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Bayesian treatment of prospective LISA parameter estimation for massive black hole mergers

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Abstract. A full understanding of LISA's science capability will require accurate models of incident waveform signals and the instrumental response. While Fisher matrix analysis is useful for some estimates, a full Bayesian treatment is needed for important cases at the limit of LISA's capability. We will apply fast analysis algorithms enabling accurate treatment with EOB waveforms and the full-featured LISA response to study the significance of higher spherical harmonics and mergers in LISA analysis.

1. Introduction
A LISA-like space-based gravitational-wave instrument is currently planned as part of the European Space Agency's Cosmic Vision Programme with NASA planning to participate as a minority partner. Programmatically labeled L3, the mission follows two other missions in the large mission category with launch expected in the mid 2030s

A key target of a LISA-like mission will be the direct observation of signals from merging MBHs. Previous studies have shown that despite cosmological distances, $2 < z < 10$ typically, LISA-like mission variants could precisely measure the component MBHs, measuring masses to typically better than 1% and spins within a few %. Distance and sky position measurements are more challenging and more sensitive to design choices and subtle features, thus motivating Bayesian analysis. Among the challenges of this analysis, although details of the waveform response encode important information, studies to date have all left out some features. Computationally the signals cover a large dynamic range with frequencies up to 1 Hz for signals lasting sometimes longer than a year. Bayesian analysis requires millions of likelihood samples demanding very fast codes.

2. Fast and accurate likelihoods
To bring computation times down to milliseconds per likelihood we need fast methods for waveform computation, for the LISA response and for the innerproducts to compare signals. Our implementation begins with a computationally fast Fourier domain reduced order treatment in amplitude/phase form for each of several EOB spherical harmonic modes.

The LISA response includes both modulations $F(t)$ representing the change of orientation of the constellation and delays $d(t)$ representing the motion of the detectors in the wavefront itself, for a signal of the form $s(t) = F(t)h(t + d(t))$. In the Fourier domain this becomes

$$\tilde{s}(f) = \int df' \tilde{h}(f - f')G(f, f').$$

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To improve speed we take advantage of the binary MBH waveform property allowing it to be written as sum of a few components $\tilde{h}_{lm}(f) = A(f)\exp(-i\Psi(f))$, each with gently varying amplitude and phase. Then drawing on local properties of A and Ψ we can factor the signal as $\tilde{s}(f) = T(f)\tilde{h}(f)$ where $T(f)$ provides an excellent approxmation of the convolved result, but can be computed quickly. At leading order, this resembles a stationary phase approximation treatment but the approach is applicable more generally and additional correction terms are also available.

The last component of our fast-likelihood computation is to analytically integrate the signal overlaps as piecewise polynomials between relatively few evaluation points.

3. LISA performance

We apply these methods to study the capability of a 5-year classic LISA instrument to measure nonspinning mergers. Fig. 1 shows the SNR for these mergers. We apply the Multinest/BAMBI nested-sampling code or our own MCMC code to generate posterior distributions for simulated observations with no added noise; see example in Fig. 2. On a set of 10 broadly selected example cases we achieve typical speeds of about $15-20$ ms per likelihood in practice in runs with order 10 million samples each.

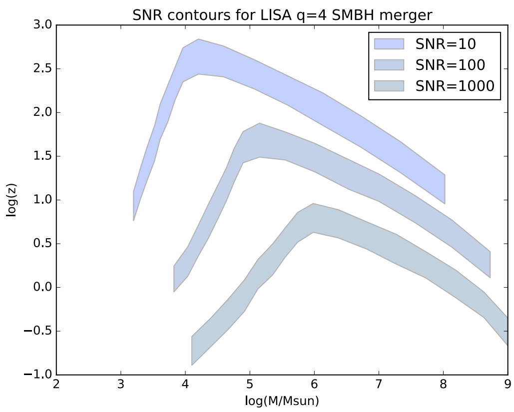

Figure 1. Typical redshifts (log scale) for non-spinning 4:1 mass ratio mergers at various LISA SNRs and total masses. Bands indicate 1-σ logarithmic range over 120 random sets of angle params.

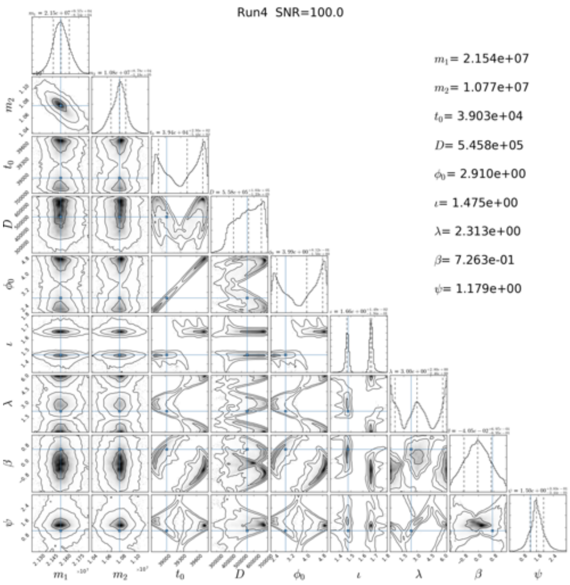

Figure 2. Example of posterior distribution sections over the 9 nonspinning (and non-eccentric) merger parameters.

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