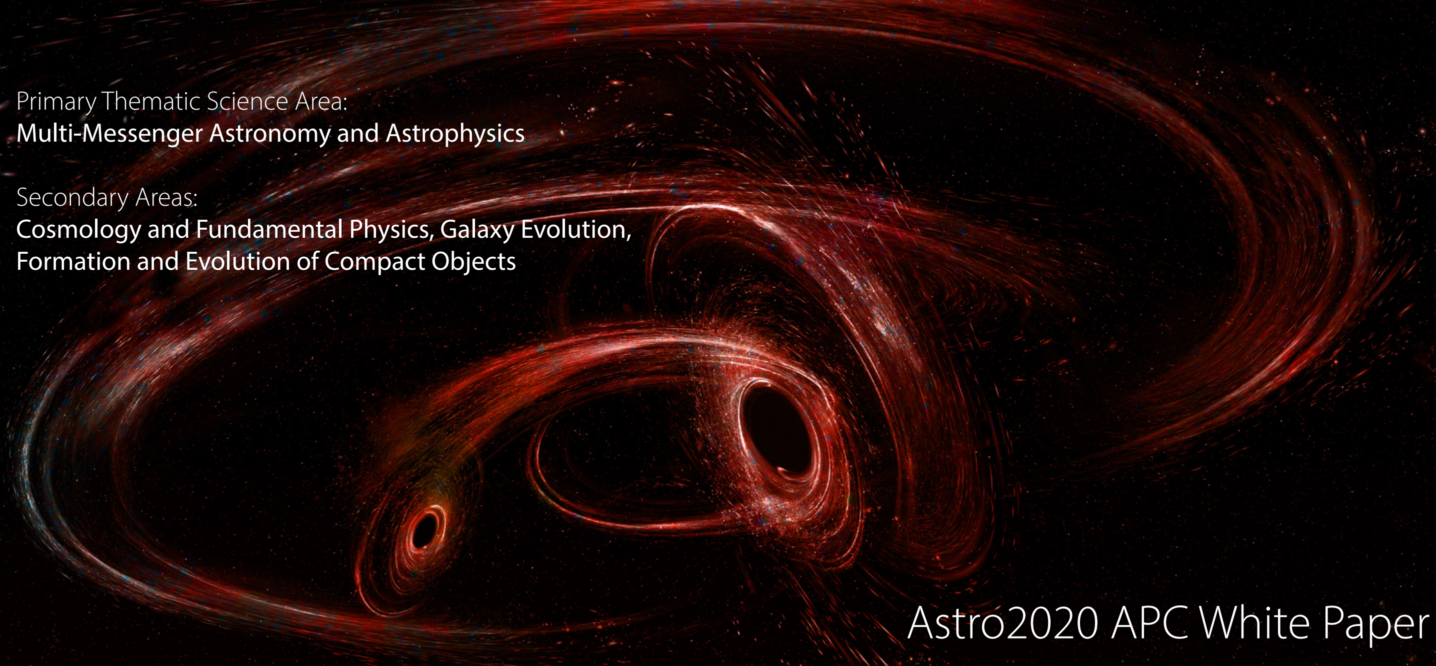
Primary Thematic Science Area:
Multi-Messenger Astronomy and Astrophysics

Secondary Areas:
Cosmology and Fundamental Physics, Galaxy Evolution, Formation and Evolution of Compact Objects



Astro2020 APC White Paper

Space Based Gravitational Wave Astronomy Beyond LISA

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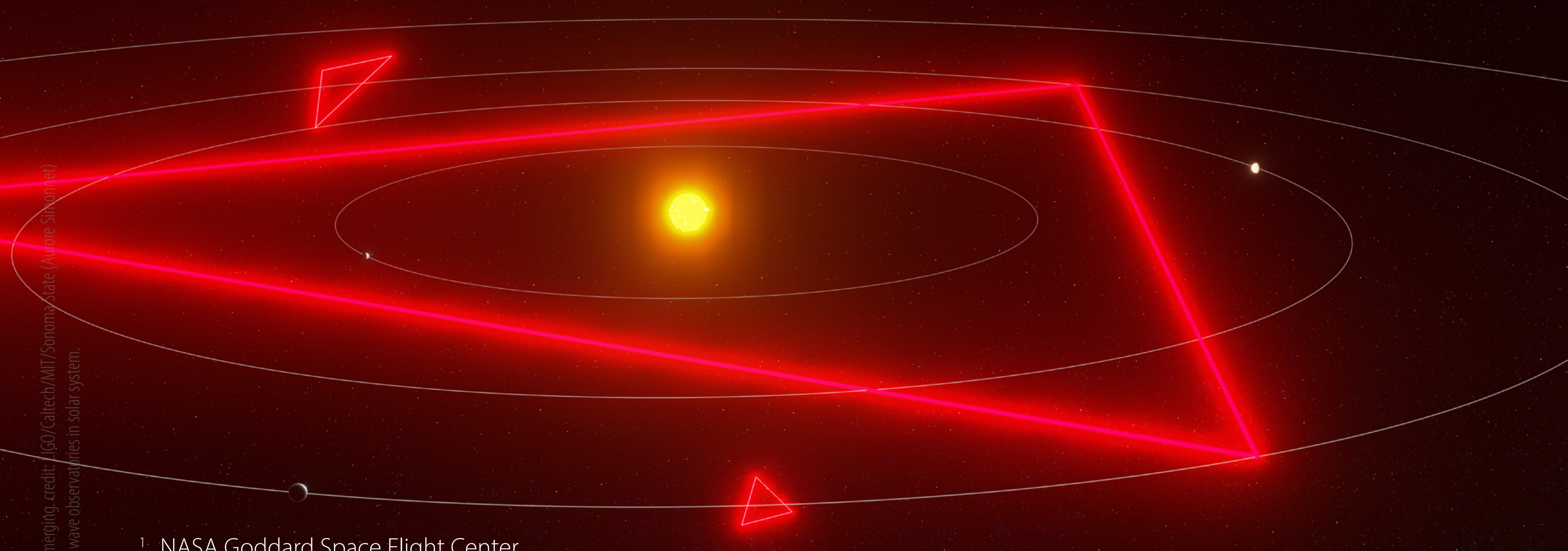

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top image: artist's illustration of two black holes merging, credit: LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)
bottom image: artist's illustration of gravitational wave observatories in solar system.

I. Executive Summary

The Laser Interferometer Space Antenna (LISA) will open three decades of gravitational wave (GW) spectrum between 0.1 and 100 mHz, the mHz band [1]. This band is expected to be the richest part of the GW spectrum, in types of sources, numbers of sources, signal-to-noise ratios and discovery potential. When LISA opens the low-frequency window of the gravitational wave spectrum, around 2034, the surge of gravitational-wave astronomy will strongly compel a subsequent mission to further explore the frequency bands of the GW spectrum that can only be accessed from space. The 2020's is the time to start developing technology and studying mission concepts for a large-scale mission to be launched in the 2040's. The mission concept would then be proposed to Astro2030.

Only space-based missions can access the GW spectrum between 10^{-8} and 1 Hz because of the Earth's seismic noise. This white paper surveys the science in this band and mission concepts that could accomplish that science. The proposed small scale activity is a technology development program that would support a range of concepts and a mission concept study to choose a specific mission concept for Astro2030. In this white paper, we will refer to a generic GW mission beyond LISA as *bLISA*.

II. Advancing mHz Gravitational Wave Astronomy Beyond LISA

Gravitational Wave astronomy is a new and promising field. LIGO [2] has shown that gravitational-wave observatories can make routine observations of sources that are invisible to electromagnetic (EM) observations, and of sources for which complementary EM and GW information is extraordinarily powerful. In the first ever observation of GWs, GW150914 [3], LIGO demonstrated the discovery potential of GW observations, by detecting merging stellar black holes with masses substantially higher than expected. The subsequent observation of a merging neutron star binary, GW170817 [4], that was also widely observed across the EM spectrum simultaneously showed the power of coordinated observations and the power of multiple detectors (i.e., LIGO Hanford, LIGO Livingston, and Virgo). The extraordinary campaign of EM observations that followed GW170817 provided a tremendous impetus to multi-messenger and time domain astronomy.

The GW spectrum in Figure 1 shows the detection strategies for GW astronomy. Roughly speaking, GW sources are inspiraling binaries (or triples) of compact objects whose GW frequency chirps up to a final merger frequency, followed by ring-down of the final object. The gravitational wave frequency roughly scales inversely with system mass. Pulsar timing arrays (PTAs) detect the largest SMBHs over a decade of frequency in the nHz region, and ground-based interferometers detect stellar-mass systems between 40 and 1000 Hz. LISA spans 0.1 to 100 mHz. All three strategies are amplitude – not power – detectors, meaning signal falls off as $1/\mathrm{R}$, rather than $1/\mathrm{R}^2$.

Based on the success of LISA Pathfinder [6–11] ESA is leading the LISA mission to open up the mHz GW band, with NASA as a junior partner. This band is expected to have many more detectable types of sources than any other in the GW spectrum: $10^4 - 10^7 \mathrm{M}_\odot$ massive black hole binaries (MBHBs), intermediate mass black hole binaries (IMBHBs), extreme-mass-ratio inspirals (EMRIs) with mass ratios of 10^4 to 10^5 with a system mass $< 10^7 \mathrm{M}_\odot$, intermediate-mass-ratio inspirals (IMRIs) with smaller system masses of $10^3 - 10^4 \mathrm{M}_\odot$, close compact binaries in the Milky Way, and the heavy stellar binaries (10's of $\mathrm{M}_\odot$) seen by LIGO and Virgo. Larger sources will be detectable back into the re-ionization era. The number of sources is expected to be 10's of thousands. Signal-to-noise ratios (SNRs) can range into the thousands for the strongest signals. Further, the detectable mass of sources at cosmological distances is augmented by their redshift, a substantial boost at, say, $z \sim 10$. LISA's discovery potential includes cosmic strings, cosmological phase transitions, unexpected bursts and a stronger cosmological GW background than standard inflationary models predict. LISA's impact on GW astronomy will parallel LIGO's impact and a space-based GW detector to follow LISA will be critical to NASA's portfolio.

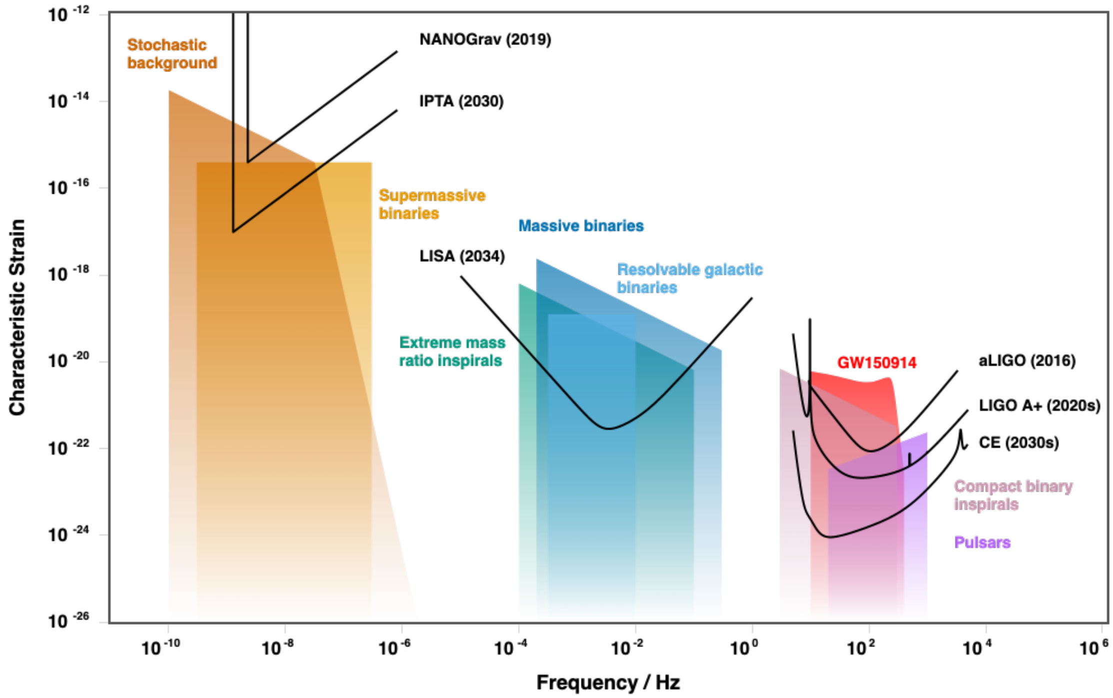

FIG. 1. GW Spectrum, showing frequency bands where PTAs, LISA and ground-based GW detectors operate (generated by http://gwplotter.com/, see [5] for details).

Below 10 nHz, pulsar timing arrays (PTAs) observe through long-term, precisely timed observations of rapidly rotating radio pulsars. It is widely anticipated that they will measure signals from the largest MBH binaries ($\sim 10^9 M_\odot$) at low redshifts in the 2020's. PTA sensitivity improves with the discovery and long-term observation of highly stable pulsars [12].

At the high frequency end of the spectrum (40-1000 Hz), ground-based GW detectors like LIGO and Virgo are currently alternating between observations that are producing ever more sources, and upgrades leading to increased sensitivity and duty cycle. Increased sensitivity improves SNR and enlarges the observable volume as the cube because these are amplitude detectors. Improved seismic isolation and suspensions are extending the useful observing band down towards 10 Hz. During the current observing run, slated to end in 2020 after a year of operation, LIGO and Virgo are releasing detection alerts about once per week. Upgrades are scheduled to continue for several years. Sky localization will continue to improve as new detectors, KAGRA [13] in Japan and LIGO-India, come online over the same time scale. So-called 3G detectors [14, 15], with longer armlengths, improved suspensions and other technology improvements, are in the early planning stages, with implementation notionally in the 2030s. These detectors would further improve sensitivity, extend their operating band down towards 1 Hz and capitalize on the benefits of a global network for the best sky localization.

To advance beyond LISA, we survey the science goals and then consider two illustrative examples of mission concepts. So far in advance of LISA, it is unwise to focus on a single design. It is more prudent to examine a range of designs, evaluate the technology needs, some of which are shared, and down-select to a concept when the technology challenges are better understood and science priorities are more refined. The schedule advanced here is for technology development and a mission concept study in the 2020s leading to a concept selection in time to propose to Astro2030. Ideally, bLISA would start implementation when LISA is in its extended mission.

There have been previous efforts to examine possible missions succeeding LISA. One of the earliest was the Big Bang Observer [16], a visionary concept to detect the cosmological GW background. Crowder and Cornish [17] compared LISA, BBO, ALIA [18] (to be described below) and stereo versions of LISA and ALIA.

In 2012, a NASA study team produced a wide-ranging study of alternative designs to LISA [19]. While this study did not address science beyond LISA science, it did comprehensively survey the architectural choices for space-based GW detectors. The low-frequency Folkner design described below was derived from this study. The GADFLI [20] and GEOGRAWI (now published under the acronym gLISA) [21] concepts, mentioned below, also originated from this study.

III. Key Science Goals

Similar to the EM-spectrum, GW sources are present throughout the universe and emit over many decades in frequency space. GW emission is directly linked to the mass of the emitting system; heavier binary systems merge at lower frequencies while lighter masses pass through the low frequency band, often with detectable amplitudes, and merge then at higher frequencies. Closing frequency gaps in the observed spectrum has two distinct scientific ramifications: (1) mergers can be measured across (nearly) all mass ranges and out to very large redshifts; and (2) the inspiral phase can be tracked over many months and often over many years prior to the merger. Both improvements provide unique opportunities to test GR. At least as important are improvements in the 3D localization of these sources to enable coordinated EM observations.

Improving angular resolution is an age-old goal for many areas of astronomy, and this may be especially important for gravitational wave astronomy, where the GW signal unequivocally identifies the source while EM and particle observatories identify the EM/particle signatures of these sources. LISA localizations may typically be on the order of a few square degrees (varying significantly for different sources). With incident wavelengths measured in millions of km, the Rayleigh criterion $\delta\theta \leq \lambda/D$ indicates the challenge of directly resolving gravitational wave sources. A large fraction of GW science, however, relies primarily on astrometric location of point sources, enhanced beyond the resolving power by the SNR (ρ). So increases in sensitivity are less important for a census of the black hole population but are crucial to improve the angular resolution and enable multi-messenger observations.

A key detection milestone will be to achieve angular (and distance) location with sufficient precision to localize extragalactic events such as EMRI's and merged massive or super-massive BHB systems to a single galaxy (or cluster). Approximate localization of these BHB systems to within arcminutes in advance of merger would enable deep coincident observations to identify an EM counterpart and thus locate the galaxy. These multi-messenger observations would then also enable studies of accretion flows and physics along with details of galaxy properties, all with precise knowledge of the black hole masses, spins and recent merger history. Some MBHB galaxy identifications may be possible with LISA, but future GW missions, in concert with advanced EM facilities should be able to dramatically expand the rich multi-messenger data set to enable a robust understanding of the roles black holes and galaxies play in shaping each other through accretion and mergers.

A. The mHz to Hz frequency band

The mHz to Hz frequency band is the band in which intermediate mass black hole binaries, even from lower-mass MBH seeds from Pop-III stars, would merge. A future observatory with significantly improved sensitivity compared to LISA provides clear statistics on these still uncertain objects. Beyond proving their existence and identifying their role between stellar mass BHs and massive BHs, precise measurements of the phasing of these mergers would probe for extensions of GR, testing the presence of additional physical fields with (effective) mass (e.g. ultralight fields/dark matter candidates).

Another unique source for this frequency range are (typically extra-galactic) double white dwarf (DWD) systems which could be observed at periods around their point of initial contact, allowing for example the observation of a gravitational-wave signal accompanying a type Ia supernova. Based on the known rate of type Ia supernovae, this also requires significant improvements in the high frequency sensitivity of LISA. Such a DWD-merger signal would provide unprecedented early warning for a supernovae.

Observations in this band also provide improved and advanced localization of the stellar-mass NS and BH chirping binaries with mergers observed by 3G ground-based GW observatories. Mergers would be precisely forecast enabling unique options for multi-messenger observations. If intermediate mass BHs exist in the universe, joint observations of these systems on the ground and in space will allow us to localize these sources well before they merge and to break parameter estimation degeneracies. At sufficiently high sensitivities it could be possible to independently resolve all such systems to high redshift, providing a complete census of these systems, while clearly exposing any primordial background like that predicted by some models of inflation.

LISA will be able to detect extreme mass-ratio inspirals (EMRIs) composed of a $10\,M_\odot$ black hole falling into a $3\times10^5 M_\odot$ BH to as far as $z=3$, but this horizon decreases rapidly for different BH mass, or for smaller secondary masses. While the rates of these remain quite uncertain, we might expect LISA to detect a few per year based on current models, but increased sensitivities just above a mHz would enhance the rate roughly as ρ^3. Plausible sensitivity improvements would provide a census of the EMRI population to moderate redshift, providing insights into the dynamics in stellar clusters. More sensitive observations of EMRIs would enable high precision spacetime mapping to verify the Kerr nature of astrophysical black holes. For the strongest EMRI signals we might even gain access to the overtones in the ring-down radiation.

B. The sub-μHz to mHz band

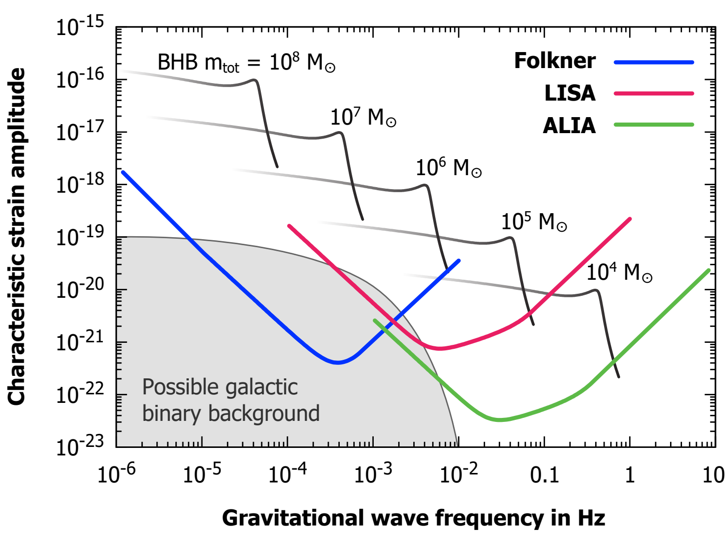

FIG. 2. Two potential future mission designs compared to the current LISA design. The low frequency, or Folkner design, assumes that we can extend LISA's acceleration noise into the low frequency band while the high frequency design (ALIA) assumes a frequency independent order of magnitude improvement in the current acceleration noise. The graph also shows the traces of a few equal-mass black hole mergers as examples of the science return of each of these missions. The grey shaded area is a potential representation of the still unknown stochastic gravitational wave emission from the millions of galactic binaries.

A similar gain in sensitivity and therefore angular resolution in the sub-mHz frequency band is frustrated by the stochastic background of the myriad of GW signals from galactic binary systems. The exact shape of this spectrum is subject to debate; current and future survey missions as well as LISA will provide some answers over the next 20 years. However, it is expected that the sensitivity of LISA might be limited by this background below about one mHz. The grey area in Figure 2 shows one of many possibilities for this background. *One person's noise is another person's signal.* Any future space mission probing below the LISA band will be able to measure the spectral and spatial distribution of these binaries over more than two decades in frequency space and will be able to identify and isolate probably hundreds of thousands of the stronger binary systems in our galaxy.

The different models of the galactic binary background still allow detection of gravitational waves from merging super-massive black holes in the $10^{7-9}M_\odot$ mass range out to large redshifts. These signals will not only map out the Kerr nature of super-massive black holes with high SNR but also shed light on many of the most fundamental questions in cosmology and galaxy evolution.

One example is the still unsolved puzzle of the rapid emergence of the high-z QSOs with big implications not only on the cosmic evolution of super-massive black holes but also on their impact on early galaxy formation. Do they regulate the entropy of the intergalactic medium, hence the fuel of galaxy formation? LISA will probe the $10^{4-6}M_\odot$ seeds of the early QSOs but will not tell us how and how fast they reached $10^{8-9}M_\odot$ (e.g., by Super-Eddington accretion). At high z it is expected that merger rates of galaxies and subsequent mergers between their central MBHs is very high. The observation of the generated GWs is a good probe of the growth function and is probably the only tool for a reliable census of MBHs during this epoch. In the mid range of this low frequency detector, we could possibly see thousands of inspiraling MBHBs with periodicities of days accessible with future (post LSST) time domain surveys. GWs would provide the luminosity distance and the EM-observatories the redshift for these standard sirens. These multi-messenger observations would also provide powerful insight onto accretion on binaries, the physics of disk-binary interaction, and many other aspects which need the masses and spins of the central engines behind these sources. Sensitivity at the high frequency end of this detector enables earlier detection and localization of LISA's MBHBs which will greatly expand opportunities for multi-messenger observations before and during merger.

IV. Example Mission Concepts

Looking to the future, we need to explore the science opportunities beyond LISA, and also the technological hurdles necessary to realize a beyond-LISA mission. Figure 2 compares the sensitivity curves of two example mission designs to LISA. These designs were chosen to illustrate the range of mission concepts, and to show what is possible if a healthy technology development program for future gravitational wave missions is established parallel to the LISA project itself.

One mission design explores the frequency band below LISA and is based on orbits in which the three spacecraft form an equilateral triangle with the Sun in its center. The arms are about 100 times longer than the LISA arms. This design keeps one spacecraft in the vicinity of Earth to simplify communication with the constellation. Communication to the other spacecraft would probably have to be carried by the laser links. These orbits were originally suggested by William Folkner during the GW Mission Concept Study [19] prior to the LISA Pathfinder success. He predicted some sensitivity to large massive black hole merger systems in a mission without inertial sensors where each spacecraft would act as a test masses. We added a drag free system back into the spacecraft and assumed that it maintains a frequency independent acceleration noise identical to the LISA requirement.

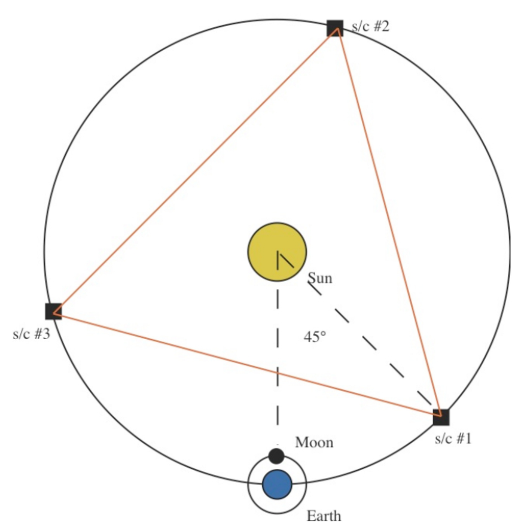

FIG. 3. The Folkner low-frequency mission concept placed three spacecraft in this triangular configuration around the Sun.

The second mission design, the Advanced Laser Interferometer Antenna (ALIA) [18], assumes a ten times improved acceleration noise in the high frequency part of the LISA spectrum. This example mission is five times shorter than LISA but uses significantly more laser power and larger telescopes to increase the interferometric sensitivity. The orbits for ALIA are still heliocentric but other mission designs with shorter arms explored also geocentric orbits (GADFLI and GEOGRAWI, a.k.a. gLISA).

A. Low-Frequency Mission Example

The orbits proposed in the Folkner mission would separate the spacecraft by around 260 Gm (see Fig. 3). One of them has to be kept at a reasonable distance to Earth to allow for spacecraft to ground communication which means that lasercom between the spacecraft has to be part of the mission design.

Folkner also provided an initial study of the orbital dynamics for the first five years of the mission. He found that differential velocities will stay below 3m/s, which affects the Doppler shifts and therefore the frequencies of the beat signals between the laser beams. Furthermore, changes in the opening angles between the spacecraft stay below 0.02° and would likely not require in-flight adjustments of the opening angle between the two outgoing beams on each spacecraft.

For the long arm interferometer, we used parameters which are very similar to LISA: 30 cm telescopes and a 3 W laser system. The received power at the far end would be approximately 150 fW and the shot noise limited displacement sensitivity would be a factor 200 below LISA leading to the same strain sensitivity when expressed as a linear spectral density; the sensitivity curves in Figure 2 are scaled by $\sqrt{f}$ to take into account the longer observation time for low-f signals. As shown in Figure 2, the galactic binary background will likely limit the sensitivity well before shot noise.

B. High-Frequency Mission Example

We use the ALIA mission design as an example for a high frequency beyond LISA mission. ALIA's orbits are LISA-like heliocentric orbits trailing or leading Earth by a few degrees. The distance between the spacecraft is 500,000 km; five times shorter than LISA. The resulting loss in low frequency sensitivity is (over-) compensated by an assumed ten-fold improvement in acceleration noise. These two parameters can be fine-tuned once the galactic binary background radiation has been characterized by LISA. The main improvement comes from a 40,000-fold increase in the received laser power which ALIA achieves by increasing the telescope diameter to 1 m and the laser power to 30 W. This leads to a factor 200 improvement in phase/displacement sensitivity and, due to the factor 5 shorter arms, to a 40-fold improvement in strain sensitivity. The dynamics of the orbits, relative spacecraft velocities and angular changes, scale with the arm length (assuming all other parameters stay the same) and will be reduced by a factor five compared to LISA.

The spacecraft in the geostationary mission designs were separated by 73,000 km. The shorter arm length shifts the sensitivity curve further to the right. Using ALIA's laser power and telescope diameter would give the same strain sensitivity at higher frequencies; the increase in received laser power is compensated by the decrease in length. However, it requires further improvements in the phase sensing system. The advantage of geostationary orbits is the reduced launch costs and simple ground to space communication links. On the other hand, geostationary constellations likely require station-keeping to manage the relative velocities (Doppler shifts) and changes in the opening angles.

V. Technology

Space-based GW detectors, based on laser interferometry, generally have two noise regimes that determine the performance. Residual accelerations on the inertial reference masses from unwanted disturbances limit the low frequency performance. Displacement measurement noise from the interferometry limit the high frequency performance. Together with the frequency response of a chosen armlength to the GW wavelength, these two noise types give the bucket-shaped noise curves that characterize laser-interferometer-based detectors. Any technology improvements naturally have to address these noise types. Changing a detector's operating band also requires adjustments to the treatment of these noise types.

A. Acceleration Noise

LPF improved on existing drag free systems by several orders of magnitude and represents the state of the art in force free motion. The LISA Pathfinder team has done a tremendous job of understanding and characterizing the limiting noise sources of their gravitational reference sensor (GRS) which is now baselined for LISA. However, the initial concept was born in the mid '90s based on a design sensitivity which was defined prior to understanding the true limitations of such a system. Now we have a much better understanding of these limitations and, with that knowledge, should be able to take a fresh look at the design and find ways to improve it.

The LPF team has analyzed hundreds of different potential noise sources. The leading contributors together with the LISA requirement and current best estimate are shown in Figure 4 [22]. At high frequencies, the noise in the actuation forces between the spacecraft and the test mass limit the performance. These forces are typically described as a stiffness along each translational and rotational degree of freedom. In a perfect drag free system, the spacecraft is tracking the motion of the test mass and the forces would be constant. A real drag free system is limited by sensor noise; in LISA we assume $\sim \mathrm{nm}/\sqrt{\mathrm{Hz}}$ and a few hundred $\mathrm{nrad}/\sqrt{\mathrm{Hz}}$ noise in the capacitive sensors, and by the response time of the μN-thrusters. The later is responsible for the increased noise at higher frequencies. A related noise source is gravitational noise or changes in the local gravitational field due to spacecraft motion. At high frequencies, this is again coupled to the non-suppressed spacecraft motion mostly along the non-sensitive axis due to cross coupling between the different degrees of freedom. In LISA, these degrees are only sensed using the capacitive sensors. One possible improvement in future missions would be to add a much more sensitive interferometric sensing system to monitor all degrees of freedom of testmass to spacecraft motion and not only the one along the optical axis. The design of such a system, the required sensitivity along the other degrees of freedom, added complexity and all ramifications with respect to the payload design need to be explored.

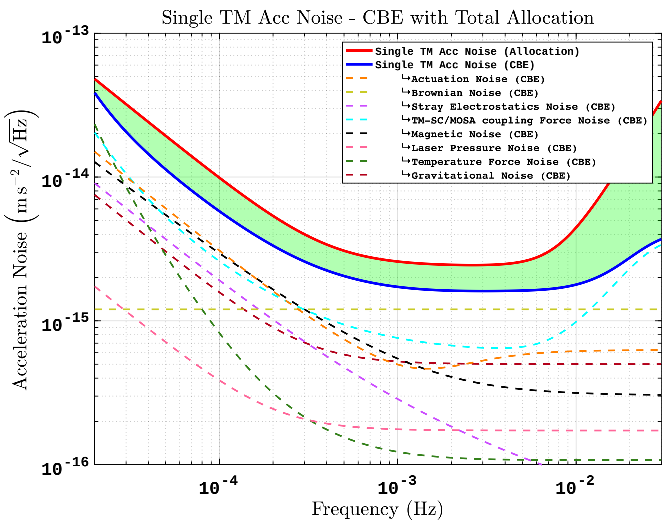

FIG. 4. The CBE of LISA's acceleration noise is based on LPF data and offers opportunities for future improvements [22].

At lower frequencies, thermo-elastic deformations of the spacecraft will also contribute to the overall noise budget. This noise falls off with distance cubed. Potential needed changes include improved thermal stability which has been identified as one of the driving forces behind many of the low frequency noise terms. In addition to passive shielding, LISA will also actively stabilize the temperature of the outer thermal shields which encapsulate the sensitive parts of the payload. The requirements on this shielding and the active temperature stabilization system has to be extended towards much lower frequencies; again a potentially solvable problem with significant design implications. A parallel approach is to use only low-CTE materials (with low water content) in the vicinity of the test mass to minimize thermo-elastic deformations. Low-CTE materials in this context might not be restricted to ULE or Zerodur but might also include support structures build from negative and positive CTE materials of similar density.

The limiting force in LPF in the most sensitive frequency range is Brownian noise caused by residual gas molecules bouncing off the test mass. This frequency independent Brownian motion scales with the area to mass ratio of the test mass, the residual gas pressure which in LPF was estimated to be $\sim 2\,\mu$Pa at the end of life, and on the gap size between test mass and housing. LISA carries a requirement of $1\,\mu$Pa to provide additional margin, which is still well above the ultra-high vacuum pressure that can be achieved in modern laboratories and many orders of magnitude away from the residual pressure in orbit. The gap size was optimized to reduce this gas pressure noise while maintaining enough sensitivity in the capacitive sensors and control authority in the electrostatic actuators. 1/f-noise in the electrostatic actuators was one of the dominant frequency dependent noise sources limiting LPF at low frequencies. Alternative mission concepts might use a single test mass which is gravitationally balanced within the center of the spacecraft. If feasible, such a design could significantly reduce the needs for test mass actuation and allow to increase the gap size by maybe even an order of magnitude. Obviously, such a design would again benefit from an all interferometric sensing system but other aspects such as redundancy are a major concern.

Another noise source, named stray electrostatic noise in Figure 4, is related to the test mass charge and electrostatic fields. LPF used a discontinuous UV discharging system which was turned on regularly to keep the charges below a few million electrons. LISA is planning to use a continuous UV discharging system which is expected to reduce the test mass charge significantly and reduce this noise as well. However, further improvements in the charge sensing technique might be needed to reduce the residual charge on the test mass again. The current charge sensing system relies on the electrostatic actuators which would limit the proposed increase in gap size to overcome other noise sources.

One example for a noise that scales with the volume of the test mass is magnetic force noise. Changing magnetic fields couple to the non-vanishing magnetic susceptibility of the test mass material and to the magnetic dipole moment from ferromagnetic inclusions. A specific gold-platinum alloy was chosen because of its vanishing magnetic susceptibility. A third and, based on LPF experience, likely dominant noise related to magnetic fields is the interaction and down-conversion of test mass eddy currents with time dependent magnetic fields, both originating in the audio band. The current best estimate for LISA is that the acceleration noise caused by eddy current damping and these magnetic fields will be at $0.3\,\mathrm{fm/s^2}\sqrt{\mathrm{Hz}}$ above a few mHz and then increases with f^{-1}. Possible mitigation strategies could include μ-metal and reductions in magnetic fields at audio frequencies.

All these mitigation steps might allow to reduce the acceleration noise in the high frequency region by an order of magnitude, as required by ALIA, and will also increase the frequency band in which the acceleration noise meets the LISA requirement of $3\,\mathrm{fm/s^2}\sqrt{\mathrm{Hz}}$. For even lower frequencies, not surprisingly, temperature variations are among the most crucial disturbances. Temperature fluctuations and time dependent gradients push and pull on the test mass for example through differential outgassing and differential radiation pressure as well as the already discussed gravitational forces. Based on LPF experience, LISA models assume a steep increase of the temperature fluctuations towards lower frequencies ($f^{-3.5}$) starting with $100\,\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$ at $100\,\mu$Hz. However, an active temperature sensing and control scheme could significantly reduce the temperature fluctuations.

To summarize, now is the time to build on the extensive LPF experience and use the lessons learned to improve acceleration noise beyond its performance at higher frequencies and expand the performance to even lower frequencies. The knowledge is fresh, the field is growing, and starting the technology development now allows to develop a mature mission concept for the next Decadal survey. But this requires a dedicated technology development program which builds on the LPF experience but should also evaluate alternative technologies and methods.

B. Measurement Noise

A second key technology is required to sense the minute changes in distance between the two widely separated spacecraft. Laser interferometric distance measurements are fundamentally limited by the intrinsic phase noise which is inversely proportional to the amplitude of the metering laser field. However, reaching this level is often very difficult especially when the amplitude is large. Ground-based observatories such as Advanced LIGO use optical cavities to amplify the response and a Michelson interferometer to suppress the common parts of the amplitude before they reach and saturate the detector. Both of these techniques will be very difficult to implement between drag free spacecraft. LISA is in that sweet spot where the received amplitude is at a level which allows shot noise limited detection of $\sim 10\,\mathrm{MHz}$ beat signals with current technology. LISA still requires clock noise transfer between the spacecraft and pilot tones to remove phase noise added by the analog components. A sophisticated timing and ranging system allows to suppress laser frequency noise using time delay interferometry. All of these technologies have been demonstrated at the $\sim \mathrm{pm}/\sqrt{\mathrm{Hz}}$-level in the LISA band sufficient to meet the LISA requirement of $10\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ equivalent single link displacement noise, twice as high as the allocated shot noise limit. Figure 5 shows the breakdown for the sensing noise in the long arm interferometer. It is dominated by shot noise above 1 mHz which will also limit the overall LISA sensitivity at these frequencies. Technical noise sources are allowed to increase with f^{-2} below 1 mHz where acceleration noise is expected to dominate.

The Folkner mission uses hundred times longer arms which reduces the received power by four orders of magnitude and increases the shot noise limit by a factor 100, likely well below the galactic binary background. If the overall performance of all technical noise sources in the displacement measurement system continues to raise only with f^{-2} down to sub-μHz, acceleration noise would be a factor 100 above these noise sources. This provides some needed margin to accommodate expected faster increases in temperature fluctuations towards the lower end of the μHz spectrum which might otherwise degrade the performance of the phase measurement chain. Note that increases in the received laser power by either increasing the laser power itself or the diameter of the telescopes is likely required to enable for example inter-spacecraft communication or acquiring lock. There are many other challenges related to this mission including reaching the orbits, sunshades, and communication, however, the technical challenges for the principle payload of such a low frequency mission appear to be mostly related to acceleration noise.

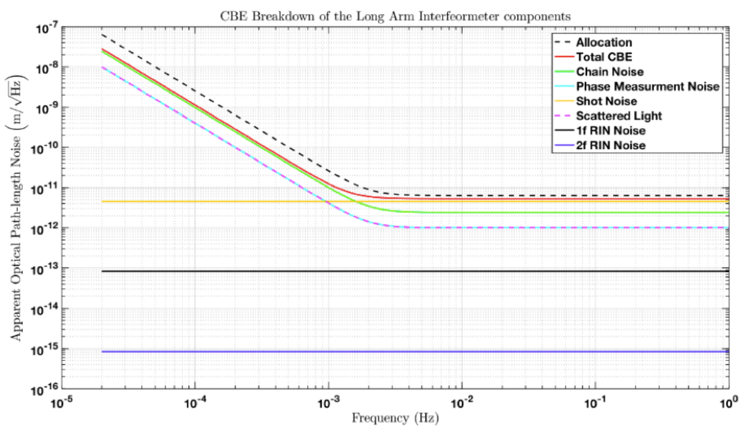

FIG. 5. The CBE of the most critical of LISA's long arm interferometer noise sources [22].

The 200-fold improved shot limit for ALIA present significant challenges for many subsystems within the interferometric measurement system. LISA's photo detector noise and phase noise in the analog chain is already state of the art for the $10-20\,\mathrm{MHz}$ laser beat frequencies. ALIA's orbit should allow for reduced Doppler shifts resulting in lower laser beat frequencies if the intrinsic laser noise can be suppressed below shot noise (1f-RIN-line) at these lower frequencies; the current laser systems are not shot noise limited below $\sim 8\,\mathrm{MHz}$. However, even if the relative intensity noise can actively be suppressed, phase noise and timing jitter in the analog parts of the phase measurement chain still need to be reduced by at least one order of magnitude. This requires a dedicated effort to develop and study electrical, electro-optical, and optical components starting from RF cables; the temperature dependency of the electric susceptibility of the dielectric inside the cable (often Teflon) is already a concern for phase noise in LISA, to analog to digital converters and the timing of them.

Beyond the individual components, the phase measurement system in its entirety needs to be re-evaluated. Are strategies such as comparing clock noise using the laser links still valid? What alternatives exist? Are there designs which reduce the laser beat frequencies by a few orders of magnitude to reduce demands on timing stability. What other laser sources will be available in time for a new mission? Using a lower laser wavelength decreases diffraction losses and increases the phase shift. Furthermore, the amount of scattered light will increase with the laser power while the sensitivity to scattered light increases by a factor 200. This requires new strategies to reduce and/or cancel stray light. Or generally speaking, to take full advantage of the increased received laser power, LISA's typical $\sim$ pm-requirements for most technical noise sources in the measurement system turn into $\sim 5\,$fm-requirements above $\sim 20\,$mHz.

The feasibility of improvements at this magnitude need to be studied and demonstrated in a dedicated technology development program before a believable and mature bLISA mission concept can be developed and presented to the next decadal survey.

VI. Organization, Partnerships, and Current Status

We imagine that the technology development work proposed here could be carried out within the structure of the ROSES program, in a manner analogous to the Beyond Einstein Foundation Science (2005-2007) or LISA Preparatory Science (2018) calls. The directed calls could be formulated by NASA Headquarters APD and PCOS staff with input from the LISA project team and the concept study. The concept study would be a panel of experts from the GW and astrophysics community similar to the many panels created by APD over the last 2 decades. An initial panel would identify promising concepts and the technology required early in the decade. A second study would meet later in the decade to evaluate the science return, the technology development progress and the outstanding technology risk, in time to make a recommendation to Astro2030, likely to commence in 2028.

VII. Schedule

The goal of this proposal is to have a bLISA mission concept ready for consideration by Astro2030. To accomplish this goal, the technology challenges for candidate mission concepts have to be understood and surmountable in order to select the concept. Hence, the technology development work needs to proceed during the 2020s, accompanied by mission concept studies to identify the requisite technologies and support a selection. LISA technology development will continue into the mid-2020s, when LISA goes into Phase C. The pace of technology development for bLISA should be set to support a concept down-select no later than 2028. That down-select will need to appraise the relative challenges of the candidate missions and the technology development path to flight for each. That could require only a low TRL, say 3-4, i.e., proof of concept. After that time, technology development for bLISA should focus on advancing toward TRLs of 5-6 in anticipation of a Phase A start early in the 2030s. If LISA launches in 2034, as currently planned, it would be finishing extended operations in the mid-2040s. Optimally, a bLISA would launch in the latter half of that decade.

VIII. Cost

This is a (very) small proposal for space related activities. At this time, the technologies to be developed are not well-enough understood to produce a detailed roadmap with schedule and budget profile. At best, we can only offer ROM costs. Based on our experience with LISA technology development, we estimate that the technology development needed in the decade of the 2020s will be about \$20M. The cost of a mission concept study will be about \$2M. The study might reasonably span two episodes, an early study to identify the candidate concepts and their requisite technologies, and then a later study ending by 2028 that evaluates the development progress, the development remaining and the potential science return of the candidate mission concepts in order to make the down-select. Then a proposal would be made to Astro2030.

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