# Testing dark energy and modified gravity with GWs

Michele Maggiore

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique théorique

Madrid, Sept. 2019

# What is dark energy?

- In the last two decades cosmology has become a precision science

- new territories explored + high quality data $\Longrightarrow$ surprises

  dark matter, dark energy

- DE: accelerated expansion of the Universe

  first proved with type Ia SNe (Riess et al; Perlmutter et al 1998)

  Nobel Prize 2011

- why we call it `dark energy'? In General Relativity

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \qquad\qquad p = w\rho$$

$$= -\frac{4\pi G}{3}(1+3w)\rho \quad \Rightarrow \quad w < -1/3$$

no known or unknown form of matter!

observationally, $w_{DE}$ very close to -1 → cosmological constant ?

$$G^\mu_\nu + \Lambda\delta^\mu_\nu = 8\pi G\, T^\mu_\nu$$

$$T^\mu_\nu = (-\rho, p, p, p) \quad \Rightarrow \quad p_\Lambda = -\rho_\Lambda$$

$$\rho_\Lambda = \frac{\Lambda}{8\pi G}$$

# $\Lambda$CDM is the standard cosmological paradigm

from Planck 2018,

$$\Omega_\Lambda \equiv \rho_\Lambda / \rho_0 = 0.685(7)$$

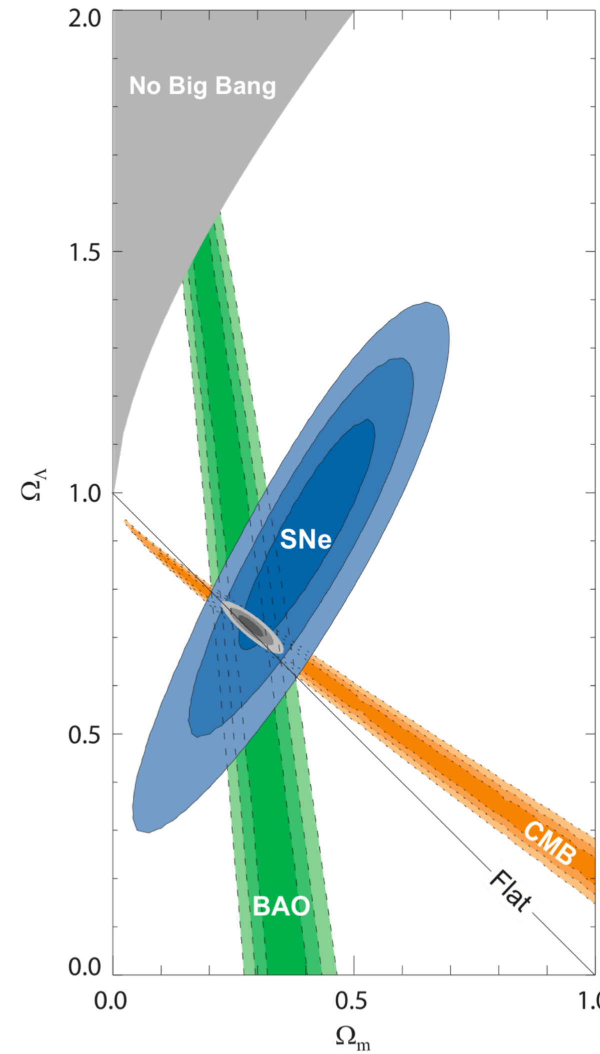
dark energy eq of state:

$$w_{\rm DE}(z) = w_0 + \frac{z}{1+z} w_a$$

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

$(w_0, w_a)$ : $\quad w_0 = -0.961 \pm 0.077$

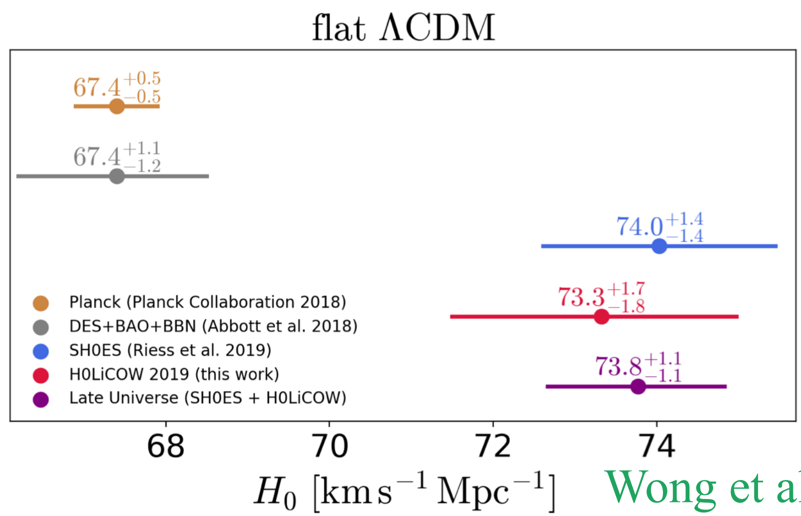
$$w_a = -0.28^{+0.31}_{-0.27}$$




Kowalski et al. (2008)
(old data but nice figure!)

# However, not all is well with ΛCDM

- Observational tensions, in particular early- vs late-Universe probes of $H_0$




Wong et al., H0LiCOW 2019

- Conceptual perplexities raised by a cosmological constant technically unnatural value, coincidence problem

good observational and theoretical reasons for testing ΛCDM and, especially, present and future data good enough to test it

Need to modify GR on cosmological scales?

# Where to look for a non-trivial DE sector?

**background evolution**

deviations in $w_{DE}$ from -1 bounded at (3-7)%

**scalar perturbations**

from growth of structures and lensing, bounds at the (7-10)% level

**tensor perturbations (gravitational waves)**

a new window on the Universe, that we have just opened

our talk: exploring dark energy with GWs

# GWs from coalescing binaries provide an absolute measurement of the distance to the source

- measure r without the need of calibration ("standard sirens")  (Schutz 1986)
- need an independent determination of z (electromagnetic counterpart, statistical methods)

in cosmology there are several different notions of distance. For coalescing binaries at cosmological distances

$$\frac{1}{r} \to \frac{1}{d_L}\,, \qquad \mathcal{F} \equiv \frac{\mathcal{L}}{4\pi d_L^2}$$

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

$$\Omega_M = \frac{\rho_M(t_0)}{\rho_0}\,, \quad \rho_0 = \frac{3H_0^2}{8\pi G}$$

- low z: Hubble law, $d_L \simeq H_0^{-1} z$
- moderate z: access $\Omega_M\,, \rho_{\rm DE}(z)$

# Low-z important for the tension in $H_0$:

Planck 2018+BAO+SNe: $H_0 = 68.34 \pm 0.83$

local measurements (Riess et al) $H_0 = 74.22 \pm 1.82$

4.4 discrepancy: indication for deviation from ΛCDM?

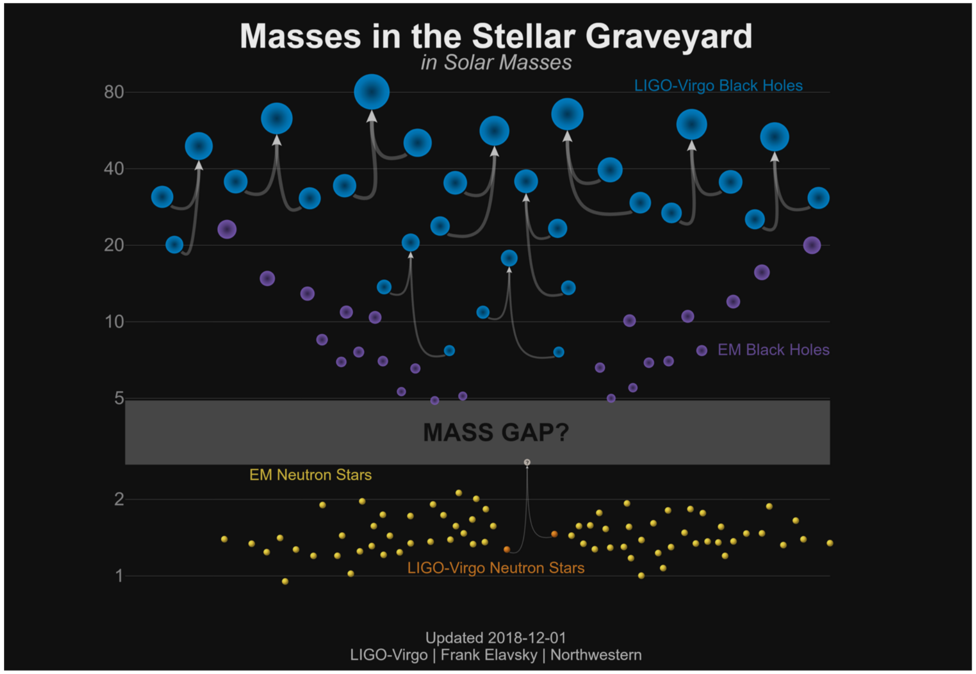
LIGO/Virgo measurement of $H_0$ from GW170817 $(z \simeq 0.01)$:

$$H_0 = 70.0^{+12.0}_{-8.0}$$

O(50-100) standard sirens at advanced LIGO/Virgo needed to arbitrate the discrepancy

Moderate z: access $\rho_{DE}(z)$ and test ΛCDM against modified gravity

- LIGO/Virgo detections in O1/O2

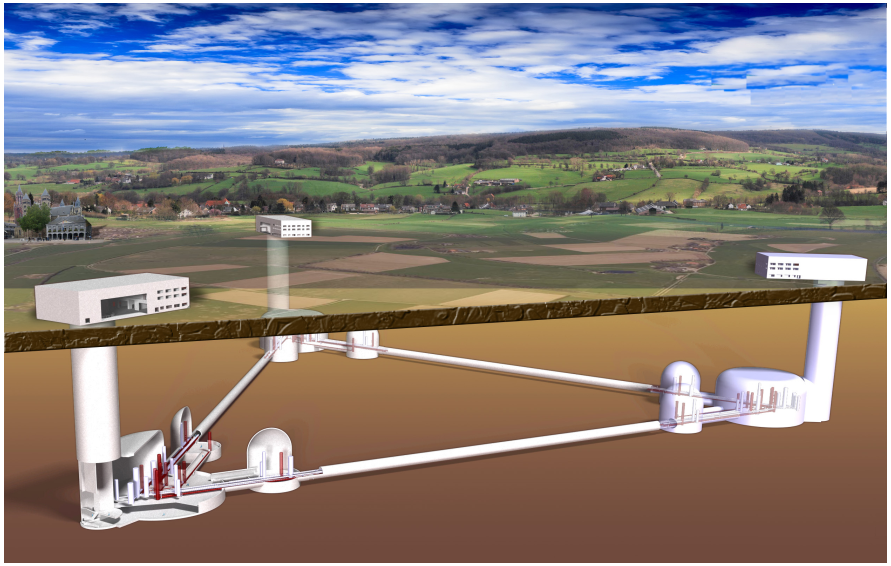



farthest BH-BH detection at $z=0.48$

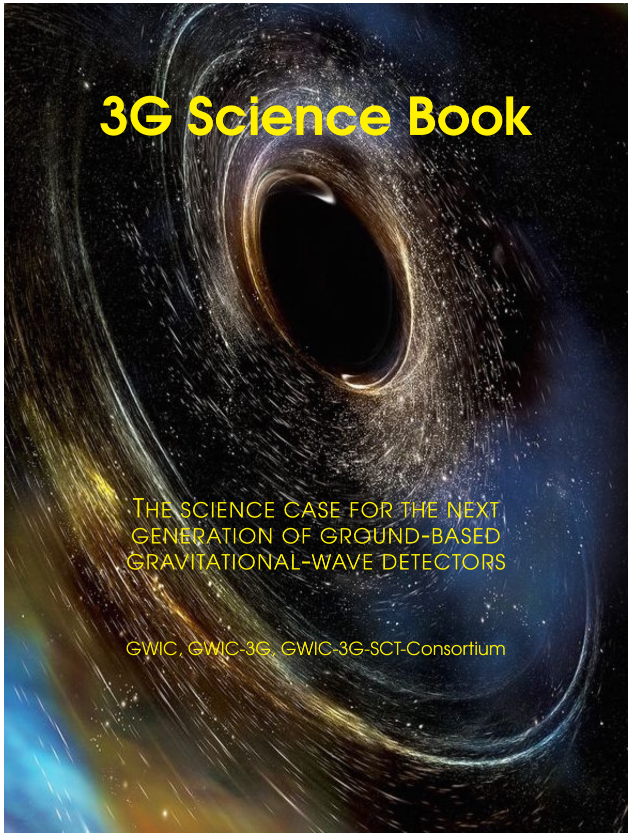
- during O3, detections are becoming a routine (1/week)

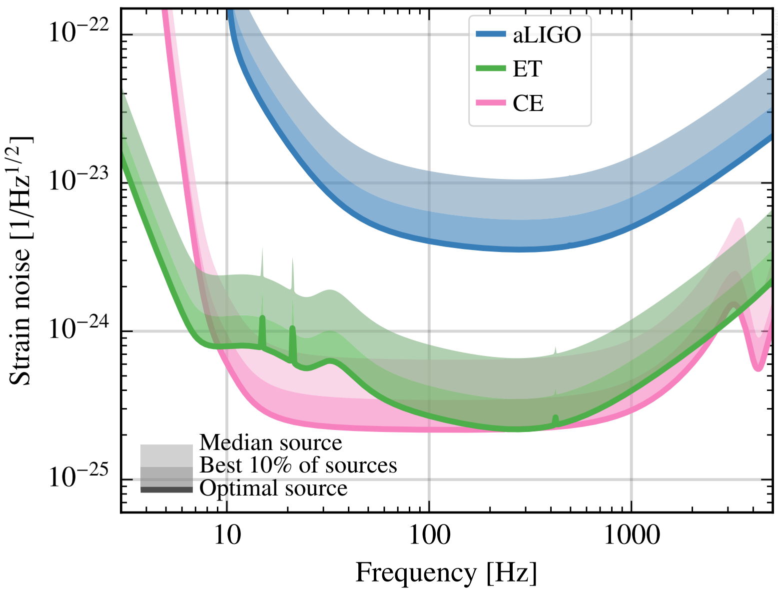
A real jump will however take place with 3G ground-based detectors and with LISA

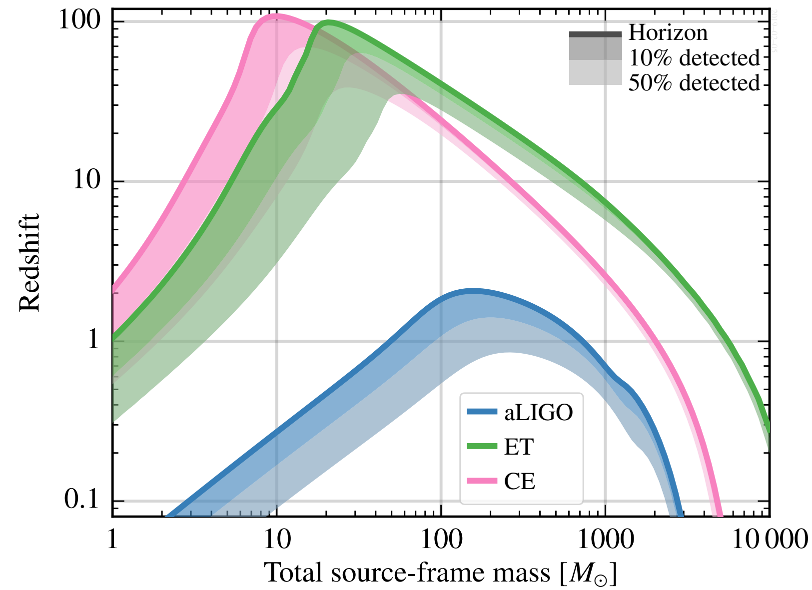
# 3G detectors
# (Einstein Telescope, Cosmic Explorer)



our Geneva group is part of the ET collaboration and currently contributes to the cosmology/dark energy section of the 3G Science Case paper

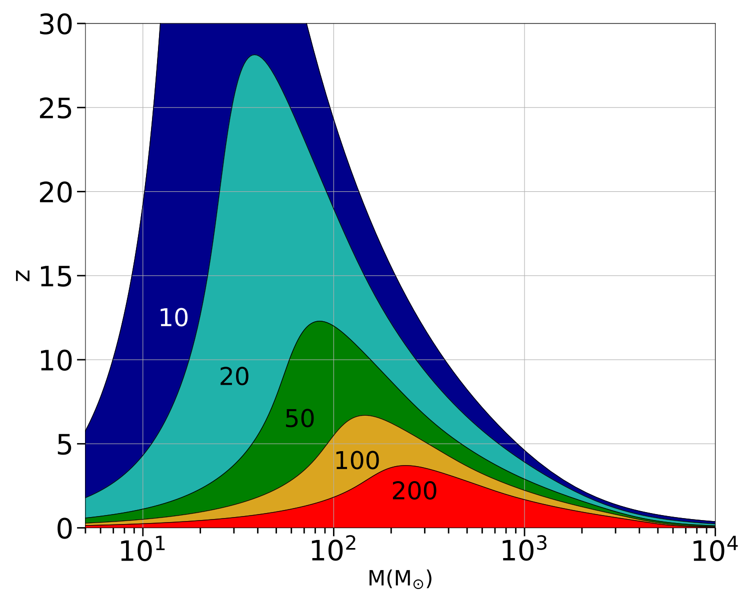





Sathyaprakash et al 2019

- NS-NS to z ≈ 2
- BH-BH to z ≈ 20
- $10^5$-$10^6$ events yr !
- high SNR




courtesy Colpi and Mangiagli

# Several studies of forecasts for $w_{DE}$ at ET

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; Belgacem, Dirian, Foffa, MM 2017,2018

typical assumptions:

- $O(10^3)$ BNS with em counterpart over 3 yr
- BNS distributed uniformly in comoving volume for $0<z<2$, or using a fit to the rate evolution
- generate a catalog of detections assuming a sensitivity curve for ET and SNR>8
- assume a fiducial cosmological model ($\Lambda$CDM) for $d_L(z)$
- scatter the data according to the error $\Delta d_L(z)$
- run a MCMC (or Fisher matrix) and use priors from CMB, BAO, SNe to reduce degeneracies between cosmological parameters

Result: not a significant improvement on $w_{DE}$ compared with what we already know from CMB+BAO+SNe

# A potentially more interesting observable?
# Modified GW propagation

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

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

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

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

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:

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

This is completely generic in modified gravity:

(Belgacem et al., LISA CosmoWG, JCAP 2019)

- non-local modifications of gravity
- DGP
- scalar-tensor theories (Brans-Dicke, Horndeski, DHOST,..)
- bigravity

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

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

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

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 !

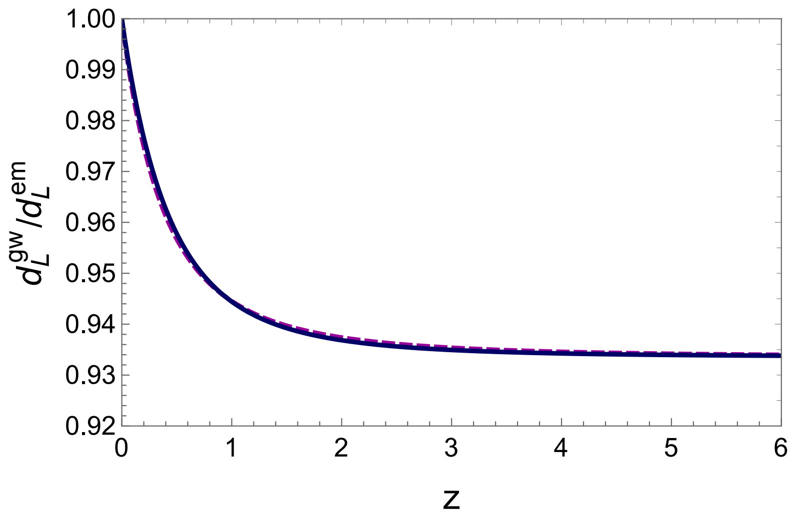
Deffayet and Menou 2007
Saltas et al 2014,
Lombriser and Taylor 2016,
Nishizawa 2017,
Belgacem et al 2017, 2018

in terms of δ(z) :

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

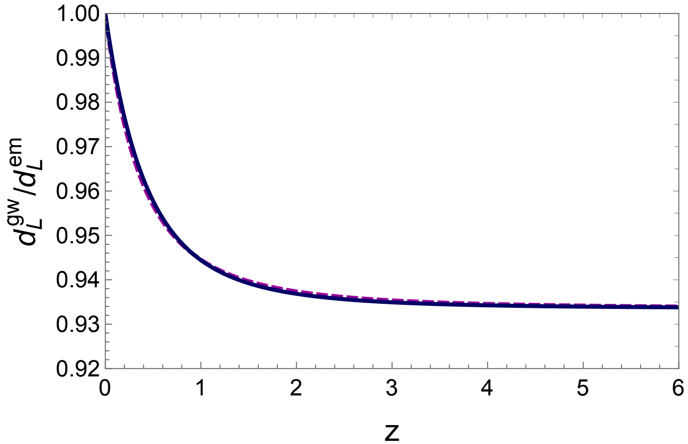
eg, prediction of the minimal RT nonlocal model:

6% effect at z>1



# a general parametrization of modified GW propagation

Belgacem, Dirian, Foffa, MM
PRD 2018, 1805.08731




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

e.g. for the minimal RT model:

$$\Xi_0 \simeq 0.934\,, \quad n \simeq 2.6$$

However, the parametrization is very natural, and indeed we find (LISA CosmoWG) that it fits the result of (almost) all modified gravity models

parametrizing extension of the DE sector:

background: $(w_0,w_a)$; scalar pert: $(\Sigma, \mu)$ ; tensor pert: $(\Xi_0, n)$

for standard sirens, the most important parameters are $w_0$, $\Xi_0$

The observation of GW170817 already gives a limit modified GW propagation

Belgacem et al 2018

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:

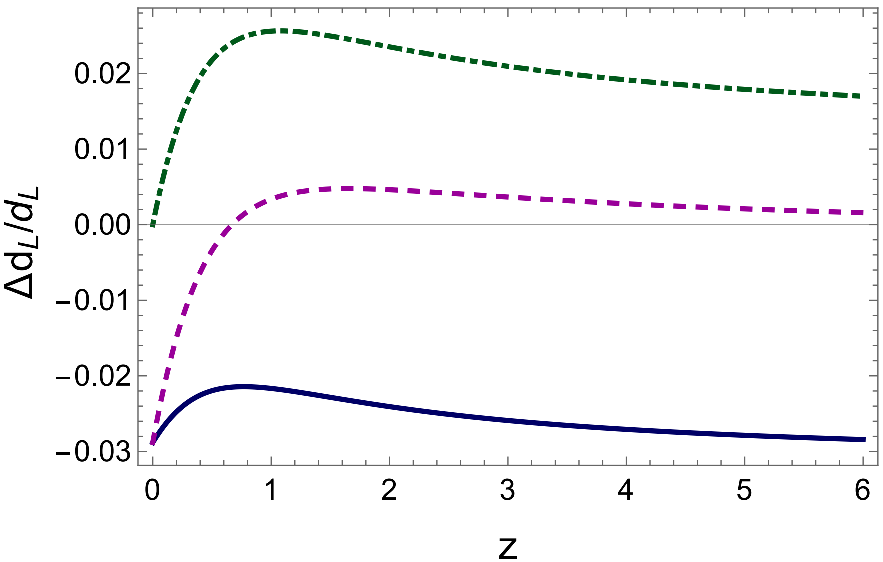
$$\delta(0) = -5.1^{+20}_{-11}$$

# at ET and 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)



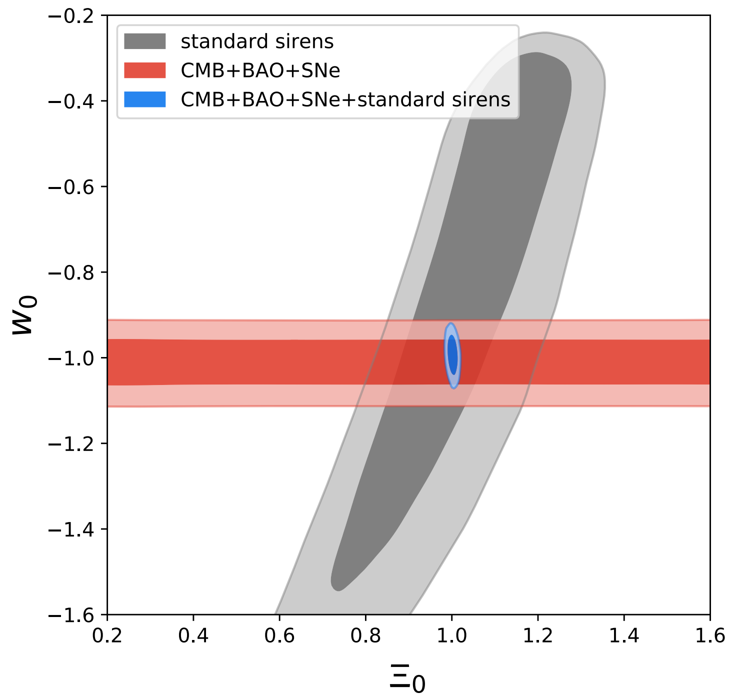

relative difference of e.m. luminosity distance RR-LCDM for the same values of $\Omega_M$ and $H_0$

relative difference with the respective best-fit parameters

relative difference of gw luminosity distance

# Forecasts for DE with ET

Belgacem, Dirian, Foffa, MM 2018



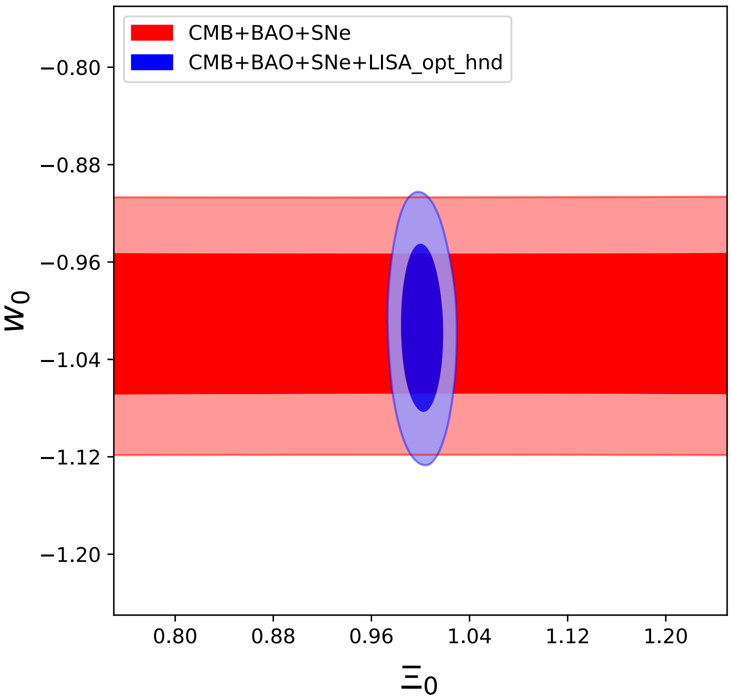

| | $\Delta\, w_0$ | $\Delta\, \Xi_0$ |
|---|---|---|
| CMB+BAO+SNe+ET | 0.032 | 0.008 |

with $10^3$ standard sirens at ET,
$\Xi_0$ can be measured to better than 1%

More detailed analysis of coincidences with a GRB detectors such as THESEUS in
Belgacem, Dirian, Foffa, Howell, MM, Regimbau 2019

# Forecasts for LISA

Belgacem et al LISA CosmoWG 2019




using supermassive BH binaries,

$\Delta\Xi_0$ =(1-4), $\Delta w_0$ =4.5%

(depending on formation scenarios for SMBH binaries)

# Predictions for $\Xi_0$ from modified gravity

- at the background level and for scalar perturbations, deviations from GR are bounded at the level (5-10)%

- one would expect similar deviations in the tensor sector
- instead, we will display a viable model where deviations can be 60%  !

$\Longrightarrow$ GWs could become  the best experiments for studying dark energy

# Nonlocal IR modifications of gravity

a generic denomination for models in which the fundamental theory is local but non-local terms, relevant in the IR, emerge at some effective level

Example: DGP model (Dvali,Gabadadze, Porrati 2000)

$$S = \frac{1}{2} M_{(5)}^3 \int d^5X \sqrt{-G} R(G) + \frac{1}{2} M_{(4)}^2 \int d^4x \sqrt{-g} R(g)$$

linearizing over flat space $h_{\mu\nu}(x,y) = e^{-y\sqrt{-\Box}} h_{\mu\nu}(x)$

the resulting effective 4-dime theory (at the linearized level) is governed by (Dvali, Gabadadze, Shifman 2002)

$$\left(1 + \frac{m}{\sqrt{-\Box}}\right) G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

example of how can emerge a nonlocal term, relevant in the IR, and associated to a mass scale

## The quantum effective action is nonlocal and gauge-invariant (or diff-invariant) mass terms can be obtained with nonlocal operators

eg massive electrodynamics

Dvali 2006

$$\Gamma = -\frac{1}{4}\int d^4x \left( F_{\mu\nu}F^{\mu\nu} - m_\gamma^2 F_{\mu\nu}\frac{1}{\Box}F^{\mu\nu} \right)$$

in the gauge $\partial_\mu A^\mu = 0$ we have $\frac{1}{4}m_\gamma^2 F_{\mu\nu}\frac{1}{\Box}F^{\mu\nu} = \frac{1}{2}m_\gamma^2 A_\mu A^\mu$

it is a nonlocal but gauge-invariant photon mass term!

equivalently, $\left(1 - \frac{m_\gamma^2}{\Box}\right)\partial_\mu F^{\mu\nu} = 0 \quad \rightarrow \quad \begin{cases} \partial_\mu A^\mu = 0 \\ (\Box - m_\gamma^2)A^\mu = 0 \end{cases}$

- Numerical results on the gluon propagator from lattice QCD and OPE are reproduced by adding to the quantum effective action a term

$$\frac{m_g^2}{2}\mathrm{Tr}\int d^4x\, F_{\mu\nu}\frac{1}{\Box}F^{\mu\nu}$$

$$F_{\mu\nu}=F^a_{\mu\nu}T^a\,,\quad \Box^{ab}=D^{ac}_\mu D^{\mu,cb}\,,\quad D^{ab}_\mu=\delta^{ab}\partial_\mu-gf^{abc}A^c_\mu$$

(Boucaud et al 2001,Capri et al 2005,Dudal et al 2008)

it is a nonlocal but gauge invariant mass term for the gluons, generated dynamically by strong IR effects

# Is it possible that a mass is dynamically generated in GR in the IR?

difficult non-perturbative question. Some hints:

- Euclidean lattice gravity suggests dynamical generation of a mass m, and a running of $G_N$

$$G(k^2) = G_N \left[ 1 + \left( \frac{m^2}{k^2} \right)^{\frac{1}{2\nu}} + \mathcal{O}\left( \frac{m^2}{k^2} \right)^{\frac{1}{\nu}} \right]$$

$\nu \approx 1/3$

Hamber 1999, .., 2017

- recent results based on causal dynamical triangulation find in the quantum effective action a mass for the conformal mode, just as in the model that we had previously postulated

(Knorr and Saueressig PRL 2018)

- massive photon: can be described replacing

$$\partial_\mu F^{\mu\nu} = j^\nu \quad \rightarrow \quad \left(1 - \frac{m^2}{\Box}\right) \partial_\mu F^{\mu\nu} = j^\nu$$

(Dvali 2006)

- for gravity, a first guess for a massive deformation of GR could be

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \quad \rightarrow \quad \left(1 - \frac{m^2}{\Box_g}\right) G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

(Arkani-Hamed, Dimopoulos, Dvali and Gabadadze 2002)

however this is not correct since $\nabla^\mu (\Box_g^{-1} G_{\mu\nu}) \neq 0$

we lose energy-momentum conservation

- to preserve energy-momentum conservation:

$$G_{\mu\nu} - m^2(\Box^{-1}G_{\mu\nu})^T = 8\pi G T_{\mu\nu}$$

(Jaccard,MM, Mitsou, 2013)

however, instabilities in the cosmological evolution

(Foffa,MM, Mitsou, 2013)

- $$G_{\mu\nu} - m^2(g_{\mu\nu}\Box^{-1}R)^T = 8\pi G T_{\mu\nu}$$

(MM 2013)

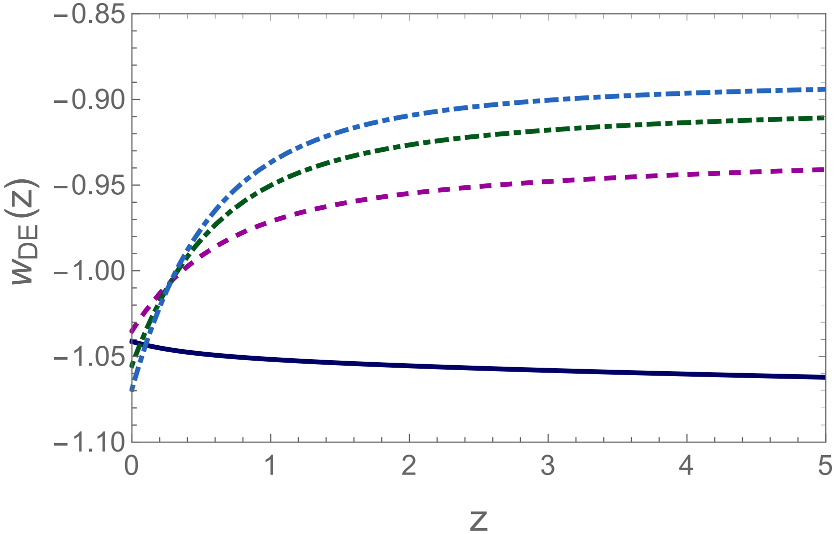
stable cosmological evolution ``RT model"

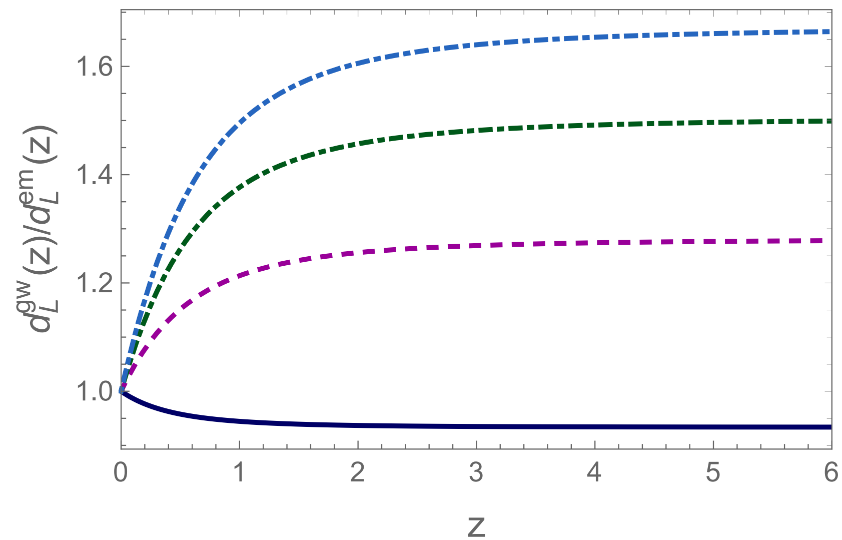
Extensive studies of the various possibilities have shown that it is the only known viable nonlocal model

- generates a dynamical DE and has stable cosmological perturbations in the scalar and tensor sectors
- fit CMB, BAO, SNe and structure formation data at a level statistically equivalent to $\Lambda$CDM
- passes solar system tests and bounds on time-variation of G
- predicts $c_{gw} = c$
- predicts modified GW propagation
- implicit dependence on the number of efold during inflation through the initial conditions

# predictions of the RT model

Belgacem et al 1907.02047




- for ΔN=64, at large z deviations from GR at the level of 60% ! Detectable with a single standard siren at ET or LISA and possibly even by LIGO/Virgo/Kagra

- example of the fact that a viable model can give surprises in the tensor sector

Take-away message:

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

- it is specific to GW observations
- $\Xi_0$ can be measured with better accuracy than $w_0$
- there are phenomenologically viable models with large deviations from GR in the tensor sector

GW detectors could offer the best window on dark energy and modified gravity!

# Thank you!