Late-time cosmology with eLISA

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eLISA in one slide

- Proposed space-based laser interferometer
- ESA L3 mission (2034): “the gravitational universe”
- Final design under discussion:
  - 4 or 6 links (2/3 arms)
  - 1 to $5 \times 10^6$ Km arms
  - Expected noise
- Main target sources: SMBHBs with $10^4 - 10^7 M_{\odot}$

For more information see talk on Friday
Cosmology with eLISA

- How can eLISA be used to probe late-time cosmology?
- What kind of information can we obtain?
Evolution history of the universe

Map the late-time expansion using the distance-redshift relation:

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

- \( z \) is the redshift
  (gives size of the Universe at time of emission)
- \( d_L \) is the luminosity distance
  (gives time of emission: \( t = d_L/c \))
- \( H(z) \) is the Hubble rate
  (contains the cosmological parameters/information)
Fitting the distance-redshift relation

Need independent measures of:
1. Distance \((d_L)\)
2. Errors on \(d_L\)
3. Redshift \((z)\)

Fit the data with the theory and find constraints

Exactly as for SNIa
1. Measuring distances with GWs

Directly from the measured waveform:

\[ h(t) = \frac{M_z^{5/3} f(t)^{2/3}}{d_L} F(\text{angles}) \cos(\Phi(t)) \]

With EM waves:

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

With GW:

- **Measuring distance is easy**: directly from the waveform (standard sirens)
- **Measuring redshift is hard**: need EM counterpart
2. Accuracy on $d_L$

What is the accuracy on the distance $d_L$?

- Depends on the detector (specific eLISA design)
- Might improve once an EM counterpart has been observed
- Degrades due to inhomogeneities of the Universe:
  - **Peculiar velocities** (low redshifts)
  - **Weak-lensing** (high redshifts)
3. How to measure redshift?

- Need to identify the **hosting galaxy** with an **EM counterpart** (large uncertainties for SMBBHs)
  - Optical
  - Radio
  - X-rays

- Need good sky location accuracy from eLISA

- Redshift measured only from **optical light**
  - Spectroscopically
    - (low magnitude high accuracy)
  - Photometrically
    - (high magnitude low accuracy)
The big issue

- How many standard sirens will be detected by eLISA?

- How many SMBHBs are out there (main target sources of eLISA)?
- For how many it will be possible to observe a counterpart?
Our work

- We are trying to answer all these questions
  (in collaboration with E. Barausse, C. Caprini, A. Klein, A. Petiteau, A. Sesana)
- Focus on 5 years eLISA mission
  (the longer the better for cosmology)
- **Realistic approach:**
  - SMBBH merger rates from simulations
  - Simple model of EM emissions from SMBBH
  - Observation of EM counterpart and measurement of redshift using future telescopes designs
- Work in progress: the results that follow are preliminary
Detecting GWs with eLISA

- Start from simulating SMBBHs 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 eLISA (SNR > 8)
- Among these select the ones with a good sky location accuracy ($\Delta\Omega < 10 \text{ deg}^2$)
We generally consider two mechanisms of EM emission at merger (based on [Palenzuela et al, 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 SMBBHs and galactic evolution
Detecting the counterparts

To detect the **EM counterpart** of an eLISA 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
Standard sirens with eLISA

Number of standard sirens (5 years mission)

- Light seeds (popIII)
- Heavy seeds (delay)
- Heavy seeds (no delay)
Fit the data with a 5 parameters \( \theta_i = (\Omega_M, \Omega_\Lambda, h, w_0, w_a) \) cosmological model giving

\[
H(z) = H_0 \left[ \Omega_M (z + 1)^3 + (1 - \Omega_\Lambda - \Omega_M) (z + 1)^2 \\
+ \Omega_\Lambda \exp \left( -\frac{3w_az}{z + 1} \right) (z + 1)^{3(1+w_0+w_a)} \right]^{\frac{1}{2}}
\]

entering the distance-redshift relation

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

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Late-time cosmology with eLISA
Cosmological models

- Impossible to constrain all 5 parameters simultaneously.
- Like other probes (e.g. SNe): difficult to constrain 5 parameters without combining with other datasets.
- Consider cosmological models with less parameters:
  - **Cosmological constant + curvature:**
    - 3 parameters ($\Omega_M, \Omega_\Lambda, h$)
    - fix $w_0 = -1 \ & \ w_a = 0$
  - $\Lambda$CDM:
    - 2 parameters ($\Omega_M, h$)
    - fix $\Omega_M + \Omega_\Lambda = 1, \ w_0 = -1 \ & \ w_a = 0$
  - **Dynamical dark energy:**
    - 2 parameters ($w_0, w_a$)
    - $\Omega_M = 0.3, \ \Omega_\Lambda = 0.7 \ & \ h = 0.67$
Fisher matrices and FoMs

Compute the **Fisher matrix** as

\[
F_{ij} = \sum_n \frac{1}{\sigma_n^2} \left. \frac{\partial^2 d_L(z_n)}{\partial \theta_i \partial \theta_j} \right|_{\text{fid}}
\]

Define a **figure of merit** (FoM)

\[
\text{FoM} = \det(F_{ij})^{\frac{1}{2N}}
\]

as a useful tool to compare the constraining power of different eLISA configuration.
FoMs for $\Lambda$CDM

2 PARAMETERS MODEL ($\Omega_M$, $h$)

- Light seeds (popIII)
- Heavy seeds (delay)
- Heavy seeds (no delay)

FoM

PARAMETERS

$H$, $W$, $M$, $h$
Estimated constraints with eLISA

For $\Lambda$CDM + curvature cosmology:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\Delta \Omega_M \approx$</th>
<th>$\Delta \Omega_\Lambda \approx$</th>
<th>$\Delta h \approx$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L6A5M5N2</td>
<td>0.1</td>
<td>0.3</td>
<td>0.07</td>
</tr>
<tr>
<td>L4A2M5N2</td>
<td>0.2</td>
<td>0.8</td>
<td>0.15</td>
</tr>
</tbody>
</table>

For $\Lambda$CDM:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\Delta \Omega_M \approx$</th>
<th>$\Delta h \approx$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L6A5M5N2</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>L4A2M5N2</td>
<td>0.09</td>
<td>0.03</td>
</tr>
</tbody>
</table>

For dark energy:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\Delta w_0 \approx$</th>
<th>$\Delta w_a \approx$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L6A5M5N2</td>
<td>0.3</td>
<td>1.6</td>
</tr>
<tr>
<td>L4A2M5N2</td>
<td>0.5</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Comparing with CMB

From L6A5M5N2 with $\Lambda$CDM:

\[
\begin{align*}
\Omega_M &= 0.30 \pm 0.04 \\
\Omega_\Lambda &= 0.70 \pm 0.04 \\
H_0 &= 67 \pm 3 \text{ km/s/Mpc}
\end{align*}
\]

From today CMB [Planck2015]:

\[
\begin{align*}
\Omega_M &= 0.3121 \pm 0.0087 \\
\Omega_\Lambda &= 0.6879 \pm 0.0087 \\
H_0 &= 67.51 \pm 0.64 \text{ km/s/Mpc}
\end{align*}
\]
Comparing with Supernovae ($\Lambda$CDM)

Expected from L6A5M5N2 (fixing $H_0$ & curvature):

$$\Omega_M = 0.30 \pm 0.019$$

From today SNe (fixing $H_0$ & curvature) [Betoule et al (2014)]:

$$\Omega_M = 0.289 \pm 0.018$$
Comparing with Supernovae (dark energy)

Expected from L6A5M5N2: (fixing $\Omega_M$, $\Omega_\Lambda$, $h$)

\[
\begin{align*}
    w_0 &= -1.0 \pm 0.3 \\
    w_a &= 0.0 \pm 1.6
\end{align*}
\]

From CMB + SNe + BAO: [Betoule et al (2014)]

\[
\begin{align*}
    w_0 &= -1.073 \pm 0.146 \\
    w_a &= -0.066 \pm 0.563
\end{align*}
\]
Summary of cosmological constraints

Curvature & energy content:
- At best $\Delta \Omega_\Lambda$ and $\Delta \Omega_M$ within 10%
- Comparable to present SNe, but worse than CMB

Local expansion:
- At best $H_0$ within 5%
- Slightly worse than present CMB constraints

Dark energy EoS:
- At best $\Delta w_0$ within 30% and $\Delta w_a \sim 1.6$
- Comparable with present SNe
- Slightly worse than all present constraints combined
Conclusions

- SMBBHs can be used as excellent standard sirens
  - Systematic-free measures of distance (no calibration needed as for SNe)
- Need low sky location error
  - L6 much better than L4
- Need to identify EM counterparts for measuring redshift
  - Will depend on capacities of future telescopes and magnitude of EM emission
- Low accuracy not comparable with future probes, but
  - New cosmological information from GWs (not EM only)
  - First direct probe of expansion at ultra-high redshifts (up to \( z \sim 8 \))