Gravitational wave data analysis in a signal rich environment.

Stas Babak

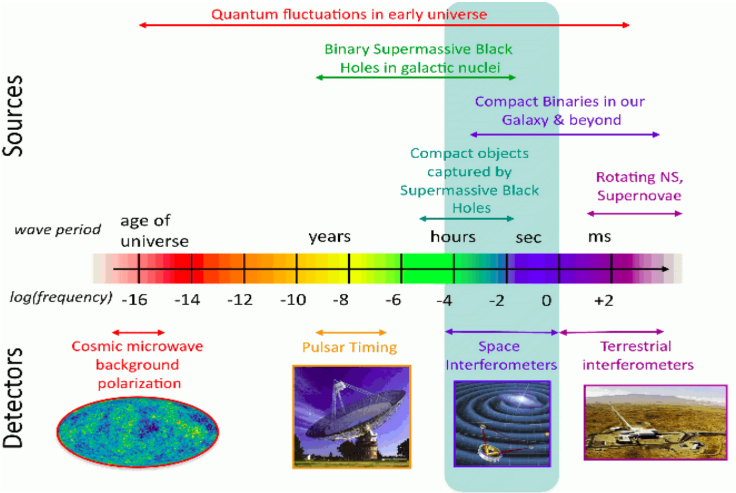
AEI, Golm

12 December, 2014, RAS meeting

GW Observatories

- On the ground: LIGO, GEO600, VIRGO, KAGRA. Main sources: coalescing compact (solar mass) binaries, assymetric fast rotating NS, Supernovae, cosmological GW background. Next generation: ET.
- In space: (e)LISA: three satellites in heliocentric orbit exchanging laser light. Main sources: merging massive black hole (MBH) binaries, white dwarf binaries in our Galaxy, Extreme mass ratio inspirals (EMRIs), cosmological GW background
- Pulsar timing array: millisecond pulsars as ultra-stable clocks. Main sources: GW background from cosmic strings and from multiple wide MBH binaries in the local Universe.

GW Observatories



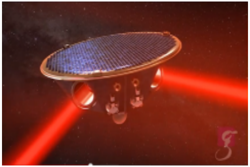
Detecting GW in space: eLISA

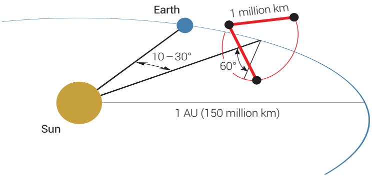
eLISA (evolving Laser Interferometer Space Antenna) is a project (replaced LISA) proposed to ESA for L1 launch (JUICE was chosen) and scheduled for L3 slot (2034) see arXiv:1305.5720 or http://www.elisascience.org/.

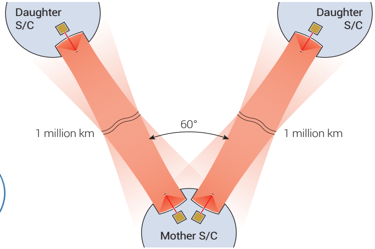
References:

white paper: arXiv:1305.5720, Yellow book: arXiv:1202.0839, arXiv:1201.3621

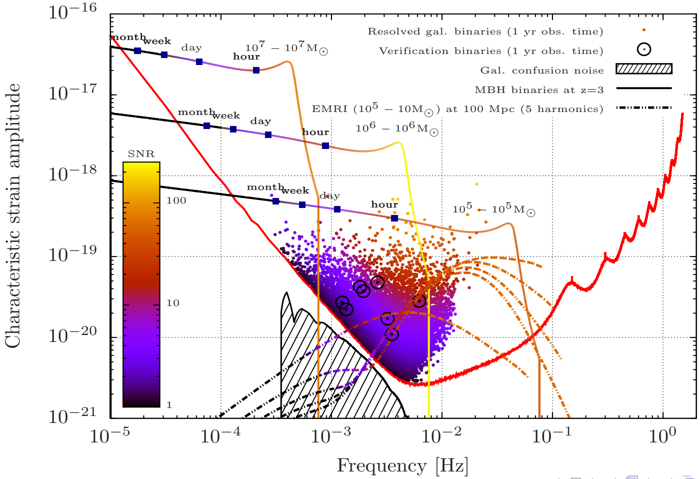
Detecting GW in space: eLISA



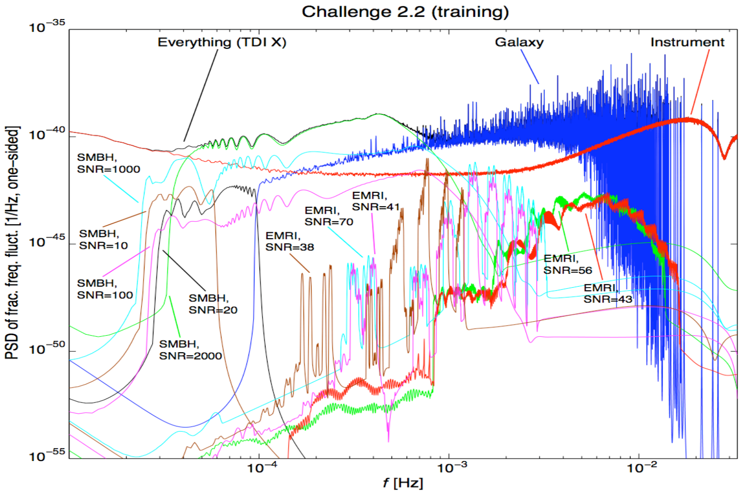




eLISA sensitivity and GW signals

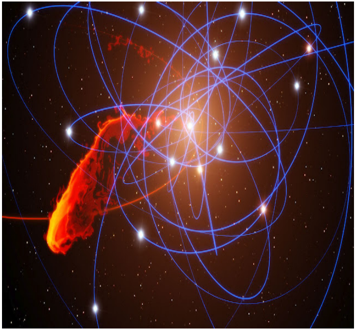


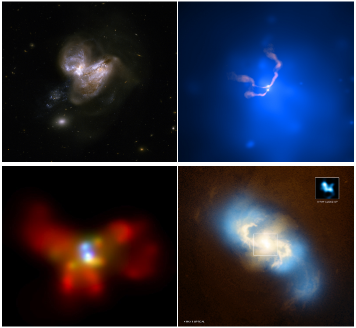
Simulated data: Mock LISA Data Challenge



Massive Black Hole (MBH) binaries

There are many convincing evidences for existence of MBH is the nuclei of almost every galaxy.

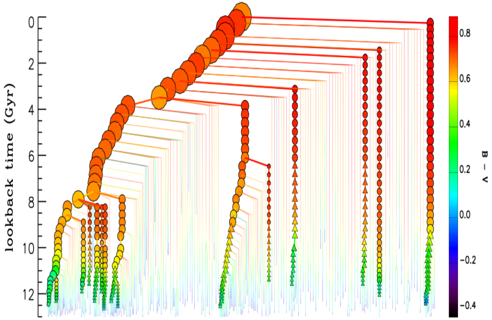




(MPG, ESO, NASA)

Massive Black Hole (MBH) binaries

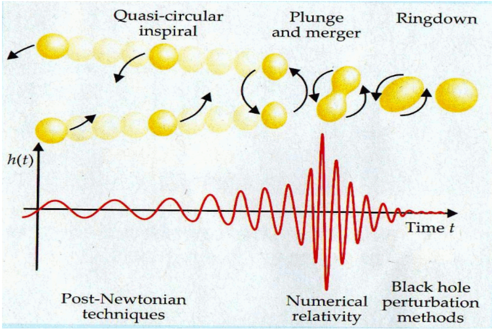
The main model assumes that MBH are formed starting from small ($10^2 - 10^3\ M_\odot$) or large ($10^4 - 10^5\ M_\odot$) seeds by accreting gas and by mergers during the cosmic history.



(M. Volonteri)

MBH: GW signal

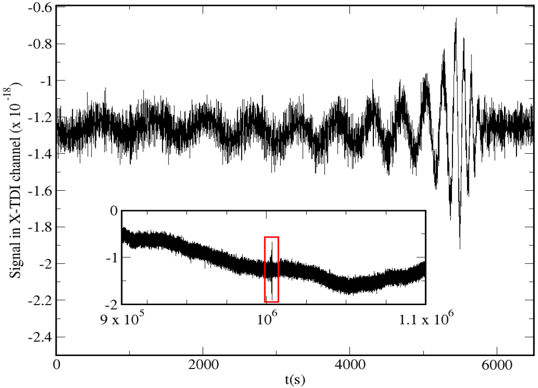
The GW signal from MBH binary can be conventionally split into inspiral, merger and ring-down



(Baumgarte and Shapiro 2011)

MBH: GW signal

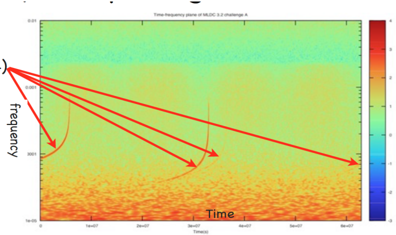
GW signal from MBH binary ($m_1/m_2 = 2, (1+z)(m_1+m_2) = 2 \times 10^6 M_\odot, a_1 = 0.6, a_2 = 0.55, z = 5$) in the simulated eLISA data.

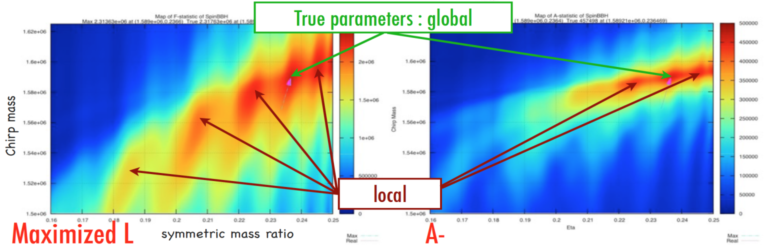


MLDC: spinning, precessing MBH binaries

By plotting spectrogram (time-frequency map) we can clearly see 3(4) signals

Petiteau, Babak, Shang Yu, CQG 2009, PRD 2010.





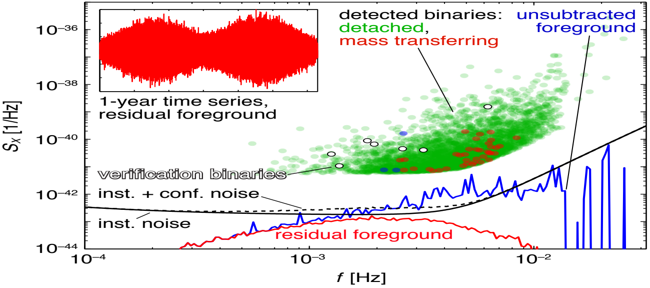
MLDC: spinning, precessing MBH binaries

DA methods: parallel tempering MCMC, Genetic Algorithm.
Genetic Algorithm: stochastic optimisation method based on the natural selection principles: Selection, Breeding, Mutation (+ customized accelerators)

Source	mode	$\Delta M_c/M_c$ $\times 10^{-5}$	$\Delta\eta/\eta$ $\times 10^{-4}$	Δt_c (sec)	Δ Sky (deg)	Δa_1 $\times 10^{-3}$	Δa_2 $\times 10^{-3}$	$\Delta D/D$ $\times 10^{-3}$	$\Delta\hat{S}_1$ (deg)	$\Delta\hat{S}_2$ (deg)	$\Delta\hat{L}$ (deg)	$\Delta\phi_c$ $\times 10^{-2}$	$\mathcal{O}$	$\mathcal{F}_{Full}$
	True	1.3	4.4	6.1	1.18	2.7	6.2	6.2	8.30	6.06	1.07	7.5	1.0	1387732
srcMC1	A	10.1	9.2	25.7	1.92	0.7	44.3	13.1	64.39	79.59	84.02	259.6	0.999870	1387772
MBH-1	B, C	13.5	8.6	24.6	8.04	6.7	28.9	22.4	9.39	15.70	7.70	14.7	0.999944	1387946
		10.8	6.3	24.2	7.04	7.1	21.8	20.8	48.18	19.07	6.20	40.6	0.999952	1387914
	True	4.3	7.2	9.1	0.82	2.9	5.3	7.2	1.52	3.29	0.95	2.9	1.0	355588
srcMC2	A	13.6	4.8	29.0	1.33	2.8	28.3	19.8	104.65	55.92	138.55	4.1	0.999939	355755
MBH-3	B	11.0	92.5	154.6	176.51	24.1	3.5	24.7	55.37	54.86	81.31	135.7	0.999827	355769
	C	15.6	44.6	158.9	169.3	52.4	15.0	66.1	16.49	64.82	14.68	25.0	0.997845	354301
	True	10.1	55.3	26.7	0.47	29.2	151.4	138.7	22.90	65.30	16.17	102.2	1.0	12814.2
srcMC3	A, B, C	9.2	139.0	40.5	0.34	55.9	390.1	181.3	159.55	74.93	63.38	7.3	0.999311	12834.4
MBH-4		17.7	8.5	234.0	179.48	96.5	506.7	319.6	60.55	87.22	42.61	413.2	0.998723	12818.8

Galactic white dwarf binaries

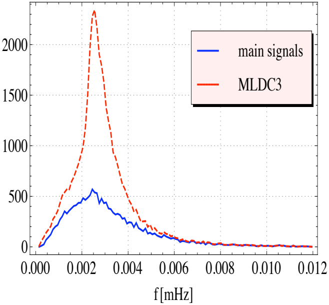
We expect $10^6 - 10^7$ Galactic binaries in the (e)LISA band, majority are below the noise level. Binaries are (i) detached (ii) interacting. The population of binaries will form GW foreground. There are binaries observed in e/m $\rightarrow$ verification binaries

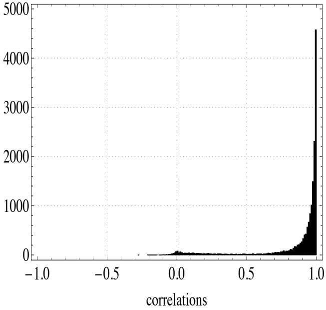


MLDC: Galactic WD binaries

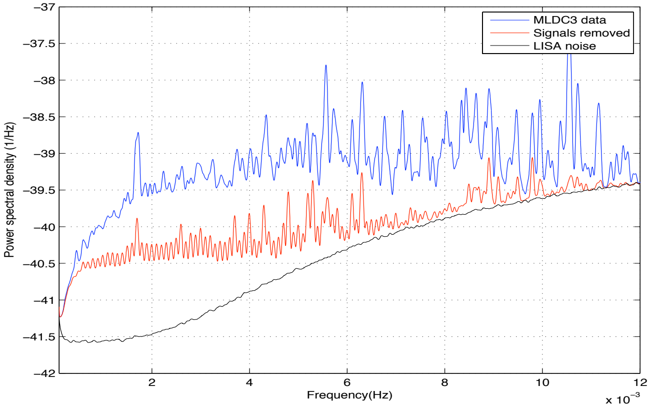
- Found and subtracted $\approx$ 24000 binaries in simulated LISA data (factor 7 less expected in eLISA).
- The search method: template bank search in 4-D (sky location, frequency and frequency derivative). The iterative method: find the brightest/loudest signal, estimate parameters, subtract, repeat analysis. Works well for high frequency source not well at low/intermediate

MLDC: Galactic WD binaries





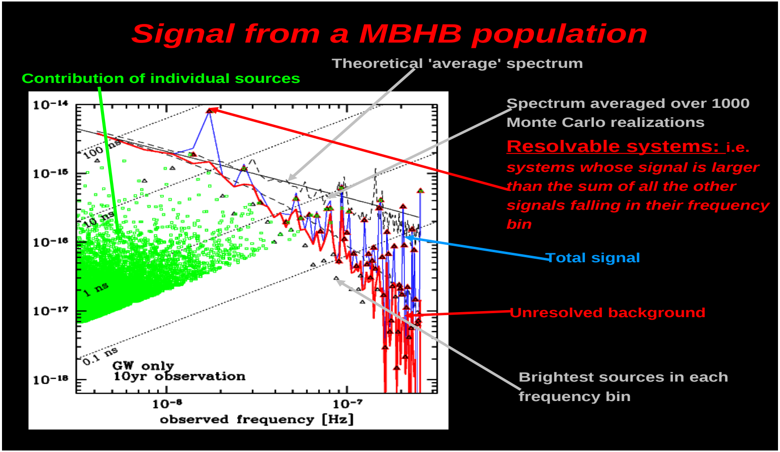
MLDC: Galactic WD binaries



PTA in SKA era

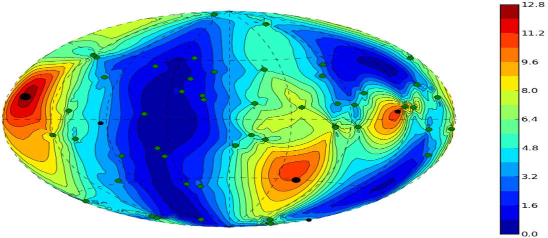
Detecting GWs with PTA (see talk by Lindley Lentati).

In SKA era (after about 10 years of data collecting) we could get into DA problem similar to Galactic WD binaries in (e)LISA.

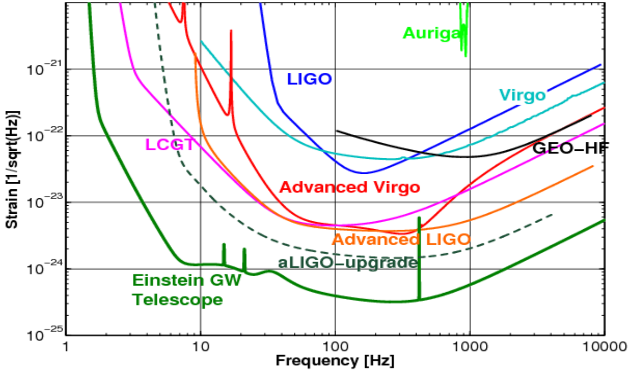


PTA: simulated data

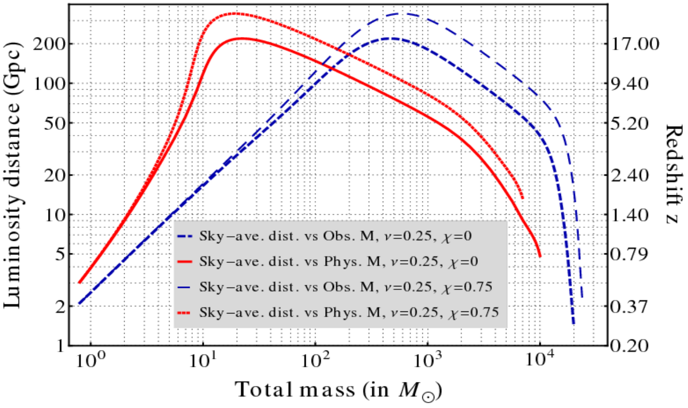
Example of the sky map (high frequency of PTA band).



3rd generation of GW detectors on the ground: ET

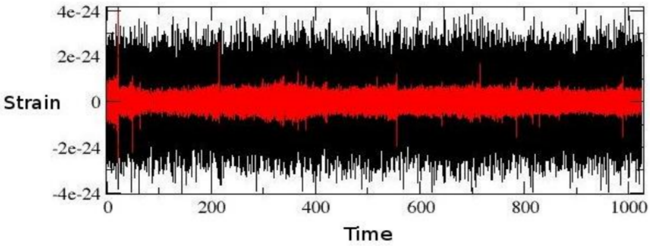


3rd generation of GW detectors on the ground: ET



3rd generation of GW detectors on the ground: ET

expects to have $10^5 - 10^6$ NS binaries per year. The signal become long lasting (week with 1000 overlapping signals). Mock data challenge, LIGO-VIRGO pipeline was used to search for BNSs: 2419200 s. of data, 36774 events found out of 177350 simulated with 2.3% FAP



ET

Conclusion

- In about 20 years time we expect to have GW observatories operating in the signal dominated regime across the whole frequency range (IPTA, eLISA, ET)
- If/when the signals are strong/loud ($SNR \geq 20 - 100$), the "detection" means identification of the number of signals and accurate estimation of signal parameters
- The biggest problem is a signal confusion (global fit) and transition from the "resolvable" signals to "unresolvable" (noise-like) GW foreground.