# Getting Work from Gravity: LISA and Black Hole Mergers

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The advent of gravitational wave astronomy will open a new window on the Universe. Unlike electromagnetic radiation, gravitational radiation interacts very weakly with matter. This is both a blessing and a curse, since the weak interaction allows gravitational radiation to travel across the Universe essentially without absorption, but it also makes detection of the gravitational radiation exceedingly difficult.

The strongest and most readily detectable waves are generated by large masses concentrated in small volumes and moving at high velocities. Therefore, the coalescence of black hole binaries (BHB) is one of the richest potential sources of scientific discovery in gravitational wave astronomy. If two black holes are orbiting each other closely enough, the emission of gravitational radiation will cause them to spiral inward before colliding to form a single, perturbed black hole. This single black hole will then emit exponentially decaying gravitational waves as it settles into a quiescent Kerr state. These three stages of a BHB's evolution are referred to, respectively, as the inspiral, the merger, and the ringdown.

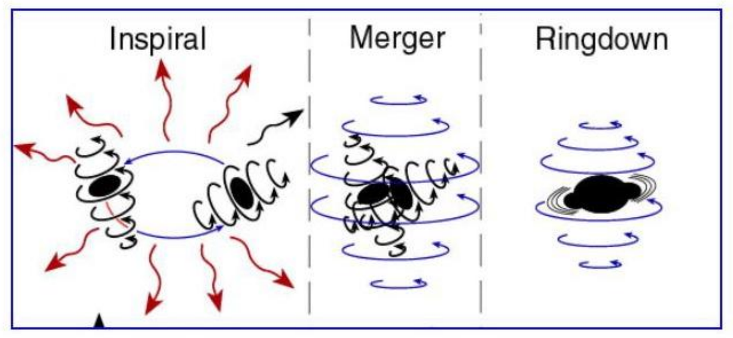
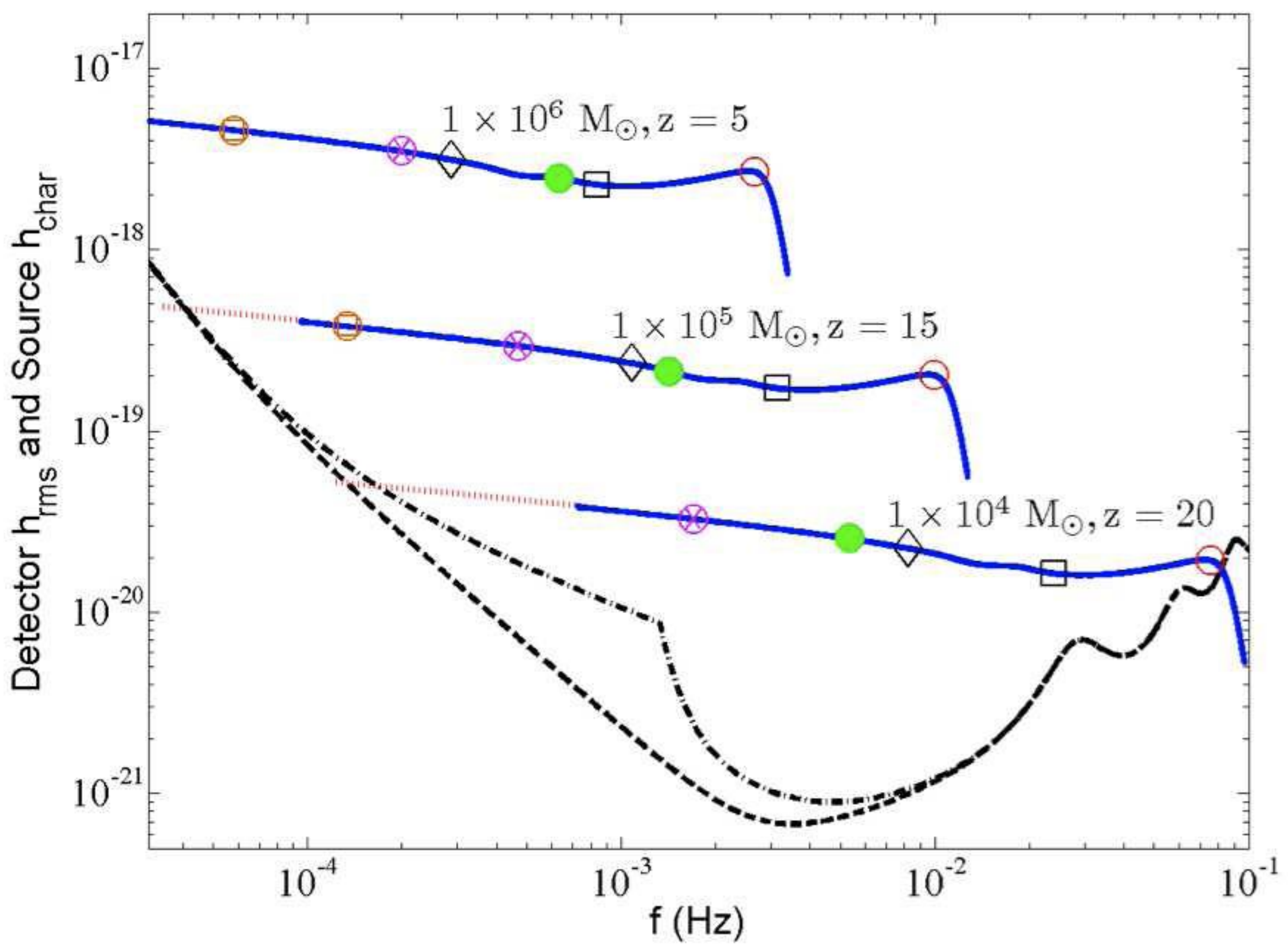
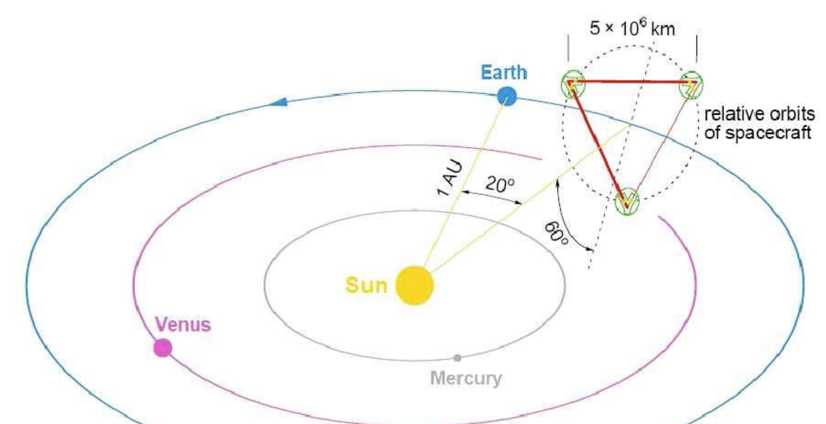



Illustration by Thorne

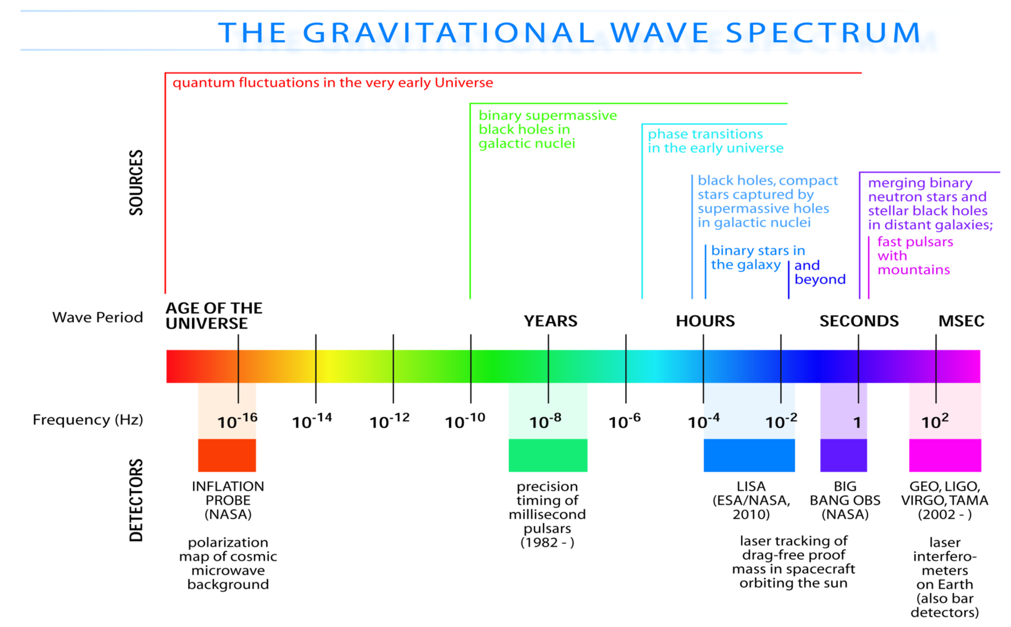
Until recently only the inspiral and ringdown phases have been well understood however thanks to recent advances in numerical relativity the merger phase can now be calculated and the gravitational wave signal predicted. The high computational cost of running merger simulations make it difficult to generate sufficiently long waveforms that cover the entire astrophysically interesting parameter space. A number of groups, including those at Goddard and Maryland, are therefore concentrating on combining numerical and analytical techniques to design quasi-analytical templates to cover the entire inspiral, merger and ringdown for a range of relative masses and spins. Some early results for equal mass, zero spin mergers were used to generate the plot below.



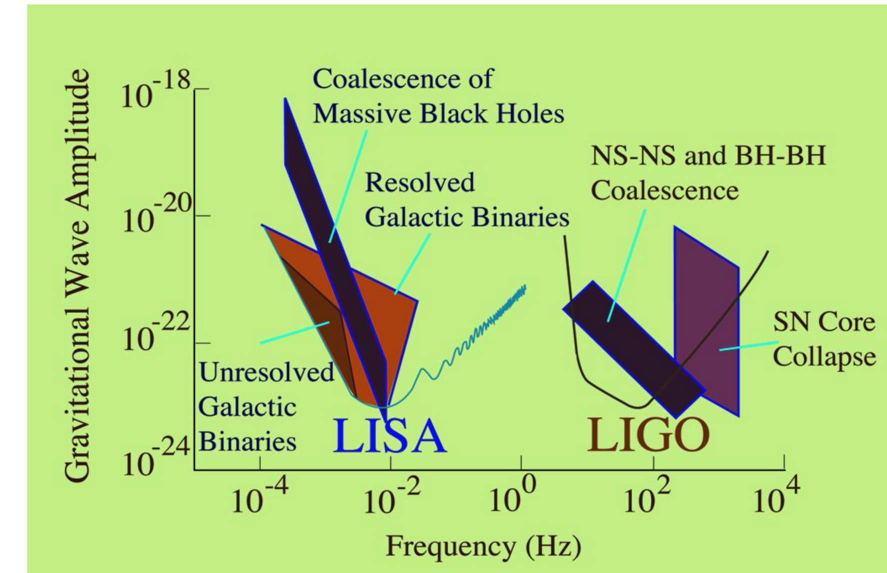

LISA rms noise amplitude $h_{rms}$ from the detector only (dashed) and from the detector combined with the anticipated white dwarf binary confusion (dash-dotted) with the characteristic amplitudes $h_{char}$ of three example sources (solid). The locations on each $h_{char}$ curve corresponding to the peak amplitude (circle), 1 hour before the peak (filled circle), 1 day before the peak (circle with inscribed cross), and 1 month before the peak (circle with inscribed square) in the observer's frame, as well as t = −50M (square) and t = −1000M (diamond) in the source's frame, are as marked. The mass given is the combined rest mass of each black hole. From Baker et al. (2007) gr-qc/0612117v2




LISA is a joint ESA/NASA project to fly three "sciencecraft" carrying proof masses in Keplerian orbits trailing the Earth. Laser interferometers track distance changes between proof masses over the 5 million kilometer baseline.

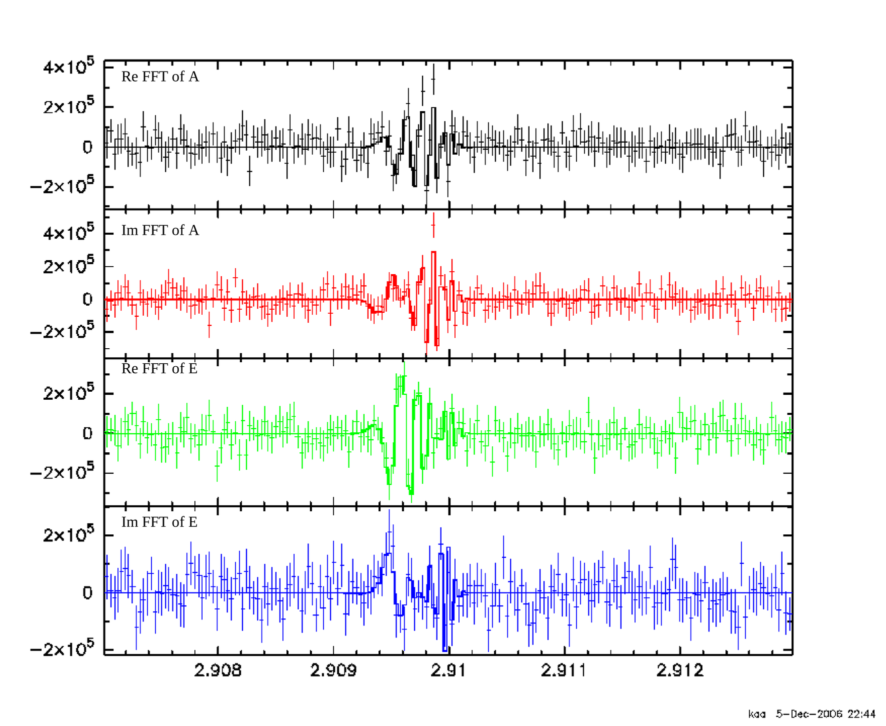


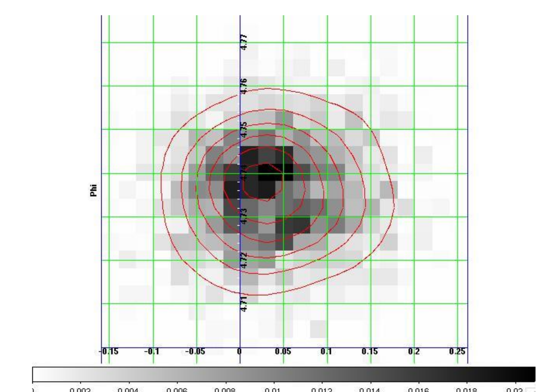

Gravitational wave astronomy potentially covers 20 orders of magnitude in frequency. The higher frequency signals can be measured directly either from the ground or in space. Backgrounds at lower frequencies can be inferred from radio pulsar and cosmic microwave background observations.

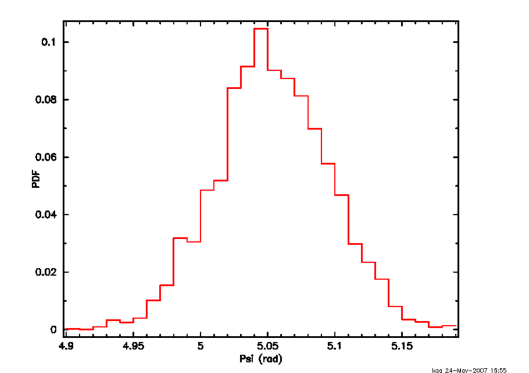



Ground-based interferometers such as LIGO or VIRGO are sensitive to asymmetric collapses in SN and mergers of neutron stars or Solar-mass black holes. LISA will detect interactions of more massive black holes as well as every WD-WD dwarf binary in the Galaxy, most of which will produce an unresolved, confusion background.

A gravitational observatory sees essentially the entire Universe all the time. This has the advantage that any source has near continuous coverage but the disadvantage that the signals from all sources are superimposed. This has been described as the "cocktail party" problem – how to recognize an individual voice in the hubbub. The solution is to use the expected input source waveform and the time-dependent response of LISA. As the spacecraft constellation moves round its orbit the Doppler shifting of the signals varies. Because the plane of the three spacecraft is tilted relative to the ecliptic the amplitude of the detected signal also varies round the orbit. This enables positions of sources to be estimated and sources with similar frequency signals but different positions to be separated.



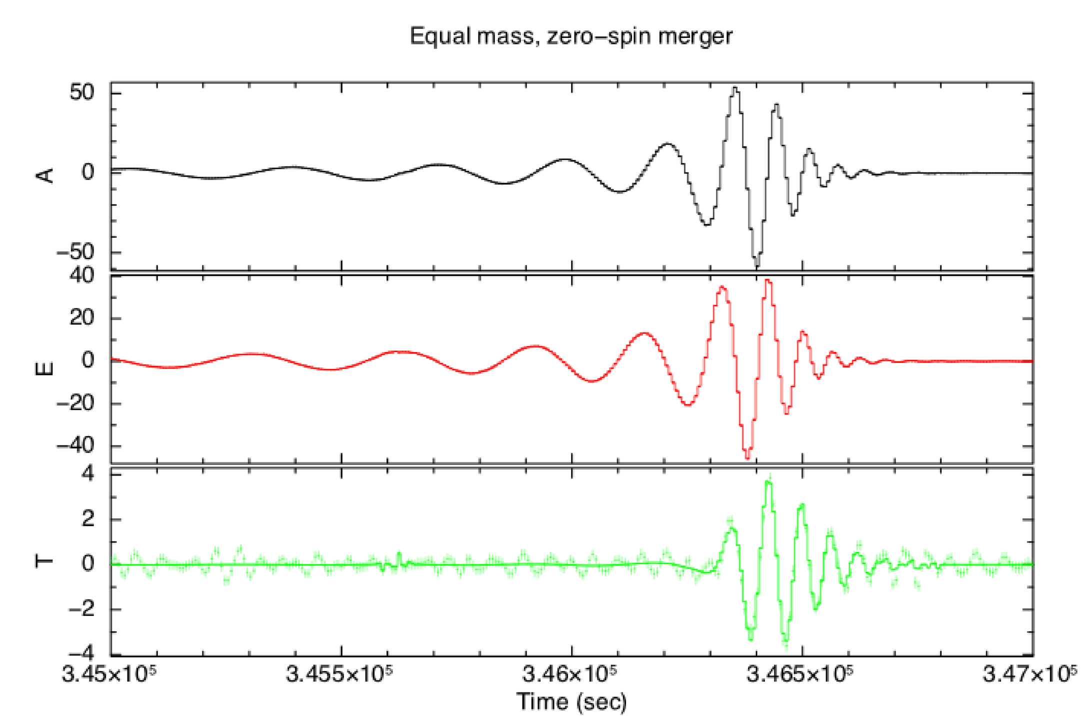


The figures above show a simple example. The input signal is from a Galactic binary assumed to have a constant frequency. LISA produces three independent data streams (for the three pairs of linked spacecraft). These streams can be combined in different ways depending on the signal being searched for. The left-hand figure shows the real and imaginary Fourier transform of two of these combinations which are optimized for this frequency range. The simulated data covers a year and all the structure visible is due to the Doppler and amplitude modulation. This structure can be used to estimate the input parameters as shown in the two figures on the right which are generated from Markov Chain Monte Carlo runs using xspec.

An investigation of the utility of these methods is the aim of the Mock LISA Data Challenge. This is a series of data challenges organized by the LISA Science Team and hosted on the HEASARC servers at Goddard. Successive challenges have got closer to the complete LISA analysis problem. The first series of challenges comprised separate data sets with a few Galactic binaries, the inspiral phase of massive black hole merger, and a model for the inspiral of a Solar-mass black hole around a massive black hole. The Galactic binary data sets were designed to test methods of separating signals with nearby frequencies. The second and third challenges have included a model of the entire Galaxy and test the ability to separate discrete sources out of the confusion. The third round, which will end on November 30th this year adds chirping binaries and bursts.

These challenges require the development of fast models for the LISA response and the ability to perform fits to the data involving tens of thousands of free parameters.

We have been investigating the effect on determining parameters of including the merger phase based on numerical relativity calculations. The work done so far in the Mock LISA Data Challenge and elsewhere has only used the inspiral waveform. Since the merger itself has considerable S/N and high frequency time variability it should provide a significant improvement in parameter estimation. The figure below shows the time series for the merger of two equal mass, zero-spin black holes with a combined mass of $10^6$ Solar masses at a luminosity distance of 10 Gpc. None of the signal shown here has been included in parameter estimation analysis based on the inspiral. The bottom time series, the T channel, is more sensitive to higher frequencies.




Some preliminary results are shown below. The black Run 2 histograms are for inspiral only while the red Run 1 histograms include the merger and ringdown phases. Each case assumed equal mass black holes with a combined mass of 5 x $10^7$ Solar masses at z = 1 with all other parameters randomly generated. The figures show the fractional accuracy of determining the total mass and luminosity distance and the absolute measurement of the position. We will be expanding this to non-equal mass black holes and a wider range of input parameters.