Dark energy with standard sirens

- GW observations of compact binary coalescences measure the luminosity distance (Schutz 1986)

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M (1+\tilde{z})^3 + \rho_{\rm DE}(\tilde{z})/\rho_0}}$$

- low z: Hubble law, $d_L \simeq H_0^{-1} z$ (GW170817)

  moderate z: access $\Omega_M, \rho_{\rm DE}(z)$

- need independent determination of z

  (e.m. counterpart, statistical methods)

- low z:

Planck2018+ BAO+SNe: $H_0 = 68.34 \pm 0.83$

local measurements (Riess et al): $H_0 = 73.48 \pm 1.66$

3.7σ discrepancy: indication for deviation from ΛCDM?

- moderate z: non-trivial DE?

$$\dot{\rho}_{\mathrm{DE}} + 3H(1 + w_{\mathrm{DE}})\rho_{\mathrm{DE}} = 0$$

typical parametrization $$w_{\mathrm{DE}}(z) = w_0 + \frac{z}{1+z} w_a$$

Planck2018+ BAO+SNe:

w_0 only: $w_0 = -1.0281 \pm 0.031$

(w_0, w_a): $w0 = -0.961 \pm 0.077$, $w_a = -0.28^{+0.31}_{-0.27}$

- What can LISA add?

very detailed analysis in

Tamanini, Caprini, Barausse, Sesana, Klein, Petiteau 2016

- MBHB coalescence expected to have an em counterpart
  - optical (LSST)
  - radio jet or flare (SKA+ELT)

- select events with SNR>8, $\Delta\Omega$ <10 deg^2

- use different scenarios for generating the catalog of sources
  - heavy seeds (protogalactic disk) vs light seeds (pop III)
  - different delay between BH merges and galaxy mergers

Results:

- in the most optimistic scenario (heavy seeds-no delay)

$$\Delta H_0/H_0 = 0.5\%, \qquad \Delta w_0 = 2.5\ \%$$

- significant result because it has different systematics from e.m. observations
- however, in terms of accuracy not really better than what we know already from e.m. observations (particularly for w_0)

generalization to interacting DE (Caprini-Tamanini 2016)

statistical analysis in progress (Tamanini et al. LISA WG)

Modified GW propagation

Belgacem, Dirian, Foffa, MM
PRD 2018, 1712.08108
and PRD 2018, 1805.08731

in GR : $$\tilde{h}''_A + 2\mathcal{H}\tilde{h}'_A + k^2\tilde{h}_A = 0$$

writing $$\tilde{h}_A(\eta,\mathbf{k}) = \frac{1}{a(\eta)}\tilde{\chi}_A(\eta,\mathbf{k})$$

we get $$\tilde{\chi}''_A + \left(k^2 - a''/a\right)\tilde{\chi}_A = 0$$

inside the horizon $a''/a \ll k^2$, so $\tilde{\chi}''_A + k^2\tilde{\chi}_A = 0$

1. GWs propagate at the speed of light
2. $h_A \propto 1/a$

   For coalescing binaries this gives $h_A \propto 1/d_L(z)$

in several modified gravity models (eg the RR nonlocal model):

$$\tilde{h}''_A + 2\mathcal{H}[1-\delta(\eta)]\tilde{h}'_A + k^2\tilde{h}_A = 0$$

$$\tilde{h}_A(\eta,\mathbf{k}) = \frac{1}{\tilde{a}(\eta)}\tilde{\chi}_A(\eta,\mathbf{k}) \qquad \frac{\tilde{a}'}{\tilde{a}} = \mathcal{H}[1-\delta(\eta)]$$

$$\tilde{\chi}''_A + (k^2 - \tilde{a}''/\tilde{a})\tilde{\chi}_A = 0$$

and again inside the horizon $\tilde{a}''/\tilde{a} \ll k^2$

1. $c_{GW} = c$ ok with GW170817

2. $\tilde{h}_A \propto 1/\tilde{a}$

the ``GW luminosity distance" is different from the standard (electromagnetic) luminosity distance !

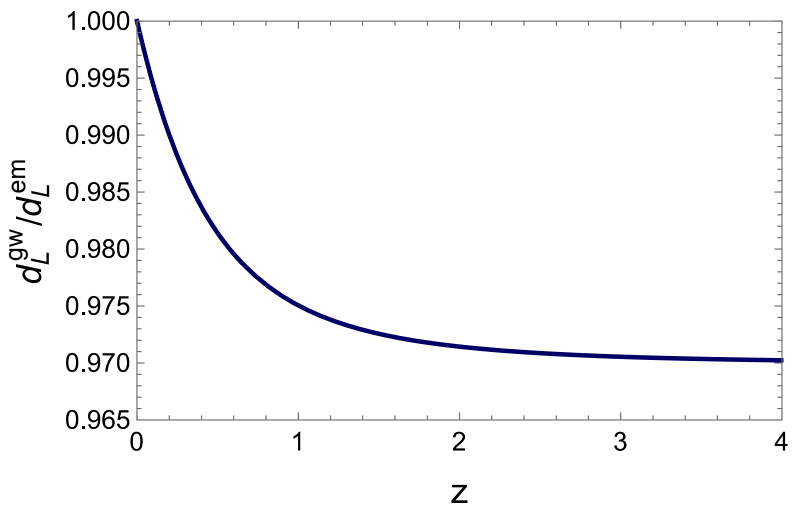
Deffayet and Menou 2007
Saltas et al 2014,
Lombriser and Taylor 2016,
Nishizawa 2017,
Belgacem et al 2017, 2018

in terms of δ(z) :

$$d_L^{\rm gw}(z) = d_L^{\rm em}(z)\exp\left\{-\int_0^z \frac{dz'}{1+z'}\,\delta(z')\right\}$$

prediction of the

RR model :

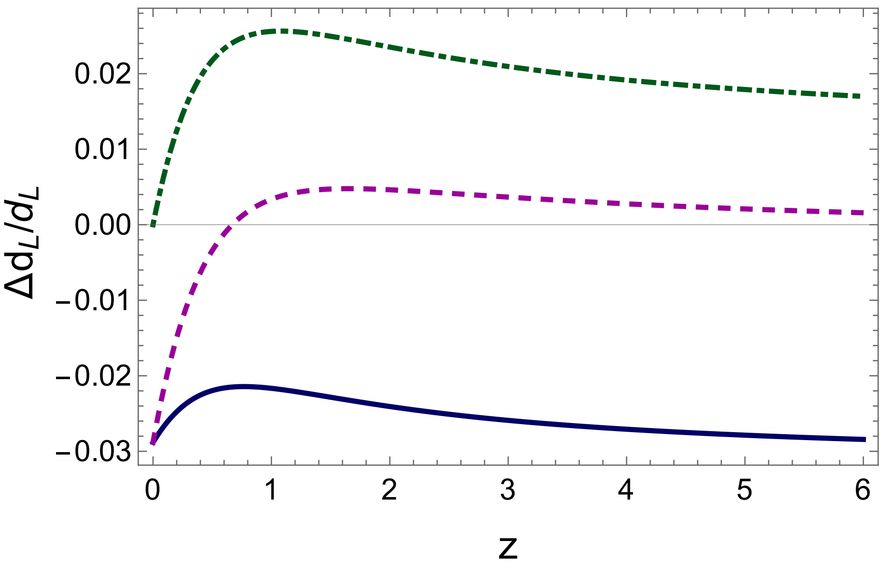


at LISA this propagation effect dominates over that from the dark energy EoS !

recall that

$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M(1+\tilde{z})^3 + \rho_{\rm DE}(\tilde{z})/\rho_0}}$$

(neglect radiation for standard sirens)



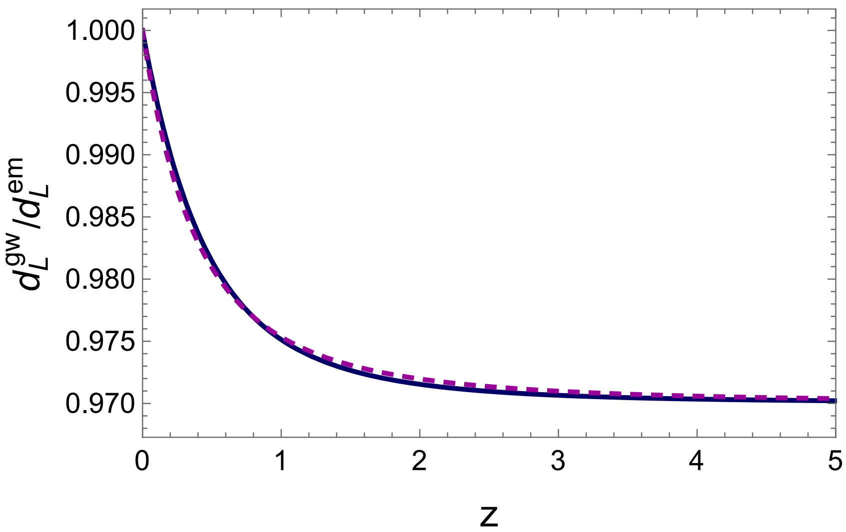
relative difference of e.m. luminosity distance RR-LCDM for the same values of Ω_M and H_0

relative difference with the respective best-fit parameters

relative difference of gw luminosity distance

a general parametrization of modified GW propagation

Belgacem, Dirian, Foffa, MM
PRD 2018, 1805.08731



$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

for the minimal RR model:

$$\Xi_0 = 0.970, \quad n = 5/2$$

However, the parametrization looks very natural and convenient in general !

parametrizing the DE sector:

- background: (w_0, w_a)
- scalar sector: (Σ, μ) tensor sector: (Ξ_0, n)

for standard sirens, the most important parameters are w_0, Ξ_0

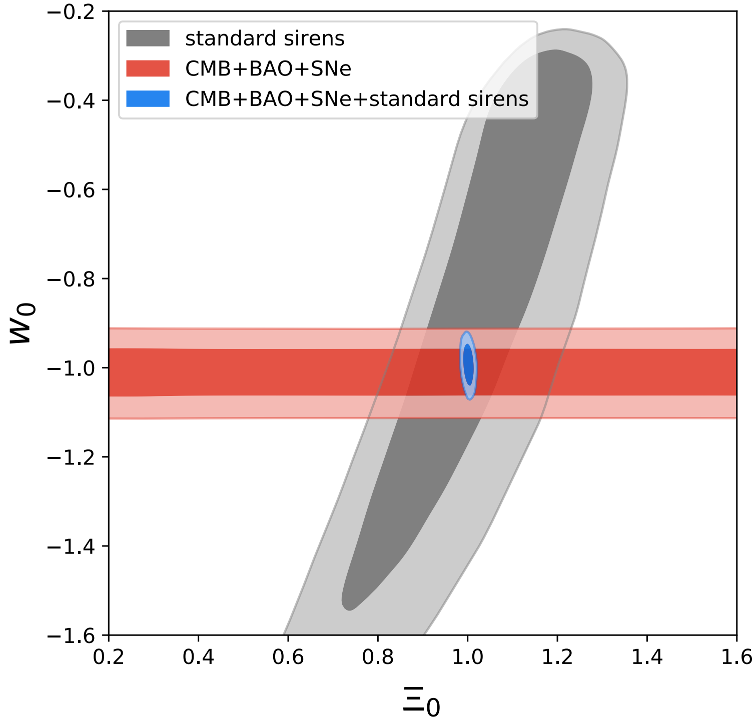
- Forecasts for the Einsten Telescope

(Belgacem, Dirian, Foffa, MM PRD 2018, 1805.08731)

ET could detect $\sim 10^5$ - 10^6 BNS/yr up to large z

assume $\sim 10^3$ em counterparts

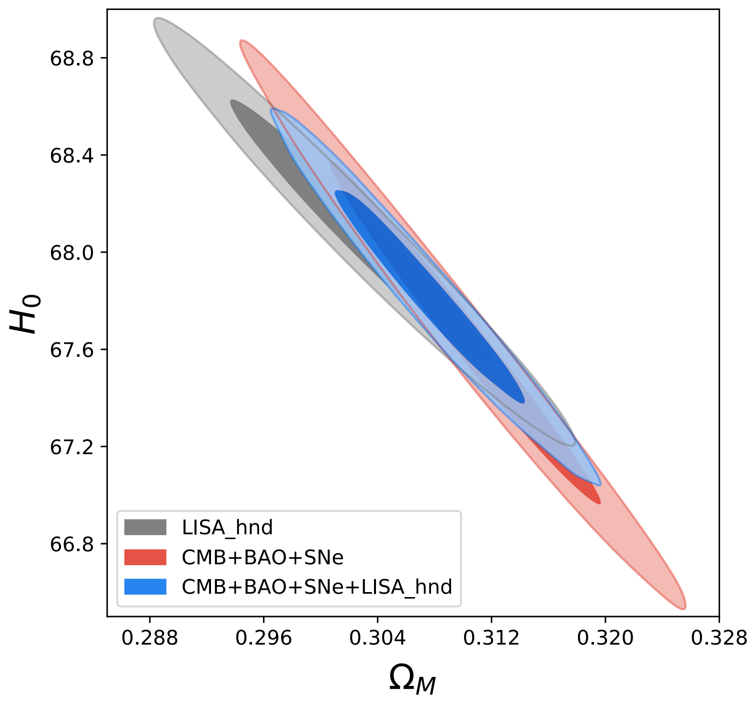
(more detailed modelization of the GRB detection and of a ET+CE+CE network in progress, with T.Regimbau and E. Howell)

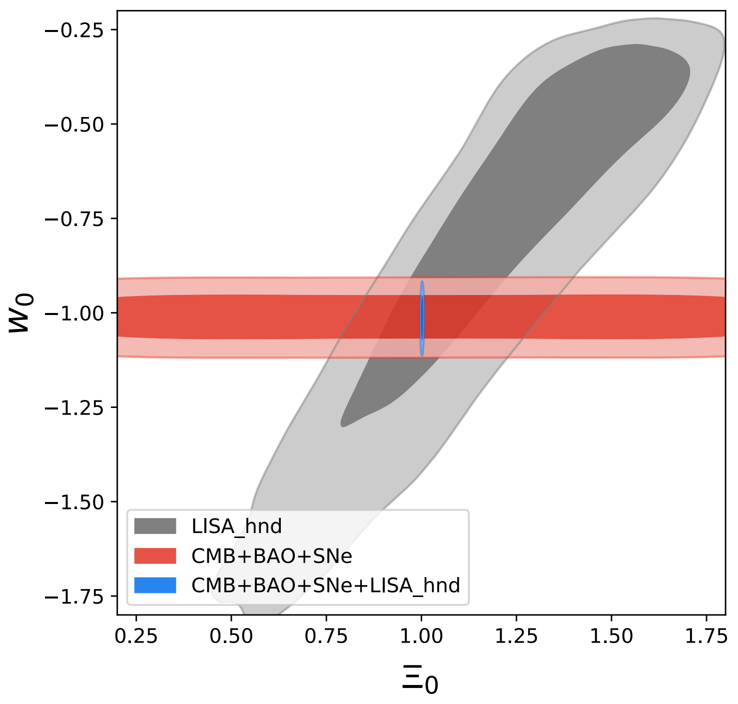


Δw_0=3.2%, $\Delta\Xi_0$=0.8%

Forecasts for LISA

Belgacem et al (LISA Cosmology WG), in preparation





for heavy seeds-no delay: Δw_0=4.0%, $\Delta\Xi_0$=0.2%

Take-away message:

modified GW propagation can be a major science driver for LISA and for 3G detectors

- it is specific to GW observations

(while the accuracy of GW observations on w_{DE} will not be terribly competitive even with present Planck/DES observations)

- Ξ_0 can be measured with better accuracy than w_0

significant test of dark energy and modified gravity

The observation of GW170817 already gives a limit modified GW propagation

Belgacem, Dirian, Foffa, MM
PRD 2018, 1805.08731

at low z:

$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = e^{-\int_0^z \frac{dz'}{1+z'}\,\delta(z')} \simeq 1 - z\delta(0)$$

- comparing directly d^{em} for the host galaxy (obtained from surface brightness fluctuations):

$$\delta(0) = -7.8^{+9.7}_{-18.4}$$

- comparing the values of H_0 inferred from GW170817 with the Riess et al. value from standard candles:

$$\delta(0) = -5.1^{+20}_{-11}$$