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

Citation for published version:
(DES Collaboration), LIGO Scientific Collaboration & Virgo Collaboration 2019, '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', Astrophysical Journal Letters, vol. 876. https://doi.org/10.3847/2041-8213/ab14f1

Digital Object Identifier (DOI):
10.3847/2041-8213/ab14f1

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Astrophysical Journal Letters

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
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
MEASUREMENT OF THE HUBBLE CONSTANT FROM GW170814

70 INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
71 International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India
72 NCSA, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
73 Università di Pisa, I-56127 Pisa, Italy
74 INFN, Sezione di Pisa, I-56127 Pisa, Italy
75 Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain
76 OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia
77 Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France
78 University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA
79 SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom
80 California State University Fullerton, Fullerton, CA 92831, USA
81 APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France
82 Università di Roma Tor Vergata, I-00133 Roma, Italy
83 INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
84 INFN, Sezione di Roma, I-00185 Roma, Italy
85 Laboratoire d'Annecy de Physique des Particules (LAPP), Univ. Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France
86 Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
87 Montclair State University, Montclair, NJ 07043, USA
88 Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany
89 Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
90 Korea Institute of Science and Technology Information, Daejeon 34141, South Korea
91 West Virginia University, Morgantown, WV 26506, USA
92 Università di Perugia, I-06123 Perugia, Italy
93 INFN, Sezione di Perugia, I-06123 Perugia, Italy
94 European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
95 Syracuse University, Syracuse, NY 13244, USA
96 University of Minnesota, Minneapolis, MN 55455, USA
97 SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom
98 LIGO Hanford Observatory, Richland, WA 99352, USA
99 Caltech CaRT, Pasadena, CA 91125, USA
100 Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary
101 University of Florida, Gainesville, FL 32611, USA
102 Stanford University, Stanford, CA 94305, USA
103 Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
104 Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
105 INFN, Sezione di Padova, I-35131 Padova, Italy
106 Montana State University, Bozeman, MT 59717, USA
107 Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
108 OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia
109 Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany
110 INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
111 Rochester Institute of Technology, Rochester, NY 14623, USA
112 Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Northwestern University, Evanston, IL 60208, USA
113 INFN, Sezione di Genova, I-16416 Genova, Italy
114 RRCAT, Indore, Madhya Pradesh 452013, India
115 Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
116 OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia
117 Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
118 Artemis, Université Côte d’Azur, Observatoire Côte d’Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France
119 Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
120 Univ Rennes, CNRS, Institut FOTON - UMR6082, F-35000 Rennes, France
121 Cardiff University, Cardiff CF24 3AA, United Kingdom
122 Washington State University, Pullman, WA 99164, USA
123 University of Oregon, Eugene, OR 97403, USA
124 Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
125 Università degli Studi di Urbino ‘Carlo Bo,’ I-61029 Urbino, Italy
126 INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
127 Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
128 VU University Amsterdam, 1081 HV Amsterdam, The Netherlands
129 University of Maryland, College Park, MD 20742, USA
130 School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
131 Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France
132 Università di Napoli ‘Federico II’, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
133 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
134 RESCEU, University of Tokyo, Tokyo, 113-0033, Japan.
135 Tsinghua University, Beijing 100084, China
136 Texas Tech University, Lubbock, TX 79409, USA
137 The University of Mississippi, University, MS 38677, USA
138 Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, I-00184 Roma, Italy
139 The Pennsylvania State University, University Park, PA 16802, USA
140 National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China
141 Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
142 Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada
143 The Chinese University of Hong Kong, Shatin, NT, Hong Kong
144 Seoul National University, Seoul 08826, South Korea
145 Pusan National University, Busan 46241, South Korea
146 Carleton College, Northfield, MN 55057, USA
147 INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
148 INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
149 Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
150 OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia
151 Columbia University, New York, NY 10027, USA
152 Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain
153 Université Libre de Bruxelles, Brussels 1050, Belgium
154 Sonoma State University, Rohnert Park, CA 94928, USA
155 Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
156 University of Rhode Island, Kingston, RI 02881, USA
157 The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA
158 Bellevue College, Bellevue, WA 98007, USA
159 MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, 1117 Budapest, Hungary
160 Institute for Plasma Research, Bhat, Gandhinagar 382428, India
161 The University of Sheffield, Sheffield S10 2TN, United Kingdom
162 IGFAE, Campus Sur, Universidade de Santiago de Compostela, 15782 Spain
163 Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
164 California State University, Los Angeles, 5151 State University Dr. Los Angeles, CA 90032, USA
165 Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
166 Università di Roma ‘La Sapienza,’ I-00185 Roma, Italy
167 Colorado State University, Fort Collins, CO 80523, USA
168 Kenyon College, Gambier, OH 43022, USA
169 Christopher Newport University, Newport News, VA 23606, USA
170 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
171 Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
172 School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom
173 Institute Of Advanced Research, Gandhinagar 382426, India
174 Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
175 University of Szeged, Dóm tér 9, Szeged 6720, Hungary
176 Tata Institute of Fundamental Research, Mumbai 400005, India
177 INAF, Osservatorio Astronomico di Capodimonte, I-80131, Napoli, Italy
178 University of Michigan, Ann Arbor, MI 48109, USA
179 American University, Washington, D.C. 20016, USA
180 GRAPPA, Anton Pannekoek Institute for Astronomy and Institute of High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
181 Delta Institute for Theoretical Physics, Science Park 904, 1090 GL Amsterdam, The Netherlands
We present a multi-messenger measurement of the Hubble constant $H_0$ using the binary–black–hole merger GW170814 as a standard siren, combined with a photometric redshift catalog from the Dark Energy Survey (DES). The luminosity distance is obtained from the gravitational wave signal detected by the LIGO/Virgo Collaboration (LVC) on 2017 August 14, and the redshift information is provided by the DES Year 3 data. Black–hole mergers such as GW170814 are expected to lack bright electromagnetic emission to uniquely identify their host galaxies and build an object–by–object Hubble diagram. However, they are suitable for a statistical measurement, provided that a galaxy catalog of adequate depth and redshift completion is available.
Here we present the first Hubble parameter measurement using a black–hole merger. Our analysis results in $H_0 = 75^{+40}_{-32}$ km s$^{-1}$ Mpc$^{-1}$, which is consistent with both SN Ia and CMB measurements of the Hubble constant. The quoted 68% credible region comprises 60% of the uniform prior range [20,140] km s$^{-1}$ Mpc$^{-1}$, and it depends on the assumed prior range. If we take a broader prior of [10,220] km s$^{-1}$ Mpc$^{-1}$, we find $H_0 = 78^{+34}_{-30}$ km s$^{-1}$ Mpc$^{-1}$ (57% of the prior range). Although a weak constraint on the Hubble constant from a single event is expected using the dark siren method, a multifold increase in the LVC event rate is anticipated in the coming years and combinations of many sirens will lead to improved constraints on $H_0$.

**Keywords:** catalogs — cosmology: observations — gravitational waves — surveys

### 1. INTRODUCTION

Unlike most extragalactic distance observables, mergers of neutron star and black hole binary systems are absolute distance indicators. Often referred to as “standard sirens”, they emit gravitational waves (GW) from which the luminosity distance can be inferred without relying on any calibration with respect to another source: the rate of change in frequency gives the system’s size and thus the intrinsic amplitude, which is compared against the observed signal amplitude to obtain the distance to the source. If redshifts are associated with those sirens (in the simplest case, the host galaxy is identified and its redshift is obtained via spectroscopic follow up), a measurement of the present rate of expansion of the Universe $H_0$ can be achieved via the distance–redshift relation. The use of gravitational wave sources as cosmological probes was first proposed by Schutz (1986), and recently revisited in several works (e.g. Holz & Hughes 2005).

For dark energy research, the possibility of measuring $H_0$ directly and independently from other methods is of great interest. Local measurements obtained from type Ia Supernovae (SN Ia) and other distance indicators, as well as the predicted value inferred from the cosmic microwave background at $z \sim 1100$, have achieved remarkable precision of 1–2.5% (e.g. Riess et al. 2018; Planck Collaboration et al. 2018). They disagree, however, by more than 3σ and interpreting this tension as evidence for beyond–ΛCDM dark energy or new physics at the early universe requires new measurements of great precision and accuracy (Freedman 2017; Mörtsell & Dhawan 2018). Those measurements are one of the greatest challenges faced by current experiments in cosmology because the observables are subject to correlated systematic effects arising from their complex astrophysics. As estimates become more precise, this challenge becomes more severe and the need for novel independent methods becomes more pressing. Those methods, however, are few and hard to come by. One possibility is standard sirens, which remained elusive for almost 30 years, until the detection of the first gravitational wave event (GW150914; Abbott et al. 2016).

The first standard siren-based $H_0$ measurement (Abbott et al. 2017a) came with the discovery of the binary–neutron–star (BNS) merger GW170817 (Abbott et al. 2017) and its associated electromagnetic counterpart (LIGO Scientific Collaboration et al. 2017; Soares-Santos et al. 2017; Arcavi et al. 2017; Coulter et al. 2017; Lipunov et al. 2017; Tanvir et al. 2017; Valenti et al. 2017). Several studies have developed methodologies to infer cosmological parameters from standard sirens and establish their constraining power (Schutz 1986; Holz & Hughes 2005; MacLeod & Hogan 2008; Nissanke et al. 2010; Del Pozzo 2012; Nissanke et al. 2013; Nishizawa 2017; Chen et al. 2018; Feeney et al. 2018; Vitale & Chen 2018; Mortlock et al. 2018). Chen et al. (2018) predict that we will be able to constrain $H_0$ with 2% precision within 5 years with standard sirens detected by LIGO/Virgo, while Nair et al. (2018) predict a 7% measurement with just 25 binary black hole (BBH) events from the Einstein telescope.

Anticipating that the LIGO/Virgo Collaboration (LVC) network of gravitational wave detectors would eventually achieve sensitivity sufficient to enable standard siren–based measurements, the Dark Energy Survey (DES) collaboration and external collaborators launched in 2015 the DES gravitational waves (DESWG) program. DESGW uses DECam to search for optical emission associated with LVC detected mergers and pursues cosmological measurements with standard sirens. In particular, the multi-messenger shared discovery of the neutron–star merger GW170817 and its optical kilonova, resulted in a measurement of $H_0$ (Abbott et al. 2017a) that inaugurated the era of siren-based cosmology. We have also performed the most comprehensive searches for optical emission to black hole events, including GW150914 (Soares-Santos et al. 2016), GW151226 (Cowperthwaite et al. 2016), and GW170814 (Doctor et al. 2018). These events are expected to be dark, although the possibility of optical emission has yet to be observationally excluded.

Dark sirens can also be used for cosmology using a statistical method, as first proposed in Schutz (1986). Provided a catalog of potential host galaxies within the event localization region, their redshifts will contribute in a probabilistic way to the measurement of $H_0$, depending on the galaxies’ distance and sky position. This approach has been developed

---

* Deceased, November 2017.
† Deceased, July 2018.
within a Bayesian framework by Del Pozzo (2012) and Chen et al. (2018) and implemented in Fishbach et al. (2018) using GW170817, which produced results consistent with the first measurement (Abbott et al. 2017a) where the identified host galaxy, NGC 4993 (e.g., Palmese et al. 2017), was used. Eventually, a large sample of events will enable precise cosmological measurements using the dark siren approach.

In this work, we measure $H_0$ using the gravitational wave event GW170814 (Abbott et al. 2017b) as a dark siren. GW170814 resulted from the inspiral and merger of a binary black hole system at a luminosity distance of $540_{-310}^{+230}$ Mpc (median value with 90% credible interval). The masses of the black holes were $30.5_{-5.0}^{+5.7}$ and $25.3_{-4.2}^{+8.4} M_\odot$, each. GW170814 is the first BBH detected by a triple network (including LIGO Hanford and Livingston, plus Virgo), and it has the smallest localization volume of any of the BBH events detected by LVC thus far. Therefore the number of potential host galaxies is lower compared to other events, making GW170814 the most appropriate event for this measurement. Additionally, the event localization region falls within the DES footprint, making DES galaxy catalogs a prime sample for measurement of $H_0$. With this one event, our goal is to provide a proof of principle measurement, addressing the challenges that are specific to the dark siren method, and establishing its potential to yield precision cosmology results in the near future.

A key component of the measurement is crafting the appropriate galaxy catalog: completeness, as well as precise and accurate photometric redshifts (photo-z’s), throughout the entire volume probed are required. The overlap of GW170814’s area with DES allows us to employ galaxy catalogs produced from the first three years of the survey (DES Y3; Abbott et al. 2018). This first dark siren measurement is a step towards incorporating this new cosmological probe into the portfolio of cosmic surveys for dark energy.

A detailed description of the data used in this analysis is provided in §2, followed by a description of our implementation of the method in §3. We present our results and discussion in §4, and our conclusions in §5. Throughout this paper we assume a flat ΛCDM cosmology with $\Omega_m = 0.3$ and $H_0$ values in the $20 - 140$ km s$^{-1}$ Mpc$^{-1}$ range. All quoted error bars represent the 68% confidence level (CL), unless otherwise stated.

2. DATA

2.1. The LVC sky map

The sky map used in this work is the publicly available LALInference map (LIGO Scientific Collaboration & Virgo Collaboration 2017)\(^1\), provided in HEALPix (Górski et al. 2005) pixels. The luminosity distance probability distribution is approximated with a Gaussian in each pixel. The region of interest, enclosing 90% of the localization probability, is 61.66 deg\(^2\). The projected sky map and the distribution of luminosity distance mean values from the LVC distance likelihood in each pixel within the region of interest are shown in Figure 1. The probability peak is located at RA, Dec = (47.523, −44.856) deg. At the peak location, the luminosity distance is 504.7 Mpc and the Gaussian width is 91.9 Mpc. Using the limiting values of our $H_0$ prior range ([20,140] km s$^{-1}$ Mpc$^{-1}$) we can convert the 90% and 99.7% distance range into a redshift range ($0.02 < z < 0.26$ and $z < 0.3$, respectively) for this analysis.

2.2. The DES galaxy catalog

The DES$^2$(The Dark Energy Survey Collaboration 2005; Dark Energy Survey Collaboration et al. 2016) is an optical-near-infrared survey that images 5000 deg$^2$ of the South Galactic Cap in the grizY bands. The survey is being carried out using a $\sim 3$ deg$^2$ CCD camera (the DECam, see Flaugher et al. 2015) mounted on the Blanco 4-m telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. The data used here are from the first 3 years of observations (September 2013 – February 2016, Abbott et al. 2018).

The DES Data Management (DESDM) pipeline was used for data reduction (Morganson et al. 2018). The process includes calibration of the single-epoch images, which are co-added after background subtraction and then cut into tiles. The source catalogue was created using Source Extractor (SExtractor, Bertin & Arnouts 1996) to detect objects on the $riz$ co-added images. The median 10σ limiting magnitudes of Y3 data for galaxies are $g = 24.33$, $r = 24.08$, $i = 23.44$, $z = 22.69$, and $Y = 21.44$ mag (Abbott et al. 2018). The photometry used in this work is part of a value-added Y3 catalog not released with DR1, and is the result of the Multi-Object Fitting (MOF) pipeline that uses the ngmix code.\(^3\) Following a procedure similar to Drlica-Wagner et al. (2017) for Year 1 data, the DES collaboration made further selections to produce a high-quality object catalog called the Y3 “gold” catalog. For this sample, redshifts have been computed using the Directional Neighborhood Fitting (DNF; De Vicente et al. 2016), and they are not included in DR1.

The DNF method applied to Y3 data provides redshift information for each galaxy in the form of a probability distribution function (PDF), from which a mean redshift, and half of the central 68th percentile width are computed. The width of the PDF can be over or under-estimated due to the sampling of the training set and algorithmic details of DNF. This

\(^1\) https://dcc.ligo.org/LIGO-T1700453/public

\(^2\) www.darkenergysurvey.org

\(^3\) https://github.com/esheldon/ngmix
issue is particularly relevant for the redshift range used in this work, which is low compared to that exploited in weak lensing and large scale structure cosmology, for which the DNF method was optimized. We find that the typical uncertainty below redshift $z \sim 0.1$ is underestimated by a factor of 10 when compared to the typical scatter found for the subset of the galaxies with available spectroscopic redshifts (where the standard deviation is $\sigma \gtrsim 0.015$). Thus, we add a minimum uncertainty of 0.015 for these low-\(z\) galaxies. At $0.1 < z < 0.3$, the uncertainty is well behaved and the average value follows $\sigma_z(z) \simeq 0.013 (1+z)^3$, as we find using an empirical fit.

We produce alternative photo-\(z\) estimates with another machine learning code, ANNz2 (Sadigh et al. 2016). This allows us to test the impact of the correction applied to the DNF errors on the posterior of the Hubble constant. Photo-\(z\) with ANNz2 have previously been validated for cosmological analyses using DES Science Verification data (Bennett et al. 2016; Leistedt et al. 2016; Abbott et al. 2016) and for the Kilo–Degree Survey (KiDS; Bilicki et al. 2018), and are produced as part of the DES photo-\(z\) pipeline (Gschwend et al. 2018). In particular, it provides error estimates through a \(k\)-nearest neighbor (\(k\)NN) method, and dedicated redshifts for the purposes of this analysis. We additionally employ a reweighting technique (Lima et al. 2008) specifically for our galaxy sample to further tune our redshifts. We run ANNz2 in randomized regression mode with 50 Boosted Decision Trees (BDTs), using a spectroscopic sample of 245,458 matching Y3 galaxies out to redshift $z \simeq 1$, randomly split into subsamples for training, testing and validation. The training and the reweighting use \textit{griz} MOF magnitudes. We find that the typical error roughly follows $\sim 0.02 (1+z)^3$ in the redshift range of interest. The two algorithms, DNF and ANNz2, gave similar results, see section §4.
These redshifts, together with publicly available spectroscopic redshifts from 2dF, 6dF and SPT-GMOS (Colless et al. 2001; Jones et al. 2009; Bayliss et al. 2016) and the DES MOF photometry, are used to estimate galaxy properties (including stellar mass and absolute magnitude) of this sample. This is achieved through a broadband Spectral Energy Distribution (SED) fitting of galaxy magnitudes with LePhare (Arnouts et al. 1999, Ilbert et al. 2006). Estimates of the galaxy properties used here from DES data alone have been tested and studied in several DES works (Palmese et al. 2016; Etherington et al. 2017; Palmese et al. 2019). We add a 0.05 systematic uncertainty in quadrature to the magnitudes, to account for systematic uncertainties in magnitude estimation and model variance.4 The simple stellar population (SSP) templates used for the fitting are Bruzual & Charlot (2003), with three metallicities (0.2 Z⊙, Z⊙, and 2.5 Z⊙), a Chabrier (2003) Initial Mass Function (IMF) and a Milky Way (Allen 1976) extinction law with five different values between 0 and 0.5 for the E(B−V) reddening. The star formation history (SFH) chosen is exponentially declining as e^{−t/τ} with τ = 0.1, 0.3, 1, 2, 3.5, 10, 15 and 30 Gyr.

The source list of the Y3 gold catalogue is 95% complete for galaxies within our apparent magnitude limit, r < 23.35 (Abbott et al. 2018). This value is computed through the recovery rate of sources from the deeper CFHTLenS survey (Erben et al. 2013), and thus includes the correct distribution of surface brightnesses. Nevertheless, extended, low surface brightness galaxies near our flux limit may be preferentially missed by the detection pipeline. We therefore provide an approximate completeness of sources throughout the redshift range of interest. Using DNF mean redshifts we convert the source completeness to r < 23.35 from Abbott et al. (2018) (Figure 12) into a completeness in redshift intervals, ∆z = 0.02. By taking the peak of the magnitude distribution in each bin as roughly our observed magnitude limit at that redshift, we find our sample is > 93% complete across the range 0 < z < 0.26. We further determined that the fraction of low redshift, extended galaxies missed by the DES Y3 pipeline is ∼ 1%, when compared with the 2MASS extended source catalog (Huchra et al. 2012). For the purpose of this paper, we choose to ignore those ultra-low z sources as most of them are at z < 0.02 and are not relevant for the present analysis.

The DES Y3 gold catalog is nonetheless an observed magnitude–limited sample. This analysis requires a volume–limited sample, which we obtain by applying a luminosity cut. In order to determine the appropriate cut to create a volume–limited sample, we compute the completeness limits in terms of absolute quantities (luminosity and stellar mass). We follow the method outlined in Pozzetti et al. (2010) and Hartley et al. (2013). We identify galaxies with observed magnitudes that are bright enough to be complete and representative of the real galaxy population within redshift bins. To compute the 95% completeness limit in (rest–frame) luminosity, we scale the luminosities of this sample to that which they would have if their observed magnitude were equal to the survey completeness limit, and take the 95th percentile of the resulting luminosity distribution. This value corresponds to −17.2 in r-band absolute magnitude and ∼ 3.8 × 10^8 M⊙ in stellar mass for the redshift range of interest. We cut the DES catalog at the specific absolute luminosity value mentioned above. We conclude that our volume–limited galaxy sample is complete within the redshift range of interest for galaxies down to stellar masses of ∼ 3.8 × 10^8 M⊙. In other words, our galaxy catalog contains ∼ 77% of the total stellar mass in the volume considered by assuming that the galaxies follow a Schechter stellar mass function with the best fit values from Weigel et al. (2016).

The final galaxy stellar mass and redshift distributions of galaxies are shown in Figure 1. The stellar mass map clearly shows the presence of large scale structure, including clusters, voids and filaments. We recognize a number of well–known clusters within the volume of interest, including several Abell clusters. A uniform distribution of galaxies in comoving volume (dN/dz)com has been subtracted from the observed galaxies’ redshift distribution in Figure 1 to highlight the overdensities. The (dN/dz)com distribution has been obtained by assuming H0 = 70 km s^-1 Mpc^-1 and it contains the same total number of galaxies as the observed dN/dz over the redshift range shown. We are able to identify a “wall”–like structure around z = 0.06 spanning most of the area between 35 < RA < 55 and −55 < Dec < −35, which is spectroscopically confirmed by 2dF, LCRS (Shectman et al. 1996), and especially 6dF. A broader galaxy overdensity is found around z = 0.12 (also seen in LCRS and 2dF, and composed of several Abell galaxy clusters). This broad peak is also identified in redshift distributions by other photo–z codes, including a template based code, the Bayesian Photometric Redshift (BPZ; Benítez 2000). We have further verified that overdensities at the lowest redshifts (z ∼ 0.06) are also present in spectroscopic samples outside of the region of interest. This is expected at these low redshifts, where large scale structure projects onto vast areas of the sky. In summary, there are 77,092 galaxies within the 90% LIGO/Virgo probability volume, and 105,011 when 99.7% of the distance probability is considered, of which ∼ 6,000 have spectroscopic redshifts.

---

4 This is a regularization to compensate for the synthetic model set grid and the fact that many SED fitting codes do not include a model error function. The value chosen is based on past experience of what gives stable results.

3. METHOD
In order to estimate the posterior probability of \( H_0 \) given GW data \( d_{GW} \) from a single event detection, and electromagnetic (EM) data from a galaxy survey, we follow Chen et al. (2018). By applying Bayes’ theorem, one can write the posterior as:

\[
p(H_0|d_{GW}, d_{EM}) \propto p(d_{GW}, d_{EM}|H_0)p(H_0).
\]  

(1)

We assume that all cosmological parameters except for \( H_0 \) are fixed (Flat \( \Lambda \)CDM cosmology with \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \)). We treat the joint GW and EM likelihood

\[
p(d_{GW}, d_{EM}|H_0)
\]

as the product of two individual likelihoods (since the processes involved in producing the data from the two experiments are independent) marginalized over all variables except for the true luminosity distance \( d_L \) and solid angle \( \Omega_{GW} \) of the GW source, and for the true host galaxy redshift \( z \) and solid angle \( \Omega_i \). Note that the solid angles \( \Omega \) are vectors with the angular position of the source/galaxy as direction, and they all subtend the same area \((\sim 3 \times 10^{-3} \text{deg}^2)\) as the sky is pixellized with HEALPix maps in this work. If we assume that the event happened in one of the observed galaxies \( i \), then \( \Omega_{GW} \) and \( \Omega_i \) are related, and so are \( d_L \) and \( z \) through the cosmology (in this case, \( H_0 \)). By marginalizing also over the choice of galaxy \( i \), the joint, marginal likelihood can be written as:

\[

p(d_{GW}, d_{EM}|\{z_i, \Omega_i\}, H_0) \propto \sum_i w_i \int dL d\hat{\Omega}_{GW} p(d_{GW}|d_L, \hat{\Omega}_{GW}) \times p(d_{EM}|\{z_i, \Omega_i\}) \delta_D(d_L - d_L(z_i, H_0)) \delta_D(\hat{\Omega}_{GW} - \hat{\Omega}_i),
\]

(2)

where \( \delta_D \) is the Dirac delta function, \( w_i \) are weights that represent the relative probability that different galaxies host a GW source, and \( \{z_i, \Omega_i\} \) represents all the galaxies’ redshift and solid angle. These weights could be based on some galaxy properties, such as luminosity or star–formation rate, but here we assume they are uniform across all galaxies given our lack of knowledge of GW host galaxy properties.

We also need to marginalize over the galaxies’ redshifts and sky positions, with a reasonable choice of prior \( p(z_i, \Omega_i) \). If one assumes that the galaxies are uniformly distributed in comoving volume \( V \), and volume–limited within \( V_{\text{max}} \):

\[
p(z_i, \Omega_i) \, dz_i \, d\Omega_i \propto \frac{1}{V_{\text{max}}} \frac{d^3V}{dz_i d\Omega_i} = \frac{1}{V_{\text{max}}} \frac{r^2(z_i)}{H(z_i)} \, dz_i \, d\Omega_i,
\]

(3)

\[
p(H_0|d_{GW}, d_{EM}) \propto \frac{p(H_0)}{V[d_{GW}^{\text{max}}(H_0)]} \sum_i \int dz_i \, p(d_{GW}|d_L(z_i, H_0), \hat{\Omega}_i) \frac{r^2(z_i)}{H(z_i)},
\]

(7)

where \( r \) is the comoving distance to the galaxy. While this assumption holds on average over sufficiently large volumes, it is possible that future precision cosmology analyses will require taking into account the real clustering of galaxies in this formalism.

Assuming that we precisely know the galaxies’ positions \( \{\Omega_i\} \) (which is realistic especially in the limit in which spatial probabilities are considered within HEALPix pixels), we can integrate over the galaxies’ positions as delta functions about the observed values. The marginal EM likelihood reduces to \( p(d_{EM}|\{z_j\}) \), which we approximate for simplicity by a product of Gaussian distributions, \( N \), for each galaxy, centred around the observed redshift values \( z_{\text{obs}} \), with a width given by the redshift’s uncertainty \( \sigma_{z_i} \) for each galaxy \( i \):

\[
p(d_{EM}|\{z_j\}) = \prod_i p(z_{\text{obs},i}|z_i) = \prod_i N(z_{\text{obs},i}, \sigma_{z_i}, z_i).
\]

(4)

The marginal GW likelihood \( p(d_{GW}|d_L, \Omega) \) can be computed as prescribed in Singer et al. (2016):

\[
p(d_{GW}|d_L, \Omega) \propto p(\Omega) \frac{1}{\sqrt{2\pi} \sigma(\Omega)} \exp\left[ -\frac{(d_L - \mu(\Omega))^2}{2\sigma^2(\Omega)} \right] N(\hat{\Omega}),
\]

(5)

where the position probability, location, normalization and scale \( p(\Omega), \mu, \sigma_N \text{ and DISTSTD } \sigma \) respectively) of the luminosity distance at each position are provided in the sky map.

We now consider the selection effects of GW events and galaxies introduced by the experiments’ sensitivities and detection pipelines. We follow the approach of Chen et al. (2018) and Mandel et al. (2018), and include a \([\beta(H_0)]^{-1}\) factor that normalizes the likelihood over all possible GW and EM data. Given that our galaxy catalog is volume–limited out to larger distances than the maximum observable distance for the GW events, this term reduces to:

\[

\beta(H_0) = \frac{V[d_{GW}^{\text{max}}(H_0)]}{V_{\text{max}}(H_0)},
\]

(6)

where \( V[d_{GW}^{\text{max}}(H_0)] \) is the maximum observable volume for the GW events considered.

Finally, Eq. (1) becomes:

\[

p(H_0|d_{GW}, d_{EM}) \propto \frac{p(H_0)}{V[d_{GW}^{\text{max}}(H_0)]} \sum_i \int dz_i p(d_{GW}|d_L(z_i, H_0), \hat{\Omega}_i) \frac{r^2(z_i)}{H(z_i)},
\]

(7)

each term of the sum. This formalism can be extended to
combine data \( \{d_{GW,j}\} \) and \( d_{EM} \) from a sample of multiple events, assuming that the GW events are independent and that the galaxy catalog is fixed for all events:

\[
p(H_0|\{d_{GW,j}\},d_{EM}) \propto p(H_0) \int d^2z_d d^4\Omega_k p(z_d,\Omega_k) \times
\]

\[
p(d_{EM}|\{z_k,\Omega_k\}) \prod_j p(d_{GW,j}|\{z_k,\Omega_k\}).
\]

In the following, we assume a flat prior on \( H_0 \) within [20,140] km s\(^{-1}\) Mpc\(^{-1}\), unless otherwise stated. This is a very broad prior, covering a range much larger than current estimates of \( H_0 \). This choice was made as a compromise between the following aspects: i) a result which is mostly informed by the LVC and DES data rather than by external constraints, ii) a result which can be compared with the first standard siren estimate, and iii) a complete galaxy sample which contains most of the stellar mass within the localization volume to minimize the chance of missing the real host galaxy. As explained in more detail in §4, the redshift cut is related to the \( H_0 \) prior range, and in order to explore higher values of \( H_0 \), one needs to include higher redshift galaxies, and make a higher luminosity cut to preserve the volume limited sample.

A blinded analysis has been performed when estimating the \( H_0 \) posterior from the data to avoid confirmation bias. The values of the Hubble constant have been randomly displaced by an unknown amount, and we unblinded after our pipeline was able to reliably reproduce the input cosmology on simulation tests.

4. RESULTS AND DISCUSSION

We apply the described methodology to the DES galaxies’ redshifts and the GW170814 LIGO/Virgo sky map to produce a posterior distribution for the Hubble constant. We find that changes in the \( H_0 \) estimate and its uncertainty between using the corrected DNF photo-z’s or the ANNz2 outputs are below the percent level. This agreement is expected, since the two methods produce redshift distributions that are consistent with similar uncertainties. We also add a 0.001 systematic redshift error in quadrature (corresponding to a typical peculiar velocity of \( \sim 300 \) km s\(^{-1}\)). The effect of this correction on the posterior is negligible because only a few percent of the galaxies have a spectroscopic redshift, and the effect of peculiar velocities on the remaining galaxies is more than an order of magnitude below their typical photo-z error.

Our maximum a posteriori estimate of the Hubble constant is \( H_0 = 75.0_{-3.8}^{+4.0} \) km s\(^{-1}\) Mpc\(^{-1}\) using a flat prior between 20 and 140 km s\(^{-1}\) Mpc\(^{-1}\). The full posterior distribution is shown in Figure 2, and Table 1 summarizes our findings. The presence of a main, though broad, peak, is expected given the large scale structure seen in the observed volume.

As described in section 2.1, the galaxy sample used in these results is selected as described in §2, and covers the LIGO/Virgo 90% credible localization volume. The distance cut is translated into a redshift cut (made on the mean photo-z value of each galaxy) for a given \( H_0 \) prior. This cut ensures that the galaxy catalog is as complete as possible throughout the whole redshift range of interest for the cosmological parameters used, and includes the fainter galaxies observable for a volume–limited sample defined as in §2. In fact, in order to include more distant galaxies, the luminosity cut needs to be brighter to ensure that the sample is still volume–limited, with the risk of missing the true host galaxy. We have explored the impact of the redshift cut on the \( H_0 \) posterior, while keeping the angular selection to be within the 90% credible localization area. The effect of including galaxies out to 99.7% of the distance localization (corresponding to \( z < 0.3 \)) is most pronounced at high \( H_0 \) values, as shown by the shaded red region in Figure 2. With this less restrictive cut, the credible region shifts to \( H_0 = 77.5_{-3.3}^{+4.1} \) km s\(^{-1}\) Mpc\(^{-1}\), showing a \( \sim 2\% \) change of the maximum. The effect described here arises from tens of thousand of galaxies at the higher redshifts included with the more relaxed distance cut and the ansatz of Gaussianity of the luminosity distance posterior. In fact, these galaxies contribute with a non–negligible probability to the posterior because of the high \( d_L \) tail shown in the bottom right panel of Figure 1, and they contribute more significantly at high \( H_0 \) values. This few percent effect is insignificant at the current levels of precision, but will need to be explored in the future using a more realistic luminosity distance posterior.

Our result agrees well (as expected, due to the large uncertainty) with the latest CMB estimate of the Hubble constant by the Planck Collaboration (67.36 ± 0.54 km s\(^{-1}\) Mpc\(^{-1}\) from TT,TE,EE+lowP+lensing; Planck Collaboration et al. 2018), and with results using distance ladder methods by ShoES (73.52 ± 1.62 km s\(^{-1}\) Mpc\(^{-1}\); Riess et al. 2016) and by DES (67.77 ± 1.30 km s\(^{-1}\) Mpc\(^{-1}\) from SN+BAO; Macaulay et al. 2018).

For the bright standard siren measurement using GW170817 and its electromagnetic counterpart, Abbott et al. (2017a) found \( H_0 = 70.0_{-4.8}^{+5.1} \) km s\(^{-1}\) Mpc\(^{-1}\) at 68% credible interval. Without an EM counterpart leading to a unique host galaxy redshift, we would have recovered a broader \( H_0 \) posterior since we average over all possible host galaxies in the localization volume. For example, Fishbach et al. (2018) applied the statistical standard siren method to GW170817 and found a larger uncertainty than the counterpart standard siren result: \( H_0 = 76.0_{-4.5}^{+4.8} \) km s\(^{-1}\) Mpc\(^{-1}\) for a uniform prior over the range \([10,220]\) km s\(^{-1}\) Mpc\(^{-1}\). For a BBH standard siren measurement, as in this work, the combination of the larger
localization volume (implying a significantly greater number of potential host galaxies) and the large photometric redshift uncertainty for each galaxy results in an even broader $H_0$ posterior. Therefore, while applying the statistical standard siren method to GW170817 yields a 68% credible region on $H_0$ comprising 34% of the prior range (Fishbach et al. 2018), in this work we obtain a 68% credible region on $H_0$ that is 60% of the prior range. We note that the prior used in Fishbach et al. (2018) is 1.75 times broader than the prior used in this work; if we adopt the same broader prior of [10,220] for our analysis of GW170814, we find $H_0 = 78_{-24}^{+36}$ km s$^{-1}$ Mpc$^{-1}$. The dependence of the width of the $H_0$ posterior on the prior width is a consequence of the fact that the GW observation, which provides only a luminosity distance estimate, is consistent with arbitrarily large $H_0$'s, if there are galaxies at sufficiently large redshifts. If the galaxy catalogue extends to some redshift, $z_{\text{max}}$, the posterior would fall off around $H_0 \approx c z_{\text{max}} / d_L$, where $d_L$ is the typical luminosity distance from the GW posterior. However, this fall off is artificial since there are galaxies at greater redshifts which are not included in the catalogue. These may be accounted for using catalogue incompleteness corrections. We chose the prior range for this analysis rather than a larger one such that we did not need to include such corrections, which simplifies the analysis. However, dark siren measurements will become particularly interesting when multiple events can be combined and this effect becomes irrelevant (Chen et al. 2018).

The analysis in Fishbach et al. (2018) for GW170817 used the GLADE galaxy catalog (Dálya et al. 2018), and accounted for incompleteness at the distance of GW170817. GLADE becomes significantly incomplete at the distance to GW170814. As GW detectors improve in sensitivity, the majority of dark standard sirens will be detected at even greater distances and with larger localization volumes, well beyond the reach of spectroscopic galaxy catalogs. This highlights the need for reliable and complete photometric galaxy catalogs. Surveys such as DES, Pan–STARRS1 (Chambers et al. 2016) and LSST are therefore likely to play an important role in future constraints from BBH standard sirens.

The assumption throughout this work is that even if the event occurred in a galaxy below our luminosity threshold, large scale structure predicts that fainter galaxies follow the clustering pattern of the more luminous galaxies in our sample. We have verified in our simulations that a threshold up to 1 magnitude brighter than the limit used here to place events
Table 1. Hubble constant estimate from this work. All $H_0$ values and errors are in km s$^{-1}$ Mpc$^{-1}$. The uncertainty from the flat prior only is derived by assuming the same $H_0$ maximum found in the analysis. Quoted uncertainties represent 68% confidence level around the maximum of the posterior, and they are statistical only. The last column quantity ($\sigma_{H_0}/H_0$ prior) corresponds to 68% times the prior width divided by $H_0$

| Prior | $H_0$ | +$\sigma_{H_0}$ | $-\sigma_{H_0}$ | $\sigma_{H_0}/H_0$ | $\sigma_{H_0}/H_0$ prior |
|-------|-------|----------------|---------------|----------------|-----------------|
| [20,140] | 75 | 40 | 32 | 47.8% | 54.3% |

has a negligible impact over a sample of 100 events, provided that the catalog is volume–limited for the range of redshifts relevant to the measurement.

Since galaxies are biased tracers of the Universe’s dark matter, some theories predict that the origin of the black holes involved in these GW events is primordial, constituting part or all of the dark matter (Bird et al. 2016; Clesse & García-Bellido 2017; García-Bellido 2017; Clesse & García-Bellido 2018). In that case, GW events follow exactly the underlying dark matter distribution (presenting an unbiased tracer). Because of the stellar mass to dark matter halo connection (see Wechsler & Tinker 2018 and references therein) it is reasonable to weight galaxies by their stellar mass in Eq. (2) as $w_i \propto M_*$. The impact of this scaling with stellar mass or star–formation rate has been explored in Fishbach et al. (2018). We find that the stellar mass weighting has a negligible effect on the posterior. This is due to the large volume analyzed (over which the stellar masses tend to be averaged out) and to the precision level of this measurement. In other theories, these black hole binaries are produced in very low metallicity galaxies (e.g. Cao et al. 2018; Mapelli et al. 2018), biased relative to the dark matter distribution differently than the luminous galaxies in our catalog. Annis et al. (in prep.) explore the effect of the tracer bias assumptions on the $H_0$ posterior for future analyses aiming at precision measurements.

Another assumption of our analysis that needs attention concerns the redshift likelihood. As anticipated above for the GW likelihood, this will not, in general, be well approximated by a Gaussian. In the future, we plan to explore the impact of realistic photometric redshift PDFs on the $H_0$ posterior, in order to enable precision cosmology with binary–black–hole events. An analysis with the full, asymmetric, GW likelihood will also be required. While an estimate of those effects is needed, tests on off–source lines–of–sight show that our constraint is likely not strongly impacted by the photo–$\text{z}$ training sample or systematic failures.

In the past two LVC observing seasons, black–hole mergers outnumbered neutron star events at a rate of approximately 10 to 1. Uncertainties on the expected detection rate are large, but conservative estimates predict $\sim$ 1 event per week for the upcoming observing campaign (scheduled to start in April 2019). The majority of these events will have larger localization volumes than GW170814 (Chen & Holz 2016 estimate $\lesssim$ 1% of BBHs will be localized to better than $10^4$ Mpc$^3$) and hence provide poorer constraints than those reported here. However, given the high expected event rate for dark sirens, larger event samples will be available in the future. Chen et al. (2018) provide forecasts using a distribution of realistic localization area, finding that the dark siren method will reach $\sim$ 10% statistical precision on $H_0$ by 2026 from BBH mergers only, and 5–10% precision from BNS mergers if none of them have EM counterparts.

5. CONCLUSIONS

In this paper, we have performed the first measurement of the Hubble constant using a gravitational wave detection of a binary–black–hole merger as a dark standard siren and the DES galaxies as a sample of potential host galaxies. Our analysis was blinded to avoid confirmation bias. Our main results, discussed in §4, include a measurement of $H_0 = 75^{+13}_{-12}$ km s$^{-1}$ Mpc$^{-1}$ for a flat prior within [20,140] km s$^{-1}$ Mpc$^{-1}$, consistent with previous measurements of $H_0$. The 68% confidence interval quoted here is 60% of the uniform prior range, and it depends on the width of the prior. For example, with a broader prior of [10,220] km s$^{-1}$ Mpc$^{-1}$, we find $H_0 = 78^{+26}_{-24}$ km s$^{-1}$ Mpc$^{-1}$. Albeit weak, this measurement is not uninformative and the method becomes more powerful when we combine large numbers of dark sirens (Chen et al. 2018).

Future dark siren measurements will require complete galaxy catalogs. A wide field galaxy catalog with a DES–like depth is currently available only for $\sim$ 1/8 of the sky. However, DES can be complemented with other datasets taken with DECam (such as the Blanco Imaging of the Southern Sky, BLISS, and the Dark Energy Camera Legacy Survey, DECors), to cover the whole Southern sky to a good depth ($r \sim 23.4, 5\sigma$ depth). An even deeper survey with more precise photo–$\text{z}$’s, such as the Large Synoptic Survey Telescope (LSST; LSST Dark Energy Science Collaboration 2012), would be of great value for further improving these constraints.

At the expected level of precision from hundreds of events ($< 10\%$), systematics will play an important role. In future work, we plan to incorporate systematic uncertainties in our simulated data studies, in order to prepare for precision cosmology analyses on real data. We anticipate that some of the main sources of systematics will be photo–$\text{z}$ biases and catastrophic outliers, photo–$\text{z}$ training sample sample variance, galaxy catalog cuts and galaxy catalog completeness. In order to achieve the full potential of statistical standard siren cosmology, wide and deep galaxy surveys such as DES and LSST are necessary. Overall, our findings show that the synergy between gravitational wave black–hole merger de-
tections and new generation large galaxy surveys will establish a new powerful probe for precision cosmology.

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación, the Vicepresidencia i Conselleria d’Innovació, Recerca i Turisme and the Conselleria d’Educació i Universitat del Govern de les Illes Balears, the Conselleria d’Educació, Investigació, Cultura i Esport de la Generalitat Valenciana, the National Science Centre of Poland, the Swiss National Science Foundation (SNSF), the Russian Foundation for Basic Research, the Russian Science Foundation, the European Commission, the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the Paris Île-de-France Region, the National Research, Development and Innovation Office Hungary (NKFIH), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the Natural Science and Engineering Research Council Canada, the Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, Innovations, and Communications, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Leverhulme Trust, the Research Corporation, the Ministry of Science and Technology (MOST), Taiwan and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS and the State of Niedersachsen/Germany for provision of computational resources.

Funding for the DES Projects has been provided by the DOE and NSF(USA), MEC/MICINN/MINECO(Spain), STFC(UK), HEFCE(UK), NCSA(UIC), KICP(U. Chicago), CCAPP(Ohio State), MIFPA(Texas A&M), CNPQ, FAPERJ, FINEP (Brazil), DFG(Germany) and the Collaborating Institutions in the Dark Energy Survey.

The Collaborating Institutions are Argonne Lab, UC Santa Cruz, University of Cambridge, CIEMAT-Madrid, University of Chicago, University College London, DES-Brazil Consortium, University of Edinburgh, ETH Zürich, Fermilab, University of Illinois, ICE (IEEC-CSIC), IFAE Barcelona, Lawrence Berkeley Lab, LMU München and the associated Excellence Cluster Universe, University of Michigan, NOAO, University of Nottingham, Ohio State University, University of Pennsylvania, University of Portsmouth, SLAC National Lab, Stanford University, University of Sussex, Texas A&M University, and the OzDES Membership Consortium.

Based in part on observations at Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

The DES Data Management System is supported by the NSF under Grant Numbers AST-1138766 and AST-1536171. The DES participants from Spanish institutions are partially supported by MINECO under grants AYA2015-71825, ESP2015-88861, FPA2015-68048, and Centro de Excelencia SEV-2016-0588, SEV-2016-0597 and MDM-2015-0509. Research leading to these results has received funding from the ERC under the EU’s 7th Framework Programme including grants ERC 240672, 291329 and 306478. We acknowledge support from the Australian Research Council Centre of Excellence for All-sky Astrophysics (CAASTRO), through project number CE110001020.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.
REFERENCES

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, Phys. Rev. Lett., 116, 061102
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, Nature, 551, 85
—. 2017b, Physical Review Letters, 119, 141101
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, Phys. Rev. Lett., 119, 161101
Abbott, T., Abdalla, F. B., Allam, S., et al. 2016, PhRvD, 94, 022001
Abbott, T. M. C., Abdalla, F. B., Allam, S., et al. 2018, ArXiv e-prints, arXiv:1801.03181 [astro-ph.IM]
Allen, D. A. 1976, MNRAS, 174, 29P
Arcavi, I., Hosseinzadeh, G., Howell, D. A., et al. 2017, Nature, 551, 85
Arnouts, S., Cristiani, S., Moscardini, L., et al. 1999, MNRAS, 310, 540
Bayliss, M. B., Ruel, J., Stubbs, C. W., et al. 2016, ApJS, 227, 3
Benítez, N. 2000, ApJ, 536, 571
Bertin, E., & Arnouts, S. 1996, Astronomy and Astrophysics Supplement, 117, 393
Bilicki, M., Hoekstra, H., Brown, M. J. I., et al. 2018, A&A, 616, A69
Bird, S., Cholis, I., Muñoz, J. B., et al. 2016, Phys. Rev. Lett., 116, 201301
Bonnett, C., Troxel, M. A., Hartley, W., et al. 2016, 94, 042005
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Buczynski, M. B., Ruel, J., Stubbs, C. W., et al. 2016, ApJS, 227, 3
Chabrier, G. 2003, PASP, 115, 763
Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv e-prints, arXiv:1612.05560
Chen, H.-Y., Fishbach, M., & Holz, D. E. 2018, Nature, 562, 545
Chen, H.-Y., & Holz, D. E. 2016, arXiv e-prints, arXiv:1612.01471
Clesse, S., & García-Bellido, J. 2017, Physics of the Dark Universe, 15, 142
Clesse, S., & García-Bellido, J. 2018, Physics of the Dark Universe, 22, 137
Colless, M., Dalton, G., Maddox, S., et al. 2001, MNRAS, 328, 1039
Coulter, D. A., Foley, R. J., Kilpatrick, C. D., et al. 2017, Science, 358, 1556
Cowperthwaite, P. S., Berger, E., Soares-Santos, M., et al. 2016, ApJL, 826, L29
Dílya, G., Galgóczi, G., Dobos, L., et al. 2018, MNRAS, 479, 2374
Dark Energy Survey Collaboration, Abbott, T., Abdalla, F. B., et al. 2016, MNRAS, 460, 1270
De Vicente, J., Sánchez, E., & Sevilla-Noarbe, I. 2016, MNRAS, 459, 3078
Del Pozzo, W. 2012, PhRvD, 86, 043011
Doctor, Z., Kessler, R., Herner, K., et al. 2018, arXiv e-prints, arXiv:1812.01579
Drlica-Wagner, A., Sevilla-Noarbe, I., Rykoff, E. S., & et al. 2017, submitted to PRD
Erben, T., Hildebrandt, H., Miller, L., et al. 2013, MNRAS, 433, 2545
Etherington, J., Thomas, D., Maraston, C., et al. 2017, MNRAS, 466, 228
Feeney, S. M., Peiris, H. V., Williamson, A. R., et al. 2018, ArXiv e-prints, arXiv:1802.03404
Fishbach, M., Gray, R., Magaña Hernandez, I., et al. 2018, ArXiv e-prints, arXiv:1807.05667
Flaugher, B., Diehl, H. T., Honscheid, K., et al. 2015, AJ, 150, 150
Freedman, W. L. 2017, Nature Astronomy, 1, 0169
García-Bellido, J. 2017, in Journal of Physics Conference Series, Vol. 840, Journal of Physics Conference Series, 012032
Górski, K. M., Hivon, E., Banday, A. J., et al. 2005, ApJ, 622, 759
Gschwend, J., Rossel, A. C., Ogando, R. L. C., et al. 2018, Astronomy and Computing, 25, 58
Hartley, W. G., Almaini, O., Mortlock, A., et al. 2013, MNRAS, 431, 3045
Holz, D. E., & Hughes, S. A. 2005, ApJ, 629, 15
Huchra, J. P., Macri, L. M., Masters, K. L., et al. 2012, ApJS, 199, 26
Ilbert, O., Arnouts, S., McCracken, H. J., et al. 2006, A&A, 457, 841
Jones, D. H., Read, M. A., Saunders, W., et al. 2009, MNRAS, 399, 683
Leistedt, B., Peiris, H. V., Elsner, F., et al. 2016, ApJS, 226, 24
LIGO Scientific Collaboration, & Virgo Collaboration. 2017, GCN 21934
LIGO Scientific Collaboration, Virgo Collaboration, GBM, F., et al. 2017, ArXiv e-prints, arXiv:1710.05833 [astro-ph.HE]
Lima, M., Cunha, C. E., Oyaizu, H., et al. 2008, MNRAS, 390, 118
Lipunov, V. M., Gorbovskoy, E., Kornilov, V. G., et al. 2017, ApJL, 850, L1
LSST Dark Energy Science Collaboration. 2012, ArXiv e-prints, arXiv:1211.0310 [astro-ph.CO]
Macaulay, E., Nichol, R. C., Bacon, D., et al. 2018, ArXiv e-prints, arXiv:1811.02376
MacLeod, C. L., & Hogan, C. J. 2008, PhRvD, 77, 043512
Mandel, I., Farr, W. M., & Gair, J. R. 2018, ArXiv e-prints, arXiv:1809.02063 [physics.data-an]
Mapelli, M., Giacobbo, N., Toffano, M., et al. 2018, MNRAS, 481, 5324
Morganson, E., Gruendl, R. A., Menanteau, F., et al. 2018, PASP, 130, 074501
Mortlock, D. J., Feeney, S. M., Peiris, H. V., Williamson, A. R., & Nissanke, S. M. 2018, arXiv e-prints, arXiv:1811.11723
Mörtsell, E., & Dhawan, S. 2018, JCAP, 9, 025
Nair, R., Bose, S., & Deep Saini, T. 2018, ArXiv e-prints, arXiv:1804.06085
Nishizawa, A. 2017, PrRvD, 96, 101303
Nissanke, S., Holz, D. E., Dalal, N., et al. 2013, ArXiv e-prints, arXiv:1307.2638 [astro-ph.CO]
Nissanke, S., Holz, D. E., Hughes, S. A., Dalal, N., & Sievers, J. L. 2010, ApJ, 725, 496
Palmese, A., Annis, T. J., Burgad, J. C., et al. 2019, in prep.
Palmese, A., Lahav, O., Banerji, M., et al. 2016, MNRAS, 463, 1486
Palmese, A., Hartley, W., Tarsitano, F., et al. 2017, ApJL, 849, L34
Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2018, ArXiv e-prints, arXiv:1807.06209
Pozzetti, L., Bolzonella, M., Zucca, E., et al. 2010, A&A, 523, A13
Riess, A. G., Macri, L. M., Hoffmann, S. L., et al. 2016, ApJ, 826, 56
Riess, A. G., Casertano, S., Yuan, W., et al. 2018, ApJ, 861, 126
Sadeh, I., Abdalla, F. B., & Lahav, O. 2016, PASP, 128, 104502
Schutz, B. F. 1986, Nature, 323, 310
Shectman, S. A., Landy, S. D., Oemler, A., et al. 1996, ApJ, 470, 172
Singer, L. P., Chen, H.-Y., Holz, D. E., et al. 2016, ApJS, 226, 10
Soares-Santos, M., Kessler, R., Berger, E., et al. 2016, ApJL, 823, L33
Soares-Santos, M., Holz, D. E., Annis, J., et al. 2017, ArXiv e-prints, arXiv:1710.05459 [astro-ph.HE]
Tanvir, N. R., Levan, A. J., González-Fernández, C., et al. 2017, ApJL, 848, L27
The Dark Energy Survey Collaboration. 2005, preprint (arXiv:astro-ph/0510346), astro-ph/0510346
Valenti, S., David, Sand, J., et al. 2017, ApJL, 848, L24
Vitale, S., & Chen, H.-Y. 2018, Physical Review Letters, 121, 021303
Wechsler, R. H., & Tinker, J. L. 2018, ARA&A, 56, 435
Weigel, A. K., Schawinski, K., & Bruderer, C. 2016, MNRAS, 459, 2150