Laser Interferometer Space Antenna
Science Requirements Document

LISA International Science Team

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I. INTRODUCTION

A. Overview and purpose

The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA project to design, build and operate a space-based gravitational-wave (GW) observatory. LISA will use laser interferometry to detect GWs from astrophysical and cosmological sources throughout the Universe at frequencies between about $3 \times 10^{-5}$ Hz (0.03 mHz) and 1 Hz. The mission and its science are summarized in Sec. II of this document.

This Science Requirements Document (ScRD) specifies the top-level performance requirements for the combined flight and ground systems that make up the LISA mission and instrument. These performance requirements are the necessary consequences of a set of observation requirements for LISA’s expected astrophysical and cosmological sources, which in turn are deduced from the fundamental science objectives and the investigations by which those objectives are met. The performance requirements are summarized in Sec. III. At their core is an instrument sensitivity model, which bears an exact but nontrivial relation both to characteristics of the sources and the instrument. That relation, and the validation of the sensitivity model as suitable for meeting the observation requirements, is described in Sec. IV. The observation requirements and their relation to the original science objectives are traced in Sec. V.

The LISA science objectives, investigations, observation requirements, and performance requirements have been established by the LISA International Science Team (LIST), which functions as the joint ESA-NASA science definition team for the LISA mission. The LIST was established in 2001 to succeed previous LISA science organizing bodies in both Europe and the U.S., dating as far back as 1993.

This LISA ScRD is the primary description of the science that the LISA mission should accomplish, and the performance requirements that must be met to accomplish that science. It is submitted by the LIST to the Project to guide the project formulation studies, and to the science program management of both ESA and NASA. For ESA it serves as the top-level science statement; for NASA, it supports the writing of level-1 requirements, which establish the ultimate scientific and technical requirements that govern the Project. This version of the ScRD supersedes all previous versions.

B. Configuration Management

The LIST produces this ScRD and initiates any changes to it. The LISA Project receives the document from the LIST, evaluates the design consequences, and notifies the LIST of its findings so that the science team can consider further changes to optimize the mission’s science return within the larger context of space science. After several such iterations, the Project will accept the document as the baseline performance requirements to which the Project designs the mission and instru-

C. Applicable Documents

The current understanding of the science objectives and associated science investigations that are the foundation of this Science Requirements Document is described in LISA: Probing the Universe with Gravitational Waves (LISA Mission Science Office 2007). The science objectives for LISA and associated performance requirements have been developed over a long period. During the multiple-decades history of the LISA concept, and especially in recent years, there have been major advances in understanding of the astrophysics and the fundamental physics that underlie LISA science. Among the most important prior documents are:

- LISA – A Cornerstone Mission for the observation of gravitational waves: System and Technology Study Report, ESA-SCI(3000)11, corrected version 1.04 (13 Sep. 2000), 342 pp (2000); and

The science objectives of the LISA mission are consistent with the following U.S. and ESA reviews, agency roadmaps and strategic plans:

D. Definitions and conventions

The following definitions and conventions apply throughout this document.

1. Performance Requirements

Performance Requirements are specifications for parameters of the mission and instrument which must be met or exceeded and, where agreed as necessary and possible, must be verified before launch by appropriate analyses, tests, and demonstrations. For the mission, these include a minimum useful science observing time, maximum data latency (time between measurements made and data received on the ground), and caveats for protected observing periods during which there shall be no scheduled interruptions in data collection. For the instrument, these include a minimum spectral strain sensitivity (see “Sensitivity” below) over the designated LISA measurement band, a minimum duty cycle, and minimum times during which the design must provide for all six laser links among the spacecraft to be operational.

2. Strain sensitivity

Sensitivity: LISA sensitivity requirements are stated in terms of the strain spectral amplitude \( \sqrt{S_h(f)} \), which has units of Hz\(^{-1/2} \) and is formally equal to the square root of the single-sided, sky-averaged, polarization-averaged power spectral density of GW strain measured by the “Michelson” X observable of time-delay interferometry (TDI), an observable formed from measurements made with any two arms of the LISA Interferometer. (For a discussion of TDI see, e.g., Estabrook, et al. 2002.)

Signal-to-Noise Ratio (SNR): The sky-averaged SNR of a source that “sweeps” across LISA’s measurement band with characteristic GW strain amplitude \( h_c \) is defined to be the square root of the following integral:

\[
\text{SNR}^2 = \int \frac{h_c^2(f)}{fS_h(f)} d\ln(f)
\]  

(1.1)

All SNRs quoted here are for isolated sources, noise consisting of both Gaussian instrumental noise plus Galactic foreground white-dwarf confusion noise (modeled using the conventional Gaussian approximation), optimal signal processing, and measurement duty cycle \( \eta = 1 \).

\( T_{\text{obs}} \): Time during which science measurements are recorded for processing analysis.

\( \text{Links} \): One-way measured time delays (distances) among spacecraft.

3. Observation Requirements

Observation Requirements (ORs) are derived from LISA’s science objectives and the specific investigations needed to fulfill those objectives. The observation requirements vary for different kinds of sources, but in general list the distance (or redshift) to which a certain source class should be “visible” to LISA (to be able to confidently predict enough detections to meet the science requirement), the particular source parameters that should be measured for the investigation, and how accurately. We use forward calculations of instrument performance for these measurements to confirm that LISA meets its ORs.
4. Performance Goals

Performance Goals specify particular system parameters, instrument capabilities, or mission characteristics that would significantly enhance scientific return and are not precluded by the mission design, but which are not required to be verified and need not drive the mission design. Goals are provided as information to the Project so that they can be accommodated where resources and schedule allow.

II. MISSION DESCRIPTION

The LISA mission concept has been under development for over two decades (cf. Faller, et al. 1985), and it has been studied intensively since being proposed for ESA’s M3 opportunity in May 1993. The current concept has been stable since 1997, with the basic elements unchanged. Significant advances in technology as well as more detailed design and analysis have matured the LISA mission concept and made the long-envisioned instrument performance now feasible. LISA's basic elements are: three spacecraft, three roughly-equal measurement baselines, passive heliocentric orbits, “drag-free” spacecraft following free-falling proof masses, interferometric ranging among the spacecraft, solid-state lasers, and electro-spray (microNewton) thrusters.

By contrast to the long-standing design for LISA instrument performance, our understanding of the science LISA will accomplish has deepened and expanded considerably. We now have evidence to indicate that massive black holes are commonplace in galaxies with bulges, and that they co-evolve with their host galaxies. Massive black hole mergers resulting from mergers of their host galaxies likely occur much more frequently than was believed ten years ago. Numerical relativists have succeeded in calculating the complicated waveforms from merging black holes, which provide a test of extreme dynamical gravity. Cosmology has become an experimental science. Dark energy has been discovered. These advances have made LISA’s science reach more vast and profound than originally realized, for the same or even less demand on instrument performance. The LISA Science Requirements have also matured as a consequence of sustained review of mission design, instrument performance, and science opportunities.

A. LISA Science

The overall science objectives and science investigations of the LISA mission are summarized at the start of Sec. V of this Science Requirements Document (ScRD). They are taken from the comprehensive document LISA: Probing the Universe with Gravitational Waves noted in Section IC above. That document provides a detailed description of the science LISA is expected to perform, and it is a useful primer on gravitational waves, their detection, and their astrophysical sources.

To carry out these scientific investigations, LISA will measure gravitational-wave signals from many different types of astrophysical sources:

- Massive black hole binaries (MBHBs) Mergers of binaries involving two black holes with mass M in the range $10^4 M_\odot < M < 10^7 M_\odot$. Normally, LISA will detect the late inspiral when sufficient gravitational radiation is being produced (lasting months to years), and in some instances LISA will detect the merger event itself and subsequent ringdown of the event horizon. Depending on the source parameters, LISA can detect signals from events as far away as $z \sim 30$, although the luminosity distance may not be precisely determined at these very high redshifts. Current estimates suggest that LISA should see tens to hundreds of massive black hole mergers per year.

- Intermediate-mass black hole binaries (IMBHBs) Mergers of binaries consisting of at least one black hole with mass $10^5 M_\odot < M < 10^7 M_\odot$. LISA can detect these events out to $z \sim 20$, and can get accurate parameter estimation out to $z \sim 10$ (see the observation requirements in Sec. V for accuracy specifications). Estimates of likely event rates are uncertain, but indications are that these events could be frequent.

- Extreme-mass ratio inspirals (EMRIs) Stellar-mass compact objects (black holes, neutron stars, or white dwarfs) with $M \sim 10 M_\odot$ scattered into long-lived, highly elliptical capture orbits around massive black holes in galactic nuclei. LISA can detect these events and get valuable parameter estimates out to $z \sim 1$. The best estimate of the detection rate is $20-40/yr$, but uncertainty is large.

- Close binaries of stellar-mass compact objects Close binary systems of stellar-mass black holes, neutron stars and white dwarfs in the Milky Way Galaxy with orbital periods between 100 and 10,000 seconds. These will be very numerous, and LISA will easily detect several thousand of the brightest sources. The remainder will constitute a diffuse foreground signal between 0.2 and 2 mHz. Extragalactic systems of the same type will contribute a weak diffuse foreground signal between 2 and 3 mHz.

LISA is also capable of detecting signals from cosmological backgrounds, bursts from cosmic string cusps, and signals from unforeseen sources.

The LISA science and sources are qualitatively different from the science and sources of ground-based gravitational-wave detectors. A space-based instrument can detect gravitational radiation of much lower frequency, and the Universe offers the richest array of sources at those lower frequencies.

The mission and instrument performance requirements necessary to support LISA science are presented in Sec. III of this
ScRD, organized around the science objectives. A brief introduction to the relationship between instrument performance and science objectives follows.

LISA will measure the time-varying strains in space-time caused by gravitational waves in the frequency band 0.1 millihertz (mHz) to 1 Hz. It does this through very accurate laser metrology between pairs of spacecraft in a constellation of three spacecraft. The measurement methodology is that of laser spacecraft Doppler tracking. Ability to identify a strain spectral amplitude on the order of $10^{-20}/\sqrt{\text{Hz}}$ is needed in order to detect expected astrophysical and cosmological gravitational-wave signals, to extract scientific information from them, and to carry out tests of fundamental physics. Based on conservative estimates of source event rates, to meet all of the stated science objectives, LISA should have this measurement capability for about five years.

The required instrument performance takes the form of a model of measurement sensitivity over the desired range of gravitational-wave frequencies. That sensitivity, given as a spectral amplitude function over the LISA measurement band, is a carefully calculated convolution of the noise contributions to the instrument measurements and the response function of the instrument to incoming gravitational waves.

There is no trivial or direct way to translate LISA’s Observation Requirements, which are written in terms of the measurements LISA must be able to infer for astrophysical and cosmological sources of gravitational waves, into Performance Requirements vis a vis instrument strain sensitivity. Extensive and detailed calculations have been made in a “forward direction” to assess the science (e.g., source parameters and their estimation accuracies) that can be performed with a given model for instrument performance. These, together with an understanding of the limiting noise levels arising both from within the instrument and from the space environment, have led to a set of performance requirements for the mission (involving total observing time, duty cycle, data latency, protected observing periods, etc.) and for the instrument that include a strain sensitivity spectral amplitude, over a prescribe range of frequencies, which the LISA instrument must meet or exceed (i.e., be more sensitive than, which means to exhibit an instrument performance sensitivity curve that lies below the required curve). Other requirements on the instrument include the total number of operating laser links (which need not be the full number of six throughout the mission). This sensitivity model for the instrument performance requirements is described in Sec. III of this ScRD.

**B. Mission Concept**

The concept described in this section has notional values of some top-level design parameters. The particular values used here are not a prescription for those parameters, but rather are suggestive of the approximate order of magnitude intrinsic to the underlying concept. LISA is a gravitational wave detector based on an interferometer. It measures time-varying strains in space-time by interferometrically monitoring changes in baselines millions of kilometers long. The mission concept requires two basic functions: undisturbed masses to act as the endpoints of the baselines and a measurement system to monitor changes in the lengths of the baselines. The disturbance of the masses must be sufficiently small that the resulting motions are less than the apparent length changes associated with gravitational waves to be detected. Likewise, the measurement system must be able to detect those apparent length changes. The baselines are defined by three spacecraft orbiting the Sun (see Fig. 1). A key feature of the LISA concept is that there exist orbits that do not require station-keeping to maintain a near-equilateral triangular formation a fixed distance from the Earth for the duration of the mission. The spacecraft at the corners house interferometry equipment for measuring changes in the baselines and “proof masses” which define their endpoints.

The proof masses are protected from disturbances by careful design and “drag-free” operation. In drag-free operation, the mass is free-falling, but a housing around the proof mass senses the relative position of proof mass and spacecraft, and a control system commands the spacecraft’s thrusters to follow the free-falling mass. Drag-free operation keeps force gradients arising in the spacecraft from applying time-varying disturbances to the proof masses.

The distance measuring system is essentially a continuous interferometric laser ranging scheme. Lasers at each end of each arm operate in a “transponder” mode. A beam is sent out from one spacecraft to a distant one. The laser in the distant spacecraft is phase-locked to the incoming beam and returns a high power phase replica. When that beam returns to the original spacecraft, it beats against the local laser. Variants of this basic scheme are repeated for all long baselines, and the lasers illuminating different baselines are also compared. Optical path difference changes, laser frequency noise, and
clock noise are determined.

Achievable levels of disturbance on proof masses and achievable sensitivities of laser ranging system make is possible to obtain a useful measurement bandwidth in the frequency regime of $10^{-5}$ to 1 Hz. This band has many types and large numbers of gravitational wave sources, some likely very strong.

The three arms can simultaneously measure both polarizations of quadrupolar waves. The source direction is decoded from amplitude, frequency, and phase modulation caused by annual orbital motion of the antenna and its sensitivity pattern across the sky.

III. SUMMARY OF SCIENCE REQUIREMENTS

In this LISA Science Requirements Document, a model of instrument sensitivity is the main description of the requirements levied by the science against the mission design. In Sec. V, the science objectives and science investigations are rendered into Observation Requirements. A selected Instrument Sensitivity Model (ISM) is evaluated against the Observation Requirements to show that a mission design whose performance equals or exceeds the model sensitivity can fulfill the science objectives. The ISM is a relatively generic model of the space-based gravitational wave-detector concept described in Sec. II.B, based on three parameters: an acceleration noise, a displacement noise, and the arm length of the interferometer.

The ISM is given in Sec. III.A. The model and other baseline requirements are summarized in Sec. III.B. Additional performance goals are summarized in Sec. III.C. The process for validating the ISM is described in Sec. IV.

A. Instrument Sensitivity Model

The noise model for the LISA instrument calculates the strain noise amplitude spectral density, $S_\delta(f) = \Delta L(f)/2L$, as the product of several terms:

$$\sqrt{S_\delta(f)} = \sqrt{5} \times \frac{2}{\sqrt{3}} \times T(f) \times \frac{\sqrt{S_{\delta_{\text{IMS}}}(f)} + \sqrt{S_{\delta_{\text{DRS}}}(f)}}{L},$$

(3.1)

where the measurement band is defined from 0.1 to 100 mHz. The first coefficient, $\sqrt{5}$, represents the results of averaging the antenna response over the full sky. The second coefficient, $1/\sin(60\text{deg}) = 2/\sqrt{3}$, accounts for the projection effect of the equilateral triangular geometry of the detector onto the response of the optimum detector, which is an L-shaped Michelson. The transfer function $T(f)$, described in Sec. III.A, represents the conversion of individual measurement uncertainty into the detector strain response, including the finite light-travel time along the arms and the Time Delay Interferometry (TDI) Michelson X variable response. The variables $S_{\delta_{\text{IMS}}}(f)$, $S_{\delta_{\text{DRS}}}(f)$, and $L$ are the power spectral density of the displacement noise from the measuring system, the power spectral density of the displacement noise from spurious accelerations on the proof masses, and the arm length of the interferometer, respectively.

The LISA sensitivity model is plotted in Fig. 2.

1. Instrument Noise Model

The single-link equivalent position uncertainty is expressed as an amplitude spectral density whose power spectral density is the sum of two terms—the displacement noise of the Interferometry Measurement System (IMS), and the acceleration noise of the Disturbance Reduction System (DRS), which is responsible for minimizing the residual acceleration of the proof masses:

$$\sqrt{S_{\delta_{\text{single link}}}(f)} = \sqrt{S_{\delta_{\text{IMS}}}(f)} + \sqrt{S_{\delta_{\text{DRS}}}(f)}. \quad (3.2)$$

The displacement-noise amplitude spectral density $S_{\delta_{\text{IMS}}}(f)$ for the uncertainty in the interferometry measurement system is given by:

$$S_{\delta_{\text{IMS}}}(f) = \Delta X_0 \times 10^{-12} \frac{m}{\sqrt{\text{Hz}}} \times \sqrt{1 + \left(\frac{f_0}{f}\right)^4}$$

$$10^{-4} \leq f \leq 10^{-1} \text{Hz}, \quad (3.3)$$

with $\Delta X_0 = 18$, $f_0 = 0.002$ Hz.

The displacement-noise amplitude spectral density $S_{\delta_{\text{DRS}}}(f)$ for the uncertainty in the DRS is calculated from an amplitude spectral density for the residual acceleration on the proof
masses,
\[
\sqrt{S_{\delta \text{DRS}}(f)} = \Delta A_0 \times 10^{-16} \frac{m}{s^2\sqrt{\text{Hz}}} \\
\times \sqrt{1 + \left(\frac{f_0}{f_H}\right)^4} \sqrt{1 + \left(\frac{f_L}{f}\right)^4} \quad 10^{-4} \leq f \leq 10^{-1}\text{Hz},
\]
with \(\Delta A_0 = 30\), \(f_L = 0.0001\text{ Hz}\), \(f_H = 0.008\text{ Hz}\).

The equivalent displacement-noise amplitude spectral density is then given by:
\[
\sqrt{S_{\delta \text{DRS}}(f)} = 2 \sqrt{\frac{S_{\delta \text{DRS}}(f)}{(2\pi f)^2}} \quad 10^{-4} \leq f \leq 10^{-1}\text{Hz},
\]
where the factor of two accounts for the presence of four proof masses in the measurement of the difference in length of two arms, and the \(1/(2\pi f)^2\) is the conversion from acceleration to position in Fourier space.

2. Instrument Transfer Function

The instrument transfer function describes the instrument’s response to gravitational waves of different frequencies. Because LISA’s response to gravitational waves depends in a complex way on the position of the source in the sky, the polarization of the wave and its frequency, the sensitivity is conventionally averaged over all possible sky locations and polarizations.

The instrument transfer function is often written containing all the effects of the averaging, but it is clear that any transfer function can always be normalized to be 1 at a given frequency and the remaining numerical factor be absorbed in the instrument sensitivity. The choice made in this document is to normalize the transfer function at low frequencies, where it shows a flat frequency dependence, i.e., LISA’s response does not depend on the frequency of a gravitational wave if its frequency is low enough.

For high frequencies \(f > c/(2L)\), where \(L\) is the arm length, the response of LISA decreases. When the arm length \(L\) is an integer multiple of half the effective wavelength of the gravitational wave, the effect of the wave on that arm vanishes. So only the difference of the arm length to the maximum number of half effective wavelengths, the effective arm length, is affected by the gravitational wave. The higher the frequency of the gravitational wave, and consequently the shorter its wavelength, the smaller the effective arm length becomes and the smaller the absolute change of the effective arm length becomes. So, in general, a decrease proportional to \(1/f\) should be expected, with a transition between the constant part at low frequencies and the high frequency decline at \(f_0 = c/(2L)\).

Furthermore, at frequencies where the wavelength of the gravitational wave is an exact integer multiple of an arm length, the effect in this arm vanishes. In an interferometer with two identical arms, the overall effect vanishes. This leads to a loss of sensitivity for a given frequency. As gravitational waves from sources at different sky positions but same frequency have different angles of incidence on LISA, their effective wavelength, i.e., the wavelength projected on the arm, differs. This causes the transfer function to never go to infinity but to just increase by about a factor of 2 at these frequencies.

Unfortunately, there is no analytic model of the instrument transfer function that accurately displays all its features. A numerical representation of the transfer function is plotted in Fig. 3. If the more complex structure at higher frequencies is not of interest, one can use the approximation
\[
T(f) = \sqrt{1 + \left(\frac{a f}{f_0}\right)^2},
\]
where \(f_0 = c/(2L)\) and \(a = 0.41\).

B. Performance Requirements

The LISA Performance Requirements consist of the ISM that satisfies all of the Observation Requirements in Sec. V and of any other miscellaneous requirements on the performance of the mission stated in the Observation Requirements. Specifically:

- LISA shall have a sensitivity better than or equal to the Instrument Sensitivity Model given in Sec. III.A. The requirement for LISA’s actual sensitivity curve at each frequency should be interpreted operationally as a requirement that at each frequency \(f\) the integral of \(S_0 df\) from 0.7\(f\) to 1.4\(f\) should lie below the ISM (i.e., small bumps above the ISM are allowed provided a smoothed sensitivity curve lies below the specified one).
• LISA shall have a useful science observing time of 5 years.
• LISA shall be designed for 3 spacecraft with 6 working links, and the design shall ensure 4 working links for the full mission duration.
• Protected observing periods may be specified with as little as two weeks’ notice. During such a period there shall be no scheduled interruptions during the (up to) 4 days of the protected period.
• LISA data from all three satellites shall be downlinked with a delay of not more than 6 days.
• The LISA design shall permit a latency in data transmission of less than 6 hours during protected observing periods, provided the ground stations are available.

C. Performance Goals

This section summarizes the goals requested by the science objectives and investigations in Sec. V.

• LISA shall have as a goal a sensitivity better than or equal to the Instrument Sensitivity Model given in Sec. III.A, extended up to 1 Hz and down to 0.03 mHz.
• LISA shall have as a goal 6 working links for the full mission duration.
• LISA shall have as a goal an extended mission duration of 8.5 years.

IV. VALIDATING THE SENSITIVITY MODEL

The Instrument Sensitivity Model is the core of the baseline requirements derived from the mission science. Since it is very difficult, if not impossible, to directly invert the Observation Requirements in Sec. V for the required instrument performance, it is necessary to do the forward calculation of the instrument performance with a instrument model to verify that the Observation Requirements can be met. The process of verifying that the ISM will in fact enable the required observations is generically summarized in this section. This section is not intended to provide all technical details of the calculation, but rather give the reader a sense of the undertaking. An extensive literature on the gravitational wave emission, propagation and detection has developed over the last 30 years. The desired products are predictions of the signal-to-noise ratio in the detector and the uncertainty of source parameters extracted from the data. The number of extractable source parameters depends on the specific source, but may be as many as 17. Examples of parameters that might be extracted from a fully chirping binary are polar location ($\theta$), azimuthal location ($\phi$), inclination ($i$), polarization ($\psi$), initial orbital phase ($\phi_0$), coalescence time ($t_c$), luminosity distance ($D_L$), chirp mass ($M_c$), and reduced mass ($\mu$). The process generically involves computing waveforms from the post-Newtonian equations of motion and/or from numerical relativity simulations for the source of interest, taking account of the relative orientation and separation of the source and the detector, invoking the response of the detector in conjunction with both astrophysical and instrumental noise, and taking into account the estimation of the many parameters in the signal. The ISM enters this process as the instrument response and noise. This general process differs from source to source with assumptions and methodologies appropriate to the source being considered. The best example of this process for binary black holes of the scenarios in many of the Observation Requirements in Sec. V, see Lang and Hughes (2006). Their calculations underlie the tables shown there and other science investigations, though with slightly different assumptions than described in their published paper. After each Observation Requirement discussed in Sec. V, there is a review of the supporting calculation for that requirement.

The LISA Calculator (http://www.physics.montana.edu/LISA/lisacalculator) is a particularly handy web-based tool for exploring the LISA performance in specific situations. Note that spin effects are not included, orbits are assumed to be circular, and mass rations much greater than 100 may be suspect. Many considerations enter into the details of this process. For example where binaries are concerned, the mass ratios, redshift, spin and precession effects, merger and ring-down signals, sky and polarization averaging, orbital eccentricity all affect choices in how the calculations are done. Background and burst detection pivots on still other considerations.

The following assumptions are made for the calculations supporting this document:
• Unless noted, only a single interferometer is used in the calculation. This is taken to add some redundancy against the risk of partial failure. Aside from conservative rate calculations, no other margin is carried in the science requirements.

• Both galactic and extragalactic binaries of compact stellar mass objects will be so numerous as to give confusion noise background at some level. Consequently, a complete noise model for the detection and parameter estimation process must include the astrophysical noise. Figure 4 illustrates a typical model (http://www.srl.caltech.edu/~shane/sensitivity) of the galactic and extragalactic confusion noise backgrounds relative to the ISM from Sec. III.A.

• In all cases, the ISM is assumed to have no useful sensitivity below 0.03 mHz. In some cases, the ISM is assumed to have no useful sensitivity below 0.1 mHz.

• Except where specific sources known, these calculations usually use sky position and orientation averaging as a benchmark.

V. REQUIREMENTS BY SCIENCE OBJECTIVES

This section connects the science objectives of LISA to the baseline performance requirements that drive the design of the mission. For each science objective, one or more science investigations are listed that will meet the objective. The investigations require that particular observations be made, and those are stated as Observation Requirements. A standard Instrument Sensitivity Model (ISM) was proposed in Sec. III that satisfies the Observation Requirements given below. That ISM and ancillary requirements summarized in Sec. III.B constitute the science requirements for the mission.

The science objectives are set out in Appendix 1 of LISA: Probing the Universe with Gravitational Waves (LISA Mission Science Office 2007). The science objectives and their investigations are summarized in Table I.

Each science investigation will lead to an observation of one or more of the anticipated source types. Consequently, there will be more than one observing requirement levied against a source type if more than one investigation relies on an observation of that source. This may lead to multiple observation requirements with similar values; such observations are more valuable for the multiple science investigations they support.

A. Trace the formation, growth and merger history of MBHs as a function of redshift

Background Information: Massive black holes are essential components of galaxies, and their evolutionary states appear to be closely linked to those of their hosts. Today, MBHs are ubiquitous in the nuclei of nearby galaxies (Ferrarese & Ford 2005; Tremaine et al. 2002; Greene, Barth & Ho 2006). The available data show a tight correlation between black-hole mass and the stellar-velocity dispersion of the host bulge (Gebhardt et al. 2000; Ferrarese & Merritt 2002; Tremaine et al. 2002). In elliptical and spiral galaxies, the bulge velocity dispersion appears to correlate tightly with the value of the circular velocity measured at distances of 20–80 kpc from the center, suggesting that the mass of nuclear black holes correlates with the mass of the host’s dark-matter halos (Ferrarese 2002). The association between MBHs and their host galaxies suggests a common evolutionary path and implies that MBH masses trace their surrounding mass concentrations of baryons and dark matter (Silk & Rees 1998; Haehnelt & Kauffmann 2000; Adams, Graf & Richstone 2001; Murray, Quataert & Thompson 2005; McLaughlin, King & Nayakshin 2006). The merger rates of MBHs as a function of cosmic time can then be used to constrain the mass assembly history of their host galaxies.

The nomenclature describing black holes varies in the astrophysical literature. In this document, black holes with mass $M < 10^2 M_\odot$ are referred to as “stellar-mass,” those with $10^2 M_\odot < M < 10^4 M_\odot$ as “intermediate-mass black holes” (IMBHs), and those with $10^4 M_\odot < M < 10^6 M_\odot$ as “massive black holes” (MBHs).

The study of the formation, accretion history, and environmental impact of massive black holes in the nuclei of galaxies provides invaluable insights into the quasar phenomenon, the evolution of active galactic nuclei, the relation between black holes and their host halos, the hierarchical growth of cosmic structures, and the astrophysics of some of the earliest sources of light to be formed.

Standard CDM hierarchical cosmologies predict that the earliest MBHs formed at $z > 15$ in the centers of small dark-matter halos (Abel, Bryan & Norman 2002; Bromm, Coppi & Larson 2002; Madau & Rees 2001; Volonteri & Rees 2005). We have however a poor understanding of the astrophysical processes that led to the formation of these first seed black holes, and to their growth into the supermassive variety that powers bright quasars at $z = 6$. Seed black holes may have formed from the coalescence of stellar-mass black holes, from the collapse of the first generation of massive stars (population III), or from the collapse of supermassive stars formed out of dense low-angular-momentum gas.

Population III stars with masses between 40 and $140 M_\odot$ or above $260 M_\odot$ are predicted to collapse to black holes with masses exceeding half of the initial stellar mass (Heger & Woosley 2002). Some of these IMBHs may grow quickly through gas accretion and mergers to masses above $10^4 M_\odot$. Furthermore, whether or not IMBHs from population III stars played an important role in the growth history of the MBHs found in galactic nuclei, they may have formed close IMBH–IMBH binaries that later merged. This investigation aims to bound the event rate for merging MBH–MBH, IMBH–IMBH, and IMBH–MBH binaries at both early and later epochs.

SR1.1: Trace the formation, growth, and merger history of
TABLE I LISA science objectives and supporting science investigations.

<table>
<thead>
<tr>
<th>Science Objectives</th>
<th>Science Investigations</th>
</tr>
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| Trace the formation, growth, and merger history of massive black holes | • Trace the formation, growth, and merger history of IMBHs and MBHs out to redshift \( z = 15 \)  
• Determine the merger history of MBHs with masses of \( 10^4 - 3 \times 10^5 M_\odot \) from the era of the earliest known quasars, \( z \sim 6 \)  
• Determine the merger history of MBHs with masses between \( 3 \times 10^5 \) and \( 10^7 M_\odot \) at later epochs, \( z < 6 \). |
| Explore stellar populations and dynamics in galactic nuclei | • Characterize the immediate environment of MBHs in \( z < 1 \) galactic nuclei from EMRI capture signals  
• Study intermediate-mass black holes from their capture signals  
• Improve our understanding of stars and gas in the vicinity of galactic black holes using coordinated gravitational and electromagnetic observations |
| Survey compact stellar-mass binaries and study the morphology of the Galaxy | • Elucidate the formation and evolution of Galactic stellar-mass binaries; constrain the diffuse Galactic and extra-Galactic foreground  
• Determine the spatial distribution of stellar mass binaries in the Milky Way and environs  
• Improve our understanding of white dwarfs, their masses, and their interactions in binaries, and enable combined gravitational and electromagnetic observations |
| Confront General Relativity with observations | • Detect gravitational waves directly and measure their properties precisely  
• Test whether the central massive objects in galactic nuclei are the black holes of General Relativity  
• Perform precision tests of dynamical strong-field gravity |
| Probe new physics and cosmology with gravitational waves | • Study the expansion history of the Universe using gravitationally calibrated distances to merger events (in cases where redshifts can be measured)  
• Measure the spectrum of cosmological gravitational-wave backgrounds, or set upper limits on them  
• Search for gravitational-wave bursts from cosmic-string cusps  
• Search for unforeseen sources of gravitational waves |

IMBHs and MBHs out to redshift \( z = 15 \).

**LISA's expected contribution:** Different models of MBH birth, growth, and merger at high \( z \) lead to different predictions for the numbers and mass distribution of MBH mergers that LISA will observe. Therefore LISA’s measurements of the earliest merger events of IMBHs and MBHs will shed light on the origin and early growth mechanisms of the first seeds.

**OR1.1:** LISA shall have the capability to detect the mergers of IMBHs and MBHs with masses in the range \( 300 M_\odot < M_2 < M_1 < 3 \times 10^4 M_\odot \) with \( M_2/M_1 > 1/100 \), out to redshift \( z = 15 \), with sufficient SNR to enable determination of the MBH masses, the spin of the larger MBH, and the luminosity distance to the binary.

Figure 5 shows a contour plot of the redshift \( z \) out to which LISA can detect a merging MBH binary with masses \( (M_1, M_2) \), assuming a required detection SNR of 10 (averaged over sky positions and binary orientations), the use of a single synthesized Michelson observable, and integrating SNR only on the inspiral part of the waveform. Thus, these redshift values are conservative. By inspection, the mass range specified in OR1.1 lies inside the \( z = 15 \) contour, so LISA’s baseline sensitivity meets this requirement. As further elucidation, Fig. 6 shows several contour plots of black-hole binary SNRs.

**FIG. 5** Contour plot of the redshift \( z \) out to which a MBH binary of masses \( (M_1, M_2) \) is detectable: specifically, the \( z \) for which the rms (sky- and orientation-averaged) SNR = 10, assuming only one synthesized-Michelson TDI observable and integrating only over the inspiral part of the waveform down to a separation \( r = 6M \).
as a function of the component masses $M_1$ and $M_2$, for several different redshifts $z$. Again, these SNRs are for a single synthesized Michelson; for two, they would (approximately) increase by a factor $\sqrt{2}$.

**Science Ramifications:** Table V.A shows current estimates for the LISA measurement uncertainty of black-hole-binary luminosity distances and spins (Hughes 2007a), for binaries at $z = 10$ with representative masses. These estimates were performed as outlined in Lang and Hughes (2006, §3.5). Uncertainties are not shown for redshifted masses, which will be determined extremely well ($\sim 1\%$).

The spin of the final merged (remnant) MBH is best measured by observing its ringdown, following the merger (Dreyer et al. 2004). The ringdown waveform carries away $\sim 1\%$ of the remnant’s rest mass (Laguna 2006, private communication). Assuming this emission efficiency, LISA can detect and measure the spin of remnant black holes with masses $3 \times 10^4 M_\odot < M < 3 \times 10^5 M_\odot$, at redshifts up to $z = 10$ (Finn 1992).

**Robustness:** For IMBH and MBH mergers in these mass and redshift ranges, LISA will almost always resolve component masses well (with $\Delta M_i/M_i < 10\%$); this is true whether LISA has 1 or 2 operating IFOs. With 2 IFOs, the mass-normalized spin magnitude $\chi_1$ of the larger black hole can typically be measured with an error $\sim 0.01–0.1$; this accuracy decreases by a factor of only $\sim 2$ for the case of 1 IFO. Even with 2 IFOs, only a small fraction of sources (typically $\lesssim 10\%$) can be localized on the sky; with 1 IFO, the area of the error box on the sky (as measured, e.g., in steradians) typically increases by more than an order of magnitude, so that practically no sources can be localized. Finally, for these low-mass, high-

### Table II

<table>
<thead>
<tr>
<th>$M_1/M_\odot$</th>
<th>$M_2/M_\odot$</th>
<th>$D_L$ uncertainty</th>
<th>spin uncertainty</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$</td>
<td>$3 \times 10^4$</td>
<td>31.9%</td>
<td>0.012</td>
<td>10.80</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$3 \times 10^4$</td>
<td>34.1%</td>
<td>0.029</td>
<td>18.50</td>
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<td>43.2%</td>
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<td>30.90</td>
<td></td>
</tr>
<tr>
<td>$10^4$</td>
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<td>$3 \times 10^4$</td>
<td>$3 \times 10^4$</td>
<td>28.5%</td>
<td>0.005</td>
<td>14.90</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$3 \times 10^4$</td>
<td>26.8%</td>
<td>0.008</td>
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<tr>
<td>$3 \times 10^3$</td>
<td>25.0%</td>
<td>0.016</td>
<td>45.30</td>
<td></td>
</tr>
<tr>
<td>$10^4$</td>
<td>$3 \times 10^4$</td>
<td>24.2%</td>
<td>0.041</td>
<td>79.50</td>
</tr>
<tr>
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<td>31.7%</td>
<td>0.005</td>
<td>14.60</td>
</tr>
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<td>23.3%</td>
<td>0.006</td>
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<tr>
<td>$3 \times 10^4$</td>
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<td>46.00</td>
<td></td>
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<td>$3 \times 10^4$</td>
<td>19.3%</td>
<td>0.020</td>
<td>75.00</td>
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<td>$3 \times 10^5$</td>
<td>$3 \times 10^4$</td>
<td>22.5%</td>
<td>0.016</td>
<td>10.20</td>
</tr>
</tbody>
</table>

**SR1.2:** Determine the merger history of MBHs with masses of $10^4–3 \times 10^5 M_\odot$ from the era of the earliest known quasars, $z \sim 6$.

**LISA’s expected contribution:** Active galactic nuclei pow-
OR1.2: LISA shall have the capability to detect the mergers of MBHs with masses in the range $10^4 M_\odot < M_1,M_2 < 3 \times 10^5 M_\odot$, out to redshift $z = 6$, with sufficient SNR to enable determination of the MBH masses, the spin of the larger MBH, and the luminosity distance to the binary.

Science Ramifications: Table 3 illustrates that the baseline LISA sensitivity satisfies OR1.2 for angular resolution, distance accuracy, and spin-determination accuracy. For mergers in this range, mass determinations are typically accurate to better than 1%.

Robustness: The basic fact that LISA will provide excellent accuracy in determining the MBH masses is quite robust against moderate changes in LISA’s noise, and against the availability of 1 vs. 2 IFOs. Less robust is LISA’s accuracy in determining the merging binary’s distance and sky position. It is reasonable to expect that one might find electromagnetic counterparts for many of the sources that LISA observes in this class. For the purposes of this document, we shall refer to an event as “localizable” on the sky if the major axis of its 1-$\sigma$ error ellipse on the sky is < 3 degrees; i.e., small enough to fit inside the LSST field of view. LISA data analysts will learn fairly precisely when each merger will occur several weeks in advance; however, accurate sky locations will usually become available only hours to days before the mergers. Indeed, the fraction of localizable sources will typically double in the last 6–12 hours before merger. Therefore, the requirement that one be able to point telescopes at the right location prior to merger leads directly to a performance requirement that the LISA design should permit latency in data transmission (from all three satellites) of < 6 hours. Also, the fraction of these mergers that are localizable typically decreases by a factor $> 10$ when the number of IFOs decreases from 2 to 1. This drives the performance requirement that LISA be designed with six working links. Finally, we note that LISA’s noise performance at frequencies below $10^{-4}$ Hz has a minimal effect on the number of localizable events in this mass range.

SR1.3: Determine the merger history of MBHs with masses between $3 \times 10^5$ and $10^7 M_\odot$ at later epochs, $z < 6$.

LISA’s expected contribution: Since all bright galaxies at these redshifts appear to host MBHs, LISA will detect all galaxy mergers that ultimately lead to the coalescence of $< 10^5 M_\odot$ MBHs. These are the strongest sources in the LISA band, yielding precise measurements of system parameters (Lang and Hughes 2006). The determination of sky position to a few arcminutes, together with luminosity distance to 0.1%, will facilitate the search for electromagnetic counterparts of the merger event among the $\sim 10^4$ galaxies in the error box. Even a few identifications and redshifts will permit precision measurements of cosmic-expansion history, geometry, and dark-energy density (see Sec. V.E).

<table>
<thead>
<tr>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$D_L$ Uncertainty</th>
<th>Spin Uncertainty</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$</td>
<td>$3 \times 10^2$</td>
<td>17.40%</td>
<td>0.009</td>
<td>12.70</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$3 \times 10^3$</td>
<td>22.80%</td>
<td>0.022</td>
<td>22.60</td>
</tr>
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<td>$10^4$</td>
<td>$3 \times 10^3$</td>
<td>31.30%</td>
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<td>37.20</td>
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<td>$3 \times 10^4$</td>
<td>$3 \times 10^3$</td>
<td>31.00%</td>
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<td>61.40</td>
</tr>
<tr>
<td>$10^3$</td>
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<td>16.70%</td>
<td>0.003</td>
<td>18.60</td>
</tr>
<tr>
<td>$3 \times 10^3$</td>
<td>$3 \times 10^3$</td>
<td>17.00%</td>
<td>0.006</td>
<td>33.00</td>
</tr>
<tr>
<td>$10^4$</td>
<td>$3 \times 10^3$</td>
<td>15.10%</td>
<td>0.004</td>
<td>56.50</td>
</tr>
<tr>
<td>$10^4$</td>
<td>$3 \times 10^3$</td>
<td>17.30%</td>
<td>0.009</td>
<td>95.10</td>
</tr>
<tr>
<td>$3 \times 10^5$</td>
<td>$3 \times 10^4$</td>
<td>17.80%</td>
<td>0.003</td>
<td>22.90</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$3 \times 10^4$</td>
<td>14.90%</td>
<td>0.003</td>
<td>42.40</td>
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<td>$3 \times 10^3$</td>
<td>$3 \times 10^4$</td>
<td>11.80%</td>
<td>0.010</td>
<td>72.10</td>
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<tr>
<td>$10^4$</td>
<td>$3 \times 10^4$</td>
<td>11.40%</td>
<td>0.026</td>
<td>124.00</td>
</tr>
</tbody>
</table>
For the redshifts and masses in this range, the principal limitation of the standard noise model is the low-frequency cut-off. The gravitational waves from larger black holes at larger redshifts have frequencies that are too low for LISA, for most of the inspiral. In general, the parameters of an MBH binary redshifts have frequencies that are too low for LISA, for most off. The gravitational waves from larger black holes at larger...
masses of the IMBHs.

Finally, coordinated electromagnetic and GW observations of both MBH merger, IMRIs, and EMRIs could all reveal a great deal about gas dynamics in the vicinity of the MBH, as discussed below under SR2.3.

**SR2.1:** Characterize the immediate environment of MBHs in $z < 1$ galactic nuclei from EMRI capture signals.

**LISA’s expected contribution:** It should be possible to observationally distinguish between the different channels, at least in a statistical sense: EMRIs resulting from 2-body encounters should have roughly random orbital orientations and can remain moderately eccentric right up until the final plunge. Objects tidally torn from binaries should have very low eccentricity (by the time they enter the LISA band) but roughly arbitrary inclination angle between their orbital plane and the MBH spin. Compact objects created in the accretion disk should have very low eccentricity and orbital angular momentum nearly aligned with the spin of the MBH.

The EMRI observation requirements below are set somewhat conservatively, because the event rate for EMRIs is still quite uncertain. White dwarfs, neutron stars, and stellar-mass black holes are all potential EMRI sources (i.e., all plunge through the MBH horizon before being tidally disrupted. The best current estimates suggest that inspirals of $\sim 10 M_\odot$ BHs will dominate the LISA detection rate (Hopman 2006, 2009). The reasons are two-fold: mass segregation in the galactic nucleus concentrates heavier stars towards the center, and $10 M_\odot$ BHs can be detected $\sim 10$ times further away than $0.6 M_\odot$ WDs (based on comparing the SNRs for the last 3 years of inspiral), so the volume of space in which they can be detected is $\sim 10^3$ times larger.

A recent estimate is that the BH inspiral rate in the Milky Way is $2.5 \times 10^{-7}$ yr$^{-1}$ (Hopman 2006). Extrapolating this rate out to $z = 1$, Gair et al. (2004) show that signals with SNR $> 30$–$35$ should be detected at the rate of $\sim 50$–$100$ EMRIs per year with standard LISA noise and response function and two interferometers, or $\sim 20$–$40$/yr with one interferometer. However, there are a number of uncertain ingredients in the overall rate calculation. The space density of $10^6 M_\odot$ BHs and the stellar mass function in galactic nuclei are both poorly known. These uncertainties argue for the full sensitivity of the reference instrument noise model. Recall that raising the noise curve by a factor 2 decreases the detection rate by a factor $\sim 8$.

For EMRIs involving stellar mass black holes, most of the SNR accumulates in the last $\sim 1$–$2$ years of inspiral, corresponding to $\sim 200,000$ observable gravitational wave cycles. The EMRI signals will typically be buried in noise (both instrumental noise and confusion noise from white-dwarf binaries), but it will be possible to dig the EMRI signals out of the noise using matched filtering. Due to the huge number of independent templates required to cover the space of waveforms, it has been estimated that the matched filtering SNR must be at least $\sim 14$ to yield a confident detection. However, again due to the vast number of templates, straightforward optimal matched filtering over the entire parameter space will not be computationally feasible. So sub-optimal methods will be required. The best current estimate is that a SNR of 30–35 will be required for detection, with realistic computing power (Gair et al. 2004).

Note that accurately determining the source parameters (including distance) from EMRIs comes almost automatically with the ability to detect EMRIs at all. Excellent parameter-estimation accuracy is due to the great predictability of the waveforms, combined with the high number of detected GW cycles, and the relatively high SNR ($\sim 50$). That is, they do not entail significant measurement performance beyond the capability just to detect these sources, and so come “at no extra charge.” Therefore, the observation requirements below are mostly just set by overall sensitivity (including to a range of MBH masses).

Also, determining the MBH spins will significantly constrain their accretion and merger history. Large spins suggest a long period of disk accretion, while low spin suggests mass buildup through mergers.

This investigation will:

- Determine precise masses and spins for a substantial sample of quiescent massive black holes at galactic centers.
- Determine the relative importance of different EMRI channels from the distribution of observed eccentricities and inclination angles.
- Constrain the stellar environment of the central star clusters around massive black holes by making use of the observed rates, the masses of the orbiting compact objects, and correlations with central black hole mass.

**OR2.1:** LISA shall have the capability to detect gravitational waves emitted during the last three years of inspiral for a stellar-mass compact-object ($m_2 \sim 5$–$100 M_\odot$) orbiting a massive black hole (with $m_1 \sim 10^5$ – few $\times 10^5 M_\odot$) at $z = 1$ with SNR $> 30$ (averaged over source locations and orientations).

**Science Ramifications:** EMRI detection requires the full sensitivity in the range $\sim 1$–$10$ mHz, where the SNR accumulates. Calculations by Gair et al. (2004) and Barack et al. (2004) estimate that the standard noise and response model satisfies this criterion (for two interferometers) if the compact-object mass is $m_2 \gtrsim$ several $-10 M_\odot$ and if $m_1 \gtrsim$ several $\times 10^5 M_\odot$; see Table IV. Compact objects with masses $m_2 \lesssim 1 M_\odot$ (white dwarfs and neutron stars) will be detectable only to smaller distances ($\sim 1$ Gpc; see Table VI). For a $m_2 = 10 M_\odot$, $m_1 = 10^5 M_\odot$ EMRI, extrinsic parameters such as the masses, spins, and eccentricity are typically measured to fractional accuracies of $\sim 10^{-4}$ (Barack & Cutler 2004). These errors scale roughly as $1/m_2$. Extrinsic parameters like spin direction and distance are typically measured with
TABLE IV  Signal-to-noise estimates for Extreme Mass Ratio Inspir- 
 al events at redshift z = 1, assuming baseline LISA, optimistic WD subtraction (5 yr), and volume-inclination averaging. Left columns refer to the masses of the MBH, the compact object mass, and the eccentricity at plunge. AET refers to SNRs computed with Synthetic LISA using the optimal combination of TDI variables. X refers to the TDI output for a single-interferometer, unequal-arm Michelson combination. Values are taken from Table III of the LIST WG1 EMRI taskforce (Barack et al. 2004; also reproduced here in Table VI), but with the values scaled to z = 1 by multiplying by (2/1.2)^5/6 / 6.6 ≈ 0.23.

<table>
<thead>
<tr>
<th>m (final)</th>
<th>S/N(AET)</th>
<th>S/N(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3mo</td>
<td>1yr</td>
</tr>
<tr>
<td>3 \times 10^3</td>
<td>100</td>
<td>0.25</td>
</tr>
<tr>
<td>3 \times 10^5</td>
<td>100</td>
<td>0.25</td>
</tr>
<tr>
<td>10^6</td>
<td>10</td>
<td>0.25</td>
</tr>
<tr>
<td>10^6</td>
<td>100</td>
<td>0.25</td>
</tr>
<tr>
<td>10^6</td>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>10^6</td>
<td>100</td>
<td>0.4</td>
</tr>
</tbody>
</table>

accuracies ~ 5 \times 10^{-2}; sky position is typically measured to within ~ 3 sq. deg.

Robustness: EMRI sources lie close to the LISA noise floor and thus set the minimum of LISA's required sensitivity. If LISA is functional in only a single-interferometer configuration, the event rate will drop by roughly a factor of 2^{5/2} ~ 3. The requirement of a 3-yr observation period comes partly from the uncertain rate, and partly from “edge effects”: the first ~ 8 months of observation will yield very few EMRI detections, since not enough SNR could have built up in this time. An observation time of at least 3 years is necessary to keep the fractional loss of sources to “edge effects” below ~ 20%.

SR2.2: Study intermediate-mass black holes from their capture signals.

LISA's expected contribution: Since the SNR for EMRIs and IMRIs scales as the square root of the smaller mass, IMRIs have roughly 3-30 times higher SNR than EMRIs containing a 10M⊙ BH (at the same distance). However, the inspiral rate for IMRIs is much less well understood than for EMRIs, and is presumably considerably lower. Miller (2005) estimates a few to tens of LISA detections per year for both scenarios.

The various hierarchical merger models in Sesana et al. (2007) predict that most IMRI mergers involving 10^6M⊙ MBHs, like those found in fully-formed galactic nuclei, only begin in appreciable numbers after z ~ 6, and peak at z = 2. Consequently, a redshift of 3 is chosen for the observation requirement on IMBHs merging with supermassive black holes.

OR2.2: LISA shall have the capability to detect gravitational waves emitted by a 10^3–10^4M⊙ IMBH spiraling into a MBH with mass in the range 3 \times 10^5–1 \times 10^6M⊙, out to z = 3 (with SNR ~ 30). LISA shall maintain this detection capability for a 3 yr observing period.

Science Ramifications: Based on SNR estimates assuming circular orbits, LISA will meet the above requirement. For some masses, sufficient SNR will have built up on timescales of order 1 week to 1 month. For larger IMBH masses the situation improves roughly in proportion to the square root of the IMBH mass. Besides measuring the IMBH inspiral rate (which is clearly proportional to the average number density of IMBHs in galactic nuclei), LISA will be able to measure the masses of these IMBHs to ~ 1% or better, which 2 – 3 orders of magnitude better than they are known from current observations of their X-ray luminosity.

Robustness: For one interferometer, calculations indicate that IMBH inspirals into MBHs are still easily detected, although with at least ~ 1 month required for sufficient SNR to build up.

SR2.3: Improve our understanding of stars and gas in the vicinity of galactic massive black holes using coordinated gravitational and electromagnetic observations.

LISA's expected contribution: Identification of electromagnetic emission from gas around the black holes whose properties LISA measures is exciting both for the rich tests this would enable of models of the behavior of gas around black holes, and for the opportunity it offers to identify the redshift of the source, and thus enable precision cosmography [cf. SR5.1]. Three scenarios in which this might happen are: (1) the onset of accretion after the merger of a MBH binary, (2) emission from a circumbinary disk disturbed by the mass loss and recoil of a merger, and (3) tidal disruption of a captured star in the late stages of an EMRI event.

A binary of comparable mass black holes (m_2/m_1 > 0.01) in a galactic nucleus will attract and accumulate gas in a circumbinary disk. The binary’s varying gravitational potential supplies energy and angular momentum to the disk, largely preventing accretion until after the merger (Milosavljević & Phinney 2005, MacFadyen & Milosavljević 2006) when the disk will be able to fill in on a timescale of 1-10 years (depending on disk mass and viscosity), and an AGN would turn on, bright enough to be detected by current and planned X-ray satellites (Milosavljević & Phinney 2005, Dotti et al 2006). Electromagnetic observation of this AGN, combined with LISA’s measurements of the merger, would offer the unique opportunity to unambiguously and precisely measure the mass and spin of the remnant black hole and compare with the mass and spin inferred from traditional modeling of electromagnetic emission from AGN (e.g. QPO models, line widths of broad optical emission lines, X-ray Fe-K shell fluorescence).

To identify the source galaxy with an electromagnetic observation, the sky location and redshift must be localized well enough that the field can be monitored in the optical-UV-Xray bands, and the new AGN distinguished from other large-amplitude variable sources. Depending on mass and redshift,
the sky location must be determined to degree scales and the distance to a precision of 10% (cf. Kocsis et al 2006). Note that if the event can be localized ∼ 4 days before merger, one could hope also to get pre-merger images, which would make any case more convincing.

In addition to this afterglow AGN, there may well be emission within minutes to days after merger from acoustic and shock waves excited in the circumbinary disk by the sudden mass loss (of order ∼ 5%) and recoil (of order ∼ 100–1000 km/s) arising from the energy and momentum carried away by gravitational waves (Phinney et al. 2007; Haiman et al. 2009; see Corrales et al. 2009 and Tanaka & Menou 2010 for references and recent work in this rapidly developing field). This would be most readily detected in the rest-frame UV (optical at earth for z > 1) by wide field synoptic survey telescopes such as LSST, and would enable the first precise determination of the internal structure of accretion disks around the black holes in galactic nuclei.

To ensure that at least one merger can be observed during a clear night in the hemisphere accessible to LSST, LISA should localize ∼ 10 sources to within the 3.5 degree LSST field with enough notice (∼ 6 hours) to enable pre-merger deep fields to be observed. Also, at least ∼ 4 days before merger the instant of merger should be known to within 1, and it should be localized to within ∼ 20 degrees so astronomers can reschedule the appropriate telescope for observations during and immediately after the merger. See SR 2.1 and 5.1 for related discussion.

For mass ratios < 0.01, matter can more efficiently ‘leak’ from the circumbinary disk onto the black holes, and the accretion rate may become highly enhanced even before the merger (Armitage & Natarayan 2002). EMRI events involving helium stars, low mass white dwarfs, and brown dwarfs (the latter in the local group only) can lead to tidal disruption of the captured star in the late stages of the EMRI event (Kobayashi et al. 2004; Sesana et al. 2008). As with other proposed tidal disruption events (cf. Komossa et al. 2004, Gezari et al. 2006), the aftermath would be an ultraviolet-X-ray flare, but with the unique feature that the masses, spins and initial orbit will have been precisely defined by the gravitational-wave measurement. Success here would require localization during the EMRI event to within the field of view of whatever UV and X-ray telescopes are flying at the time.

The localization requirements here are the same as those in SR5.1. Briefly, LISA will be capable of determining the sky position of ∼ 10^5–10^6 M⊙ MBH mergers out to z = 1 to within 3.5 degrees at least 6 hours before merger. Luminosity distances will be determined to within several percent. For EMRIs and IMRIs with SNR > 50, LISA will determine the luminosity distance to within 3% and the sky position to within 5 sq. deg.

Same observational requirement as OR5.1.1 and OR5.1.2. See corresponding sections for more details.

C. Survey compact stellar-mass binaries and study the morphology of the Galaxy

Background Information: Ultra-compact galactic binaries, where at least one member is a white dwarf or neutron star, have orbital periods below a few hours. At present, due to their electromagnetic faintness, only fifty to a hundred such systems are known. However, many compact stellar-mass binaries in the Milky Way and its surroundings will be bright in gravitational radiation, so LISA will increase the observational sample ten-fold. The systems detectable by LISA will be strongly dominated by white-dwarf binaries, but will also contain neutron-star systems and possibly stellar-mass black holes (Evans et al. 1987, Hils et al. 1990, Nelemans et al. 2001b). Unlike electromagnetic observations that are biased against short orbital periods, LISA is best suited to detect tight systems. The LISA stellar-mass binary sample will, therefore, be complementary to the electromagnetic one. In addition, simultaneous observations with electromagnetic and astrometric surveys will enable otherwise unobtainable measurements of masses, distances, stellar sizes, tidal effects and mass transfer. LISA will thus provide a radically new arena for studies of the formation and evolution of such exotic objects, the physical mechanisms (radiation reaction, tidal effects and mass transfer/loss) that drive their orbital evolution, and it will provide new insights on white-dwarf internal structure and, possibly, on the formation scenario of SN Type Ia.

At the low-frequency end of LISA’s sensitivity band (below ∼ 1 mHz), the gravitational wave signals from Galactic compact binaries will overlap to the extent of producing a confusion-limited foreground from tens of millions of binaries. Foreground radiation from extra-Galactic white-dwarf binaries will also be present and potentially observable above ∼ 2 mHz (Hils et al. 1990; Farmer and Phinney, 2004). [Note that any spectral continuum not of cosmological origin is referred to as a “foreground” in this section.]

SR3.1: Elucidate the formation and evolution of Galactic stellar-mass binaries; constrain the diffuse Galactic and extra-Galactic foreground.

LISA’s expected contribution: LISA will discover at least a few thousand previously unknown stellar-mass binaries within the Milky Way (Evans et al. 1987, Hils et al. 1990, Nelemans et al. 2001b, Nelemans et al. 2004), associated globular clusters (Benacquista et al. 2001), and nearby satellite galaxies (Cooray and Seto 2005). The number of detected systems as a function of the binary period can be used to determine the formation rate and the evolutionary history of the population. For instance, observations of binaries in stellar clusters may provide a signature of different evolutionary channels (Benacquista et al. 2001), and observations of double neutron stars may allow for a new means, complementary to electromagnetic observations (e.g. radio pulsar observations) and the likely ground-based GW observations, to quantify their formation rate.
FIG. 7 Expected LISA signal of several known ultra-compact “verification” binaries. Binary parameters are accurately determined only for a handful of AM CVn systems (Roelofs et al. 2007). The dashed lines show the LISA instrument sensitivity with a SNR of 5 (upper) and 1 (lower). The solid coloured lines denote different LISA foreground noise estimates (Nelemans et al. 2004, Nelemans et al. 2001a (Alt CE), Nelemans et al. 2001b, Hils and Bender 1997). Figure courtesy of Gijs Nelemans (2010).

Information on the evolutionary history of the Galactic population of compact stellar-mass binaries is also encoded in the spectrum of the Galactic and the extra-Galactic foreground (Hils et al. 1997; Farmer and Phinney, 2003), which depends on the cosmological star-formation rate and white-dwarf binary evolution. LISA has therefore the capability of constraining these models, by exploiting the time variation of the Galactic foreground signal (Cornish, 2001; Ungarelli and Vecchio 2001, Edlund et al. 2005) and by discriminating between the instrumental noise and the isotropic component of the diffuse foreground using suitable TDI combinations (Tino et al. 2001; Hogan and Bender, 2001; Seto and Cooray 2004, Tanuya and Kudoh 2005).

This investigation will:

- Quantify the birth rate and evolutionary history of stellar-mass binary populations by discovering at least 1,000 ultra-compact binaries (primarily white dwarfs, together with a handful of neutron stars, and possibly stellar-mass black holes), including those systems in globular clusters and the Magellanic Clouds.

- Constrain the birth rate of Galactic white-dwarf binary systems by measuring the spectrum of the Galactic foreground at frequencies below 1 mHz.

- Constrain the cosmological white-dwarf binary formation rate by attempting to detect a background of extra-Galactic white dwarf binaries at frequencies of 2–5 mHz.

**SR3.1.1:** LISA will have the capability to detect at least 1,000 binaries at SNR > 10 with orbital periods shorter than approximately six hours, and to determine their period. LISA shall maintain this detection capability for at least one year.

**SR3.1.2:** LISA shall have the capability to measure the spectral amplitude and frequency dependence of the unresolved Galactic foreground below 1 mHz, and to constrain the spectral amplitude of the unresolved extra-Galactic foreground between 2 and 5 mHz. LISA shall maintain this detection capability for at least one year.

**Science Ramifications:** Based on population synthesis models (e.g., Nelemans et al. 2001b; Nelemans et al. 2004), our current understanding predicts that LISA will individually resolve several thousand systems within our Galaxy (Nelemans et al. 2001b, Seto 2002, Nelemans et al. 2004), the surrounding globular clusters (Benacquista et al. 2001), and nearby satellite galaxies (Cooray and Seto, 2005). Due to the paucity of electromagnetic observations, the majority of studies until now involving galactic binaries in the context of LISA have been based on population synthesis. Recently, significant observational progress has been made in detecting new systems of compact single or double white-dwarf binaries. In the case of interacting AM CVns, where a white dwarf is accreting helium-rich material from a hydrogen-deficient companion, SDSS-calibrated local space density estimates are at least ten to twenty times smaller than those derived from theoretical models (Roelofs et al. 2007). Such revised local space-density estimates of compact binaries will impact the number of resolvable detached and semi-detached systems observed by LISA. In addition, depending critically on the assumed binary formation channel, the astrophysical foreground of galactic ultra-compact binaries around ~ 1 mHz can decrease. For illustrative purposes, Figure 7 shows different LISA theoretical foreground estimates.

**Robustness:** LISA will require six laser links to clearly discriminate between instrumental and environmental noise and the unresolved Galactic and extra-Galactic foregrounds. However these foregrounds could be distinguished from instrumental and environmental noise by differences in their spectral shape. Even with a single synthesized interferometer, LISA will still detect several thousand galactic binaries over the mission lifetime.

**SR3.2:** Determine the spatial distribution of stellar-mass binaries in the Milky Way and environs.

**LISA’s expected contribution:** The majority of stellar-mass binaries will be essentially monochromatic over the period of the LISA mission (Nelemans et al. 2001b, Benacquista et al. 2004); nonetheless, several hundred will show a significant frequency drift (Nelemans et al. 2001b, Nelemans et al. 2004). For those, LISA may provide a 3D map (distance and sky location). In fact, measurements of the intrinsic change
of gravitational-wave frequency allows the “mass-luminosity distance” degeneracy to be broken (unless other effects, such as mass transfer and/or tides significantly alter the orbital evolution; see, e.g., Stroeer et al. 2005), and one can simultaneously solve for both the chirp mass and the distance to the emitting binary. In the event that the frequency derivative is not measurable, simultaneous electromagnetic and/or astrometric observations of LISA-identified sources will provide additional information, such as distance and/or masses, to break the degeneracy (e.g., Nelemans et al. 2004, Cooray and Seto 2005, Stroeer et al. 2005, Nelemans 2009).

Even in the absence of distance measurements, LISA will be able to produce a 2D map of binary populations in the Galaxy by determining the sky location of the whole LISA detected sample. Combining measurements from the diffuse foreground radiation and the resolved systems, LISA will produce a statistical assessment of the contributions to different Galactic components, such as the Galactic bulge with its bar, the disk and, in particular, the halo (Benacquista et al. 2007, Ruiter et al. 2007, Ruiter et al. 2010). This investigation will:

- Measure the moments of the distribution of binaries in the Galaxy through the distribution of the Galactic foreground and the individually resolved binaries, including compact-binary systems in globular clusters and the Magellanic Clouds, and hence probe the structure of the Galaxy and its environs.

- Identify the three dimensional distribution of at least a hundred binaries whenever the mass-distance degeneracy can be broken.

**OR3.2.1:** LISA shall have the capability to determine the position of at least a hundred sources with angular resolution better than a square degree, as well as the frequency derivative to a fractional uncertainty of 10%.

**OR3.2.2:** LISA shall measure the first two moments of the distribution of the unresolved Galactic foreground.

**OR3.2.3:** LISA shall measure distances to 10% for the binaries for which an EM counterpart is available. LISA shall maintain this detection capability for at least two years.

**Science Ramifications:** The reference sensitivity and the detector motion will allow the instrument to reconstruct the source position in the sky using the frequency and amplitude modulations of the signals (see, e.g., Cutler 1998; Takahashi and Seto, 2001). Moreover, the Galactic foreground radiation is anisotropic as recorded by the LISA instrument (Cornish 2001, Ungarelli and Vecchio 2001, Seto 2004, Benacquista et al. 2004, Edlund et al. 2005), and therefore the spatial distribution can be measured using the directional sensitivity of the antenna.

<table>
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<tr>
<th>$T$ (yr)</th>
<th>$\rho$</th>
<th>$\Delta A/A$</th>
<th>$\Delta \Omega_N$ (deg$^2$)</th>
<th>$\Delta \cos \iota$</th>
<th>$\Delta f_0/f_0$</th>
<th>$\Delta \dot{f}_0/f_0$</th>
<th>$\Delta n$</th>
</tr>
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<td>1 23</td>
<td>0.13</td>
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<td>0.31</td>
<td>$1.3 \times 10^{-3}$</td>
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<td>0.30</td>
<td>0.29</td>
<td>0.68</td>
<td>$2.3 \times 10^{-3}$</td>
<td>–</td>
<td>–</td>
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<tr>
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<td>0.004</td>
<td>0.2</td>
<td>$4.1 \times 10^{-5}$</td>
<td>8.1 $\times 10^{-3}$</td>
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<tr>
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<td>0.14</td>
<td>0.01</td>
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<td>$6.5 \times 10^{-5}$</td>
<td>1.3 $\times 10^{-2}$</td>
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</tr>
<tr>
<td>median</td>
<td>1 33</td>
<td>0.09</td>
<td>0.12</td>
<td>0.26</td>
<td>$4.4 \times 10^{-3}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>90%</td>
<td>1 20</td>
<td>0.20</td>
<td>0.31</td>
<td>0.56</td>
<td>$7.4 \times 10^{-3}$</td>
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<td>–</td>
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<tr>
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</tr>
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<td>1.2 $\times 10^{-1}$</td>
<td>0.45</td>
</tr>
</tbody>
</table>

**Robustness:** A simple scaling argument for Fisher-matrix-derived parameter errors shows that the error in the first frequency derivative scales as $1/T^{5/2}$, where $T$ is the LISA observation timescale. Similarly, parameter errors in the frequency derivative, sky position and distance errors increase by a factor $\sim \sqrt{2}$ when one rather than two synthesized interferometers are available.

**SR3.3:** Improve our understanding of white dwarfs, their masses, and their interactions in binaries, and enable combined gravitational and electromagnetic observations.

**LISA's expected contribution:** Gravitational-wave measurements can provide complementary information about the evolution of ultra-compact binaries where tidal effects or mass transfer compete or even dominate the other physics driving the system evolution, enabling detailed studies of such processes. As Table V illustrates, measurements of the first and second gravitational-wave frequency derivative provide a straightforward test of whether radiation reaction is responsible for the period evolution of the binary (Nelemans et al. 2004; Stroeer et al. 2005, Stroeer et al. 2009). However, richer information can be gained if the masses can be determined. This requires electromagnetic observations of LISA-detected sources if the period evolution is not determined solely by radiation reaction, highlighting the importance of coordinated gravitational-wave and electromagnetic observations. As shown in Figures 7 and 8 respectively, there are a hand-
ful of “verification binaries” (such as RXJ0806, V407 Vul and AM CVn) as well as possibly many tens or hundreds of currently unknown systems for which complementary electromagnetic observations will be possible (Cooray et al. 2004, Nelemans et al. 2004). In this case, one can directly estimate temperature and age if broadband colors can be measured, and one can even measure individual masses and radii if the system is eclipsing or if spectra can be taken. This investigation will:

- Explore the influence of tidal coupling and mass transfer on the orbital period evolution of compact binaries, thus improving our understanding of the masses, internal structure, and orbital couplings in compact object binaries.
- Combine electromagnetic observations with gravitational-wave observations whenever possible, to make direct measurements of a range of properties (e.g. temperatures, masses, mass transfer rates, stellar radii) of specific systems.

**OR3.3.1:** LISA shall have the capability to measure the second frequency derivative of binary systems with gravitational wave frequencies above 20 mHz to 1% and their sky location to better than 0.1 square degree. LISA shall maintain this detection capability for at least five years.

**Science Ramifications:** Parameter measurement errors for the first and second frequency derivatives have been computed for three fiducial detached and AM CVn binaries at 10 kpc, averaging over different sky positions and orientations (Stroeer et al. 2005; cf., Table V above). Such systems are representative of the dominant resolvable sources.

**Robustness:** LISA requires a one- and five-year observation times, respectively, to measure the first and the second frequency derivative to ~ 1%. A simple scaling argument for Fisher-matrix-derived parameter errors shows that the errors in the first and second frequency derivatives scale as $1/T^5/2$ and $1/T^7/2$ respectively, where $T$ is the LISA observation time. Similarly, parameter errors in both the first and second frequency derivatives increase by a factor $\sim \sqrt{2}$ when only one synthesized interferometer is available, rather than two.

**D. Confront General Relativity with observations**

**Background Information:** General relativity contains no free parameters and so makes unambiguous predictions for the production of gravitational waves (from a given source model), their propagation through space, and their influence on the trajectories of, and the light propagation time between, the LISA sciencecraft. LISA’s excellent sensitivity gives it the opportunity to test gravitation theory to high precision in situations not previously accessible to observation or experiment.

Observations of binary pulsars, especially of the classic Hulse-Taylor pulsar system PSR 1913+16 and the double pulsar system PSR J0737-3039 A/B, give us great confidence that General Relativity describes gravity accurately enough for LISA to observe and measure gravitational waves. The gravitational waves emitted by known binary pulsars are near the lower end of the LISA frequency band ($\sim 0.1$ mHz), and the orbital period derivatives for the binary pulsars are consistent with energy loss to gravitational radiation as predicted by general relativity, to within the $\sim 1\%$ error bars of the measurements. These and Solar System measurements give considerable confidence that General Relativity is at least close to correct at macroscopic scales.

Nevertheless, just as the precession of Mercury’s perihelion revealed a flaw in Newton’s theory of gravity, so it is important to confront General Relativity with observations and search for any discrepancies. When LISA observes the mergers of two massive black holes, it will be measuring the effects of gravity in a strong-field, highly-dynamical regime that has not yet been probed. Since the SNRs for the strongest such events will be $\sim 10^3$, one will be able to observe the fine details of the emitted waveforms roughly a hundred times more accurately than will be possible from the ground with any other source. When LISA observes EMRIs, it will be able to effectively map out spacetime around the MBH. By comparing these observations with the predictions of general relativity theory, LISA can look for deviations that may not even be modeled by existing alternative theories.

LISA has unique advantages in making these observational tests. First, gravitational radiation propagates through the Universe without scattering or absorption. One does not have to model corrections for propagation effects before using the
observations to test fundamental theory. Second, many of LISA's sources are “clean”—they consist of black holes or objects so compact that their internal structure is not needed in the source model. It is only possible to test a theory if the other properties of the system being observed are well under control. Black holes are the ideal system for performing such tests.

**SR4.1:** Detect gravitational waves directly and measure their properties precisely.

**LISA’s expected contribution:** This investigation will directly determine whether waves such as those predicted by Einstein propagate away from dynamic, massive objects and whether they interact with test bodies in the way described by General Relativity. This observation of the gravitational-wave signal from the inspiral of two compact objects with the LISA constellation will test the predictions of General Relativity over 1.5 decades in orbital frequency, terminating in the highly relativistic regime near coalescence.

The investigation yields two requirements: direct detection of gravitational waves from one or more white-dwarf binary systems in the galaxy (OR4.1.1) and detection of gravitational waves from the inspiral, merger, and ringdown of MBH binaries (OR4.1.2).

**Direct detection of gravitational waves from compact white-dwarf binary systems in the galaxy.** By the time LISA is launched, it is expected that numerous compact white dwarf binary systems will be known whose orbital periods, distances, and other system parameters (such as the masses) will have been measured. These systems will be detectable by LISA in weeks to months and can be used to verify LISA's performance. The corresponding requirement is:

**OR4.1.1:** LISA shall have the capability to detect and study three or more optically observable verification binaries between 1 and 10 mHz with SNR > 20 in two years of mission lifetime.

**Science Ramifications:** This requirement is easily satisfied by the nominal LISA sensitivity performance.

**Robustness:** Based on the list of verification binaries compiled by Nelemans (2010), four sources (RX J0806.3+1527, V407 Vul, ES Cet, AM CVn) have an angle-averaged SNR > 40. This ensures that OR4.1.1 is satisfied with a single Michelson interferometer.

**Detection of gravitational waves from coalescing MBH binaries.** LISA must be capable of detecting the inspiral, merger, and ringdown signals from coalescing MBH binaries with sufficient SNR to compare measured waveforms to predictions.

**OR4.1.2:** LISA shall be capable of observing the gravitational waves from at least 50% of all $z \sim 2$ coalescing binary systems consisting of compact objects with masses between $10^5$ and $10^8 M_{\odot}$ and mass ratios between 1:1 and 1:3. LISA shall detect these systems with SNR ≥ 5 in each of five equal logarithmic frequency bands between 0.03 mHz (or the lowest observed frequency) and the highest inspiral frequency.

**Science Ramifications:** LISA satisfies this requirement assuming a standard noise model as can be verified by conventional calculations using the strain signal from the binary inspiral phase of a MBH binary.

**Robustness:** This requirement is quite robust and will be easily satisfied with a single interferometer.

**SR4.2:** Test whether the central massive objects in galactic nuclei are the black holes of General Relativity.

**LISA’s expected contribution:** The central massive objects known to exist in the centers of most galaxies are presumed to be black holes. LISA can uniquely confirm that these objects are black holes and at the same time validate the predictions of general relativity that all vacuum black holes are described by the Kerr metric. We adopt the operational definition that the spacetime contains a black hole if it contains an event horizon. By observing whether the radiation from EMRIs terminates when the compact object reaches the expected location of the horizon, LISA will determine whether or not the spacetime contains a horizon and hence whether the central objects are black holes. If they are black holes, then the details of the phase and polarization of the waves emitted by EMRIs contain information that can be used to determine whether the metric outside the horizon has the properties of the Kerr metric. In particular, such measurements determine whether all aspects of the geometry are fit by just the two Kerr parameters describing the mass $M$ and spin angular momentum $J$ of the black hole. This is a test of the famous black-hole no-hair theorem (Israel 1967).

This science investigation will test whether astrophysical black holes exist with the properties predicted by general relativity and whether highly relativistic EMRI waveforms are consistent with the predictions of General Relativity. EMRI waveforms will measure the mass quadrupole of the central object, which can be compared to the predictions of the BH no-hair theorem. Any observations of IMRI events will also contribute to these science goals.

**OR4.2** below is quite similar to OR2.1, but in OR4.2 we focus on the closest EMRIs likely to be observed, since the "brightest" sources typically provide the strongest tests.

**OR4.2:** LISA shall have the capability to detect gravitational waves emitted during the last year of inspiral for a $10 M_{\odot}$ black hole orbiting a $3 \times 10^3 - 3 \times 10^6 M_{\odot}$ black hole at 1 Gpc with SNR > 30. LISA shall have a science mission duration with adequate observation time for EMRIs to sweep over a range of orbital separations sufficient to map spacetime, and to provide a good sample of events.

**Science Ramifications:** The SNRs obtained by LISA for $10 M_{\odot}$ black hole infalling into a $3 \times 10^3 M_{\odot}$ black hole and
a $3 \times 10^6 M_\odot$ black hole at 1 Gpc were calculated in the LIST Working Group 1 EMRI Taskforce Report [Barack et al. (2004); see Table VI]. LISA easily satisfies the above requirement on timescales as short as a week. Barack and Cutler (2007) have estimated that the dimensionless quadrupole moment $Q/m^2_\odot$ of Kerr BHs with masses $10^{-3} M_\odot$, $10^0 M_\odot$, and $10^3 M_\odot$ can be measured to accuracies of $\sim 10^{-4}$, $10^{-3}$, and $10^{-2}$ (respectively), assuming a total SNR of 100 for a 1 year observation of an inspiraling $10 M_\odot$ BH. Including the quadrupole moment as a separate search parameter will presumably degrade the precision of the masses by a factor $\lesssim 2$ and the MBH spin by a factor $\sim 50$.

**Robustness:** Table VI shows that for nominal LISA noise performance, SNR > 30 is achieved for a single interferometer (X) and the relevant masses for observation times of at least one month or longer. In a single interferometer configuration, the errors in the quadrupole moment will likely increase by a factor $\sim 2$.

SR4.3: Perform precision tests of dynamical strong-field gravity.

**LISA's expected contribution:** When a binary black-hole system coalesces, a single, new black hole is formed. The formation of black holes in this way is the ultimate manifestation of strong dynamical gravity. With LISA we have the opportunity to test whether Einstein’s theory correctly describes gravity in this most extreme regime. The gravitational radiation associated with the merger and its aftermath depends critically on the structure and composition of the binary components. The observation of the radiation from the inspiral will determine the initial masses and spins. The merger phase radiation will be compared with numerical relativity simulations of the full Einstein’s equations. The mass and spin of the final merged black hole will be measured from the ringdown radiation it emits as it settles into a stationary state. This set of observations provides a unique link between the properties of stationary black holes (as measured by EMRI events) and the dynamics of the strongest possible gravitational fields that lead to their production.

OR4.3: Observe the merger and ringdown radiation from all $10^5$ to $10^6 M_\odot$ black holes formed from approximately equal mass ($m_2/m_1 \gtrsim 1/3$) mergers to $z \leq 8$, and measure the mass and spin parameters of the final black hole. This will include essentially all systems with these masses as the rates are expected to be vanishingly small for higher redshifts ($a < 5$ requirement, for example, would also include almost all likely events).

**Science Ramifications:** Berti et al. (2006) have studied LISA's ability to measure the mass and spin. Recent numerical relativity simulations suggest that merged black holes will have spins in the range $0.35 < a/M < 0.95$ (Campanelli et al. 2006), with $\sim 1\%$ of the rest-energy radiated in the ringdown for equal-mass systems (Baker et al. 2006). For variations in the mass ratio, we generally expect the ringdown energy to scale with the square of the reduced mass. With these specifications, the results of Berti et al. (2006) indicate that the requirement is met with the standard sensitivity.

**Robustness:** Figure 8 of Berti et al. 2006 indicates that LISA will measure ringdown waves with SNR $\gtrsim$ 100 at $z = 10$. So the merger and ringdown waves should easily be detected out to the required redshift, even in the case of a single interferometer. A worst-case estimate for the errors (see e.g., Berti et al.’s Fig. 10) indicates an error no worse than 0.06 on the dimensionless spin (and a factor of 3 better on the mass) at $z = 10$.

**E. Probe new physics and cosmology with gravitational waves**

**Background Information:** One of the most surprising discoveries of recent years is that the expansion of our Universe is currently accelerating. The cause is generally attributed to some form of “dark energy” that accounts for $\sim 70\%$ of the energy density of the Universe, but it remains a profound mystery what dark energy consists of, and why it is so tiny by comparison to the energy scales of particle physics.

LISA could provide important contributions to our understanding of cosmology, in two rather different ways. First, LISA observations of cosmologically distant EMRIs, IMRIs, and MBH mergers will allow us to determine the luminosity distance to these sources, in a manner that follows directly from fundamental physics, and that is essentially independent of all other distance-measurement techniques. Unfortunately, GW measurements alone do not allow us to infer the redshift of the source; however, it is reasonable to expect that some of these events will be accompanied by an electromagnetic outburst that will allow astronomers to pinpoint the host galaxy and obtain its redshift. Such joint detections will provide cosmologists with new, accurate data points on the distance–redshift ($D_L - z$) plot, which will provide an independent check on concordance cosmology, and could perhaps lead to more accurate measurements of basic cosmological parameters, such as the Hubble constant $H_0$ and the dark-energy scale.

The second and potentially much more dramatic way that LISA could contribute to cosmology and new physics is by directly detecting GWs produced in the very early Universe. Phase transitions occurring at TeV temperatures, when the horizon size was $\sim 1$ mm, may have produced GWs that today would be redshifted directly into the LISA band. From the point of view of fundamental interactions, the TeV energy scale corresponds to the electroweak symmetry-breaking scale. The TeV scale is the frontier of known physics: indeed, the corresponding length scale of 0.1 mm is the lower limit below which classical gravity remains to be probed. Inflation provides another mechanism for generating a stochastic GW background, the parametric amplification of zero-point fluctuations. While for standard inflation such a background would
TABLE VI  Signal-to-noise estimates for Extreme Mass Ratio Inspiral events at 1 Gpc assuming baseline LISA, optimistic WD subtraction (5 yr), and volume-inclination-averaging. Left columns refer to the masses of the MBH, the compact object mass, and the eccentricity at plunge. AET refers to SNRs computed with Synthetic LISA using the optimal combination of TDI variables. X refers to the TDI output for a single-interferometer, unequal-arm Michelson combination. From the LIST WG1 EMRI taskforce (Barack et al. 2004).

<table>
<thead>
<tr>
<th>$M$</th>
<th>$m$</th>
<th>$e$ (final)</th>
<th>S/N(AET)</th>
<th>S/N(X)</th>
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<tr>
<td></td>
<td></td>
<td></td>
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<td>(1wk) (1mo) (3mo) (1yr) (3yr) (5yr)</td>
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</tr>
<tr>
<td>$10^6$</td>
<td>100</td>
<td>0.4</td>
<td>405.0</td>
<td>639.0</td>
</tr>
<tr>
<td>$3 \times 10^5$</td>
<td>0.6</td>
<td>0.4</td>
<td>3.2</td>
<td>6.1</td>
</tr>
<tr>
<td>$3 \times 10^5$</td>
<td>10</td>
<td>0.4</td>
<td>46.3</td>
<td>84.5</td>
</tr>
<tr>
<td>$3 \times 10^5$</td>
<td>100</td>
<td>0.4</td>
<td>370.0</td>
<td>596.0</td>
</tr>
</tbody>
</table>

lie well below LISA’s sensitivity range, other non-standard inflationary models would produce backgrounds detectable by LISA.

Finally, LISA could detect GWs produced by cosmic (super-)strings, which are essentially one-dimensional (in space) defects that became “frozen in” in the very early Universe. Cosmic strings are predicted in some modern theories of the fundamental interactions, where they appear from the breaking of Abelian symmetries, and in fundamental string theories as macroscopic structures. Oscillating string loops produce a spectrum of background GWs that is expected to be rather flat over many decades in frequency. LISA will probe several orders of magnitude below the current limit from millisecond pulsar timing. For a large range of string parameters, LISA would be sensitive to both a GW background from string oscillations, and to individual GW bursts created by cusps or kinks on the strings. For further discussion and references, see LISA: Probing the Universe with Gravitational Waves (LISA Mission Science Office 2007).

GW bursts from cusps or kinks on cosmic (super-)strings could be another very exciting window onto new physics. Damour and Vilenkin (2000, 2001) were the first to point out that these features, which form generically on strings, emit beamed GW bursts, observable by GW detectors (especially the cusp-bursts) for a large range of string parameters. There are two fundamental string parameters: the string’s tension $\mu$ (energy/length), and the probability $p$ that two strings “intercommute” (i.e., break and re-attach with the other string) when they cross. New loops are created when strings intersect or self-intersect. In principle, the typical size $\epsilon$ of string loops at their birth (as a fraction of the instantaneous Hubble length) can be derived from $(\mu, p)$, but in practice these calculations are not reliable, so in exploratory work $\epsilon$ is often treated as another unknown parameter. As discussed below, LISA would be capable of detecting cusp-bursts (if they exist) over a very large range of string parameters; indeed, LISA will be far more sensitive to such bursts than ground-based GW detectors, owing to its much lower frequency band.

SR5.1: Study the expansion history of the Universe using gravitationally calibrated distances to merger events (in cases where redshifts can be measured).

LISA’s expected contribution: Gravitational waves from the inspiral of two black holes provide a direct measurement of the luminosity distance to the source, without the usual complications of reddening by dust or incompletely understood source models. The source is completely understood – two Kerr black holes – and the emitted waveform follows simply from fundamental physics – the two-body problem in general relativity. Therefore, for sources for which the redshift can also be determined, LISA promises to provide completely independent measurements of the Universe’s expansion as a function of redshift. The observational requirements for this investigation are the same as in section V.A for MBH mergers (OR5.1.1) and EMRI events (OR5.1.2), respectively.

Localization of MBH mergers. For MBH mergers, possible
EM counterparts can be divided into two classes: EM outbursts (presumably short-lived) that occur very close to the instant of merger, or outbursts that occur significantly later (months to years). Phinney and Bode (2009) and Milosavljević and Phinney (2005) have identified mechanisms for producing coincident and delayed EM outbursts, respectively; see the discussion under SR2.3.

To search for a coincident EM signal, it would be very helpful if LISA could localize the source location on the sky to within ≈ 3.5 degrees (so that the 1-σ error ellipse on the sky fits into the field of view of future wide-field telescopes such as LSST), and achieve this resolution at least several hours prior to merger. (Several hours are the least imaginable amount of time required for the LISA data to be telemetered to Earth, and for ground systems to optimally process the data, extract the source’s best-fit sky location, and arrange for a suitable telescope to be pointed at the right spot at the right time.) For EM events taking place months to years after the merger, this time limit does not of course apply, and we will be able to rely on the better localization available by analyzing the entire waveform. For both coincident and delayed EM signals, more precise localization allows deeper searches.

The extraction of the source’s luminosity distance \( D_L \) is affected by another source of error besides the noisiness of the data: weak lensing by galaxies in the line of sight to the source will alter the apparent GW amplitude (just as it affects the brightness of background galaxies), causing fractional rms distance errors \( \Delta \log D_L \approx 0.044 \sigma_z \) (Holz & Hughes 2005). Therefore, for sources at \( z \gtrsim 1 \), cosmological-parameter measurements would not be helped by reducing the \( D_L \) error due to LISA noise below several percent. Together, these considerations lead to the following requirement.

**OR5.1.1:** LISA shall be capable of providing sky localizations of 3.5 degrees (not squared degrees) or better, for MBH mergers with component masses in the range \( 10^5 - 10^6 M_\odot \) at \( z \lesssim 2 \). For a large fraction of these, LISA shall be capable of attaining sub-3.5-degree resolution at least 6 hours before the merger. LISA shall also be capable of determining the luminosity distance to these mergers to \(< 5\% \).

**Science Ramifications:** Various authors have calculated LISA’s parameter-estimation accuracy for MBH mergers, under a variety of simplifying approximations. Here we give some representative results.

Hughes (2007b) calculated luminosity-distance and sky-position uncertainties, assuming a conservative low-frequency performance for LISA, and considering cases of both one and two synthesized interferometers. Typical uncertainties, shown in Table VII, indicate that two synthesized interferometers are needed to satisfy the requirement, and do so (for representative mass and mass ratios) out to \( z \lesssim 3 \). Kocsis et al. (2007) calculated these uncertainties for a variety of cases, with an emphasis on how accuracy improves with time in the days prior to merger. The basic results are summarized in Figs. 9–11.

The bottom line is that LISA needs two synthesized interferometers to achieve the required accuracy. This is mainly due to the fact that most of the SNR is acquired in the last days to weeks of the inspiral, so single-interferometer information about GW polarization is poor, and this uncertainty is covariant with sky-position uncertainty (see the discussion under “robustness” for OR1.3, on page 14).

**Robustness:** Again, meeting the requirements for position accuracy and latency requires two interferometric observables. As long as LISA has 2 IFOs, meeting the LISA noise goal below \( 10^{-4} \) Hz is not critical for this requirement.

**Localization of EMRI events.** In addition to possible counterparts from MBH mergers, there may be astrophysical mechanisms that could lead to EM counterparts for observed EMRI or IMRI events. The following requirement is driven by the capability to use EMRI observations to determine the Hubble constant \( H_0 \) to < 3\%.

**OR5.1.2:** LISA shall have the capability to provide sky localization of 10 square degrees or better, and luminosity-distance measurements to 3\% or better, for EMRI or IMRI binary sources with SNR > 50.

**Science Ramifications:** For high-SNR GW signals, the lumi-
TABLE VII  Median values of fractional luminosity-distance uncertainty and sky-position uncertainty (major and minor axis) assuming the standard noise model, randomly distributed sky position, orbital-plane orientation, and spin orientations, and spin magnitudes uniformly distributed in \([0, 1]\). Results provided courtesy of Scott Hughes (2007b).

<table>
<thead>
<tr>
<th>(m_1/M_\odot)</th>
<th>(m_2/M_\odot)</th>
<th>(z)</th>
<th>(\Delta D_L)</th>
<th>(\Delta) sky localization (major &amp; minor)</th>
<th>(\Delta D_L) Uncertainty (major &amp; minor)</th>
<th>(\Delta) sky localization (major &amp; minor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^6)</td>
<td>(3 \times 10^5)</td>
<td>1</td>
<td>2.9%</td>
<td>((4.8 \times 1.2)) deg</td>
<td>0.5%</td>
<td>((33 \times 14)) arcmin</td>
</tr>
<tr>
<td>(10^6)</td>
<td>(3 \times 10^5)</td>
<td>3</td>
<td>20%</td>
<td>((38 \times 6)) deg</td>
<td>0.7%</td>
<td>((40 \times 18)) arcmin</td>
</tr>
</tbody>
</table>

FIG. 10  Advance-warning times (days) for binary inspirals with mass ratio 10:1, as a function of total mass \(M\) and redshift \(z\), for a variety of source parameters and LISA configurations. See captions and legends. From Kocsis et al. (2007).

Robustness: LISA’s estimated EMRI detection rate is \(\sim 50/\text{yr}\), but is uncertain by at least an order of magnitude. The detection rate is tied closely to LISA’s sensitivity at \(\sim 5\ \text{mHz}\) (near the bottom of the noise floor). The accuracies quoted above are for two synthesized IFOs; for one interferometer (keeping a fixed distance to the source), the sky-position error increases by a factor \(\sim 2\) (in degrees, not square degrees) and so does the luminosity-distance error. The improvement in accuracy with two (as opposed to one) interferometers comes roughly half from the increased SNR, and half from the breaking of partial-degeneracies.

SR5.2: Measure the spectrum of cosmological gravitational-wave backgrounds, or set upper limits on them.

LISA’s expected contribution: As described above, there are a variety of mechanisms that could quite plausibly fill the Universe with observable amounts of stochastic GWs in the LISA band, most likely a stochastic GW background produced in the very early Universe, or more recently by cosmic strings that have themselves formed in the very early Universe. The main existing constraint on possible cosmological...
backgrounds in the LISA frequency band is an upper limit derived from Big Bang nucleosynthesis, $h_{	ext{BG}}^2 \Omega_{\text{GW}} \lesssim 5 \times 10^{-6}$. The frequency-flat background from a network of cosmic (super-)strings is constrained by pulsar timing observations, taken at $f \sim 10^{-8}$, to $\Omega_{\text{GW}} \lesssim 10^{-8}$. Both these constraints lie well above LISA’s sensitivity curve, so they leave a large discovery space for LISA.

**OR5.2.1:** LISA shall be capable of detecting or setting an upper limit on the spectrum of a stochastic gravitational-wave background in the $10^{-4} - 10^{-1}$ Hz band.

**Science Ramifications:** Hogan and Bender (2001) proposed a method to “dig down” below the LISA instrumental noise, using all six laser links together, to discover stochastic backgrounds with $\Omega_{\text{GW}} \gtrsim 10^{-11}$. However, the level of the GW foreground from Galactic and extragalactic binaries is likely above this value: to be detectable by LISA, a stochastic GW background originating from the early Universe would have to lie above $\Omega_{\text{GW}} \sim 10^{-10}$. (Because the early-Universe background would probably have a different spectrum than the foreground, it should be possible to distinguish them as long as the former is a few times larger than the latter.) Detectable stochastic backgrounds from phase transitions, non-standard inflation, and cosmic strings and all possible.

**Robustness:** To confirm the existence of stochastic backgrounds, or to set limits on them, it is necessary to determine the level of the instrumental and environmental noise, and to differentiate it from GWs, with moderate frequency resolution over a broad band. Hogan and Bender (2001) proposed using the “symmetrized Sagnac” TDI observable (which is quite insensitive to GWs) to measure instrumental noise. This observable however requires all six links, so the requirement that LISA at least be launched with six links is crucial to this application. Once it is clear that an observed stochastic background is not a noise artifact, the importance of six links for OR5.2.1 drops substantially.

**SR5.3:** Search for gravitational-wave bursts from cosmic-string cusps.

**LISA’s expected contribution:** LISA will be much more sensitive to cusp-bursts than ground-based detectors. Indeed, for large ranges of string parameters, LISA would detect both a stochastic background from oscillating strings and the GW bursts emitted by cusps that form on the loops.

**OR5.3:** LISA shall be capable of detecting gravitational-wave bursts from cosmic (super-)strings, or of setting cosmologically interesting upper limits on their rate.

**Science Ramifications:** Damour and Vilenkin (2001, 2005) showed that LISA should be able to detect GW bursts from cosmic string cusps over a large region of string-parameter space. For instance, for the $p = 1$ case, LISA should be able to detect cusp-bursts for $\mu \gtrsim 10^{-10} e^{-1/3}$. (As mentioned above, $\mu$ is the string tension and $e$ parametrizes the size of string loops at birth.) The spectrum of a single cusp-burst is given approximately by $h(\omega) \propto f^{-4/3} \theta(\omega_{\text{max}} - f)$, where $\theta$ is the Heaviside step function, and $\omega_{\text{max}} \propto \delta^{-3}$, with $\delta$ is the angle between the instantaneous velocity of the cusp and the observer’s line of sight. Both the $f^{-4/3}$ factor and the high-frequency cut-off make LISA far more sensitive to cusp-bursts than ground-based GW detectors: LISA’s detection rate will be of order $10^6$ times greater than Advanced LIGO’s.

By detecting cosmic superstrings, LISA could thus provide direct experimental evidence confirming superstring theory—a momentous discovery.

**Robustness:** If LISA’s noise is stationary and Gaussian (to a good approximation), it will be straightforward to detect string-bursts (if they exist). Difficulties would arise only if there were a substantial rate of instrumental glitches that resembled these bursts. While such glitches are not expected, it is reassuring to note that, because cusp-bursts have a distinctive and precisely known spectral profile, it should be straightforward to significantly reduce any instrumental background from glitches by vetoing bursts that do not have the right shape.

As with stochastic-background searches, six working links should allow much greater confidence that any observed string bursts are not instrumental artifacts: for instance, a real GW burst would appear far more weakly in the symmetrized Sagnac observable than in the other synthesized interferometers. As for stochastic-background searches, six links are most crucial at the beginning of the mission, to increase confidence that any observed bursts are not instrumental artifacts.

**F. Search for unforeseen sources of gravitational waves**

In addition to exotic sources with predictable signals, such as first-order phase transitions, inflaton decay, warped extra dimensions, and cosmic strings, there may be other phenomena in the Universe that have significant GW emission, but for which there is no evidence from electromagnetic radiation or particles.

There could be new, purely gravitational structures, such as vacuum solutions to Einstein’s equations that are “self bound,” but are not black holes. (To our knowledge, very little is known regarding the possibility of "solitonic" vacuum solutions that are not black holes. The "topological censorship theorem" of Friedman et al. (1993) suggests, but certainly does not prove, that wormholes collapse to black holes. And the classic black-hole uniqueness theorems state that black holes are described by the Kerr-Newman geometry, which does not limit the possibilities for non-black-hole solutions.)

There may also be new dark- or “hidden” sector particles that do not interact with Standard Model particles except through gravitation; certainly many ideas of this kind have been put forward to help explain cosmic Dark Matter and Dark Energy—which are themselves examples of new physics discovered only via gravitation. Surprises of a similar
magnitude may be in store once we deploy LISA, an exploration tool of unprecedented sensitivity in this domain.

**SR6.1:** Search for unforeseen sources of gravitational waves.

The science investigation associated with this science objective requires that, after the LISA data stream is mined for all known classes of astrophysical sources and instrumental and environmental artifacts, we develop and test models for the residual time series and spectra. Such models will include both bursty, non-Gaussian signals with an apparent time-domain structure, and also new quasi-Gaussian backgrounds with spectra that do not agree with predictions for known, modeled sources.

**OR6.1:** LISA shall be sensitive over discovery space for unforeseen effects (e.g., even at frequencies where we cannot predict likely signals from known classes of astrophysical sources). LISA shall allow for reliable separation of real strain signals from instrumental and environmental artifacts.

**Science Ramifications:** LISA will be the first GW observatory with meaningful sensitivity in the $10^{-4}$–$10^{-1}$ Hz band, which clearly opens up the potential of a large discovery space. In the LISA band, the strongest constraint on GW power comes from Big Bang nucleosynthesis (BBN): any broadband GW source generated before BBN must have $\Omega_{GW} \lesssim 10^{-5}$. On the other side, to be detectable by LISA, any broadband source must have $\Omega_{GW} \gtrsim 10^{-10}$ if it is to be visible above the foreground from Galactic and extra-Galactic compact binaries. Thus the discovery space is wide. LISA should be sensitive to GW bursts of unexpected origin down to $h \gtrsim 10^{-21}$ (within the LISA) band, which represents completely unexplored territory.

**Robustness:** Extending LISA’s measurement band up from $10^{-1}$ Hz to 1 Hz at the high end, and from $10^{-4}$ Hz to $3 \times 10^{-5}$ Hz on the low end – even at much worse sensitivity – would clearly increase LISA’s already wide and deep discovery space. However, there seems to be no good way of quantifying the fractional increase in the probability of a discovery in these bands, nor to quantify their likely importance. It is therefore reasonable to maintain these bandwidth extensions as goals, not requirements. For burst-like sources, six working laser links would allow an important check that any unexpected, unrecognized bursts in the output data correspond to actual GW signals, and not instrumental artifacts.
VI. REFERENCES

VII. APPENDIX A. ACRONYMS

BH: Black hole
CWDB: Compact white dwarf binary
EM: Electromagnetic
EMRI: Extreme mass ratio inspiral: a compact object inspiraling into a massive black hole, with mass ratios $m_2/m_1 \lesssim 10^{-5}$
ESA: European Space Agency
Gpc: Gigaparsec
GRS: Gravitational Reference Sensor
GW: Gravitational wave
IMBH: Black hole, with $10^2 M_\odot < M < 10^4 M_\odot$
IMRI: Intermediate mass ratio inspiral, with mass ratios $10^{-4} \lesssim m_2/m_1 \lesssim 10^{-2}$
ISM: Instrument Sensitivity Model, defined in Sec. III.A
IFO: Interferometer
LISA: Laser Interferometer Space Antenna
LMC: Large Magellanic Cloud
MBH: Massive black hole, with $10^4 M_\odot < M < 10^7 M_\odot$
mHz: millihertz
MRD: Mission Requirements Document
NASA: National Aeronautics and Space Administration
OR: Observation requirement
ScRD: Science Requirements Document (to distinguish from SRD, used by ESA to refer to the Systems Requirements Document)
SMC: Small Magellanic Cloud
SNR: Signal-to-Noise Ratio
TBD: To be determined
TBR: To be reviewed
TDI: Time Delay Interferometry