Standard sirens: cosmology with gravitational waves

Nicola Tamanini

Max Planck Institute for Gravitational Physics (Albert Einstein Institute)

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut)

LIGO Scientific Collaboration

LISA

Outline

- Standard siren: theory and methodology
  - with EM counterpart
  - without EM counterpart
- Standard sirens for LIGO/VIRGO
  - Current status of Earth-based GW detectors
  - Possible GW sources used as standard sirens
  - GW170817
  - Future prospects
- Standard sirens for LISA
  - Mission design and roadmap
  - Possible sources used as standard siren
  - Current cosmological forecasts
  - Future prospects

The concept of standard siren

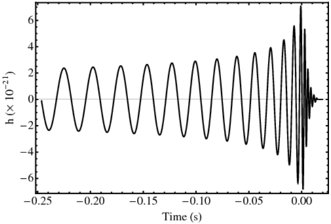
The luminosity distance can be inferred directly from the measured waveform produced by a binary system

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

$\Rightarrow$ 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



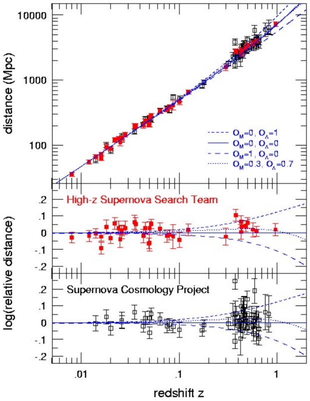
The distance-redshift relation

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

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 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**)

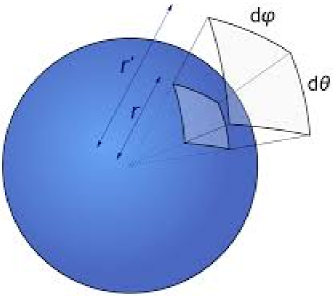
With GW:

- Measuring distance is easy: directly from the waveform (**standard sirens**)
- Measuring redshift is hard:
  - Degeneracy with masses in the waveform (GR is scale-free)
  - 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

Standard sirens without counterparts

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

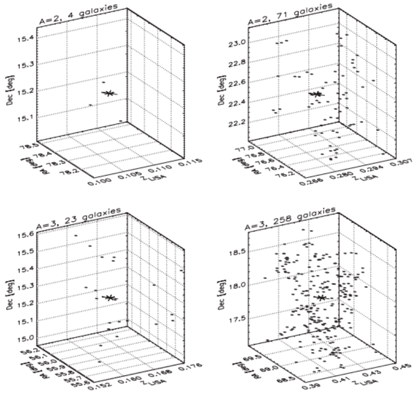
The idea is the following:
consider each galaxy within the volume error box ($d\Omega \times dz$) of the GW source to have a non-zero probability of being the hosting galaxy and then statistically add up the information coming from all the galaxies in all boxes, with enough GW events the true value of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



Standard sirens without counterparts

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

<u>The idea is the following</u>: 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

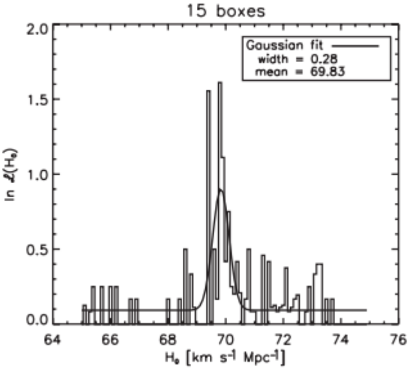


[MacLeod & Hogan, 0712.0618]

Standard sirens without counterparts

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

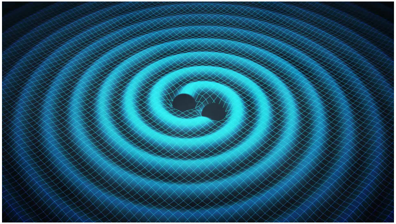
The idea is the following:
consider each galaxy within the volume error box ($d\Omega \times dz$) of the GW source to have a non-zero probability of being the hosting galaxy and then statistically add up the information coming from all the galaxies in all boxes, with enough GW events the true value of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

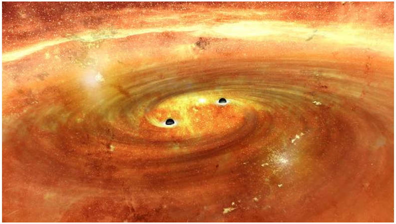


[MacLeod & Hogan, 0712.0618]

What sources can be used as standard sirens?

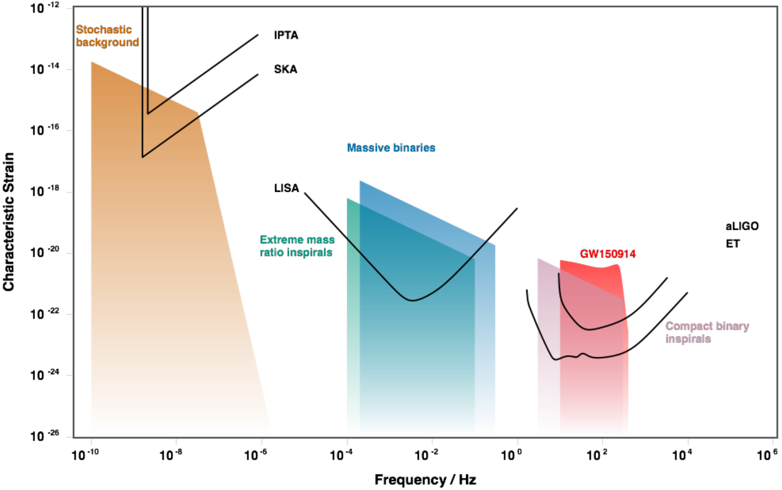
- How many **standard sirens** will be detected by LIGO/VIRGO?
- How many by LISA?



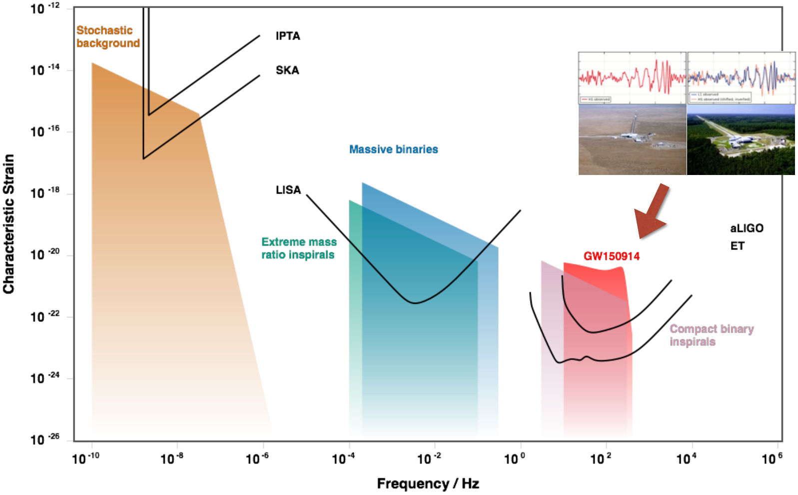


- What type of sources can be used?
- For how many it will be possible to observe a counterpart?

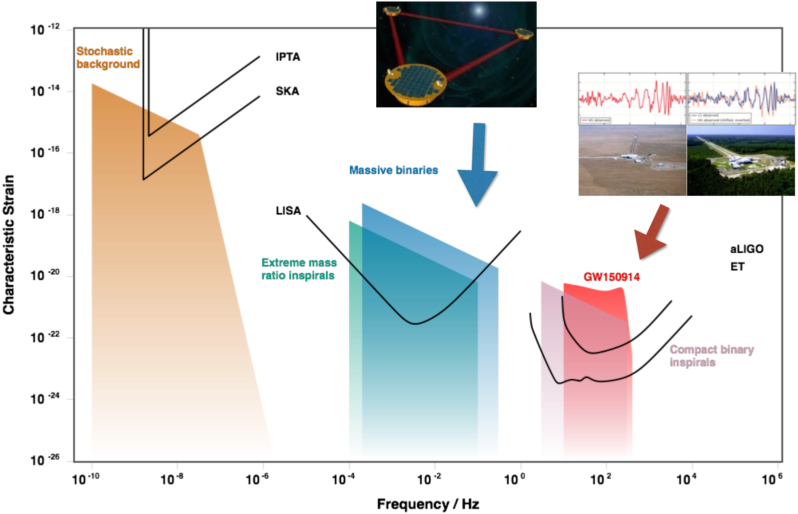
The Gravitational Wave Landscape



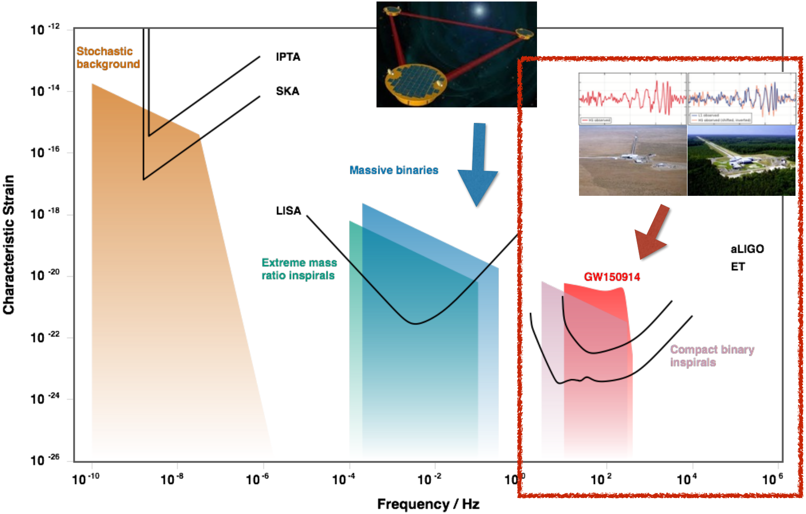
The Gravitational Wave Landscape



The Gravitational Wave Landscape

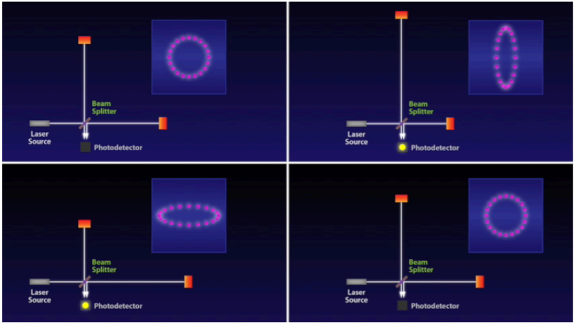


The Gravitational Wave Landscape



Standard sirens for LIGO/VIRGO

Earth-based detectors: current status and next future



Main target sources:

- stellar mass BHBs ($1 - 100\, M_\odot$) ✓
- NSBs ✓
- NS-BH binaries ✗
- Supernovae ✗
- Periodic sources ✗

Earth-based detectors: current status and next future

Roadmap for Earth-based interferometers:

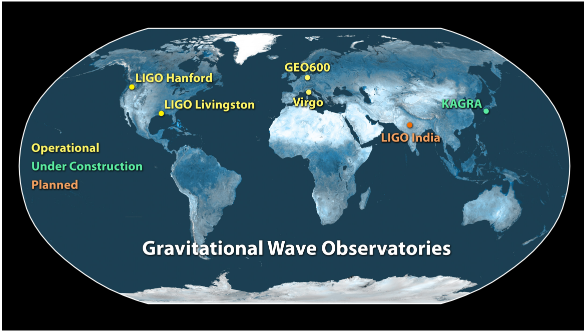
O1: 2015 (completed), LIGO only, 4 months of data,
2 BHBs detected **(GW150914, GW151226)**

O2: 2016 (completed), LIGO+VIRGO(only GW1708xx), 6 months of observations, 3 BHBs **(GW170104,GW170608,GW170814)** + 1 NSB **(GW170817)**

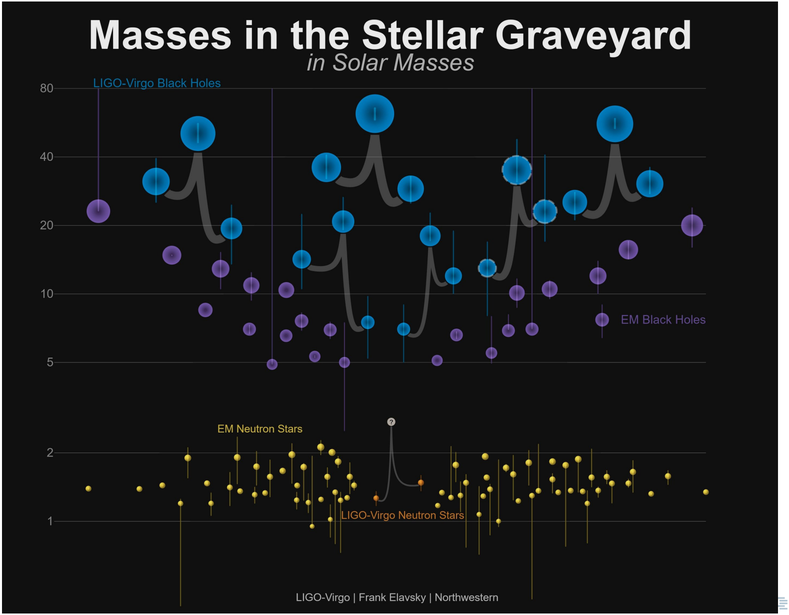
O3: 2018 (planned), LIGO + VIRGO, 9 months observations

O4: 2020 LIGO + VIRGO + KAGRA(?)

O?: ∼2022 LIGO India should join



The Black Hole Landscape



Standard sirens for LIGO/VIRGO

Possible standard sirens sources for LIGO/VIRGO:

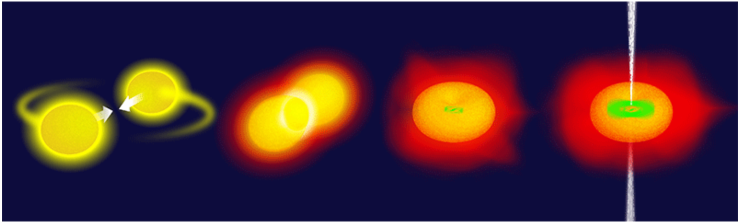
- Neutron Star binaries ($\sim 1.4\, M_\odot$)
- NS-BH binaries ($1 - 10\, M_\odot$)
- Stellar origin BHBs ($10 - 100\, M_\odot$)

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 ($10 - 100\, M_\odot$)

Characteristics of NS inspiral:

- Very-low redshifts ($\lesssim 0.01$)
- Production of GRBs and kilonovae at merger $\rightarrow$ *EM counterparts expected!*



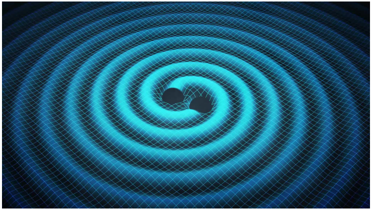
Standard sirens for LIGO/VIRGO

Possible standard sirens sources for LIGO/VIRGO:

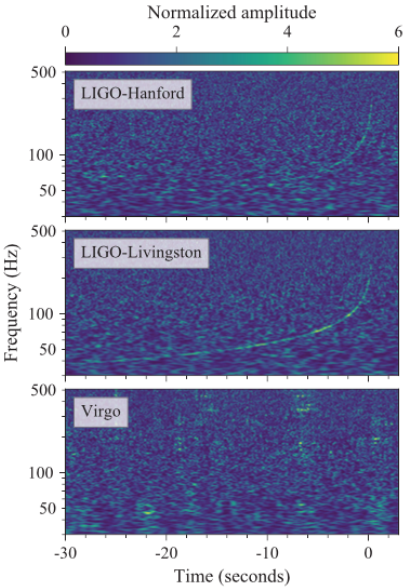
- Neutron Star binaries ($\sim 1.4\, M_\odot$)
- NS-BH binaries ($1 - 10\, M_\odot$)
- Stellar origin BHBs ($10 - 100\, M_\odot$)

Characteristics of SOBHBs:

- High SNR $\rightarrow$ good sky location with LIGO+VIRGO
- Low redshifts ($\lesssim 0.1$)
- Gas poor environment $\rightarrow$ *No EM counterparts expected!*

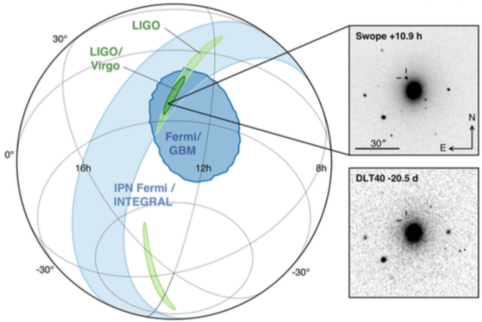


GW170817: the first ever standard siren [1710.05832]

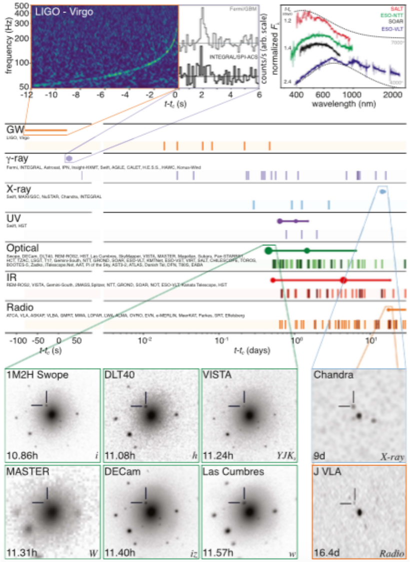


Detection of a NSB inspiral:

- Primary mass: $1.4 - 1.6\, M_\odot$
- Secondary mass: $1.2 - 1.4\, M_\odot$
- Luminosity distance: 40^{+8}_{-14} Mpc

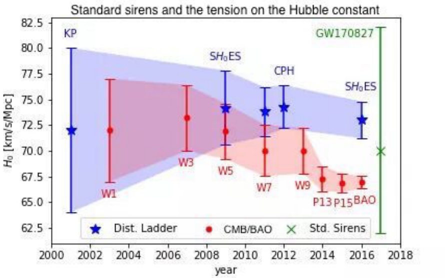


GW170817: the first ever standard siren [1710.05832]



- First ever detection of the EM counterpart of a GW event [1710.05833]
- From EM observations 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)

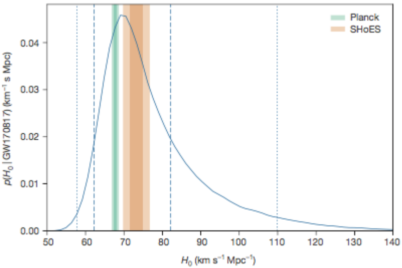
$$d_L = c\frac{z}{H_0}$$

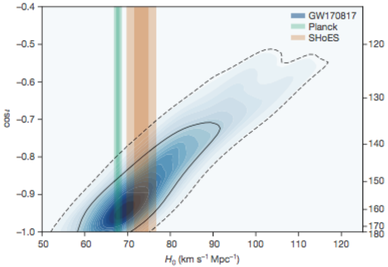


New independent measure of H_0 with GW170817 [1710.05835]

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

$\Rightarrow$ future data can be used to solve the tension between CMB and local measurements





Future prospects for Earth-based GW detectors

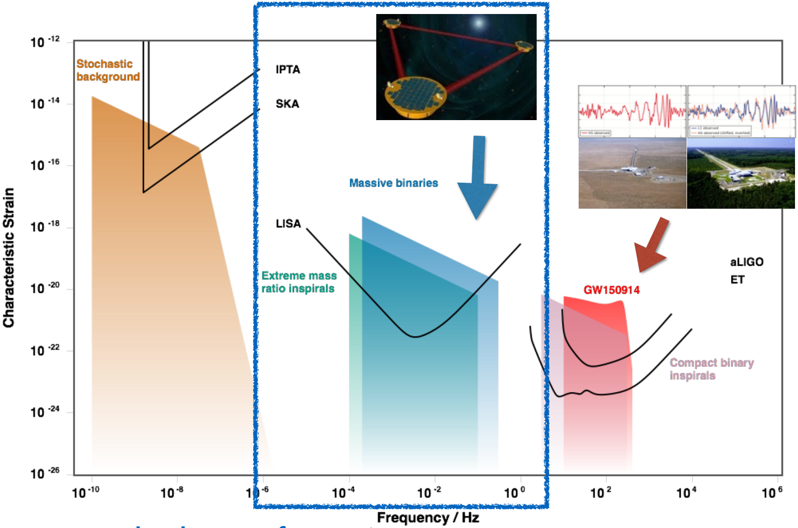
Cosmological forecasts for LIGO/VIRGO: [1612.06060,1710.06424]

- few % constraints on H_0 can be obtained either
  - with ~ 50 standard sirens with EM counterpart (NSBs)
  - with ~ 100 standard sirens without EM counterpart (BHBs)
- This accuracy will be achieved in the next years, but probably not with O3
- No estimates with NS-BH binary mergers yet

Cosmological forecasts for ET: [0906.4151]

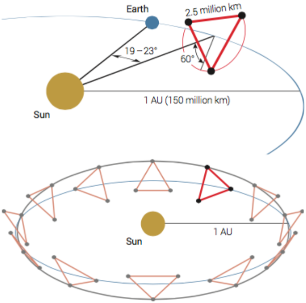
- ET will detect thousands of NSB and BHB mergers up to $z \sim 3$
- Precise probe of the cosmic expansion at large redshifts
- Accurate measurement of the cosmological parameters

The Gravitational Wave Landscape



Standard sirens for LISA

The LISA mission



[lisamission.org]

Laser Interferometric Space Antenna

Proposed 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

Main target sources:

- MBHBs: $10^4 - 10^7\ M_\odot$
- Stellar mass BHBs: $10 - 100\ M_\odot$
- Stochastic background: astrophysical & cosmological origin
- Extreme mass ratio inspirals (EMRIs)

LISA: current status and roadmap

LISA roadmap:

- ESA L3 slot selected for a GW mission (2013)
- Pathfinder mission (2015→2017): [lisapathfinder.org]
  - Free fall and interferometric technology tested
  - **Noise tested at the LISA requirement!**
- Call for L3 mission: [arXiv:1702.00786]
  - **LISA mission selected by ESA in June 2017**
- Proposed design (result of GOAT studies with LISA WGs):
  - 3 arms + 2.5 Gm armlength + 4 years nominal duration
- Technological R&D phase (2017→2022)
  - Test laser and telescope technology (industry)
- Space system development (2022→2030)
- LAUNCH ∼2030-2034

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:

- 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 ∼10-15)
- Merger within LISA band ↴
- Gas rich environment → *EM counterparts expected!*

Standard sirens for LISA

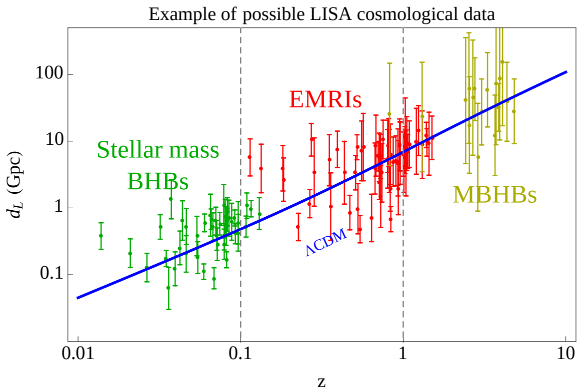
Possible standard sirens sources for LISA:

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

Characteristics of StMBHBs and EMRIs:

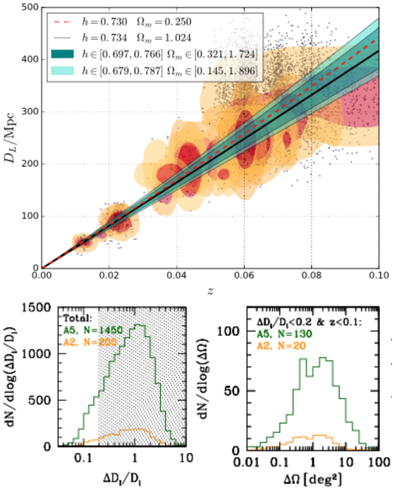
- Low redshifts ($\lesssim 0.1$ for StBHBs and $\lesssim 1$ for EMRIs)
- Merger outside the LISA band (StMBHBs)$\neg$
- Gas poor environment → *No EM counterparts expected!*

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: stellar mass BHBs

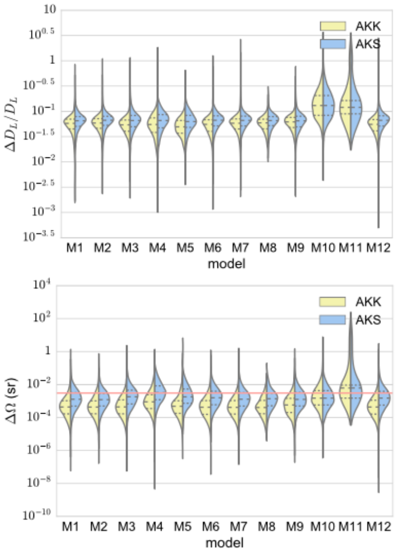


- *Redshift range*: $z \lesssim 0.1$
- *Method*: without counterparts
- *Expected detections*: $\sim 50/\mathrm{yr}$
- *Useful standard sirens*: $\sim 5/\mathrm{yr}$
- *Average LISA errors*:
  - $\Delta d_L/d_L < 20\%$
  - $\Delta\Omega \sim 1\,\mathrm{deg}^2$
- *Results*: H_0 to few %

[Del Pozzo *et al*, 1703.01300]

[Kyutoku & Seto, 1609.07142]

Standard sirens for LISA: EMRIs

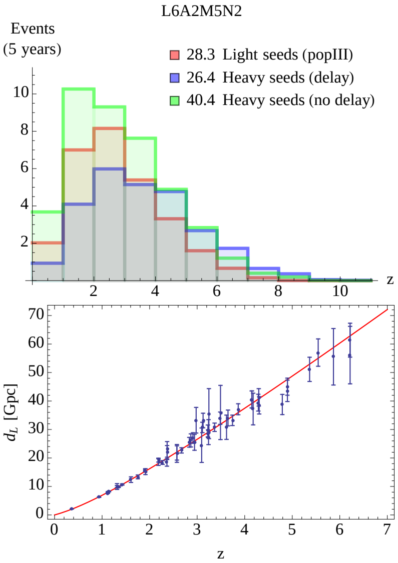


- *Redshift range*: $0.1 \lesssim z \lesssim 1$
- *Method*: without counterparts
- *Expected detections*:
  $1 - 1000/\mathrm{yr}$
- *Average LISA errors*:
  - $\Delta d_L/d_L \lesssim$ few %
  - $\Delta\Omega \lesssim$ few deg^2
- *Useful standard sirens*: ?
- *Results*: H_0 to $\sim$1% with 20 EMRIs 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*: with counterparts
- *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*:
  $\sim 6/\mathrm{yr}$ (with counterpart)
- *Results*:
  - H_0 to $\sim$1%
  - w_0 to $\sim$ 15%

[Tamanini *et al*, 1601.07112]

MBHBs: data simulation approach

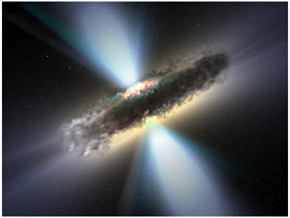
To obtain cosmological forecasts, we have adopted the following **realistic strategy**:

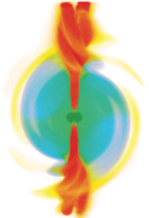
[NT, Caprini, Barausse, Sesana, Klein, Petiteau, arXiv:1601.07112]

- 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)

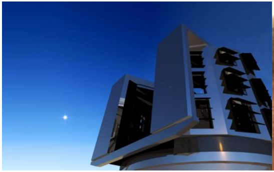
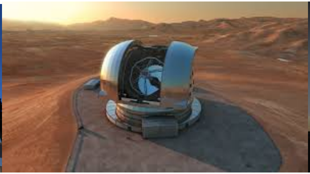




MBHBs: data simulation approach

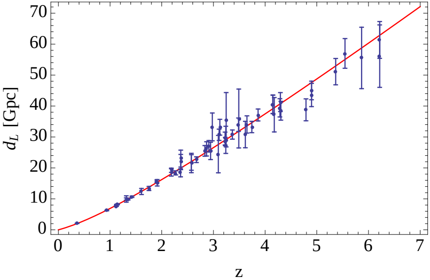
Finally **to detect the EM counterpart** of an LISA event sufficiently localized in the sky we use the following two methods:

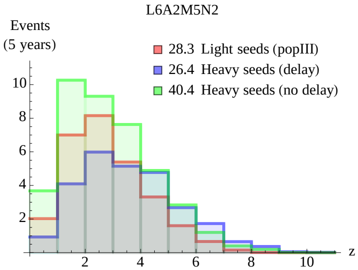
- **LSST**: direct detection of optical counterpart
- **SKA + E-ELT**: first use SKA to detect a radio emission from the BHs and pinpoint the hosting galaxy in the sky, then aim E-ELT in that direction to measure the redshift from a possible optical counterpart either
  - Spectroscopically or Photometrically


MBHBs: standard sirens rate

Example of simulated catalogue of MBHB standard sirens:





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 on can use SNIa and other GW sources)

LISA forecasts: standard cosmological models

We first analysed the following 3 cosmological models:

- Λ**CDM**:
  - 2 parameters (Ω_M, h)
  - fix $\Omega_M + \Omega_\Lambda = 1$, $w_0 = -1$ & $w_a = 0$
- Λ**CDM + curvature**:
  - 3 parameters $(\Omega_M, \Omega_\Lambda, h)$
  - fix $w_0 = -1$ & $w_a = 0$
- **Dynamical dark energy**: $w = w_0 + \frac{z}{z+1} w_a$
  - 2 parameters (w_0, w_a)
  - $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ & $h = 0.67$

Performing a **Fisher matrix** analysis from the simulated data:

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

MBHBs: cosmological parameter constraints

RESULTS: [NT et al, arXiv:1601.07112]

1σ constraints with 5 million km armlength:

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

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

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

- Similar results with 1 or 2 million km armlength

MBHBs: cosmological parameter constraints

RESULTS: [NT et al, arXiv:1601.07112]

1σ constraints with 5 million km armlength:

$$\textbf{ΛCDM:} \begin{cases} \Delta\Omega_M & \simeq 0.025 \quad (8\%) \\ \Delta h & \simeq 0.013 \quad (2\%) < 1\% \text{ (with Planck)} \end{cases}$$

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

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

- Similar results with 1 or 2 million km armlength

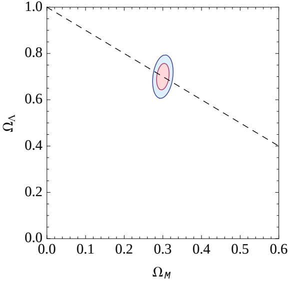
Comparing with Supernovae (ΛCDM):

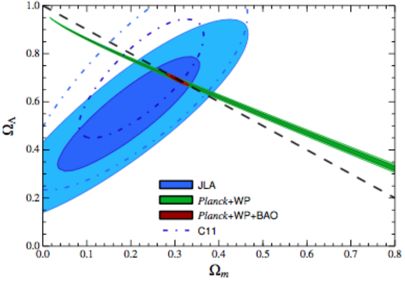
Expected from LISA:

$$\Omega_M = 0.3 \pm 0.009$$

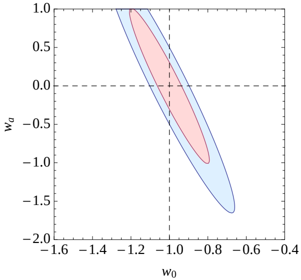
From today SNe: [Betoule *et al* (2014)]

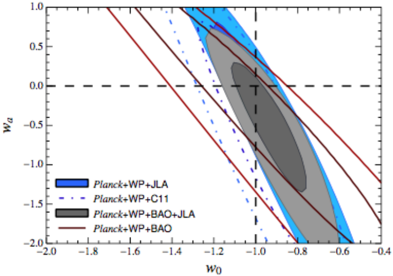
$$\Omega_M = 0.289 \pm 0.018$$





Comparing with SNIa/CMB/BAO (dark energy):





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

$$w_0 = -1.00 \pm 0.16$$
$$w_a = 0.00 \pm 0.83$$

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

$$w_0 = -1.073 \pm 0.146$$
$$w_a = -0.066 \pm 0.563$$

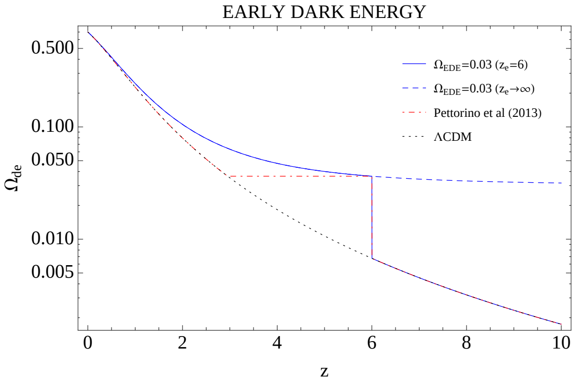
LISA forecasts: alternative cosmological models

Investigation of alternative cosmological models:

[C. Caprini & NT, arXiv:1607.08755]

- Same approach to construct standard sirens catalogues and analyse data
- Focus on interesting and simple phenomenological models:
  - **Early dark energy** (EDE): non-negligible amount of DE at early times [arXiv:1301.5279]
  - **Interacting dark energy** (IDE): mild indications for a non-vanishing late-time dark interaction [arXiv:1406.7297]
- Deviations from ΛCDM allowed only up to a determined redshift (z_e, z_i)

LISA forecasts: alternative cosmological models

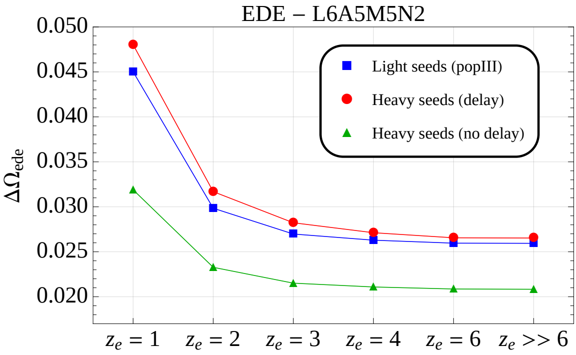


Early dark energy: non negligible DE energy density at early times: $\Omega_{de}(z) \to \Omega_{de}^{e} \neq 0$ as $z \to \infty$

$$\Omega_{de}(z) = \frac{\Omega_{de}^{0} - \Omega_{de}^{e}\left[1 - (z+1)^{3w_0}\right]}{\Omega_{de}^{0} + \Omega_{m}^{0}(z+1)^{-3w_0}} + \Omega_{de}^{e}\left[1 - (z+1)^{3w_0}\right]$$

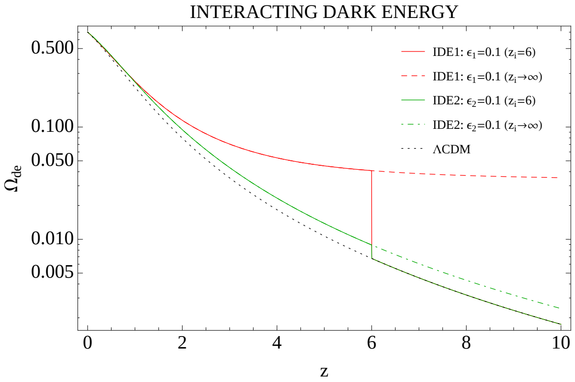
LISA forecasts: alternative cosmological models

Results for EDE: [C. Caprini & NT, arXiv:1607.08755]



- If $z_e \gtrsim 10$ then strong constraints from CMB: $\Delta\Omega_{\rm ede} = 0.0036$ [Planck, 2015]
- However if $z_e \lesssim 10$ then CMB results do not apply and only LISA can constrain deviations from ΛCDM

LISA forecasts: alternative cosmological models



IDE1:
$Q = 3H\epsilon_1\rho_{dm}$

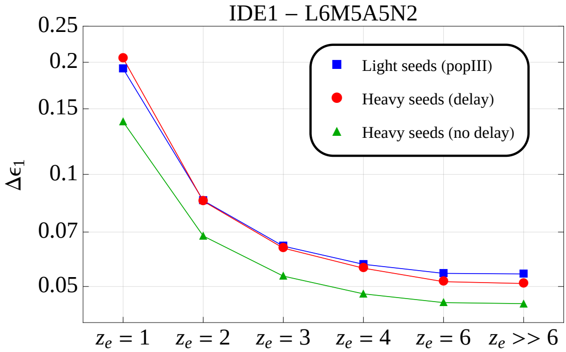
IDE2:
$Q = 3H\epsilon_2\rho_{de}$

Interacting dark energy:
non-gravitational interaction between DM and DE

$$\dot{\rho}_{dm} + 3H\rho_{dm} = Q \qquad \dot{\rho}_{de} + 3H(1+w_0)\rho_{de} = -Q$$

LISA forecasts: alternative cosmological models

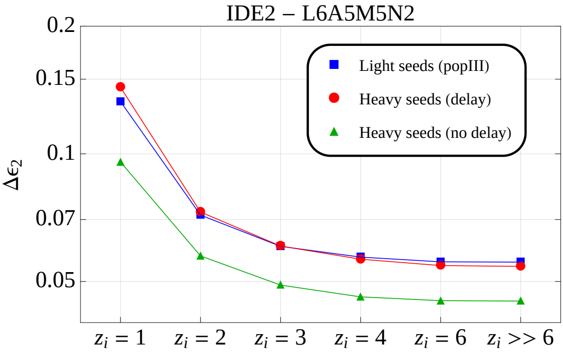
Results for IDE1: [C. Caprini & NT, arXiv:1607.08755]



- If $z_i \gg 10$ present constraints are better by two order of magnitude: $\sim 10^{-4}$ (Planck+SNIa+BAO+H_0) [1506.06349, 1605.04138]
- No analyses with current data if $z_i \lesssim 10$

LISA forecasts: alternative cosmological models

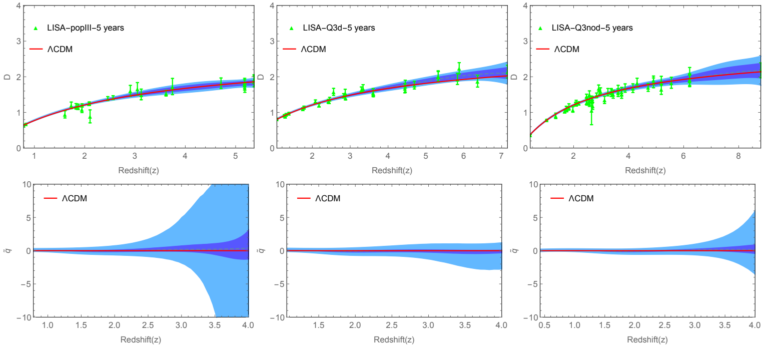
Results for IDE2: [C. Caprini & NT, arXiv:1607.08755]



- If $z_i \gg 10$ presents constraints give comparable results: $\sim 10^{-2}$ (Planck+SNIa+BAO+H_0) [1506.06349, 1607.05567]
- If $z_i \lesssim 10$ then LISA is expected to perform much better

LISA forecasts: reconstructing the dark sector interaction

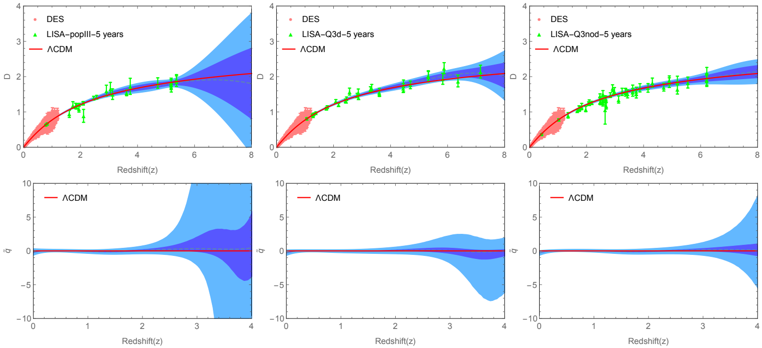
Using Gaussian processes to reconstruct the interaction in a model independent way [Cai, NT, Yang, arXiv:1703.07323]



LISA MBHB standard sirens reconstruct the interaction well for $1 \lesssim z \lesssim 3$ (5 yr) and $1 \lesssim z \lesssim 5$ (10 yr)

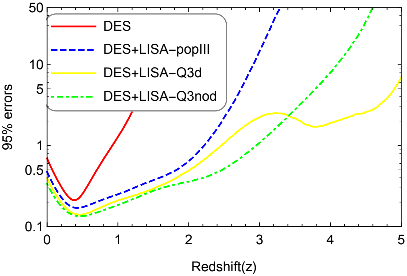
LISA forecasts: reconstructing the dark sector interaction

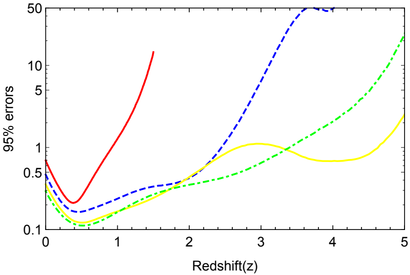
Adding simulated data for DES ($\sim$ 4000 SNIa) help in reconstructing the dark interaction also at low redshift



LISA forecasts: reconstructing the dark sector interaction

LISA cosmological data can thus be used to improve the reconstruction of the dark sector by SNIa at higher redshift





LISA can be used to push beyond-ΛCDM tests at higher redshift

Future work

Future perspectives for LISA cosmology:

- Check the cosmological potential of EMRIs
- Improve MBHB standard siren models (formation and counterpart models)
- Combine all LISA sources into a single cosmological analysis
- Combine LISA forecasts with future EM forecasts
- Analyse other alternative cosmological models

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 $z \sim 10$
- Useful to test H_0 and alternative cosmological models