Science Impact of the Low Frequency Performance of LISA

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Abstract

The LIST has been asked to comment on the impact on LISA science of the low-frequency noise performance of LISA. In particular, the LISA pre-Phase A design assumes pure acceleration noise at least for $f > 10^{-4}$Hz. Yet the current baseline for the SMART-2/LISA Test Package tests of the gravitational reference sensor involve measuring its performance only for frequencies $f > 10^{-3}$Hz. Predictions of LISA's actual performance at lower frequencies would therefore be based largely on extrapolation, and unexpected noise sources at lower frequencies might substantially degrade its performance. Consequently we have examined the impact on science of dramatic increases in LISA's noise (a 'noise wall') at frequencies $f < f_w$, with f_w in the range $3 \times 10^{-5} < f_w < 10^{-3}$ Hz. What constitutes a 'noise wall' depends on the individual sources considered. For Galactic binaries and extragalactic backgrounds, it would be an acceleration noise more than 10 times LISA's nominal 10^{-15}m s^{-2}Hz$^{-1/2}$. For merging supermassive black holes, it would be 30-100 times LISA's nominal acceleration noise.

Our overall conclusion is that even with a noise wall at 10^{-3}Hz, the LISA mission would be worth flying. But science would be substantially impacted. Therefore there is strong motivation to ensure (e.g. through design of the LISA test mission) that the LISA noise goals are reached in the range $3 \times 10^{-5} - 10^{-3}$Hz.

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We also comment on the desirability of using the test mission to characterize non-Gaussian aspects of the gravitational reference sensor noise: e.g. sudden large deflections. If the LISA mission records all the data streams so that multiple noise-cancelling combinations can be formed, a 'glitch' rate of a few per day can be accepted without losing S/N for burst sources. If all the data streams are not recorded, the constraints on the 'glitch' rate are far more stringent.

1 Introduction and Conclusions

LISA sources whose numbers are reasonably well established (better than an order of magnitude) by other astronomical observations are: (1) Galactic binary stars, principally double degenerate binaries (close pairs of white dwarfs) and some classes of cataclysmic binary (white dwarfs accreting from companion stars). Loss of performance below 10^{-3}Hz will lose about half of the calibrations from known sources. It will remove our ability to test population synthesis of non-degenerate compact binaries, and to probe the star formation history of the Milky Way. (2) Merging super-massive black holes in galactic nuclei at redshifts 0-30. Loss of low frequency performance is likely to prevent us from measuring the parameters of a many of these events, particularly if the black holes are slowly rotating. We may be able to detect them, but not extract much science. We will also not be able to detect mergers from supermassive black holes of the only masses securely measured in nearby galaxies ($> 10^6 M_\odot$). (3) stellar-mass compact objects (black holes, neutron stars) in the nuclear star clusters around super-massive black holes in galactic nuclei, captured by gravitational radiation onto bound inspiraling orbits, at redshifts < 1. Loss of low frequency performance will not significantly impact this science.

LISA sources whose numbers or gravitational wave spectrum are very uncertain include: (4) intermediate mass black holes captured by super-massive black holes. Loss of low frequency performance could substantially reduce the detected event rate. (5) bursts, e.g. from cosmic string cusps, collapse of super-massive Population III stars. Loss of low frequency performance would not substantially affect the detected event rate, provided the data streams from six arms are recorded and transmitted to the ground, so that multiple noise-cancelling interferometer combinations can be formed, and the non-gaussian 'glitch' rate does not exceed a few per day. (6) backgrounds from phase or other transitions in the early universe. Here loss of low frequency performance affects the science primarily by reducing the range of parameters (temperature of early universe when the interesting transition occured, nucleation rate, etc.) explored.

2 Galactic binary stars

Typical binaries (say $0.4M_\odot$ pairs) with gravitational wave frequency $f = 10^{-4}$Hz have a time to merge $\sim 10^{10}$y (the age of the universe) and an orbital separation of $a = 1.5R_\odot$. Those with $f = 10^{-3}$Hz have a time to merge $\sim 10^7$y and orbital separation $a = 0.3R_\odot$. The minimum orbital period for a binary containing at least one star of cosmic abundance (i.e. mostly hydrogen) is 80 min, giving a maximum $f = 4 \times 10^{-4}$Hz. Stars in binaries of higher frequency than this must both be composed of helium (or heavier elements) -i.e., they must be double degenerates or their immediate progenitors (sdB stars). The best available estimate for the birth/merger rate of these helium systems is $\sim 0.03\text{y}^{-1}$ (Nelemans et al 2001 A&A 365, 491), or around 2.5×10^8 in the Milky Way with $f > 10^{-4}$Hz, and a local space density $\sim 5 \times 10^{-4}\text{pc}^{-3}$. These systems dominate the Galactic gravitational waves in the LISA frequency band, $10^{-4}\text{Hz} < f < 10^{-2}\text{Hz}$. CO and heavier white dwarfs, neutron stars, black hole binaries etc are expected to comprise increasingly small fractions (0.1, 0.00001, 0) of the double degenerate population. Except for the neutron star and black hole binaries, all are expected to be in exquisitely circular orbits, due to tidal dissipation in the progenitor stars. The gravitational wave signals will thus be sinusoids at twice the orbital frequency.

The above estimates of the Galactic population consider only the Galactic disk (dominant), bulge, bar and spheroid. There have been recent suggestions from gravitational micro-lensing (Alcock et al 2000 ApJ 542, 281) and direct detection (Oppenheimer et al 2001 Science 292, 698, but see Reid et al astro-ph/0104110 and Koopmans & Blandford astro-ph/0107358 for alternative interpretations) of a much larger halo population of white dwarfs, which could increase the 'noise' from galactic binaries by a factor of 2-3 above standard models.

As gravitational radiation causes double degenerate systems to spiral together and fill their Roche lobes (at $f \sim 0.01$Hz), mass transfer begins. This reduces the mass, and increases the size of the less massive white dwarf, driving the binary back to longer orbital period and more extreme mass ratio. After 10^{10}y, the f has decreased to $\sim 4 \times 10^{-4}$Hz (orbital period $\sim$ 1.5h) and the less massive white dwarf reduced to $\sim 0.006 M_{\odot}$. About 9 of these systems have been discovered by optical and X-ray observation. They are named AM CVn stars, after the prototypical system. [Note: systems of somewhat longer initial orbital period, in which the red giant ignites helium before its envelope is stripped by spiral-in, produce a helium burning horizontal branch star with a white dwarf companion. Gravitational radiation can bring these into contact, leading to mass transfer and a maximum orbital frequency of $f \sim 0.003$Hz before the companion becomes degenerate and the resulting expanding double degenerate looks much like those formed from double degenerates. The birthrates may be comparable: see Nelemans et al 2001 A&A 368, 939] The best available population synthesis predicts $2 - 8 \times 10^{8}$ of these systems in the Milky Way today, and a local space density of $0.4 - 2 \times 10^{-4}\mathrm{pc}^{-3}$ (Nelemans et al 2001 A&A 368, 939). The nearest such system (very old and faint, with a $0.006 M_{\odot}$ companion) should thus be at $10 - 20$pc distance. However there is a strong selection bias in optical astronomy towards the young, high accretion rate systems, so it is not surprising that the presently *observed* systems are all estimated to be at distances $\sim 100 - 200$pc and have companions of much larger mass $\sim 0.02 - 0.07 M_{\odot}$. However, by the time LISA is launched, all-sky variability monitoring or spectroscopic surveys might have discovered one or two orders of magnitude more such systems.

Hydrogen Cataclysmic variables (CVs, which come in nonmagnetic novae, dwarf nova subtypes U Gem, SU UMa and Z Cam depending on whether they show regular outbursts, superoutbursts or standstills, and rarer strongly (synchronous) and moderately (asynchronous) magnetic types AM Her and DQ Her [aka intermediate polars]) are Roche-lobe filling dwarf stars losing mass to a white dwarf. At least at orbital periods less than 2h, the evolution of the nonmagnetic systems is believed to be driven by gravitational radiation. As the mass of the companion is reduced below the mass limit for hydrogen burning, $\sim 0.07 M_{\odot}$, it becomes supported by degeneracy pressure and expands in response to further mass loss, causing the orbit to re-expand. The minimum period is $\sim$ 80min. After $\sim 10^{10}$y, the orbital period has increased to $\sim$ 2h, the companion mass reduced to $\sim 0.02 M_{\odot}$, and the accretion rate very low, so the system would be extremely faint. Until recently the local space density of observed (hence optically quite bright) CVs was more than an order of magnitude lower than the theoretically predicted $\sim 10^{-4}\mathrm{pc}^{-3}$, but systematic deep surveys appear to be reducing the discrepancy (Marsh et al astro-ph/0108334). Population synthesis models (cf. Politano 1996 ApJ 465, 338) predict a total number $\sim 5 \times 10^7$ of CVs in the Galaxy, most of which would have $2.5 \times 10^{-4} < f 4 \times 10^{-4}$Hz. In this narrow range of frequencies, they make a modest (∼30%) contribution to the Galactic gravitational wave background.

The shortest known orbital period for a W UMa contact binary (pair of main-sequence stars filling their Roche lobes) is $P = 0.221$d, $f = 1.0 \times 10^{-4}$Hz (CC Com, $M_V = 6.7$, $m_V = 11.5$), though intrinsically fainter, lower mass systems may exist at even shorter periods. The best available estimate for the space density of these systems ($f = 5 \times 10^{-5} - 1.0 \times 10^{-4}$Hz) is $\sim 1/100$ per main sequence star with $2.5 < M_V < 7.5$ (Rucinski 1998 AJ 116, 2998), or about 2.5×10^8 in the Milky Way. Thus these systems should make a modest (∼40%) contribution to the Galactic gravitational wave background in the octave around 10^{-4}Hz.

We remind the reader that at frequencies $10^{-4}\text{Hz} < f < 10^{-3}$Hz, the pre-Phase A LISA noise $S_h(f)^{1/2}$ lies a factor of 2-10 below the expected 'noise' of unresolved Galactic binaries. This 'noise' will be concentrated towards the galactic plane, with substantial monopolar and dipolar components. As the orientation of the LISA baselines changes over the year, the amplitude of the strain 'noise' produced in the synthesised Michelson interferometers will also vary, and can be distinguished from instrumental noise by comparison with a synthesised Sagnac interferometer, which has a much lower response to low-frequency gravitational waves. At frequencies $> 2 \times 10^{-3}$, LISA should be able to individually distinguish $\sim 10^4$ double degenerate systems [Note that the Doppler modulation of the frequency and intensity measured by the orbiting and rotating LISA helps distinguish sources as the confusion limit of one source per (1/mission lifetime) frequency resolution is approached (-cf Hellings gr-qc/0110052). Note also that this total includes a few hundred systems in the Magellanic Clouds and (Benacquista 1999 ApJ 520, 233) globular clusters]. At $3 \times 10^{-4} < f < 2 \times 10^{-3}$Hz, the nearest sources with large secondary masses (i.e. the nearest double degenerate systems, but not the nearest dwarf novae or AM CVn) will poke up above the Galactic 'noise'.

Increased LISA noise below 10^{-3}Hz will not affect the detection and study of the vast majority of the individually distinguishable 10^4 Galactic binary sources, virtually all of which will be at $f > 2 \times 10^{-3}$Hz.

Known binaries, such as those listed in the table below, are important calibrators for LISA. As sources of known orbital period and position, and at least approximately known masses and distances, they can be used as measures of the LISA sensitivity and as tests of the data analysis system. They can also be used to provide some tests of relativity: e.g. that the gravitational waves are emitted at twice the orbital frequency. Several AM CVn sources, and one LMXB are known with $f > 10^{-3}$Hz, so even with increased noise below 10^{-3}Hz, some of these tests would be possible.

However, none of the (dominant, and gravitationally cleanest) WD+WD or WD+sdB systems are now known with $f > 10^{-3}$Hz. Furthermore the (yet to be discovered) nearest of these systems with $f \sim 4 \times 10^{-4}$Hz could have its orbit and parallax determined astrometrically by SIM or TPF, giving a direct measure of the orbital inclination and orientation on the sky. Since these should also be determined by comparison of h_+ and $h_\times$, this would provide a stringent test of the LISA data analysis.

Losing the ability to measure the Galactic binary background below 10^{-3}Hz would eliminate the possibility of testing population synthesis models for CVs and W UMa systems. The frequency region $5 \times 10^{-5}\text{Hz} < f < 2 \times 10^{-4}$Hz contains a unique record of the (binary) star formation history of the Milky Way.

class	source	dist pc	$f = 2/P_b$ mHz	M_1 $M_\odot$	M_2 $M_\odot$	τ_{mrg} 10^8y	h
WD+WD	WD 0957-666	100	0.38	0.37	0.32	2	4×10^{-22}
	WD 1101+364	100	0.16	0.31	0.36	20	2×10^{-22}
	WD 1704+481	100	0.16	0.39	0.56	13	4×10^{-22}
	WD 2331+290	100	0.14	0.39	> 0.32	< 30	$> 2 \times 10^{-22}$
WD+sdB	KPD 0422+4521	100	0.26	0.51	0.53	3	6×10^{-22}
	KPD 1930+2752	100	0.24	0.5	0.97	2	1×10^{-21}
AM CVn	RXJ1914+245	100	3.5?	0.6	0.07	–	6×10^{-22}
	AM CVn	100	1.94	0.5	0.033	–	2×10^{-22}
	HP Lib	100	1.79	0.6	0.03	–	2×10^{-22}
	CR Boo	100	1.36	0.6	0.02	–	1×10^{-22}
	V803 Cen	100	1.24	0.6	0.02	–	1×10^{-22}
	CP Eri	200	1.16	0.6	0.02	–	4×10^{-23}
	GP Com	200	0.72	0.5	0.02	–	3×10^{-23}
LMXB	4U1820-30	8100	3.0	1.4	< 0.1	–	2×10^{-23}
	4U1626-67	3-8000	0.79	1.4	< 0.03	–	6×10^{-24}
W UMa	CC Com	90	0.105	0.7	0.7	–	6×10^{-22}

3 Merging Supermassive Black Holes

The maximum gravitational wave frequency from a pair of nonrotating black holes of mass $M = 10^6 M_6 M_\odot$ merging at redshift z is $f_{\max} \sim 0.02/M \sim 4 \times 10^{-3} M_6^{-1}(1+z)^{-1}$Hz. For rapidly rotating black holes, the maximum frequency can be about 10 times higher if the spin and orbital angular momenta are all aligned, or substantially lower if the spins and orbital angular momenta are antiparallel. For typical inclinations, however, the differences are much less: for example for a/M=0.95, estimating $f_{\max}$ as twice the orbital frequency at the ISCO, $M f_{\max} = (0.085, 0.058, 0.025, 0.0147, 0.0124)$ for angles of (0, 45, 90, 135, 180) degrees, respectively between the black hole's spin axis and the orbital angular momentum. Stars captured from a surrounding cluster will have approximately random inclination angles, so 70% of the captured stars would have $M f_{\max}$ within a factor of two of 0.03, close to the Schwarzschild value 0.02. However, the nearly equatorial, prograde orbits of maximally spinning black holes are much more tightly bound, so they may be over-represented in a sensitivity-limited (as opposed to volume limited) sample. This deserves further investigation.

Taking the Schwarzschild value for the maximum frequency, a noise wall at f_w will prevent *detection* of merging supermassive black holes for $(1+z)M > 2 \times 10^5 M_\odot (f_w/3 \times 10^{-4}\mathrm{Hz})^{8/5}$. Since only one black hole is known in any galactic nucleus with $M < 10^6 M_\odot$, this is potentially the most serious loss of science.

For primary black holes of mass $M < 2 \times 10^6 (1+z)^{-1} M_\odot$, the final merger occurs at $f > 2 \times 10^{-3}$Hz, where the Galactic binary background can be removed. Most of the total S/N for signal *detection* is thus accumulated above this frequency. Increases in the noise below 10^{-3}Hz will therefore not much affect *detection* of these sources.

However the accuracy of parameter determination depends on measurements made during the long inspiral preceding the final merger. The *time* spent above frequency f is

$$t_{mrg} = 1\,\mathrm{month}(f/3 \times 10^{-4}\mathrm{Hz})^{8/3}[(1+z)M/2 \times 10^5 M_\odot]^{-5/3} \,. \qquad (1)$$

When this duration is less than one month, LISA moves through only half a radian during the lifetime of the source, and the position of the source is determined to worse than a steradian. This means that the polarisations h_+ and h_x cannot be defined.

So unless the black holes are rapidly rotating, so that their spin-orbit precession can be used to determine the inclination of the orbit to the line of sight, the distance to the source and hence also the masses and mass ratio of the two black holes are not determined. Details of calculations by S. Hughes are at

`http://www.tapir.caltech.edu/~hughes/Research/LISA/param.html`

4 Inspiralling compact objects captured by supermassive black holes

Because the gravitational wave amplitude of such events is proportional to the mass of the compact object, these signals are much weaker than those from merging supermassive black holes. They will therefore be detected only near LISA's total (Galactic plus instrumental) noise minimum -i.e. for $2 \times 10^{-3} < f < 2 \times 10^{-2}$Hz -i.e. for supermassive black holes of mass in the approximate range $10^5 - 10^6 M_\odot$. Most of the captures events from galactic nuclei occur for black holes in this range. Thus additional noise below 10^{-3}Hz will have negligible impact on either the science or event rate.

5 Intermediate mass black holes captured by super-massive black holes

Inspirals of $10^3 - 10^4 M_\odot$ black holes into supermassive black holes, long suggested as a means of forming supermassive black holes, and recently revived by the discovery of substantially superEddington variable X-ray sources outside of galactic nuclei, can be detected by LISA with good S/N above the Galactic binary background at $< 2 \times 10^{-3}$Hz. Unlike the capture of stellar mass compact objects, the volume from which these captures can occur increases rapidly with black hole mass, and most of the event rate is likely to occur for black holes more massive than $10^6 M_\odot$. Loss of low frequency performance could substantially reduce the event rate.

6 Bursts

The rate and spectrum of burst sources in the LISA bands are quite uncertain. Cosmic strings produce a characteristic spectrum (Damour & Vilenkin 2000, PRL 85, 3761). The radiation from cusps is an $h(f) \propto f^{-1/3}$ powerlaw, and that from kinks an $h(f) \propto f^{-2/3}$ powerlaw, with a cutoff at an upper frequency which decreases as the angle of the observer to the axis of the cusp or kind increases. If the LISA noise is purely Gaussian, the number of templates required for an optimal fit increases only logarithmically with the width of the frequency window, and the total SNR depends mainly on the sensitivity of LISA at its most sensitive frequency, and not so strongly on the actual window. So for pure Gaussian noise, degradation in the performance below 10^{-3}Hz would not impact detection of cosmic strings much.

Intially, we worried that the rare bursty waveforms of string cusps/kinks could easily be confused with nongaussian instrumental noise ('glitches'). However J. Armstrong, T. Creighton and M. Tinto studied vetoing schemes to distinguish gravitational-wave bursts from instrumental glitches. These turn out to be quite successful, provided the glitch rate is not much higher than a few per day.

For bursts having durations much less than the round-trip light travel time between spacecraft (17s for the nominal LISA), one can resolve the multiple-pulse response function of the instrument: the pulse times will be different between gravitational waves, which affect the various spacecraft nonlocally, and instrumental glitches local to a particular spacecraft. In particular, proof-mass glitches (sudden change in proof mass velocity large compared to the usual statistically stationary noise) produce a 2-pulse instrument response, while a gravitational wave burst produces an 8-pulse (7-pulse for exactly equal arm lengths) response in the Michelson configuration (for notation, see ETA2000= Estabrook, Tinto, Armstrong Phys Rev D, 62, 042002 (2000) and AET1999= Armstrong, Estabrook, Tinto Ap. J. 527, 814 (1999)).

For short glitches, measuring a complete set of laser-phase noise cancelling combinations (e.g., the three Michelson combinations) allows inference of which of the 6 proof masses "glitched". This is a further argument for a LISA architecture where all the data streams are recorded so that multiple noise-cancelling combinations can be formed, both for science and for glitch veto/on-orbit calibration.

For bursts whose SNR is generated mostly at frequencies below $2 \times$

10^{-3}Hz, a gravitational wave can be distinguished by its much larger SNR in the synthesized Michelson combination as compared to the Sagnac combination. The SNR of an instrumental glitch will in general be amplified, allowing the presence of a signal in both channels to serve as a veto.

Both these vetoes will reject all but one in 10^5 glitches for reasonable thresholds, allowing us to *tolerate raw glitch rates of up to one every few hours*. However, there is not at yet a scheme for vetoing bursts having frequency support above 2×10^{-3}Hz but durations on the order of the round-trip light travel time or more.

6.1 Pulse Timing Veto

When looking for short-duration gravitational wave bursts, one can veto many instrumental glitches by means of their pulse structure in the synthesized Michelson channel. Glitches local to a spacecraft will typically produce pulses separated by the round-trip light travel times between spacecraft; i.e. at times t, $t + 2L/c$, and $t + 4L/c$. On the other hand, nonlocal influences will produce pulses at different times: a generic gravitational wave will give a series of pulses within a time $2L/c$ of each other. [The GW response function for the Michelson combination is in general an 8-pulse response (see AET99, equation 24). In the special case of equal arm lengths, this degenerates to a 7-pulse response. The relative amplitudes and relative positions of these 8 pulses depends on the angle of arrival of the wave and the armlengths.] Thus even without any careful discrimination of pulse amplitudes, one can veto any burst event that does not consist of a triplet of significant pulse peaks within a time $2L/c$. [For the case of proof mass glitches, if we take all the data, so that we can form e.g. X, Y, Z (all the Michelson combinations), Armstrong has shown that one can even identify which proof mass glitched.]

Of course this veto could be fooled by a multiple coincidence of instrumental bursts, which could resemble a gravitational wave. If individual glitches occur at uncorrelated times (Poisson distribution) at a rate of $\lambda \gg c/2L$, then the rate of such false coincidences will be $\sim \lambda^3(2L/c)^2$. Thus if we desire a false alarm rate of less than 1%/year, we can tolerate individual glitches at a rate of up to 1/4.3h.

The downside of this veto is that it only works for bursts that can be resolved in time to well within the round-trip time $2L/c$; it will thus probably not work well for bursts with characteristic frequencies below a few $\times 10^{-3}$ Hz. It will also falsely veto actual gravitational-wave bursts that produce only a pulse doublet during this time, leading to blind spots both along the arms of and in the plane bisecting the synthesized interferometer.

6.2 Sagnac Veto

At low frequencies, one can make use of the fact that one can synthesize a laser-noise-free channel, called the Sagnac channel, that is symmetric in the positions of the three spacecraft, and is therefore much less sensitive to long-wavelength gravitational waves. Thus gravitational wave bursts will tend to have strongly attenuated SNRs in the Sagnac channel compared with the Michelson channel. One can thus construct a veto in which candidate signals above a certain threshold in the Michelson channel are *rejected* if they are above another threshold in the Sagnac channel.

This veto is not very effective for bursts that generate most of their SNR at frequencies above 10^{-2} Hz, since these will not be attenuated very strongly in the Sagnac channel. At these frequencies the veto will reject a significant fraction of true events.

The Sagnac veto is also only marginally effective between about 2×10^{-3} Hz and 10^{-2} Hz, since in this band the SNR of instrumental glitches is also attenuated in the Sagnac channel by a factor of $\sim$1–3. Thus if a majority of instrumental glitches appear with SNRs only marginally above the Michelson threshold, a significant fraction (up to $\sim$15%) will be attenuated below the Sagnac threshold, and thus be indistinguishable from gravitational waves.

However, below about 2×10^{-3} Hz, gravitational waves are strongly attenuated in the Sagnac channel, while most instrumental artifacts will actually be *amplified* in relative SNR. One can then set reasonable thresholds such that less than ~ 1 in 10^5 of all instrumental glitches will sporadically appear in only the Michelson channel and not in the Sagnac channel. Thus if we demand fewer than 1%/year false detections due to glitches, then we can tolerate raw glitch rates of up to one every 8 hours or so.

Similar considerations apply to other burst sources, e.g. from the collapse of super-massive Population III stars. Though in contrast to the string bursts, other burst sources may have preferred natural frequencies, so loss of a frequency band could also lose them entirely (or conversely, have little effect).

6.3 High-Q bursts:

The pulse-timing and Sagnac vetoes cover most of the spectrum of low-Q (Q$\sim$1–2) bursts, since such bursts will typically have mostly low-frequency support (and thus be attenuated in the Sagnac channel) or else have short duration (and thus be resolvable by the pulse-timing veto). However, for bursts with several cycles, it is possible that they may be both too high in frequency for the Sagnac veto to be useful, but too long in duration for their pulse-response structure to be readily resolvable. A more detailed numerical analysis is required to determine how one could veto instrumental glitches having this form.

7 Backgrounds from the early universe

Gravitational wave backgrounds can be produced by to phase transitions, dimensionality transitions, Goldstone modes and other features of the very early universe. Waves produced at redshift z when the universe had temperature T can have a spectrum only at frequencies above the (redshifted) inverse of time it would take light to cross the horizon size at redshift z:

$$f > H(z)/(1+z) \simeq 2 \times 10^{-4}\mathrm{Hz}\frac{kT(z)}{1\mathrm{TeV}} \tag{2}$$

Examples include QCD ($kT \sim 1$GeV), Electroweak ($kT \sim 100$GeV), dimensionality ($kT > 1$TeV, cf. astro-ph/0009136) transitions. In many models, the spectrum is peaked near, or rapidly falling above this frequency, so sensitivity at a frequency f corresponds approximately to sensitivity to events at a particular time (or equivalently, temperature or energy scale) in the evolution of the universe. Losing the low-frequency part of LISA's frequency spectrum can thus be crudely characterised as losing the ability to explore about 30% of the parameter space for discovery of signals of uncertain reality but enormous potential impact on science.

One of the better studied potential backgrounds is due to the Electroweak phase transition (cf review by Kosowsky et al astro-ph/0102169). In the Standard Model of particle physics (one Higgs), and minimal supersymmetric Standard Models (two Higgs doublets) the gravitational wave amplitudes would be undetectably tiny. However in non-minimal supersymmetric models, which do succeed at baryogenesis, many (but *not* most) choices of the unknown parameters lead to strongly first order transitions and LISA-detectable gravitational wave amplitudes.

The actual wave spectrum then depends on two derived parameters: the characteristic velocity of the bubble walls (at least $0.02c$ for successful baryogenesis), and the nucleation rate β in units of the Hubble expansion rate H during the phase transition (believed to be in the range $10 - 10^3 H$. $h_c(f)$ peaks above 10^{-3} Hz for $\beta > 100$. However, the amplitudes are larger for smaller β, and gravitational waves emitted by turbulence after the percolation of bubble walls produce a rather flat high-frequency tail to the gravitational wave spectrum. So the background could be detected even for lower β, though confirmation of its origin would be harder if the peak is not seen in the LISA frequency band.