A Dark Energy Camera Search for Missing Supergiants in the Lmc After the Advanced Ligo Gravitational-Wave Event Gw150914

Draft version February 19, 2016
Preprint typeset using LaTeX style emulateapj v. 5/2/11

A DARK ENERGY CAMERA SEARCH FOR MISSING SUPERGIANTS IN THE LMC AFTER THE ADVANCED LIGO GRAVITATIONAL WAVE EVENT GW150914

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Draft version February 19, 2016

ABSTRACT

The collapse of the core of a star is expected to produce gravitational radiation. While this process will usually produce a luminous supernova, the optical signatue could be subluminous and a direct collapse to a black hole, with the star just disappearing, is possible. The gravitational wave event GW150914 reported by the LIGO Virgo Collaboration (LVC) on 2015 September 16, was detected by a burst analysis and whose high probability spatial localization included the Large Magellanic Cloud. Shortly after the announcement of the event, we used the Dark Energy Camera to observe 102 deg^2 of the localization area, including a 38 deg^2 area centered on the LMC. Using a catalog of 152 LMC luminous red supergiants, candidates to undergo a core collapse without a visible supernova, we find that the positions of 144 of these are inside our images, and that all are detected — none have disappeared. There are other classes of candidates: we searched existing catalogs of red supergiants, yellow supergiants, Wolf-Rayet stars, and luminous blue variable stars, recovering all that were inside the imaging area. Based on our observations, we conclude that it is unlikely that GW150914 was caused by the core collapse of a supergiant in the LMC, consistent with the LIGO Collaboration analyses of the gravitational waveform as best described by a high mass binary black hole merger. We discuss how to generalize this search for future very nearby core collapse candidates.

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1. INTRODUCTION

On 2015 September 14 the Advanced LIGO interferometer network detected a high significance candidate gravitational wave (GW) event (designated GW150914; Abbott et al. 2016) and two days later provided spatial location information in the form of probability sky maps (LIGO Virgo Collaboration 2015a). The analysis that produced the trigger was sensitive to bursts, suggested a high source mass, and yielded localization contours that enclosed the Large Magellanic Cloud (LMC) at high confidence. Burst-like gravitational wave signals could originate from the core-collapse of massive stars, and there is evidence that $\sim 20\%$ of core-collapse events fail to produce a luminous supernova (SN); see for example, (Kochanek 2015).

Motivated thus, we initiated observations of the LMC with DECam on 2015 September 18 in an effort to search for a potential failed SN through the disappearance of a massive star. We select 152 high luminosity supergiants that are candidates for becoming failed supernova, locate and verify that the 144 inside our DECam data are still present after the LIGO event, making it unlikely that GW150914 originated from a failed SN in the LMC. In January 2016 an improved analysis of the LIGO data for GW150914 changed both the spatial localization (moving it away from the LMC) and the source model (now shown to be consistent with a binary black hole merger by Abbott et al. (2016)); this GW source did not originate from the death of a massive star in the LMC. Our analysis, however, represents an important template for the follow up of future burst-like GW events coincident with very nearby galaxies.

2. LIGO EVENT GW150914

On 2015 September 14 at 09:50:45 UT the Advanced LIGO interferometers at Hanford and Livingston recorded burst candidate event GW150914 during Engineering Run 8. This event was triggered by the cWB (coherent WaveBurst) unmodeled burst analysis during real-time data processing. On 2015 September 16, the LIGO Virgo Collaboration (LVC) provided two all-sky localization probability maps for the event, generated from the cWB and LALInferenceBurst (LIB) analyses (LIGO Virgo Collaboration 2015a). The cWB online trigger analysis makes minimal assumptions about signal shape by searching for coherent power across the LIGO network (Klimenko et al. 2008). The LIB analysis is a version of the the LALInference analysis (Veitch et al. 2015) Bayesian forward-modeling-based follow up tool that uses a Sine-Gaussian signal morphology instead of models of compact binary mergers; for information on both algorithms see Essick et al. (2015). No LALInference detection using a compact binary mergers model was announced. Stellar core collapses cause significant signals in the cWB analysis (but not in LALInference) though the core collapse would have to be nearby (Fryer & New 2011; Gossan et al. 2015).

The LVC released localization sky maps of the GW150914 event to make possible electromagnetic follow-up of the GW150914 event (Abbott et al. 2016a; see also Aasi et al. 2014). The maps provided spatial localizations of 50% and 90% confidence regions encompassing about 200 and 750 deg^2, respectively. The area enclosing 50% of the total probability passed through the center of the Large Magellanic Cloud, a 0.2 $L^\star$ galaxy at a distance of 50 kpc (Walker 2012; de Grijs et al. 2014): see the dotted lines showing the enclosed cWB sky map probability in Figure 1. The high probability ridge line passed over 30 Doradus and the proto-globular cluster R136.

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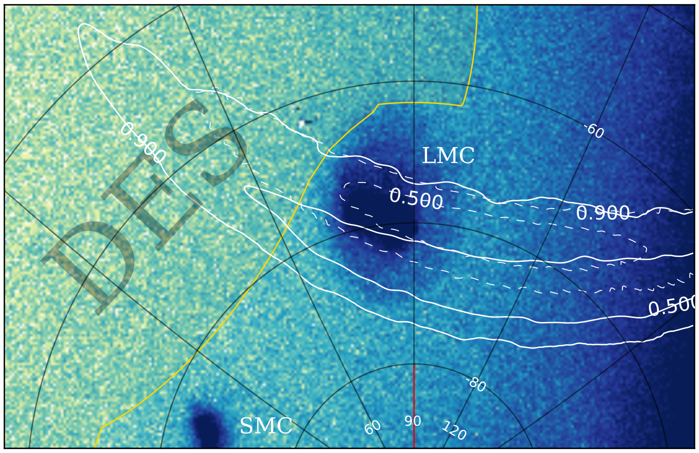

FIG. 1.— A map of the logarithm of 2MASS J-band star counts around the LMC with the LIGO localization contours shown in white. The contour labels indicate the fraction of the LIGO localization probability enclosed. The dotted contours are for the initial (Sept 2015) `skyprobcc_cWB_complete` map, while the solid contours are for the final (Jan 2016) `LALInference_skymap`. There is an island of significant probability in the Northern hemisphere in the `skyprobcc_cWB_complete`, not present in the `LALInference_skymap`, so the dotted contours do not show the complete 50% or 90% areas. The data are shown on an equal-area McBryde-Thomas flat-polar quartic projection, as is Figure 3.

We recently began an observational program using the wide-field Dark Energy Camera (DECam; Flaugher et al. 2015) on the Blanco 4-m telescope at Cerro Tololo Inter-American Observatory to search for optical counterparts to GW triggers. Our wide-field search for counterparts to GW150914 is described in the companion paper Soares-Santos et al. (2016); an overview of the program is in DES Collaboration et al. (2016). We additionally designed a specific set of observations to search for failed SNe in the LMC, using 5-sec i and z band observations covering 38 deg^2 centered on the LMC on 2015 September 18 and 27, in seeing of 1.1–1.3″.

Subsequently, on 2015 October 3, the LVC revised its analysis: the data were most consistent with a binary black hole merger (LIGO Virgo Collaboration 2015b). On 2016 January 13, the LVC provided new skymaps, the most accurate and authoritative of which was the LALInference analysis (LIGO Virgo Collaboration 2016). The new contour enclosing 50% of the total probability shifted southward of the LMC, although the LMC is still inside the 90% contour.

3. CORE-COLLAPSE SIGNATURES

A normal core-collapse SN in the LMC is a remarkably obvious event— SN1987A was found by eye as a new 5th magnitude object 24 hours after the core collapse. Core-collapse SNe have peak absolute magnitudes of $\sim$ -21 to $\sim$ -14, which at the distance of the LMC corresponds to apparent magnitudes of -2.5 to 4.5.

However, it has been argued that up to ∼20% of core-collapse SNe are not optically luminous (Kochanek et al. 2008), and there is recent evidence that luminous supergiants specifically are prone to be failed SNe. Two candidates are currently known: the Large Binocular Telescope survey (Gerke et al. 2015) found a $18-25$ M$_\odot$ star missing, and a Hubble Space Telescope archival survey (Reynolds et al. 2015), found a $25-30$ M$_\odot$ star missing.

TABLE 1
PREDICTED OPTICAL SIGNATURES OF A FAILED SUPERNOVA IN THE LMC

	i	$(g-i)$	K	$(J-K)$	timescale
supergiants	8.0-11.5	1.5-2.3	6.0-8.0	0.9-1.4	$\gg$ 1 year
shock break out[a]	$\sim$ 5.1-7.6	$\sim$ 0.2	$\sim$ 4.6-7.1	$\sim$ 0.07	$\sim$ 1 week
Nadezhin[b]	$\sim$ 6.7-9.3	$\gtrsim$ 1.5	$\sim$ 4.6-7.1	$\gtrsim$ 0.9	$\sim$ 1 year
disappear	—	—	—	—	

[a] Assuming a blackbody spectrum
[b] Assuming a supergiant-like spectrum

These objects are sufficiently nearby that a SN associated with the event would have been detected, by the Large Binocular Telescope survey itself in that case. In addition, the population of known progenitors to Type IIP SNe lacks red supergiants above $\gtrsim 17$ M$_\odot$ (Smartt et al. 2009), suggesting that that more massive red supergiants end in a failed SN. This line of argument reproduces the current black hole mass function (Kochanek 2015); similarly the purely theoretical study of core collapses by Sukhbold et al. (2015) reproduces both the neutron star and black hole mass functions. Pre-collapse, red supergiants are very luminous: Smartt 2015 shows that the missing SN progenitors have $\gtrsim 10^{5.1}$ L$_\odot$.

4. OPTICAL SIGNATURES OF A FAILED SUPERNOVA

There are three viable signatures for a failed supernova: (1) the star might simply collapse to a black hole; (2) the unbound outer atmosphere of the star may expand and cool, gaining in luminosity as it expands; and (3) there might be a shock from the creation of the neutrinosphere that propagates through the atmosphere to the outer layer, causing a shock breakout flash.

We briefly discuss these potential signatures here. The hydrogen atmospheres of these supergiants are so marginally bound to the star that the creation and free streaming of the neutrinosphere during core-collapse may remove enough mass to unbind the atmosphere (Nadezhin 1980). If the shock from the neutrinosphere creation is energetic enough it will cause the unbound atmosphere to expand, necessarily cooling and gaining in luminosity as it expands. Lovegrove & Woosley (2013) simulated this process using realistic models of 15 and 25 M$_\odot$ red supergiants, finding that the transient is long ($\sim$ year, 10^3 K, 10^6 L$_\odot$), and that the unbinding of the atmosphere was more likely in the 15 M$_\odot$ than in the 25 M$_\odot$ star. The shock breakout signature was studied by Piro (2013) who found that it would present a short, hot transient ($\sim$ week, 10^4K, $10^{6.5}-10^{7.5}$ L$_\odot$). At the distance of the LMC this would be remarkably bright: $i \approx$ 5.1 - 7.6 (see Table 1). The existence of a shock breakout does, however, depend on sufficient energy in the shock, and this is unclear.

The Nadezhin brightening of signature 2 lasts hundreds of days, with a lower bound in luminosity of the pre-collapse luminosity of the star, but possibly rising to $L \sim 10^{5.5}-10^{6.5}$ L$_\odot$, presumably with an effective temperature starting close to the pre-collapse star and cooling thereafter. At the distance of the LMC, this is $i \sim$ 6.7 - 9.3. These objects would look much like the supergiant has brightened by a couple of magnitudes.

5. LMC RED SUPERGIANTS

Our search focuses on high luminosity red supergiants in the LMC; we will consider other candidate failed supernova progenitors in the next section. The two best studies of large numbers of LMC supergiants are by Neugent et al. (2012) and González-Fernández et al. (2015). Both combine 2MASS point source data (Skrutskie et al. 2006) with astrometric catalogs (UCAC-3 or USNO-B1; Monet et al. 2003), using proper motions to reject Milky Way (MW) stars, and then using infrared colors and K magnitudes to select the supergiants. Both studies performed spectroscopy for their final identifications.[1].

The distinction between red supergiants and yellow supergiants, for our purpose at $(J-K) = 0.9$ mag, is useful here as it brings out the nature of the contamination in the catalogs. As one moves from yellow to red supergiants, the contamination from Milky Way dwarfs and giants decreases substantially. Neugent et al. (2012) found 22% purity for their yellow supergiant catalog and a 97% purity for their red supergiant catalog. González-Fernández et al. (2015), performing a more detailed spectral analysis, measured a 53% purity for the red supergiants, largely contaminated by carbon stars and MW giants. At $M_K \lesssim -9.5$ mag ($K \sim 9$ mag), the purity was $\gtrsim 95\%$, consistent with Neugent et al. (2012).

The aforementioned studies did not cover the entire LMC: Neugent et al. (2012) covered ~ 22 deg^2 of the LMC, about 60% of the relevant area, while González-Fernández et al. (2015) covered a ~ 3 deg^2 field at the densest part of the LMC. In the region of overlap, the latter analysis recovered about 3 times as many red supergiants as the former analysis. Both studies are also likely incomplete in regions of very high stellar density (e.g., R136). Reddening is not a factor for the J and K bands, except for progenitors obscured by molecular clouds. Otherwise, the highest extinction 3 arcmin^2 field in the LMC has $E(B-V) \approx 2.0$ mag, and only 0.26 deg^2 in the 200 deg^2 around the LMC has $E(B-V) \gtrsim 1$ mag; these correspond to only 0.6 and 0.3 mag of extinction in the K-band, respectively.

5.1. *Constructing a LMC Red Supergiant Catalog*

We construct a catalog of luminous red supergiants in the LMC following a similar analysis to that of González-Fernández et al. (2015). We begin with the 2MASS point source catalog within 3.5° from $\alpha, \delta = 79.5, -68.8$, and apply the following selection criteria:

1. $K > 9$ mag, $(J-K) > 0.9$ mag,
2. the pseudo-color cut of $0.1 \geq q \geq 0.4$, where $q \equiv (J-H) - 1.8(H-K)$,
3. $10^5 L_\odot < L < 10^6 L_\odot$,
4. reject stars which have proper motions of $\sqrt{\mu_{ra}^2 + \mu_{dec}^2} > 6$ mas yr^{-1} with $\sqrt{\mu_{ra}^2 + \mu_{dec}^2} > 3\sqrt{\sigma_{mu\_ra}^2 + \sigma_{mu\_dec}^2}$ in the NOMAD catalog(Zacharias et al. 2004).

The bolometric luminosity cut calculation follows Neugent et al. (2012), namely, the $(J-K)$ color is used to estimate the effective temperature, and the effective temperature is in turn used to calculate the bolometric correction.

[1] We will drop the proper subscript s from the 2MASS filter notation K_s thoughout this paper for notational simplicity.

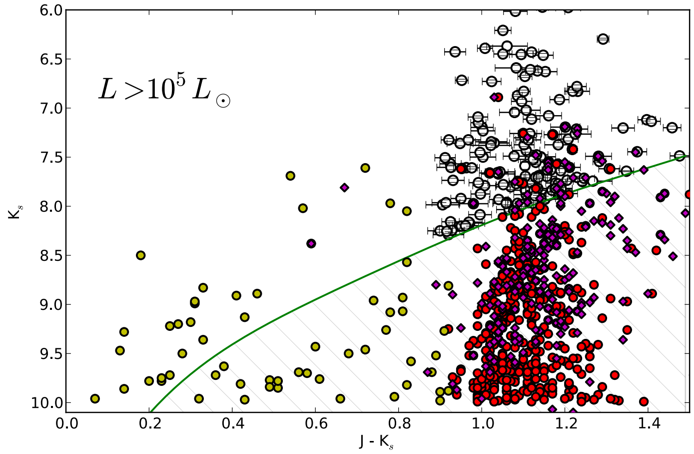

Fig. 2.— 2MASS $J-K$ vs. K diagram for the Neugent et al. (2012) yellow supergiants (yellow circles) and red supergiants (red circles), González-Fernández et al. (2015) red supergiants (purple diamonds), and the 152 supergiant candidates found here (white circles). For our candidates, the uncertainties in both $(J-K)$ and K are plotted; for K they are smaller than the symbols. The line shows the dividing line for 10^5 L$_\odot$.

This process yields 152 red supergiant candidates. This is smaller than the number of supergiants in either the catalogs of Neugent et al. (2012) or González-Fernández et al. (2015) as these studies go to much lower luminosities than we are concerned with here. This is evident from Figure 2. The highest luminosity candidates are likely all MW stars; the Neugent et al data show that 90% of their candidates at $K < 7$ were MW stars. As we aim for completeness we find this acceptable. In Figure 3 the candidate supergiants are shown overlaid on a stellar density map of the LMC.

6. OTHER FAILED SUPERNOVA PROGENITORS

The red supergiant catalog has the advantage of being well defined and motivated by observational evidence, but it does have uncertainties. These include the calculation of the 10^5 L$_\odot$ limit and model uncertainties when mapping the mass to luminosity.

There are more profound uncertainties in the theory. Smartt's analysis does not imply that only high luminosity red supergiants could fail to explode. The current theoretical models of core collapsing stars either have islands of core-collapse to black holes at $\sim$20M$_\odot$ and $\sim$40M$_\odot$, (O'Connor & Ott 2011; Pejcha & Thompson 2015) or have most stars above $\sim$20M$_\odot$ core collapsing to black holes (Sukhbold et al. 2015, with the interesting exception of an island of explosion at $\approx$26M$_\odot$), though examples of core collapse to black holes occur throughout the range 15M$_\odot$–120M$_\odot$ in the latter study.[2] The lack of explosion depends on many parameters, notably metallicity (Pejcha & Thompson 2015) as the LMC averages half solar metallicity. In theory, then, a direct collapse to black holes may occur in many observational classes of massive stars: yellow supergiants, blue supergiants, luminous blue variable stars (LBVs), Wolf-Rayet (WR)

[2] Throughout this paper, masses quoted are zero age main sequence masses.

stars, sgB[e], and more (see e.g., Kashiyama & Quataert 2015). Fortunately, these classes of stars have been extensively studied in the LMC.

7. THE SEARCH FOR MISSING LMC SUPERGIANTS IN THE DECAM DATA

The area covered in our DECam LMC campaign is shown in Figure 3. The DECam images were analyzed with the DES first cut reductions (Sevilla et al. 2011; Mohr et al. 2012; Desai et al. 2012; Gruendl et al. 2016), which include producing astrometrically calibrated reduced images. We visually inspected the locations of the red supergiants in our catalog. The supergiants were mostly saturated in the images, so we could not investigate the brightening discussed in the previous section. Our imaging and subsequent visual inspection covered 144 supergiants, 95% of the original catalog, and all of these stars were recovered. We argue that this is the level of confidence excluding a luminous red supergiant undergoing a failed SN in the LMC at the time of GW150914.

The catalogs of other possible failed SN progenitors are present in the literature. We can check for the disappearence of less luminous red supergiants and yellow supergiants using the catalog of Neugent et al. (2012): 813 of 846 (96%) are in the imaged area and all of these are present in the images. We can check for the disapperance of WR stars using the catalog of Hainich et al. (2014), extensive but known not to be complete (Massey et al. 2015): 105 of 108 (97%) are in our imaged area and we can confirm that 102 (97%) are present. The three that we cannot confirm are in the very compact cluster R136, and are unresolved in our data. We can check for the disappearence of LBVs using the stars from Smith & Tombleson (2015), which are all the confirmed, not highly reddened, LBVs in the LMC: we recover 16 of 16 (100%) in the DECam imaging. We could have checked blue supergiants, including the interesting subclass sgB[e], using the catalog in Bonanos et al. (2009). As these catalogs are incomplete, it is difficult to state how confident we are that these kinds of progenitors did not undergo a failed SN in the LMV at the time of GW150914, but given the uncertainty in theoretical predictions for which observational classes of stars undergo failed SN, a reasonable compromise is to check the known catalogs of potential progenitors.

8. DISCUSSION AND CONCLUSIONS

GW150914 was first detected by a LIGO analysis sensitive to a burst of GW and the high probability localization contours enclosed the LMC. Burst-like gravitational wave signals could originate from the core-collapse of massive stars, perhaps ∼20% of which fail to explode as luminous SNe. This motivated us to search for a failed SN in the LMC. We constructed a catalog of 152 high luminosity LMC supergiants, of which 144 were observed in our DECam imaging; all of these stars are still present after the LIGO event. It is unlikely that the then candidate event GW150914 originated from a failed SN in the LMC. The subsequent publication of the GW150914 analysis shows that the GW event is consistent with a merging massive binary black hole model at $z \approx 0.09$ (Abbott et al. 2016).

The spatial uncertainty present in GW150914 will be a feature of all non-electromagnetic core-collapse triggers.

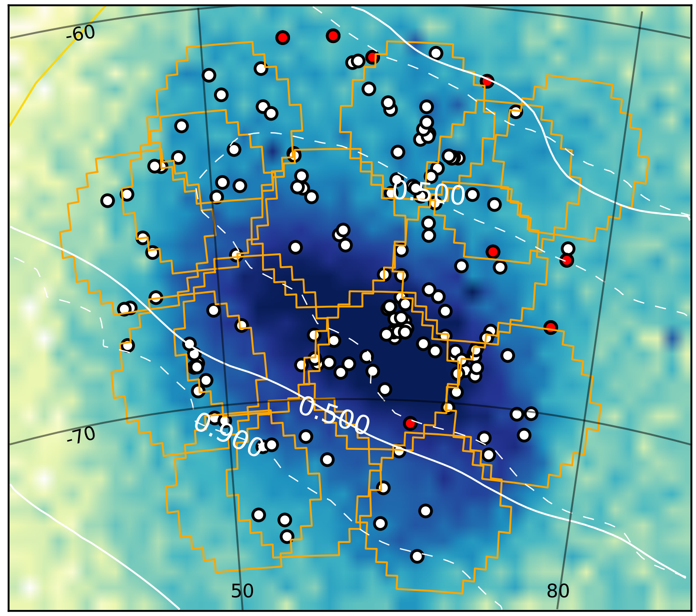

FIG. 3.— A map of the logarithm of 2MASS J-band star counts around the LMC with the LIGO localization contours shown in white. The DECam i-band images are shown as orange camera outlines; some of the z-band images are offset from these. The white points are the luminous red supergiant catalog developed in this paper, with those marked red not having a visual inspection. Six are outside our imaging area. The four remaining fell into chip gaps and/or on bad CCDs.

Most models of a core collapse, whether the final stage is a neutron star or a black hole, include the formation of a neutrinosphere (see Scholberg 2012, and references therein). Thirty years ago the LMC core-collapse that produced SN1987A was detected by two neutrino detectors, Kamiokande and IMB (Hirata et al. 1987; Bionta et al. 1987). There are seven neutrino detectors contributing to the SNEWS supernova early warning system (Vigorito et al. 2011), and the Super-Kamiokande neutrino detectors and the IceCube neutrino telescope should detect an LMC core-collapse unassisted (Ikeda et al. 2007; Abbasi et al. 2011). Notably for this paper, the MeV neutrino burst mode of IceCube did not trigger for ±500 seconds around the time of GW150914 (Abbott et al. 2016b) which it would have for a core-collapse in the LMC. The spatial localization of the neutrino detectors is several degrees (Adams et al. 2013)—that would be good enough to say the event likely occured in the LMC, but not where in the LMC it is located.

The use of the luminous red supergiant catalog makes it possible to perform a specific search without prior template imaging, and therefore without difference imaging. A sensible generalization of this technique is to perform very shallow g and i band imaging of very nearby galaxies to prepare template images for difference imaging; g band added to catch the very blue signature of a breakout shock. Difference imaging in the crowded regions of the LMC will likely be challenging, but would extend the discovery space to other possible low luminosity core collapse progenitors, of which there are many. The durations between local group core collapses are measured in decades and we should be prepared to learn as much as possible when they do occur.

Funding for the DES Projects has been provided by the U.S. Department of Energy, the U.S. National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute of Cosmological Physics at the University of Chicago, the Center for Cosmology and Astro-Particle Physics at the Ohio State University, the Mitchell Institute for Fundamental Physics and Astronomy at Texas A&M University, Financiadora de Estudos e Projetos, Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Conselho Nacional de Desenvolvimento Científico e Tecnológico and the Ministério da Ciência, Tecnologia e Inovação, the Deutsche Forschungsgemeinschaft and the Collaborating Institutions in the Dark Energy Survey.

The Collaborating Institutions are Argonne National Laboratory, the University of California at Santa Cruz, the University of Cambridge, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Madrid, the University of Chicago, University College London, the DES-Brazil Consortium, the University of Edinburgh, the Eidgenössische Technische Hochschule (ETH) Zürich, Fermi National Accelerator Laboratory, the University of Illinois at Urbana-Champaign, the Institut de Ciències de l'Espai (IEEC/CSIC), the Institut de Física d'Altes Energies, Lawrence Berkeley National Laboratory, the Ludwig-Maximilians Universität München and the associated Excellence Cluster Universe, the University of Michigan, the National Optical Astronomy Observatory, the University of Nottingham, The Ohio State University, the University of Pennsylvania, the University of Portsmouth, SLAC National Accelerator Laboratory, Stanford University, the University of Sussex, and Texas A&M University.

The DES data management system is supported by the National Science Foundation under Grant Number AST-1138766. The DES participants from Spanish institutions are partially supported by MINECO under grants AYA2012-39559, ESP2013-48274, FPA2013-47986, and Centro de Excelencia Severo Ochoa SEV-2012-0234. Research leading to these results has received funding from the European Research Council under the European Unions Seventh Framework Programme (FP7/2007-2013) including ERC grant agreements 240672, 291329, and 306478.

R.J.F. gratefully acknowledges support from NSF grant AST-1518052 and the Alfred P. Sloan Foundation. FS acknowledges financial support provided by So Paulo Research Foundation (FAPESP) under grants 2015/12338-1.

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