The GW luminosity distance in modified gravity

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Vacuum Fluctuations at Nanoscale and Gravitation: theory and experiments

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GW propagation in GR

- Tensor perturbations around FRW background, with Fourier modes $\tilde{h}_A\,(\eta, \mathbf{k})$

$$\tilde{h}''_A + 2\mathcal{H}\tilde{h}'_A + k^2\tilde{h}_A = 0 \qquad\qquad \mathcal{H} \equiv \frac{a'(\eta)}{a(\eta)}$$

- Write $\tilde{h}_A\,(\eta, \mathbf{k}) = \frac{\tilde{\chi}_A(\eta,\mathbf{k})}{a(\eta)}$ to obtain $\tilde{\chi}''_A + \left(k^2 - \frac{a''}{a}\right)\tilde{\chi}_A = 0$

- For modes inside the horizon, it gives a wave equation for $\tilde{\chi}_A\,(\eta, \mathbf{k})$

$$\tilde{\chi}''_A + k^2\tilde{\chi}_A = 0$$

- speed of GWs = speed of light $\quad c_{gw} = c$

GW propagation in modified gravity

- Tensor perturbations around FRW background, with Fourier modes $\tilde{h}_A(\eta, \mathbf{k})$

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

EB, Dirian, Foffa, Maggiore
PRD 2018, 1712.08108
PRD 2018, 1805.08731

- It holds very generally for modified gravity theories, e.g.

  - Nonlocal gravity: RR and RT models
  - Scalar-tensor theories: Horndeski, DHOST
  - Higher dimensions: DGP
  - Bigravity

Deffayet and Menou 2007
Saltas et al 2014,
Lombriser and Taylor 2016,
Nishizawa 2017,
EB, Dirian, Foffa, Maggiore 2017, 2018
EB et al. (LISA Cosmology WG), appearing soon

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

and obtain $$\tilde{\chi}_A'' + \left(k^2 - \frac{\tilde{a}''}{\tilde{a}}\right)\tilde{\chi}_A = 0$$

- For modes inside the horizon, it gives a wave equation for $\tilde{\chi}_A(\eta,\mathbf{k})$

$$\tilde{\chi}_A'' + k^2\tilde{\chi}_A = 0$$

- No modification in the $k^2\tilde{h}_A$ term to comply with constraints on speed of GWs

GW170817/GRB 170817A $-3\times 10^{-15} < \frac{c_{gw}-c}{c} < +7\times 10^{-16}$ B. P. Abbott et al., ApJ 848, L13 (2017)

Standard sirens: coalescing binaries

$$\tilde{\chi}_A'' + k^2 \tilde{\chi}_A = 0$$

GR ⟵ $\tilde{\chi}_A'' + k^2 \tilde{\chi}_A = 0$ ⟶ **Modified gravity**

GR

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

$$\Downarrow$$

- Amplitude decreases as the inverse of the (EM) luminosity distance

$$\tilde{h}_A(\eta, \mathbf{k}) \propto \frac{1}{d_L(z)}$$

- Direct measurement of the (EM) luminosity distance

Modified gravity

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

$$\delta(\eta) \neq 0 \quad \longrightarrow \quad \tilde{a}(\eta) \neq a(\eta)$$

$$\Downarrow$$

- Amplitude decreases as the inverse of a new GW luminosity distance different from the EM one

$$\tilde{h}_A(\eta, \mathbf{k}) \propto \frac{1}{d_L^{gw}(z)}$$

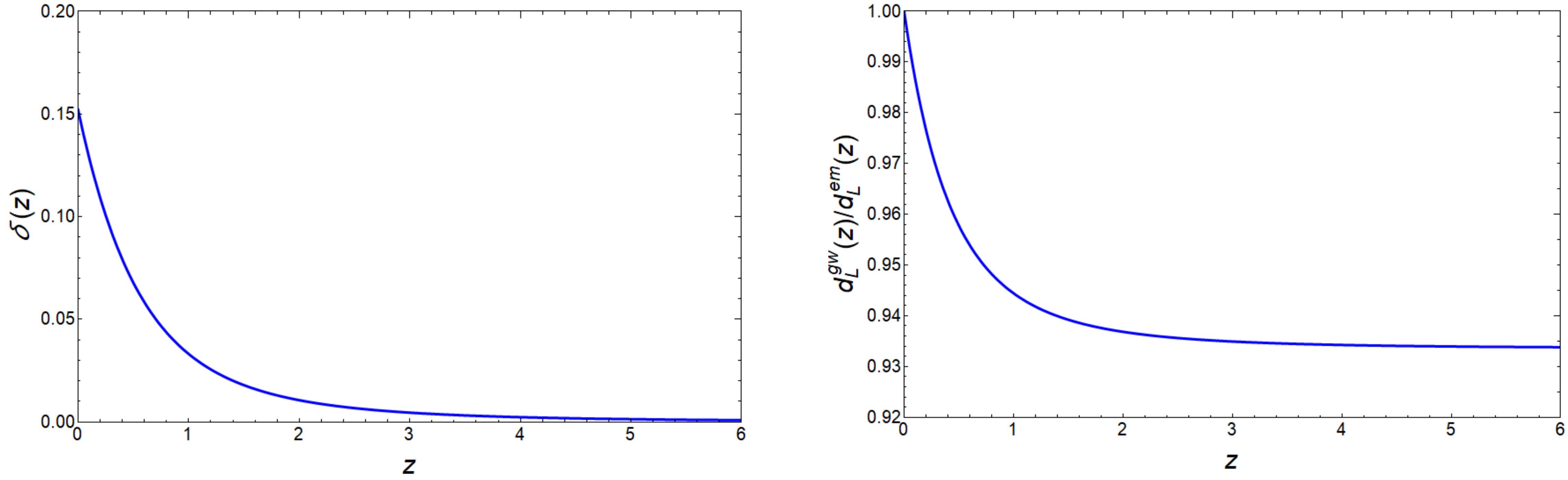
$$d_L^{gw}(z) = \frac{a(z)}{\tilde{a}(z)} d_L^{em}(z)$$

- Direct measurement of the GW luminosity distance

- Expression for $d_L^{gw}(z)$ in terms of the function $\delta(z)$

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

- Example, RT nonlocal model: relative difference between $d_L^{gw}(z)$ and $d_L^{em}(z)$ of 6.6% at $z > 1$



Standard sirens can be used to probe gravity on cosmological scales and to test ΛCDM cosmology against modified gravity.

ΛCDM

There is only one notion of luminosity distance, valid for both standard candles and standard sirens

$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3+\Omega_\Lambda}}$$

Modified gravity cosmology

There are 2 effects:

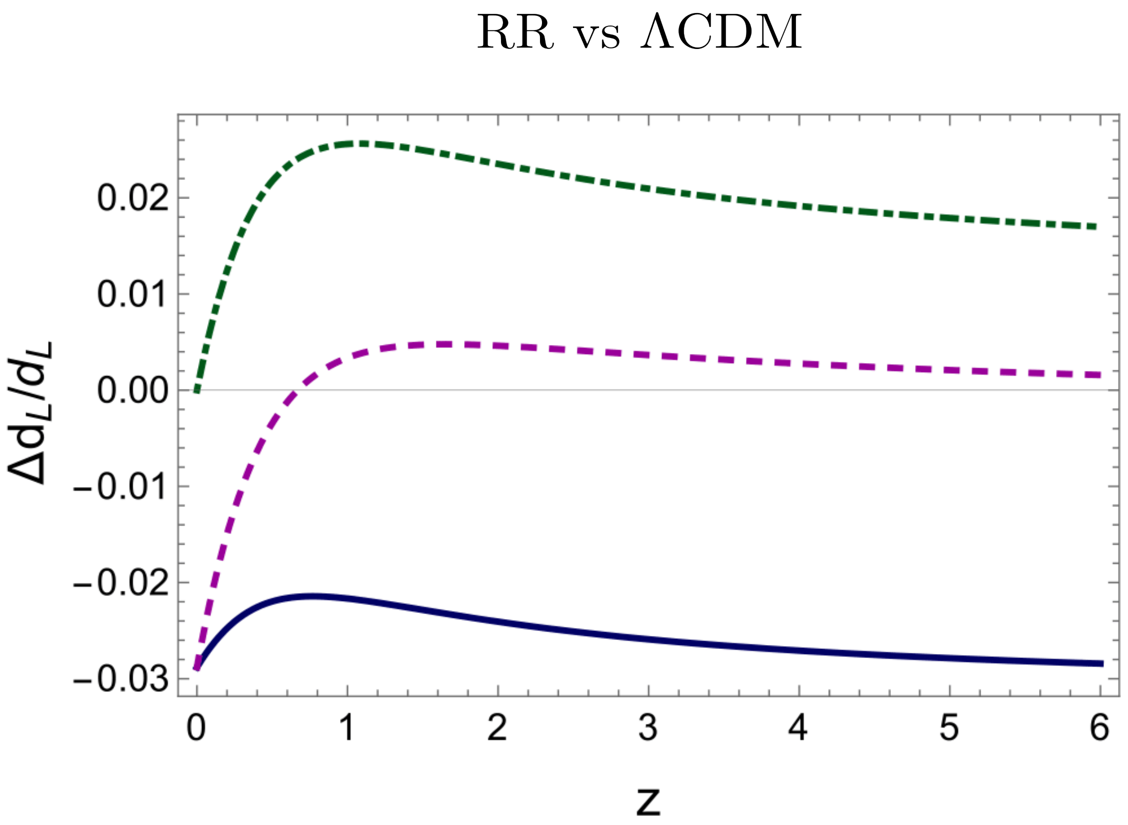
1) The EM luminosity distance is different because of the different values of cosmological parameters and a non-trivial DE EoS

$$d_L^{em}(z) = \frac{1+z}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3+\rho_{DE}(z')/\rho_0}}$$

2) On top of that, modified GW propagation must be taken into account

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

The importance of modified GW propagation for dark energy studies



Green: $\left(d_L^{RR,em} - d_L^{\Lambda CDM}\right)/d_L^{\Lambda CDM}$ fixing H_0 and Ω_M to the same values.

Purple: $\left(d_L^{RR,em} - d_L^{\Lambda CDM}\right)/d_L^{\Lambda CDM}$ using their respective best-fit values.

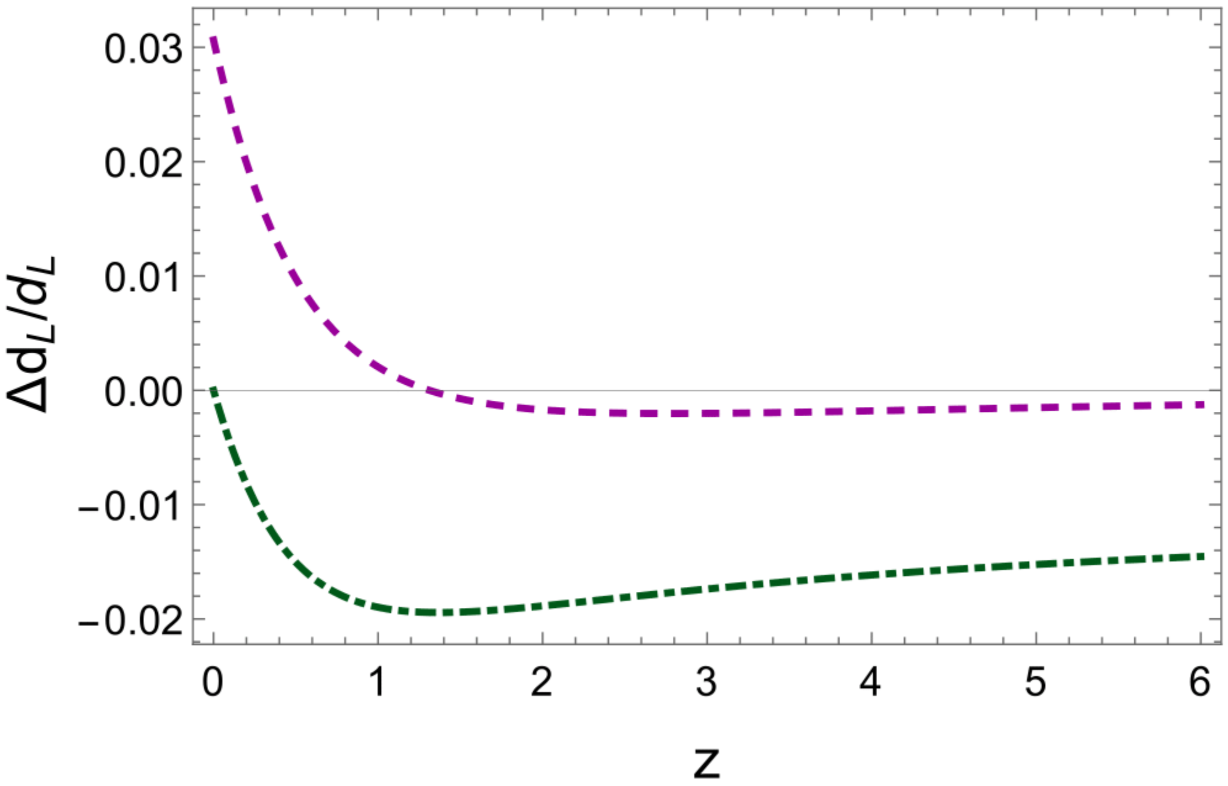
Blue: $\left(d_L^{RR,gw} - d_L^{\Lambda CDM}\right)/d_L^{\Lambda CDM}$

Parameter estimation compensates the differences in EM luminosity distance.

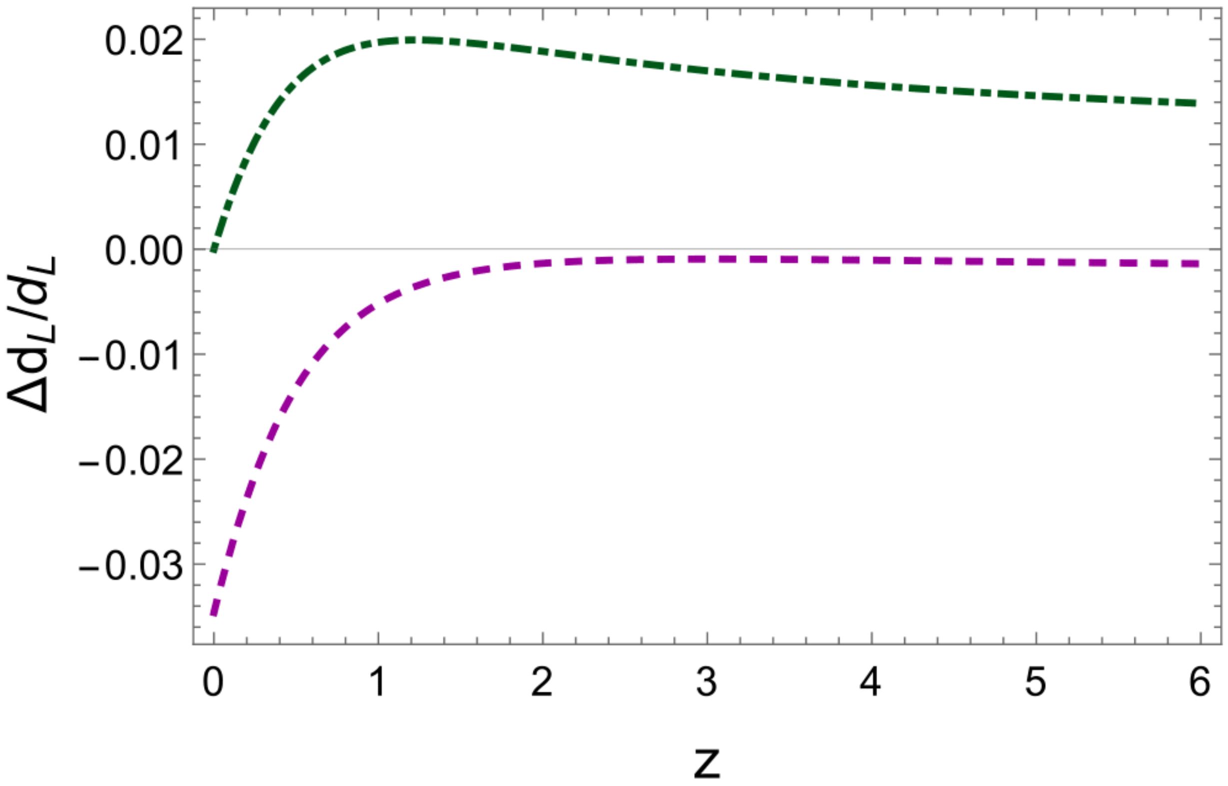
Modified GW propagation is not compensated: it is the dominant contribution!

The compensation effect for d_L^{em} is confirmed in $w\mathrm{CDM}$

$w=-0.9$



$w=-1.1$



Green: $\left(d_L^{wCDM,em}-d_L^{\Lambda CDM}\right)/d_L^{\Lambda CDM}$ fixing H_0 and Ω_M to the same values.

Purple: $\left(d_L^{wCDM,em}-d_L^{\Lambda CDM}\right)/d_L^{\Lambda CDM}$ using their respective best-fit values.

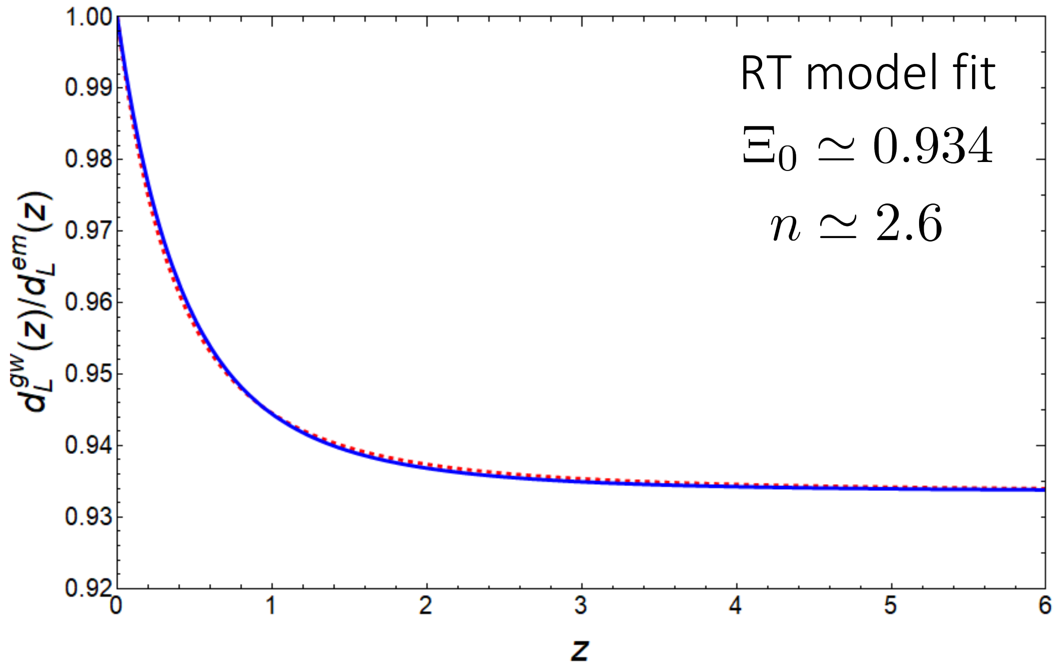
General parametrization for modified GW propagation

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

EB, Dirian, Foffa, Maggiore
PRD 2018, 1805.08731

It fits practically all the modified gravity models

EB et al. (LISA Cosmology WG)



Resulting DE sector parametrization:

background	(w_0, w_a)
scalar perturbations	(Σ, μ)
tensor perturbations	(Ξ_0, n)

Ξ_0 and w_0 are the most relevant parameters for standard sirens

Observational limits on modified GW propagation

It is methodologically interesting that some (not that strict) limits can already be extracted from GW170817/GRB 170817A

EB, Dirian, Foffa, Maggiore
PRD 2018, 1805.08731

Redshift is obtained from EM counterpart and it is small: $z \simeq 0.01$

Low-z approximation: $\frac{d_L^{gw}(z)}{d_L^{em}(z)} = \exp\left[-\int_0^z \frac{dz'}{1+z'}\delta(z')\right] \simeq 1 - z\delta\left(0\right)$

Method A: Comparison of the Hubble parameter

Compare the value obtained from GW170817 $H_0^{gw} = z/d_L^{gw}\left(z\right)$ to the local EM measurements by Riess et al. $H_0^{em} = z/d_L^{em}\left(z\right)$

$$\delta\left(0\right) = \frac{H_0^{gw} - H_0^{em}}{H_0^{gw} z} = -5.1^{+20}_{-11}$$

Method B: Source-by-source comparison of luminosity distance

Compare the d_L^{gw} measured by GW170817 to the distance d_L^{em} from the host galaxy NGC4993 determined using surface brightness fluctuations

$$\delta\left(0\right) = \frac{d_L^{em} - d_L^{gw}}{d_L^{em} z} = -7.8^{+9.7}_{-18.4}$$

Dark energy and modified GW propagation with ET and LISA

ET

Sources:

- BNS up to $z \sim 2$ $(10^5 - 10^6$ events/yr)
- NS-BH and BH-BH up to $z \sim 8$

But only a fraction of those events is expected to have an observed associated GRB

Typical assumption for DE studies:
$10^3 - 10^4$ BNS with EM counterpart in 3 years

We are currently working with a more accurate modelization of joint GW/GRB detections (some preliminary results in the next slides)

EB, Dirian, Foffa, Howell, Maggiore, Regimbau, in preparation

LISA

Sources:

- MBHBs at $z \gtrsim 1$
- EMRIs at $0.1 \lesssim z \lesssim 2-3$
- stellar mass BHBs at $0.01 \lesssim z \lesssim 0.1$

A powerful EM counterpart is expected only for MBHBs (optical and radio bands): sources used in

EB et al. (LISA Cosmology WG), appearing soon

Statistical methods can be used to determine redshift for EMRIs and stellar mass BHBs events

Planned work within LISA Cosmology WG

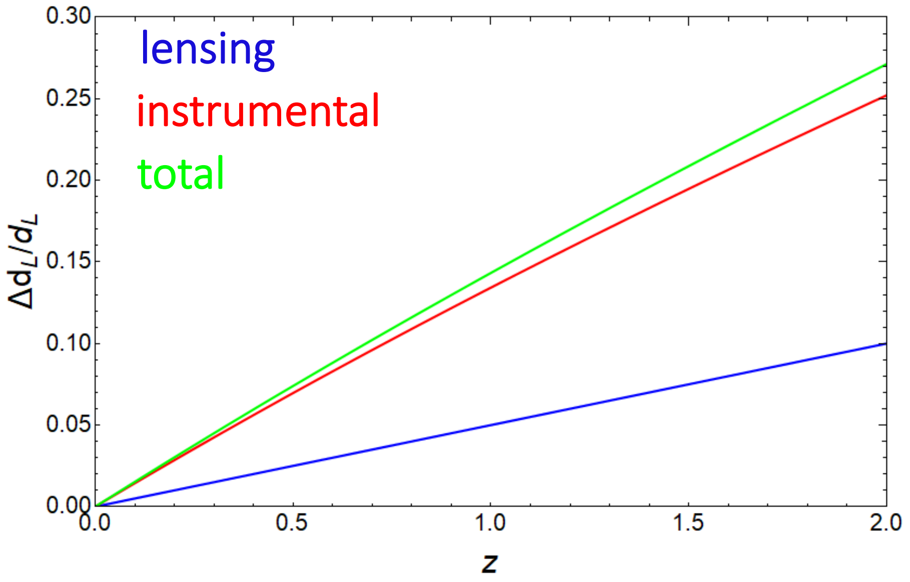
Standard sirens at ET

Forecasts for DE EoS in Sathyaprakash, Schutz, Van Den Broeck 2009; Zhao, Van Den Broeck, Baskaran, Li 2011; Taylor and Gair 2012; Camera and Nishizawa 2013; Cai and Yang 2016; EB, Dirian, Foffa, Maggiore 2017,2018

General strategy

- Assume 10^3 BNS events with EM counterpart will be detected
- Redshift range $0 < z < 2$
- Distributed in redshift according to a simple fit for the formation rate
- $d_L(z)$ from a fiducial cosmology
- $\Delta d_L(z)$ from ET sensitivity curve + lensing + peculiar velocity at low z
- Scatter data around $d_L(z)$ with error $\Delta d_L(z)$
- Constrain cosmological parameters by MCMC (or Fisher matrix) and use CMB, BAO, SNe data to reduce degeneracies

Relative error on luminosity distance at ET



There is not much improvement on w_{DE} compared to CMB+BAO+SNe

The most interesting results are those for modified GW propagation!

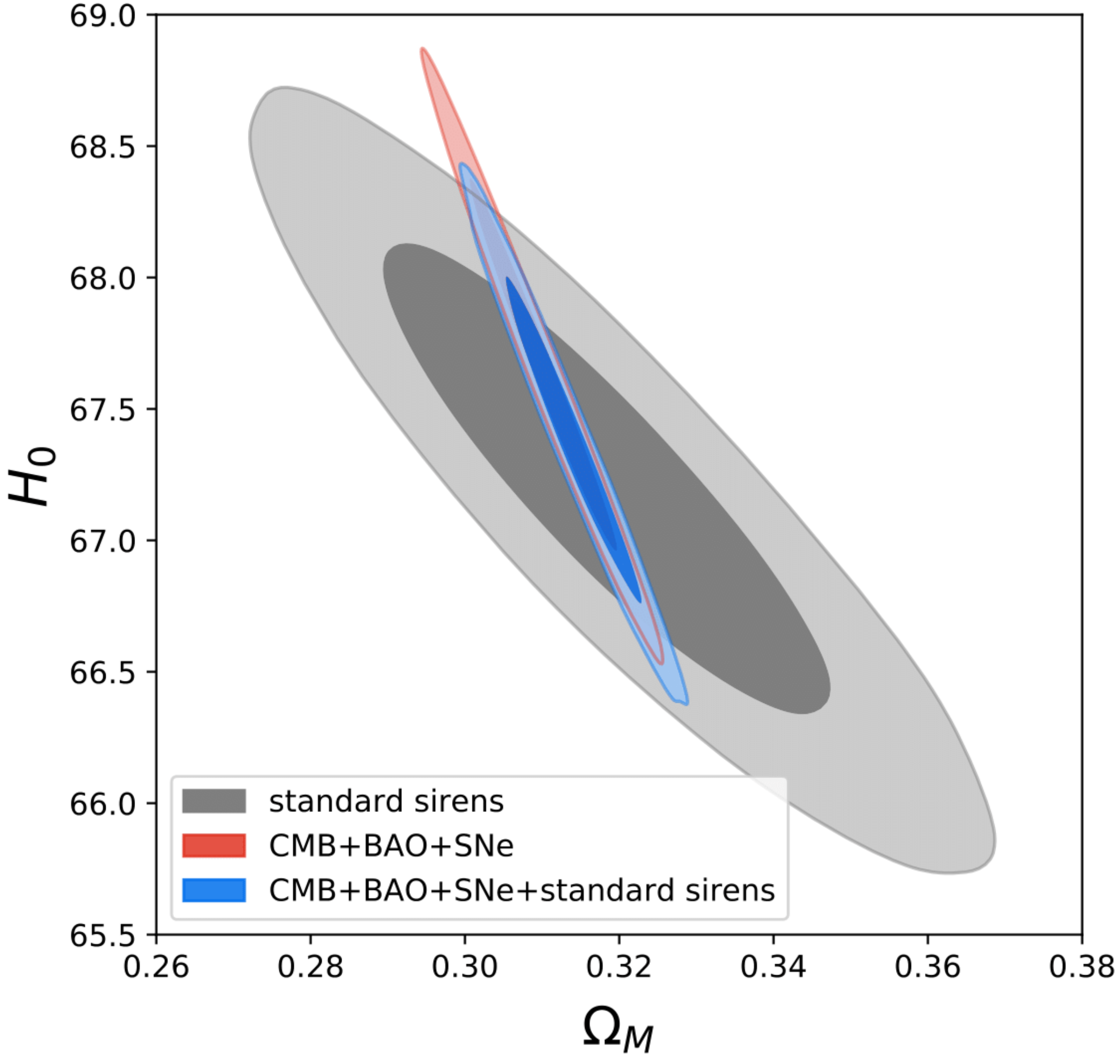
EB, Dirian, Foffa, Maggiore PRD 2018, 1805.08731

Constraints on ΛCDM parameters

	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
ET	0.9 %	6.5 %
CMB+BAO+SNe	0.7 %	2.1 %
CMB+BAO+SNe+ET	0.6 %	1.9 %

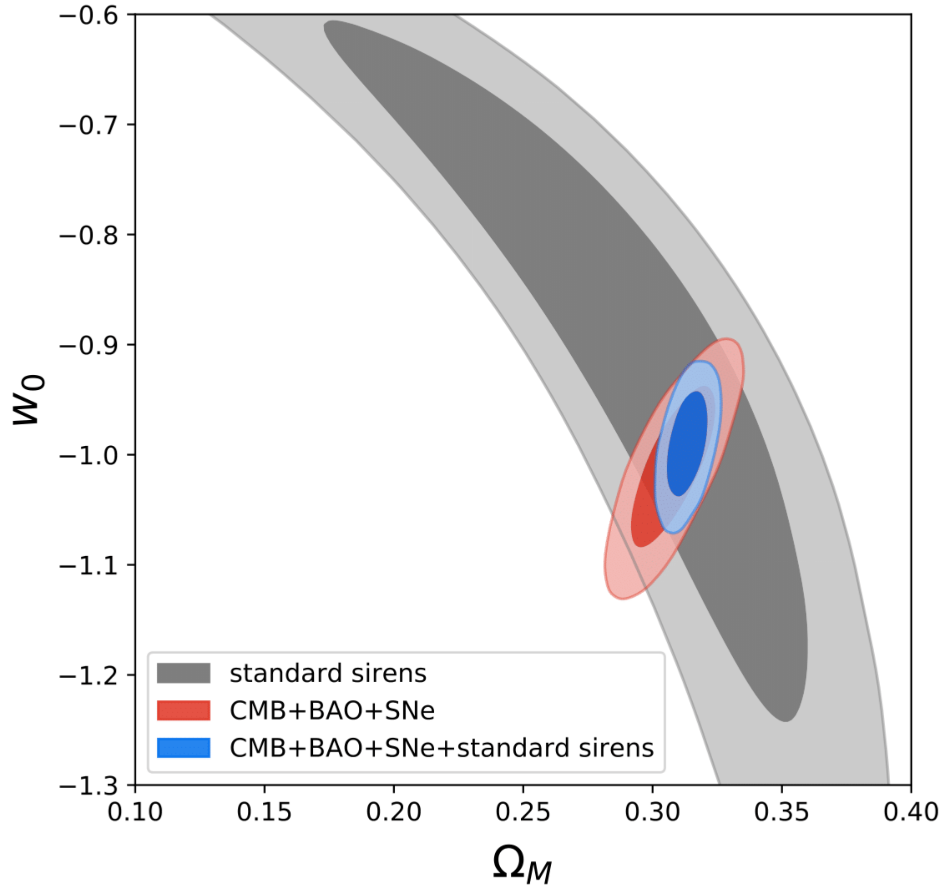
ET alone already gives an accuracy on H_0 comparable to CMB+BAO+SNe

Only small improvements on H_0 and Ω_M when combining all datasets



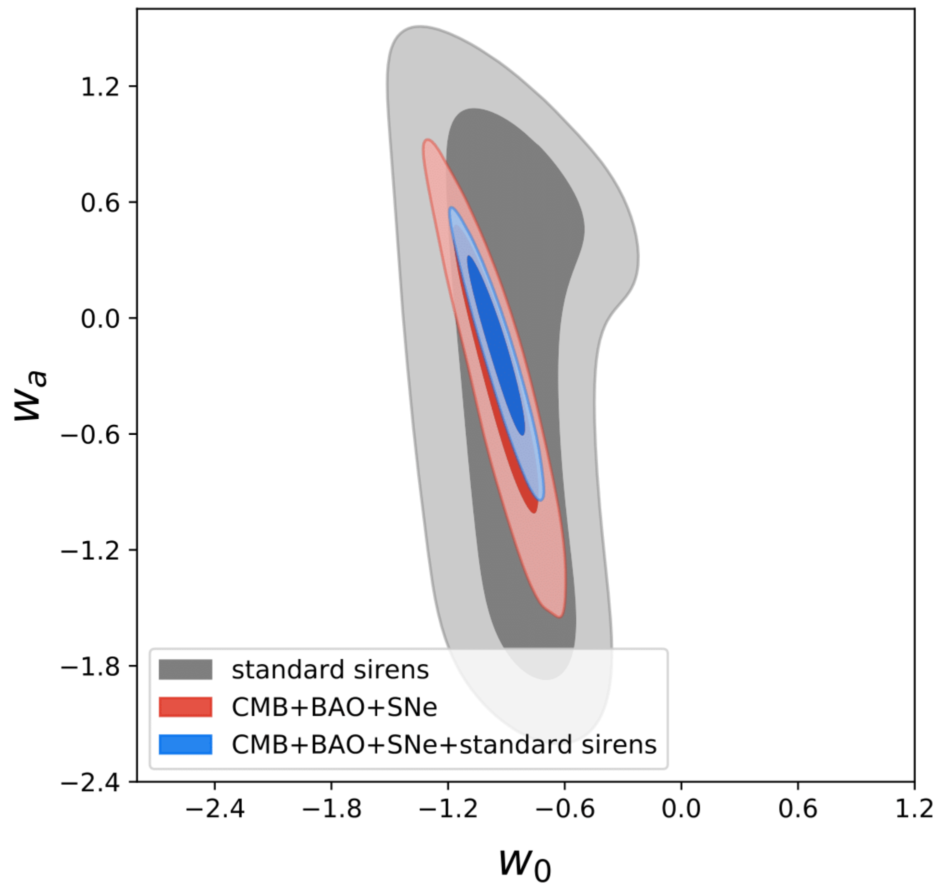
Constraints on DE EoS

w_0 only extra parameter



	Δw_0
CMB+BAO+SNe	0.045
CMB+BAO+SNe+ET	0.031

(w_0, w_a) extension



	Δw_0	Δw_a
CMB+BAO+SNe	0.140	0.483
CMB+BAO+SNe+ET	0.099	0.313

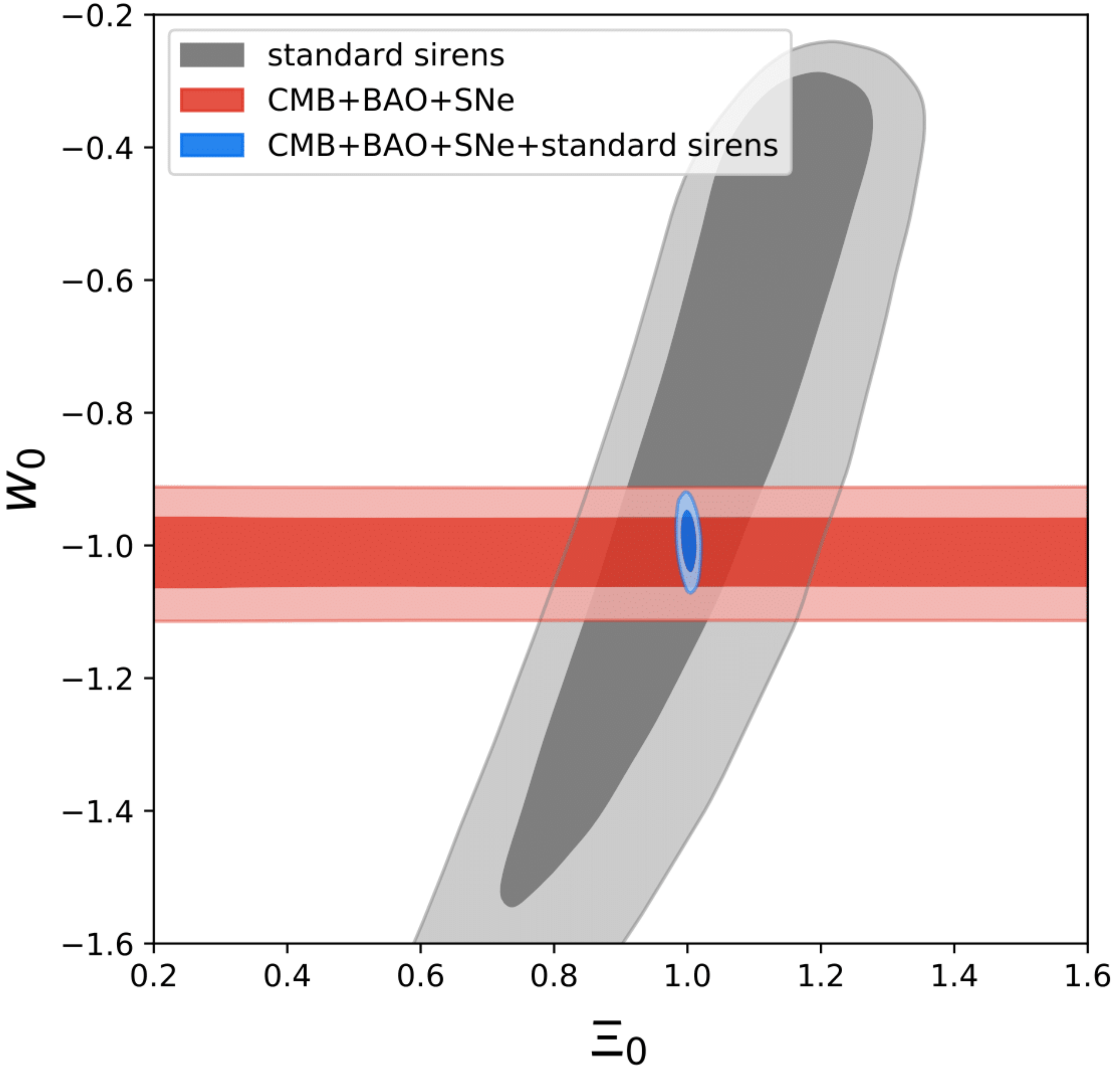
Limited improvements on w_{DE} from ET

Including modified GW propagation: (Ξ_0, w_0) extension

CMB+BAO+SNe+ET $\begin{cases} \Delta\Xi_0 = 0.008 \\ \Delta w_0 = 0.032 \end{cases}$

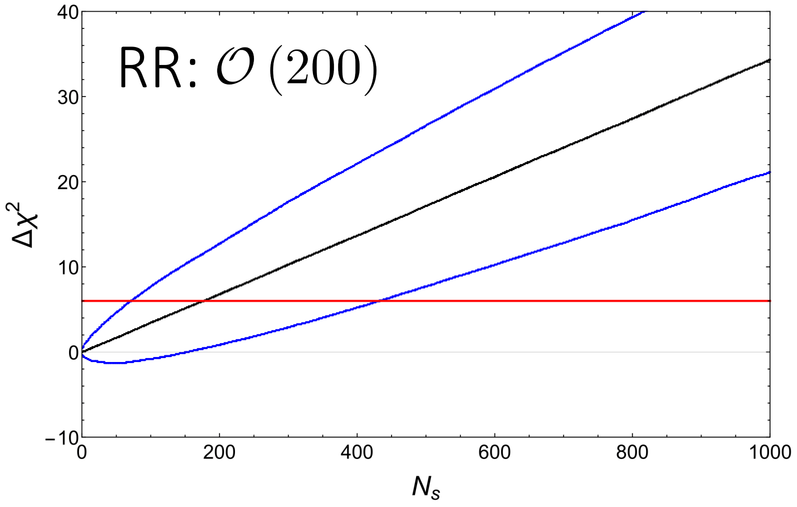
Ξ_0 can be measured better than w_0 !
(in agreement with the importance of modified GW propagation for standard sirens)

The precision on Ξ_0 (better than 1 %) is sufficient to test several modified gravity models
(e.g. 6.6% deviation for the RT model)

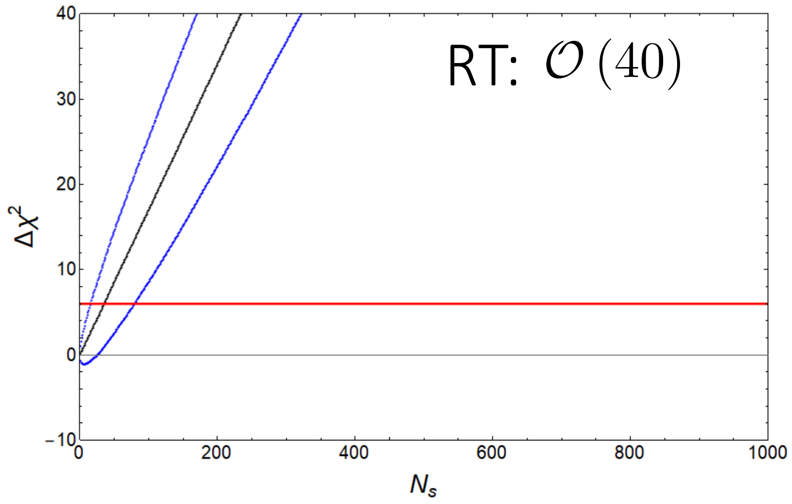


Testing specific models with ET: nonlocal IR modifications of gravity

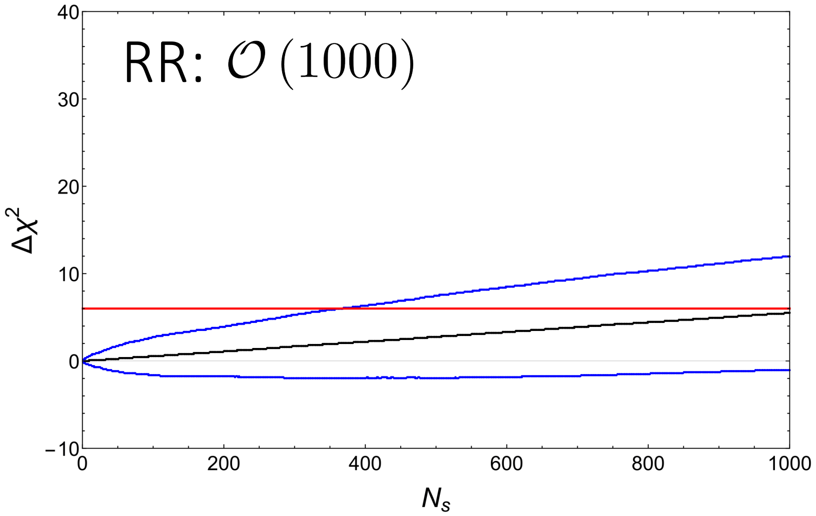
How many sources to tell nonlocal gravity and ΛCDM apart?



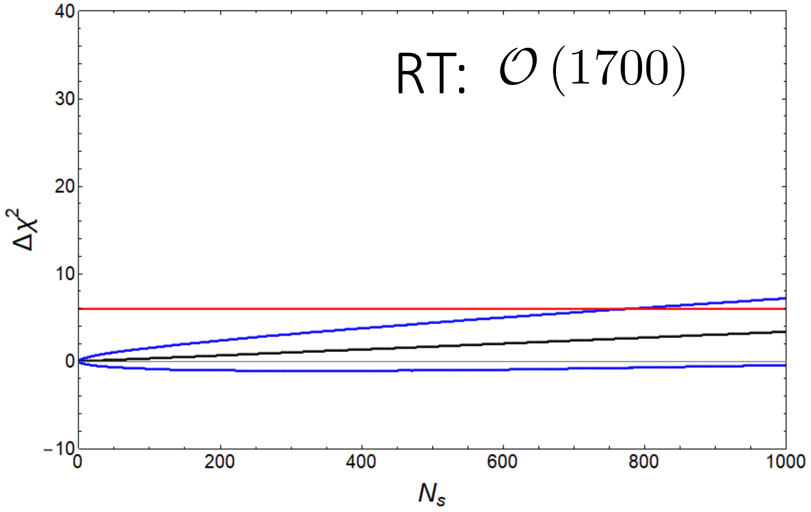
Nonlocal gravity can be tested at ET...



Turning off modified GW propagation would increase a lot the required number



...thanks to modified GW propagation!



A more detailed modelization for joint GW/GRB detections at ET/THESEUS

EB, Dirian, Foffa, Howell, Maggiore, Regimbau, in preparation

[In this work we actually consider different networks of 2G (HLV, HLVIK) and 3G (ET alone, ET+2 CE)]

All the results in the next 2 slides should be taken as preliminary

Simulation of a population of BNS based on Regimbau et al. 2015, ApJ 799, 69

- Evaluation of coalescence rate using SFR and a probability distribution for the delay between formation and coalescence of the binary system (modeled according to Dominik et al. 2012, ApJ 759, 52)
- Exponential probability distribution for the time interval between two successive events (i.e. assume coalescence in the observer frame is a Poisson process)
- We consider 2 possibilities for the neutron stars mass distribution: flat or gaussian
- Compute the SNR for each event to assess its GW detectability

EM counterpart

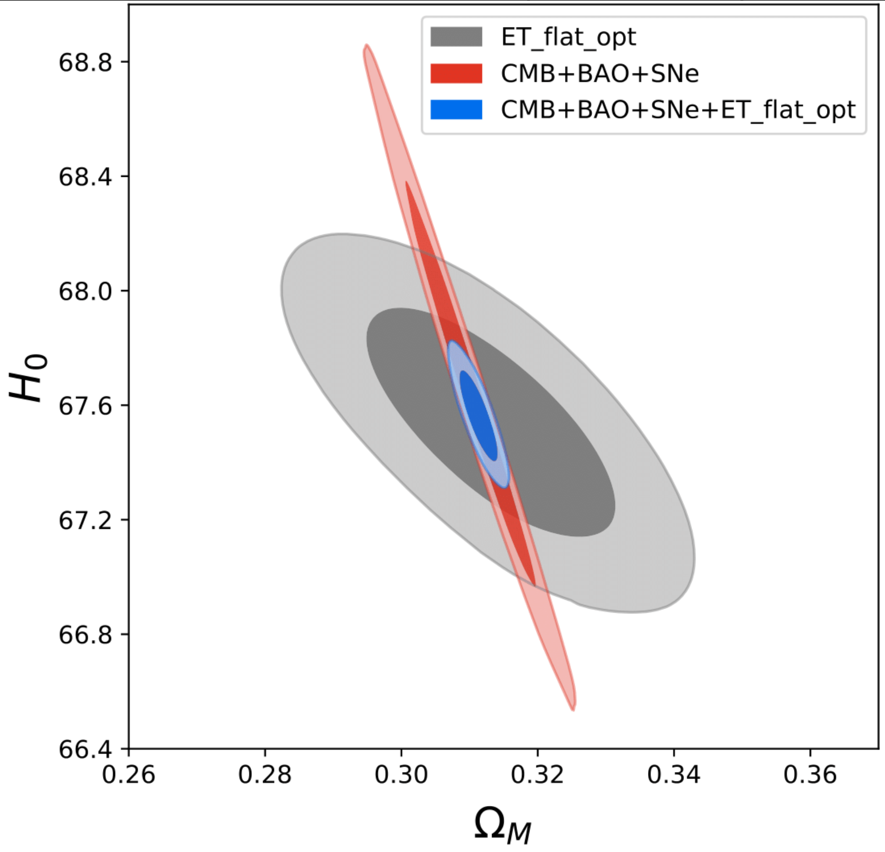
- Redshift is determined from temporal coincidence with GRB, assumed to be detected by the proposed THESEUS mission Amati et al., Adv. Space Res. 62 (2018) 191-244, 1710.04638
Stratta et. al., Adv. Space Res. 62 (2018) 662-682, 1712.08153
Stratta, Amati, Ciolfi, Vinciguerra, 1802.01677
- We consider 2 different possibilities for the THESEUS FoV: 6 sr (optimistic) and 2 sr (more realistic)

Number of events at ET with EM counterpart at THESEUS (10 years of data)

FLAT OPT	GAUSSIAN OPT	FLAT REAL	GAUSSIAN REAL
389	511	128	169

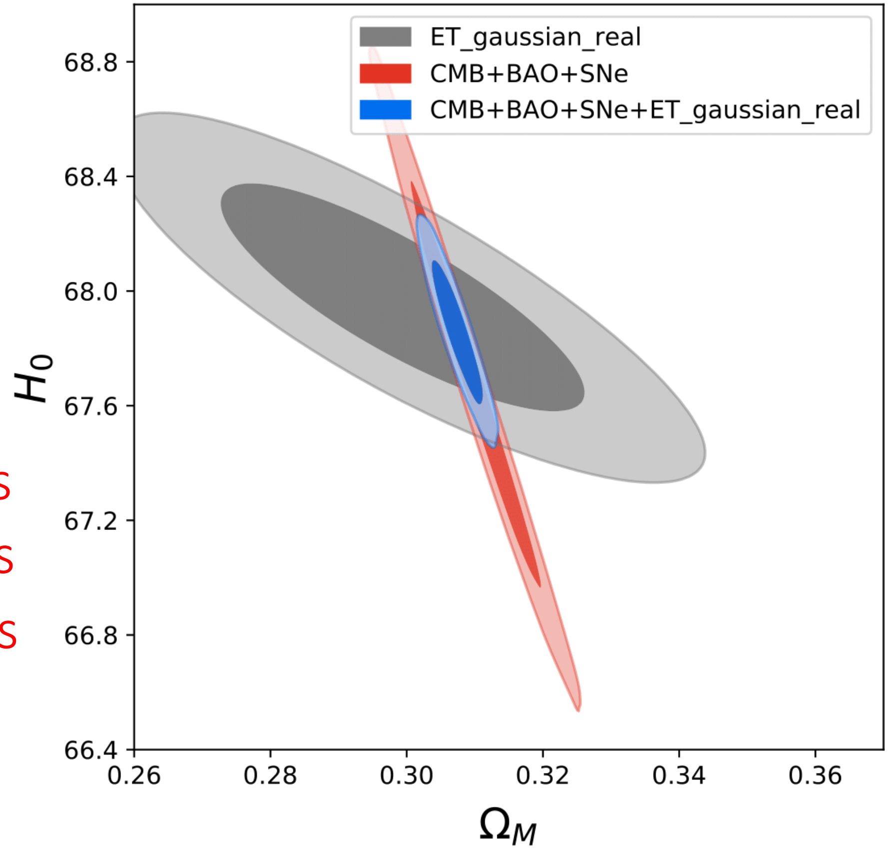
	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
ET_flat_opt	0.3 %	3.7 %
CMB+BAO+SNe	0.7 %	2.1 %
CMB+BAO+SNe+ET_flat_opt	0.2 %	0.6 %

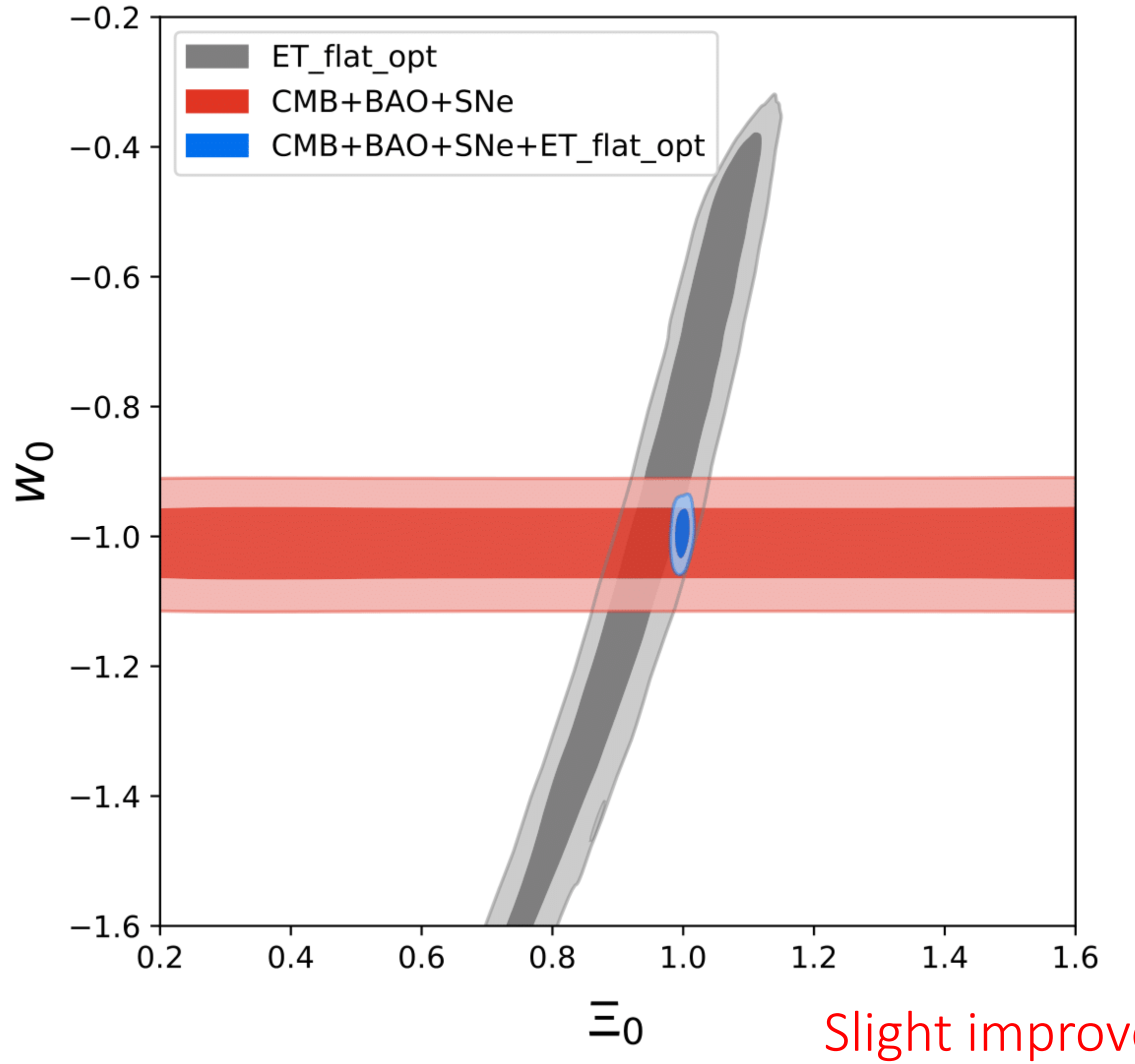
	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
ET_gaussian_real	0.3 %	3.7 %
CMB+BAO+SNe	0.7 %	2.1 %
CMB+BAO+SNe+ET_gaussian_real	0.2 %	0.6 %

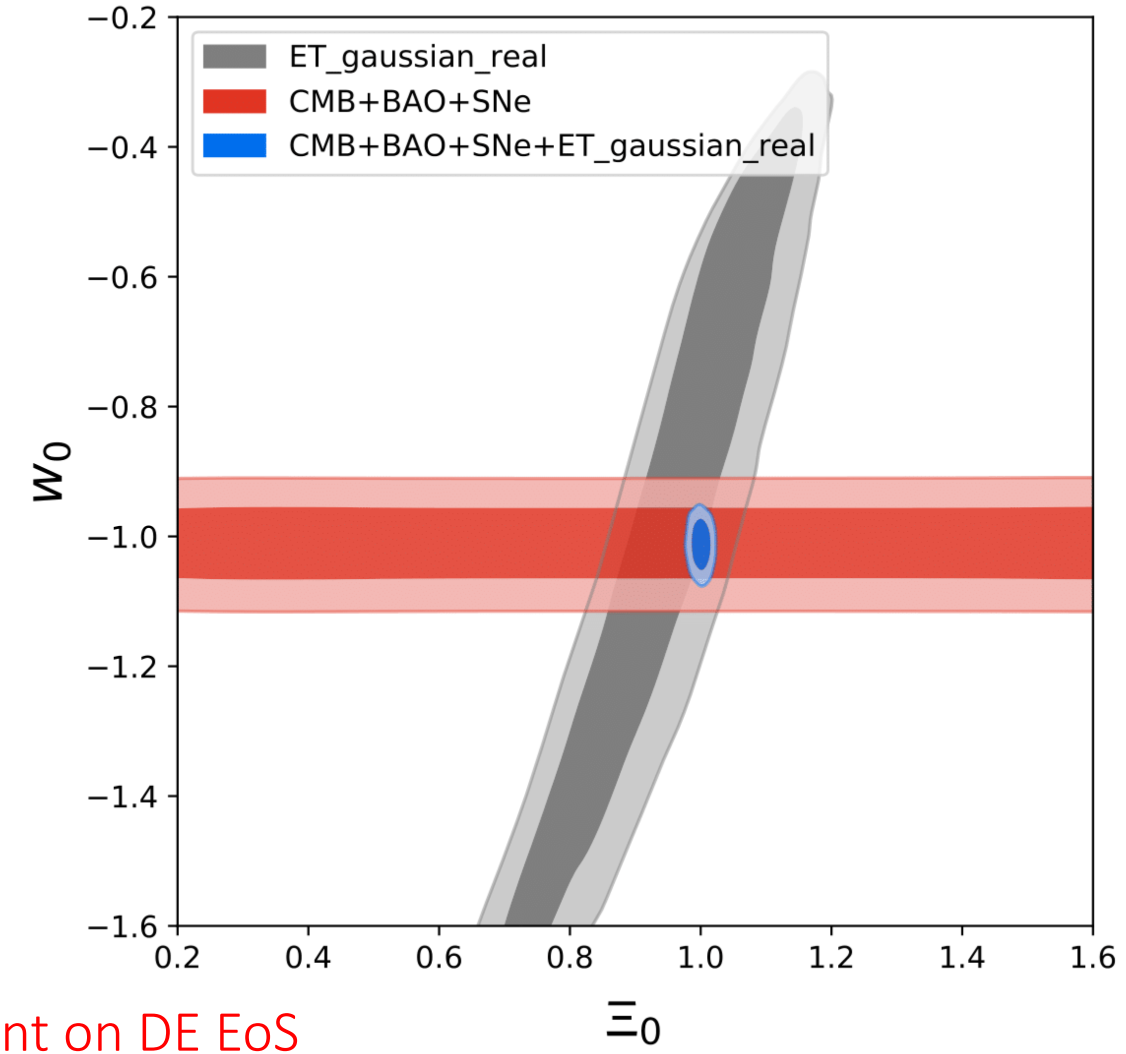


Constraints on ΛCDM parameters

Significant improvements on H_0 and Ω_M from this more accurate ET analysis







Slight improvement on DE EoS from this second analysis

CMB+BAO+SNe+ET_flat_opt

$\Delta\Xi_0 = 0.008 \qquad \Delta w_0 = 0.026$

The error on Ξ_0 turns out to be very similar to the one found before

CMB+BAO+SNe+ET_gaussian_real

$\Delta\Xi_0 = 0.010 \qquad \Delta w_0 = 0.026$

Standard sirens at LISA

EB et al. (LISA Cosmology WG), appearing soon

The **construction of mock catalogs of MBHBs** follows Tamanini et al. JCAP 1604 (2016) 002, 1601.07112

- 2 scenarios for the massive black hole seeds:
  - light seeds (remnants of popIII stars) $\sim 100 M_\odot$
  - heavy seeds (bar instabilities of protogalactic disks) $\sim 10^5 M_\odot$

In the heavy seeds case, the initial bar instability is regulated by a parameter Q_c (critical Toomre parameter)

- Inclusion (or not) of delays between galaxy and massive black hole mergers

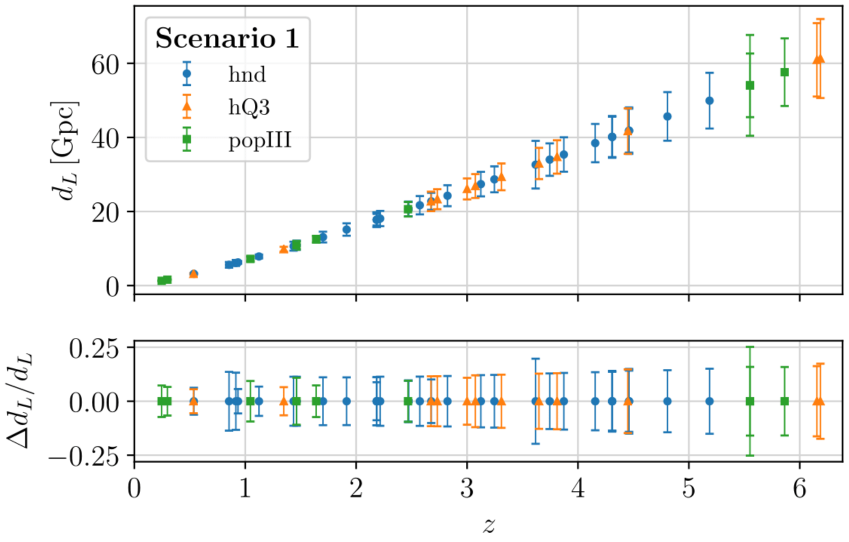
- We use 3 different models:
  - heavy seeds, no delays (hnd)
  - heavy seeds, with delay and $Q_c = 3$ (hQ3)
  - light seeds, with delay (popIII)

EM counterpart: optical luminosity flares, radio flares and jets expected from merging simulations

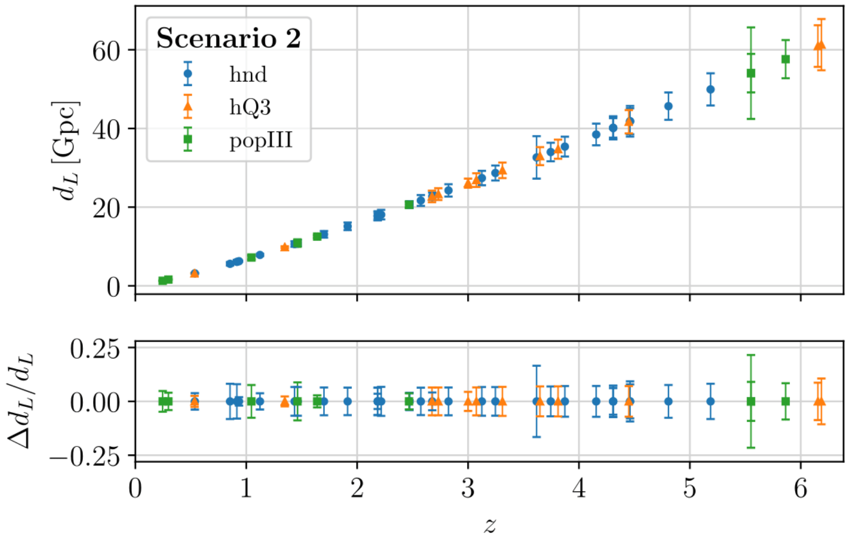
Palenzuela, Lehner, Liebling, Science 329 (2010) 927, 1005.1067; Giacomazzo et al., ApJ 752 (2012) L15, 1203.6108

- Detection of EM counterparts by LSST, SKA and ELT
- We distinguish 2 scenarios for the error on redshift: one optimistic (where we also assume that a delensing procedure by 50% is possible) and one more realistic, taking into account both spectroscopic and photometric redshift measurements

Realistic

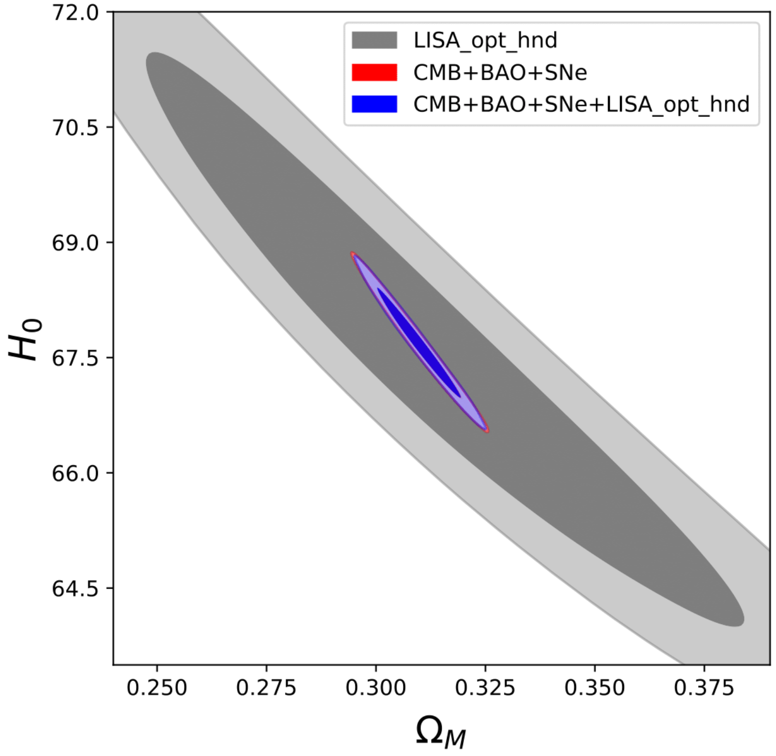


Optimistic



Number of events
(4 years of data)

hnd	hQ3	popIII
23	12	9



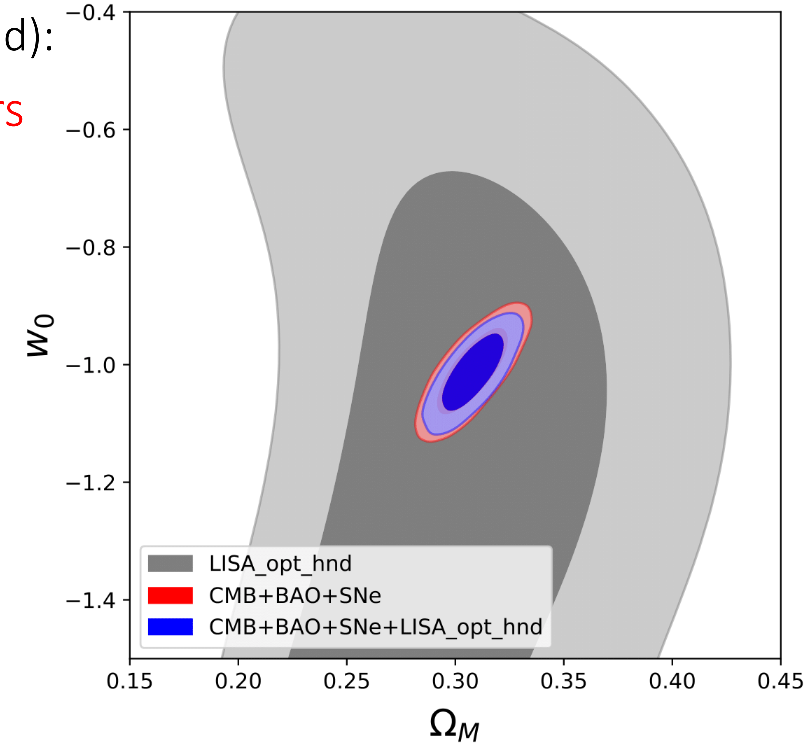
Even in the most favorable case (optimistic, hnd):

No improvement on ΛCDM parameters

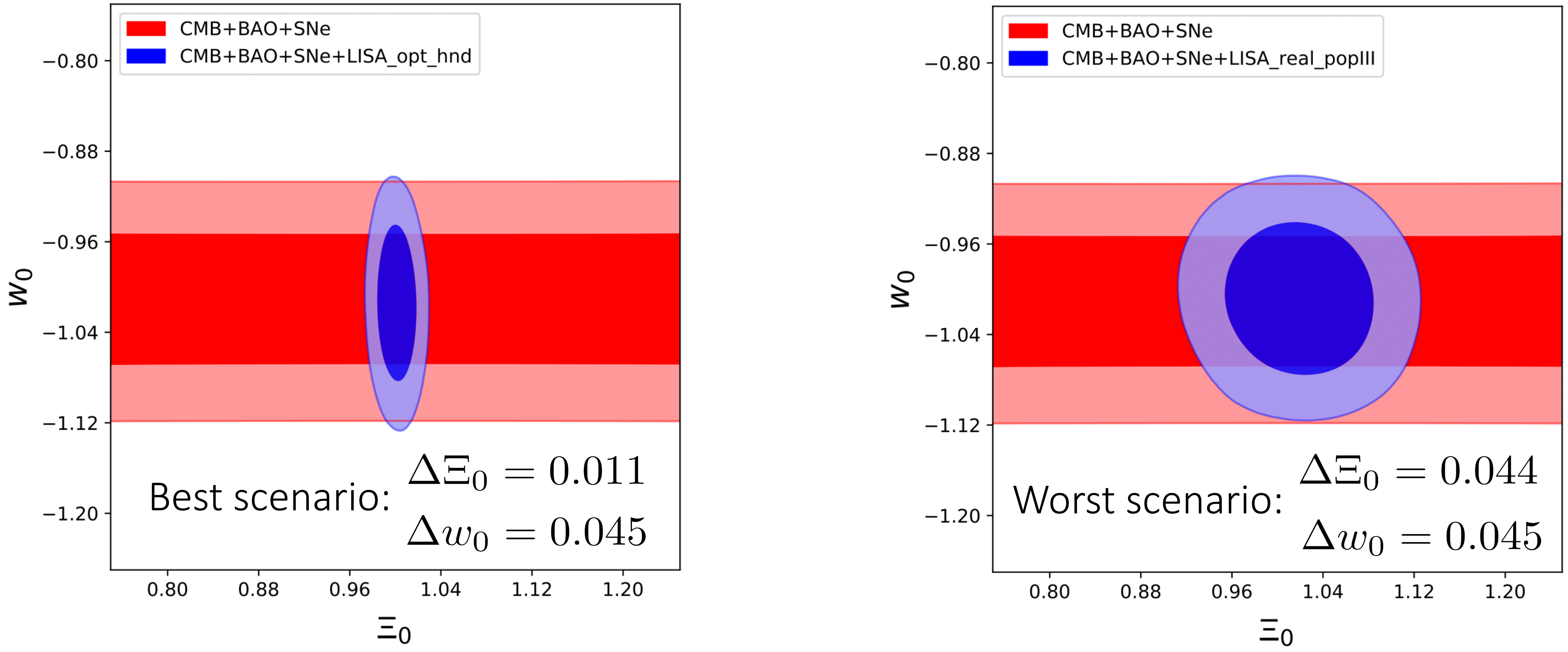
	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
LISA	3.8 %	14.7 %
CMB+BAO+SNe	0.7 %	2.1 %
CMB+BAO+SNe+LISA	0.7 %	2.0 %

No improvement on w_0

	Δw_0
CMB+BAO+SNe	0.045
CMB+BAO+SNe+LISA	0.044



Constraints on (Ξ_0, w_0)



Modified GW propagation is an extremely interesting observable for LISA!

N.B. The sources used in the analysis are only MBHBs, but further informations at LISA will be extracted from EMRIs and stellar mass BHBs using the statistical method

CONCLUSIONS

- It is necessary to introduce a notion of GW luminosity distance in modified gravity
- Modified GW propagation is of fundamental importance for DE studies using standard sirens:

1) It can only be probed by GW observations
2) Ξ_0 can be measured better than w_0
3) It allows significant tests of modified gravity models in cosmology

- It will be a primary physical observable for future GW detectors (for both ET and LISA)