Standard sirens for LISA

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The concept of standard sirens

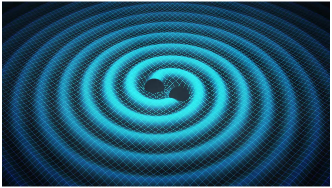
The luminosity distance can be inferred directly from the measured waveform produced by a binary system

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

$\Rightarrow$ GW sources are standard distance indicator (standard sirens)

The problem with GW is to obtain the redshift of the source through the detection of an EM counterpart such as

- EM emission at merger
- Hosting galaxy



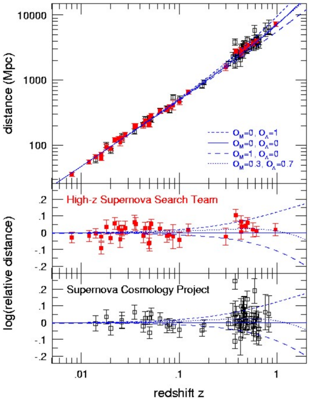
The distance-redshift relation

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

The distance-redshift relation connects the luminosity distance (d_L) to the redshift (z) at any point in the universe and depends on the cosmological parameters

$\Rightarrow$ if for some astrophysical object both d_L and z are known, one can fit the distance-redshift relation and obtain constraints on the cosmological parameters

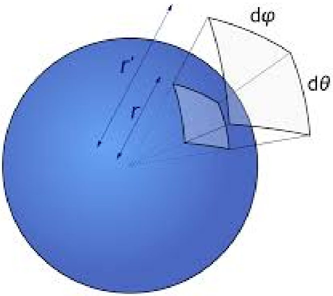
Example: Supernovae type-Ia (standard candles)



Standard sirens without counterparts

Even without a counterpart BHB inspirals can still be used to extract cosmological information statistically [Schutz, 1986]

The idea is the following:
consider each galaxy within the volume error box ($d\Omega \times dz$) of the GW source to have a non-zero probability of being the hosting galaxy and then statistically add up the information coming from all the galaxies in all boxes, with enough GW events the true value of cosmological parameters will emerge



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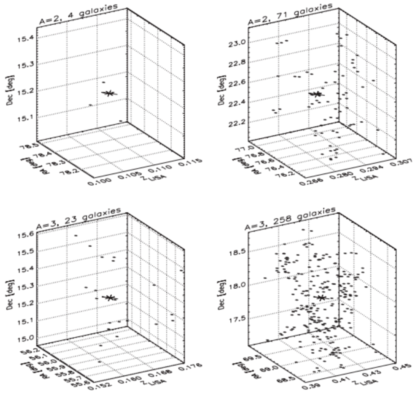

[MacLeod & Hogan, 0712.0618]

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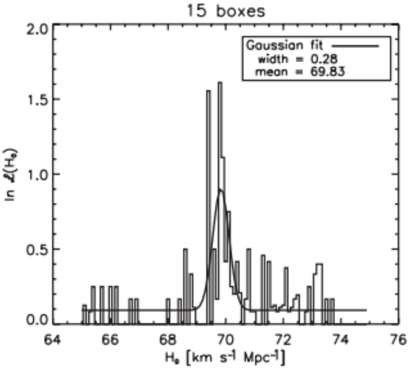
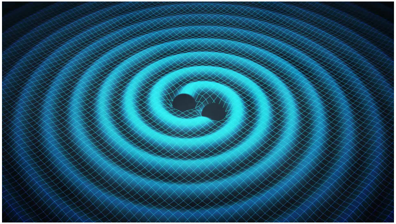
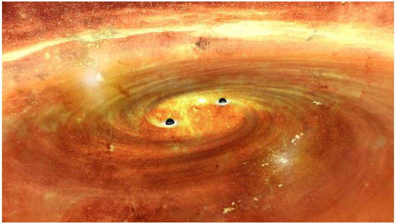


[MacLeod & Hogan, 0712.0618]

- 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:

- Massive BHBs ($10^4 - 10^7\, M_\odot$)
- Stellar mass BHBs ($10 - 100\, M_\odot$)
- EMRIs

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- EMRIs

Characteristics of Massive BHB mergers:

- High SNR
- High redshifts (up to $\sim$10-15)
- Merger within LISA band $\lnot$
- Gas rich environment $\rightarrow$ *EM counterparts expected!*

Standard sirens for LISA

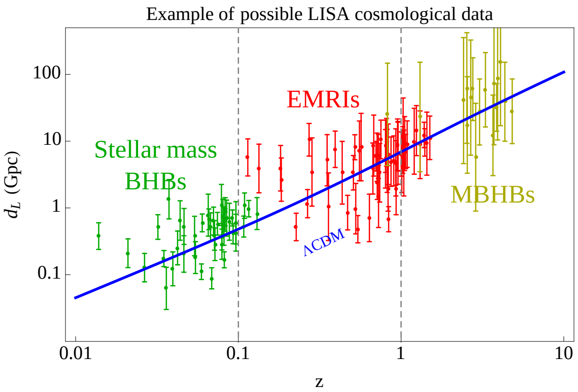
Possible standard sirens sources for LISA:

- Massive BHBs ($10^4 - 10^7\,M_\odot$)
- Stellar mass BHBs ($10 - 100\,M_\odot$)
- EMRIs

Characteristics of StMBHBs and EMRIs:

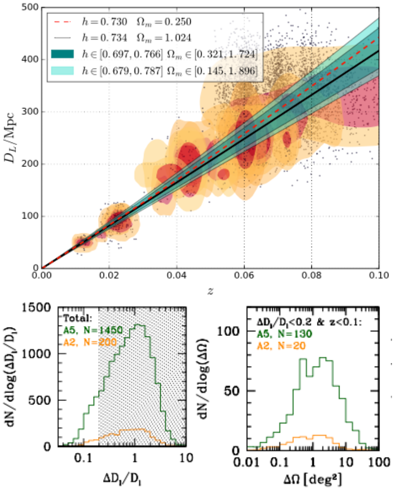
- Low redshifts ($\lesssim 0.1$ for StBHBs and $\lesssim 1$ for EMRIs)
- Merger outside the LISA band (StMBHBs)
- Gas poor environment $\rightarrow$ *No EM counterparts expected!*

Standard sirens for LISA



- StMBHBs: [Del Pozzo *et al*, 1703.01300; Kyutoku & Seto, 1609.07142]
- EMRIs: [MacLeod & Hogan, 0712.0618]
- MBHBs: [Tamanini *et al*, 1601.07112; Petiteau *et al*, 1102.0769]

Standard sirens for LISA: stellar mass BHBs

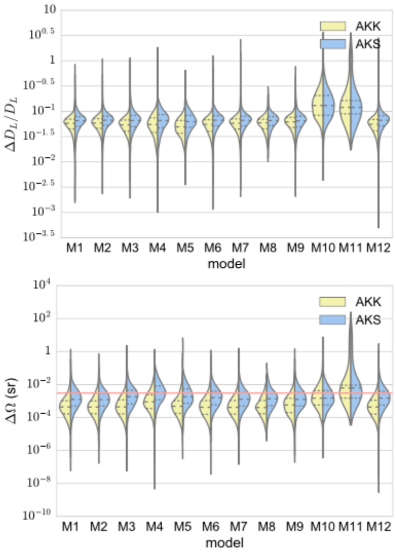


- *Redshift range*: $z \lesssim 0.1$
- *Method*: without counterparts
- *Expected detections*: $\sim 50/\mathrm{yr}$
- *Useful standard sirens*: $\sim 5/\mathrm{yr}$
- *Average LISA errors*:
  - $\Delta d_L/d_L < 20\%$
  - $\Delta\Omega \sim 1\,\mathrm{deg}^2$
- *Results*: H_0 to few %

[Del Pozzo *et al*, 1703.01300]

[Kyutoku & Seto, 1609.07142]

Standard sirens for LISA: stellar mass BHBs



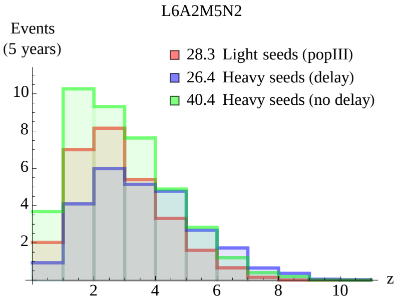
- *Redshift range*: $0.1 \lesssim z \lesssim 1$
- *Method*: without counterparts
- *Expected detections*:

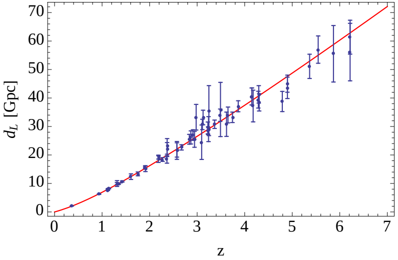
  $1 - 1000$/yr
- *Average LISA errors*:
  - $\Delta d_L/d_L \lesssim$ few %
  - $\Delta\Omega \lesssim$ few deg^2
- *Useful standard sirens*: ?
- *Results*: H_0 to $\sim$1% with 20 EMRIs at $z \sim 0.5$ (obsolete)

[MacLeod & Hogan, 0712.0618]

[Babak *et al*, 1703.09722]

Standard sirens for LISA: massive BHBs





- *Redshift range*: $1 \lesssim z \lesssim 8$
- *Method*: with counterparts
- *Expected detections*: $10 - 100/\mathrm{yr}$
- *Average LISA errors*:
  - $\Delta d_L/d_L \lesssim \mathrm{few}\,\%$ (inc. lensing)
  - $\Delta\Omega < 10\,\mathrm{deg}^2$
- *Useful standard sirens*:

  $\sim 6/\mathrm{yr}$ (with counterpart)
- *Results*:
  - H_0 to $\sim$1%
  - w_0 to $\sim$ 15%

[Tamanini *et al*, 1601.07112]

MBHBs: data simulation approach

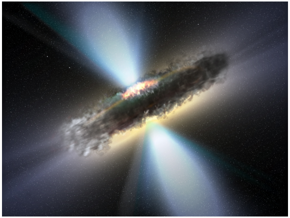
To obtain cosmological forecasts, we have adopted the following **realistic strategy**:

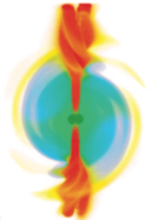
[NT, Caprini, Barausse, Sesana, Klein, Petiteau, arXiv:1601.07112]

- 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)

MBHBs: data simulation approach

- **To model the counterpart** we generally consider two mechanisms of EM emission at merger:
(based on [Palenzuela et al, 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
- EM transients expected long after the merger (up to weeks/months)

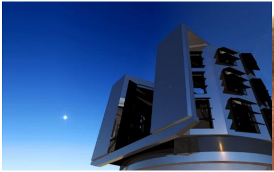
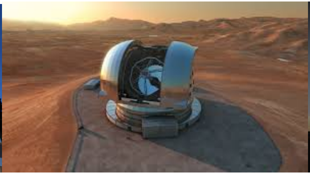




MBHBs: data simulation approach

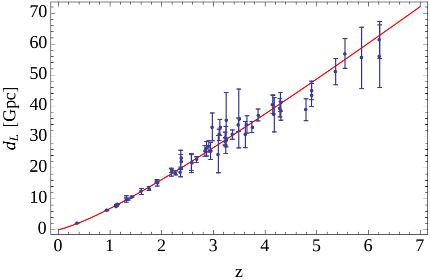
Finally **to detect the EM counterpart** of an LISA event sufficiently localized in the sky we use the following two methods:

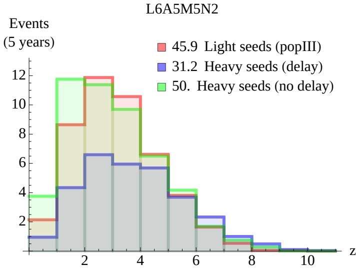
- **LSST**: direct detection of optical counterpart
- **SKA + E-ELT**: first use SKA to detect a radio emission from the BHs and pinpoint the hosting galaxy in the sky, then aim E-ELT in that direction to measure the redshift from a possible optical counterpart either
  - Spectroscopically or Photometrically


MBHBs: standard sirens rate

Example of simulated catalogue of MBHB standard sirens:





<u>Note 1</u>: LISA will be able to map the expansion at very high redshifts (data up to $z \sim 8$), while SNIa can only reach $z \sim 1.5$
<u>Note 2</u>: Few MBHBs at low redshift $\Rightarrow$ bad for DE (but on can use SNIa and other GW sources)

MBHBs: cosmological parameter constraints

RESULTS: [NT et al, arXiv:1601.07112]

1σ constraints with 5 million km armlength:

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

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

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

- Similar results with 1 or 2 million km armlength

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Conclusions

Future & further perspectives:

- Checking the cosmological potential of EMRIs
- Improving MBHB standard siren models (formation and counterpart models)
- Combining all the LISA sources into a single cosmological analysis
- High redshift LISA data (MBHBs) useful to constrain alternative cosmological models

  [Caprini & Tamanini, 1607.08755; Cai, Tamanini, Yang, 1703.07323]

Conclusions

Summary:

- BHB inspirals represents excellent distance indicators (standard sirens)
- LISA will probe the expansion of the universe at all redshifts with different classes of standard sirens:
    - Stellar mass BHBs ($z \lesssim 0.1$): H_0 to few %
    - EMRIs ($0.1 \lesssim z \lesssim 1$): H_0 to 1% (?)
    - Massive BHBs ($1 \lesssim z \lesssim 8$): H_0 to 1%
- Interesting to solve tension on the value of H_0 between local and CMB measurements
- Direct probe of the cosmic expansion at very high redshift with MBHBs