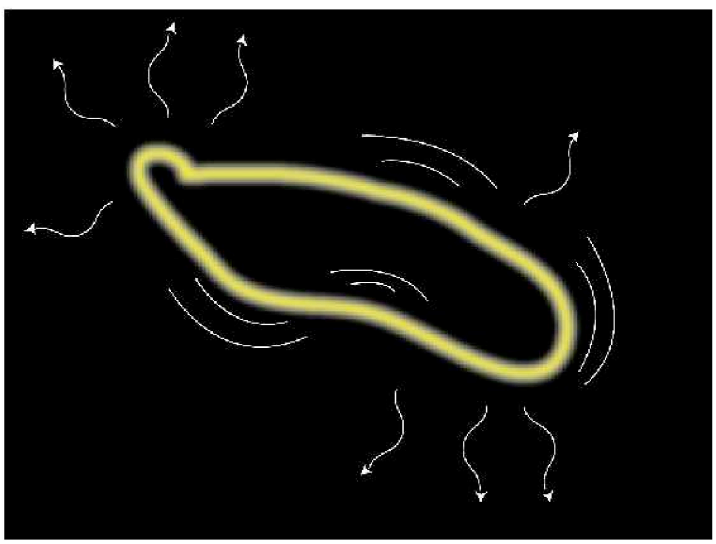
Gravitational Waves from New Physics

Craig Hogan

University of Chicago and Fermilab, +1 630 840 5523, craighogan@uchicago.edu

and Pierre Binetruy



Gravitational waves reach us directly from all of cosmic history back to and including the inflationary era; indeed the waves are almost unattenuated right back to the Planck time, where the very notion of classical spacetime becomes inconsistent with quantum mechanics. They are generated by motions of all forms of mass-energy, including those that emit no light or other particles. The gravitational waves in the universe today preserve a record of all macroscopic mass-energy flows over the entire history of the universe. They can be used to probe certain aspects of new physics never before explored.

Gravitational waves directly sense motions of new forms of mass-energy

LISA can detect gravitational waves from first-order phase transitions with critical temperature from about 100 GeV to 1000 TeV, which may be associated with electroweak or supersymmetry breaking, dynamically active submillimeter extra dimensions, or the creation of matter/antimatter asymmetry. Line radiation may be detectable from loops of cosmic superstrings.

At the same time, new ideas in physics suggest that there may be forms of mass-energy that have not yet been detected directly, which could be expected to produce cataclysmic motions at various stages of cosmic evolution that would emit copious gravitational radiation. Such behavior occurs in natural extensions of the Higgs scalars that are integral to the Standard Model of particles and forces, or of the supersymmetry that underlies unification theories. Fields of this type can create relativistic flows of mass-energy on macroscopic scales due to first-order phase transitions, which are also a key ingredient in some scenarios for generating the cosmic excess of matter over antimatter. Symmetry breaking is often associated with the creation of stable, macroscopic defects such as cosmic superstrings that generate copious gravitational radiation.

A sensitive low-frequency detector, such as LISA, opens up an enormous range of discovery space, since it explores motions of all forms of mass-energy, including those currently unknown, from a wide range of scales, epochs, and physical processes not accessible in any other way. Although it is unlikely that we have thought of the strongest new-physics sources that will be discovered, it is useful to review some ideas in frontier physics that give a flavor of the type of new discoveries we might hope to make.

A detectable gravitational wave signal in the LISA band is predicted by a number of new physical ideas for early cosmological evolution. Two important mechanisms for generating gravitational waves are relativistic phase transitions and cosmic strings:

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

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

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

Science questions

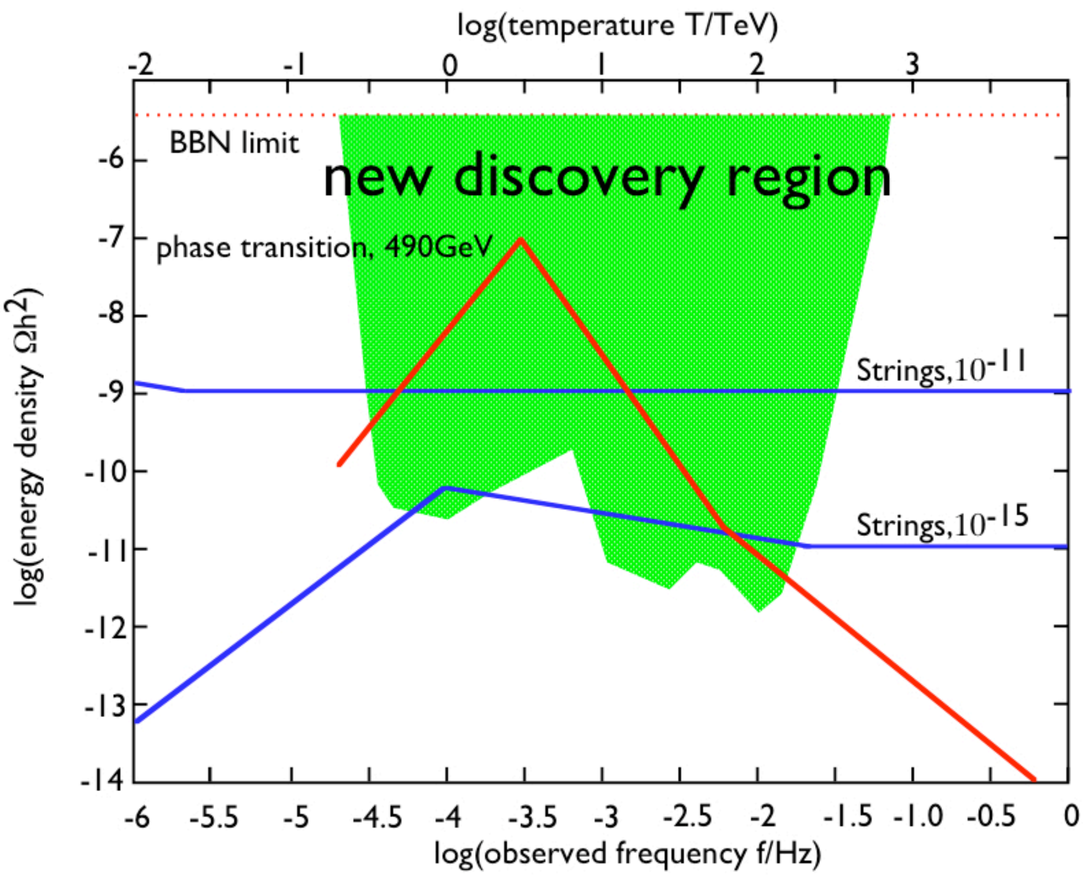
- What can astronomy tell us about new physics?
- Are there extra dimensions of space?
- What forms of invisible matter and energy exist?
- What caused the cosmic excess of matter over antimatter?
- How did the Universe begin?
- Were there violent events in the early Universe?

- Fundamental string theory, the subject of intense theoretical study as a unified framework for all particles and forces of nature, as well as generic forms of symmetry breaking in field theory, predict the possibility of new fundamental objects called cosmic superstrings, stretched to astronomical size by the cosmic expansion, that lose energy principally through gravitational radiation with uniquely identifiable spectral signatures. LISA will be our most sensitive probe for these objects by many orders of magnitude and so offers the possibility of detecting direct evidence of fundamental strings.

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

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

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



Schematic “Discovery Space” for stochastic backgrounds. Gravitational wave background broad-band energy density is shown in units of the critical density for $h_0 = 1$. The new discovery region is shown for LISA. LISA’s sensitivity extends about seven orders of magnitude below the energy density of thermal radiation, and six orders of magnitude below current limits from Big Bang Nucleosynthesis (BBN). The background spectrum from cosmic superstrings is shown for two values of string tension, $G\mu/c^4 = 10^{-11}$ and 10^{-15}. A model spectrum is shown from a first order phase transition of warped extra dimensions (Randall & Servant 2006), which is typical of strongly first order transition spectra. Top axis is labeled by the temperature of the Universe when waves of the specified observed frequency were at the size of the cosmological horizon.

Dynamics of warped submillimeter extra dimensions

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

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

The dynamics associated with the stabilization of extra dimensions at a certain size or warp radius might introduce a source of free internal energy released coherently on a "mesoscopic" (submillimeter to nanometer) scale, leading to a detectable background. Brane condensation also introduces a new kind of mechanism for generating gravitational waves: motion and curvature of our Standard Model brane in the extra dimensions. LISA's high frequency limit at 1000 TeV corresponds to direct probes of extra dimensions as small as 10^{-6} mm.

LISA, the LHC and the electroweak phase transition

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

Terascale inflationary reheating

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

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

Exotic inflationary quantum vacuum fluctuations

The amplification of quantum vacuum fluctuations during inflation leads to a background of primordial gravitational waves. An optimistic estimate of this background in the case of conventional inflation limits these to less than about 10^{-10} of the cosmic microwave background energy density, far below LISA's sensitivity, and indeed in many inflation models it is much less. However, some unconventional versions of inflation, particularly pre-Big-Bang or "bouncing brane" scenarios, predict possibly detectable backgrounds in the LISA band. Although key parameters remain unknown, which limits the predictive power of these models, they are significantly constrained by gravitational wave backgrounds. If such a background is detected, its spectrum also contains information about the Universe at the time perturbations "re-enter" the horizon.

Backgrounds, bursts, and harmonic notes from cosmic strings

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

The primordial network of strings spawns isolated, oscillating loops that ultimately radiate almost all of their energy into gravitational waves. Their gravitational radiation is mainly governed by a single dimensionless parameter $G\mu/c^4$ reflecting the fundamental physics of the strings, where μ is the energy per unit length, or tension. This number is known to be very small; if cosmic strings exist, they must be so light that they have no observable effects apart from their gravitational radiation.

The predicted stochastic background spectra from strings spans a wide range of scenarios motivated by inflation and string theory. The spectrum from cosmic strings is distinguishably different from that of phase transitions or any other predicted source. LISA's sensitivity to cosmic strings in terms of $G\mu/c^4$ is many orders of magnitude deeper than current limits from pulsar timing.

In some situations, gravitational waves from individual loops can be isolated from the stochastic background. Occasional distinctive bursts might be seen from loops that happen to beam gravitational waves in our direction from "cusp catastrophes", where a momentary event produces a sharply-bent bit of string moving at nearly the speed of light. These rare events, if they are intense enough to stand out above the background, are recognizable from their universal waveform, which derives just from the geometry of the cusps.

Observational evidence for a theory of everything

The discovery of string radiation would be direct evidence of new physics far beyond the reach of any accelerator. Its properties would tell about the connection between particles, fields, spacetime and fundamental strings, and would help shape the deep unifying mathematical insights of string theory into a model of the real world.

Another possibility opens up for very light strings. String loops emit gravitational waves in a perfect harmonic series of extremely narrow gravitational wave "spectral lines," unlike any ordinary astrophysical source. For light strings, surviving loops have a size that puts their fundamental or low-order harmonic modes into the sensitive millihertz detection band of LISA. In this case, line radiation from individual nearby loops in our Galactic halo would appear above the background. Such signals would provide not just a stochastic background but a sample of detailed loop waveforms for study, a rich source of detailed information about these exotic objects.

This brief survey has given a glimpse of what nature might deliver. Although these examples are too speculative to motivate by themselves a risky and expensive mission, they highlight the profound transformational possibilities of gravitational wave astronomy for fundamental physics. They show that an experiment that we can actually build, such as LISA, can reach deep into the unknown.

Boyle L A, Steinhardt P A 2008, Phys Rev D 77: 063504

Buonanno A 2003 “Gravitational waves from the early Universe” gr-qc/0303085

Chongchitnan S, Efstathiou G 2006 “Prospects for direct detection of primordial gravitational waves” *Phys Rev D* **73**, 083511

Damour T, Vilenkin A 2005 “Gravitational radiation from cosmic (super)strings: Bursts, stochastic background, and observational wind” *Phys Rev D* **71**, 063510

Dolgov A, *et al*. 2002 “Relic backgrounds of gravitational waves from cosmic turbulence” *Phys Rev D* **66**, 103505

Easther R, Lim E 2006 “Stochastic gravitational wave production after inflation” *J Cosmol Astropart Phys* **0604**, 010

Farmer A, Phinney E 2003 “The gravitational wave background from cosmological compact binaries” *MNRAS* **346**, 1197–1214

Grojean C, Servant G 2007 “Gravitational waves from phase transitions at the electroweak scale and beyond” , Phys Rev D 75:043507

Hogan C 2000 “Gravitational waves from mesoscopic dynamics of the extra dimensions” *Phys Rev Lett* **85,** 2044–2047

Hogan C 1986 “Gravitational radiation from cosmological phase transitions” *MNRAS* **218**, 629–636

Hogan C, Bender P 2001 “Estimating stochastic gravitational wave backgrounds with the Sagnac calibration” *Phys Rev D* **64**, 062002

Kosowsky A, *et al.* 2002 “Gravitational radiation from cosmological turbulence” *Phys Rev D* **66**, 024030

Maggiore M 2000 “Gravitational wave experiments and early universe cosmology” *Physics Rep* **331**, 283–367

Polchinski J 2005 “Cosmic superstrings revisited” *Int J Mod Phys A* **20**, 3413

Randall L, Servant G 2006 “Gravitational waves from warped spacetime” hep-ph/0607158

Siemens X, *et al.* 2006 “Gravitational wave bursts from cosmic (super)strings: Quantitative analysis and constraints” *Phys Rev D* **73**, 105001

Witten E 1984 “Cosmic separation of phases” *Phys Rev D* **30**, 272–285