Studying Inhomogeneous Universes and Modified Gravity with Standard Sirens

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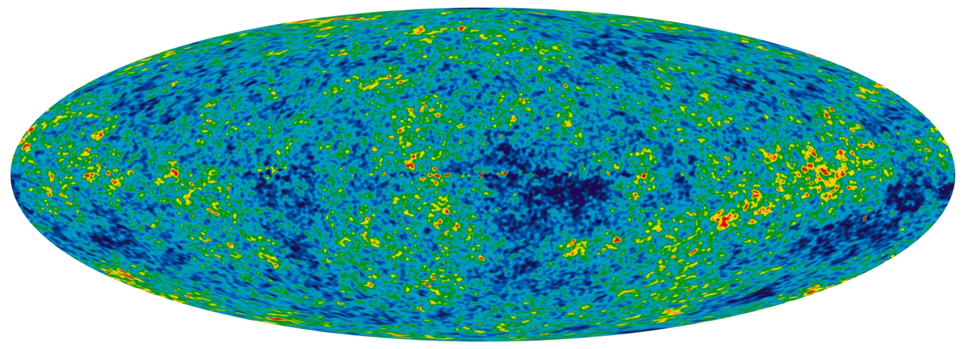
Background

The observation of gravitational wave (GW) sources with independent redshift information ("Standard Sirens") allows us to investigate fundamental assumptions about cosmology. By studying the propagation of GWs in cosmological simulations, we aim to:

- Constrain effective models of inhomogeneous universes and test the Friedman-Lemaitre-Robertson-Walker (FLRW) metric.
- Investigate the level of the degeneracy between GW signals expected in modified gravity theories and cosmological models based on standard gravity, but including matter density inhomogeneities.



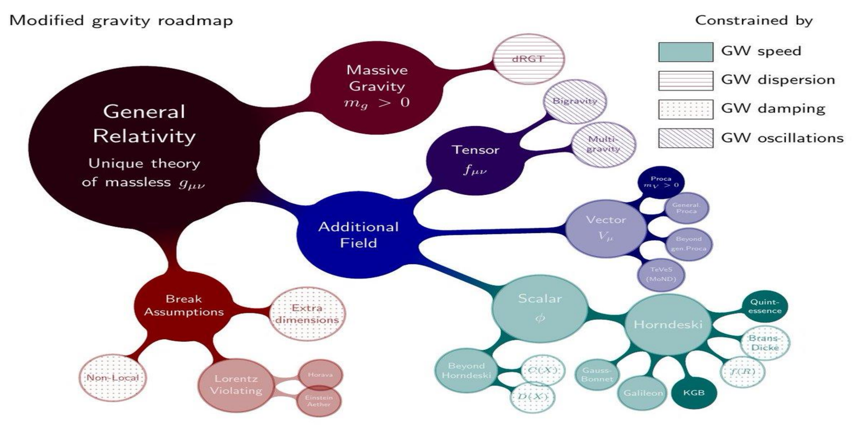
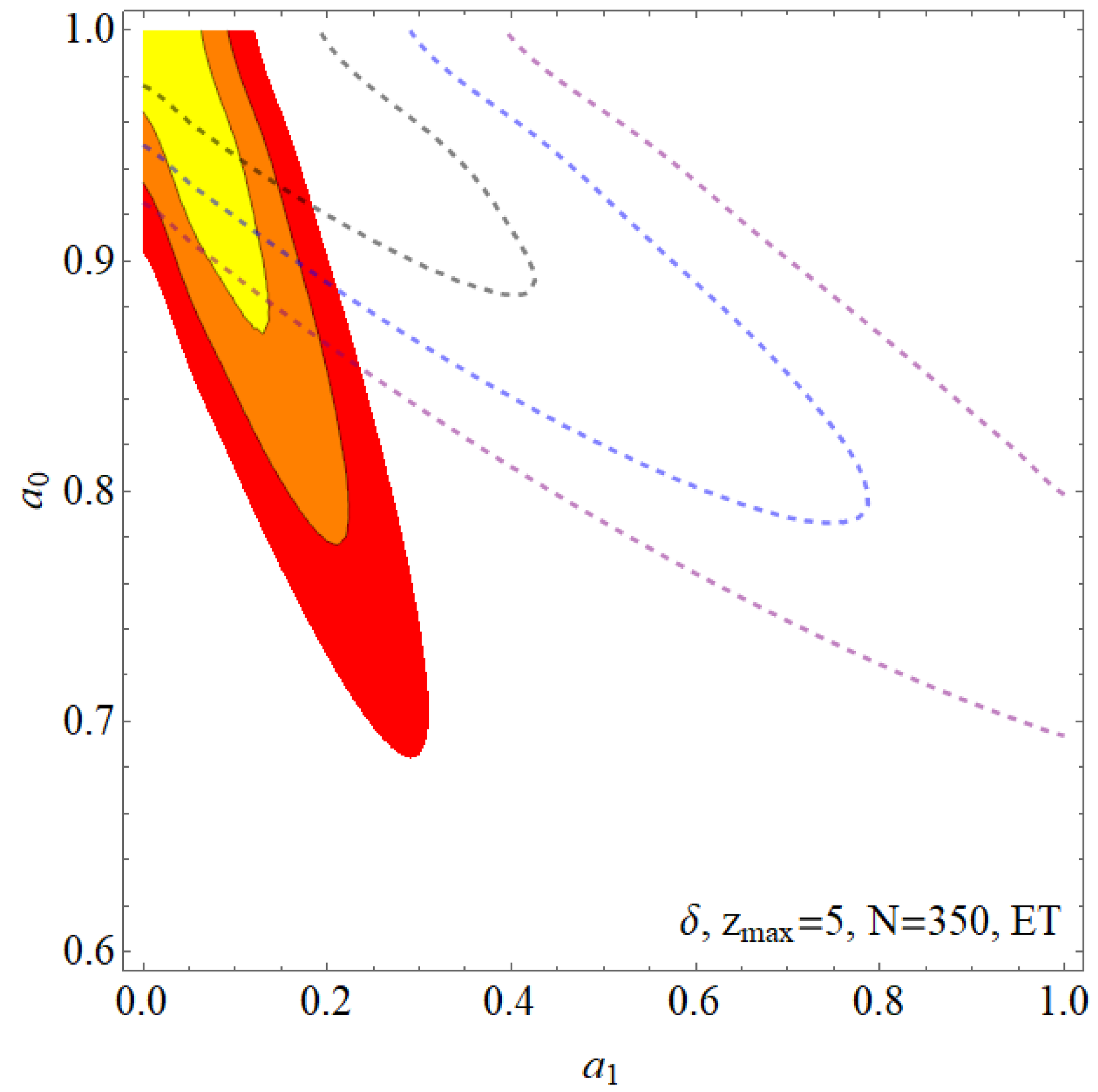


Fig. 1 – The concordance model of cosmology is based on homogeneity on the largest scales and Einstein's theory of gravity. Both of these fundamental assumptions can be examined by future GW experiments.

Homogeneity Probe (Case Study 1)



In our work, we exploit two inhomogeneous distance models the Dyer-Roeder (DR) and the modified Dyer-Roeder (mDR) [2], that include a parameter α, which describes the clustering of the matter in the universe (α=1 corresponds to the standard ΛCDM cosmology, while α=0 to the extreme "empty beam" case, where all matter in the universe is highly clustered).

This effective description has been further parameterised either with two arbitrary parameters ($a = a_0 + a_1 z$) or connected to the average present-time density contrast along a ray $\overline{\delta}_{1D}$, where $\delta = \delta\rho/\rho$, the density contrast [3].

For our constraints we mock 350 GWs sources from redshift z=0 to z=5. Their masses are based on a population synthesis model and we exploit the sensitivity curves of ET & CE. Future detectors can lead to strong constraints on the different inhomogeneous models.

Fig. 3 – Constraints on the inhomogeneity parameters (a_0, a_1) based on a realistic density distribution from numerical simulations from future GW detectors (results are similar for CE). For both cases (DR - filled contours, mDR - dashed contours) there is consistency with an FLRW background, where $(a_0, a_1) = (1, 0)$ and the parameters are significantly constrained.

Model & Simulations

A "Standard Siren" detection offers two independent observables: the **luminosity distance** to the source d_{GW} and its **redshift** z.

Assuming an effective inhomogeneous cosmological model, we can convert the observed redshift to a luminosity distance d_{Inh}. Comparing this distance with d_{GW}, we can constrain the parameters that enter these models. We forecast constraints for future, ground-based detectors, like Einstein Telescope (ET) and Cosmic Explorer (CE).

We create mock GW observations based on a population synthesis model and use the LEGACY suite of cosmological N-body simulations (V $=(1.6\ \text{Gpc/h})^3$, 2048^3particles) to obtain realistic anisotropies along (straight) rays.

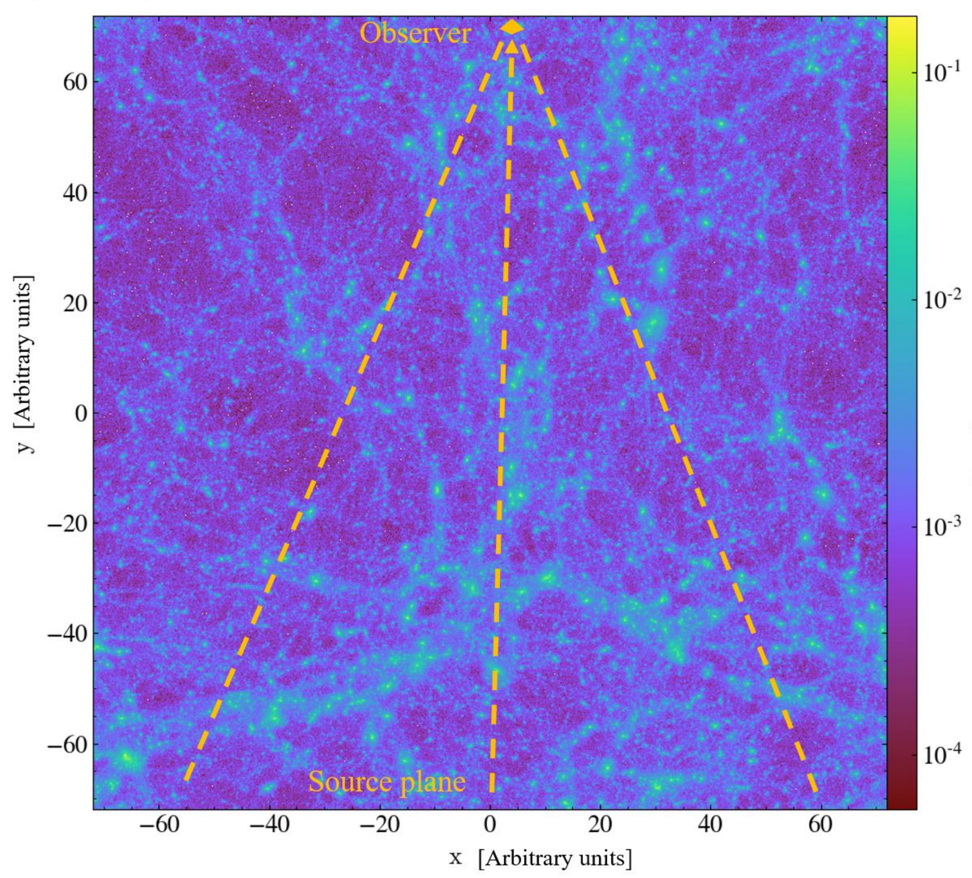


Fig. 2 – Schematic view of our method. We "throw" straight rays from a source plane to an observer, taking into account the realistic density anisotropies along the way.

Degeneracy with Modified Gravity (Case Study 2)

Modifications to General Relativity (GR) can also induce changes in the distances calculated from GWs. More specifically, there are models that include an extra "friction term" ν, leading to larger inferred distances $d_L^{GW}(z) = d_L^{EM}(z)\,(1+z)^{\nu/2}$. Inhomogeneous models also result in higher distances. Hence a deviation from ΛCDM, can occur both ways and an investigation of possible systematics due to inhomogeneities need to be done before constraining modified gravity parameters.

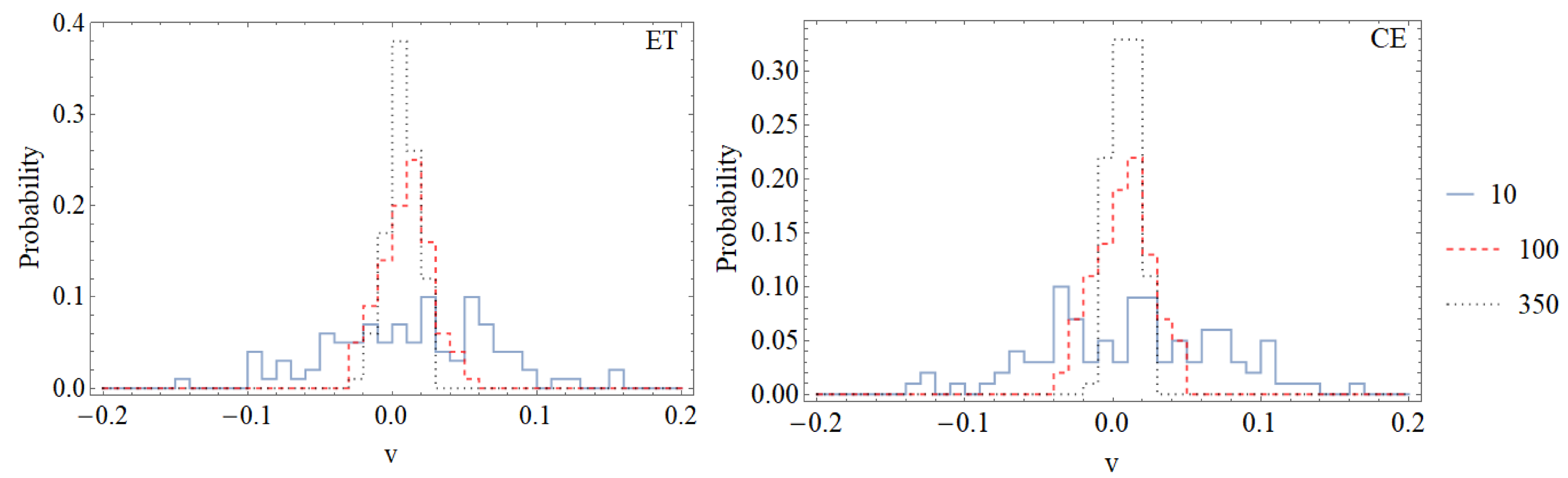


Fig. 5 – Probability distribution for the ν parameter based on different number of observations. The presence of inhomogeneities can mimic a deviation from GR, leading to higher uncertainties when constraining ν. For 350 GWs observations with EM counterparts the accuracy on ν is increased to the order of 1%.

Conclusions

The main results of our work show that:

- Future, ground-based GW detectors will be crucial for cosmological studies, putting strong constraints on the inhomogeneity parameters.
- An inhomogeneous background can "mimic" modified gravity models in the amplitude decay of a GW.
- Future, ground-based GW detectors can break the degeneracy between modified gravity effects and matter anisotropies.
- An accuracy of 1% on the friction parameter can be achieved with 350 observations.

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References

1. Kalomenopoulos, M. et al., MNRAS (accepted), arXiv:2007.15020
2. Clarkson, C. et al., MNRAS 426, 1121 (2012)
3. Bolejko, K., MNRAS 412, 1937 (2011)