

Cosmology with standard sirens

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Outline:

- ▶ Basics and current constraints
 - ▶ The concept of standard siren
 - ▶ Constraints from GW170817 with/without EM counterpart
- ▶ Cosmological forecasts for LIGO/Virgo
- ▶ Cosmological forecasts for LISA
- ▶ Conclusions

Standard sirens:

Basics and current constraints

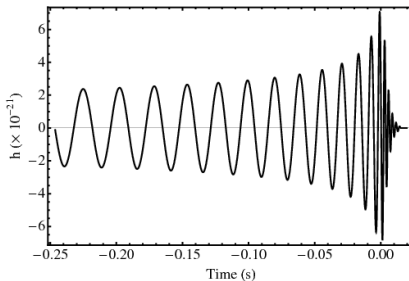
The concept of standard siren

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

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

⇒ Compact binaries
emitting GWs are standard
distance indicator:

standard sirens



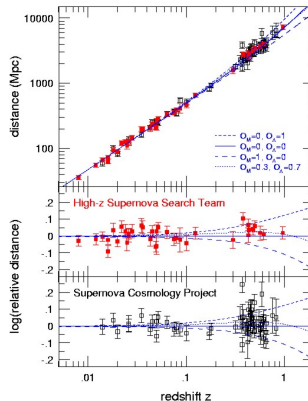
The distance-redshift relation

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

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

⇒ 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**)



Obtaining the redshift information

How can we obtain information about the redshift of a GW source?

Two main approaches:

- ▶ Identify a (transient) EM counterpart
- ▶ Use “statistical method” with galaxy catalogs

GW170817 with EM counterpart

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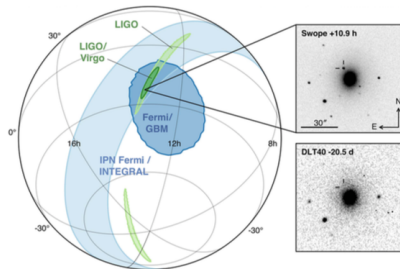
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- ▶ Identify a (transient) EM counterpart \Rightarrow **GW170817**
- ▶ Use “statistical method” with galaxy catalogs

The identification of an EM counterpart to GW170817 allowed the **first cosmological measurement with GW standard sirens**:

$$H_0 = 70_{-8}^{+12} \text{ km s}^{-2} \text{ Mpc}^{-1}$$

[LVC+ 1710.05835]



GW170817 without EM counterpart

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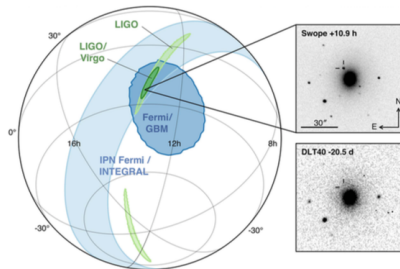
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Method already tested with GW170817 data!

[Fishbach et al., 1807.05667].



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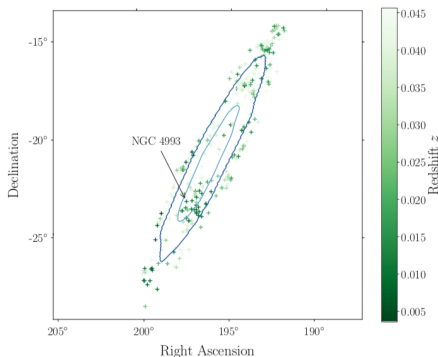
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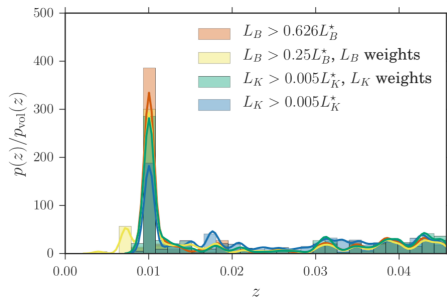
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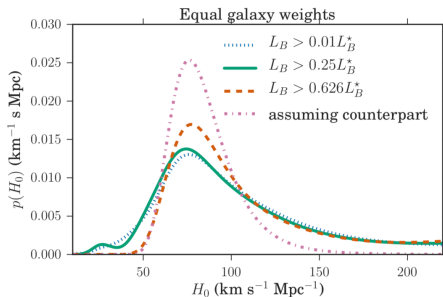
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Cosmological forecasts for LIGO/Virgo

Standard sirens for LIGO/VIRGO

Possible standard sirens sources for LIGO/VIRGO:

- ▶ Neutron Star binaries ($\sim 1.4 M_{\odot}$)
- ▶ NS-BH binaries ($1 - 10 M_{\odot}$)
- ▶ Stellar origin BHBs ($10 - 100 M_{\odot}$)

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Characteristics of NS inspiral:

- ▶ Low redshifts (~ 0.01)
- ▶ Good sky localization
- ▶ Production of GRBs and kilonovae at merger
→ *EM counterparts expected!*

Standard sirens for LIGO/VIRGO

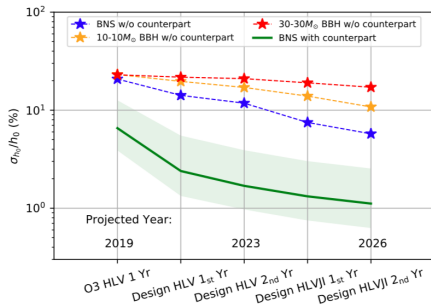
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Characteristics of SOBHBs:

- ▶ Poor sky localization
(unless high mass ratio and/or spin precession)
- ▶ Intermediate redshifts (~ 0.1)
- ▶ Gas poor environment → *No EM counterparts expected!*

Cosmological forecasts for LIGO/Virgo



[Chen et al., 1712.06531]

BNSs with EM counterpart:

- ▶ 2% constraints on H_0 with ~ 50 events (~ 2023)

BNSs without EM counterpart:

- ▶ $\sim 10\%$ constraints on H_0 with ~ 50 events (~ 2023)

BBHs without EM counterpart:

- ▶ $\sim 10\%$ constraints on H_0 with ~ 15 “well localized” ($\Delta V < 10^4 \text{ Mpc}^3$) events (~ 2026)

Cosmological forecasts for LIGO/Virgo

NSBHs with EM counterpart(?):

[Vitale & Chen, 1804.07337]

- ▶ 1% constraints on H_0 with ~ 50 events (~ 2026 if merger rate is high: $> 100 \text{ Gpc}^3 \text{ year}^{-1}$)
- ▶ Good sky localization due to high mass ratio and spin precession
- ▶ Unknown merger rate and EM counterpart production

BNSs with EM counterpart:

- ▶ 2% constraints on H_0 with ~ 50 events (~ 2023)

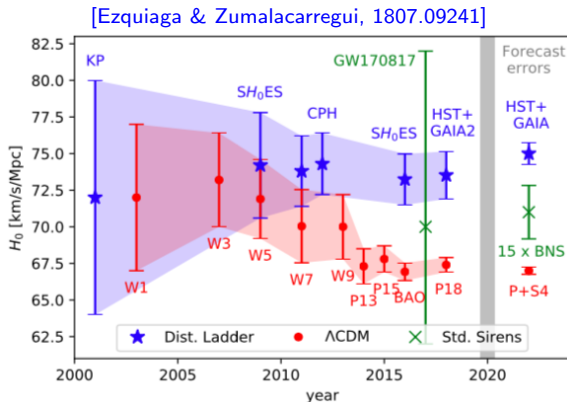
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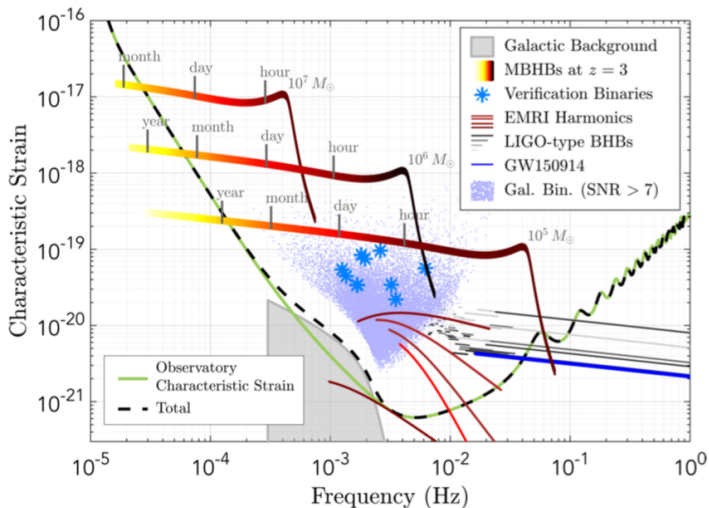
Standard sirens and the H_0 tension



A few % constraints on H_0 with GWs will solve the current tension between local and CMB measurements

Cosmological forecasts for LISA

What sources can be used as standard sirens for LISA?



[LISA call paper, arXiv:1702.00786]

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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Characteristics of Massive BHB mergers:

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

Standard sirens for LISA

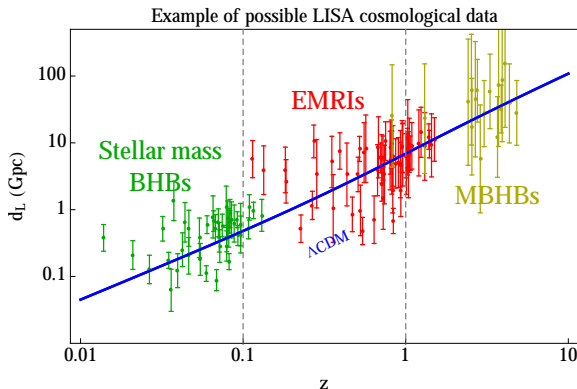
Possible standard sirens sources for LISA:

- ▶ Massive BHBs ($10^4 - 10^7 M_{\odot}$)
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- ▶ EMRIs

Characteristics of StMBHBs and EMRIs:

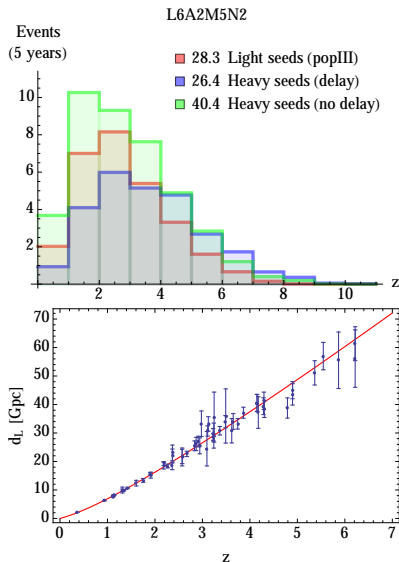
- ▶ Low redshifts ($\lesssim 0.1$ for StBHBs and $\lesssim 1$ for EMRIs)
- ▶ Merger outside the LISA band (StMBHBs) →
- ▶ Gas poor environment → *No EM counterparts expected!*

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]

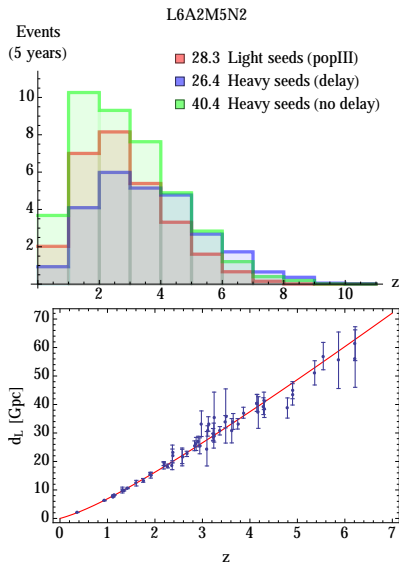
Standard sirens for LISA: massive BHBs



- *Redshift range:* $1 \lesssim z \lesssim 8$
- *Method:* with counterparts
- *Expected detections:* 10 – 100/yr
- *Average LISA errors:*
 - $\Delta d_L / d_L \lesssim \text{few } \%$ (inc. lensing)
 - $\Delta \Omega < 10 \text{ deg}^2$
- *Useful standard sirens:*
 - $\sim 5/\text{yr}$ (with counterpart)
- *Results:*
 - ▶ H_0 to $\sim 1\%$
 - ▶ w_0 to $\sim 15\%$

[Tamanini et al, 1601.07112]

Standard sirens for LISA: massive BHBs



High redshift MBHB data with EM counterpart useful to:

- ▶ Test alternative cosmological models

[Caprini & Tamanini, 1607.08755]

[Cai, Tamanini & Yang, 1703.07323]

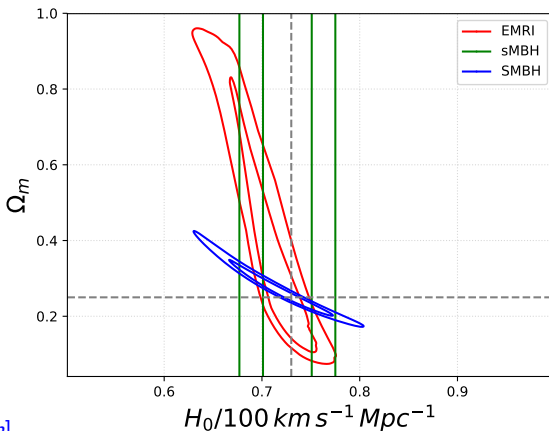
- ▶ Test modified gravity (modified GW propagation)

[Belgacem et al., 1805.08731]

Combined cosmological analysis with all GW sources

We are currently completing the cosmological forecasts combining together all standard siren sources: smBHBs, EMRIs and MBHBs.

Preliminary results: Realistic case for Λ CDM



[Tamanini,
Del Pozzo,
Sesana et al.
in preparation]

Conclusions

Standard sirens are excellent distance indicators:

- ▶ Do not require calibration and are not affected by systematics
- ▶ Can be used with or without an EM counterpart

Standard sirens for LIGO/VIRGO:

- ▶ Three possible sources:
SOBHs (no EM cp), NSBs (EM cp) and NS-BH (?)
- ▶ First standard siren just discovered: GW170817
- ▶ Forthcoming observations useful for tension in H_0

Standard sirens for LISA:

- ▶ Three possible sources:
SOBHs (no EM cp), EMRIs (no EM cp), MBHBs (EM cp)
- ▶ Probing the cosmic expansion from $z \sim 0.01$ to $z \sim 10$
- ▶ Useful to test standard and alternative cosmological models