Cosmological Gravitational Wave Backgrounds
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Abstract. An overview is presented of possible cosmologically distant sources of gravitational wave backgrounds, especially those which might produce detectable backgrounds in the LISA band between 0.1 and 100 mHz. Examples considered here include inflation-amplified vacuum fluctuations in inflaton and graviton fields, bubble collisions in first-order phase transitions, Goldstone modes of classical self-ordering scalars, and cosmic strings and other gauge defects. Characteristic scales and basic mechanisms are reviewed and spectra are estimated for each of these sources. The unique impact of a LISA detection on fundamental physics and cosmology is discussed.

I INTRODUCTION

In relativistic Big-Bang cosmology, the Universe is optically thin to gravitational waves all the way back to the Planck epoch; once a wave is produced, absorption is negligible, with energy losses due to redshift alone. The cosmological background of gravitational waves thus contains directly observable information from the entire history of the macroscopic universe—an unobstructed view of our past light cone. Here I present a broad survey of ideas for processes in the early universe which may produce gravitational waves, including guesses at their amplitudes and frequency spectra, and what a detection by LISA might teach us about the early universe. I direct the reader to other recent documents and reviews for more detailed and comprehensive descriptions of many of these ideas and for more thorough surveys of the literature. [1-4]

As in so many areas of astrophysics, gravitational waves offer insights into cosmological processes quite distinct from those accessible by electromagnetic observations. Direct light paths come to us from a temperature $T \approx 3000K$ and a cosmic age $t \approx 0.5Myr$; the thermal spectrum of the primordial radiation was fixed when the last efficient photon-production processes froze out at $T \approx 500eV$ and a cosmic age of a few weeks. By contrast, the LISA gravitational wave backgrounds, if they exist, illuminate much earlier events, and probe directly the physics of very high energies: the electroweak, GUT, and Planck scales. LISA is sensitive to gravitational waves produced by cosmic strings in the temperature interval 10 keV—10MeV, and cosmic ages from $10^{-2}$ to $10^4$ seconds; our current knowledge of these epochs comes only from fossil low-bandwidth information such as the light element abundances. Large-scale relativistic flows of energy during phase transitions above 100 GeV or so (earlier than about $10^{-10}$ seconds) produce waves in the LISA band but have few other observable effects; it is possible that production of these waves may be associated with our only other relics of these epochs, the cosmic baryon number and perhaps the dark matter. The physics which shaped the metric on the largest scales of space and time, currently described by inflation models, probably also generated gravitational waves in ways akin to the generation of the perturbations which led to cosmic structure, perhaps at the GUT epoch. There are also ways in which many spacetime dimensions and other internal degrees of freedom now being explored for fundamental physics near the Planck scale could lead to intense gravitational wave backgrounds in the LISA band, produced at temperatures of 1 to 1000 TeV. Detection of a cosmological background by LISA would provide our first view of early mesoscopic gravitational phenomena about which no other trace survives, with a likely connection to the frontier problems of cosmological theory—the production of baryons, dark matter, and fluctuations in binding energy which led to cosmic structure—as well as the structure of fundamental fields at very high energies.

1) This work was supported at the University of Washington by NASA.
II REDSHIFTED HUBBLE FREQUENCY

As a reference point for the following discussion, it is useful to define a characteristic frequency associated with most classical production mechanisms for cosmological gravitational waves, the Hubble rate divided by the cosmological redshift:

\[ \omega_0(z) \equiv \frac{H(z)}{(1 + z)} \approx 2 \times 10^{-5}\text{Hz} \frac{T(z)}{100\text{GeV}}, \]  

(1)

where \( T \) is the temperature of the universe. (There is a weak dependence \( \omega_0 \propto g_*^{1/4} \) on the number of effective degrees of freedom \( g_* \) which varies only slowly in the Standard Model, from about \( g_* \approx 60 \) at 1 GeV to about 100 at 1 TeV.) This is the frequency of gravitational waves observed today which were produced on the horizon scale at temperature \( T \). Gravitational waves in the LISA band can be produced by horizon-scale processes at temperatures between a few hundred GeV and a few hundred TeV, by relativistic processes well within the horizon at lower temperature, or by inflationary processes at much higher temperature.

III BROAD-BAND ENERGY

We specify the gravitational wave spectrum \( \Omega_{GW}(f) \) in terms of energy density per unit of log frequency, in units of the critical density. After gravitational waves are produced they redshift in the same way as electromagnetic waves and other relativistic forms of energy. Therefore, the integrated energy density of the gravitational wave background(s) scale in proportion to the energy density of the sum of the other relativistic components. Currently this sum is (assuming massless neutrinos)

\[ \Omega_{\text{rel}}(z = 0) = \Omega_{\gamma + \nu + \bar{\nu}} = 0.7 \times 10^{-4} T_{1.27}^4 k h_{75}^{-2}. \]  

(2)

We define a quantity

\[ F(f) = \frac{\Omega_{GW}((1 + z)f)}{\Omega_{\text{rel}}(z)}, \]  

(3)

the ratio of gravitational wave to other relativistic energy, which is approximately conserved. Notice that at high redshift \( \Omega_{\text{rel}} \) is shared among many more relativistic degrees of freedom than it is today, but \( F \) is conserved so long as the coupled system of particles remains highly relativistic.

The quantity \( F \) roughly corresponds to the overall gravitational wave production efficiency— the fraction of mass-energy converted into gravitational waves. Since it seems unlikely that gravitational waves would be produced more efficiently than other forms of energy, a plausible upper limit on the cosmological background is \( F < 1 \) at all frequencies.

Compare this with the LISA sensitivity as estimated in the Yellow Book [4]. The rms amplitude of a fluctuating gravitational wave in a bandwidth \( f \) about a frequency \( f \) is

\[ h_{\text{rms}}(f, \Delta f = f) = 10^{-15} \Omega_{GW}^{1/2} f_{mHz}^{-1/2} h_{75}; \]  

(4)

however the background will be distinguishable from instrumental noise only over much narrower bands; the strain produced in one frequency resolution element after a year of observation is

\[ h_{\text{rms}}(f, \Delta f = 3 \times 10^{-8}\text{Hz}) = 5.5 \times 10^{-22} \Omega_{GW}/10^{-8} f_{mHz}^{-3/2} h \]  

\[ = 4.6 \times 10^{-20} F(f)^{1/2} f_{mHz}^{-3/2} h. \]  

(5)

(6)

At a \( f \approx \) few mHz, LISA’s instrumental noise drops to as low as \( h_{\text{rms}} \approx 10^{-24} \) in this band so one can contemplate detecting effects as small as

\[ F \approx 10^{-8} \quad \text{or} \quad \Omega_{GW} \approx 10^{-12}; \]  

(7)

indeed for backgrounds larger than this the cosmological background starts to dominate the noise over some frequency intervals, becoming a nuisance for other observations.
IV CURRENT OBSERVATIONAL CONSTRAINTS ON $\Omega_{GW}$

Although within its band LISA achieves a sensitivity in $F$ and $\Omega_{GW}$ far better than any other technique, we already have some meaningful constraints on $\Omega_{GW}(f)$ in other frequency intervals which impact the candidate sources for LISA.

The most sensitive in terms of $F$ is cosmic background radiation anisotropy. [5,6] Tensor mode perturbations generate temperature fluctuations in the microwave background; on scales larger than about a degree these preserve roughly the amplitude they had entering the horizon $\delta T/T \approx h_{\text{hor}}$. Now $\Omega_{GW} \approx (f/H_0)^2 h_{\text{hor}}^2$, so observed limits (and measurements, which may not be of tensor modes) of about $\delta T/T \approx 10^{-5}$ yield a constraint $\Omega_{GW}(f = H_0) \lesssim 10^{-10}$ on the current horizon scale. The limit becomes smaller at higher frequencies, the details depending on the cosmological model. Detailed constraints are placed on inflation models from the predicted tensor modes and their effect on anisotropy. In principle, though not yet in practice, polarization allows tensor and scalar sources to be distinguished observationally. [7,9]

A scale-free process such as inflation with $h_{\text{hor}} = \text{constant}$ creates a flat background spectrum above about $f = (\Omega_{rel}(z = 0)/\Omega)^{1/2}$, with $F(f) = \text{constant} \approx h_{\text{hor}}^2 \approx 10^{-10}$ with amplitude constrained by CBR anisotropy. In the scale-free case, CBR data provide the most sensitive limits on $F$— better than LISA. However, it is still interesting to consider direct limits on waves at higher frequencies since sources are never precisely scale-free and sometimes not even approximately so.

Pulsar timing measurements directly limit the background at frequencies determined by the observation timescale of a few years. The principle resembles that of interferometric detectors. The pulsar acts as a very steady clock with timing residuals $\delta t$ of about a microsecond, and over few years the lack of deviations from steady ticking (aside from those expected from Newtonian accelerations of both us and the pulsar) constrains the strain amplitude to $h \lesssim \mu\text{sec}/10^8\text{sec} \approx 10^{-14}$. After allowing for the fact that unknowns such as the Newtonian accelerations and the precise pulsar direction are “fitted out”, the current limit [10] is $\Omega_{GW}(f = 10^{-8}\text{Hz}) h^2 \lesssim 6 \times 10^{-8}$. Note that if many pulsars are added with accurate timing and good coverage over the sky, it is possible to extract a signature indicating a positive detection of gravitational waves.

For backgrounds that were already present at the epoch of cosmic nucleosynthesis $1\text{sec} < t < 100\text{sec}$, abundances of light elements provide another constraint. The presence of gravitational waves adds to the total energy density of in the same way as adding additional relativistic degrees of freedom; for example, an extra neutrino species adds the equivalent of $F \approx 1/6$. Although the precise limits are a matter of opinion riding upon continually changing debate over observational errors [11–15], it is clear that standard nucleosynthesis fails (primarily due to overproduction of helium-4) unless $F \lesssim 0.1$. This limit applies to most of the sources we will consider for the LISA band. Notice that the limit becomes stronger for scale-free backgrounds for which many octaves of $f$ contribute to the density.

Chaotic universes with $F \approx 1$ are prone to forming many black holes. This is a disaster since the energy locked up in black holes does not redshift away and quickly comes to dominate the energy density. [16] At most $10^{-8}(T/\text{GeV})^{-1}$ of the mass can convert to black holes at temperature $T$ without exceeding the mass per photon in the universe today. So there is constraint on the production mechanism for backgrounds which approach the $F \approx 0.1$ nucleosynthesis bound— they must produce their waves efficiently in a well-regulated process that does not allow a wide dispersion of gravitational potentials since even a tiny fraction of matter in very deep potentials ($\nu \approx 1$) causes problems. The Goldstone modes discussed below offer an example of such a mechanism but the phase transition bubble collisions do not.

There are also limits from the spectrum of the background radiation. Gravitational waves create observable quadrupoles in the radiation field at each point, so the average radiation field is no longer thermal but a mixture of temperatures with a spread of the order of $h_{\text{rms}}$ times the Hubble velocity $H(z)/f$ for $f$ comparable to the scattering rate of photons at redshift $z$. The COBE/FIRAS limits on spectral distortions limit energy inputs after this epoch to the order of $10^{-4}$ [6]; but the corresponding limit on $h_{\text{hor}}$ is competitive with the CBR anisotropy limits only over a narrow range of frequencies.

V GRAVITATIONAL WAVES FROM INFLATION

Inflation generates gravitational wave backgrounds by the parametric amplification of quantum fluctuations, the same process thought to create the scalar modes that lead to large-scale cosmic structure. [17,18] Backgrounds are created both by the fluctuations of the inflaton field— which make the familiar scalar modes— and by quantum fluctuations of the gravitational field itself.

The amplitude of scalar perturbations depends on details of the inflaton potential. These are tuned to yield $h_{\text{scalar}}$ in agreement with some suite of observations including the CBR fluctuations and large scale structure. The best fit to the data for scalar modes is close to scale-free with amplitude $h_{\text{hor},\text{scalar}} \approx 10^{-5}$, but may have a small “tilt” or
slow variation of $h_{\text{hor}}$ with scale. As they enter the horizon, there is some mixing between scalar and tensor modes, since the scalar perturbations lead to quadrupolar mass flows that act as sources for gravitational waves. Very roughly, the mixing will lead to $h_{\text{hor}}$, $\delta h_{\text{hor}} \approx h^2_{\text{hor}}$, $\delta h_{\text{hor}}$. In spite of the suppression, the LISA band is so much higher in frequency than the direct observational constraints that even a small tilt can lead to essentially any amplitude in the LISA band.

In the case of gravitational field fluctuations, the amplitude is not dependent on the inflaton potential directly but essentially on just the expansion rate or density during inflation when waves of observed frequency $f$ match the inflationary expansion rate:

$$F(f) \approx \frac{V_{\text{inflation}}(f)}{m_{\text{Planck}}^4}$$

which is close to scale-free and hence limited to $F \lesssim 10^{-10}$. Inflation very close to the Planck scale generally runs into difficulties with CBR anisotropy from these tensor sources.

The conclusion is that LISA may detect gravitational waves from inflationary fluctuations (from the inflaton fluctuations) if the tilt of the spectrum is favorable, but is unlikely to detect modes directly generated by quantum fluctuations of the graviton.

VI FIRST-ORDER PHASE TRANSITIONS: RELATIVISTIC FLUID FLOWS AND BUBBLE COLLISIONS

The universe may have undergone catastrophic phase transitions at various stages, associated with a sudden change in the ground state configuration of the vacuum fields. [19–25] The macroscopic description is similar whether the fields are associated with QCD, electroweak breaking, or supersymmetry breaking.

We imagine an order parameter $\phi$ with a free energy density or effective potential $V_T(\phi)$; this potential has two distinct minima corresponding to two distinct phases; the free energy difference between them vanishes at the critical temperature $T_c$, one phase being favored at higher and the other at lower temperature. The transition from one phase to the other cannot happen smoothly because of the activation barrier between them corresponding to the energy cost of creating a surface interface between phases. The system supercools by a small amount until the free energy difference between phases is sufficient to nucleate bubbles; thermal or quantum fluctuations must create a bubble of low-temperature phase large enough that the volume energy difference exceeds the cost of creating the surface between them; above this size bubbles grow by detonation or deflagration with the phase boundary propagating close to the speed of light. The release of latent heat heats the inter-bubble medium back to almost $T_c$ and increases the pressure between bubbles, so (in the deflagration case) after the shocks from the bubbles meet, fresh nucleation slows and the transition finishes by the slow growth of already-nucleated bubbles. The universe can expand for a significant quiescent period near $T_c$ with both phases coexisting; as it expands it fills more with the lower-density, low-temperature phase. The remnants of the high phase are eventually isolated as islands by the percolation of the low phase, and finally when there is no more high phase left normal cooling resumes.

The production of gravitational waves occurs because of relativistic flows of matter of different densities in the two phases; a substantial fraction of the matter is accelerated to close to the speed of light, and asymmetric shocks are formed as bubbles collide. Not all of the processes involved are computed accurately and many depend on the detailed input physics, but the main parameter is generic: the maximum fractional supercooling $\delta$. Since this is the amount by which the universe expands during the nucleation of the typical bubbles, it determines the bubble size $\delta/H$. Because the nucleation rate depends exponentially on $\delta$, even a very strongly first order transition generically obeys [20]

$$\delta \lesssim \log[T/m_{\text{Planck}}] \approx 10^{-2}$$

From scaling we estimate the background from flows of scale $\delta/H$, maximal density contrast, and $v \approx c$; it will be a broad-band background of with a peak at frequency $f_{\text{peak}} \approx \omega_0(T)/\delta$ and peak amplitude $F(f_{\text{peak}}) \approx \delta^2$.

For example, if there is a very strongly first-order phase transition at 100GeV to 1TeV, a background could be generated with a characteristic frequency of around 2 to 20 mHz and an amplitude as large as $\Omega_{GW} \approx 10^{-8}$, which is detectable. These parameters might be associated with electroweak symmetry breaking and/or supersymmetry breaking. Although a first order transition is not required by the Standard Model, many workers believe that it is first order because that or some other significant disequilibrium is required to create the baryon asymmetry. There is at least the possibility that LISA might make an important connection here, the first direct window on the process that created cosmic matter from radiation.

On the other hand, a very strong disequilibrium may not be required and the fractional supercooling could easily be orders of magnitude less than $\delta \approx 10^{-2}$, which would make the background undetectable. This seems likely to
be the case for the QCD transition (which is probably not even first order, but had it been strong might have been detected at lower frequencies from pulsar timing).

VII SELF-ORDERING Scalars: Gravitational Waves FROM Goldstone Modes

Gravitational waves which may be generated by global excitations of new classical scalar degrees of freedom. Such fields often appear in effective theories derived from unified models such as supersymmetric theories and string theories.

We describe the behavior of active classical scalar fields with the simple Lagrangian density

\[
L = \partial_{\mu}\phi\partial^{\mu}\phi/2 - V(\phi) = \dot{\phi}^2/2 - V(\phi),
\]

leading to the evolution equation

\[
\ddot{\phi} + 3H\dot{\phi} - \nabla^2\phi + \partial V/\partial \phi = 0,
\]

We now suppose that there is more than one scalar component and that the effective potential \( V(\phi) \) has some set of degenerate minima, no longer at just one \( \phi \) but over some set of points far from the origin which all have \( |\phi| = \phi_0 \). For each direction within this surface with \( \partial V/\partial \phi = 0 \) this wave equation describes massless “Goldstone modes”, coherent classical massless modes which propagate at \( c \) and dissipate only by redshifting (via \( 3H\dot{\phi} \)). [26,27]

Typically different states \( \phi \) are reached at different points in space by cooling down from some higher symmetry (a la Kibble) which generates spatial gradients in \( \phi \). These variations excite the Goldstone modes of the field, in general with a large initial amplitude, \( \delta \phi \approx \phi \), and with random phase on all scales larger than the horizon. Modes larger than the horizon are essentially frozen in amplitude. The dominant energy density comes from modes just entering the horizon scale (when they have propagated about one wavelength), at which time they contribute a density of the order of \( (\phi_0/m_{\text{Planck}})^2 \) times the total density; after this time the amplitude and frequency of the waves redshift like other relativistic waves, and eventually dissipate. Since the waves induce coherent quadrupolar flows of energy on the horizon scale and close to the speed of light, they couple to gravitational radiation and create a gravitational wave background. Roughly a fraction \( (\phi_0/m_{\text{Planck}})^2 \) of the scalars’ energy is radiated per oscillation time in gravitational waves on the horizon scale. If the other couplings of the field are not very weak the main energy loss may not be gravitational radiation and the gravitational wave background may be as small as \( F(f = \omega_0(z)) \approx (\phi_0/m_{\text{Planck}})^4 \). (Uncertainty arises here not only from other couplings in the Lagrangian but also from the gravitational coupling to the other cosmic matter fluids, which may be dissipative and reduce the final energy in the gravitational wave channel.) A scale \( \phi_0 \) near the Planck scale is needed to produce a detectable background.

Unless some other coupling is added to damp the Goldstone oscillations at some point, this is a scale-free background and is subject to the constraints discussed above from lower frequencies, which already imply a fairly small background. This constraint can be avoided however if the theory contains fields which strongly damp the Goldstone modes after a certain epoch \( t \) which then reduces the low-frequency gravitational waves (i.e., those below \( \omega_0(t) \)). For example, a second phase transition could occur removing the degeneracy in the minima of \( V \); the fields would everywhere relax to the single minimum, removing the source of subsequent Goldstone excitation.

The excitation of these modes happens on a timescale determined by the motion in the space normal to the surface of degenerate minima. If the Higgs masses corresponding to these directions of \( V \) are very small, the Kibble excitation may not occur until temperatures much lower than \( \phi_0 \), which cuts off the spectrum at high frequencies.

Note that although the waves are generated classically at the 1—1000 TeV temperatures characteristic for \( \omega_0(T) \) to lie in the LISA band, the physics probed is on the scale of \( \phi_0 \) which can be close to the Planck scale and reflects new fundamental fields close to the scale of quantum gravity. Multitudinous internal spaces and dimensions are now being contemplated for fundamental theory near the Planck scale (“M-theory” or string theory) [28]. The ground state is far from being understood but is often described using the kind of effective theory we have just sketched with a large set of degenerate minima and many internal degrees of freedom. Since the compactifications and symmetry breakings occur close to the Planck scale, we might expect the effective theory to contain scales \( \phi_0 \) close to \( m_{\text{Planck}} \). In this case the Goldstone modes are a plausible mechanism which may come close to saturating the \( F \approx 0.1 \) (nucleosynthesis) bound in the LISA band— a spectacularly strong background

\[
\Omega_{GW} \approx 10^{-5}
\]

which could have a signal-to-noise of \( 10^7 \)! Such a strong detection would clearly enable many details to be studied and provide spectacular direct probe into degrees of freedom not seen in any other way. Although a classical macroscopic
process, it would reveal fields linked to the unification of gravity and other forces. Even though it is quite possible that nothing of the sort occurs near enough to the Planck scale to produce a detectable background, we should bear this possibility in mind.

**VIII  COSMIC STRINGS**

Strings are topologically stable defects in gauge fields, analogous to vortex lines in superfluids, within which the vacuum is trapped in the excited “false vacuum” state. They are formed again by the Kibble mechanism: the rapid quenching that occurs from the cosmic expansion prevents a global alignment of fields and guarantees plentiful defects. After forming they stretch, move, interconnect, form kinks and wave excitations, and break into loops in a complicated network teeming at close to the speed of light. Their main energy loss is by gravitational radiation. [29–34]

The gravitational interactions of strings are determined by a parameter $\mu$, the mass per unit length, or equivalently a “deficit angle” $\delta = 4\pi G \mu$ for the conical space created by a straight string. For a symmetry breaking at scale $m$, $\mu$ is of the order $m^2$, leading to $\delta \approx (m/m_{\text{Planck}})^2$. Formation of strings is quite generic and may occur even during electroweak symmetry breaking if the topology of the Higgs sector is suitable, but the gravitational effects are usually only considered for GUT scale strings with $\delta \approx 10^{-5}$ which are heavy enough to produce large scale structure and CBR anisotropy. Current calculations show that strings predict a poor fit to these two datasets (too little structure for a given anisotropy [35]) but one should bear in mind that strings may still exist at smaller $\delta$ and produce gravitational waves. Strings have many very distinct observable effects; for example, a string in the plane of the sky creates a duplicated strip of images of width $\delta$; galaxy images on the boundary of the strip have sharp, straight edges.

Although the early calculations [30,31] of the spectrum of the background were based on a rather simplified picture of the network, they agree remarkably well with recent predictions based on sophisticated simulations of the behavior of the network. In the LISA band the spectrum is flat with $F \approx \delta^{1/2}$; this is so strong that it is easily observable even if $\delta$ is too small to affect any other astrophysical observable. These may be the one type of object for which gravitational radiation is the most easily observable gravitational effect! Indeed even now the pulsar timing bound on gravitational waves is of comparable significance to CBR fluctuations in constraining $\mu$.

The waves are produced by decay of string loops and kinks which occurs after about $\delta^{-1}$ oscillations, dominated at temperature $T$ by frequencies about $\delta^{-1} \omega_0(T)$; the waves in the LISA band therefore were emitted at temperatures from 10 MeV down to about 10 keV.

Cosmic strings and Goldstone modes both rely on macroscopically excited new scalars excited by the Kibble mechanism. However, there are important differences. Strings derive from a gauge field (a local rather than a global symmetry breaking) and a nontrivial topology in the manifold of degenerate vacua (leading to the topological stability). A global field with nontrivial topology is also possible (global strings, monopoles, textures) with qualitatively similar results to the Goldstone estimates. In terms of gravitational wave production, strings are more efficient for a given $\phi_0$ and make cleaner predictions for a wide variety of phenomena; on the other hand the Goldstone modes can occur with $\phi_0$ close to the Planck scale and therefore can produce the most intense backgrounds. Gravitational waves can also be efficiently produced by “hybrid” defects. [36]

**IX  IMPACT OF A DETECTION ON COSMOLOGY**

All of the sources considered above are well motivated from some physical point of view. However, the amplitudes for many of them are almost unconstrained. It is possible that LISA will never detect a cosmological background; it is also possible that an intense cosmological background dominates the LISA noise budget by a large factor, limiting its utility for studying many sources at low redshift. In the latter case, there will at least be a big payoff in completely new knowledge of the early universe. I have not discussed here the problems of distinguishing backgrounds from noise or separating cosmological backgrounds from others such as Galactic binaries. But assuming a cosmological background is detected, how are we to interpret it?

The sources discussed here all produce highly confused isotropic stochastic backgrounds of broad-band Gaussian noise. The first clue to interpretation will be the shape of the spectrum. The spectra of the sources we have considered fall into two broad categories: (1) Scale-free sources with $\Omega_{GW}$ approximately independent of $f$, or $h_{\text{rms}} \propto f^{-3/2} \Delta f^{1/2}$, over the LISA band. These include inflation, generic Goldstone modes, and cosmic strings. Even a tilted spectrum from inflation—the only inflationary contribution likely to be detectable—will be approximately flat over the LISA band. (2) Other sources with the imprint of some characteristic scale. These include some Goldstone models (those where features imprinted by damping or Higgs modes happen to lie in the LISA band), and...
waves from bubbles or other relativistic flows which will bear the imprint of the nucleation scale where the spectrum peaks. Distinguishing between these broad categories is possible with even moderate signal-to-noise detection because of the fairly broad band available, about a factor of a thousand in frequency. The intensity of the spectrum may give another clue: for example, a very intense scale-free background points to some kind of macroscopically active scalar.

LISA surveys a domain of cosmological history which has left few other direct observables. It is worth commenting that these other observables concerning the very early universe are either very large-scale (e.g., fluctuations on galaxy clustering scales and above from inflation) or very small-scale (e.g., abundances of nuclei determined by microscopic reaction rates and thermodynamics); whereas gravitational waves probe a possibly richly varied primordial “mesoscopic” phenomenology about which all other traces have been erased. A detection of a gravitational wave background would depart from the quiescent behavior we have been led to expect from the early universe by the observed small fluctuations, tiny spectral distortions, and abundances in agreement with homogeneous nucleosynthesis; it would give us insight into a nonlinear, chaotic or turbulent stage in the early history of the universe about which we currently have no clue.

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