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Dark Sirens with the DES Y3 Galaxy Catalogue

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1. Introduction

Gravitational Wave (GW) events can be used in conjunction with electromagnetic measurements to measure cosmological parameters like the Hubble Constant. This can be done most effectively when the host galaxy of a GW event is identified, as was the case with GW170817 [1]. However, in the absence of this kind of detection, cosmological information can still be inferred using historical galaxy catalogue information in the localization region of the GW event, known as Dark Siren Analysis. Information about the location and redshift of surveyed galaxies is an integral part of the likelihood in Bayesian inference for Dark Sirens, acting as a weight on the probability of a given galaxy being the host of a GW event.

The Dark Energy Survey (DES) is currently the most comprehensive photometric galaxy survey, mapping $5000\ \ deg^2$ of the southern sky and comprising of nearly 390 million objects. For the purposes of Dark Siren Analyses, galaxy catalogue completeness and depth are limiting factors to the constraining power of the analysis. The DES Y3 Gold catalogue [5] is orders of magnitude deeper and more complete than the catalogues which are mainly used for such studies. The purpose of this work is to implement DES into the current `gwcosmo` workflow and explore its impact on inferring the Hubble Constant.

2. Line-of-Sight z Prior

In the `gwcosmo` cosmological inference software package [4], galaxy catalogue information is passed to likelihood in the form of a Line-of-Sight prior, a probability distribution of redshift for every pixel in a `HEALPix` map calculated from the galaxies which are located within that pixel. This distribution can either be weighted solely by the given error on the redshift of each galaxy or by its magnitude in a given band as a proxy for stellar mass. Where the catalogue is incomplete, the prior becomes uniform in comoving volume.

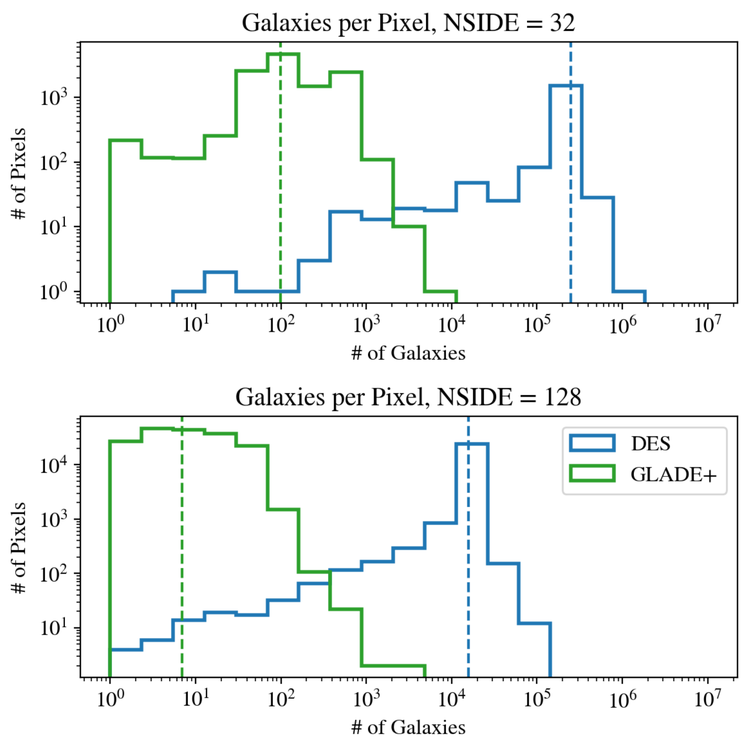

Figure 1: Galaxy density in a given pixel at different pixel sizes. DES has on average three orders of magnitude more galaxies per pixel than GLADE+. NSIDE 32 pixels have an area of $3.4\ deg^2$, and NSIDE 128 pixels have an area of $0.2\ deg^2$.

Dark Siren studies within LVK mainly use GLADE+ as the catalogue of choice [2]. GLADE+ is a combination of several separate catalogues made for the purpose of multi-messenger astronomy with GW detectors [3]. It has wide coverage across the whole sky but its completeness falls precipitously around 100 Mpc ($z = 0.02$), making it uninformative for the majority of GW events. In contrast, DES Y3 Gold increases the density of galaxies per-pixel by an average of three orders of magnitude [Fig. 1], including both smaller galaxies at low redshift as well as bright galaxies at comparatively high redshifts, $z = 0.1{-}0.5$. These are crucially informative, as many GW events suitable for Dark Sirens fall within this range. We calculate the Line-of-Sight prior for DES Y3 Gold both with uniform weights and with weights by luminosity in DECam i-band [Fig. 2]. For this work we use a `HEALPix` map resolution of NSIDE $= 32$ for the sake of computational efficiency.

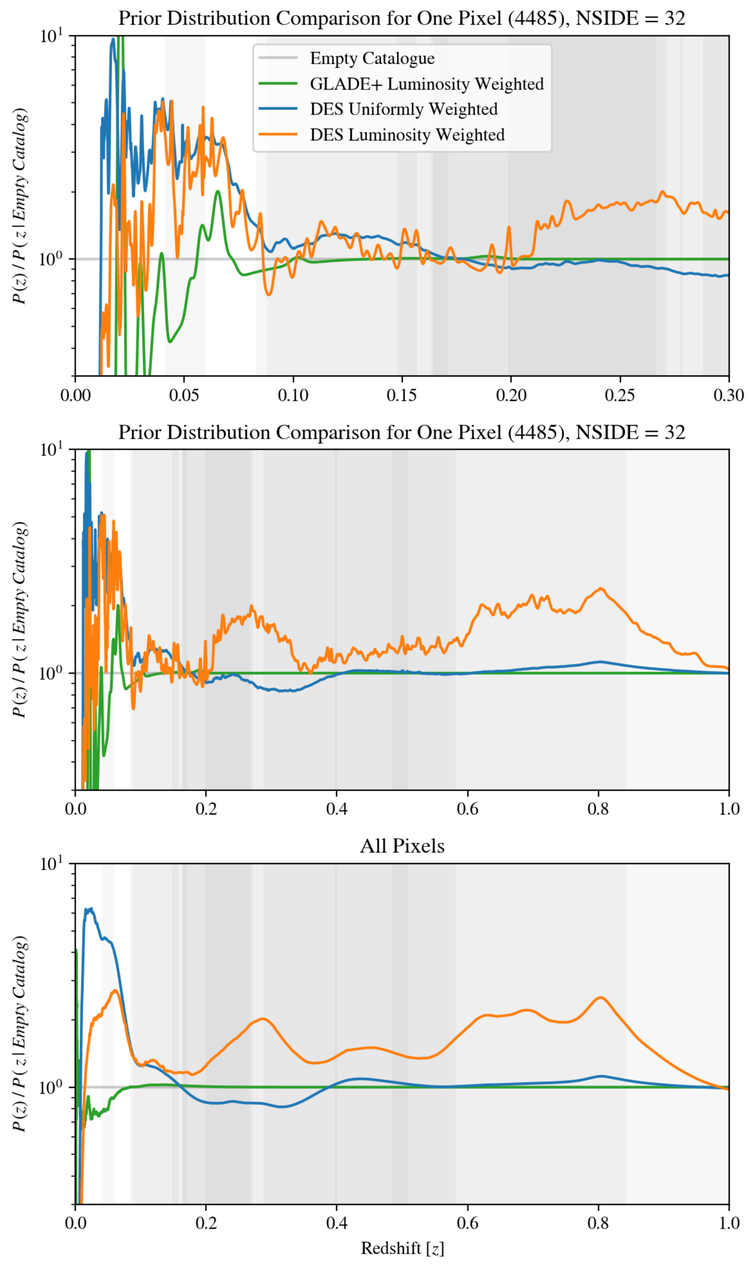

Figure 2: Comparison of DES Line-of-Sight priors with canonical GLADE+ priors, shown as a multiple of the empty catalogue prior. The 90% confidence regions of redshift for the events which lie in the DES footprint are shown as well, calculated assuming Planck cosmology.

3. H_0 Inference

Using this prior we can use `gwcosmo` workflow to infer a value of H_0 for the events which fall within the DES survey footprint. As of September 2024, there have been 11 total events with localizations that significantly overlap with the DES footprint [Fig. 3].

Along with the Line-of-Sight prior, a list of simulated injections which model the probability of detection for a given GW event must also be passed to `gwcosmo`. Such injections have already been calculated for events up to O3b. Thus, to avoid any injection-related bias, we only use GW events prior to O4 and injections that fall within the DES footprint. This leaves us with 8 BBH events to use for our analysis. We estimate the H_0 posterior with the gridded method using the DES priors and compare them to GLADE+ and the empty catalogue case [Fig. 4].

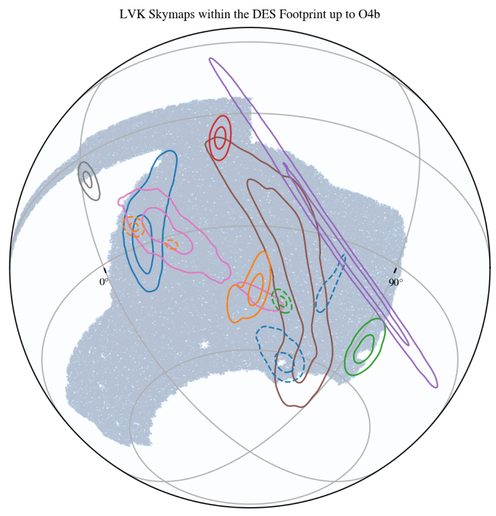

Figure 3: Significant GW detections in the DES survey footprint up to September 2024. Events used for this analysis are shown with solid lines.

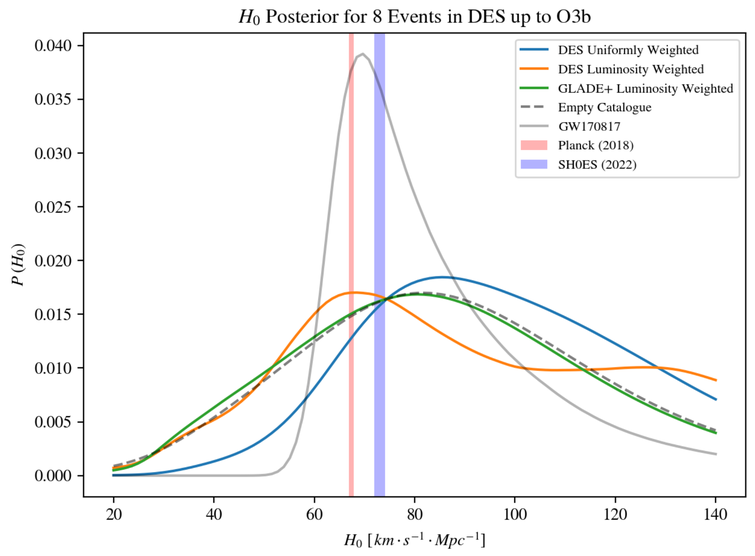

Figure 4: H_0 posteriors using 8 events in the DES footprint evaluated with each prior. Results from SH0ES, Planck, and GW170817 are shown for comparison.

4. Conclusions

The DES Y3 Gold catalogue is a rich dataset of photometric galaxies that can inform Dark Siren analysis much more than traditionally used catalogues such as GLADE+. While this does improve the H_0 posterior, the precision is likely more limited by GW localization and redshift precision. More work must be done to ensure the best use of catalogs such as DES.

5. Future Research

- Consideration of population and rate parameters with sampling
- Large scale validation with Buzzard simulated galaxy catalogue and mock GW events
- Upcoming DES Y6 data release (2x more galaxies)
- Integration of other upcoming surveys (DESI, LSST)

References

[1] B. P. Abbott et al. A gravitational-wave standard siren measurement of the Hubble constant. *Nature*, 551(7678):85–88, October 2017.

[2] R. Abbott et al. Constraints on the Cosmic Expansion History from GWTC–3. *The Astrophysical Journal*, 949(2):76, June 2023.

[3] G Dálya et al. GLADE+: An Extended Galaxy Catalogue for Multimessenger Searches with Advanced Gravitational-wave Detectors. *Monthly Notices of the Royal Astronomical Society*, 514(1):1403–1411, May 2022.

[4] R. Gray et al. Joint cosmological and gravitational-wave population inference using dark sirens and galaxy catalogues, 2023.

[5] I. Sevilla-Noarbe et al. Dark Energy Survey Year 3 Results: Photometric Data Set for Cosmology. *The Astrophysical Journal Supplement Series*, 254(2):24, May 2021.