LISA Data Analysis: Search for EMRIs

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Signal from Extreme mass ratio inspiral (EMRIs)

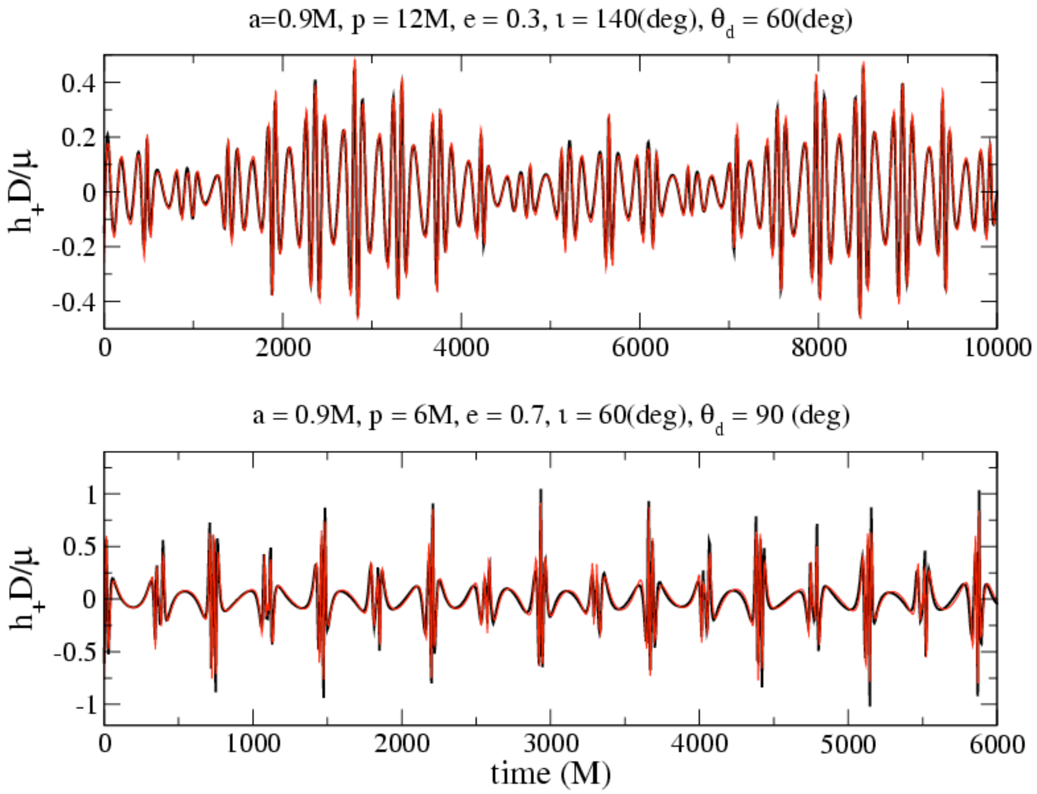
- EMRIs - result of capture of the solar mass objects by massive black hole (MBH) in the galactic nuclei. We expect between 10 and 1000 of such events during the LISA's mission time.

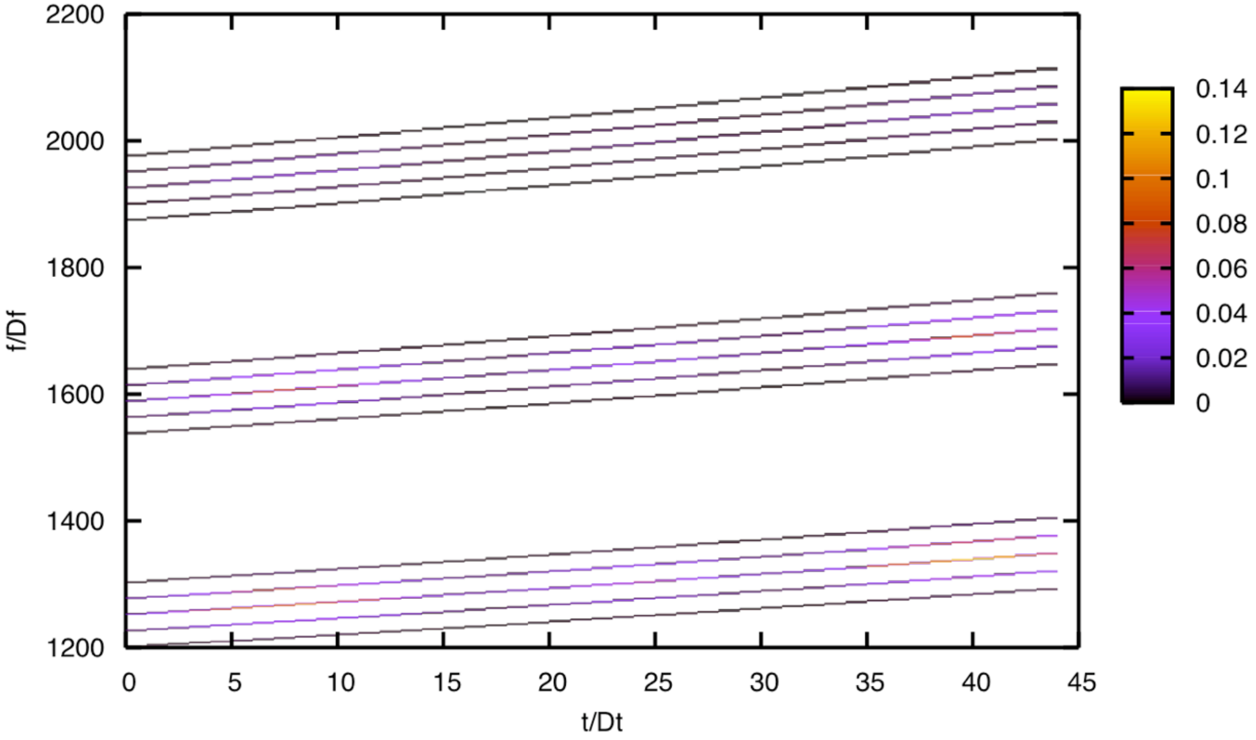
- We expect that the orbit of captured objects (CO) can be both eccentric and inclined (w.r.t. the spin of MBH): this implies three orbital frequencies: $f_\phi, \; f_r, \; f_\theta$, those frequency slowly evolve under radiation reaction $\sim m/M$

- 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:

$$h_{+,\times} \sim \sum_{k,l,m} A_{k,l,m}(t) e^{i(l\Phi_\theta(t) + k\Phi_r(t) + m\Phi_\phi(t))}$$

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: l=2, m=[-2,2]. Not all harmonics are equally strong: depends on the eccentricity, inclination, spin.





Search method

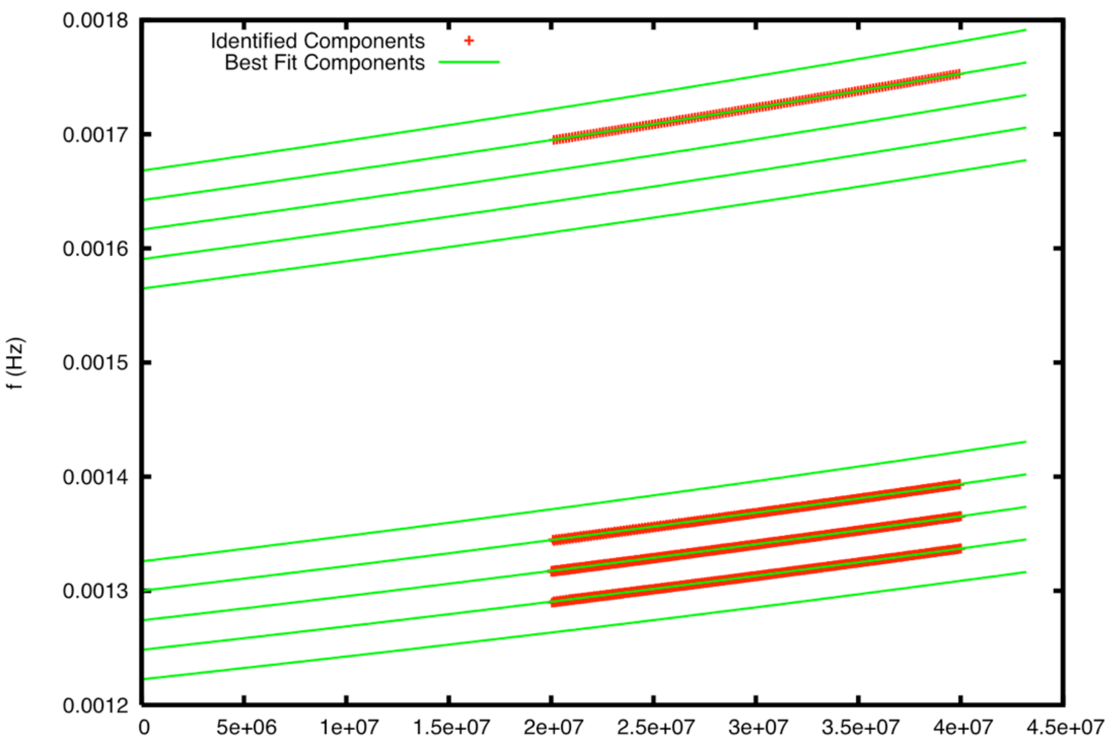
- We have started with detecting strong signals: combined SNR between 50 and 150.

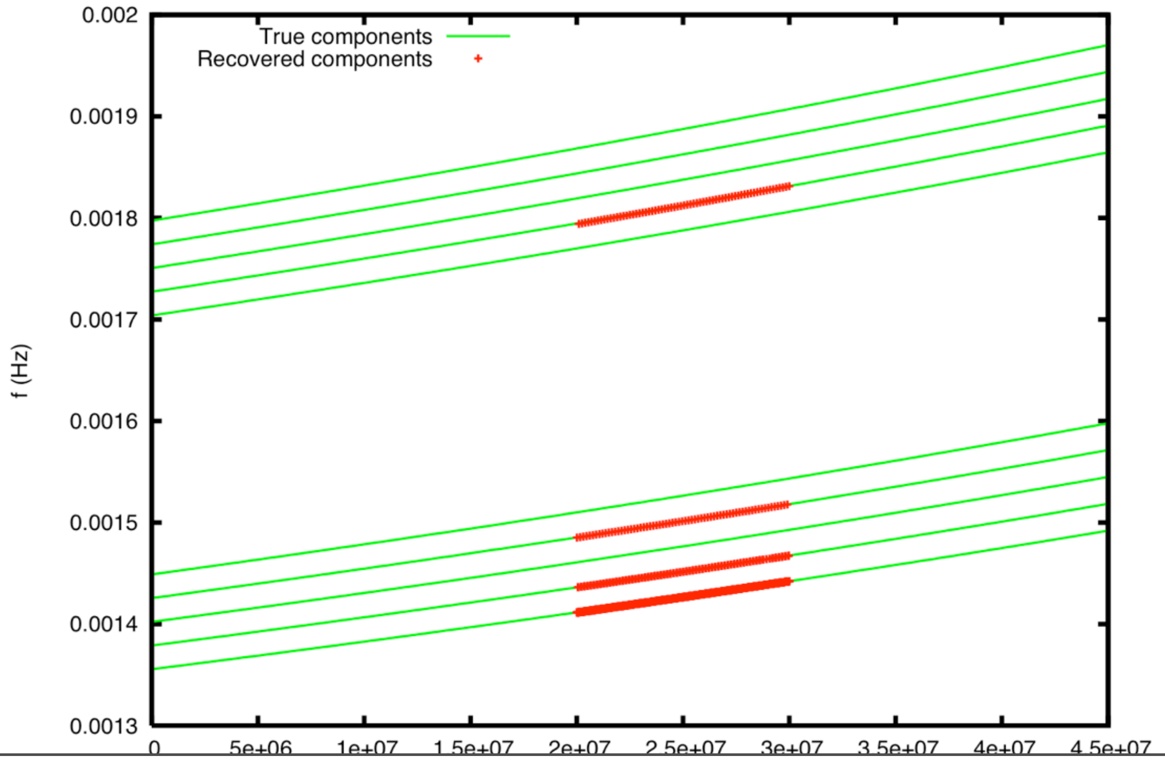
- There are several ways to detect EMRIs: (i) time-frequency (Gair et. al.) (ii) semi-coherent method (iii) harmonic finder with follow up (iv) Metropolis-Hastings stochastic search

$$\mathcal{H} = \frac{\pi(\mathbf{x}_{i+1})\,\mathcal{L}(\mathbf{s}|\mathbf{x}_{i+1})\,q(\mathbf{x}_i|\mathbf{x}_{i+1})}{\pi(\mathbf{x}_i)\,\mathcal{L}(\mathbf{s}|\mathbf{x}_i)\,q(\mathbf{x}_{i+1}|\mathbf{x}_i)}$$

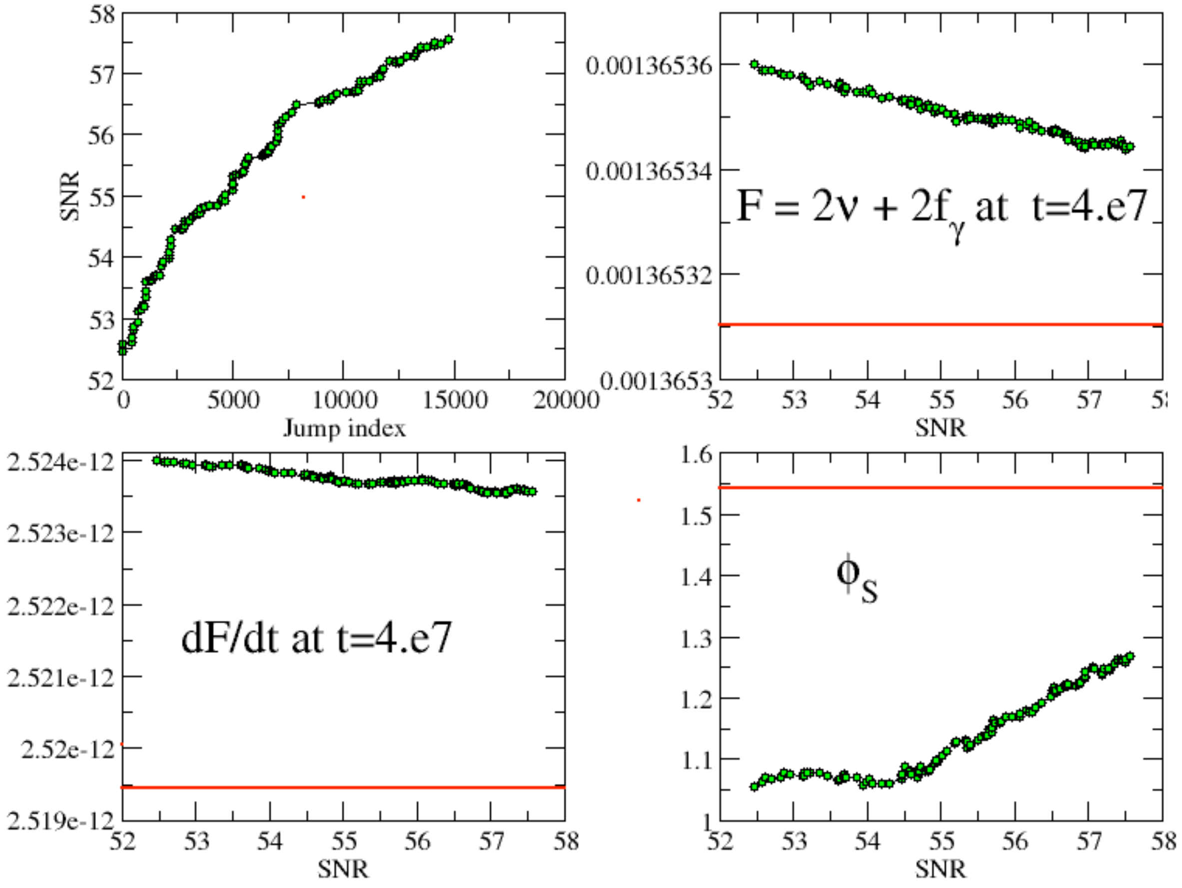
- The main problem is complexity of the likelihood surface: there are a lot of secondary maxima (relatively strong, widely spread and very isolated) -> detecting those signals is usually not very difficult (not for weak signals), but the main problem is to find the global maxima. The key point is that all secondaries share segments of harmonics with true signal

- We use several tricks in our search: simulated annealing, time annealing, multiple proposal distributions (main is jump in the eigen directions of the Fisher matrix). Chains lock onto harmonics quickly -> Run several short chains and use best points found -> Analyze overlap contributed by each harmonic -> Get phase and frequency information





- We run several chains: can get lock on different harmonics. ->
- From the analysis of detected harmonics we have an idea about orbital frequencies at a given time ->
- Use it to run constrained Metropolis-Hastings search (fixing frequencies at $t=t_{best}$) ->
- We get info about initial phases, sky location,.... ->
- Use frequencies at $t=t_{best}$ as new parameters and relax constrain



Source		S/M^2	$m/M_\odot$	$M/(10^6\,M_\odot)$	ν_0(mHz)	e_0	λ
1.3.1	*True*	0.69816	10.296	9.5180	0.19204	0.21438	0.43946
	BBGP	0.63624	10.500	10.359	0.18711	0.15810	0.50800
	MT	0.69860	10.290	9.5042	0.19204	0.21566	0.44581
1.3.2	*True*	0.63796	9.7711	5.2156	0.34228	0.20791	1.4358
	BBGP	0.63971	9.7751	5.2076	0.34223	0.20941	1.4399
	MT	0.61939	9.8353	5.0407	0.35435	0.19771	1.1474
1.3.3	*True*	0.53326	9.6973	5.2197	0.34257	0.19927	0.92822
	BBGP	0.59655	10.193	5.2344	0.34236	0.19647	0.75882
	MT	0.54648	9.5665	4.9231	0.34245	0.24960	0.89575
1.3.4	*True*	0.62514	10.105	0.95580	0.85144	0.45058	1.6707
	BBGP	0.63104	10.085	1.0439	0.79510	0.44077	2.1837
1.3.5	*True*	0.65830	9.7905	1.0334	0.83218	0.42691	2.3196
	BBGP	0.67701	9.8849	0.97872	0.83390	0.42950	2.5092

Summary and future

- We know that the described detection scheme works, but so far we suffered from:

(i) slow waveform generation code (1-2min -> 10-30 sec)
(ii) bugs in implementation
(iii) making unchecked (due to lack of time) assumptions which might not be true
(iv) mess in the search pipeline (had to do fast to meet deadline)

- Improving method by using delayed rejection and/or generalized F-statistic on a short segment

- How robust our method for weak signals?
- How robust our method w.r.t to change of EMRI model?
- How robust our method if there are multiple signals in the data
- How robust our method in presence of the Galactic WD binaries?

Ad: Search for SMBH using stochastic bank

- To search for non-spinning BHs we can use generelized F-statistic: maximize over distance and three Euler angles, time of coalescence can be found by iterations using Fourier transform. Need to search for 4 parameters: masses and sky location.

- Signal with $M > 5 \times 10^6 \ M_\odot$ does not go to very high frequencies so error ellipses on the sky are rather large (likelihood function is shallow) -> we can use flat placements of templates in sky angles.

- We can build bank of templates in $M_1, \ M_2$ using stochastic method: computing overlap of the trial signal with each template in the bank and add the signal to the bank if max. overlap is lower than minimal match. We split parameter space in several sub-regions (with approximately equal number of templates).

- The key point is that we use global properties of the ambiguity function to populate the parameter space