Testing gravity at cosmological scales with gravitational waves

Michele Maggiore

UNIVERSITÉ DE GENÈVE

FACULTÉ DES SCIENCES

Département de physique théorique

Cagliari, 24 Nov. 2022

Plan of the talk

- coalescing binaries as `standard sirens'
  - H_0
  - DE eq. of state
  - modified GW propagation

- limits on modified GW propagation from current LVK data

- perspectives with Einstein Telescope and LISA

GWs as probes of cosmology

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

$$h_+(t) = \frac{4}{r}\frac{1+\cos^2\iota}{2}\left(\frac{GM_c}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3}\cos\Phi(t)$$

$$h_\times(t) = \frac{4}{r}\cos\iota\left(\frac{GM_c}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3}\sin\Phi(t)$$

$$\Phi(t) = 2\pi\int dt\, f(t)$$

$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{GM_c}{c^3}\right)^{5/3} f^{11/3}$$

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

measure r without the need of calibration (“standard sirens")

(Schutz 1986)

For coalescing binaries at cosmological distances

$$\frac{1}{r} \to \frac{1}{d_L}\,, \qquad \mathcal{F} \equiv \frac{\mathcal{L}}{4\pi d_L^2} \qquad m_i \to m_i(1+z)$$

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

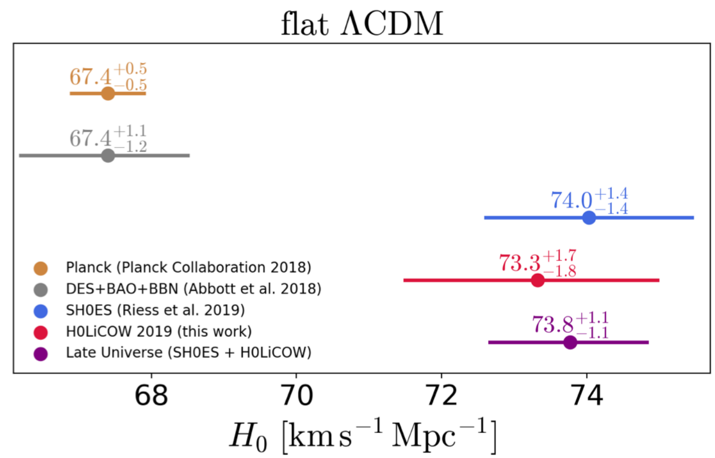
$$\Omega_M = \frac{\rho_M(t_0)}{\rho_0}, \quad \rho_0 = \frac{3H_0^2}{8\pi G}$$

- need an independent determination of z
  (electromagnetic counterpart, statistical methods)

- 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:

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



LIGO/Virgo measurement of H_0 from GW170817:

$$H_0 = 70.0^{+12.0}_{-8.0} \qquad (z \simeq 0.01)$$

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

At higher z, accessible only to 3G detectors or LISA, we access the redshift evolution of the dark energy density

$$p_{\rm DE}(z) = w_{\rm DE}(z)\rho_{\rm DE}(z) \quad \Longrightarrow \quad \frac{\rho_{\rm DE}(z)}{\rho_0} = \Omega_{\rm DE} \exp\left\{3\int_0^z \frac{d\tilde{z}}{1+\tilde{z}}\left[1+w_{\rm DE}(\tilde{z})\right]\right\}$$

Several studies of forecasts for w_{DE} at ET

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 1712.08108 , 1805.08731

Belgacem, Dirian, Finke, Foffa, MM 1907.02047, 2001.07619

Belgacem et al, LISA CosWG, 1907.01487

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, current bounds at the (7-10)% level

target of next generation of galaxy surveys

tensor perturbations (gravitational waves)

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

A potentially more interesting observable?

Modified GW propagation

Belgacem, Dirian, Foffa, MM
PRD 2018, 1712.08108
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:

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

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

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

1. $c_{GW} = c$ ok with GW170817 (otherwise the model is ruled out)

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

All dynamical theories of DE will display this effect!

(Belgacem et al., LISA CosmoWG, JCAP 2019) coalescing binaries measure a ``GW luminosity distance" different from the standard (electromagnetic) luminosity distance !

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

in terms of δ(z) :

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

a general parametrization of modified GW propagation

Belgacem, Dirian, Foffa, MM
PRD 2018, 1805.08731

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

This parametrization is very natural, and fits the result of (almost) all modified gravity models

Belgacem et al (LISA CosmoWG), 2019

Modified GW propagation can be a smoking gun of DE

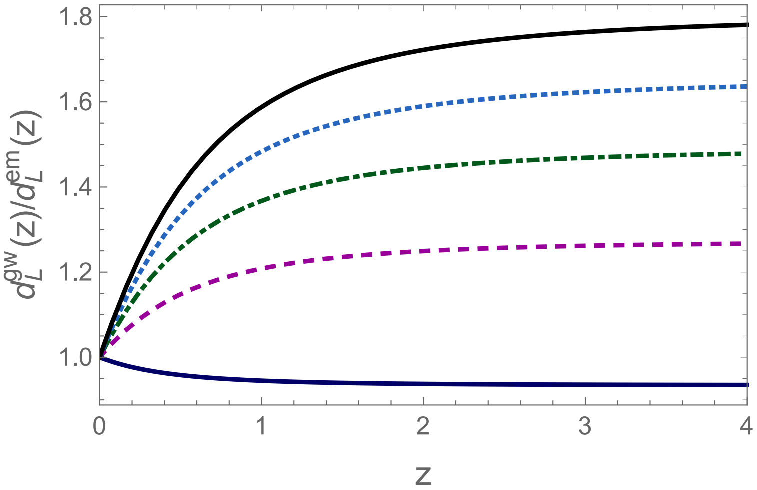
- Ξ_0 can be measured more accurately than w_0 (because of degeneracies with H_0, Ω_M)

- the sector of tensor perturbation is uncharted territory (while, for w_0, a measure with accuracy lower than a few percent would no longer be very significant)

- 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, in a viable model (non-local gravity)

 the deviations can be 80% !



⟹ GWs could become the best experiments for studying dark energy

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)

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

corresponds to Ξ_0 < O(10), very broad limit

we have then started a systematic investigation of how to extract modified GW propagation from current and future data

Dark sirens

correlating standard sirens with galaxy catalogs

The Astrophysical Journal Letters, 876:L7 (15pp), 2019 May 1
https://doi.org/10.3847/2041-8213/ab14f1

CrossMark

First Measurement of the Hubble Constant from a Dark Standard Siren using the Dark Energy Survey Galaxies and the LIGO/Virgo Binary–Black-hole Merger GW170814

M. Soares-Santos[1], A. Palmese[2], W. Hartley[3], J. Annis[2], J. Garcia-Bellido[4], O. Lahav[3], Z. Doctor[5,6], M. Fishbach[6], D. E. Holz[7], H. Lin[2], M. E. S. Pereira[1], A. Garcia[1], K. Herner[2], R. Kessler[6,8], H. V. Peiris[3], M. Sako[9], S. Allam[2], D. Brout[9],

Cosmology with LIGO/Virgo dark sirens: Hubble parameter and modified gravitational wave propagation

Andreas Finke, Stefano Foffa, Francesco Iacovelli, Michele Maggiore and Michele Mancarella

2101.12660, JCAP 2021

we correlate `dark sirens' from GWTC-2 with a galaxy catalog (GLADE)

significant developments of the methodology for dark sirens

measurements of H_0 and Ξ_0

methodology (or, the devil is in the details!)

- hierarchical Bayesian framework

$$p(\mathcal{D}^i_{\rm GW}|\lambda') = \frac{1}{\beta(\lambda')} \int d\theta \, p(\mathcal{D}^i_{\rm GW}|\theta, \lambda') \, p_0(\theta|\lambda') \,,$$

$\lambda' = \{H_0\}$ or $\lambda' = \{\Xi_0\}$ $\qquad \theta = \{d_L, \hat{\Omega}, \theta'\}$

$p(\mathcal{D}^i_{\rm GW}|\theta, \lambda')$ likelihood of the data given the parameters of the signal and of the cosmology. Here given by LVK skymaps

$p_0(\theta|\lambda')$ prior on the parameters. Here given by the galaxy catalog

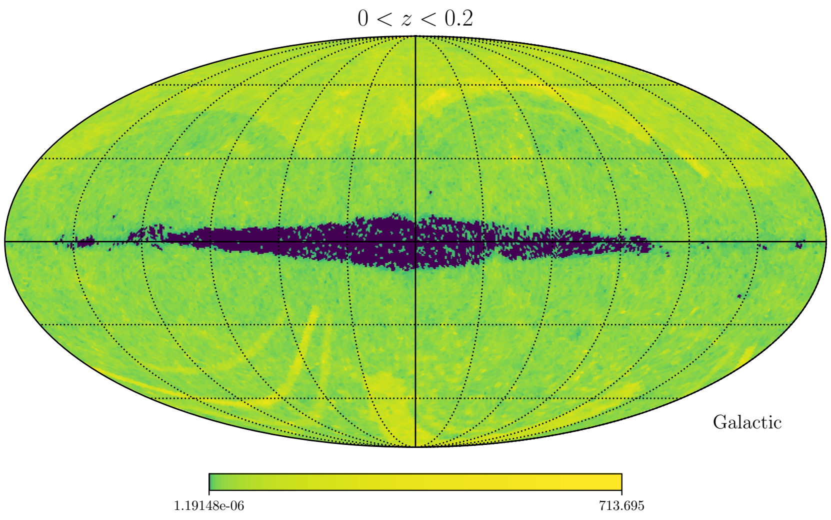
$$\beta(\lambda') = \int_{\mathcal{D}_{\rm GW} > {\rm threshold}} d\mathcal{D}_{\rm GW} \int d\theta \, p(\mathcal{D}_{\rm GW}|\theta, \lambda') \, p_0(\theta|\lambda')$$

selection effects

galaxy catalogs and completeness

in an ideal catalog $p_{\rm cat}(z,\hat\Omega) = \frac{\sum_{\alpha=1}^{N_{\rm cat}} w_\alpha \delta(z-z_\alpha)\delta^{(2)}(\hat\Omega-\hat\Omega_\alpha)}{\sum_{\alpha=1}^{N_{\rm cat}} w_\alpha}$

However, catalogs are incomplete and sample different directions in different ways



- One must understand how many galaxies are missing

  - we introduced an angular notion of completeness
  (actually two, mask completeness and cone completeness)

  - completion based on luminosity weighting, B vs K band,
  different thresholds

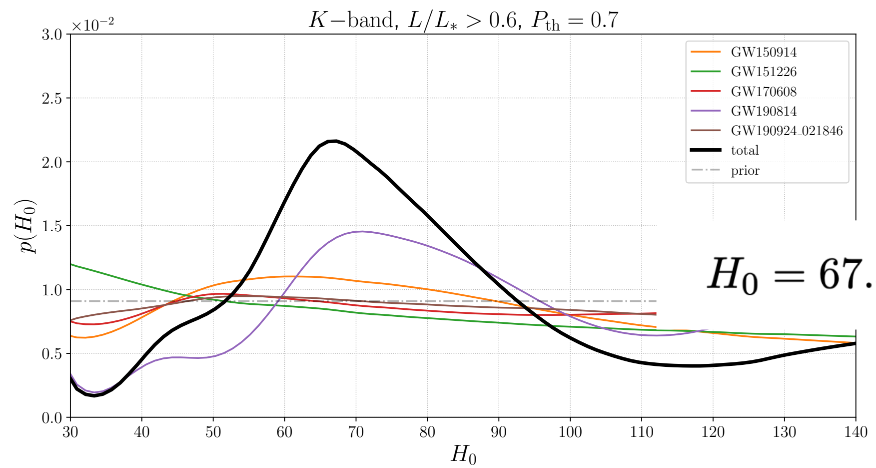
- how to best complete the catalog
  (additive vs. multiplicative competion)

- compute selection effect with MCMC

see the paper for the (very!) technical details

after all this, the prize are posteriors that are not flat, even with a limited number of useful BBH events

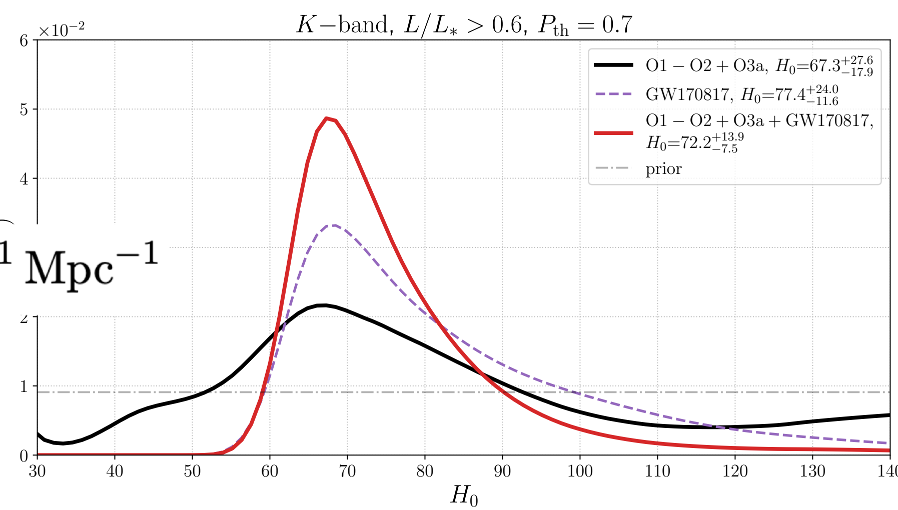
only well-localized events
that fall into sufficiently complete
region contribute



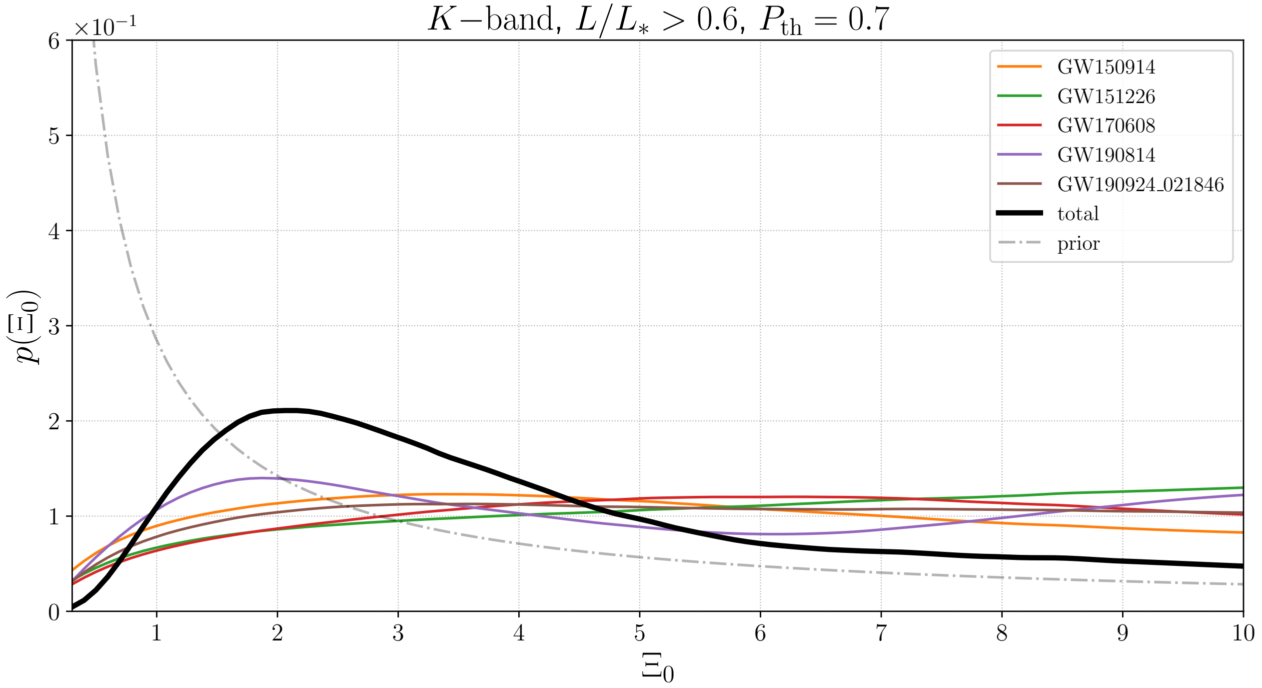
$$H_0 = 67.3^{+27.6}_{-17.9}\ \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

combining dark sirens with
GW170817

$$H_0 = 72.2^{+13.9}_{-7.5}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$



first meaningful limits on Ξ_0



$$\Xi_0 = 2.1^{+3.2}_{-1.2}$$

next step: joint population-cosmology inference

Cosmology and modified gravitational wave propagation from binary black hole population models

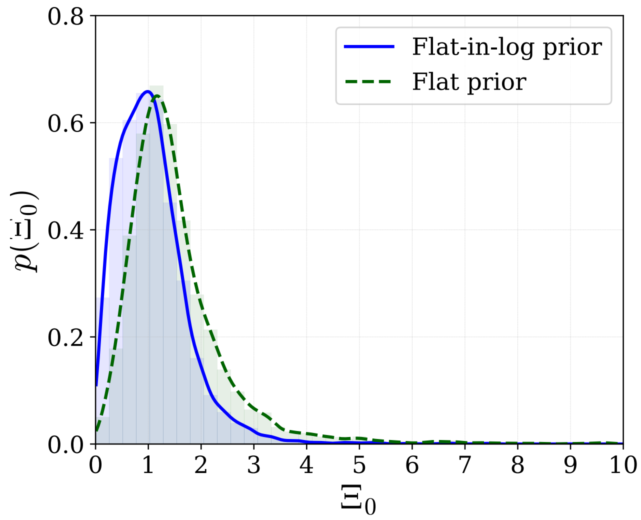
2112.05728, PRD 2022

Michele Mancarella,[1,*] Edwin Genoud-Prachex,[2,†] and Michele Maggiore[1,‡]

joint hierarchical Bayesian analysis of the BBH mass function, merger rate evolution and cosmological parameters

BBHs from GWTC-3

makes use of the mass scale in the BBH mass function due to the PISN process

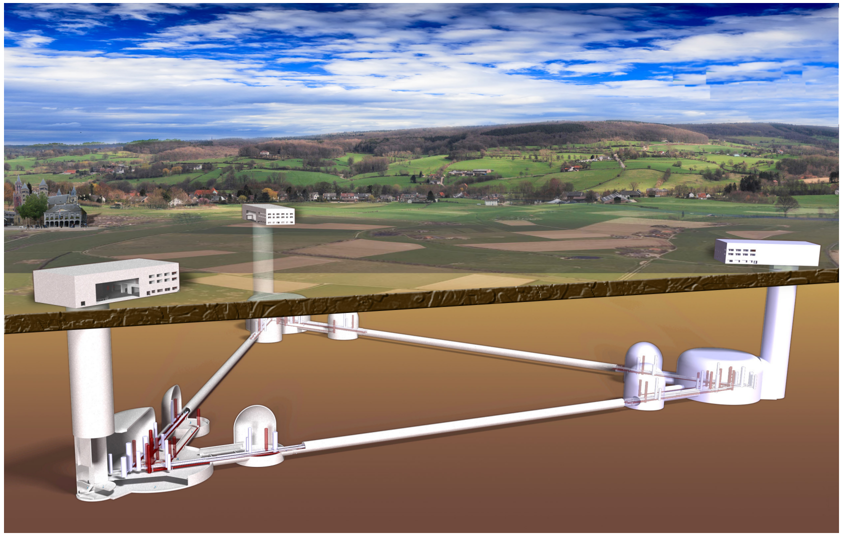


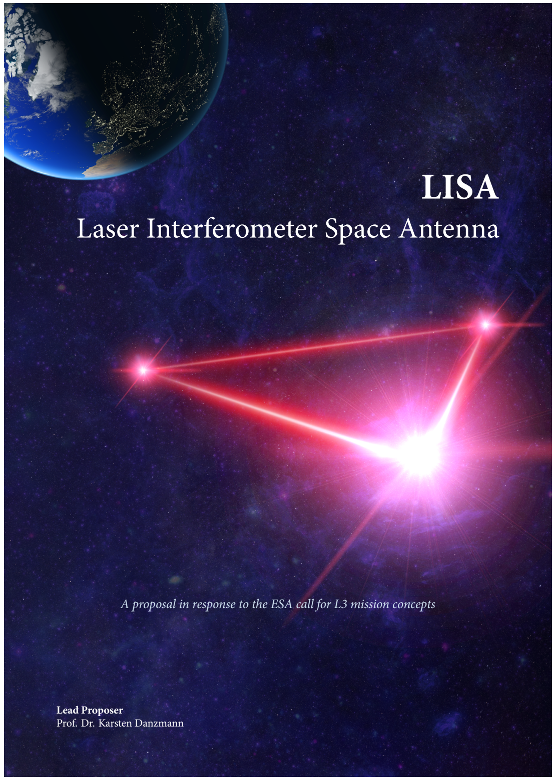
$$\Xi_0 = 1.2^{+0.7}_{-0.7} \quad \text{(68\% c.l.)}$$

Most stringent limit to date

with 5 yrs of LVK data, measure of Ξ_0 at 10-20%

To fully explore cosmological distances we need 3G ground-based detectors (Einstein Telescope, Cosmic Explorer), and LISA





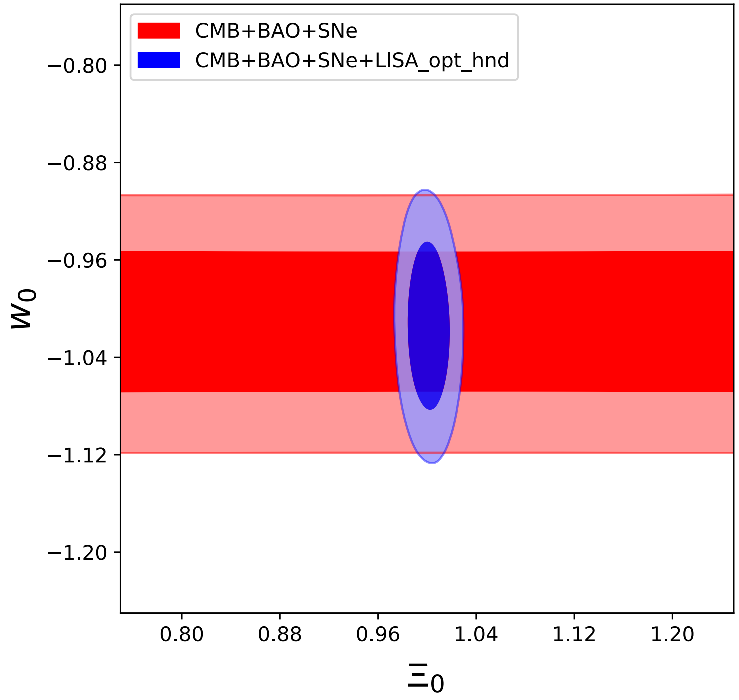
Forecasts for LISA

Belgacem et al LISA CosmoWG 2019

using supermassive BH binaries, assuming counterpart

$\Delta\Xi_0$ =(1-4)%, Δw_0 =4.5%

(depending on formation scenarios for SMBH binaries)



Modified gravitational wave propagation and the binary neutron star mass function

Andreas Finke[a], Stefano Foffa[a], Francesco Iacovelli[a], Michele Maggiore[a,*], Michele Mancarella[a]

2108.04065, Phys. Dark. Univ. 2022

GW observations give $m_{det}=(1+z)\,m$ and d_L

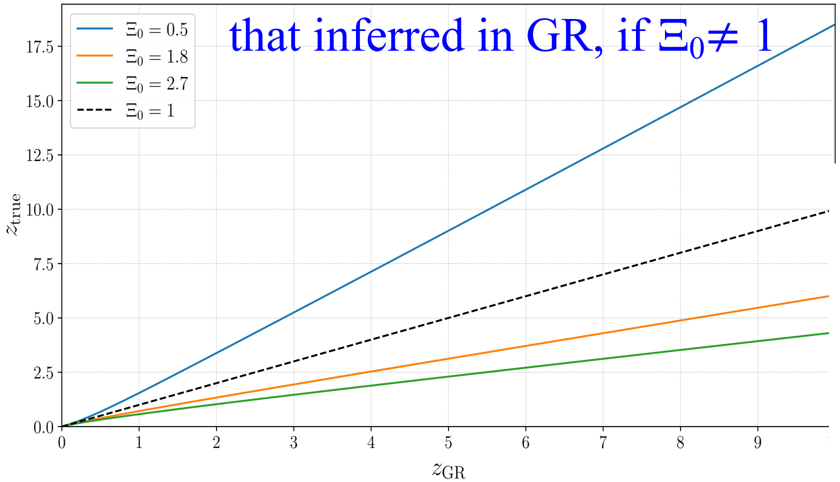
assuming ΛCDM, from d_L we get z and therefore the true mass m

however, if Nature is described by modified GW propagation, GW observations give d_L^{gw}

interpreting the data within ΛCDM, we get the wrong z and the wrong mass

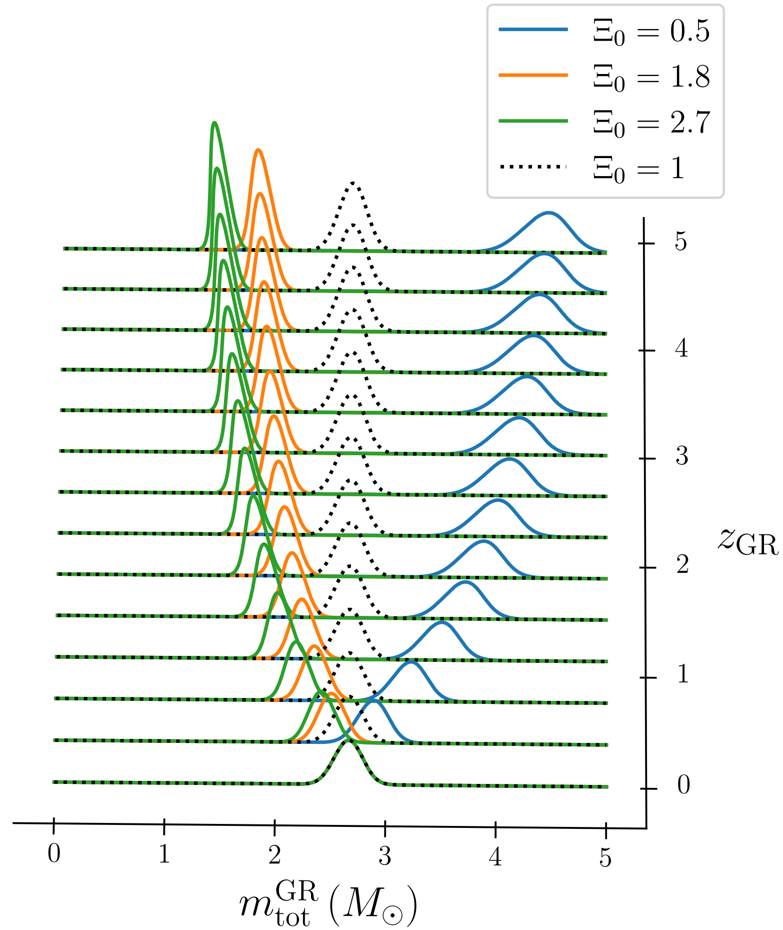
but the NS mass function is strongly constrained!

the true redshift as a function of that inferred in GR, if $\Xi_0 \neq 1$



assuming GR, at large z not a single NS with a `normal mass' !!

smoking gun of modified GW propagation



Take-away message:

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

- it is specific to GW observations
- Ξ_0 can be measured with better accuracy than w_0
- there are phenomenologically viable models with large deviations from GR in the tensor sector
- already interesting limit from LVC, extremely promising for ET and LISA

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

Thank you!

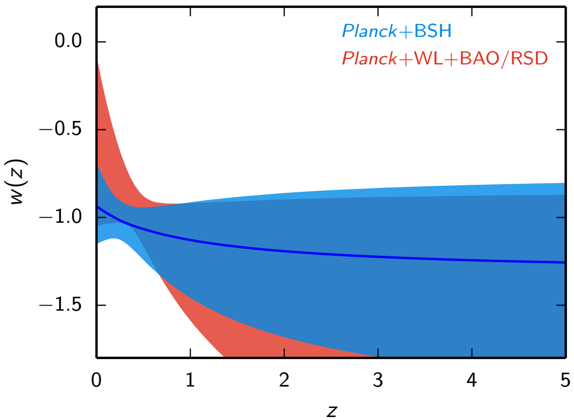
Dark energy eq. of state consistent with w=-1 at a few percent level

$$p_{\rm DE}(z) = w_{\rm DE}(z)\rho_{\rm DE}(z) \quad \Longrightarrow \quad \frac{\rho_{\rm DE}(z)}{\rho_0} = \Omega_{\rm DE} \exp\left\{3\int_0^z \frac{d\tilde{z}}{1+\tilde{z}}\left[1+w_{\rm DE}(\tilde{z})\right]\right\}$$

Reconstructing the full function $w_{\rm DE}(z)$ from the cosmological data gives a large error.

Better use a parametrization:

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



Planck XIV 2015
(Dark-energy paper)

Planck 2018+BAO+SNe:

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

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

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