolgov *et al.* 2002).

Dynamics of warped submillimeter extra dimensions

A "theory of everything" based on quantum superstrings requires many, as yet invisible, extra dimensions for mathematical consistency. The sizes of the dimensions, their shapes, and how they are stabilized are unknown. If they exist, gravity can penetrate into them, so they must be small or highly "warped" – with sizes or radii of curvature below the submillimeter scale limits set by direct laboratory tests of the gravitational inverse-square law. (The scales probed by Standard Model particles and fields are much smaller than this, but fields other than gravity might be confined to a 3-dimensional subspace or "brane" living in a larger dimensional space.)

LISA, the LHC and the electroweak phase transition

A moderately strong first order TeV-scale electroweak phase transition leads to the production of a detectable background of gravitational waves through bubble collisions and turbulence (Hogan 1986, Grojean & Servant 2006). In the Standard Model and its minimal supersymmetric extension, the phase transition associated with electroweak symmetry breaking by a Higgs field is now expected to be second order. However, other extensions of the Standard Model predict a first order phase transition, and electroweak baryogenesis generally requires it. In the next few years CERN's Large Hadron Collider will probe details of the Higgs sector and the nature of phase transitions in the Terascale region.

Since the Hubble length at the Terascale is about a millimeter, the current threshold where possible new effects of extra dimensions might appear happens to be about the same in the laboratory gravity, particle/field, and cosmological realms: that is, at present, laboratory gravity experiments, accelerator physics, and LISA cosmology converge on the same new regime in very different ways. It is even possible that new properties of gravity on this scale are related to cosmic dark energy (whose energy density is about $(0.1\text{mm})^{-4}$ in particle units).

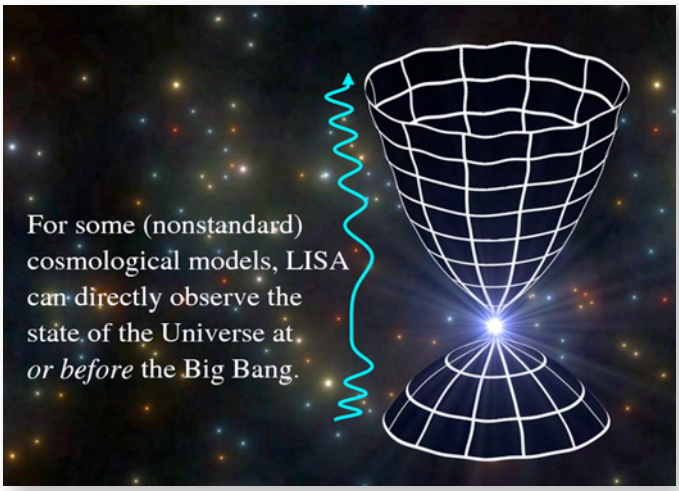
The dynamics associated with the stabilization of extra dimensions at a certain size or warp radius might introduce a source of free internal energy released coherently on a "mesoscopic" (submillimeter to nanometer) scale, leading to a detectable background (Hogan 2000, Randall & Servant 2006). If the extra dimensions are much smaller than the Hubble length when the stabilization occurs, the behavior of the extra dimensions is nearly equivalent to scalar field behavior as viewed in conventional 3-dimensional space, with effects similar to the phase transitions just discussed (Figure 7-3). Brane condensation also introduces a new kind of mechanism for generating gravitational waves: motion and curvature of our Standard Model brane in the extra dimensions. LISA's high frequency limit at 1000 TeV corresponds to direct probes of extra dimensions as small as 10^{-6} mm.

Terascale inflationary reheating

Inflation represents an extraordinarily coherent behavior of an energetic scalar field that is nearly uniform across the observable Universe. After inflation, the internal potential energy of this field is converted into a thermal mix of relativistic particles, in a process known as "reheating". The reheating temperature might be as cool as 1 TeV, especially in some braneworld models where the Planck scale is itself not far above the Terascale.

There is no reason to assume a quiet, orderly reheating process: the decay of the inflaton energy may be violently unstable. In many scenarios, the conversion begins with macroscopically coherent but inhomogeneous motions that eventually cascade to microscopic scales. Quantum coherent processes such as "preheating" transform the energy into coherent classical motions that, like the phase transitions discussed above, generate backgrounds on the order of 10^{-3} of the thermal plasma density (Khlebnikov *et al*. 1997, Felder & Kofman 2006, Easther & Lim 2006). As with those transitions, the characteristic frequency of the background matches the LISA band if the final reheating occurred at 0.1 to 1000 TeV.

Exotic inflationary quantum vacuum fluctuations



The amplification of quantum vacuum fluctuations during inflation leads to a background of primordial gravitational waves. An optimistic estimate of this background in the case of conventional inflation limits these to less than about 10^{-10} of the cosmic microwave background energy density, far below LISA's sensitivity; in many inflation models it is much less (Chongchitnan & Efstathiou 2006). However, some unconventional versions of inflation, particularly pre-Big-Bang or bouncing brane scenarios, predict possibly detectable backgrounds in the LISA band (see for example Brustein *et al.* 1995, Buonanno 2003, Buonanno *et al.* 1997). Although some key parameters remain unknown, which limits the predictive power of these models, they are significantly constrained by gravitational wave backgrounds. If such a background is detected, its spectrum also contains information about the Universe at the time perturbations "re-enter" the horizon (the second horizon intersection in Figure 7-1).

Backgrounds and bursts from cosmic strings

String theory is a leading candidate for a fundamental theory unifying all of physics: both the quantum fields of the Standard Model, and the spacetime dynamics of general relativity. Models of physics and cosmology based on string theory, as well as their field-theory counterparts, often predict the cosmological formation of cosmic superstrings (Polchinski 2005): thin quasi-stable relativistic strings that form after inflation and are stretched to enormous length by the cosmic expansion. In equivalent field-theory language, cosmic strings arise from certain types of phase transitions, and stable relics of the high-energy phase persist in the form of one-dimensional strings that resemble flux tubes or trapped vortex lines.

Observational evidence for a theory of everything

The discovery of an identifiable superstring background (and possibly, but less likely, superstring bursts) would be direct evidence of new physics far beyond the reach of any accelerator. Its properties would tell about the connection between particles, fields, spacetime and fundamental strings, and would help shape the deep unifying mathematical insights of string theory into a model of the real world.

The primordial network of strings spawns isolated, oscillating loops that ultimately radiate almost all of their energy into gravitational waves. Their gravitational radiation is mainly gov-

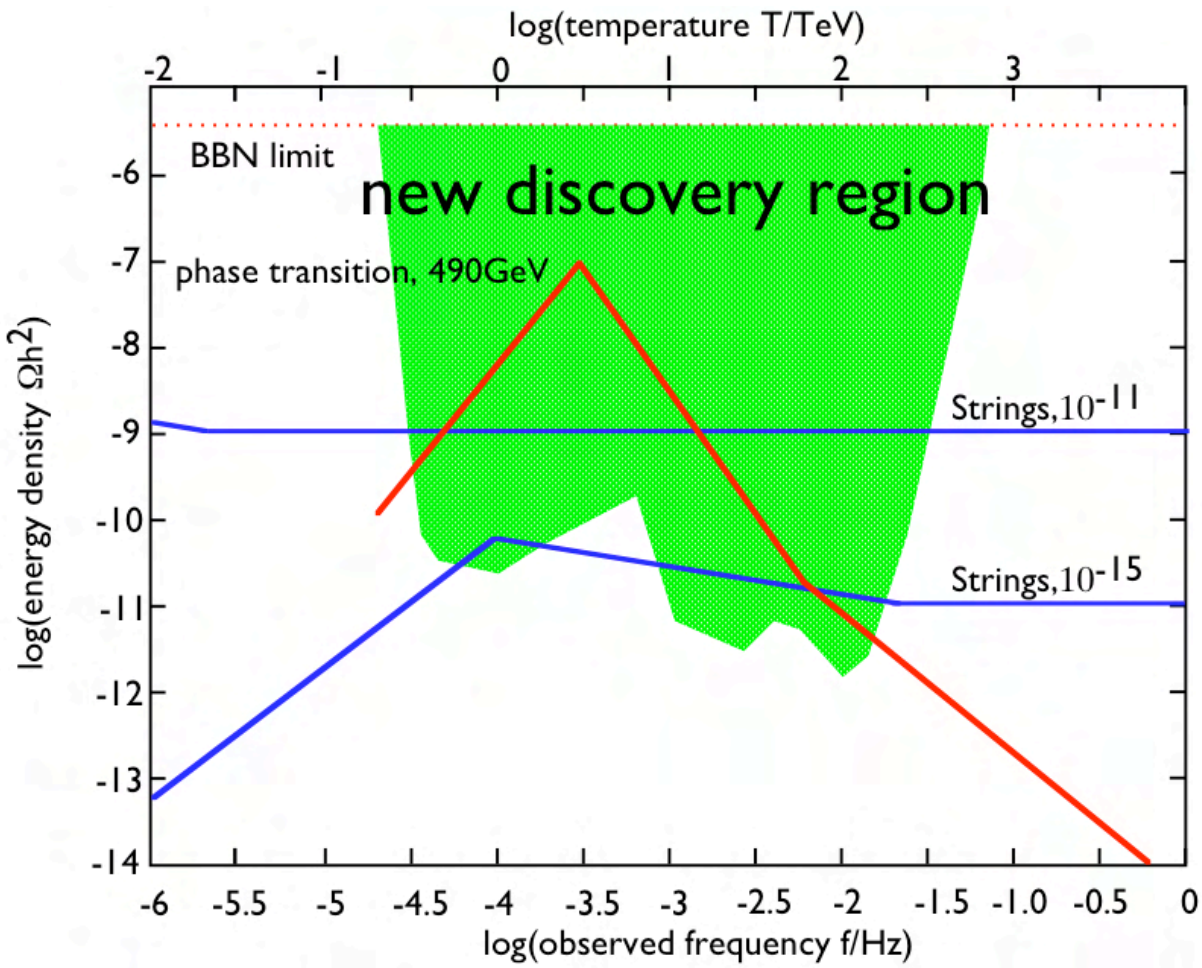


Figure 7-3: Gravitational wave background broad-band energy density is shown in units of the critical density for $h_0 = 1$. The new discovery region shown for LISA assumes a broad band limit using Sagnac calibration to distinguish instrument noise from isotropic gravitational wave backgrounds (Hogan & Bender 2001, updated with optimistic estimate for confusion from unresolved extragalactic binaries from Farmer & Phinney 2003). LISA's sensitivity extends about seven orders of magnitude below the energy density of thermal radiation, and six orders of magnitude below current limits from Big Bang Nucleosynthesis (BBN). The background spectrum from cosmic superstrings (Hogan 2006b) is shown for two values of string tension, $G\mu/c^4 = 10^{-11}$ and 10^{-15}. A model spectrum is shown from a first order phase transition of warped extra dimensions (Randall & Servant 2006), which is typical of strongly first order transition spectra; the spectrum moves to the right in the case of a higher transition critical temperature, down and right for a smaller nucleation scale or a smaller latent heat. Top axis is labeled by the temperature of the Universe when waves of the specified observed frequency were at the size of the cosmological horizon.

erned by a single dimensionless parameter $G\mu/c^4$ reflecting the fundamental physics of the strings, where μ is the energy per unit length, or tension. This number is known to be very small: current limits on gravitational wave backgrounds already indicate that if cosmic strings exist, they must be so light that they have no observable effects apart from their gravitational radiation.

Figure 7-3 includes predicted stochastic background spectra (Hogan 2006b) from strings for two values of $G\mu/c^4$ spanning a range of scenarios motivated by brane world inflation. (These estimates are plotted for a "large loop" scenario where newly formed loops are about 0.1 of the horizon size.) The spectrum from cosmic strings is distinguishably different from that of phase transitions or any other predicted source: it has nearly constant energy per logarithmic frequency interval over many decades at high frequencies, including the range where LISA is able to observe it, and falls off at low frequencies since large string loops are rare and radiate slowly. The current limit on superstring tension (about $G\mu/c^4 \sim 10^{-10}$) comes from extra noise gravitational waves at ~ nanohertz frequencies introduce into timing residuals of millisecond pulsars, but the much lighter string loops detectable by LISA radiate less at those low frequencies than confusion backgrounds from other sources. LISA's sensitivity in terms of $G\mu/c^4$ is about five orders of magnitude deeper than even the best possible future sensitivity from pulsar timing

If the strings are not too much lighter than $G\mu/c^4 \approx 10^{-10}$, where the current pulsar limits lie, occasional distinctive bursts might be seen from loops that happen to beam gravitational waves in our direction from "cusp catastrophes", where a momentary event produces a sharply-bent bit of string moving at nearly the speed of light (Damour & Vilenkin 2005, Siemens *et al.* 2006). These rare events, if they are intense enough to stand out above the background, are recognizable from their universal waveform, which derives just from the geometry of the cusps. Although individual burst events, if detected, give the clearest signature of a string source, the first detectable sign of a superstring loop population is likely their integrated stochastic background as shown in Figure 7-3 (Hogan 2006b).

LISA science objectives and investigations relevant to this section (see Appendix 1)

6. Probe new physics and cosmology with gravitational waves

6.2. Measure the spectrum of, or set bounds on, cosmological backgrounds.

6.3. Search for burst events from cosmic string cusps.

8. LISA and the Key Questions of Astronomy and Physics

LISA addresses forcefully and directly many of the research priorities and big questions raised by recent astronomy and physics decadal and community reports such *Astronomy and Astrophysics in the New Millennium*, and *Connecting Quarks with the Cosmos*. It might not be an exaggeration to say that LISA will completely transform much of physics and astronomy. Since LISA will study the universe in an entirely new way, its discoveries are also likely to expand the scope of both sciences significantly and reshape the questions of the future.

LISA science addresses a very broad cross-section of some of the most important and exciting science priorities identified by major national and international reviews and studies. For instance, the roadmap for the NASA Beyond Einstein program identified five major science objectives and thirteen research focus areas (NASA SEU 2002). LISA, as a Great Observatory in the Beyond Einstein program, addresses all five science objectives, with particularly strong emphasis on four of the five. Furthermore, LISA addresses eight of the thirteen identified research focus areas, many in a way that is unique and impossible to accomplish using conventional space- and ground-based observatories. The Beyond Einstein objectives and focus areas for which LISA has particularly powerful capabilities are given in the accompanying box.

Beyond Einstein science objectives addressed by LISA

Science Objective 1: Find out what powered the Big Bang

Research Focus Area 1. Search for gravitational waves from inflation and phase transitions in the Big Bang.

Research Focus Area 2. Determine the size, shape, and energy content of the Universe.

Science Objective 2: Observe how black holes manipulate space, time, and matter

Research Focus Area 3. Perform a census of black holes throughout the Universe.

Research Focus Area 4. Determine how black holes are formed and how they evolve.

Research Focus Area 5. Test Einstein's theory of gravity and map spacetime near the event horizons of black holes and throughout the Universe.

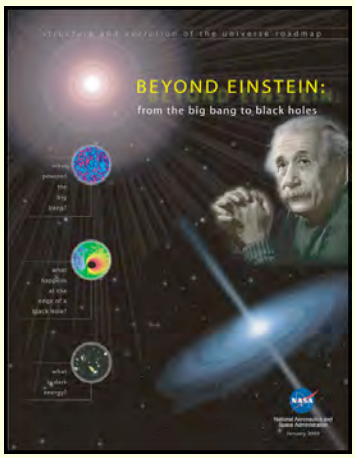
Research Focus Area 6. Observe stars and gas plunging into black holes.

Science Objective 3: Identify the mysterious dark energy pulling the Universe apart.

Research Focus Area 7. Determine the cosmic evolution of the dark energy pulling the Universe apart.

Science Objective 5: Understand the development of structure in the Universe.

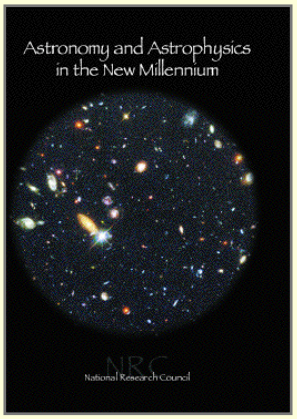
Research Focus Area 12: Discover how the interplay of baryons, dark matter, and gravity shapes galaxies and systems of galaxies.

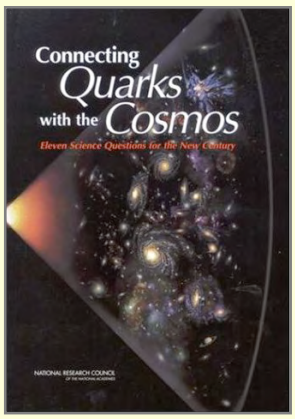


In the US, LISA has been

endorsed as a high priority mission in several influential reports. In particular, National Research Council (NRC) has issued several reports emphasizing the opportunities for exciting new science using gravitational waves. In 1999 the NRC report, *Gravitational Physics: Exploring the Structure of Space and Time* (NRC 1999), described 12 science opportunities, several of which require LISA observations to be realized. A short time later, the 2000 NRC Decadal Survey, *Astronomy and Astrophysics in the new Millennium* (AANM: NRC 2001), stated that "LISA is unique among the recommended new initiatives in that it is designed to detect the gravitational radiation predicted by Einstein's theory of general relativity. The direct measurement of gravitational radiation from astrophysical sources will open a new window onto the universe and enable

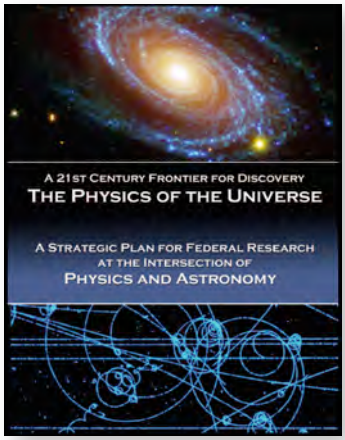
Major science questions of the AANM and Q2C reports addressed in unique ways by LISA



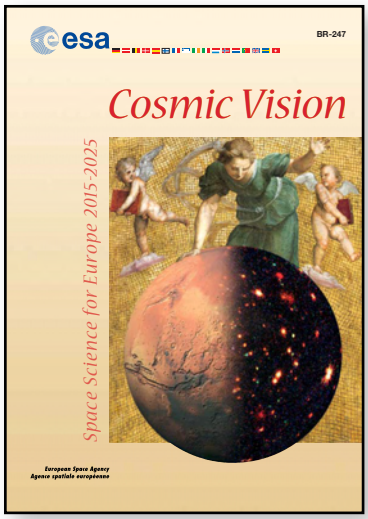


Report	Major Science Question	Relevant LISA Science
AANM & *Q2C*	How did the universe begin, evolve into today's structures, what is its destiny?	Gravitational waves are the only radiation that can be used to study the earliest beginnings of the Universe
AANM	How do galaxies form and evolve?	Massive black holes and mergers play a fundamental role in galaxy evolution
AANM	How do stars form and evolve?	Ultra-compact binaries represent the extreme endpoints of stellar binary evolution
Q2C	Did Einstein have the last word on gravity?	Black hole mergers allow precision tests of dynamic and static strong field gravity
Q2C	What is the nature of Dark Energy?	Precision distance estimates using black hole binaries offer a potentially powerful capability
Q2C	Are there additional spacetime dimensions?	Gravity is one of our best probes of the existence of extra dimensions

investigations of the physics of strong gravitational fields." Likewise, the 2003 NRC report *Connecting Quarks with the Cosmos* (Q2C: NRC 2003) endorsed LISA and characterized LISA as having "great potential to address questions that lie at the boundary between physics and astronomy". The science in the AANM and Q2C reports was summarized in a set of 16 fundamental questions, 5 from the AANM report and 11 in the Q2C report. Many of these very important questions are addressed in a new and unique way by LISA science, as indicated in the accompanying box.



Following the AANM, Beyond Einstein, and Q2C reports, the National Science and Technology Council (NSTC) issued a major report, A 21st Century Frontier of Discovery: *The Physics of the Universe - A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy*. This report endorsed the Beyond Einstein program as a key component of the strategy for federal research investment in physics and astronomy and stated that the execution of the LISA mission is "necessary to open up this powerful new window on the universe and create the new field of gravitational wave astronomy." Most recently, the NRC undertook a *Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision*, issuing a letter report (NRC 2005). This report reviewed post-AANM astronomical discoveries and highlighted in particular progress in three broad areas: the universe and the nature of matter and energy, our place in the cosmos, and the formation and evolution of black holes. LISA is recognized as a facility-class mission, together with Con-X, that will "provide a broad and flexible science return across all of astrophysics, as have HST, CGRO, Chandra and Spitzer before them."



In Europe, LISA and LISA Pathfinder are integral components of ESA's Cosmic Vision Scientific Programme announced in 2005 (ESA 2005). The ESA space science program has traditionally been organized in long-term strategic plans. The Horizon 2000 plan was brought forward in 1985, followed by Horizon 2000 Plus in 1995. All of the missions in these programs have been realized subsequently, showing a remarkable stability in strategic planning. LISA first appeared in Horizon 2000 Plus, as a Cornerstone mission in Fundamental Physics. The other Cornerstone missions in this program are Herschel and Gaia in Astronomy and Bepi Colombo in Solar System Science, all to be launched soon, to follow Rosetta, which is flying already. LISA has subsequently been reconfirmed and it is now taken for granted in the Cosmic Vision Programme: "Despite some delays and descoping owing to budgetary constraints, the promises of Horizon 2000 will be broadly fulfilled when the astronomical missions Herschel and Planck set off into space in 2007. The second step in this decadal series is Horizon 2000 Plus, including highly promising missions such as Gaia, BepiColombo, JWST, LISA and Solar Orbiter. Another challenge is LISA (Laser Interferometer Space Antenna), a joint ESA/NASA

project which, by searching for gravitational waves, will open a new window on the Universe. On LISA Pathfinder (2009), ESA will test European and American contributions to the amazing technology required for this project."

Cosmic Vision is constructed around four general Science Questions with three research topics each. While LISA as a Cornerstone mission in Fundamental Physics clearly belongs to Research Topic 3.2, it addresses all Research Topics in both Science Question 3 and Science Question 4.

1. ESA Cosmic Vision science objectives

2. ***Science Question 1: What are the conditions for planet formation and the emergence of life?***
   3. Research Topic 1.1. From gas and dust to stars and planets.
   4. Research Topic 1.2. From exo-planets to biomarkers.
   5. Research Topic 1.3. Life and habitability in the solar system.
6. ***Science Question 2: How does the solar system work?***
   7. Research Topic 2.1. From the sun to the edge of the solar system.
   8. Research Topic 2.2. The giant planets and their environments.
   9. Research Topic 2.3. Asteroids and other small bodies.
10. ***Science Question 3: What are the fundamental physical laws of the universe?***
    11. Research Topic 3.1. Explore the limits of contemporary physics.
    12. Research Topic 3.2. The gravitational wave Universe.
    13. Research Topic 3.3. Matter under extreme conditions.
14. ***Science Question 4: How did the Universe originate and what is it made of?***
    15. Research Topic 4.1. The early Universe.
    16. Research Topic 4.2. The Universe taking shape.
    17. Research Topic 4.3. The evolving violent Universe

Several of the ESA member states have roadmaps that make statements on space science and LISA in particular. In the German "Denkschrift Astronomie" (Deutsche Forschungsgemeinshaft 2003), LISA is a Golden Bullet and rated top priority. In the UK, LISA and LISA Pathfinder are contained in the Particle Physics and Astronomy Research Council (PPARC) Strategic Plan and have just been confirmed in the 2006 Delivery Plan (PPARC 2006). In the European Community's ApPEC Astroparticle Physics in Europe Roadmap (ApPEC 2006), active support for LISA is also foreseen as a top priority.

Appendix 1: LISA science objectives and investigations

1. Understand the formation of massive black holes

1.1. Search for a population of seed black holes at early epochs.

1.2. Search for remnants of the first (Pop III) stars through observation of intermediate-mass black hole captures, also at later epochs.

2. Trace the growth and merger history of massive black holes and their host galaxies

2.1. Determine the relative importance of different black hole growth mechanisms as a function of redshift.

2.2. Determine the merger history of 10^4 to 3×10^5 $M_\odot$ black holes before the era of the earliest known quasars ($z \sim 6$).

2.3. Determine the merger history of 3×10^5 to 10^7 $M_\odot$ black holes at later epochs ($z < 6$).

3. Explore stellar populations and dynamics in galactic nuclei

3.1. Characterize the immediate environment of MBHs in $z < 1$ galactic nuclei from EMRI capture signals.

3.2. Study intermediate-mass black holes from their capture signals.

3.3. Improve our understanding of stars and gas in the vicinity of Galactic black holes using coordinated gravitational and electromagnetic observations.

4. Survey compact stellar-mass binaries and study the structure of the Galaxy

4.1. Elucidate the formation and evolution of Galactic stellar-mass binaries: constrain the diffuse extragalactic foreground.

4.2. Determine the spatial distribution of stellar mass binaries in the Milky Way and environs.

4.3. Improve our understanding of white dwarfs, their masses, and their interactions in binaries and enable combined gravitational and electromagnetic observations.

5. **Confront General Relativity with observations**

5.1. Detect gravitational waves directly and measure their properties precisely.

5.2. Test whether the central massive objects in galactic nuclei are the black holes of general relativity.

5.3. Make precision tests of dynamical strong-field gravity.

6. Probe new physics and cosmology with gravitational waves

6.1. Study cosmic expansion history, geometry and dark energy using precise gravitationally calibrated distances in cases where redshifts are measured.

6.2. Measure the spectrum of, or set bounds on, cosmological backgrounds.

6.3. Search for burst events from cosmic string cusps.

7. Search for unforeseen sources of gravitational waves

Appendix 2: Acronyms

AANM	Astronomy and Astrophysics in the New Millennium, a NRC report
AGN	active galactic nuclei
AM	amplitude modulation
AU	astronomical unit (150 million km)
BAO	baryon acoustic oscillation
BBN	Big Bang nucleosynthesis
BH	black hole
BHB	black hole binary
CMB	cosmic microwave background
COBE	Cosmic Background Explorer
CGRO	Compton Gamma Ray Observatory
EM	electromagnetic
EMRI	extreme mass ratio inspiral
ESA	European Space Agency
FM	Frequency Modulation
GAIA	Global Astrometric Interferometer for Astrophysics
GLAST	Gamma ray Large Area Space Telescope
GLIMPSE	Galactic Legacy Infrared Mid-Plane Survey Extraordinaire
GR	general relativity
GUT	grand unified theory
GW	gravitational wave
GWR	gravitational wave radiation
HST	Hubble Space Telescope
IMBH	intermediate mass black hole $(10^2 M_\odot < M_{BH} < 10^4 M_\odot)$
JWST	James Webb Space Telescope
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational wave Observatory
LISA	Laser Interferometer Space Antenna
LMC	Large Magellanic Cloud
LPF	LISA Pathfinder
LSS	Large Scale Structure
MBH	massive black hole $(10^4 M_\odot < M_{BH} < 10^7 M_\odot)$
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
PN	post-Newtonian

Q2C	Connecting Quarks with the Cosmos, a NRC report
QNM	quasi-normal mode
RATS	Rapid Time Survey
RF	radio frequency
RMS	root mean square
RXTE	Rossi X-ray Timing Explorer
SDSS	Sloan Digital Sky Survey
SEGUE	Sloan Extension for Galactic Understanding and Exploration
SEU	Structure and Evolution of the Universe
SMBH	supermassive black hole $(M_{BH} > 10^7 M_\odot)$
SMC	Small Magellanic Cloud
SNAP	Supernova Acceleration Probe
SNR	signal-to-noise ratio
TDI	time delay interferometry
UV	ultra-violet
WD	white dwarf
WMAP	Wilkinson Microwave Anisotropy Probe

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