Cosmology with LIGO/Virgo dark sirens and galaxy catalogs

Francesco Iacovelli

Based on JCAP08(2021)026 and arXiv:2108.04065, in collaboration with:

Andreas Finke, Stefano Foffa, Michele Maggiore, Michele Mancarella

University of Geneva (UNIGE) – Department of Theoretical Physics

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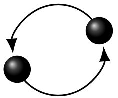
GWs and Cosmology: general idea

 $\Rightarrow \; d_L$

Complementary information on z

$$d_L(z) = \frac{c(1+z)}{\mathrm{H}_0} \int_0^z \frac{\mathrm{d}z'}{\mathrm{E}(z')}$$

Cosmology

Modified GW propagation: overview

The propagation equation of tensor modes in all theories that modify GR on cosmological scales becomes

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

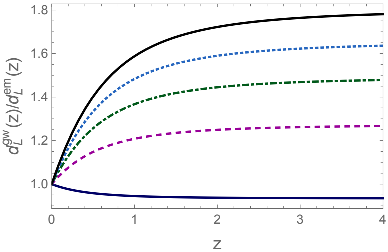
The net effect is

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

At the background level and for scalar perturbations, deviations from GR are bounded at the level of $(5-10)\%$, so one would expect similar deviations also in the tensor sector ...

Modified GW propagation: overview

...instead, in a viable model, the deviations can reach 80%!



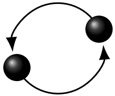
E. Belgacem et al. (2020)

A useful parametrization in most of the models is given by

E. Belgacem et al. (2019)

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

GWs and Modified Gravity



$\Rightarrow \; d_L$

Complementary information on z

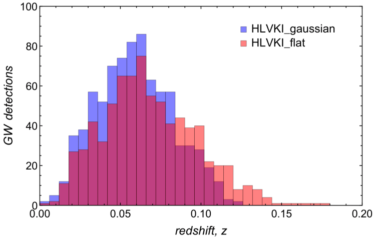
$$d_L^{\rm gw}(z) = \left[\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right] \frac{c(1+z)}{\mathrm{H}_0} \int_0^z \frac{\mathrm{d}z'}{\mathrm{E}(z')}$$

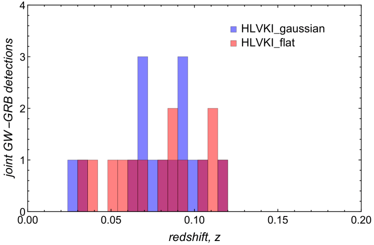
Modified GW propagation — Standard $d_L^{\rm em}(z)$

Cosmology & Modified Gravity

Which information on z?

The best option would be to have an electromagnetic counterpart, but this is expected only for a small fraction of the BNS events…





E. Belgacem et al. (2019)

…and BBH events are expected to be much more numerous, thus other methods are needed to exploit all the available information

Methodology: hierarchical Bayesian framework

$\lambda' = \mathrm{H}_0$ or Ξ_0

LVC skymaps

$$p(\lambda'|\{\mathcal{D}_{\rm GW}\}) \propto \prod_{i=1}^{N_{\rm det}} \frac{1}{\beta(\lambda')} \int \mathrm{d}\theta \; p(\mathcal{D}^i_{\rm GW}|\theta,\lambda') \, p_0(\theta|\lambda')$$

Detection model,
MC computation

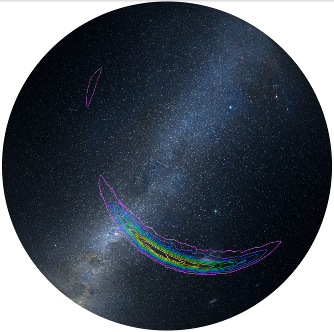
Galaxy catalog:
completeness and
completion

B. F. Schutz (1986); W. Del Pozzo (2012);
H. Y. Chen, M. Fishbach, and D. E. Holz (2018);
I. Mandel, W. M. Farr, J. R. Gair (2019); LVC (2021)...

Methodology: skymaps

For each GW event, LVC provides the so-called skymap, an approximation of its 3D localization: a Gaussian likelihood with direction-dependent parameters.

L. P. Singer et al. (2016)

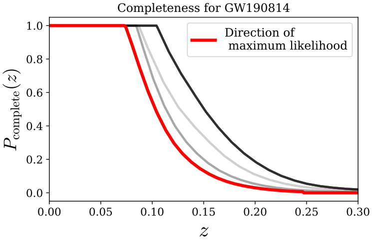


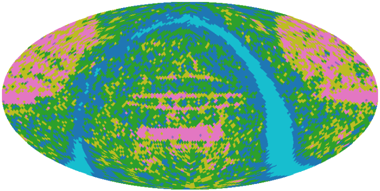
LIGO/Axel Mellinger

$$p(\mathcal{D}^i_{\rm GW}|d_L,\hat{\Omega}) = \rho_i(\hat{\Omega})\frac{\mathcal{N}(\hat{\Omega})}{\sqrt{2\pi}\sigma(\hat{\Omega})}\exp\left\{-\frac{[d_L-\mu_i(\hat{\Omega})]^2}{2\sigma_i^2(\hat{\Omega})}\right\}$$

Methodology: galaxy catalog (GLADE)

The crucial issue when dealing with a galaxy catalog is completeness, which cannot be treated as a "global" notion

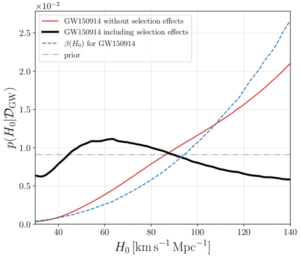




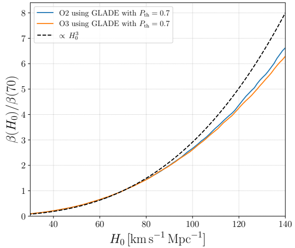
Once this is estimated, one can complete the catalog making some assumptions on the distribution of "missed" galaxies

Ingredients: $\beta(\lambda')$

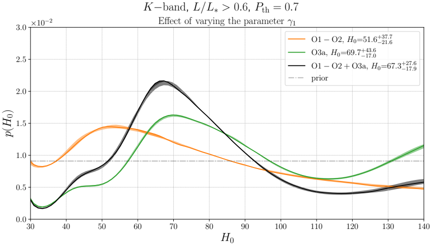
The other key point of this methodology is the estimation of the normalisation factor, needed to account for selection effects that would bias the result

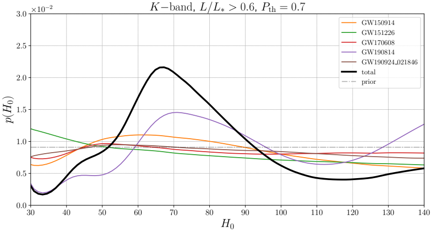


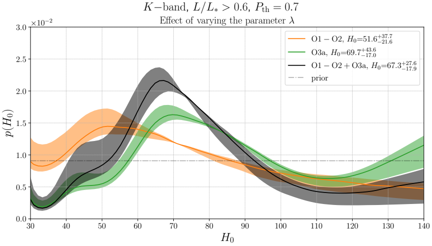
Some analytical approximations can be exploited, but to include a realistic detection model and all selection effects, a MC evaluation is the only way to proceed



Results: estimation of H_0

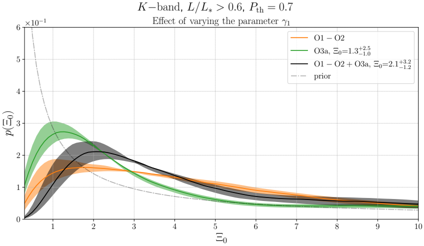


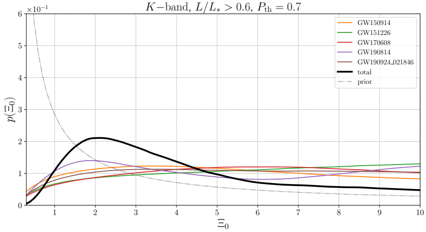


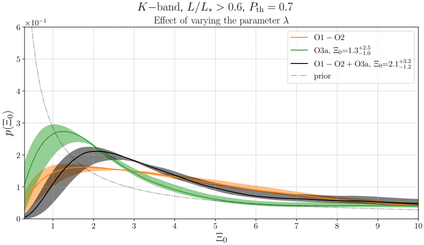


$$\mathrm{H}_0 = 67.3^{+27.6}_{-17.9}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Results: estimation of Ξ_0

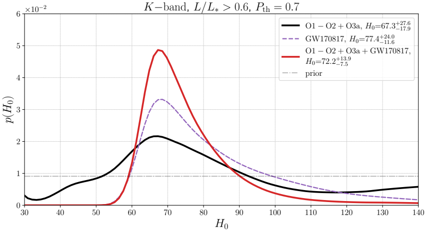




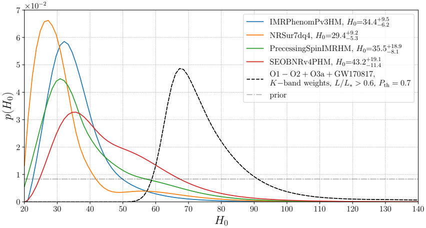


$$\Xi_0 = 2.1^{+3.2}_{-1.2}$$

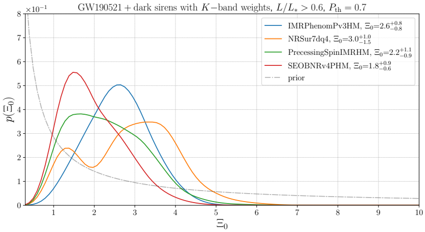
Results: counterpart case for H_0



$$\mathrm{H}_0 = 72.2^{+13.9}_{-7.5}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



Results: counterpart case for Ξ_0



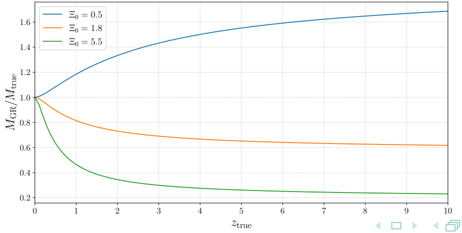
$$\Xi_0 = 1.8^{+0.9}_{-0.6}$$

Further possibilities: BNS mass function

A GW detector measures $d_L^{\rm gw}$ and the redshifted masses of a binary:

$$m_{\rm true} = \frac{m_{\rm det}}{1+z_{\rm true}} = \left(\frac{1+z_{\rm GR}}{1+z_{\rm true}}\right) m_{\rm GR}$$

The mass function of neutron stars in GW binaries is expected to be quite narrow, thus modified gravity can leave a clear signature
S. R. Taylor, J. R. Gair, I. Mandel (2012), N. Farrow et al. (2019)

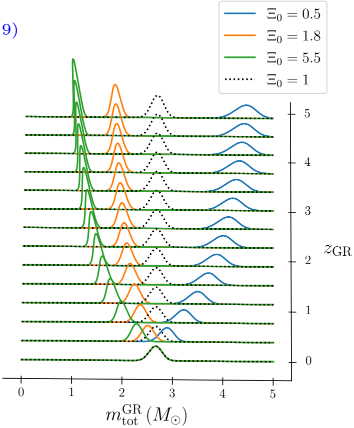


Further possibilities: modified gravity signature

Future generation experiments will detect GWs emitted by BNS systems up to very large redshift: $z \sim 2-3$ for ET and $z \sim 10$ for CE

M. Maggiore et al. (2020), E. D. Hall and M. Evans (2019)

At these distances, if Nature is described by a modified gravity theory with a large deviation from GR, ET and CE will not find a single BNS whose component masses, interpreting the data within GR, will be near the typical values



Conclusions

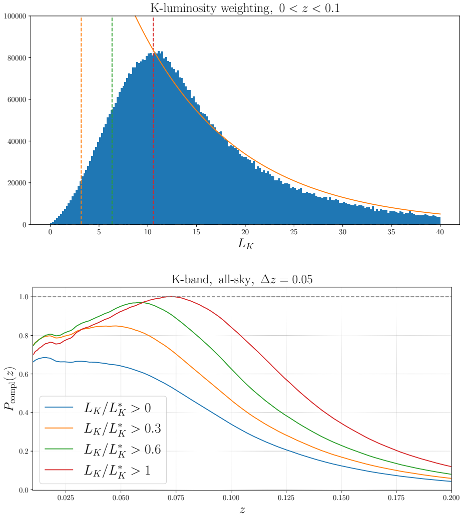
- GWs opened a new window on our universe, offering outstanding possibilities for Cosmology
- they allow us to study modified GW propagation, which is a smoking gun of modifications of gravity at cosmological scales
- current data already start to provide some interesting constraints using the galaxy catalog statistical method, but particular attention must be used when handling its "ingredients"
- the large number of detections expected in the next years will greatly improve the results, also allowing to use other techniques, so

stay tuned and open up your parameter space to Ξ_0

Thanks for your attention

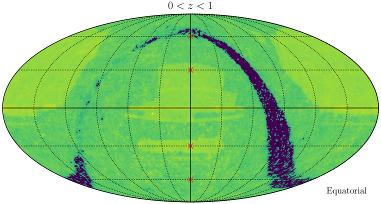
For any question or comment, contact me at
Francesco.Iacovelli@unige.ch

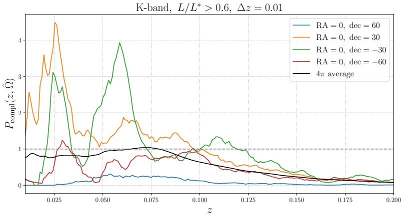
Choice of the luminosity cut

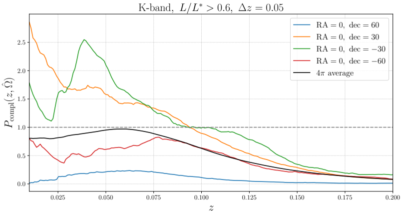


Completeness averaging region choice

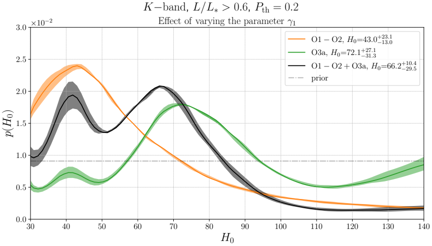
The size of region is crucial for completeness computation: too small and one smooths out structures, too large and the 'quasi-local' notion is lost

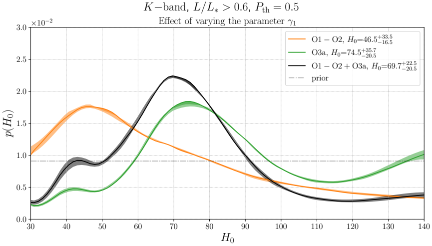


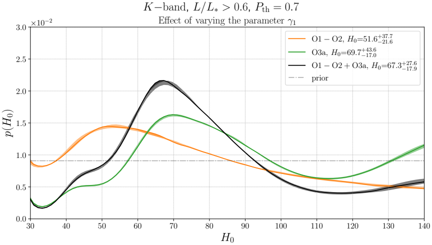




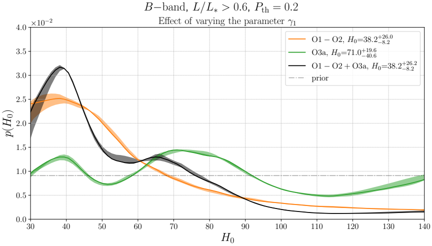
Variation of the completeness threshold

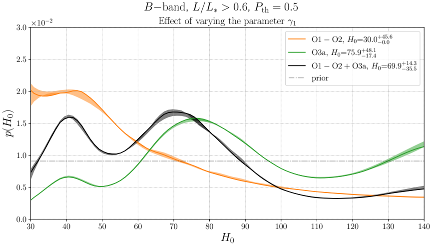


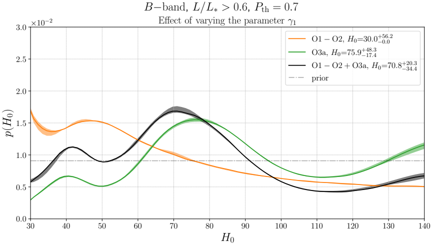




Results in B-band



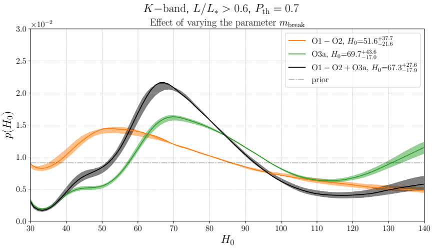


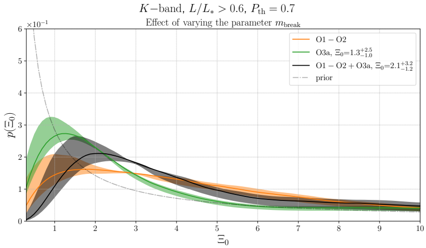


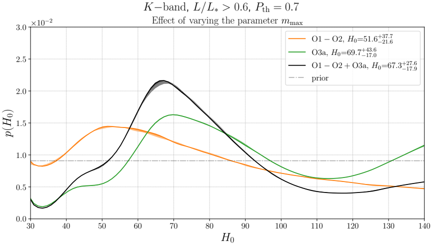
$$\rm H_0 = 70.8^{+20.3}_{-34.4}\,km\,s^{-1}\,Mpc^{-1}$$

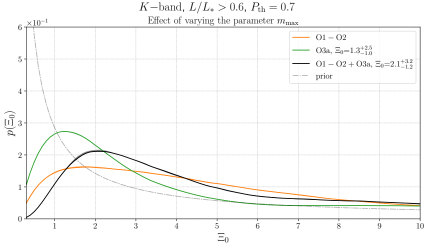
Francesco Iacovelli
Contact: Francesco.Iacovelli@unige.ch

Variation of other parameters



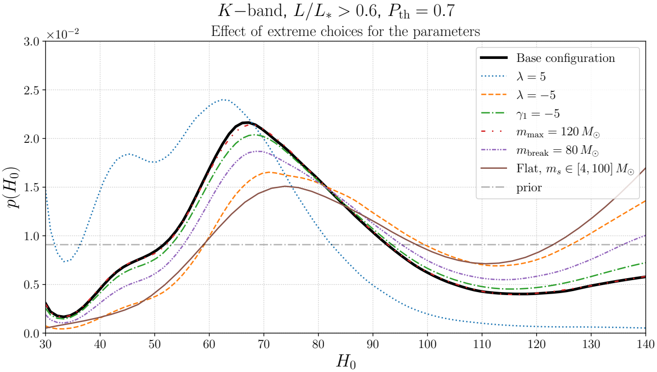






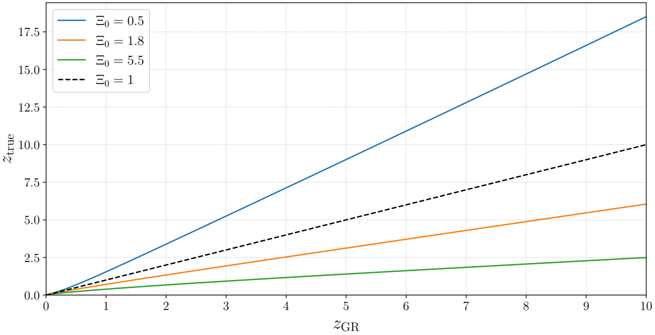
Extreme variation of the parameters

Even using extreme values of the parameters, and also a wrong mass function, the peak is still there!



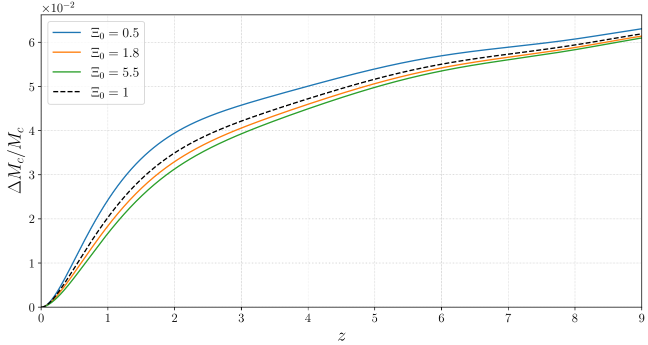
Effect of $\Xi_0 \neq 1$ on redshift reconstruction

A value of Ξ_0 bigger than 1 means that the "true" redhsift is smaller than the one inferred in GR, i.e. without taking into account modified GW propagation. The opposite happens if $\Xi_0 < 1$



Error on the mass function measurement

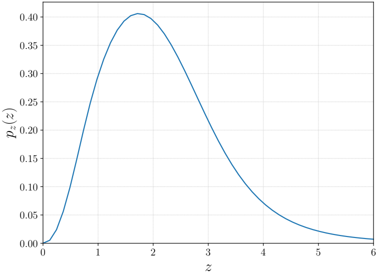
Already for ET alone the error on the detector-frame chirp mass is negligible, since $\Delta\mathcal{M}_c/\mathcal{M}_c \sim 1/\mathcal{N}_c$. More important is the error on z due to the observational error on $d_L^{\rm gw}$



Effect on the BNS merger rate

Another important signature of modified GW propagation will be given by how the BNS population is distributed in redshift, even though our prior information of it rate is not as stringent as on the BNS mass function:

the difference between $z_{\rm GR}$ and $z_{\rm true}$ will lead to a bias in the reconstruction of $R(z)$, e.g. the peak of the BNS merger distribution could appear to be at redshifts larger than the peak of the SFR



T. Regimbau et al. (2012)