Detecting signal from an extreme mass ratio inspiral

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Signal from Extreme mass ratio inspiral (EMRIs)

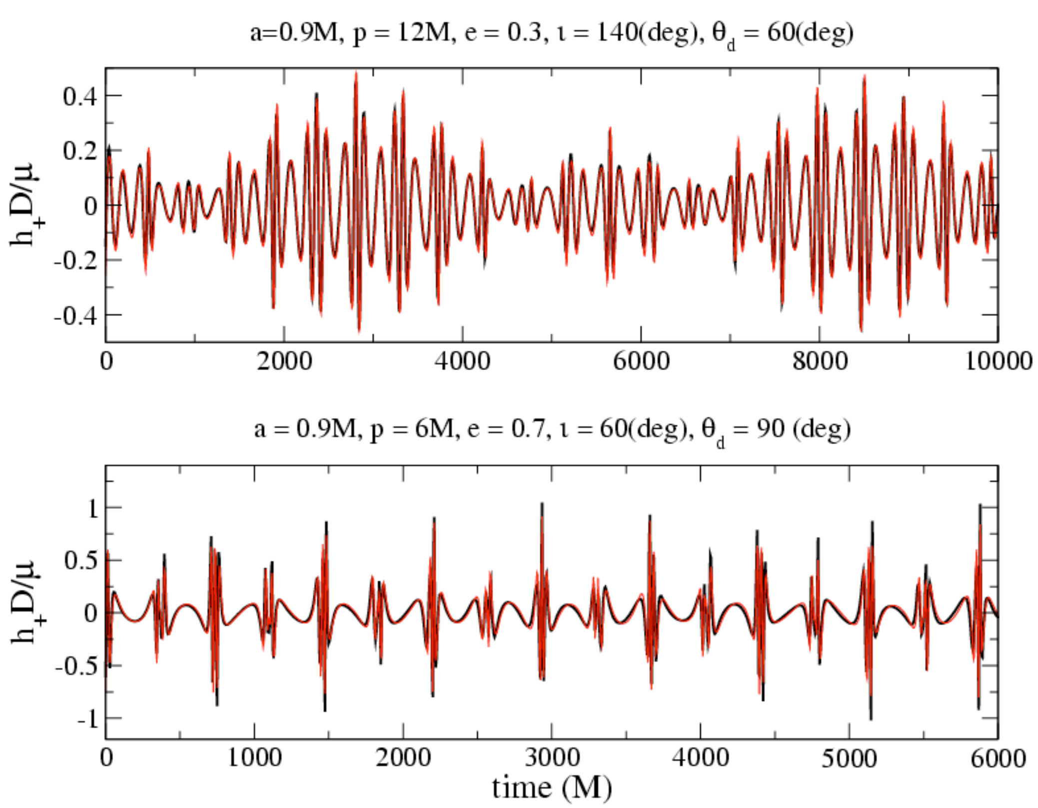
- EMRIs - result of capture of the solar mass objects by massive black hole (MBH) in the galactic nuclei. We expect between 10 and 1000 of such events during the LISA's mission time.

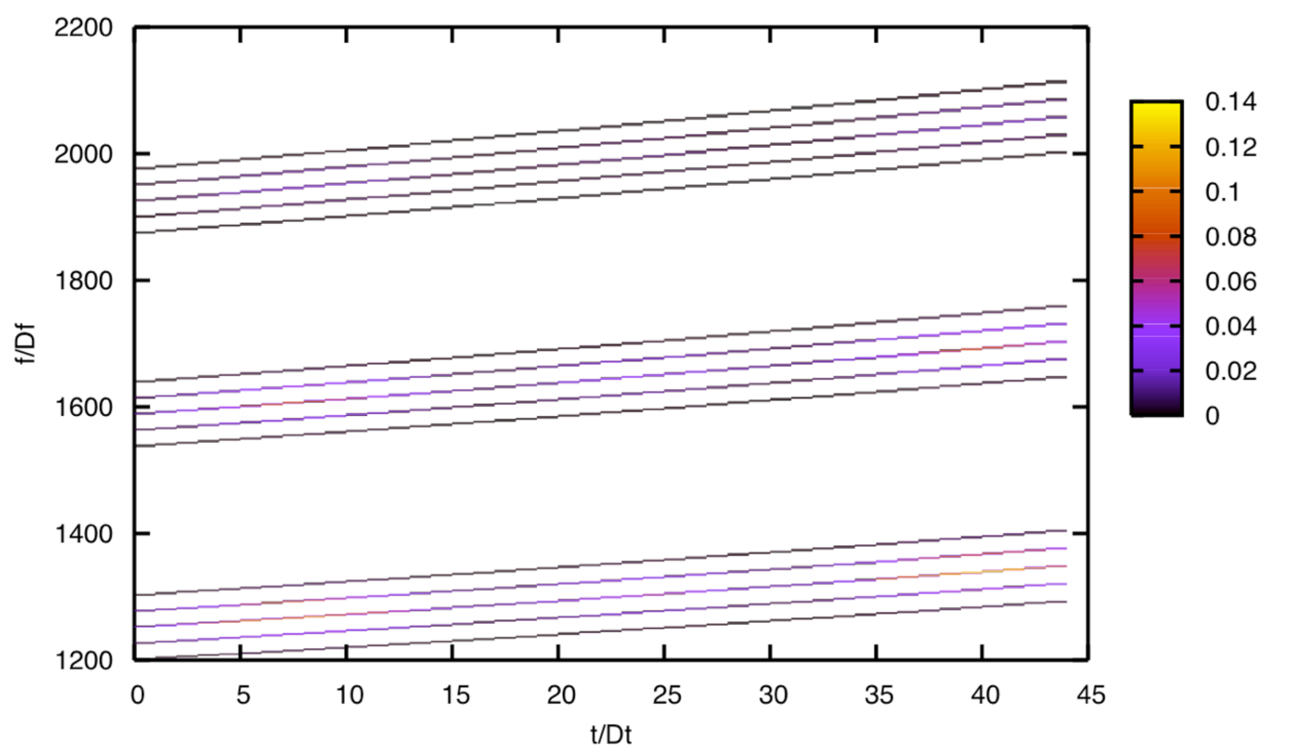
- We expect that the orbit of captured objects (CO) can be both eccentric and inclined (w.r.t. the spin of MBH): this implies three orbital frequencies: $f_\phi,\ f_r,\ f_\theta$, those frequency slowly evolve under radiation reaction $\sim m/M$

- If we fix a source frame with respect to the spin of MBH (static in first order of perturbation), then the signal can be seen as a superposition of the harmonics of three orbital frequencies:

$$h \sim \mu(2\pi M\nu(t))^{2/3} \sum_{l,n,m} A_{l,n,m}(e(t))e^{i(l\phi(t)+n\tilde{\gamma}(t)+m\alpha(t))}$$

The signal in the LISA frame is more complicated: LISA motion brings additional amplitude and phase modulation. Additional complications comes from building TDI data stream (need to cancel the laser noise). We analyze Mock LISA data which uses simplified/phenomenological EMRI signal: n=2, m=[-2,2]. Not all harmonics are equally strong: depends on the eccentricity, inclination and spin orientation.





Search method

- Uniform jumps.

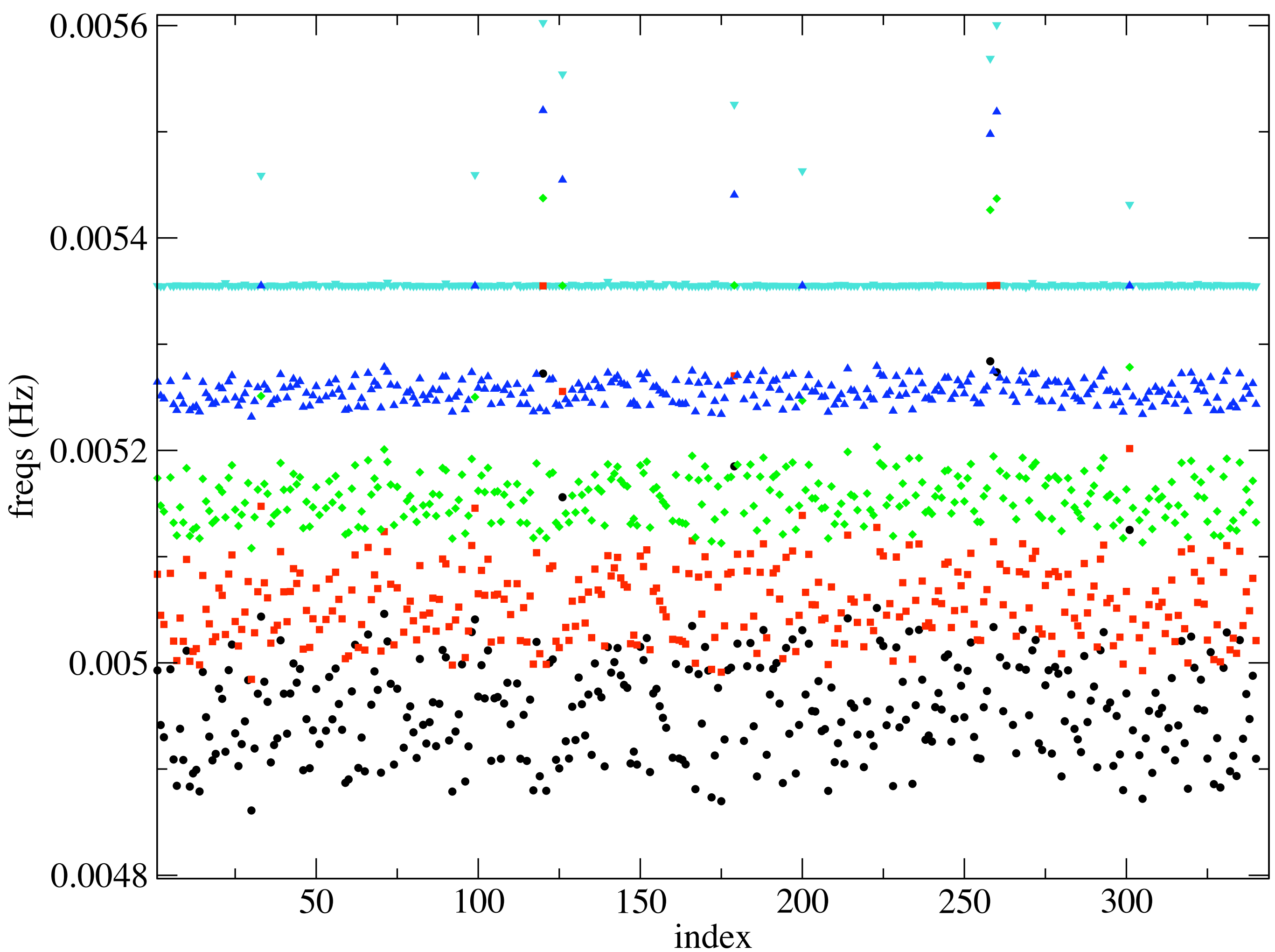
- Template: last half year before the plunge.

- We maximize over plunge time by computing the correlation

- We maximize over initial orbital phases using F-statistic and three dominant harmonics.

- The aim here is to find the signal: find the points near the maxima in likelihood. Similar to random template placement.

- About 50-100 best (high likelihood) points go to the next stage



Results of the first stage search.
We have plotted five harmonics l=2, m=-2...2. The dominant harmonic m=2 found quite well by almost all points. Other harmonics determined not as well. Note that some templates managed to fit m=2 harmonic of the signal with m=1 and m=0.

Search on small segments of data.

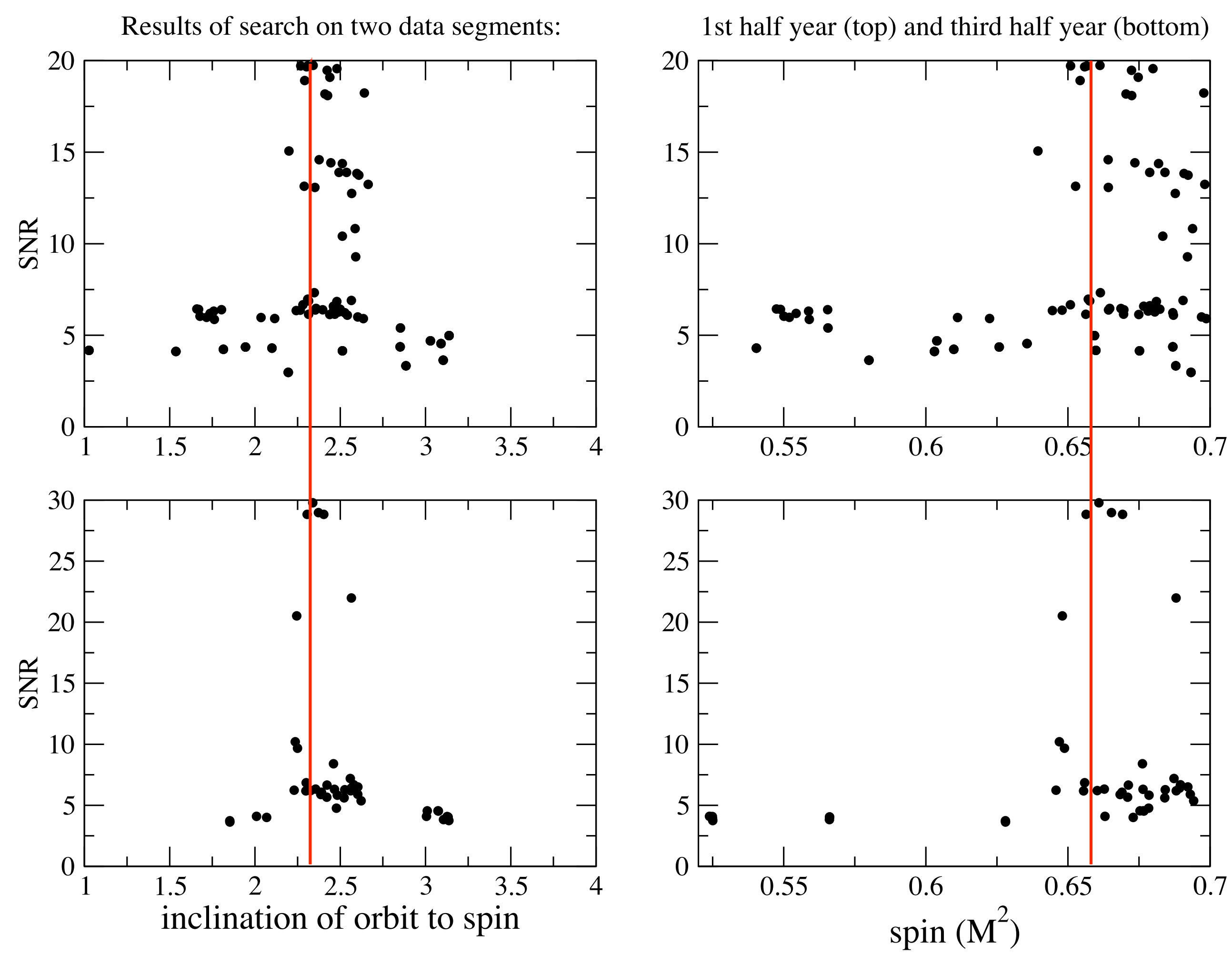
- We split two years of data in 1/2 year segments and search each segment independently. We use MCMC to find the nearest maximum in the likelihood for the points found in the prev. step. Usually those are local/ secondary maxima. Template: 1/2 year long, parametrized by 3 orb. frequencies at some ref. time, use maximization over the initial phases using three dominant harmonics.

- Next we use approximate template: N harmonics which are assumed to be independent (not really true). Use F-stat for each harmonic -> (i) tells us which harmonics were detected (ii) reduces parameter space. Usually chains detect the dominant harmonics.

- If we detected three harmonics we can estimate orbital frequencies at ref. time. using least square fit. The we start chains with orb. freqs fixed to the estimated value until SNR>SNR*.

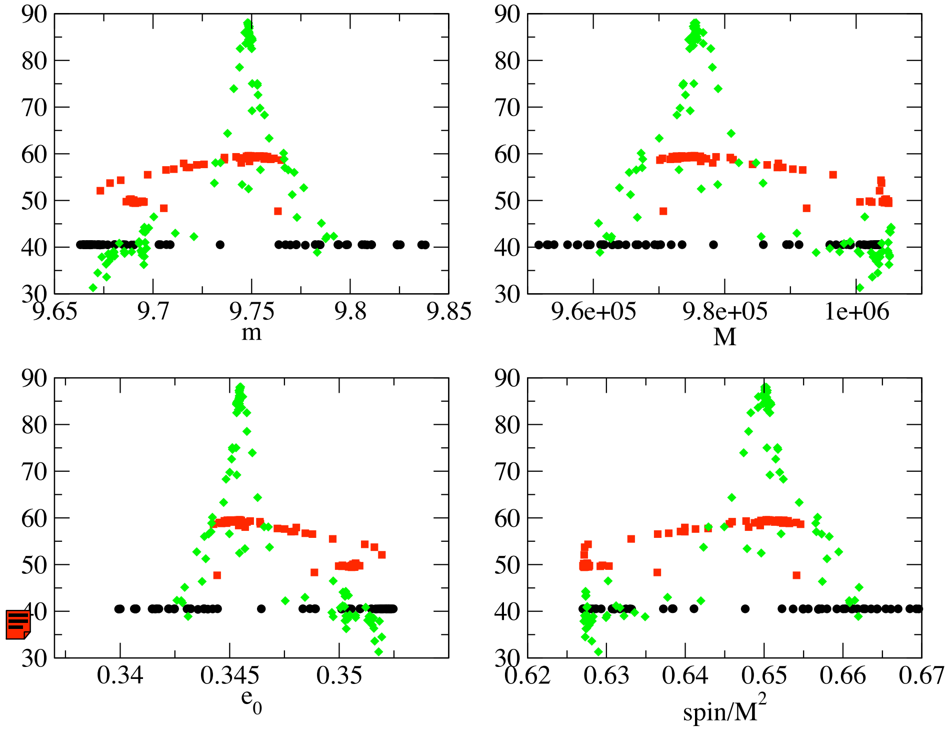
- Iterate the above procedure

The signal is found at different iterations. Min number iterations was 0, max - 3.
Plot on the right shows result of the search on first and third half year segments. Red line is a true value.



Refining parameters

Use result of the previous step and increase duration of the template to one year and then to two years



Improvement of the parameter estimation as we increase duration of the template: 1/2year -> 1 year -> 2 years

Results

TABLE I: Results of the analysis of five data sets used in the challenge1B.3

type[a]	ν (mHz)	$\mu/M_\odot$	$M/M_\odot$	e_0	θ_S	ϕ_S	λ	a/M^2	SNR
True	0.1920421	10.296	9517952	0.21438	1.018	4.910	0.4394	0.69816	120.5
Found	0.1920437	10.288	9520796	0.21411	1.027	4.932	0.4384	0.69823	118.1
True	0.34227777	9.771	5215577	0.20791	1.211	4.6826	1.4358	0.63796	132.9
Found	0.34227742	9.769	5214091	0.20818	1.172	4.6822	1.4364	0.63804	132.8
True	0.3425731	9.697	5219668	0.19927	0.589	0.710	0.9282	0.53326	79.5
Found	0.3425712	9.694	5216925	0.19979	0.573	0.713	0.9298	0.53337	79.7
True	0.8514396	10.105	955795	0.45058	2.551	0.979	1.6707	0.62514	101.6
Found	0.8514390	10.106	955544	0.45053	2.565	1.012	1.6719	0.62534	96.0
True	0.8321840	9.790	1033413	0.42691	2.680	1.088	2.3196	0.65829	55.3
Found	0.8321846	9.787	1034208	0.42701	2.687	1.053	2.3153	0.65770	55.6

[a]The columns are: radial orbital frequency, mass of CO, mass of MBH, eccentricity at $t = 0$, ecliptic co-latitude, ecliptic longitude, inclination angle λ, spin of MBH, SNR with a given template

TABLE II: Results of the blind analysis of two data sets

type	ν (mHz)	$\mu/M_\odot$	$M/M_\odot$	e_0	θ_S	ϕ_S	λ	a/M^2	SNR
True	0.1674472	10.131	10397935	0.25240	2.985	4.894	1.2056	0.65101	52.0
Found	0.1674462	10.111	10375301	0.25419	3.023	4.857	1.2097	0.65148	51.7
True	0.9997627	9.7478	975650	0.360970	1.453	4.95326	0.5110	0.65005	122.9
Found	0.9997626	9.7479	975610	0.360966	1.422	4.95339	0.5113	0.65007	116.0

Summary

- The biggest problem in the EMRI search is numerous widely separated local maxima. The search usually get stack there.

- Our search method is based on using information about the signal encoded in the secondary maxima (frequency of harmonics at some reference time) in order to direct the search to the primary maximum.

- Currently we are applying the same algorithm for weak multiple (5) signals in the stationary instrumental noise.