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

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The LISA mission

Laser Interferometric Space Antenna

Proposed design: [arXiv:1702.00786]

- Near-equilateral triangular formation orbiting around the Sun
- 6 laser links (3 active arms)
- Arm length: 2.5 million km
- Mission duration: $\geq 4$ 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!

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

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 ⇒ **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 (SNla → 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
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?
Possible standard sirens sources for LISA:

- MBHBs ($10^4 - 10^7 M_\odot$)
- LIGO-like BHBs ($10 - 100 M_\odot$)
- EMRIs
Possible standard sirens sources for LISA:

- MBHBs \((10^4 - 10^7 \, M_\odot)\)
- LIGO-like BHBs \((10 - 100 \, M_\odot)\)
- EMRI

Advantages of MBHB mergers:

- High SNR
- High redshifts (up to \(\sim 10-15\))
- Merger within LISA band
- Gas rich environment \(\rightarrow EM\) counterparts!
To obtain cosmological forecasts, we have adopted the following realistic strategy:

- 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 ($\Delta \Omega < 10 \text{ deg}^2$)
- Focus on 5 years LISA mission (the longer the better for cosmology)
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
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 ⇒ bad for DE (but one 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:

\[ \Lambda CDM: \begin{cases} 
\Delta \Omega_M & \simeq 0.025 \quad (8\%) \\
\Delta h & \simeq 0.013 \quad (2\%)
\end{cases} \]

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

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
**RESULTS**: [NT et al, arXiv:1601.07112]

1σ constraints with 5 million km armlength:

**ΛCDM:**

\[
\begin{align*}
\Delta \Omega_M &\approx 0.025 \ (8\%) \\
\Delta h &\approx 0.013 \ (2\%) < 1\% \ (\text{with Planck})
\end{align*}
\]

**ΛCDM + curvature:**

\[
\begin{align*}
\Delta \Omega_M &\approx 0.054 \ (18\%) \\
\Delta \Omega_\Lambda &\approx 0.15 \ (21\%) \\
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\end{align*}
\]

**Dynamical DE:**

\[
\begin{align*}
\Delta w_0 &\approx 0.16 \\
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\]

▶ Similar results with 1 or 2 million km armlength
Future work:

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

Example of possible eLISA cosmological data

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)
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