LATE TIME COSMOLOGY WITH GRAVITATIONAL WAVES:
The potential of the eLISA mission

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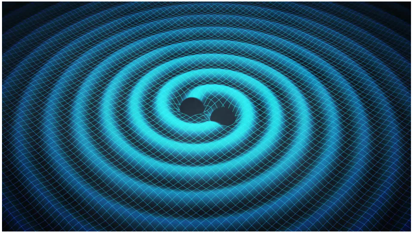
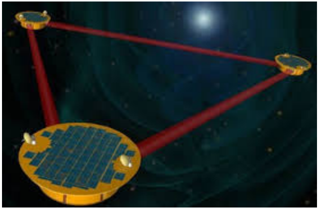


Outline

- **eLISA**:
  - Mission design and current status
- **Standard sirens**:
  - Concept and problems
- **Forecast constraints**:
  - *Approach*: simulation of MBHB mergers, detection by eLISA, observation of EM counterpart
  - *Standard cosmologies*: ΛCDM, curvature, dynamical DE
  - *Alternative cosmologies*: early and interacting DE

eLISA: mission concept & current status



[elisascience.org]

Proposed designs:

- Near-equilateral triangular formation orbiting around the Sun
- Number of laser links: 4 or 6 (2 or 3 active arms)
- Possible armlength: from 1 to 5 million km
- Mission duration: up to 5 years

Main target sources:

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

eLISA: mission concept & current status

eLISA roadmap:

- Expected noise level tested by LISA Pathfinder [lisapathfinder.org]
- ESA L3 slot selected for a GW mission (launch ∼2030-2034)
- Final design to be decided in the next future:
  - Wait for final results from LISA Pathfinder
  - Funding and membership issues (NASA & EU member states)
  - GOAT committee reported on science return [elisascience.org]
    - 3 arms and earlier launch advised for better science
    - Based on recent studies from eLISA science working groups: [Klein et al, arXiv:1511.05581] [Caprini et al, arXiv:1512.06239] [NT et al, arXiv:1601.07112] [Sesana, arXiv:1602.06951]
- Call for mission expected in Autumn 2016
  - Selection in early 2017
  - Then 3-4 years of technological developments
  - Then 10 years to build spacecrafts

eLISA: mission concept & current status

eLISA main science objectives:

- Astrophysics of SMBHs
  - Origin, evolution and mass distribution
  - Role in galaxy formation
  - AGN physics
- Ultra-compact binaries (NSs, WDs, BHs)
  - Abundance, distribution and merger rate
  - Physics of NS and SNe
  - Multi-band GW astronomy with Earth-based detector
- Test of GR
  - Test of BH geometry (Kerr?)
  - Existence of event horizons
  - Mass and speed of gravitons
- Cosmology
  - Early-times: probing the TeV scale in the early universe
  - Late-times: probing the expansion with standard sirens

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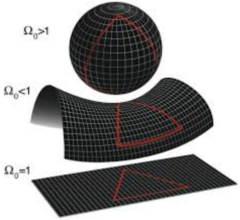
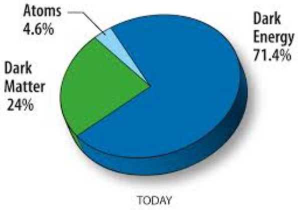
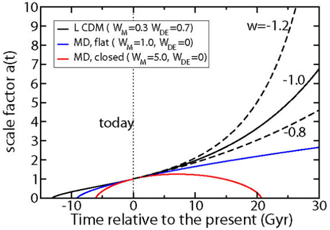
Late-time cosmology with eLISA

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







Late-time cosmology with eLISA: standard sirens

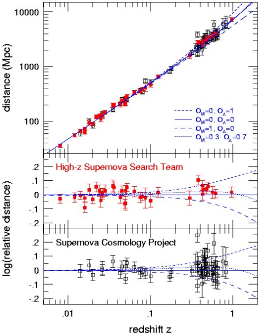
The luminosity distance can be inferred directly from the measured waveform: GW sources are standard distance indicator!

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

If the redshift of the source is known, then one can fit the distance-redshift relation:

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

- Exactly as SNIa $\Rightarrow$ standard sirens
- Need an EM counterpart!



Late-time cosmology with eLISA: standard sirens

With EM waves:

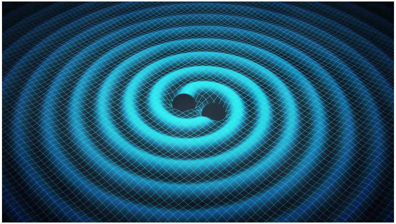
- Measuring redshift is easy: compare EM spectra
- Measuring distance is hard: need objects of known luminosity (SNIa $\rightarrow$ **standard candles**)

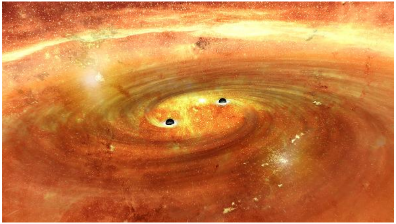
With GW:

- 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

Late-time cosmology with eLISA: standard sirens

- How many **standard sirens** will be detected by eLISA?





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

Late-time cosmology with eLISA: standard sirens

Possible standard sirens sources for eLISA:

- MBHBs ($10^4 - 10^7\ M_\odot$)
- LIGO-like BHBs ($10 - 100\ M_\odot$)
- EMRIs

Late-time cosmology with eLISA: standard sirens

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Advantages of MBHB mergers:

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

eLISA cosmological forecasts: data simulation approach

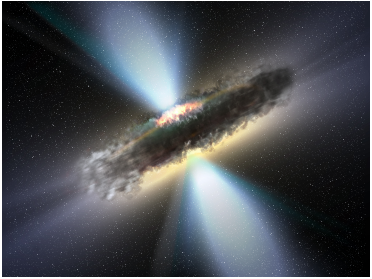
To address these questions and obtain cosmological forecasts, we have adopted the following **realistic strategy**:

[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 eLISA** (SNR>8)
- Among these select the ones with a **good sky location accuracy** ($\Delta\Omega < 10\,\mathrm{deg}^2$)
- Focus on **5 years** eLISA mission (the longer the better for cosmology)

eLISA cosmological forecasts: data simulation approach

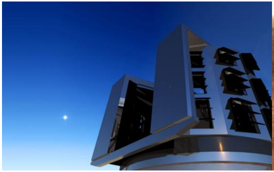
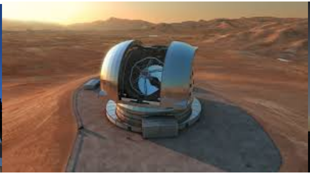
- **To model the counterpart** we generally consider two mechanisms of EM emission at merger: (based on [arXiv:1005.1067])
  - A quasar-like luminosity **flare** (optical)
  - Magnetic field induced **flare** and **jet** (radio)
- Magnitude of EM emission computed using data from simulations of MBHBs and galactic evolution



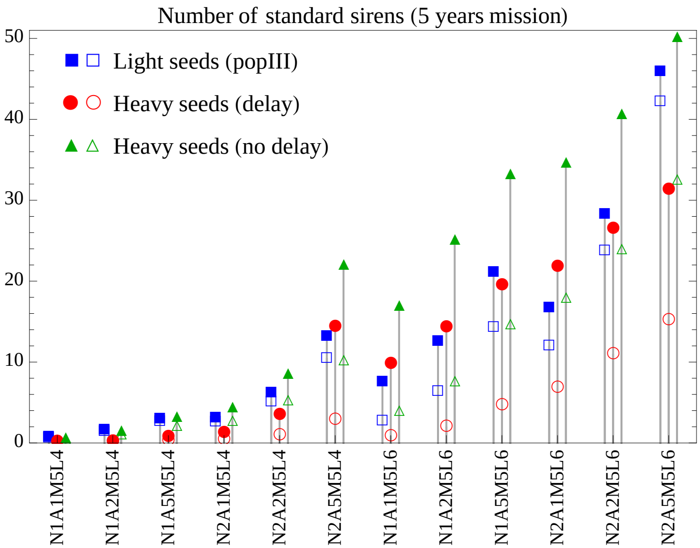
eLISA cosmological forecasts: data simulation approach

Finally **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

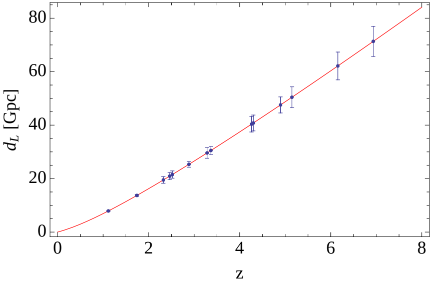



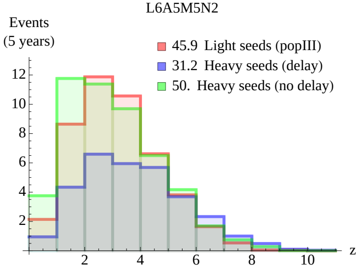

eLISA cosmological forecasts: MBHB standard sirens rate



eLISA cosmological forecasts: MBHB standard sirens rate

Example of simulated catalogue of MBHB standard sirens:





Note 1: eLISA will be able to map the expansion at very high redshifts (data up to $z \sim 8$), while SNIa can only reach $z \sim 1.5$

Note 2: Few data at low redshift $\Rightarrow$ bad for DE (but can use SNIa)

eLISA forecasts: standard cosmological models

We first analysed the following 3 cosmological models:

- **ΛCDM**:
  - 2 parameters (Ω_M, h)
  - fix $\Omega_M + \Omega_\Lambda = 1$, $w_0 = -1$ & $w_a = 0$
- **ΛCDM + 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:

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

eLISA forecasts: standard cosmological models

RESULTS: [NT et al, arXiv:1601.07112]

1σ constraints with L6A5M5N2 (best possible configuration):

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

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

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

- Similar results with A2 and A1, but much worst with L4

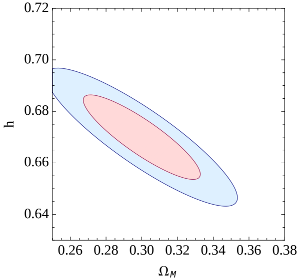
Comparing with CMB (ΛCDM):

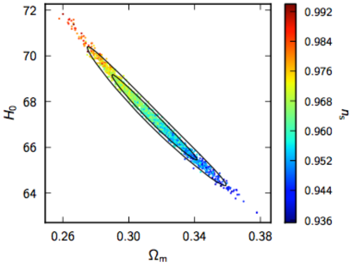
From L6A5M5N2 with ΛCDM:

$$\begin{cases} \Omega_M = 0.3 \pm 0.025 \\ \Omega_\Lambda = 0.7 \pm 0.025 \\ H_0 = 67 \pm 1.3\,\mathrm{km/s/Mpc} \end{cases}$$

From today CMB [Planck2015]:

$$\begin{cases} \Omega_M = 0.3121 \pm 0.0087 \\ \Omega_\Lambda = 0.6879 \pm 0.0087 \\ H_0 = 67.51 \pm 0.64\,\mathrm{km/s/Mpc} \end{cases}$$





eLISA forecasts: standard cosmological models

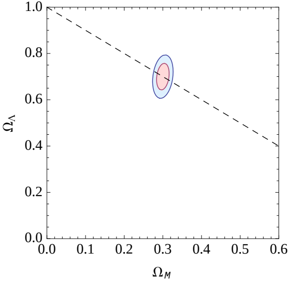
Comparing with Supernovae (ΛCDM):

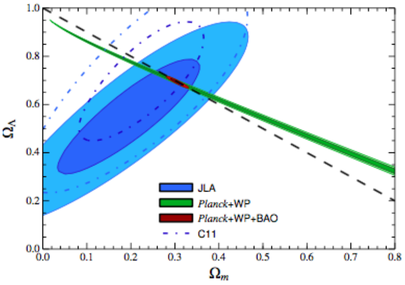
Expected from L6A5M5N2:

$$\Omega_M = 0.3 \pm 0.009$$

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

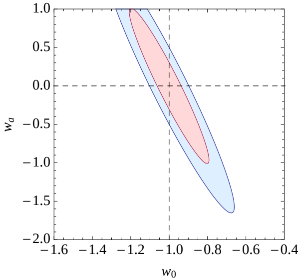
$$\Omega_M = 0.289 \pm 0.018$$

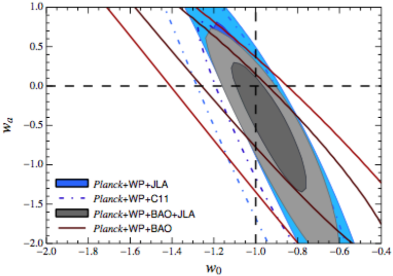




eLISA forecasts: standard cosmological models

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





Expected from L6A5M5N2:
(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)]

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

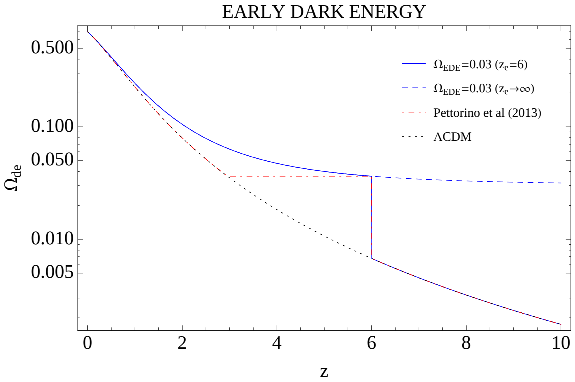
eLISA forecasts: alternative cosmological models

Investigation of alternative cosmological models:

[C. Caprini & NT, arXiv:1607.08755]

- Same approach to construct standard sirens catalogues
- Focus on simple phenomenological models:
  - Early dark energy (EDE)
  - Interacting dark energy (IDE)
- Deviations from ΛCDM allowed only up to a determined redshift (z_e, z_i)

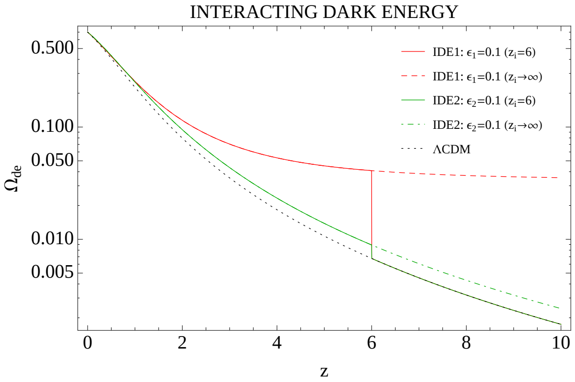
eLISA forecasts: alternative cosmological models



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

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

eLISA forecasts: alternative cosmological models



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

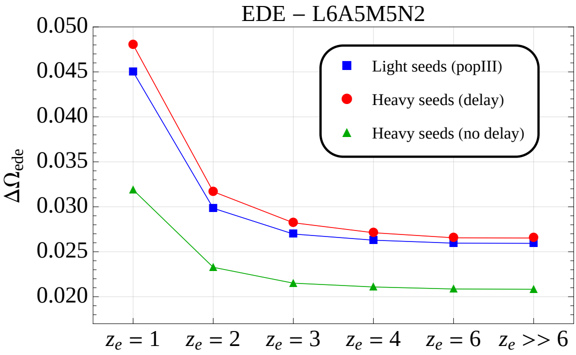
IDE2:
$Q = 3H\epsilon_2\rho_{de}$

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

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

eLISA forecasts: alternative cosmological models

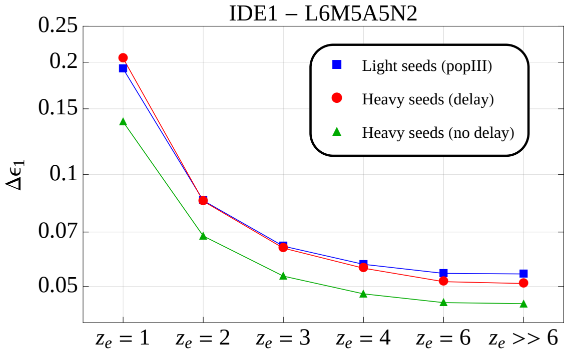
Results for EDE: [C. Caprini & NT, arXiv:1607.08755]



- 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 eLISA can constrain deviations from ΛCDM

eLISA forecasts: alternative cosmological models

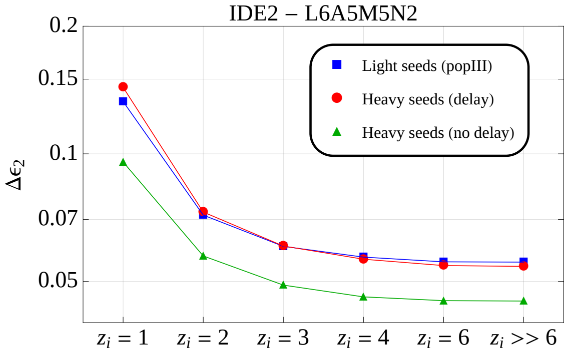
Results for IDE1: [C. Caprini & NT, arXiv:1607.08755]



- 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 $z_i \lesssim 10$

eLISA 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 eLISA is expected to perform much better

eLISA cosmological forecasts: future prospects

Possible further work:

- Exploit other eLISA GW sources for cosmology (lower z) (this will improve the results from MBHBs only)
  - EMRI
  - LIGO-like BH binaries
- Cosmology with multi-band GW observations
- Cross correlation with galaxy catalogues: anisotropies
- In general anything that can be done with SNIa can be repeated for standard sirens (with less data but at much higher redshifts)

Conclusions

- MBHBs are excellent **standard sirens** for eLISA
  - Systematic-free measures of **distance** (no calibration needed as for SNe)
- Need to **identify EM counterparts** to measure **redshift**
  - Will depend on final eLISA design, capacities of future telescopes and magnitude of EM emissions
- Forecast accuracy (with MBHBs only) comparable with present probes, but not with future ones (e.g. Euclid), **however**:
  - New cosmological **information from GWs** (not EM only): help in solving possible tensions (e.g. H_0)
  - Will improve including analysis for **other eLISA sources** (EMRIs, LIGO-like BHs, ...)
  - Direct probe of expansion at **high redshifts** (up to $z \sim 8$): good for testing alternative cosmological models