Gravitational wave friction in light of GW170817 and GW190521.

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Goal of the paper

- We use the gravitational wave (GW) events GW170817 and GW190521, together with their proposed electromagnetic counterparts, to constrain cosmological parameters and theories of gravity beyond General Relativity (GR).

- We consider time-varying Planck mass, large extra-dimensions and a phenomenological parametrization covering several beyond-GR theories.

- In all three cases, this introduces a friction term into the GW propagation equation, effectively modifying the GW luminosity distance.

Introduction - GW

- GR: gravity is merely an effect caused by the curvature of spacetime.
  Field equations of GR: $R_{\mu\nu} - (1/2) g_{\mu\nu} R = T_{\mu\nu}$
  where:
  - $R_{\mu\nu}$ the Ricci curvature tensor
  - $g_{\mu\nu}$ the metric of spacetime
  - R the Ricci scalar
  - $T_{\mu\nu}$ the energy-momentum tensor
- Einstein solved those and predicted (1916) the existence of disturbances in the curvature of spacetime that propagate as waves, called gravitational waves.

- Most promising sources of GW: Compact Binaries Coalescence (CBC)
  Binary Black Holes (BBH)
  Binary Neutron Star (BNS)
  Neutron Star Black Hole binary (NSBH)

- The metric of spacetime in case of a CBC, and sufficiently far away from it, is:

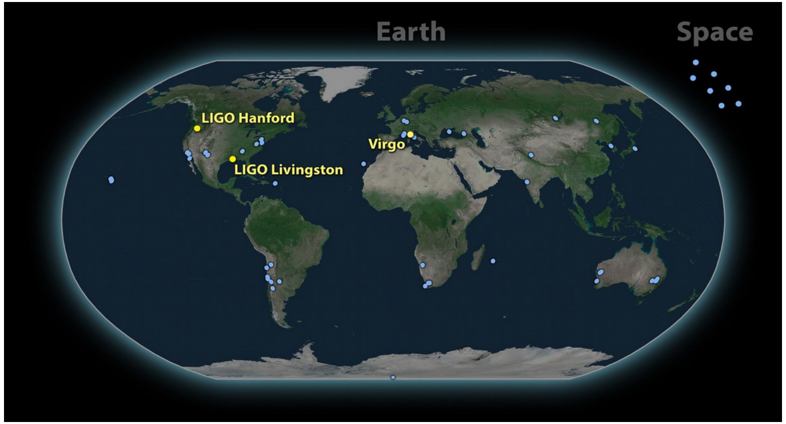
$$g_{\mu\nu} = g^{(B)}_{\mu\nu} + h_{\mu\nu}$$

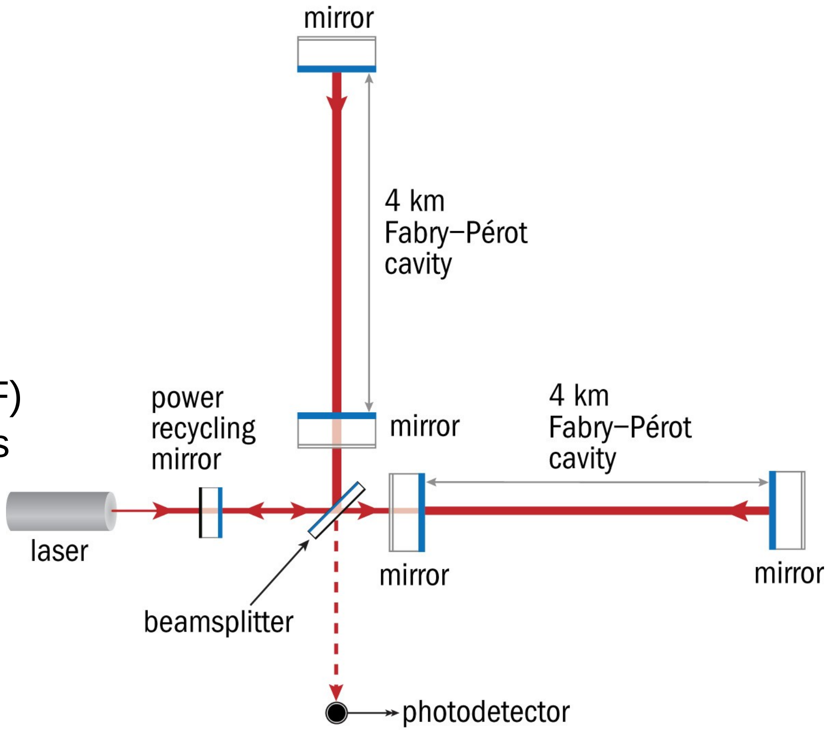
  where $g^{(B)}_{\mu\nu}$ is the metric of the background and $h_{\mu\nu}$ is the change caused by the GW.

Introduction – Detection of GW

- Small disturbances of spacetime affect the propagation of photons.

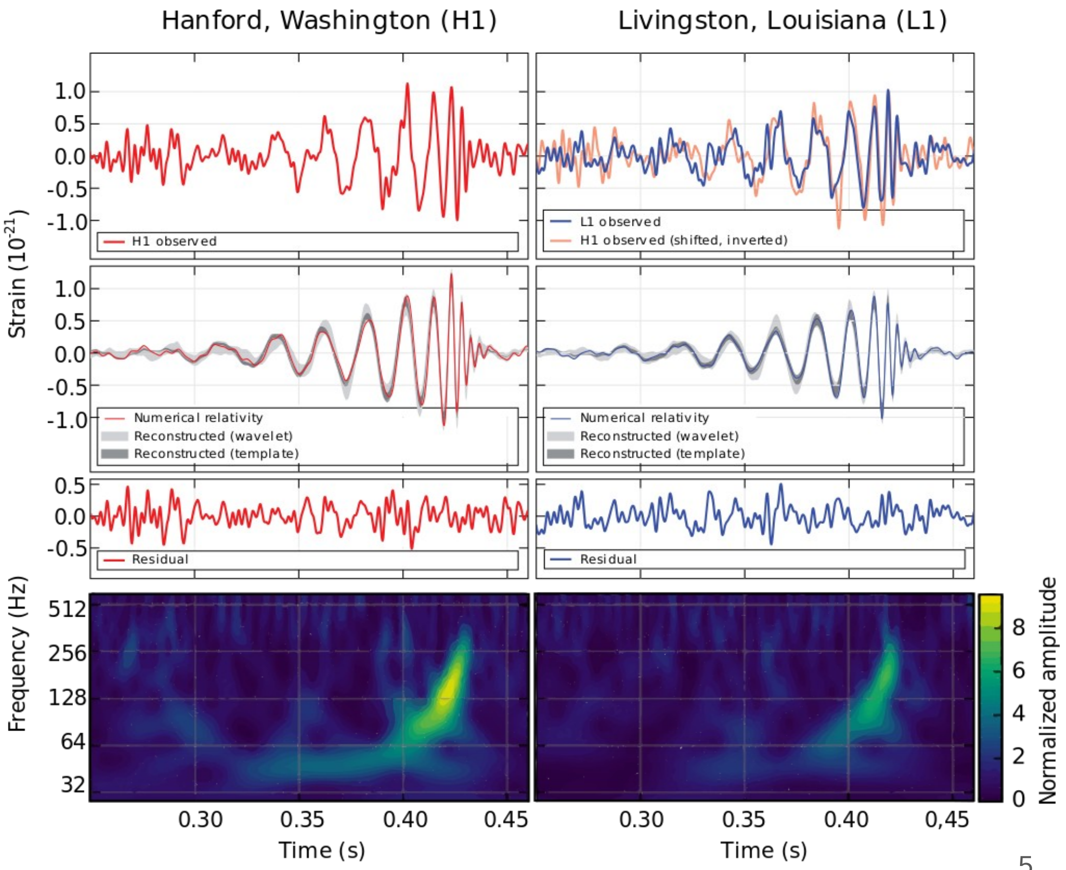
- LIGO/Virgo are ground based interferometers (ITF) designed specifically to measure tiny disturbances of spacetime geometry.





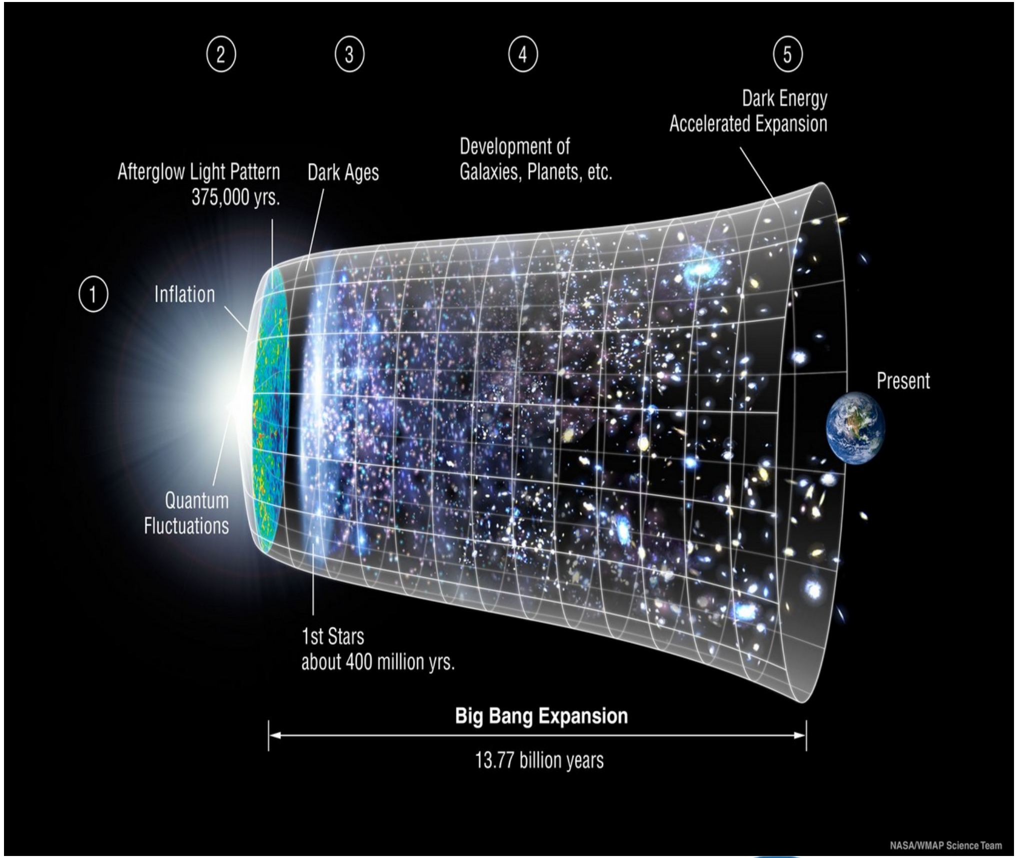
Introduction – Detection of GW

- In the plot one can see the two LIGO's responses to the first GW detection (GW150914).
  The correlation of data between ITF's plays a very important role in the detection of GW.



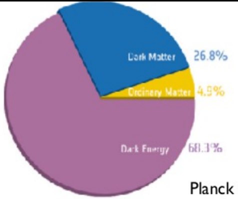
Introduction – ΛCDM

- The ΛCDM (Lambda cold dark matter) or Lambda-CDM model is a parameterization of the Big Bang cosmological model in which the universe contains three major components:
  1) a cosmological constant which is the energy density of space, or vacuum energy, denoted by Lambda (Λ) and associates with dark energy
  2) cold dark matter (CDM)
  3) ordinary matter



Radiation **Dark Energy**

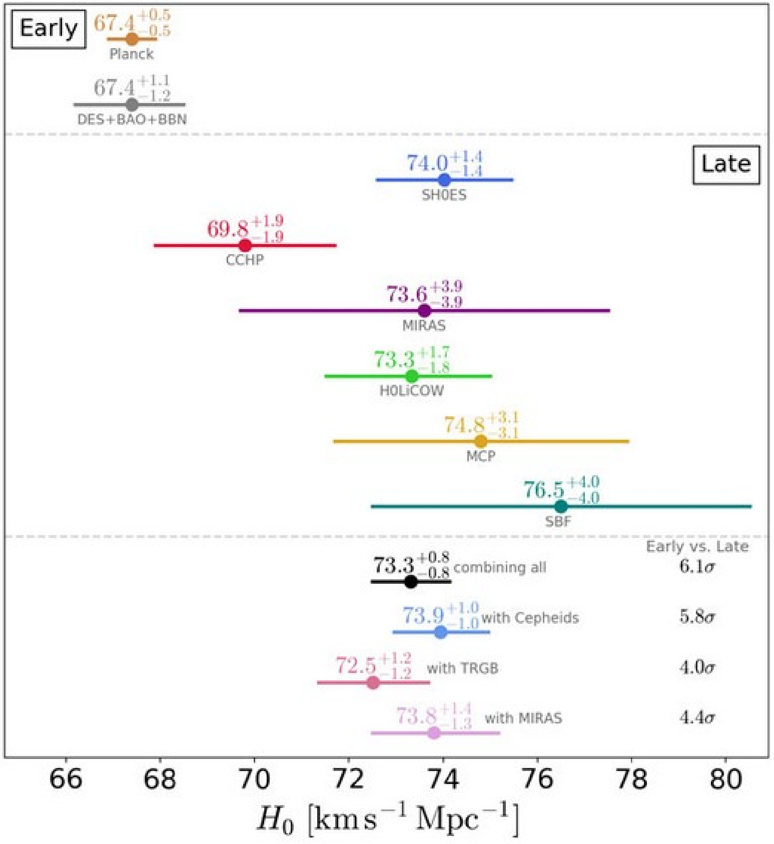
Matter (baryonic or dark) **Curvature**



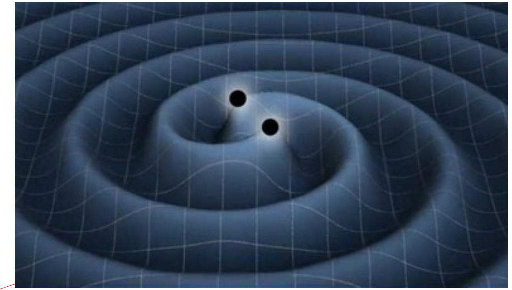
Planck satellite

Introduction - H0 Tension

- The Hubble constant (H0) describes the rate at which the Universe is expanding today.
- Several measurements of H0 are significantly different causing the famous H0 tension.
- Early measurements refer to estimations obtained from the analysis of the Cosmic Microwave Background.
- Late measurements refer to estimations obtained using nearby sources.



Introduction – Distance-redshift Relation



- GW are standard sirens which means that we can estimate the luminosity distance(Dc) directly:

$$h_{\mu\nu} \propto 1/D_c$$

- If additionally we had a redshift(z) estimation then we could estimate cosmological parameters.

Dc

cosmology

Comoving distance

$$D_C(z) = \frac{c}{H_0} \int_0^z dz' \frac{H_0}{H(z')}$$

Hubble constant (current expansion rate)

Hubble parameter (expansion rate)

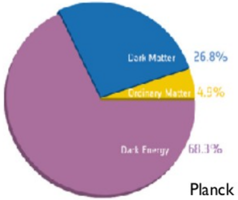
$$\frac{H^2(z)}{H_0^2} = \Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2$$

Radiation

Dark Energy

Matter (baryonic or dark)

Curvature



Planck satellite

Introduction – EM Counterpart

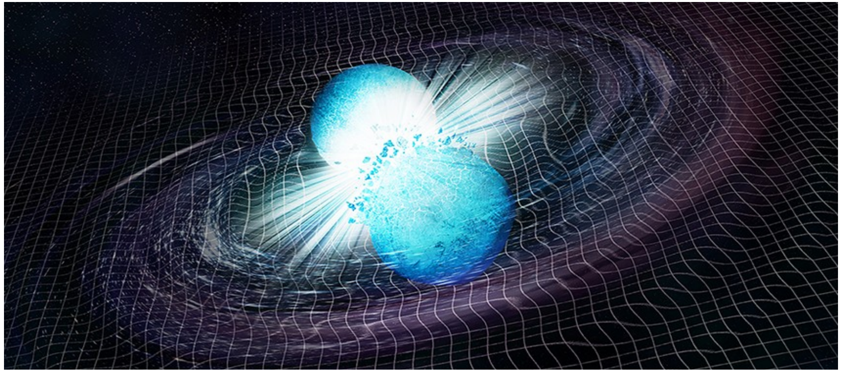
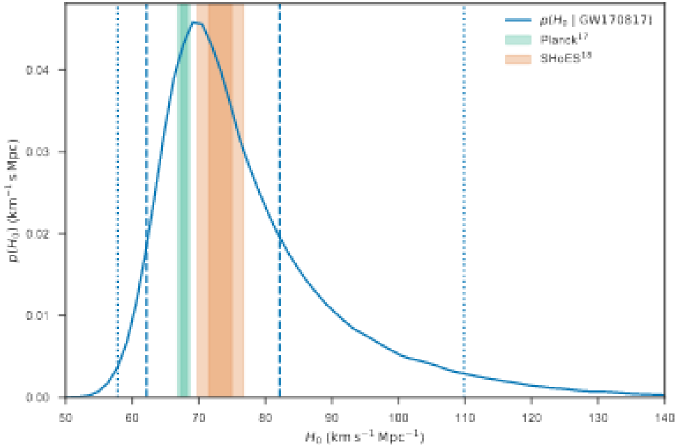


Illustration of a BNS emitting EM during merger.

- In the case of an ElectroMagnetic(EM) counterpart detection, the redshift can be acquired from the identification of the host galaxy.
- This was the case for GW170817 [1][2].
- GW170817 is the first BNS with a detected EM counterpart.
- This led to an accurate estimation of H0.

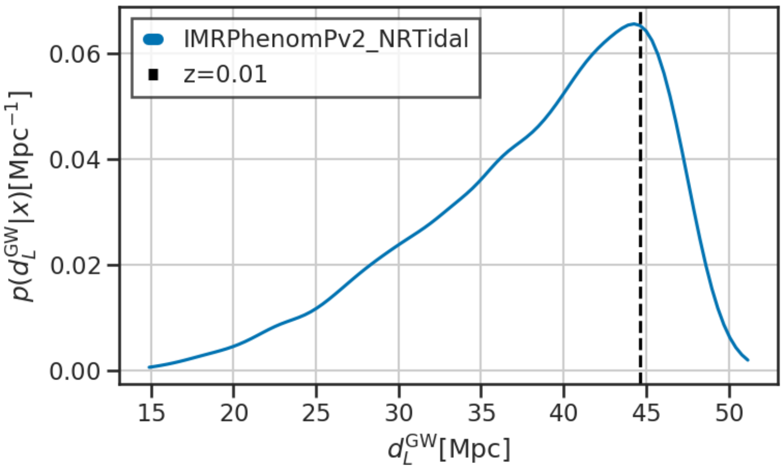
$$H_0 = 69^{+17}_{-8} \quad \text{(68\% CL)}$$



- GW190521 [3] is another GW event with a potential detected EM counterpart [4].

GW170817

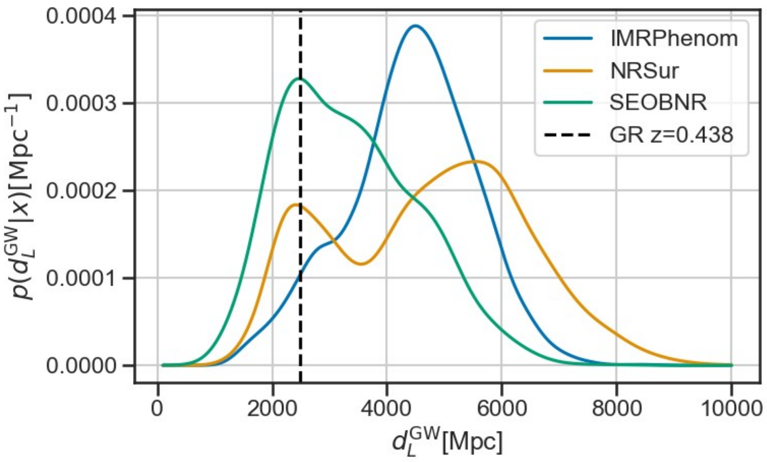
- First BNS detected.
- Only BNS with a EM counterpart.
- Identified host galaxy is at z=0.01.



Luminosity distance GW170817. The black dashed line represents the distance of the identified host galaxy assuming GR and Planck cosmology.

GW190521

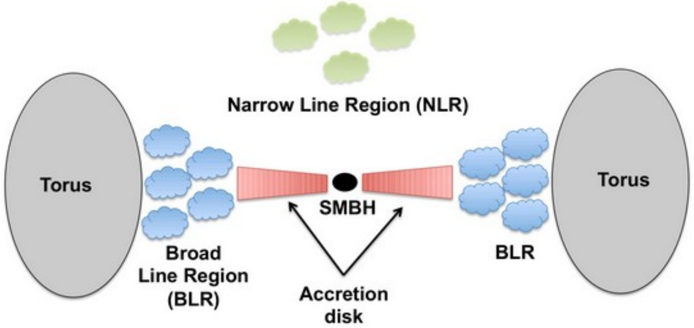
- Heaviest BBH detected so far.
- Potential EM detected from a galaxy at z=0.438.



Line-of-sight luminosity distance for 3 different waveform samples. The black dashed line represents the distance of the potential host galaxy assuming GR and Planck cosmology.

EM from a BBH?

- It is speculated that this BBH was formed in the disk of the Active Galactic Nuclei(AGN).
- Matter from the disk started falling into the newly formed BH creating a jet.
- The newly formed BH started moving towards the outside of the AGN disk due to the kick velocity from the merger.
- As it moved to the upper limits of the disk, the disk was becoming less and less dense.
- As a result, the jet managed to pierce though and reached our detectors.



The case with no GR deviation considered

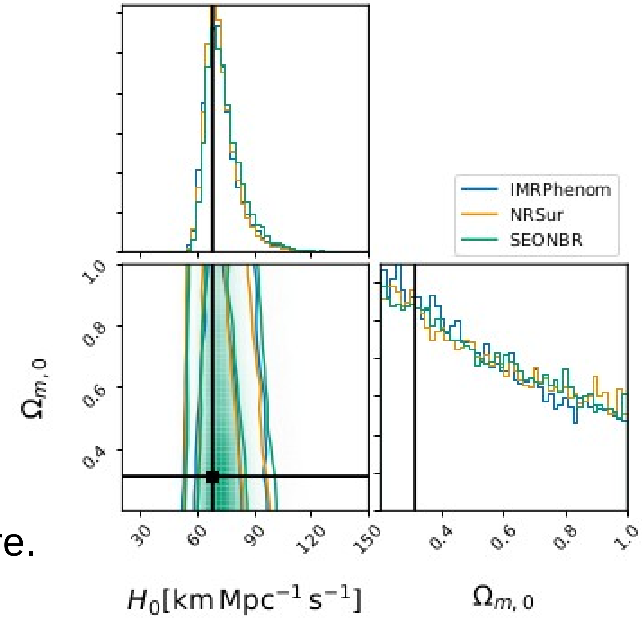
- Test the method estimating only cosmological parameters assuming no GR deviation.

- Priors: H0=Uni[20, 300], Ω_m=Uni[0.2, 1.0]

- GW190521A+GW170817 results

$$H_0 = 74^{+13}_{-7}, \Omega_m = 0.58^{+0.25}_{-0.25} \text{ (95\% CL)}$$

- In agreement with measurements in the literature.



Modified theories of gravity - GW friction term

- Modified GR theories offer possible solutions to open issues in Standard cosmological model, like dark energy, H0 tension.

- Many GR modified theories include additional terms in the GW propagation equation.

- Friction term: predicted by theories with extra energy dissipation terms

- GW friction affects the luminosity distance traveled by the GW.

$$d^{\mathrm{GW}}(z) = d_{\mathrm{EM}}(z)\exp\left[\int_0^z \frac{\alpha_M(z)}{1+z}dz\right]$$

  where a_M is the GW friction parameter, d^{GW} the luminosity distance traveled by the GW and d^{EM} the luminosity distance traveled by the EM.

- In GR a_M =0, so $d^{GW}=d^{EM}$.

Adding GW friction - Parametrizations considered

- The effect of the friction term in the GW distance can be parametrized.
- In this work we considered the following parametrizations:

➢ c_M- parametrization: A parametrization based on the evolution of the Dark Energy content of the Universe (scalar-tensor theories in the Horndeski and Beyond Horndeski families) [5].

➢ Ξ – parametrization: A theory-base parametrization able to fit many modified theories of gravity (this is applicable for some of the following: Brans-Dicke, Horndeski, beyond-Horndeski, DHOST)[6].

➢ Extra dimensions: GW energy can leak in additional dimensions eventually resulting in a different luminosity distance[7].

c_M-parametrization

- Is a parametrization of the friction term c_M:

$$\alpha_M(z) = c_M \frac{\Omega_\Lambda(z)}{\Omega_\Lambda(0)}$$

where c_M is a constant and Ω_Λ is the fractional dark energy density.

- In this case the distance is given by:

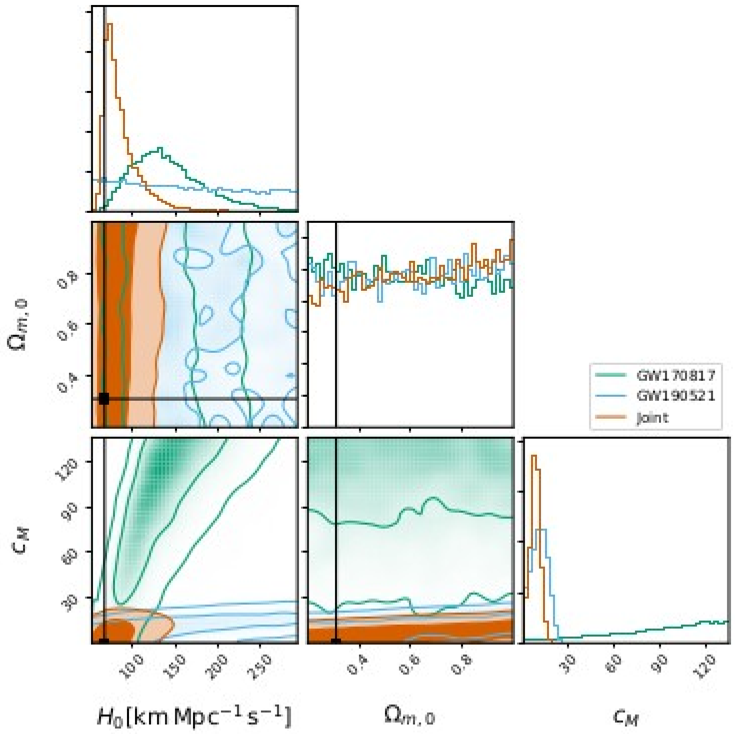
$$d_L^{\rm GW} = d_L^{\rm EM} \exp\left[\frac{c_M}{2\Omega_{\Lambda,0}} \ln \frac{1+z}{\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}}\right]$$

- Priors: H0=Uni[20, 300], Ω_m=Uni[0.2, 1.0], c_M=Uni[0,150]

- Results are consistent with Planck cosmology and GR.

$$H_0 = 80^{+67}_{-17}, \Omega_m = 0.6^{+0.4}_{-0.4}, c_M < 13 \quad \text{(95\% CL)}$$

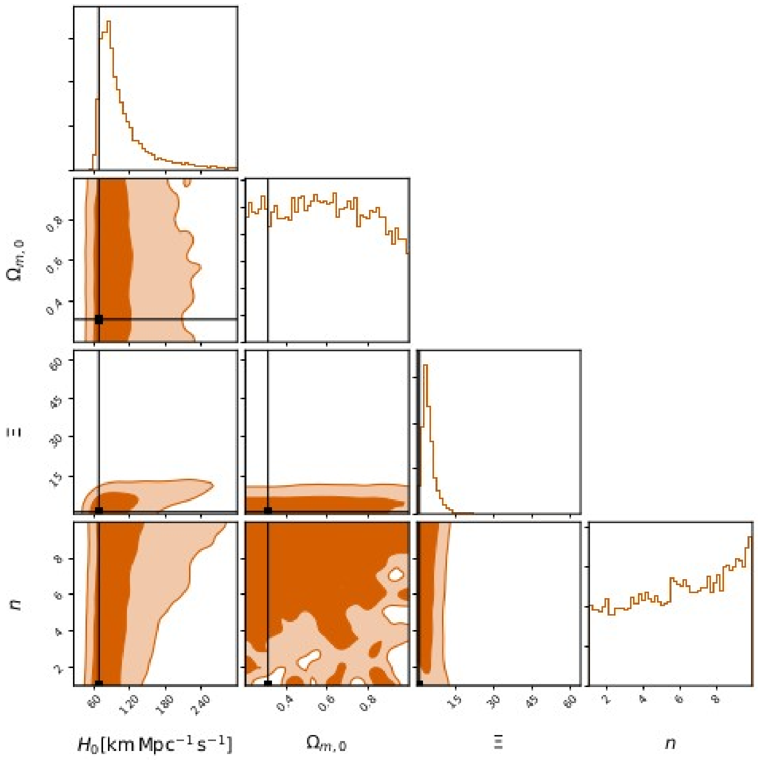
Results using NRSur for GW190521



Significant upper limit on c_M
Results not yet as accurate as CMB limits.

Ξ - parametrization

Results using NRSur for GW190521



- For many alternative theories of gravity the GW luminosity distance is parametrised by:

$$d_L^{\mathrm{GW}} = d_L^{\mathrm{EM}}\left[\Xi + \frac{1-\Xi}{(1+z)^n}\right]$$

- Priors: H0=Uni[20, 300], Ω_m=Uni[0.2, 1.0], Ξ=Log[0.01, 100], n=Uni[1, 10]

- Results are consistent with Planck cosmology and GR.

$$H_0 = 93^{+148}_{-27}, \Omega_m = 0.6^{+0.4}_{-0.4}, \Xi < 10, n = 6^{+4}_{-5}$$ (95% CL)

Significant upper limit on Ξ.

Extra dimensions

- Considering the case of possible extra dimensions the distance is parametrized as:

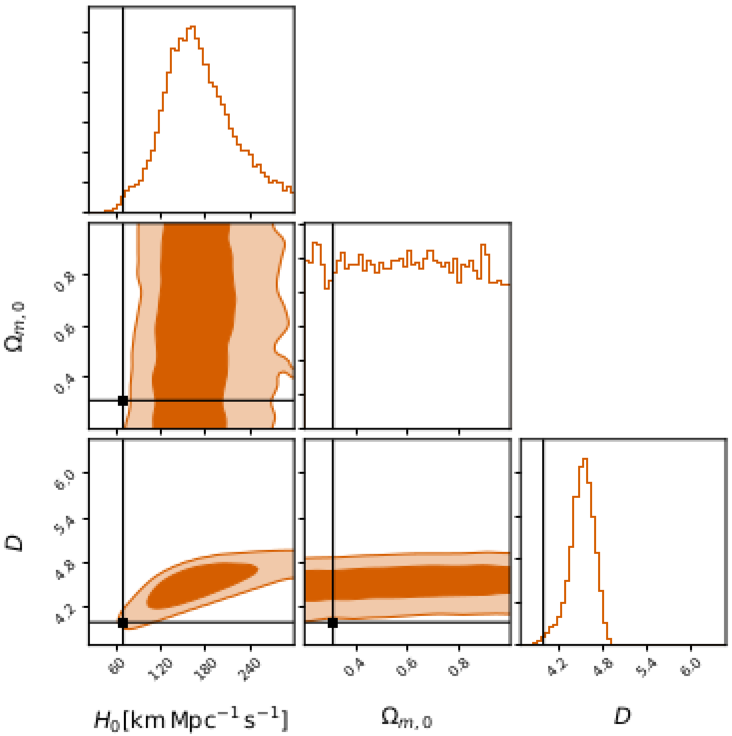
$$d_L^{\mathrm{GW}} = (d_L^{\mathrm{EM}})^{\frac{D-2}{2}}$$

- Priors: H0=Uni[20, 300], Ω=Uni[0.2, 1.0], D=Uni[3,7]

- Results are compatible with GR at 2.1σ.

$$H_0 = 167^{+113}_{-83}, \Omega_m = 0.6^{+0.4}_{-0.4}, D = 4.5^{+0.3}_{-0.4}$$ (95% CL)

Results using NRSur for GW190521



Conclusions

- GW events with EM counterparts can provide a joint constrain on cosmological and GR deviations parameters.

- The precision on the ΛCDM parameters is not enough to solve the H0 tension.

- For the three parametrizations considered all the runs are compatible in $1-2\sigma$ confidence Level with GR.

- With 3G detectors we might be able to detect GW with EM at higher redshifts and improve these estimations.

References

[1] Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A ,The LIGO and Virgo Collaboration

[2] A gravitational-wave standard siren measurement of the Hubble constant , The LIGO and Virgo Collaboration

[3] GW190521: A Binary Black Hole Merger with a Total Mass of 150 M , The LIGO and Virgo Collaboration

[4] Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational Wave Event S190521g , M. Graham et al.

[5] Standard sirens with a running Planck mass, Macarena Lagos et al.

[6] Testing modified gravity at cosmological distances with LISA standard sirens, Enis Belgacem et al.

[7] 4D Gravity on a Brane in 5D Minkowski Space, Gia Dvali et al.

Extra Slides

All results

Model	c_M-parametrization					
Waveform	NRSur		IMRPhenom		SEONBR	
Prior	Wide	Planck	Wide	Planck	Wide	Planck
$H_0[\,\mathrm{km\,Mpc^{-1}s^{-1}}]$	80^{+67}_{-17}	$67.7^{+0.8}_{-0.8}$	79^{+60}_{-16}	$67.7^{+0.8}_{-0.8}$	81^{+68}_{-18}	$67.7^{+0.8}_{-0.8}$
$\Omega_{m,0}$	$0.6^{+0.4}_{-0.4}$	$0.311^{+0.011}_{-0.011}$	$0.6^{+0.4}_{-0.4}$	$0.311^{+0.011}_{-0.011}$	$0.6^{+0.3}_{-0.4}$	$0.311^{+0.011}_{-0.011}$
c_M	< 13.4	< 7.5	< 11.7	< 6.3	< 10.8	< 5.7
Model	**Extra dimension**					
Waveform	NRSur		IMRPhenom		SEONBR	
Prior	Wide	Planck	Wide	Planck	Wide	Planck
$H_0[\,\mathrm{km\,Mpc^{-1}s^{-1}}]$	167^{+113}_{-83}	$67.7^{+0.8}_{-0.8}$	152^{+120}_{-65}	$67.7^{+0.8}_{-0.8}$	141^{+130}_{-74}	$67.7^{+0.8}_{-0.8}$
$\Omega_{m,0}$	$0.6^{0.4}_{-0.4}$	$0.311^{0.011}_{-0.011}$	$0.6^{0.4}_{-0.4}$	$0.311^{0.010}_{-0.011}$	$0.6^{0.4}_{-0.4}$	$0.311^{0.011}_{-0.010}$
D	$4.5^{+0.3}_{-0.4}$	$3.99^{+0.08}_{-0.09}$	$4.5^{+0.3}_{-0.3}$	$4.01^{+0.10}_{-0.10}$	$4.4^{+0.3}_{-0.4}$	$4.00^{+0.09}_{-0.10}$
Model	Ξ-parametrization					
Waveform	NRSur		IMRPhenom		SEONBR	
Prior	Wide	Planck	Wide	Planck	Wide	Planck
$H_0[\,\mathrm{km\,Mpc^{-1}s^{-1}}]$	93^{+148}_{-27}	$67.7^{+0.8}_{-0.8}$	90^{+126}_{-25}	$67.7^{+0.8}_{-0.8}$	87^{+119}_{-23}	$67.7^{+0.8}_{-0.8}$
$\Omega_{m,0}$	$0.6^{0.4}_{-0.4}$	$0.311^{0.011}_{-0.010}$	$0.6^{0.4}_{-0.4}$	$0.311^{0.011}_{-0.011}$	$0.6^{0.4}_{-0.4}$	$0.311^{0.010}_{-0.011}$
Ξ	< 10	< 4.4	< 8.2	< 3.6	< 7.1	< 2.9
n	6^{+4}_{-5}	4^{+5}_{-4}	6^{+4}_{-5}	5^{+5}_{-4}	6^{+4}_{-5}	5^{+5}_{-4}