What will LISA reveal about black hole astrophysics?

Emanuele Berti, University of Mississippi
GW SIG Minisymposium, Apr 14 2018
**LIGO/Virgo: 5.87 confirmed stellar mass black hole mergers + GW170817**

<table>
<thead>
<tr>
<th>GW event</th>
<th>Date published</th>
<th>Location area (deg^2)</th>
<th>Luminosity distance (Mpc)</th>
<th>Energy radiated (c^2M_☉)</th>
<th>Chirp mass (M_☉)</th>
<th>Primary</th>
<th>Secondary</th>
<th>Remnant</th>
<th>Notes</th>
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<td>GW150914</td>
<td>2016-02-11</td>
<td>600; mostly to the south</td>
<td>440 ±160 -180</td>
<td>3.0 ±0.5 -0.5</td>
<td>28.2 ±1.8 -1.7</td>
<td>BH</td>
<td>35.4 ±5.0 -3.4</td>
<td>BH</td>
<td>62.2 ±3.7 -3.4</td>
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<td>LVT151012 (Hi)</td>
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<td>1600</td>
<td>1000 ±500 -500</td>
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<td>23 ±18 -6</td>
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<td>35 ±14 -4</td>
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<td>31.2 ±8.4 -6.0</td>
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<td>48.7 ±5.7 -4.6</td>
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<td>340 ±140 -140</td>
<td>0.85 ±0.07 -0.17</td>
<td>7.9 ±0.2 -0.2</td>
<td>BH</td>
<td>12 ±7 -2</td>
<td>BH</td>
<td>18.0 ±4.8 -0.9</td>
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<tr>
<td>GW170814</td>
<td>2017-09-27</td>
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<td>540 ±130 -210</td>
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<td>24.1 ±1.4 -1.1</td>
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<td>BH</td>
<td>53.2 ±3.2 -2.5</td>
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<td>&gt; 0.025</td>
<td>1.186 ±0.004 -0.002</td>
<td>NS</td>
<td>1.36 -1.60</td>
<td>NS</td>
<td>&lt; 2.74 -0.01</td>
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</table>
eLISA-like detector [14]. The surprisingly high SNR of the 21 cm line identifies interstellar hydrogen [13].

The geometrical factor (where the angle between the arms is 60°) is then estimated by following [14]. Including redshift factors and supermassive BHs to compute the rates of events that would allow us to carry out spectroscopical tests. Below we provide the details of our analysis, but the introduction.

\[ f = 170.2 \left( \frac{100 M_\odot}{M} \right) \text{ Hz} \]

Where will we stand in the 2030s?
Complementarity! Multi-band 2030s: Einstein Telescope vs. LISA

FIG. 1: The multi-band GW astronomy concept. The violet lines are the total sensitivity curves (assuming two Michelson) of three eLISA configurations; from top to bottom N2A1, N2A2, N2A5 (from [11]). The orange lines are the current (dashed) and design (solid) aLIGO sensitivity curves. The lines in different blue flavours represent characteristic amplitude tracks of BHB sources for a realization of the flat population model (see main text) seen with S/N > 1 in the N2A2 configuration (highlighted as the thick eLISA middle curve), integrated assuming a five year mission lifetime. The light turquoise lines clustering around 0.01Hz are sources seen in eLISA with S/N < 5 (for clarity, we down-sampled them by a factor of 20 and we removed sources extending to the aLIGO band); the light and dark blue curves crossing to the aLIGO band are sources with S/N > 5 and S/N > 8 respectively in eLISA; the dark blue marks in the upper left corner are other sources with S/N > 8 in LISA but not crossing to the aLIGO band within the mission lifetime. For comparison, the characteristic amplitude track completed by GW150914 is shown as a black solid line, and the chart at the top of the figure indicates the frequency progression of this particular source in the last 10 years before coalescence. The shaded area at the bottom left marks the expected confusion noise level produced by the same population model (median, 68% and 95% intervals are shown). The waveforms shown are second order post-Newtonian inspirals phenomenologically adjusted with a Lorentzian function to describe the ringdown.

As mentioned above, for both the flat and salp models, probability distributions of the intrinsic rate $R$ are given in [3] (see their figure 5). We make 200 Monte Carlo draws from each of those, use equation (2) to numerically construct the cosmological distribution of emitting sources as a function of mass redshift and frequency, and make a further Monte Carlo draw from the latter. For each BHB mass model, the process yields 200 different realizations of the instantaneous BHB population emitting GWs in the Universe. We limit our investigation to $0 < z < 2$ and $f_r > 10^4$ Hz, sufficient to cover all the relevant sources emitting in the eLISA and aLIGO bands.

Signal-to-noise ratio computation. An in-depth study of possible eLISA baselines is under investigation [11], and the novel piece of information we provide here might prove critical in the selection of the final design. Therefore, following [11], we consider six baselines featuring one two or five million km arm-length (A1, A2, A5) and two possible low frequency noises – namely the LISA Pathfinder goal (N1) and the original LISA requirement (N2)–. We assume a two Michelson (six laser links) configuration, commenting on the effect of dropping one arm (going to four links) on the results. We assume a five year mission duration.

In the detector frame, each source is characterized by its redshifted quantities $M = M_r (1 + z)$ and $f = f_r / (1 + z)$. During the five years of eLISA observations, the binary emits GWs shifting upwards in frequency from an initial value $f_i$, to an $f_f$ that can be computed by integrating equation (3) for a time $t_r = 5yr / (1 + z)$. The sky and polarization averaged S/N in the eLISA detector...
LISA sources: “the whole enchilada”

- **MBHs**
- **Multiband binaries**
- **EMRIs**

- **Observatory**
- **Characteristic Strain**
- **Total**

**Galactic Background**
- **MBHBs at z = 3**
- **Verification Binaries**
- **EMRI Harmonics**
- **LIGO-type BHBs**
- **GW150914**
- **Gal. Bin. (SNR > 7)**
Massive black holes
Can we tell apart models with different growth/merger physics?

Models chosen to have different

- Seeds: light or heavy?
- Metallicity Z: efficiency of gas inflow
- Accretion efficiency: Eddington vs. Merloni-Heinz
- Accretion geometry: coherent vs. chaotic

[Refs: [Sesana+, 1011.5893]]
Black hole spins encode growth history

Growth by:

Mergers only: spin ~0.7

Mergers+coherent accretion: spin close to one

Mergers+chaotic accretion: spin close to zero

[EB+Volonteri, 0802.0025; Sesana+, 1402.7088]
How many binaries can we detect? Can we measure parameters/localize?

<table>
<thead>
<tr>
<th>Configuration ID</th>
<th>(\Delta m_{1,2}/m_{1,2} &lt; 0.01)</th>
<th>(\Delta \chi_1 &lt; 0.01)</th>
<th>(\Delta \chi_2 &lt; 0.1)</th>
<th>(\Delta \theta_{\chi_1} &lt; 10) deg</th>
<th>(\Delta \theta_{\chi_2} &lt; 0.1)</th>
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<td>N2A5M2L6</td>
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<td>45.3 79.8 2.6</td>
<td>41.8 44.7 3.9</td>
<td>21.0 40.9 9.4</td>
<td>3.5 31.4 10.9</td>
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<tr>
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<td>21.2 27.2 2.5</td>
<td>11.5 19.1 4.8</td>
<td>3.0 18.5 10.7</td>
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<td>71.4 99.6 10.9</td>
<td>28.3 54.4 2.0</td>
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<td>11.7 18.9 5.1</td>
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<td>2.9 12.3 9.3</td>
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<tr>
<td>N1A5M2L4</td>
<td>40.7 49.3 7.0</td>
<td>20.5 29.8 0.9</td>
<td>7.3 8.0 0.6</td>
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<td>12.6 12.6 0.2</td>
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<td>0.3 0.4 0.1</td>
<td>0.1 0.3 0.2</td>
<td>0.2 7.8 6.4</td>
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| \(\Delta \theta < 0.1 \text{ deg}^2 \) & \(\Delta D_i/D_l < 0.1 \) & \(z < 5\) | \(\Delta \theta < 0.1 \text{ deg}^2 \) & \(\Delta D_i/D_l < 0.1 \) & \(z > 7\) & \(\Delta D_i/D_l < 0.3\) |
|------------------|----------------------------------|------------------------|---------------------------|-------------------------------|-------------------------------|
| Configuration ID | \(\text{popIII} \) Q3-nod Q3-d | \(\text{popIII} \) Q3-nod Q3-d | \(\text{popIII} \) Q3-nod Q3-d | \(\text{popIII} \) Q3-nod Q3-d | \(\text{popIII} \) Q3-nod Q3-d |
| N2A5M2L6         | 14.5 34.8 6.0                    | 16.1 47.4 10.1        | 7.6 117.2 1.2             | 7.6 141.1 1.4                |
| N2A5M2L4         | 3.2 8.7 1.1                     | 4.8 16.0 4.9          | 10.2 54.4 0.6             | 30.4 96.8 1.0                |
| N2A2M2L6         | 6.8 23.2 3.8                    | 9.2 35.2 9.5          | 20.8 82.6 0.9             | 20.8 134.4 1.4               |
| N2A2M2L4         | 1.6 4.2 0.4                     | 2.6 5.8 1.6           | 2.8 18.0 0.2              | 10.1 54.0 0.7                |
| N1A5M2L6         | 3.4 14.9 2.5                    | 5.7 26.4 7.8          | 3.9 50.9 0.6              | 3.9 120.1 1.3                |
| N1A1M2L4         | 0.6 1.7 0.1                     | 1.0 2.6 0.5           | 0.5 0.8 0.0               | 2.6 41.8 0.2                |
| N1A5M2L4         | 4.0 13.7 1.9                    | 7.0 27.3 7.5          | 9.8 30.5 0.4              | 9.9 111.9 1.2                |
| N1A5M2L4         | 0.7 1.6 0.0                     | 1.2 2.6 0.2           | 1.3 2.2 0.0               | 5.2 9.0 0.2                 |
| N1A1M2L6         | 1.9 5.1 0.8                     | 4.4 18.0 5.5          | 2.3 6.6 0.2               | 2.4 77.7 1.0                |
| N1A1M2L4         | 0.4 0.5 0.0                     | 0.6 1.0 0.1           | 0.2 0.4 0.0               | 1.0 2.0 0.0                 |
| N1A1M2L6         | 0.7 1.5 0.2                     | 2.7 9.8 3.9           | 0.2 0.1 0.0               | 0.5 0.4 0.6                 |
| N1A1M2L4         | 0.2 0.2 0.0                     | 0.2 0.3 0.0           | 0.0 0.0 0.0               | 0.0 0.0 0.0                 |

[Klein+, 1511.05581]
Can we tell models apart?

![Graphs showing comparisons between different models](image)

FIG. 6 (color online). Results for comparisons of the pure models. Each plot shows all possible comparisons varying only one of the elements listed in Table I. Top left panel: we consider the effect of the accretion geometry, comparing coherent to chaotic for each of the combinations of the other ingredients. Top right panel: we consider the effect of the accretion model, comparing Eddington accretion to Merloni-Heinz accretion for the BVR-noZ models. Bottom left panel: we consider the effect of metallicity by comparing the noZ to Z models for VHM-co, VHM-ch, BVR-co, and BVR-ch. Bottom right panel: we consider the effect of the seeding assumption, comparing the VHM to BVR models for the four combinations noZ-co, noZ-ch, Z-co, and Z-ch, each with Eddington accretion.

In all panels we are making the most pessimistic assumptions about the detector, i.e., we use the transfer function $T^2$ (one interferometer, $\text{thr} = 20$). These results are for a 3 month LISA observation, except for the top left panel which is for a 1 yr observation.
Extreme mass ratio binaries
EMRIs: rates, GR tests, new physics?

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass function</th>
<th>MBH spin</th>
<th>Cusp erosion</th>
<th>$M-\sigma$ relation</th>
<th>$N_p$</th>
<th>CO mass [M$_\odot$]</th>
<th>EMRI rate [yr$^{-1}$]</th>
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<td>10</td>
<td>20000</td>
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</table>

- Rates very uncertain (1-10$^4$/yr): depend on Low-mass MBH mass function, spin, cusp erosion post-merger, M-$\sigma$, ratio of direct plunges to EMRIs, waveform model
- Tests of GR: Kerr BH quadrupole within $\Delta Q\sim 10^{-4}$
- New physics: Dark matter, scalar clouds (e.g. axions) modify dynamics
- New astrophysics: Multiband EMRIs, standard candles

[Babak+, 1703.09722]
Reveal MBH mass function at low masses?

Detect boson clouds / dark matter?

[Revealed MBH mass function at low masses? Diagram showing mass function with different colors and uncertainties.]

[Diagram showing LISA/JEO/DECIGO antennas and their interaction with EMRIs.]

[References: Babak+, 1703.09722; Ferreira+, 1710.00830]
Multiband black hole binaries
Complementarity! Multi-band

[Figures and graphs showing multi-band GW astronomy concept for aLIGO and eLISA.]

Figure 2. Crossings to LIGO band

[S/N>8, t_e<10yr]

Detected

Crossing to LIGO band

[S/N>8]

number of sources

frequency [Hz]

characteristic amplitude

[nominal bands: aLIGO, eLISA, etc.]

[Sources for a realization of the BHB population emit at different masses; different blue flavours represent characteristic amplitude tracks of BHBs for different LISA configurations: N2A1, N2A2, N2A5 (from [11]). The orange lines are the current (dashed) and historical (solid) S/N for LISA sources integrated assuming a five year mission lifetime. The light turquoise lines clustering around the N2A2 configuration (highlighted in orange) marks the expected confusion sky and polarization averaged S/N in the eLISA detector band, whereas the lower panel shows the total number of sources with S/N>8, t_e<10yr.]

[Error-bars, symbols and error-bars are the number of sources with S/N>8 detected in the last 10 years before coalescence for sources detected at aLIGO band, eLISA 4yr, eLISA 10yr, LISA 4yr, LISA 10yr assuming a mission lifetime.]
FIG. 1: The multi-band GW astronomy concept. The violet lines are the total sensitivity curves (assuming two Michelson) of three eLISA configurations; from top to bottom N2A1, N2A2, N2A5 (from [11]). The orange lines are the current (dashed) and design (solid) aLIGO sensitivity curves. The lines in different blue flavours represent characteristic amplitude tracks of BHB sources for a realization of the flat population model (see main text) seen with S/N > 1 in the N2A2 configuration (highlighted as the thick eLISA middle curve), integrated assuming a five year mission lifetime. The light turquoise lines clustering around 0.01Hz are sources seen in eLISA with S/N < 5 (for clarity, we down-sampled them by a factor of 20 and we removed sources extending to the aLIGO band); the light and dark blue curves crossing to the aLIGO band are sources with S/N > 5 and S/N > 8 respectively in eLISA; the dark blue marks in the upper left corner are other sources with S/N > 8 inside LISA but not crossing to the aLIGO band within the mission lifetime. For comparison, the characteristic amplitude track completed by GW150914 is shown as a black solid line, and the chart at the top of the figure indicates the frequency progression of this particular source in the last 10 years before coalescence. The shaded area at the bottom left marks the expected confusion noise level produced by the same population model (median, 68% and 95% intervals are shown). The waveforms shown are second order post-Newtonian inspirals phenomenologically adjusted with a Lorentzian function to describe the ringdown.

0.73) [12], and \( \frac{dt}{dr} \) describes the temporal evolution of the source due to GW emission assuming circular orbits:

\[
\frac{dt}{dr} = \frac{5}{c} \frac{\pi}{3} \left( \frac{G M}{r} \right)^{5/3} \left( \frac{f}{11/3} r \right).
\]

(3)

As mentioned above, for both the flat and salp models, probability distributions of the intrinsic rate \( R \) are given in [3] (see their figure 5). We make 200 Monte Carlo draws from each of those, use equation (2) to numerically construct the cosmological distribution of emitting sources as a function of mass redshift and frequency, and make a further Monte Carlo draw from the latter. For each BHB mass model, the process yields 200 different realizations of the instantaneous BHB population emitting GWs in the Universe. We limit our investigation to \( 0 < z < 2 \) and \( f_r > 10^{-4} \) Hz, sufficient to cover all the relevant sources emitting in the eLISA and aLIGO bands.

**Signal-to-noise ratio computation.**

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- LISA early warning (\( \Delta t_{\text{merger}} \sim 1s \)) and localization (\( \Delta \Omega \sim 0.1-1\text{deg}^2 \)) for LIGO/EM observations
- LISA can measure eccentricity: Clusters? [Rodriguez+]
  Triangles? [Antonini+]
  Primordial BHs? [Cholis, Kovetz+]
- LISA improvements on LIGO PE [Vitale 1605.01037]
- New population of standard sirens [Del Pozzo+ 1703.01300]
- Better tests of GR [Yunes’ talk]

[Sesana,1602.06951]
FIG. 1: The multi-band GW astronomy concept. The violet lines are the total sensitivity curves (assuming two Michelson) of three eLISA configurations; from top to bottom N2A1, N2A2, N2A5 (from [11]). The orange lines are the current (dashed) and design (solid) aLIGO sensitivity curves. The lines in different blue flavours represent characteristic amplitude tracks of BHB sources for a realization of the flat population model (see main text) seen with S/N > 1 in the N2A2 configuration (highlighted as the thick eLISA middle curve), integrated assuming a five year mission lifetime. The light turquoise lines clustering around 0.01Hz are sources seen in eLISA with S/N < 5 (for clarity, we down-sampled them by a factor of 20 and we removed sources extending to the aLIGO band); the light and dark blue curves crossing to the aLIGO band are sources with S/N > 5 and S/N > 8 respectively in eLISA; the dark blue marks in the upper left corner are other sources with S/N > 8ine LISA but not crossing to the aLIGO band within the mission lifetime. For comparison, the characteristic amplitude track completed by GW150914 is shown as a black solid line, and the chart at the top of the figure indicates the frequency progression of this particular source in the last 10 years before coalescence. The shaded area at the bottom left marks the expected confusion noise level produced by the same population model (median, 68% and 95% intervals are shown). The waveforms shown are second order post-Newtonian inspirals phenomenologically adjusted with a Lorentzian function to describe the ringdown. As mentioned above, for both the flat and salp models, probability distributions of the intrinsic rate R are given in [3] (see their figure 5). We make 200 Monte Carlo draws from each of those, use equation (2) to numerically construct the cosmological distribution of emitting sources as a function of mass redshift and frequency, and make a further Monte Carlo draw from the latter. For each BHB mass model, the process yields 200 different realizations of the instantaneous BHB population emitting GWs in the Universe. We limit our investigation to 0 < z < 2 and f_r > 10^{-4} Hz, sufficient to cover all the relevant sources emitting in the eLISA and aLIGO bands. Signal-to-noise ratio computation. An in-depth study of possible eLISA baselines in under investigation [11], and the novel piece of information we provide here might prove critical in the selection of the final design. Therefore, following [11], we consider six baselines featuring one two or five million km arm-length (A1, A2, A5) and two possible low frequency noises – namely the LISA Pathfinder goal (N1) and the original LISA requirement (N2)–. We assume a two Michelson (six laser links) configuration, commenting on the effect of dropping one arm (going to four links) on the results. We assume a five year mission duration. In the detector frame, each source is characterized by its redshifted quantities M = Mr(1 + z) and f = fr/(1 + z). During the five years of eLISA observations, the binary emits GWs shifting upwards in frequency from an initial value f_i, to an f_f that can be computed by integrating equation (3) for a time tr = 5yr/(1 + z). The sky and polarization averaged S/N in the eLISA detector...
Complementarity! Multi-band 2030s: 3G (e.g., ET) vs. LISA

- Limited improvements on 3G PE
  GW150914: SNR~700 (2000) in Voyager (Cosmic Explorer)

- LISA breaks degeneracies:
  $(\chi_1, \chi_2)$ from LISA, $\chi_{\text{eff}}$ and $\chi_f$ from LIGO
  $M_{\text{chirp}}$ from LISA, $M$ from LIGO

- IMBHs?

- Post-process LISA data after 3G detection:
  boost LISA multiband event rates

- Use 3G detections to remove foreground and go after stochastic backgrounds

- Use LISA for 3G phase/amplitude calibration

[Figure courtesy of Neil Cornish]
Field or cluster formation? Kozai or primordial black holes?

Kozai around MBHs [Antonini, 1509.05080] or primordial black holes [Cholis+, 1606.07437] can generate large eccentricity in LISA band

\[ e \sim f^{-19/18} \sim f^{-1} \]

Measurable if \( e_0 > 10^{-3} \) at \( f = 10^{-2} \text{Hz} \)

[Nishizawa+, 1605.01341; 1606.09295]
DISCUSSION AND OUTLOOK

Field or cluster formation? Kozai or primordial black holes?

<table>
<thead>
<tr>
<th>eLISA base</th>
<th>(N_{\text{obs}})</th>
<th>(N_{50})</th>
<th>(N_{90})</th>
<th>(N_{50})</th>
<th>(N_{90})</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2A2-2y</td>
<td>11-78</td>
<td>35</td>
<td>&gt;100</td>
<td>95</td>
<td>&gt;100</td>
</tr>
<tr>
<td>N2A5-2y</td>
<td>85-595</td>
<td>34</td>
<td>95</td>
<td>80</td>
<td>&gt;100</td>
</tr>
<tr>
<td>N2A2-5y</td>
<td>45-310</td>
<td>25</td>
<td>60</td>
<td>61</td>
<td>100</td>
</tr>
<tr>
<td>N2A5-5y</td>
<td>330-2350</td>
<td>25</td>
<td>62</td>
<td>60</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 1. Expected number of sources (column 2) for each eLISA baseline (column 1), compared with the number of observations needed to distinguish between models *field* and *cluster* at a given confidence threshold in 50\% (\(N_{50}\)) and 90\% (\(N_{90}\)) of the cases (columns 3-6).

Not enough detections?

5\(\sigma\) confidence with 90\% probability

Predictions may be pessimistic!

**Correlations** between \(e\) and masses/spins/kicks will help

Can ask the same question for **MBH vs. primordial** scenarios

[Nishizawa+, 1606.09295]
[Breivik+, 1606.09558]
Independent assessment of geometry of the Universe at all $z$

Different GW sources will allow an independent assessment of the geometry of the Universe at all redshifts. (Courtesy of N. Tamanini)

Example of possible eLISA cosmological data

$[Tamanini\text{+}, \text{in preparation}]

\begin{align*}
\text{EMRIs} \\
\text{LIGO-like} \\
\text{BHBs} \\
\text{MBHBs}
\end{align*}

\text{ACDM}
Reconstructing the massive black hole cosmic history through gravitational waves

Alberto Sesana, Jonathan Gair, Emanuele Berti, and Marta Volonteri

Science with the space-based interferometer eLISA: Supermassive black hole binaries

Antoine Klein, Enrico Barausse, Alberto Sesana, Antoine Petiteau, Emanuele Berti, Stanislav Babak, Jonathan Gair, Sofiane Aoudia, Ian Hinder, Frank Ohme, and Barry Wardell

eLISA eccentricity measurements as tracers of binary black hole formation

Atsushi Nishizawa, Emanuele Berti, Antoine Klein, and Alberto Sesana

Science with the space-based interferometer LISA. V. Extreme mass-ratio inspirals

Stanislav Babak, Jonathan Gair, Alberto Sesana, Enrico Barausse, Carlos F. Sopuerta, Christopher P. L. Berry, Emanuele Berti, Pau Amaro-Seoane, Antoine Petiteau, and Antoine Klein
Extra slides
Eccentricity: measurable if \( e_0 > 10^{-3} \) at \( f = 10^{-2} \text{Hz} \)

\[ e_0 = 0.1 \]

\[ e_0 = 0.01 \]

\[ e_0 = 0.001 \]
Correlations

Green/Blue:
In isolation

Black:
Dense stellar environments

[Breivik+, 1606.09558]
PopIII, Q3d, Q3nod (for supermassive BH binaries) are per year with Q3nod does not, and therefore yields higher detection delay between galaxy mergers and the merger of the BH seeds (light seeds coming from the collapse of Pop III ing eLISA rates, namely (i) the nature of primordial BH detectable by eLISA we consider the same three models other mechanisms (see e.g. [34–37]), and therefore our Earth-based interferometers could also be produced by 2 of [5]). Massive binaries with ringdowns detectable by eLISA contain two (or possibly more) ringdown modes. We predict 38 (533, 13) events for a 6-link N2A5 eLISA configuration with a 5-year mission lasting 5 years, but in the plot we divided these numbers by 5 to facilitate a more fair comparison in terms of events/year. Model Q3d (Q3nod, PopIII) predicts 38 (533, 13) events for a 6-link N2A5 eLISA configuration with a 5-year mission lasting 5 years, but in the plot we divided these numbers by 5 to facilitate a more fair comparison in terms of events/year. Model Q3d (Q3nod, PopIII) predicts 38 (533, 13) events for a 6-link N2A5 eLISA configuration with a 5-year mission lasting 5 years, but in the plot we divided these numbers by 5 to facilitate a more fair comparison in terms of events/year.
Earth vs. space-based: redshift distribution

As shown in Fig. 2, differences in rates between models and space-based detectors is that a very large fraction of the "spectroscopically significant" events will occur at cosmological distances. Many of the mergers for BH formation model, but it is remarkably independent of BH spectroscopy will come from a space-based detector.

Conclusions.

Perhaps the most striking difference between Earth-based and space-based detectors is that, although ringdown of these techniques and their use on actual data. Given the time lines for the construction and operation of detectors such as the Einstein Telescope [45–47], and 40-km detectors [22, 23] will be necessary to make BH spectroscopy practical-mass limit comparable to Einstein Telescope are needed to carry out high SNR that such tests routinely. This is not the case for space-based detectors. In the bottom-left panel, the estimated AdLIGO rate (Fig. 3. Left: redshift distribution of events with $\rho > 8$ and space-based detectors, ET-D becomes large enough to be detectable in complete signal. Therefore, while the implementation of BH spectroscopy with Earth-based interferometers. This conclusion is based on the simple GLRT criterion introduced in [42], and it is possible that better data could improve our prospects for gravitational wave observations here is that, although ringdown waveforms show that the ratio of mode amplitudes is, to a good accuracy, spin-independent, therefore this SNR threshold is adequate for our present purpose. Calculations [44] and a preliminary analysis of numerical odd-mass limit calculations $\rho > \rho_{GLRT}$ of events with $\rho > 1$, where the amplitude of $\rho > \rho_{GLRT}$.

Mathematical expressions and equations are used throughout the text. For example, $dN/dz$, $T_{obs}$, and $\rho$ are used to represent different quantities and relationships. The text also discusses the importance of different detection methods and the implications of using Earth-based versus space-based detectors for BH spectroscopy.
and to open the era of multi-band GW astronomy.

to mutually enhance the capabilities of aLIGO and eLISA

less than ten seconds. These figures open the possibility

1deg

ments is better than 1%, the sky location is better than

the aLIGO band, the relative errors in the mass measure-

ment accuracy. Typically few weeks before appearance in

and to the response function generally

as indicative of the realistic capabilities of an eLISA-type

eLISA, our parameter error estimates should be only taken

Given the simple waveform and detector response mod-

orbits completed by the eLISA detector over five years.

cycles emitted by the system convoluted to the multiple

Carlo realizations of the

sensitive to the specific design), taken from our 200 Monte

N2A5 configuration for five years of mission operation. Esti-

Carlo realization of 1000 sources observed with S/N

The plot was constructed by running the Fisher Matrix

full time-dependent eLISA response function.

order Post-Newtonian non spinning waveforms [13] and the

mates were obtained via Fisher Matrix analysis using second

N2A5 configuration for five years of mission operation. Esti-

Carlo realization of 1000 sources coalescing in five

The plot was constructed by running the Fisher Matrix

FIG. 3: Parameter estimation accuracy from eLISA observa-

2

2

BHB mass model. The

M 8 in the eLISA detector

localization

1 M 2

2

18

of the symmetric mass ratio

coalescence time; top right: sky localization of the sources;

[SESANA,1602.06951]
In our analysis, we considered the chirp mass at the true value, with priors assigned around their true values, assuming that the analysis (on the same signals) restricting the priors of masses and spin orientations. These are the "Ground" results. We used flat priors in the spin magnitude in the range of these sources, the masses in the detector frame will be redshifted to higher values (by a factor \(z\)).

We then performed a second parameter estimation analysis using prior eLISA mass and sky position estimates. The color bar reports the asymmetric mass ratio \(q = m_2/m_1\) and right ascension and declination \(\phi, \theta\) of the most massive BH in the binary. We look first at the measurement of the primary BH spin magnitude \(a_1\) and then address the measurement of the spin magnitude \(a_2\) of the secondary BH. We will use the word "primary" and the index 1 for the most massive BH and "secondary" and the index 2 for the least massive BH.

In this section, we use 90% CI to quote uncertainties. Given our 90% CI, the symmetric mass ratio \(q_\text{sym} \equiv m_1/m_2\), being the signal-to-noise ratio \(\text{SNR} \equiv 10^{-2}\log_{10} (\text{SNR})\) and without the eLISA information, our primary result is that the symmetric mass ratio \(q_\text{sym} = 0.70_{-0.02}^{+0.04}\) and the primary mass fraction \(q_\text{sym} = 0.69_{-0.02}^{+0.04}\) after the end of this decade.

We did not marginalize over calibration errors, implicitly assuming that by the time eLISA is online the calibration of ground-based detectors will be better than one percent (current practical limits us to 0.9%). For those runs we used flat priors in the component masses in the range \([10^{-6}, 10^{-4}]\) and without the eLISA information, our primary result is that the symmetric mass ratio \(q_\text{sym} = 0.70_{-0.02}^{+0.04}\) and the primary mass fraction \(q_\text{sym} = 0.69_{-0.02}^{+0.04}\) after the end of this decade.

The dimensionless spin magnitude of each BH was uniformly drawn from the range \([-1, 1]\). Given our choice, how our conclusions could be affected by this choice.