Cosmology with gravitational wave standard sirens: current results and future prospects

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LSC LIGO Scientific Collaboration

LISA

Outline

- Standard siren: theory and methodology
  - with EM counterpart
  - without EM counterpart
- Standard sirens for LIGO/VIRGO
  - Current observations
  - Possible GW sources used as standard sirens
  - Current cosmological measurements (GW170817+)
  - Future prospects
- Standard sirens for LISA
  - Possible GW sources used as standard siren
  - Current cosmological forecasts
  - Future prospects

The concept of standard siren [Schutz, 1986]

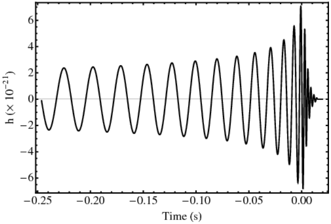
The luminosity distance can be inferred directly from the measured waveform produced by a binary system

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

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

For cosmological applications one needs also information on the redshift of the source, which can only be obtained by the detection of an EM counterpart:

- EM emission at/post merger
- Hosting galaxy



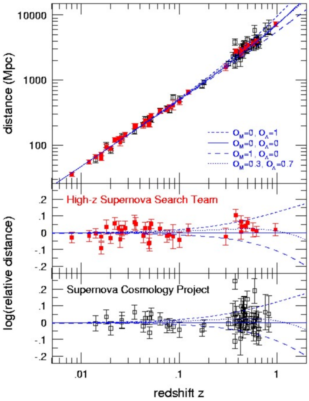
The distance-redshift relation

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

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 vs standard candles

With EM waves:

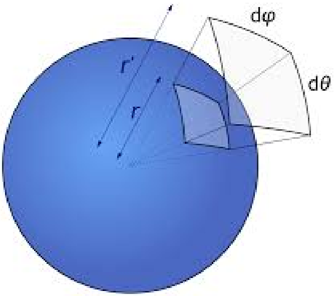
- Measuring redshift is easy: compare EM spectra
- Measuring distance is hard: need objects of known luminosity (SNIa $\rightarrow$ **standard candles**)

With GW:

- Measuring distance is easy: directly from the waveform (**standard sirens**)
- Measuring redshift is hard:
  - 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

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



Standard sirens without EM counterparts

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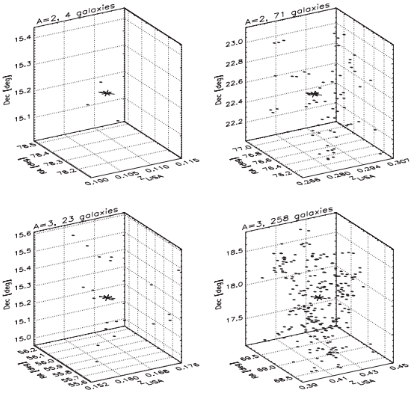

[MacLeod & Hogan, 0712.0618]

Standard sirens without EM counterparts

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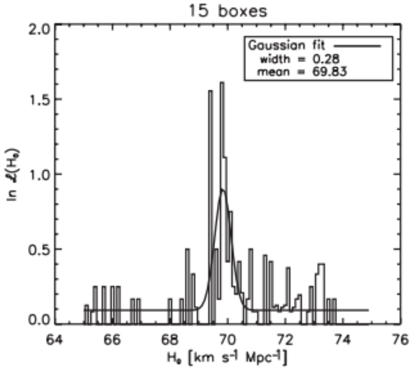
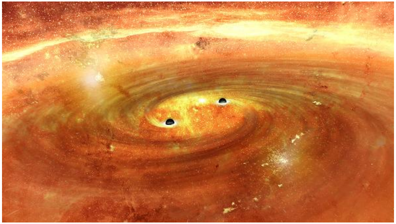
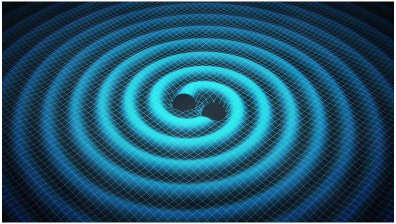


[MacLeod & Hogan, 0712.0618]

What sources can be used as standard sirens?

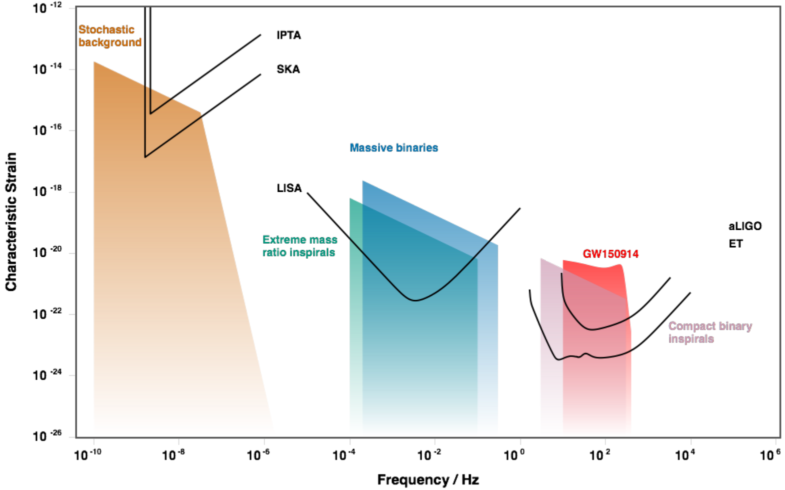
- How many **standard sirens** will be detected by LIGO/VIRGO?
- How many by LISA?





- What type of sources can be used?
- For how many it will be possible to observe a counterpart?

The Gravitational Wave Landscape



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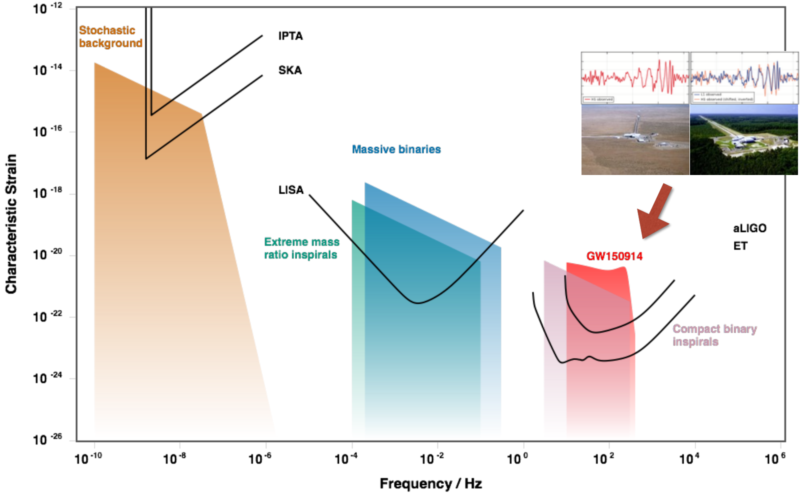

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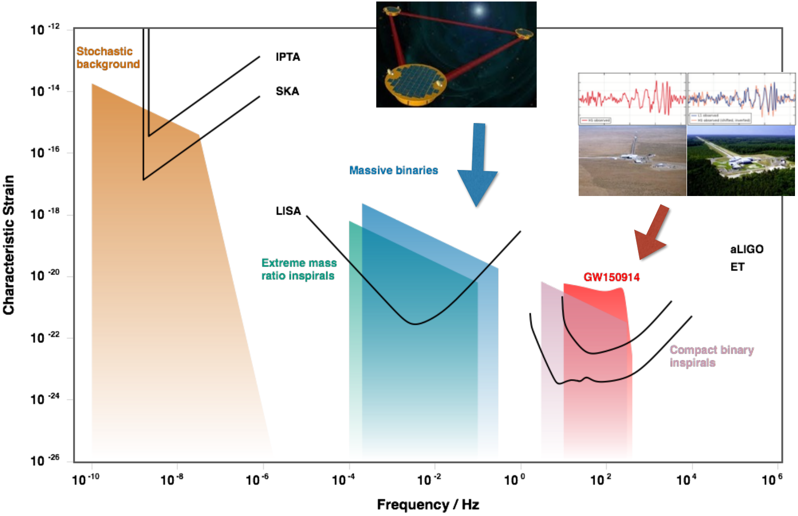

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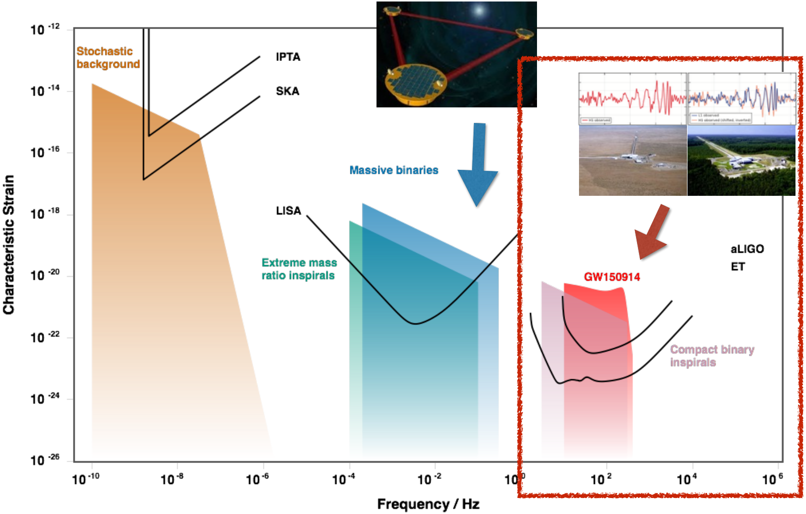


Standard sirens for LIGO/VIRGO

Earth-based detectors: current status and next future

Status of Earth-based GW observations: [LVC, arXiv:1811.12907]

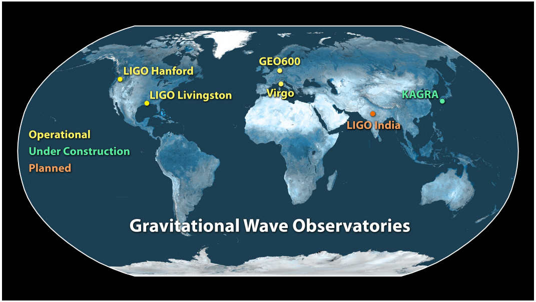
O1: 2015 (completed), LIGO only, 4 months of data,
3 BHBs detected **(GW150914, GW151012, GW151226)**

O2: 2016 (completed), LIGO+VIRGO(only GW1708xx), 6 months of observations, 7 BHBs **(GW170104, GW170608, GW170729, GW170809, GW170814, GW170818, GW170823)**
+ 1 NSB **(GW170817)**

O3: 2019 (ongoing)
LIGO+VIRGO+KAGRA(?)
1 year observations

O4: 2021 LIGO + VIRGO + KAGRA

O5: ~2024 LIGO India should join



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
  $\rightarrow$ *EM counterparts expected!*

Standard sirens for LIGO/VIRGO

Possible standard sirens sources for LIGO/VIRGO:

- Neutron Star binaries ($\sim 1.4\,M_\odot$)
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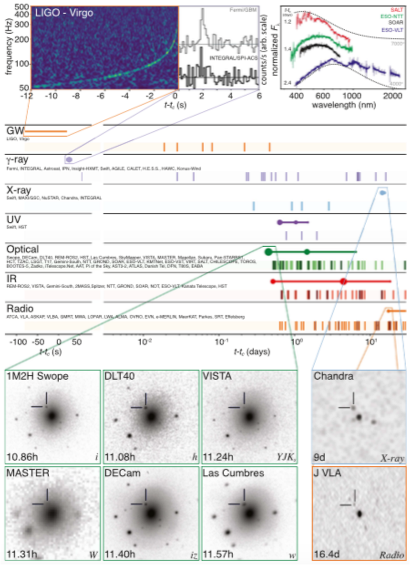
- Stellar origin BHBs ($10 - 100\,M_\odot$)

Characteristics of SOBHBs:

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

GW170817: the first ever standard siren [1710.05832]



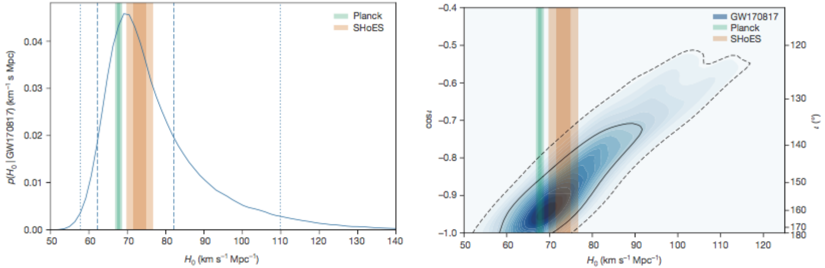
- First ever detection of a BNS and an EM counterpart of a GW event [1710.05833]
- From GW signal the luminosity distance was inferred ($d_L = 40^{+8}_{-14}$)
- From hosting galaxy the redshift has been determined [1710.05835] ($z = 0.01006 \pm 0.00055$)
- One can then measure H_0 by fitting Hubble's law (valid for small redshifts)

$$d_L = c\,\frac{z}{H_0}$$

GW170817: the first ever standard siren [1710.05832]

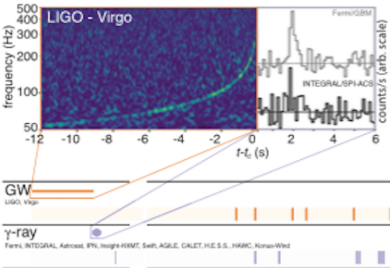
First GW measure of H_0 with GW170817:

$$\boxed{H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}$$



[LVC, 1710.05835]

GW170817: constraints on the speed of GWs



The coincident GW-EM detection of GW170817 puts stringent constraints on the speed of GW [LVC, 1710.05834]:

$$\boxed{v_{gw} = c^{+7\times10^{-16}}_{-3\times10^{-15}}}$$

This observation rules out several modified gravity models predicting $v_{gw} \neq c$ [1807.09241]

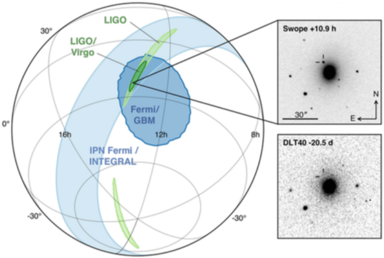
GW170817 without EM counterpart

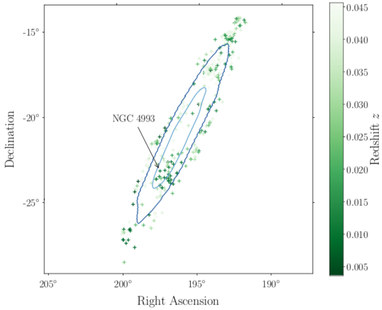
The statistical method has been applied to GW170817, pretending that no EM counterpart was observed
[Fishbach et al., 1807.05667]

$$\boxed{H_0 = 76^{+48}_{-23}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}$$

Strong dependence on the completeness and quality of the used galaxy catalogs

Competitive results from combined analysis with many GW events





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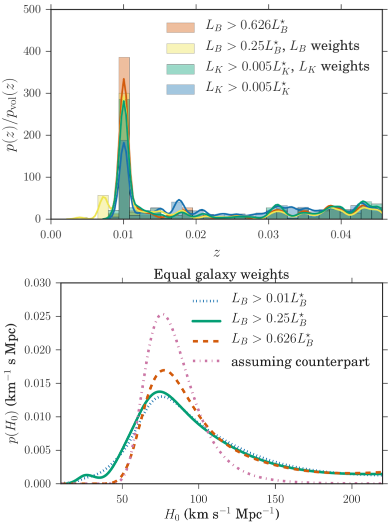
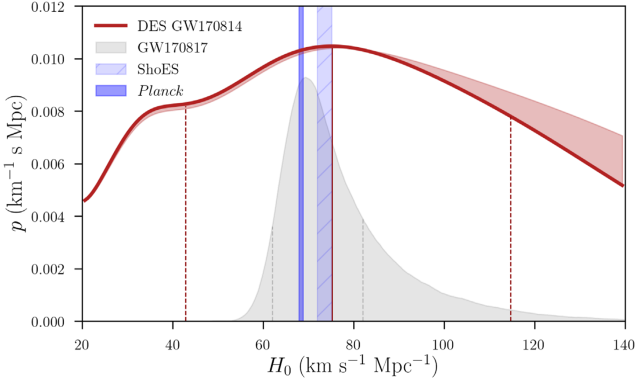


GW170814 without EM counterpart

The statistical method has also been applied to the BBH GW170814 which has no EM counterpart [DES+LVC, 1901.01540]

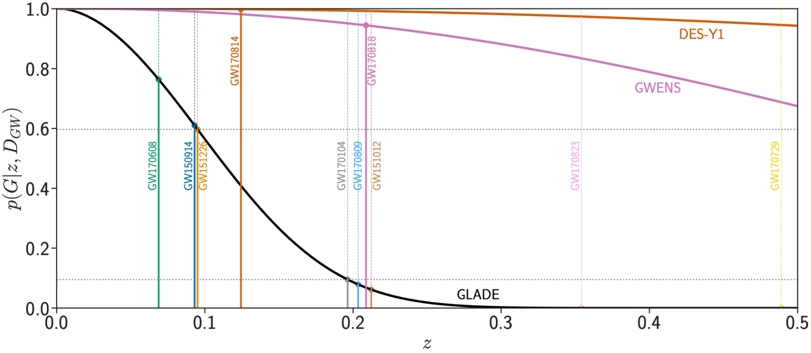
GW170814 results however are not so informative and the analysis has been performed mainly as a *proof of principle*



Constraints on H_0 from O2 combined events [1908.06060]

Event	$\Delta\Omega/\mathrm{deg}^2$	d_L/Mpc	z_{event}	V/Mpc^3	Galaxy catalog	Number of galaxies	$p(G\|z_{\mathrm{event}}, D_{\mathrm{GW}})$
GW150914	182	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	3.5×10^6	GLADE	4944	0.61
GW151012	1523	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	5.8×10^8	GLADE	45214	0.06
GW151226	1033	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	2.4×10^7	GLADE	39387	0.60
GW170104	921	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	2.4×10^8	GLADE	48786	0.10
GW170608	392	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	3.4×10^6	GLADE	20883	0.76
GW170729	1041	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	8.7×10^9	GLADE	34100	< 0.01
GW170809	308	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	9.1×10^7	GLADE	23031	0.08
GW170814	87	600^{+150}_{-220}	$0.12^{+0.03}_{-0.04}$	4.0×10^6	DES-Y1	4392112	> 0.99
GW170817	16	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	227	–	–	–
GW170818	39	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	1.5×10^7	GWENS	134040	0.94
GW170823	1666	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	3.5×10^9	GLADE	54786	< 0.01

Constraints on H_0 from O2 combined events [1908.06060]



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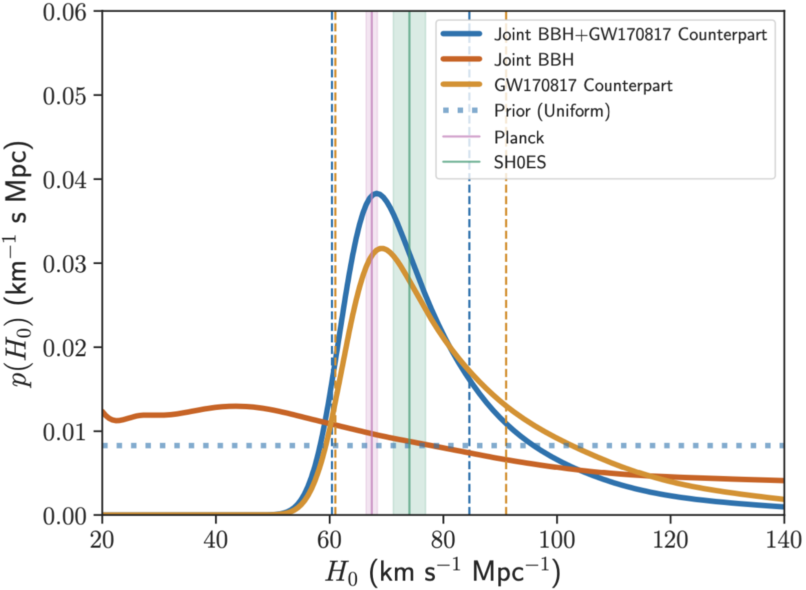
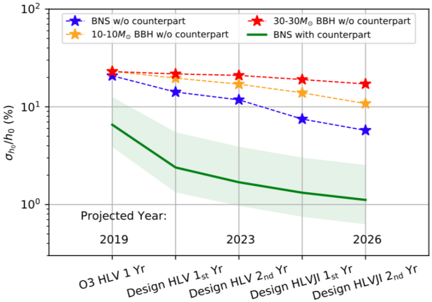


Cosmological forecasts for LIGO/Virgo



[Chen et al., 1712.06531]

BNSs with EM counterpart:

- 2% constraints on H_0 with $\sim$50 events ($\sim$2023) (systematics & rates!)

BNSs without EM counterpart:

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

BBHs without EM counterpart:

- $\sim$ 10% constraints on H_0 with $\sim$15 "well localized" ($\Delta V < 10^4$ Mpc^3) events ($\sim$2026)

Cosmological forecasts for LIGO/Virgo

NSBHs with EM counterpart(?):
[Vitale & Chen, 1804.07337]

- 1% constraints on H_0 with $\sim$50 events ($\sim$2026 if merger rate is high: > 100 Gpc^3 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 $\sim$50 events ($\sim$2023) (systematics!)

BNSs without EM counterpart:

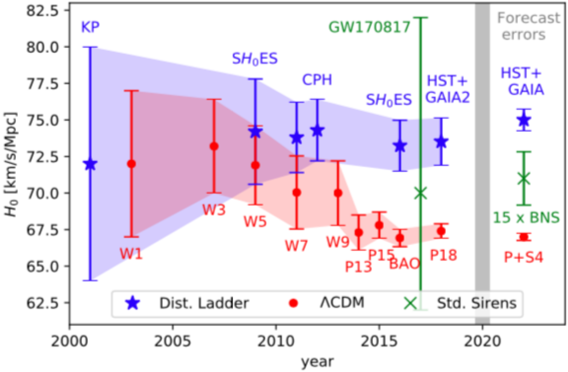
- $\sim$ 10% constraints on H_0 with $\sim$50 events ($\sim$2023)

BBHs without EM counterpart:

- $\sim$ 10% constraints on H_0 with $\sim$15 "well localized" ($\Delta V < 10^4$ Mpc^3) events ($\sim$2026)

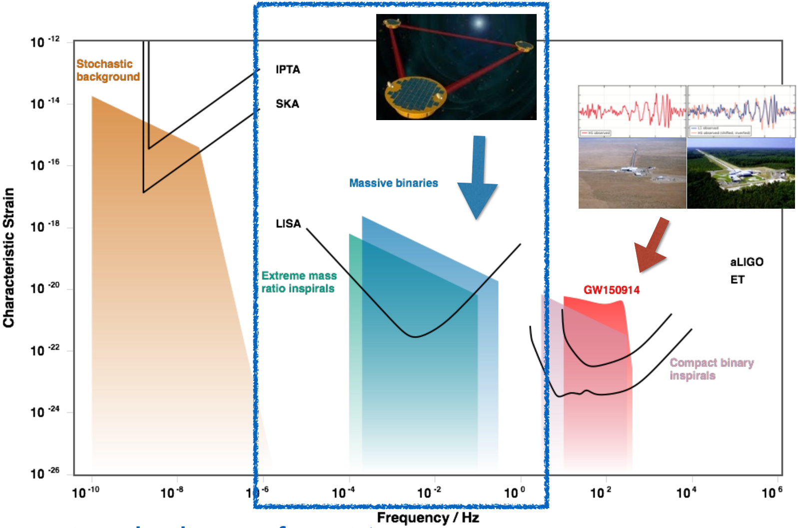
Standard sirens and the H_0 tension

[Ezquiaga & Zumalacarregui, 1807.09241]



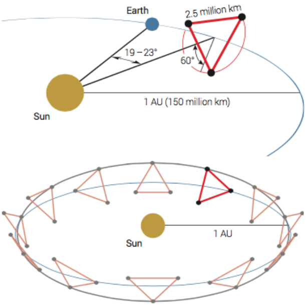
A few % constraints on H_0 with GWs might solve the current tension between local and CMB measurements

The Gravitational Wave Landscape



Standard sirens for LISA

The LISA mission



[lisamission.org]

Laser Interferometric Space Antenna

Design: [arXiv:1702.00786]

- Near-equilateral triangular formation orbiting around the Sun
- 6 laser links (3 active arms)
- Armlength: 2.5 million km
- Mission duration: $\geq$ 4 years
- Launch early 2030s

Main target sources:

- MBHBs: $10^4 - 10^7\, M_\odot$
- Stellar mass BHBs: $10 - 100\, M_\odot$
- Stochastic background (cosmo/astro)
- Galacric binaries (DWDs, BNSs, ...)
- Extreme mass ratio inspirals (EMRIs)

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

Standard sirens for LISA

Possible standard sirens sources for LISA:

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

Characteristics of Massive BHB mergers:

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

Standard sirens for LISA

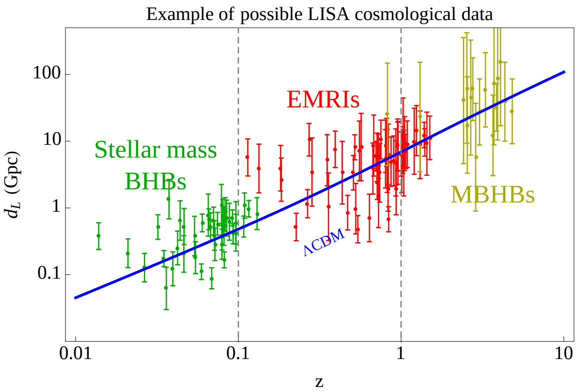
Possible standard sirens sources for LISA:

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

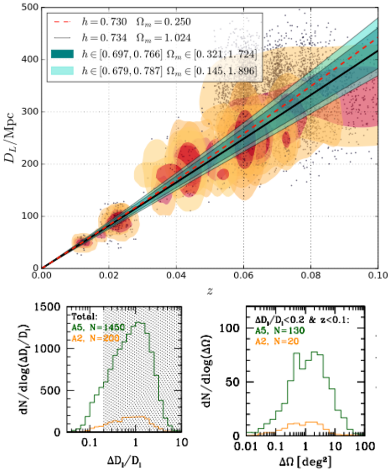
Characteristics of StMBHBs and EMRIs:

- 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]

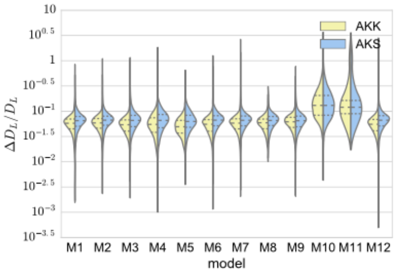


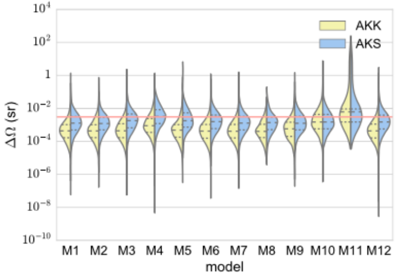
- *Redshift range*: $z \lesssim 0.1$
- *Method*: without counterparts
- *Expected detections*: $\sim 50/\mathrm{yr}$
- *Useful standard sirens*: $\sim 5/\mathrm{yr}$
- *Average LISA errors*:
  - $\Delta d_L/d_L < 20\%$
  - $\Delta\Omega \sim 1\,\mathrm{deg}^2$
- *Results*: H_0 to few %

[Del Pozzo *et al*, 1703.01300]

[Kyutoku & Seto, 1609.07142]

Standard sirens for LISA: EMRIs



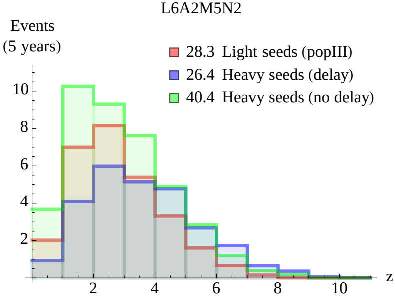


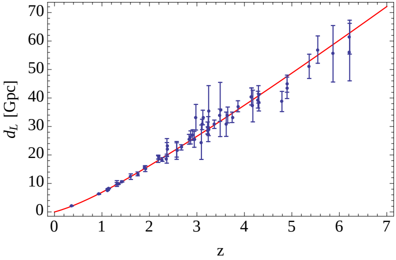
- *Redshift range*: $0.1 \lesssim z \lesssim 1$
- *Method*: without counterparts
- *Expected detections*:
  $1 - 1000/\mathrm{yr}$
- *Average LISA errors*:
  - $\Delta d_L/d_L \lesssim$ few %
  - $\Delta\Omega \lesssim$ few deg^2
- *Useful standard sirens*: ?
- *Results*: H_0 to $\sim$1% with 20 EMRIs 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*: <u>with counterparts</u>
- *Expected detections*: $10 - 100/\mathrm{yr}$
- *Average LISA errors*:
  - $\Delta d_L/d_L \lesssim$ few % (inc. lensing)
  - $\Delta\Omega < 10\,\mathrm{deg}^2$
- *Useful standard sirens*:

  $\sim 5/\mathrm{yr}$ (with counterpart)
- *Results*:
  - H_0 to $\sim$ few %

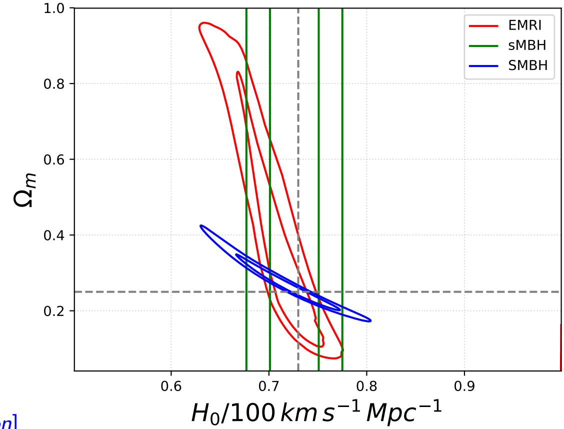
[Tamanini *et al*, 1601.07112]

[Belgacem *et al* (LISA CosWG), 1906.01593]

Combined cosmological analysis with all LISA sources

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

Preliminary results: **Realistic case** for ΛCDM



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

MBHBs: data simulation approach

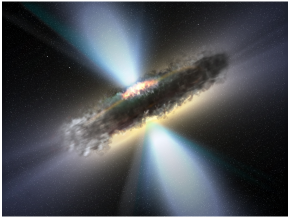
To obtain cosmological forecasts, we have adopted the following **realistic strategy**:

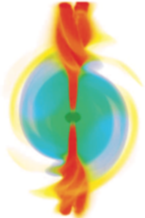
[Tamanini, Caprini, Barausse, Sesana, Klein, Petiteau, arXiv:1601.07112]

- 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)

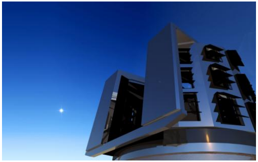
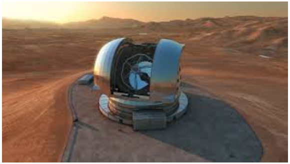




MBHBs: data simulation approach

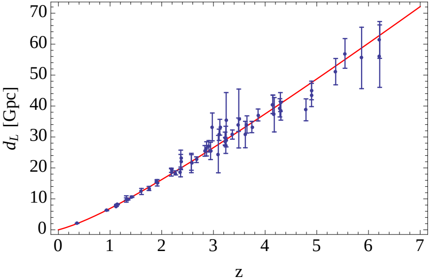
Finally **to detect the EM counterpart** of an LISA event sufficiently localized in the sky we use the following two methods:

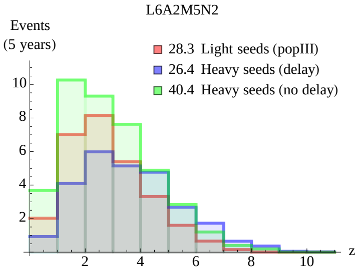
- **LSST**: direct detection of optical counterpart
- **SKA + E-ELT**: first use SKA to detect a radio emission from the BHs and pinpoint the hosting galaxy in the sky, then aim E-ELT in that direction to measure the redshift from a possible optical counterpart either
  - Spectroscopically or Photometrically


MBHBs: standard sirens rate

Example of simulated catalogue of MBHB standard sirens:





Note 1: LISA will be able to map the expansion at very high redshifts (data up to $z \sim 6$), while SNIa can only reach $z \sim 1.5$

Note 2: Few MBHBs at low redshift $\Rightarrow$ bad for DE (but one can use SNIa and other GW sources there)

MBHBs: beyond ΛCDM

The LISA high redshift MBHB data will also be useful to probe cosmologies beyond ΛCDM:

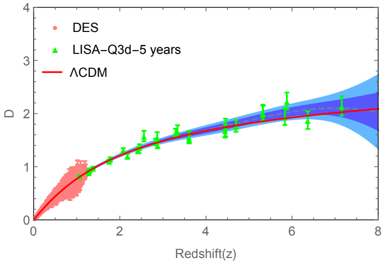
Alternative cosmologies:

- Early dark energy

[Caprini & Tamanini, 1607.08755]

- Interacting dark energy

[Cai, Tamanini, Yang, 1703.07323]



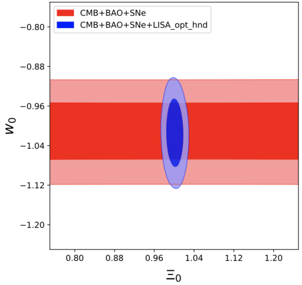
Modified gravity:

Different GW propagation gives a different measured value of d_L

$$\boxed{\frac{d_L^{GW}}{d_L^{EM}} = \Xi_0 + \frac{1-\Xi_0}{(1+z^n)}}$$

[Belgacem et al, 1805.08731]

[LISA CosWG, 1906.01593]



Propagation of GW in modified gravity

In **standard GR**:

$$h'' + 2\mathcal{H}h' + k^2 h = 0 \quad \Rightarrow \quad h \propto 1/d_L(z)$$

For **modified gravity** (with $c_{gw} = c$ and $m_{gw} = 0$):

$$h'' + 2\mathcal{H}[1 - \delta(\eta)]h' + k^2 h = 0 \quad \Rightarrow \quad h \propto 1/\tilde{d}_L(z)$$

where

$$\tilde{d}_L(z) = d_L(z) \exp\left\{ -\int_0^z \frac{dz'}{1+z'} \delta(z') \right\}$$

$\Rightarrow$ Parameter estimation over the GW signal will yield $d_L^{GW}(z) = \tilde{d}_L(z)$ while the "true" value of the luminosity distance is the one measured with EM observation $d_L^{EM}(z) = d_L(z)$

[Deffayet & Menou (2007); Saltas et al (2014); Lombrisier & Taylor (2016); Nishizawa (2017); Belgacem et al (2017,2018)]

Propagation of GW in modified gravity

By comparing the GW measurement of d_L^{GW} with a corresponding measurement of d_L^{EM} (from EM counterpart) one can constrain $\delta(z)$:

$$d_L^{GW}(z) = d_L^{EM}(z) \exp\left\{ -\int_0^z \frac{dz'}{1+z'} \delta(z') \right\}$$

A simple and quite general parametrization for $\delta(z)$ is the following: [Belgacem et al, 1805.08731]

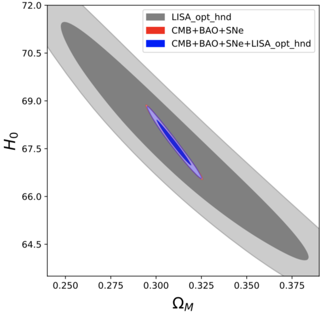
$$\boxed{\frac{d_L^{GW}}{d_L^{EM}} = \Xi_0 + \frac{1-\Xi_0}{(1+z^n)}}$$

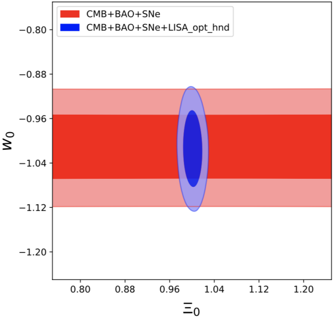
Well approximate several modified gravity models of dark energy: Horndeski, Scalar-Tensor, RR/RT models (non-local gravity), ...

Testing modified GW propagation with LISA MBHBs

LISA MBHBs (with EM counterpart) at high redshift will be extremely useful to constrain DE and modified GW propagation:

[Belgacem *et al* (LISA CosWG), 1906.01593]





Ξ_0 constrained at the $\sim$2% level

Future work for LISA

Future perspectives for LISA standard sirens:

- Check the cosmological potential of EMRIs
- Improve MBHB standard siren catalogs
  (formation, counterpart modelling and detection)
- Combine all LISA sources into a single cosmological analysis
- Combine LISA forecasts with future EM forecasts
- Analyse various modified gravity models
- Investigate other observable effects on the propagation of GWs

Summary

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:
  SOBHBs (no EM cp), NSBs (EM cp) and NS-BH (?)
- First standard siren just discovered: GW170817
- Future observations useful for tension in H_0

Standard sirens for LISA:

- Three possible sources:
  SOBHBs (no EM cp), EMRIs (no EM cp), MBHBs (EM cp)
- Probing the cosmic expansion from $z \sim 0.01$ to $z \sim 10$
- Tests of alternative cosmological models and modified gravity