JC^2, 22nd Edition, 12-14 October 2022

Gravitational wave cosmology with LISA

Danny Laghi

Laboratoire des 2 Infinis - Toulouse (L2IT-IN2P3), Université de Toulouse, CNRS, UPS, F-31062 Toulouse Cedex 9, France

CNES Post-Doctoral Fellow (since March 2022)

e-mail: `danny.laghi@l2it.in2p3.fr`

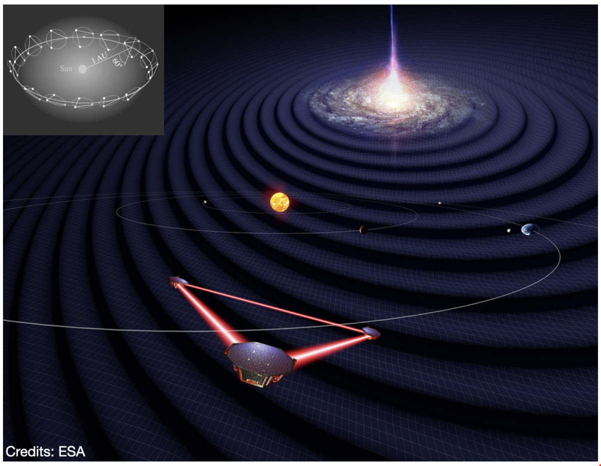
Keywords: LISA space mission, black holes, gravitational waves, cosmological parameters, Bayesian data analysis

1. OBJECTIVE

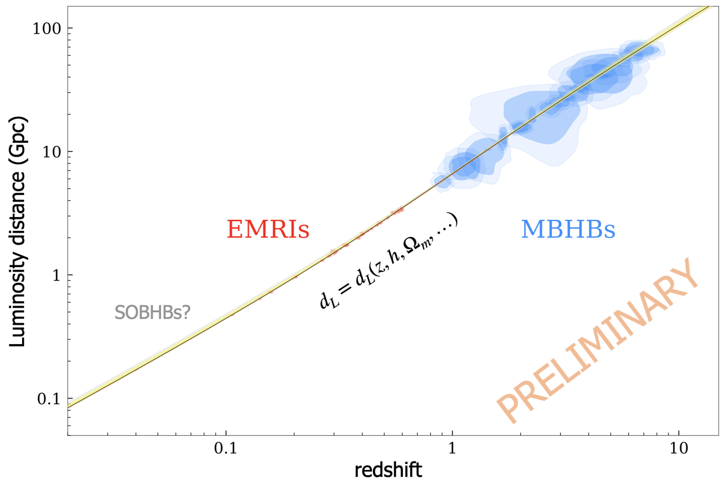
Gravitational waves (GWs) are dynamical perturbations of space-time that propagate at the speed of light away from their source. Extreme astrophysical phenomena, like the merger of a massive black hole binary (MBHB) made of two $10^6\,M_\odot$ black holes, or the inspiral and plunge of a $10\,M_\odot$ black hole into a massive black hole, also called extreme mass-ratio inspiral (EMRI), produce GWs in the mHz frequency range.

LISA (*Laser Interferometer Space Antenna*) is a future space-based GW detector that will be capable of observing GW signals emitted by systems like MBHBs and EMRIs. LISA consists of three spacecraft **(illustration on the right)**, put in a near-equilateral triangular formation, that act as an interferometer with an arm length, or *baseline*, of 2.5×10^6 km. The entire constellation will be placed in an Earth-trailing heliocentric orbit, with the plane of the triangle inclined by 60° with respect to the ecliptic. The spacecraft at the corners house interferometry equipment for measuring *changes* in the baselines, which are caused by the passage of GWs: this is how LISA can detect GW signals. The LISA mission has been selected by the European Space Agency for the L3 slot of its *Cosmic Vision* program, with launch expected in 2034. One of the Science Objectives of the LISA mission is to probe the rate of expansion of the Universe using GW sources at high redshifts.

This CNES postdoctoral project will deliver the first accurate and reliable assessment of the scientific potential of LISA to constrain cosmological parameters through joint GW and electromagnetic observations.



2. METHOD



In order to measure the expansion rate of the Universe with GWs, we first need to know the luminosity distance and the redshift of their sources.

EMRIs and MBHBs are examples of *standard sirens*, meaning that observing their GWs we can directly measure their luminosity distance, without the need of any distance scale ladder [1]. However, GWs do not contain information about the redshift of their source. There exist different strategies to extract this information depending on the class of standard sirens. MBHBs are *bright sirens*, which means that during the GW emission they are likely to emit electromagnetic signals that can be observed with telescopes, giving us their redshift directly. EMRIs are instead *dark sirens*, because they are not expected to produce any electromagnetic counterpart. In this case, we can retrieve the redshift by statistically cross-matching the EMRI 3-dimensional localisation volume, which is measured by LISA, with a galaxy catalog. Stellar-origin black hole binaries (SOBHBs), like the $50 - 100\,M_\odot$ systems observed at ~100 Hz by the LIGO-VIRGO GW observatories, are also dark sirens: the possibility of observing them with LISA is currently under study.

With the luminosity distances and redshifts at hand, LISA standard sirens can be easily displayed in a Hubble diagram **(figure on the left)**. We can then make use of mathematical relations, prescribed by a cosmological model, to fit the observed data and measure the expansion rate of the Universe, a.k.a. the Hubble constant.

3. DELIVERABLES

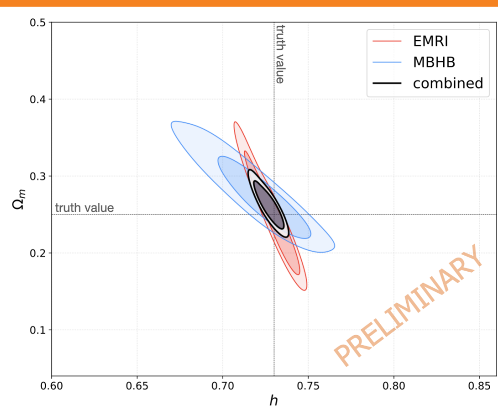
We are interested in the *posterior* probability density function for the cosmological parameters $\Omega = \{h, \Omega_m\}$, defined by the dimensionless Hubble constant $h = H_0/100\,\mathrm{km}^{-1}$ s Mpc and the dimensionless Universe density matter parameter Ω_m. The posterior is given by Bayes' theorem:

$$p(\Omega\,|\,D\,\mathcal{H}\,I) = p(\Omega\,|\,\mathcal{H}\,I)\,\frac{p(D\,|\,\Omega\,\mathcal{H}\,I)}{p(D\,|\,\mathcal{H}\,I)}\,,$$

where $\mathcal{H}$ is a cosmological model for our Universe, I represents all the relevant background information, while $D \equiv \{D_1, \ldots, D_N\}$ is the set of GW observations made by LISA during its mission lifetime.

The **figure on the right** illustrates what constraints could be placed in the h-Ω_m parameter space by LISA over 10 years of observation. The plot shows posterior iso-probability contours (50-90% CR) obtained assuming a flat Friedmann-Lemaître-Robertson-Walker cosmological model. Importantly, we can see that the *combination* of bright and dark siren observations significantly improves the parameter estimation, leading to ~1% and ~15% accuracy (90% CI) for h and Ω_m, respectively.

The statistical data analysis framework is provided by `cosmolisa` [2, 3], a code for cosmological parameter estimation that will be fully developed in this project.



4. References

[1] Schutz B. F., *Nature* **323**, 310 (1986).

[2] Del Pozzo W., Laghi D., `https://github.com/wdpozzo/cosmolisa`.

[3] Laghi D., Tamanini N., Del Pozzo W., Sesana A., Gair J., and Babak S., *Mon. Not. Roy. Astron. Soc.* **508**, 3 (2021) 4512.