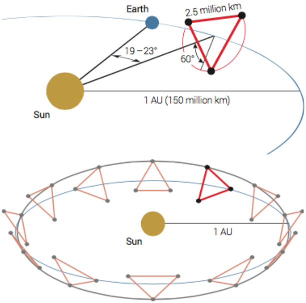
Cosmology with LISA: massive black hole binary mergers as standard sirens

Nicola Tamanini

IPhT CEA Saclay
&
APC Univ. Paris Diderot

The LISA mission



[elisascience.org]

Laser Interferometric Space Antenna

Proposed design: [arXiv:1702.00786]

- Near-equilateral triangular formation orbiting around the Sun
- 6 laser links (3 active arms)
- Armlength: 2.5 million km
- Mission duration: ≥ 4 years

Main target sources:

- MBHBs: $10^4 - 10^7\ M_\odot$
- Stellar mass BHBs: $10 - 100\ M_\odot$
- Stochastic background: astrophysical & cosmological origin
- Extreme mass ratio inspirals (EMRIs)

The concept of standard sirens

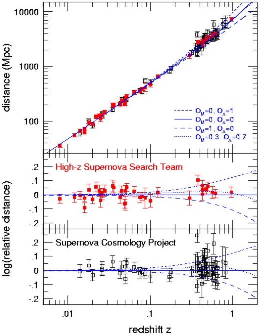
The luminosity distance can be inferred directly from the measured waveform: GW sources are standard distance indicator!

$$h_\times = \frac{4}{d_L}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}}\cos\iota\,\sin[\Phi(t)]$$

If the redshift of the source is known, then one can fit the distance-redshift relation:

$$d_L(z) = \frac{c}{H_0}\frac{1+z}{\sqrt{\Omega_k}}\sinh\left[\sqrt{\Omega_k}\int_0^z \frac{H_0}{H(z')}dz'\right]$$

- Exactly as SNIa $\Rightarrow$ standard sirens
- Need an EM counterpart to measure the redshift!



The concept of standard sirens

With EM waves:

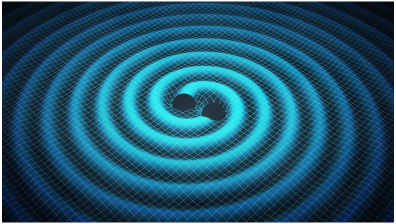
- Measuring redshift is easy: compare EM spectra
- Measuring distance is hard: need objects of known luminosity (SNIa $\rightarrow$ **standard candles**)

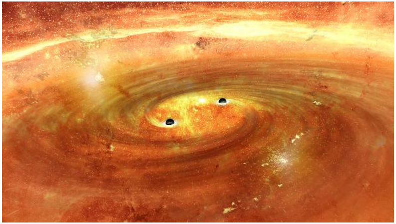
With GW:

- Measuring distance is easy: directly from the waveform (**standard sirens**)
- Measuring redshift is hard:
  - Degeneracy with masses in the waveform (GR is scale-free)
  - Need to identify an **EM counterpart**:
    - Optical, Radio, X-rays, γ-rays, ...
  - Need good sky location accuracy from GW detection to pinpoint the source or its hosting galaxy

Standard sirens for LISA

- How many **standard sirens** will be detected by LISA?





- What type of sources can be used?
- For how many it will be possible to observe a counterpart?

Standard sirens for LISA

Possible standard sirens sources for LISA:

- MBHBs ($10^4 - 10^7\ M_\odot$)
- LIGO-like BHBs ($10 - 100\ M_\odot$)
- EMRIs

Standard sirens for LISA

Possible standard sirens sources for LISA:

- MBHBs ($10^4 - 10^7\ M_\odot$)
- LIGO-like BHBs ($10 - 100\ M_\odot$)
- EMRIs

Advantages of MBHB mergers:

- High SNR
- High redshifts (up to ∼10-15)
- Merger within LISA band ↴
- Gas rich environment → *EM counterparts!*

LISA cosmological forecasts: data simulation approach

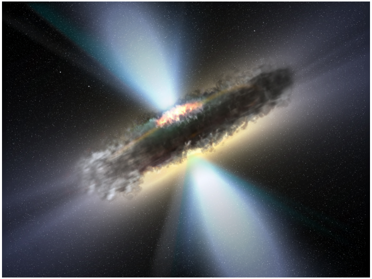
To obtain cosmological forecasts, we have adopted the following **realistic strategy**:

[NT, Caprini, Barausse, Sesana, Klein, Petiteau, arXiv:1601.07112]

- Start from simulating MBHBs merger events using **3 different astrophysical models** [arXiv:1511.05581]
  - Light seeds formation (popIII)
  - Heavy seeds formation (with delay)
  - Heavy seeds formation (without delay)
- Compute for how many of these a GW signal will be **detected by LISA** (SNR>8)
- Among these select the ones with a **good sky location accuracy** ($\Delta\Omega < 10\,\mathrm{deg}^2$)
- Focus on **5 years** LISA mission (the longer the better for cosmology)

LISA cosmological forecasts: data simulation approach

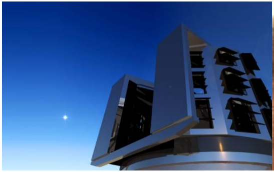
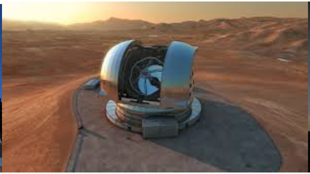
- **To model the counterpart** we generally consider two mechanisms of EM emission at merger: (based on [arXiv:1005.1067])
  - A quasar-like luminosity **flare** (optical)
  - Magnetic field induced **flare** and **jet** (radio)
- Magnitude of EM emission computed using data from simulations of MBHBs and galactic evolution



LISA cosmological forecasts: data simulation approach

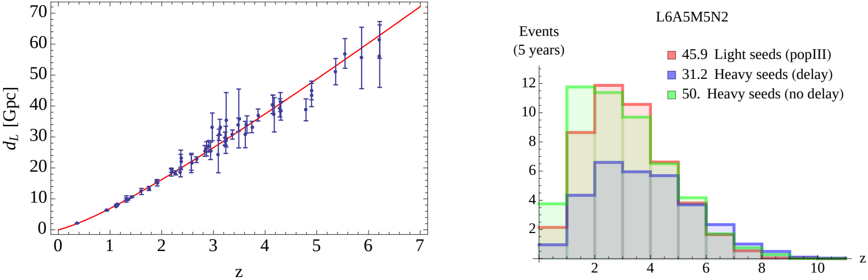
Finally **to detect the EM counterpart** of an LISA event sufficiently localized in the sky we use the following two methods:

- **LSST**: direct detection of optical counterpart
- **SKA + E-ELT**: first use SKA to detect a radio emission from the BHs and pinpoint the hosting galaxy in the sky, then aim E-ELT in that direction to measure the redshift from a possible optical counterpart either
  - Spectroscopically or Photometrically


LISA cosmological forecasts: MBHB standard sirens rate

Example of simulated catalogue of MBHB standard sirens:



Note 1: LISA will be able to map the expansion at very high redshifts (data up to $z \sim 8$), while SNIa can only reach $z \sim 1.5$

Note 2: Few MBHBs at low redshift $\Rightarrow$ bad for DE (but on can use SNIa and other GW sources)

LISA cosmological forecasts: parameter constraints

RESULTS: [NT et al, arXiv:1601.07112]

1σ constraints with 5 million km armlength:

$$\textbf{ΛCDM:} \begin{cases} \Delta\Omega_M & \simeq 0.025 \quad (8\%) \\ \Delta h & \simeq 0.013 \quad (2\%) \end{cases}$$

$$\textbf{ΛCDM + curvature:} \begin{cases} \Delta\Omega_M & \simeq 0.054 \quad (18\%) \\ \Delta\Omega_\Lambda & \simeq 0.15 \quad (21\%) \\ \Delta h & \simeq 0.033 \quad (5\%) \end{cases}$$

$$\textbf{Dynamical DE:} \begin{cases} \Delta w_0 & \simeq 0.16 \\ \Delta w_a & \simeq 0.83 \end{cases}$$

- Similar results with 1 or 2 million km armlength

LISA cosmological forecasts: parameter constraints

RESULTS: [NT et al, arXiv:1601.07112]

1σ constraints with 5 million km armlength:

$$\Lambda\textbf{CDM:} \begin{cases} \Delta\Omega_M & \simeq 0.025 \quad (8\%) \\ \Delta h & \simeq 0.013 \quad (2\%) < 1\% \,(\text{with Planck}) \end{cases}$$

$$\Lambda\textbf{CDM + curvature:} \begin{cases} \Delta\Omega_M & \simeq 0.054 \quad (18\%) \\ \Delta\Omega_\Lambda & \simeq 0.15 \quad (21\%) \\ \Delta h & \simeq 0.033 \quad (5\%) \end{cases}$$

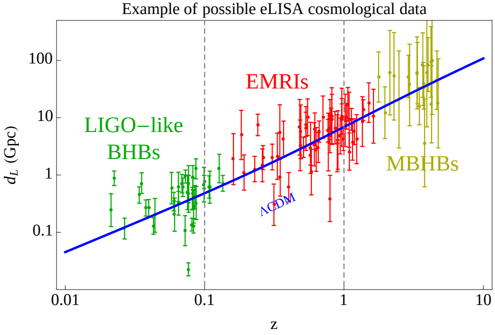
$$\textbf{Dynamical DE:} \begin{cases} \Delta w_0 & \simeq 0.16 \\ \Delta w_a & \simeq 0.83 \end{cases}$$

- Similar results with 1 or 2 million km armlength

LISA cosmological forecasts: future prospects

Future work:

- Exploit other LISA GW sources for cosmology (lower z) (this will improve the results from MBHBs only)
  - Stellar mass BH binaries ($z < 0.1$) $\neg$
  - EMRIs ($0.1 < z < 1$) $\rightarrow$ *no counterparts expected!*



Low redshift data useful to test DE and constrain H_0

[Del Pozzo et al, arXiv:1703.01300]

[Kyutoku & Seto, arXiv:1609.07142]

High redshift data useful to test alternative cosmological models

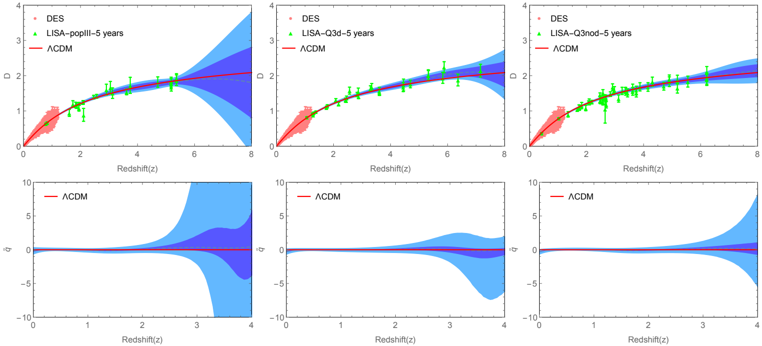
[Caprini & NT, arXiv:1607.08755]

[Cai, NT, Yang, arXiv:1703.07323]

- **Cosmology at all redshift ranges with LISA!**

LISA forecasts: reconstructing the dark sector interaction

Reconstruction of the interaction between DE and DM in a model independent way [Cai, NT, Yang, arXiv:1703.07323]



LISA MBHB standard sirens reconstruct the interaction well for $z \lesssim 3$ (5 yr) and $z \lesssim 5$ (10 yr)

Conclusions

Probing cosmology with LISA

- MBHBs will be excellent standard sirens for LISA
- Direct probe of the cosmic expansion at very high redshift
- Constraint on H_0 down to 1%
- Useful to constrain alternative models at high redshift
- LISA will provide new data complementary to EM observations to probe the expansion of the universe at all redshifts