Host Galaxies Catalog Used in LIGO Searches for Compact Binary Coalescence Events

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ABSTRACT

Coalescence events of binary systems with two compact objects are among the most promising gravitational wave sources for LIGO. Current analyses of LIGO data constrain the rates of these events given an astrophysical population model for the sources considered. We describe how the known distribution of galaxies within 100 Mpc and the asymptotic blue light density at $z = 0.1$ is used in deriving event rate limits from LIGO science data runs.

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1. INTRODUCTION

Double compact binary coalescence (CBC) events, such as neutron star or black hole mergers, are primary gravitational-wave sources for ground-based interferometers such as LIGO. LIGO's third (S3) and fourth (S4) science runs have reached significant extragalactic distances into the nearby Universe. Especially for massive compact binaries whose components are black holes, the range extended beyond the Virgo Cluster. To interpret the searches for signals from compact binary coalescence in the LIGO data sets, it is necessary to use information about putative binary compact object populations in the known nearby galaxies, as well as how the population scales at larger distances. We present a nearby

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galaxy catalog representing the distribution of such extragalactic populations, as motivated by current information about the host galaxies.

The formation and merger rates of binary compact objects are typically associated with the formation of massive stars, and hence proportional to the blue luminosity of host galaxies corrected for absorption effects (Phinney 1991). We note that the relationship between rate and blue luminosity of galaxies is well motivated assuming that binary compact objects are formed in environments of roughly continuous star formation, similar to the Milky Way. Also, LIGO's sensitivity to compact binary coalescence signals depends on the distance and sky position of the coalescence event. Therefore, the distribution of known nearby galaxies in blue luminosity and in space is the minimum information needed to properly interpret searches of the LIGO data sets.

It is possible that compact binary populations that are not related to regions of continuous star formation may exist in the Universe. For example, the contribution of elliptical galaxies to the merger rates is potentially significant beyond the Virgo cluster (de Freitas Pacheco et al. 2006), whereas their blue luminosity is not representative of their putative compact binary populations. A mass, metallicity and morphology dependent star formation history may also be needed to account for these populations. Nevertheless, the current discussion is limited to the blue-light luminosity as a tracer of the compact binary population.

We have used mostly publicly available astronomical catalogs of galaxies to compile a catalog used in the S3/S4/S5 LIGO data set analyses. We discuss the methodology used to compile this galaxy catalog and briefly describe how this information feeds into LIGO rate estimates. In §2, we describe all the elements involved in compiling the galaxy catalog and assessing the relevant errors and uncertainties. In §3, we derive a correction factor to account for incompleteness in the catalog guided also by the blue-light volume density estimated from the Sloan Digital Sky Survey and earlier surveys. In §4, we discuss how the corrected catalog and resulting blue light distribution as a function of distance is used to bound the rate of compact binary coalescence using data from the recent LIGO science runs. If the maximum distance to which a search could detect a compact binary coalescence is known, then the expected number of detectable events can be derived. Some concluding remarks are made in §5.

2. COMPILATION OF GALAXY CATALOG

We have compiled a catalog[1], the *compact binary coalescence galaxy* catalog or CBCG-catalog, of nearby galaxies which could host compact binary systems. For each galaxy out to 100 Mpc, the catalog provides the equatorial coordinates, distance to the galaxy, and the blue luminosity corrected for absorption. Estimates of the systematic errors on distance and luminosity are also provided.

The CBCG-catalog is compiled from information provided in the following four astronomical catalogs: (i) the Hubble Space Telescope (HST) key project catalog used to measure the Hubble constant (Freedman et al. 2001), (ii) Mateo's dwarf galaxies of the local group catalog (Mateo 1998), (iii) the HyperLeda (LEDA) database of galaxies (Paturel et al. 2003), and (iv) an updated version of the Tully Nearby Galaxy Catalog (generously provided by Brent Tully, 2006 private communication).

When combining these catalogs, distances and luminosities reported in the HST, Mateo and Tully catalogs were generally adopted over those in the LEDA catalog. Nevertheless, LEDA served as the baseline for comparisons in the range 10-100 Mpc since it is the most complete.

2.1. DISTANCES

One of the primary objectives of the HST key project was to discover Cepheid variables (stars which have periodic variations in brightness) in several nearby spiral galaxies and measure their distances accurately using the period-luminosity relation for Cepheids. Cepheid distance determination to nearby galaxies is one of the most important and accurate primary distance indicators. The distance information from the HST key project is considered to be the most accurate in the CBCG-catalog; there are 30 galaxies in our catalog for which we adopt distances from the HST key project.

Mateo's review (Mateo 1998) of properties of the dwarf galaxies in the Local Group provides distance and luminosity information for each galaxy considered. Since the parameters in this catalog were derived from focused studies on each individual galaxy, we consider it the most accurate next to the HST measurements for nearby galaxies. Moreover it has reasonably comprehensive information on the Local Group's dwarf galaxies; there are 18 sources

[1] http://www.lsc-group.phys.uwm.edu/cgi-bin/cvs/viewcvs.cgi/lalapps/src/inspiral/inspsrcs100Mpc.errors?cvsroot=lscsoft

in the CBCG-catalog which adopt distances (and luminosities) from Mateo's compilation.

It becomes increasingly difficult to use primary distance estimators like Cepheid stars in more distant galaxies. Therefore secondary distance methods are used to measure larger distances. Tully's catalog has up to three types of distances for each source: (i) *Quality distance* ($D_{\rm Q}$) is based on either Cepheid measurements, surface brightness fluctuations, or the tip of the red giant branch. There are 409 galaxies with such a distance in the CBCG-catalog. (ii) *HI luminosity-line-width* distances ($D_{\rm HI}$) are obtained from the Tully-Fisher relation, where the maximum rotational velocity of a galaxy (measured by the Doppler broadening of the 21-cm radio emission line of neutral hydrogen) is correlated with the luminosity (in B, R, I and H bands) to find the distances. There are 553 galaxies in the catalog with such a distance. (iii) *Input distance* ($D_{\rm I}$) is derived from an evolved dynamical mass model that translates galaxy radial velocities into distances. This model is an update of the least action model described by Shaya et al. (1995) and takes into account the deviations from a perfect Hubble flow due to a spherically symmetric distribution of mass centered on the Virgo Cluster. All galaxies have a calculated input distance. Whenever available, $D_{\rm Q}$ distances are the most preferred due to their smaller uncertainties, then the $D_{\rm HI}$ followed by $D_{\rm I}$.

The remaining galaxies come from LEDA which does not provide distances explicitly, but instead provides measured radial velocities corrected for in-fall of the Local Group towards the Virgo cluster ($v_{\rm vir}$). We obtain the LEDA distance ($D_{\rm L}$) using Hubble's law with the Hubble constant $H_0 = 73\,{\rm km\,s^{-1}\,Mpc^{-1}}$ reported by Spergel et al. (2006). Although corrections to the recessional velocity were made, this method of calculating distances is still highly uncertain. Hence, we use Hubble's law to evaluate the distances only to the galaxies for which $v_{\rm vir} \geq 500$ km/s (7Mpc) and peculiar velocities are expected to be more of a perturbation.

The error in a distance depends strongly on the method used to measure that distance. The HST sources, though a small contribution to the galaxy catalog, have the smallest errors ($< 10\%$) (Freedman et al. 2001). The three different distance methods in Tully's catalog have different errors. $D_{\rm Q}$ also has a low error (10%) followed by the $D_{\rm HI}$ (20%). To obtain an estimate for the errors of $D_{\rm I}$, we compare them with $D_{\rm Q}$ for the set of galaxies that have both types of distance estimates. The best fit Gaussian (see Fig. 1) to the fractional errors has a width of $\simeq 24\%$ which when summed in quadrature with $D_{\rm Q}$ error gives, conservatively, $\simeq 30\%$ distance error associated with $D_{\rm I}$.

Because errors in $v_{\rm vir}$ are not given in LEDA, we follow a similar procedure to find LEDA distance errors, $D_{\rm L}$. We compare the calculated $D_{\rm L}$ with $D_{\rm Q}$ for galaxies in both catalogs to obtain uncertainty estimates in $D_{\rm L}$. The plot in Fig. 2 shows the best fit Gaussian to the fractional errors with a width of $\simeq 27\%$ which, added in quadrature with $D_{\rm Q}$ distance errors, gives a total distance error $\simeq 30\%$.[2]

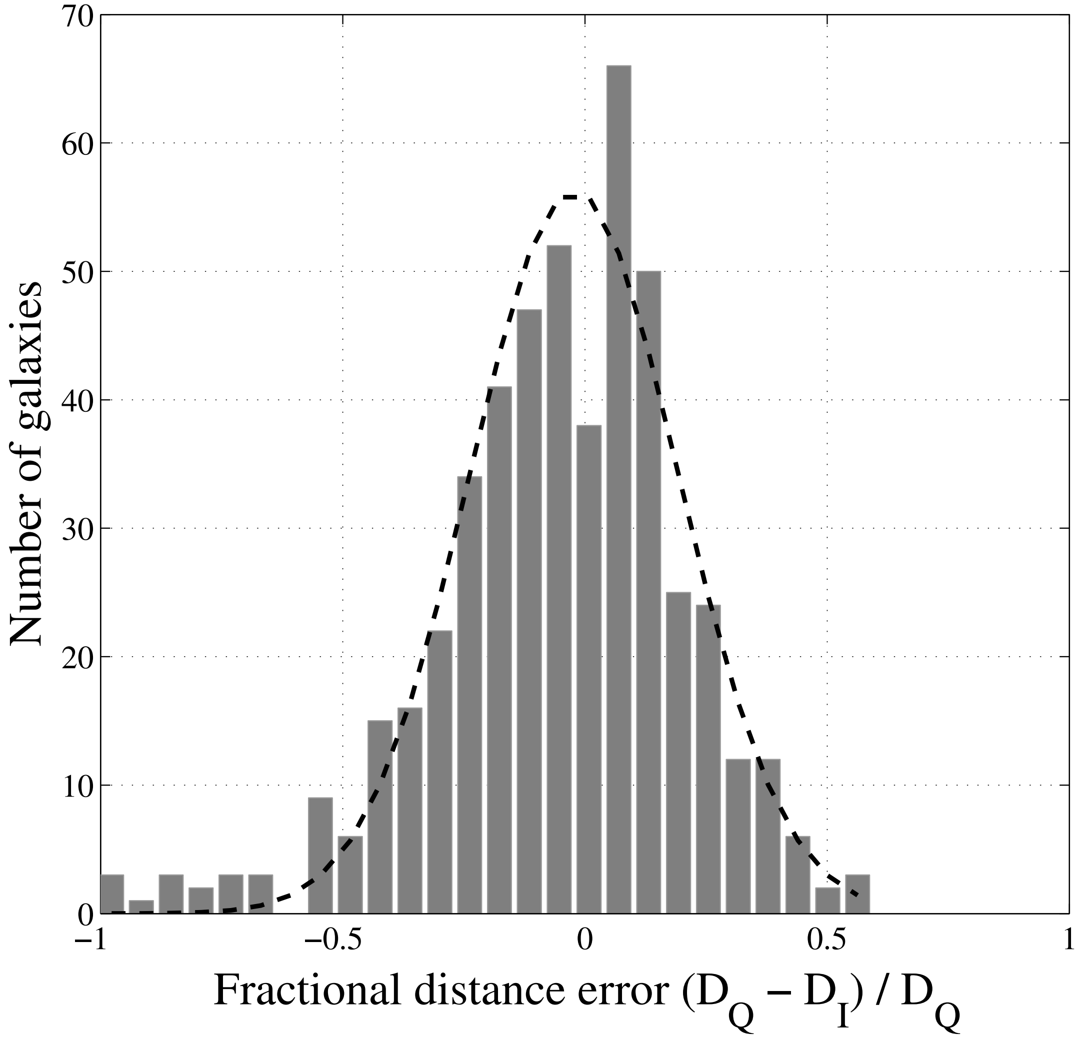

Fig. 1.— In order to obtain reasonable estimates for Tully's input distances we compare galaxies that have values for both. The Tully quality distance has roughly a 10% error. The best fit Gaussian for the fractional errors has a width of 24%. Adding these uncertainties in quadrature gives a conservative error of 30% for Tully input distances.

[2]For searches of the S3 and S4 LIGO data Abbott et al. (2007), with smaller ranges a more conservative uncertainty of 40% was used for LEDA distances.

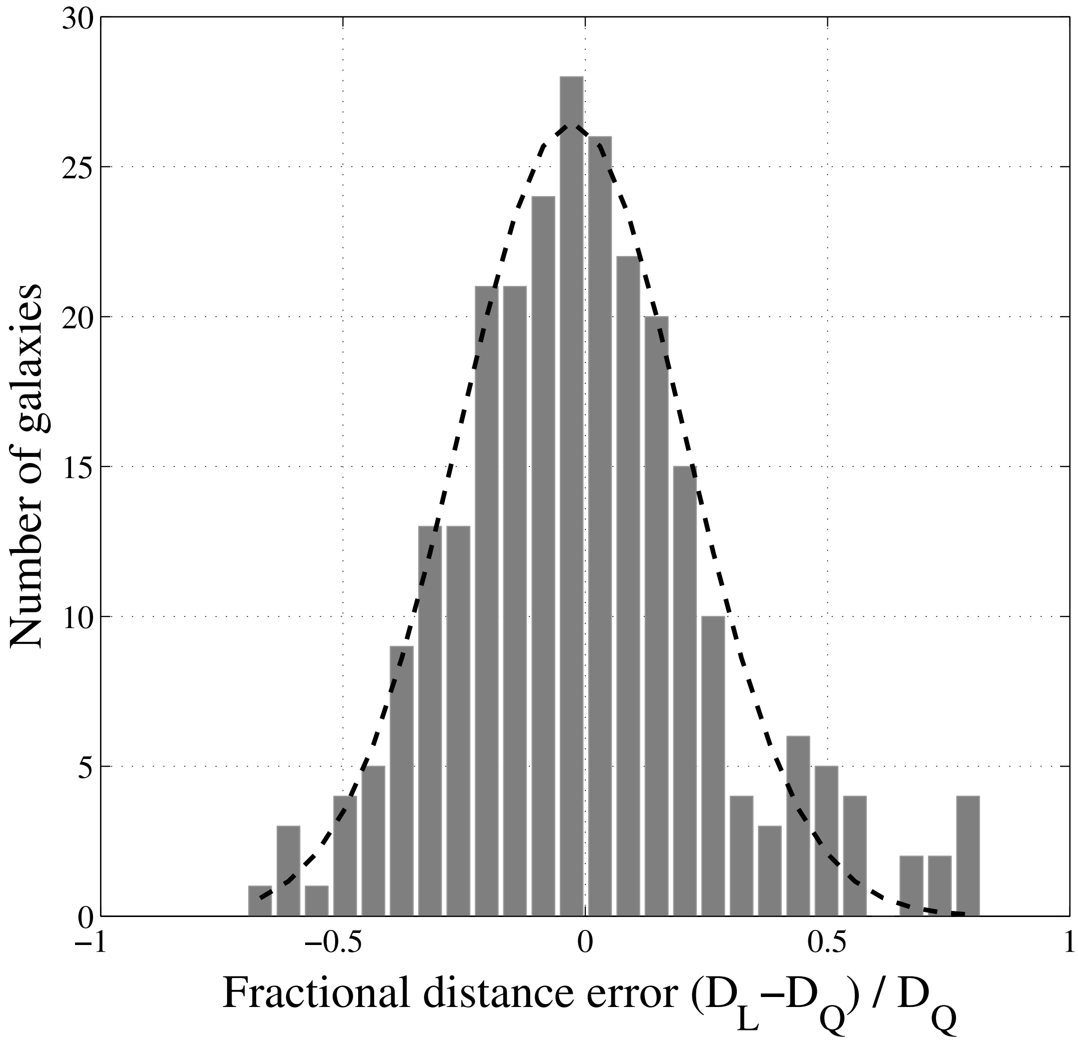

Fig. 2.— Fractional error analysis as in Fig. 1 for LEDA distances. By comparing the fractional error between LEDA distances and Tully we obtain a $\sim 30\%$ distance error for LEDA.

2.2. BLUE LUMINOSITIES

The distribution of binary compact objects in the nearby universe is expected to follow the star formation in the universe and a measure of star formation is the blue luminosity of galaxies corrected for dust extinction and reddening (Phinney 1991). Hence, for each galaxy, we calculate the blue luminosity $L_{\rm B}$ from the absolute blue magnitude of the galaxy $M_{\rm B}$ (corrected for internal and Galactic extinctions). For convenience, blue luminosity is provided in units of $L_{10} \equiv 10^{10} L_{\rm B,\odot}$, where $L_{\rm B,\odot} = 2.16\times10^{33}$ ergs/s is the blue solar luminosity derived from the blue solar magnitude $M_{\rm B,\odot} = 5.48$ (Binney & Tremaine 2000). We do not consider galaxies with luminosities less than $10^{-3} L_{10}$ because they do not contribute significantly to the total luminosity – see §3.

The Mateo, Tully and LEDA catalogs provide information on absolute B-magnitudes corrected for extinction. The galaxies in the HST key project catalog have only distance information, so for those we extract the corresponding apparent magnitude values ($m_{\rm B}$, corrected for internal and Galactic extinction) in the B-band from the Tully catalog to find $M_{\rm B}$. Table 1 summarizes relevant properties of each of these catalogs and the fraction of the total luminosity within 100 Mpc that each contributes.

Table 1: Summary information about the four astronomical catalogs used to develop the CBCG-catalog. We report the number of galaxies for which the catalog was the primary reference and fraction of the total CBCG-catalog blue luminosity accounted for by those galaxies.

	Catalog	# of galaxies	L_{10}	Fractional luminosity	Reference
(i)	HST	30	57.3	0.1%	(Freedman et al. 2001)
(ii)	Mateo	18	0.4	<0.001%	(Mateo 1998)
(iii)	Tully	1968	2390	5.3%	(Tully 2006)
(iv)	LEDA	36741	42969.4	94.6%	(Paturel et al. 2003)
	Total	38757	45417.1	100.0%	

The LEDA database quotes uncertainties in apparent magnitude. Figure 3 shows the distribution of LEDA assigned apparent magnitude uncertainties for the galaxies in the CBCG-catalog. The best-fit Gaussian gives a mean error $\Delta m_{\rm B} = 0.38$. Galaxies from Tully's catalog have a smaller observational error $\Delta m_{\rm B} = 0.30$ (Tully 2006).

3. COMPLETENESS

Observations of faint galaxies are difficult even in the nearby universe and lead to systematic incompleteness in galaxy catalogs. Studies of galaxy luminosity functions can provide

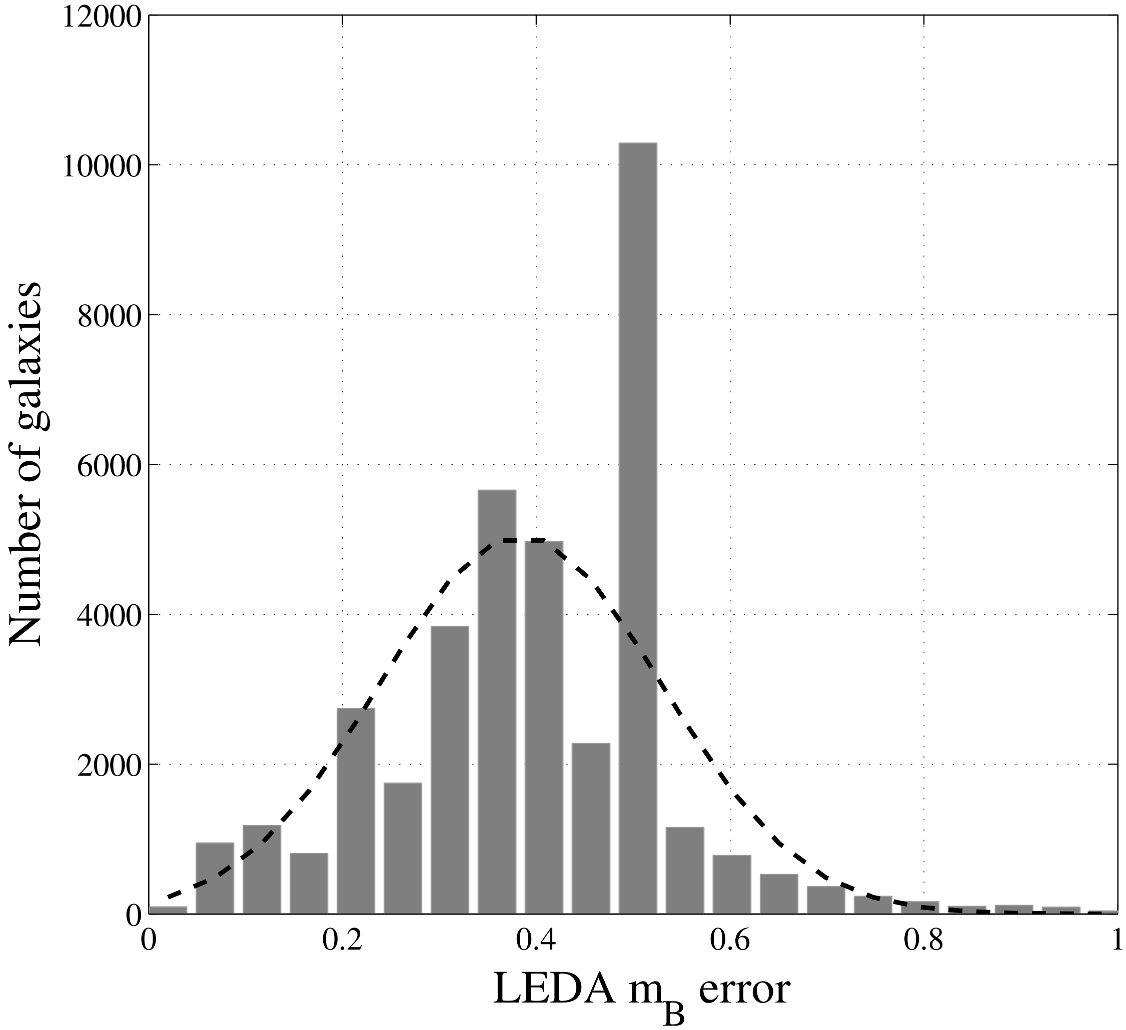

Fig. 3.— LEDA provides uncertainties in apparent magnitudes. The histogram above shows the typical uncertainty to have a mean of 0.38±0.15.

insight into how many galaxies are missing from a catalog (and hence the corresponding blue luminosity). Using the CBCG-catalog, we can generate a luminosity function $N(L, D)$ which is the number of galaxies with luminosities within a luminosity bin from L to $L + \Delta L$ normalized to the spherical volume within radius D. Specifically, we write

$$N(L, D)\Delta L = \left(\frac{3}{4\pi D^3}\right)\left[\sum_{\mathrm{j}} l_{\mathrm{j}}\right] \tag{1}$$

where

$$l_{\mathrm{j}} = \begin{cases} 1 & \text{if } (L < L_{\mathrm{j}} < L + \Delta L) \text{ and } (D_j < D) \\ 0 & \text{otherwise} \end{cases}$$

and the sum over j runs through all the galaxies in the catalog. The quantities L_{j} and D_{j} are the luminosity and distance of each galaxy. Similarly we can compute the luminosity function in terms of blue absolute magnitudes as a function of distance $N(M_{\mathrm{B}}, D)$. The solid lines in Fig. 4 show several realizations of $N(M_{\mathrm{B}}, D)$ for different distances D plotted as a function of M_{B}.

To estimate the degree of incompleteness in the CBCG-catalog, we use an analytical Schechter galaxy luminosity function (Schechter 1976)

$$\phi(L)dL = \phi^*\left(\frac{L}{L^*}\right)^{\alpha}\exp\left(\frac{-L}{L^*}\right)d\left(\frac{L}{L^*}\right) \tag{2}$$

where $\phi(L)dL$ is the number density (number of galaxies per unit volume) within the luminosity interval L and $L + dL$, L^* is the luminosity at which the number of galaxies begins to fall off exponentially, α is a parameter which determines the slope at the faint end of the luminosity function, and ϕ^* is a normalization constant. In terms of (blue) absolute magnitudes, M_{B}, the Schechter function becomes

$$\tilde{\phi}(M_{\mathrm{B}})dM_{\mathrm{B}} = 0.92\,\phi^*\exp\left[-10^{-0.4(M_{\mathrm{B}}-M_{\mathrm{B}}^*)}\right]\left[10^{-0.4(M_{\mathrm{B}}-M_{\mathrm{B}}^*)}\right]^{\alpha+1}\,dM_{\mathrm{B}}\,. \tag{3}$$

To estimate the total luminosity function, we use results from the Sloan Digital Sky Survey (SDSS) as reported by Blanton et al. (2003). Although the SDSS sky coverage is inadequate in RA and DEC, it provides excellent coverage throughout our desired distance and beyond. We therefore use the green luminosity function Schechter fit given in Table 2. of Blanton et al. (2003) and convert it into blue band using the expression given in Table 2. of Blanton & Roweis (2007). Adopting a Hubble constant value of $73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Spergel et al. 2006) and correcting for reddening,[3] the Schechter parameters are $(M_{\mathrm{B}}^*, \tilde{\phi}^*, \alpha) = (-20.3, 0.0081, -0.9)$. The dashed line in Fig. 4 shows the Schechter

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[3]We correct the value of M_{B}^* to be consistent with the reddening correction described in §3.1

function $\tilde{\phi}(M_{\rm B})$ derived from these values. Since this function is obtained from deep surveys, it does not account for the local over-density of blue light coming primarily from the Virgo cluster. For distances up about to 40 Mpc, the CBCG-catalog's luminosity function $N(M_{\rm B}, D)$ dominates $\tilde{\phi}(M_{\rm B})$.

We can now derive a completeness correction that arises at the faint end beyond about 40 Mpc, where the Schechter function exceeds the catalog $N(M_{\rm B}, D)$. We integrate the CBCG-galaxy-catalog luminosity function $N(L, D)$ over L and subtract it from the Schechter fit as a function of distance. Hence, the total corrected cumulative luminosity $L_{\rm total}$ within a volume of radius D is given by

$$L_{\rm total}(D) = L_{\rm CBCG}(D) + L_{\rm corr}(D) \tag{4}$$

where

$$L_{\rm CBCG}(D) = \int_0^D dD' \sum_{\rm j} L_{\rm j} \delta(D' - D_{\rm j}) \tag{5}$$

$$L_{\rm corr}(D) = \frac{4\pi}{3} D^3 \int_{L_{\rm min}}^{L_{\rm max}} L\, dL\; \Theta\left[\phi(L) - N(L, D)\right]\; \left[\phi(L) - N(L, D)\right]\; . \tag{6}$$

Here, the index j runs through all galaxies in the catalog, δ is the Dirac delta function, Θ is the step function and $\phi(L)$ is the adopted Schechter function (distance independent) assumed to represent the complete luminosity distribution. We note that $L_{\rm max} = 52.481\ L_{10}$ ($M_{\rm B} = -23.83$) is the maximum luminosity in the CBCG-catalog and we choose $L_{\rm min} = 10^{-3} L_{10}$ ($M_{\rm B} = -12.98$) because luminosities below this value do not contribute significantly to the net luminosity. The quantity $L_{\rm CBCG}$ in Eqs. (4) and (5) is the uncorrected cumulative luminosity from the compiled catalog; the quantity $L_{\rm corr}$ is the completeness correction. Note that the completeness correction term is always zero or positive regardless of the choice of Schechter function.

In Fig. 5, we show the cumulative blue luminosity as a function of distance as obtained directly from the compiled catalog (solid line) as well as with the completeness correction applied (dashed line). It is evident that the correction becomes significant at distances in excess of about 40Mpc.

3.1. Comparison with other results

For the sake of comparison with other results, we consider the direct computation of a redenning corrected luminosity density based on Blanton et al. (2003) which could be used

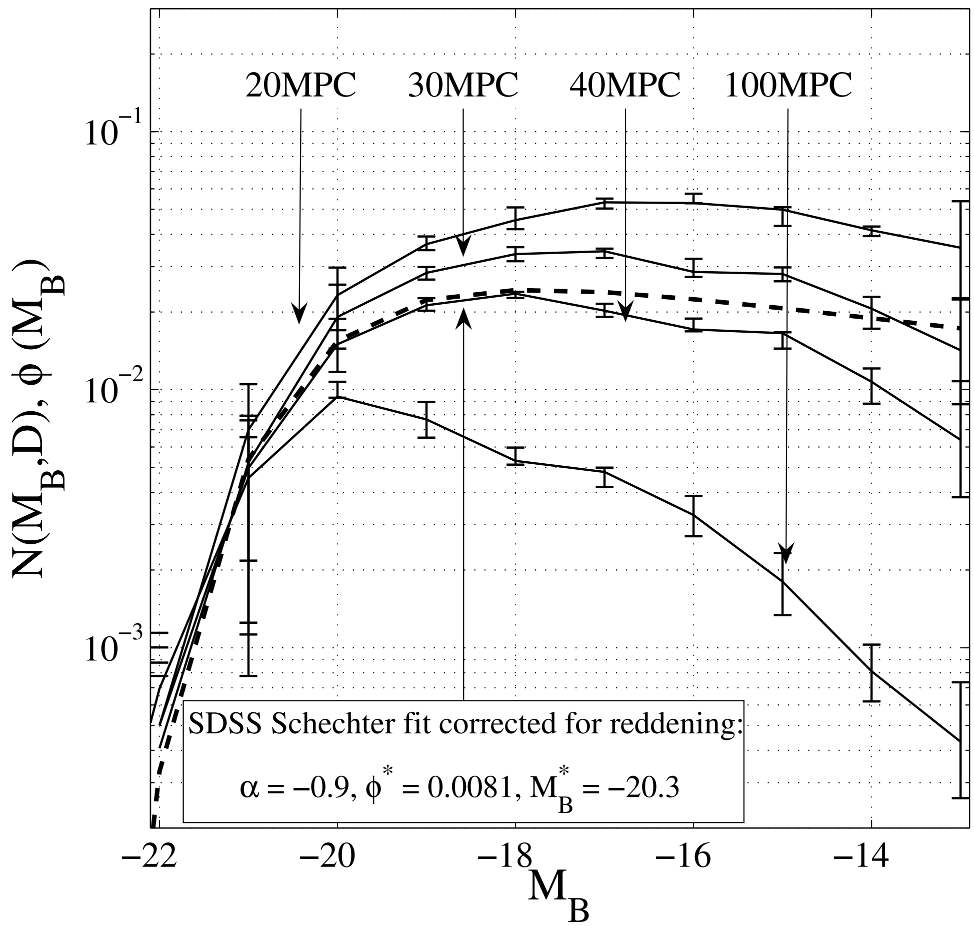

Fig. 4.— The luminosity function of CBCG catalog at various distances (solid lines) and a Schechter function fit (dashed line) given in Eq. (3) based on Blanton et al. (2003). We compensate for the incompleteness of the CBCG-catalog by applying an upward correction to the luminosity bins that are below the Schechter function fit (dashed line), according to Eqs. (4) and (6). Error bars are found by sliding the magnitudes of each galaxy according to the mean errors and recomputing the luminosity function.

at large distances. We adopt a blue luminosity density of $(1.98 \pm 0.16) \times 10^{-2} L_{10}/\mathrm{Mpc}^3$ calculated as follows:

- The blue luminosity density, in terms of blue absolute magnitudes, is -14.98 locally (redshift $z = 0$) and -15.17 for $z = 0.1$ [Table 10 Blanton et al. (2003)]. This is for a standard cosmology with $\Omega_{\mathrm{M}} = 0.3$ and $\Omega_{\Lambda} = 0.7$. We use $z = 0.1$ so that the results will be valid for advanced detectors.

- We convert the $z = 0.1$ blue magnitude density (-15.17) to luminosity units $1.33 \times 10^{-2} L_{10}/\mathrm{Mpc}^3$ and assign systematic errors ($\simeq 10\%$) associated with the photometry to obtain a luminosity density of $(1.33 \pm 0.13) \times 10^{-2} L_{10}/\mathrm{Mpc}^3$.

- We also correct for processing of blue light and re-emission in the infrared (IR) following Phinney (1991) and Kalogera et al. (2001). We use the analysis of Saunders et al. (1990), upward correct by 30% their far IR ($40\mu m - 100\mu m$) luminosity density to account for emission down to $12\mu m$ (Kalogera et al. 2001), and convert to L_{10} to obtain an IR luminosity density of $L_{\mathrm{IR}} = (0.65 \pm 0.1) \times 10^{-2} L_{10}/\mathrm{Mpc}^3$.

- Adding both luminosity densities above and accounting for the errors, we obtain a blue light luminosity density corrected for extinction equal to $(1.98 \pm 0.16) \times 10^{-2} L_{10}/\mathrm{Mpc}^3$

We use this blue luminosity density and its uncertainty and plot the implied cumulative blue luminosity as a function of distance (cubic dependence) in Fig. 5 (gray-shaded region). This uniform density distribution agrees well with the completeness corrected luminosity given above.

We can compare our results for the cumulative blue luminosity as a function of distance to similar results obtained by Nutzman et al. (2004), especially their Figure 1. The results agree qualitatively. However, the catalog described here is more up-to-date compared to the one compiled by Nutzman et al. (2004) by virtue of the updates to LEDA and by the inclusion of the current Tully catalog. The incompleteness correction derived here is also more physically and empirically motivated than the one constructed in the earlier paper. We note that the cumulative luminosity shown as the dashed line in their Figure 1 is too low by a factor of $4\pi/3$ and hence differs from the result reported here.

4. COMPACT BINARY COALESCENCE RATE ESTIMATES

For neutron star binaries, the observed binary pulsar sample can be used to predict the coalescence rate $\mathcal{R}_{MW}$ in the Milky Way (Kim et al. 2004, 2006). The coalescence rate

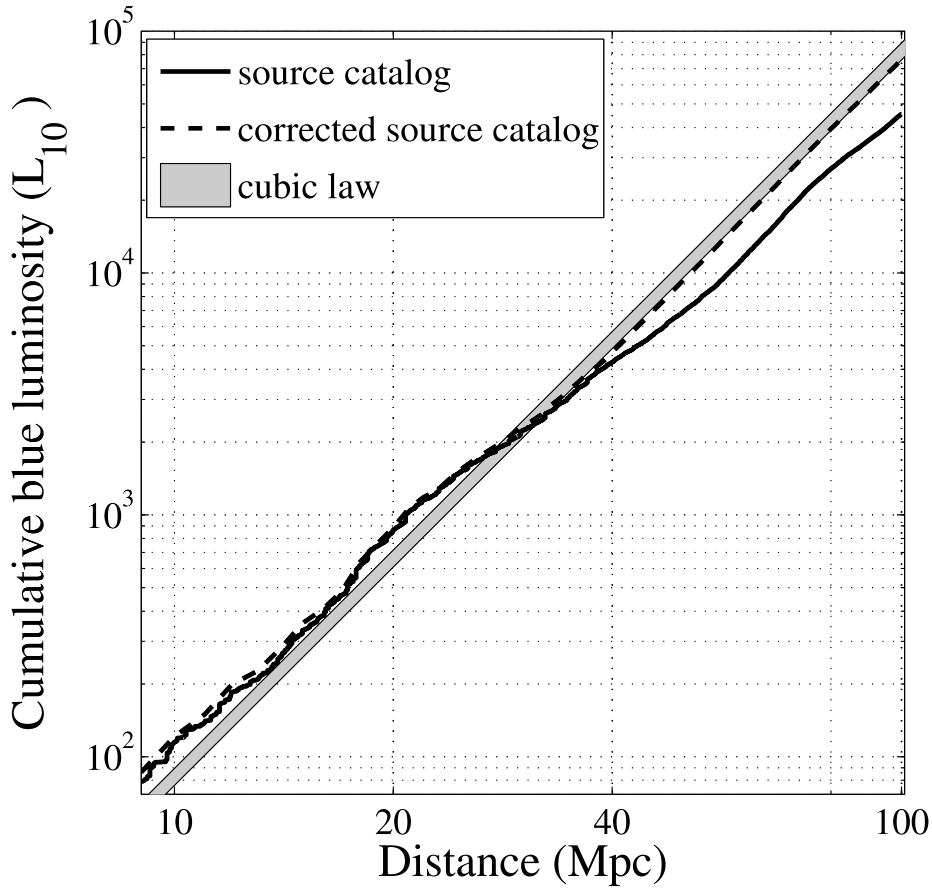

Fig. 5.— Cumulative luminosity as a function of distance from CBCG-catalog uncorrected for incompleteness (solid line), corrected for incompleteness (dashed line) and the cubic extrapolation from the assumed constant blue luminosity density corrected for extinction (gray-shaded region).

within a sphere of radius D is then simply given by

$$R = \mathcal{R}_{\rm MW} \left(\frac{L_{\rm total}(D)}{L_{\rm MW}} \right) \tag{7}$$

where $L_{\rm total}(D)$ is the total blue luminosity within a distance D and $L_{\rm MW}$ is the blue luminosity of the Milkyway, $1.7 L_{10}$ (Kalogera et al. 2001). If the rate R of a binary neutron star coalescence could be measured directly, it would provide an independent estimate of the rate of coalescence per unit of blue luminosity. Together these two measurements would deepen our understanding of stellar and binary evolution. Furthermore, the current understanding of binary evolution and compact object formation leads us to anticipate the formation of black hole binaries that will merge within a Hubble time (e.g., Belczynski et al. 2002; Belczynski et al. 2007). Experiments like LIGO will provide a direct measure of the compact binary coalescence rate and will impose constraints on the theoretical models of stellar evolution and compact binary formation.

4.1. Rate estimates and systematic errors in gravitational-wave searches

In its simplest form, the rate estimate derived from a gravitational-wave experiment will take the form

$$\mathcal{R} = \frac{\rm constant}{T\, \mathcal{C}_L} \tag{8}$$

where the constant depends on the precise outcome of the search and the statistical method used in arriving at the rate estimate, $\mathcal{C}_L$ is the cumulative blue luminosity *observable* within the search's sensitivity volume measured in L_{10}, and T is the time analyzed in years. In general the sensitivity volume is a complicated function which depends on the instrument and the gravitational waveforms searched for. Here, we focus on the influence of the host galaxy properties and the distribution of blue light with distance.

The gravitational-wave signal from a compact binary inspiral depends on a large number of parameters. It is convenient to split these parameters into two types for our discussion. Of particular interest here are the parameters which determine the location and orientation of the binary. We denote these collectively as $\vec{\lambda} := \{D, \alpha, \delta, \iota, \psi, t\}$, that is the distance to the binary, its right ascencion and declination, inclination angle relative to the line of sight, polarization angle of the waves, and the time when the binary is observed, respectively. Other parameters, including the masses and the spins, are denoted $\vec{\mu}$. Recognizing that the spatial luminosity distribution can be written as

$$L(\alpha, \delta, D) = \sum_j L_j\, \delta(\alpha_j - \alpha)\, \delta(\delta_j - \delta)\, \delta(D_j - D) \ , \tag{9}$$

we write the cumulative luminosity as

$$\mathcal{C}_L = \int L(\alpha, \delta, D)\, p(\text{detection}|\vec{\mu}, \vec{\lambda})\, p(\vec{\mu})\, p(\iota)\, p(\psi)\, p(t)\, d\vec{\mu}\, d\vec{\lambda} \tag{10}$$

Assuming that binary coalescences are uniformly distributed in time, and their orientation is random, we take the corresponding prior probabilities: $p(\iota) = \sin(\iota)/2$, $p(t) = 1/\text{day}$, and $p(\psi) = 1/2\pi$.

Systematic errors associated with the derived rate esimates are naturally associated with the errors in cumulative luminosity $\mathcal{C}_L$. The two most relevant errors in the galaxy catalog are in apparent magnitude m_B and distance D. Sky positions are known so precisely that small errors in RA and DEC do not change the detection probability of a particular binary in any significant way; for this reason, such errors are not included in the LIGO analyses (Abbott et al. 2007). The errors induced on the spatial luminosity function in Eq. (9) take the form (Fairhurst et al. 2007)

$$[L+\Delta L](\alpha, \delta, D) = \sum_j L_j\, 10^{-0.4 \Delta m_{Bj}} \left(1 + \frac{\Delta D_j}{D_j}\right)^2 \delta(\alpha_j - \alpha)\, \delta(\delta_j - \delta)\, \delta(D_j + \Delta D_j - D)\ . \tag{11}$$

When estimating the rate based on gravitational-wave observations, one can marginalize over these errors (Fairhurst et al. 2007) using the modified spatial distribution function [Eq.(11)] and the distributions of ΔD_j and Δm_{Bj} reported here.

4.2. A simplified model for estimating expected event rates

The sensitivity of a search for gravitational waves from compact binary coalescence is determined primarily by the amplitude of the waves at the detector. For a non-spinning binary with given $\vec{\mu}$, the amplitude is inversely proportional to the *effective distance* D_{eff} defined as (Allen et al. 2005)

$$D_{\text{eff}} = \frac{D}{\sqrt{F_+^2 (1 + \cos^2 \iota)^2/4 + F_\times^2 \cos^2 \iota}} \tag{12}$$

where D is the physical distance to the binary, F_+ and $F_\times$ are the response amplitudes of each polarization at the detector which depend upon the location of the binary system (Anderson et al. 2001):

$$F_+ = -\frac{1}{2}(1 + \cos^2 \theta) \cos 2\phi \cos 2\psi - \cos\theta \cos 2\phi \sin 2\psi \tag{13}$$

$$F_\times = \frac{1}{2}(1 + \cos^2 \theta) \cos 2\phi \sin 2\psi - \cos\theta \sin 2\phi \cos 2\psi\ . \tag{14}$$

Here θ and ϕ are the spherical co-ordinates of the source defined with respect to the detector and, as before, ι and ψ are the inclination and polarization angles. Since θ and ϕ are detector dependent, the effective distance is different for geographically separated detectors that are not perfectly aligned and, for a fixed source location, changes as the Earth rotates through a sidereal day. Additionally, the effective distance is always at least as large as the physical distance.

For simplicity in understanding the sensitivity of gravitational-wave searches, consider the case in which $\vec{\mu}$ is fixed, i.e. $p(\vec{\mu}) = \delta(\vec{\mu} - \hat{\mu})$. For example, these might be the parameters appropriate to a neutron star binary. The horizon distance $D_{\rm horizon}$, defined as the physical distance to an optimally oriented and located binary system that would be detected with a signal-to-noise ratio of 8, provides a good estimate of sensitivity of a particular detector. Since the amplitude of the gravitational wave is determined by the effective distance, the horizon distance defines an effective distance sphere. Furthermore, consider a search which can perfectly detect these binaries if they have an effective distance $D_{\rm eff} < D_{\rm horizon}$ at a particular detector, then

$$p(\text{detection}|\hat{\mu}, \vec{\lambda}) = \Theta(D_{\rm eff}(\vec{\lambda}) < D_{\rm horizon}) \tag{15}$$

and we can write

$$\mathcal{C}_L(D_{\rm horizon}) = \int L(\alpha, \delta, D)\, \Theta(D_{\rm eff}(\vec{\lambda}) < D_{\rm horizon})\, p(\iota)\, p(\psi)\, p(t)\, d\vec{\lambda}\,. \tag{16}$$

Thus, the cumulative blue luminosity accessible to such a detector is the blue luminosity within an effective distance sphere of radius $D_{\rm horizon}$, averaged over the time of day and possible orientations of the binary. The lower curve in Fig. 7 shows $\mathcal{C}_L(D_{\rm horizon})$. Figure 7 also illustrates the significant difference between the cumulative luminosity $\mathcal{C}_L(D_{\rm eff})$ and total luminosity $L_{\rm total}(D)$ at a given distance. If galaxies are distributed uniformly in space the ratio between these is ≈ 11.2.

While this approach provides a reasonable estimate of the observable blue light luminosity in a single detector, it does not provide the whole story. For example, the $16°$ difference in latitude between the LIGO Observatories in Hanford, Washington and Livingston, Louisiana, implies the $\mathcal{C}_L(D_{\rm horizon})$ depends on the site used. Figure 6 shows two-dimensional contours of this function.

Based on the galaxy catalog presented in this article, the cumulative blue luminosity $\mathcal{C}_L$, measured in L_{10}, accessible to a search with a given horizon distance sensitivity can be derived from Fig. 7 and is tabulated in Table 2. We can combine the calculated cumulative blue luminosity with estimates of $\mathcal{R}$, the rate of binary mergers per L_{10}, to estimate the

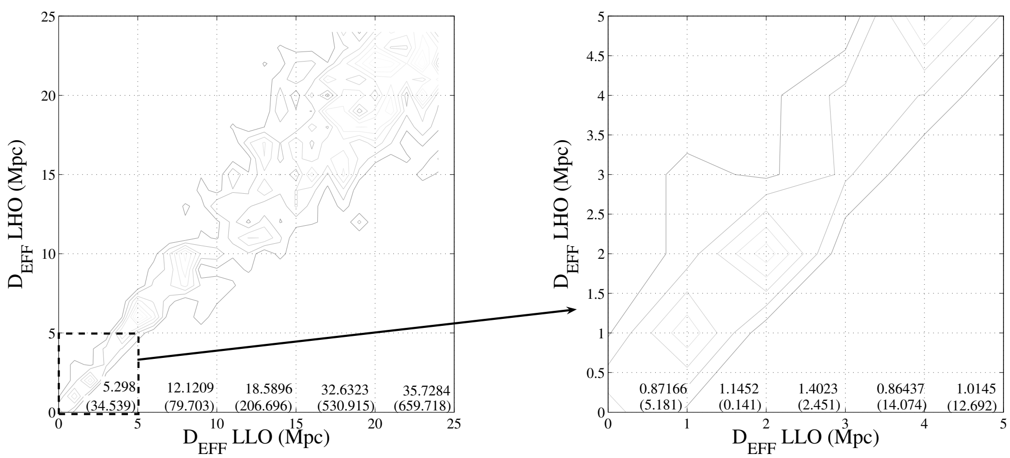

Fig. 6.— Luminosity contours per effective distance bin in the two LIGO sites. The effective distance to a source in one galaxy is different for both detectors, changes as a function of the sidereal day and also on the orientation of the particular source. Since the effective distance is always larger than the real distance the luminosity available within a given effective distance bin is considerably smaller than the luminosity within the physical distance bin. The upper horizontal numbers refer to the luminosity per bin in effective distance. The parenthetical lower numbers refer to the luminosity per physical distance bin. It is also possible to have a systematically different luminosity between detectors as is indicated in the right panel zoom of the first 5 Mpc. The available luminosity within 5 Mpc (mostly from Andromeda) is slightly better located for LLO and therefore stretches the contours to higher effective distances for LHO. LIGO rate upper limits for searches with limited range thus depend on the non-uniformity of the Local Group.

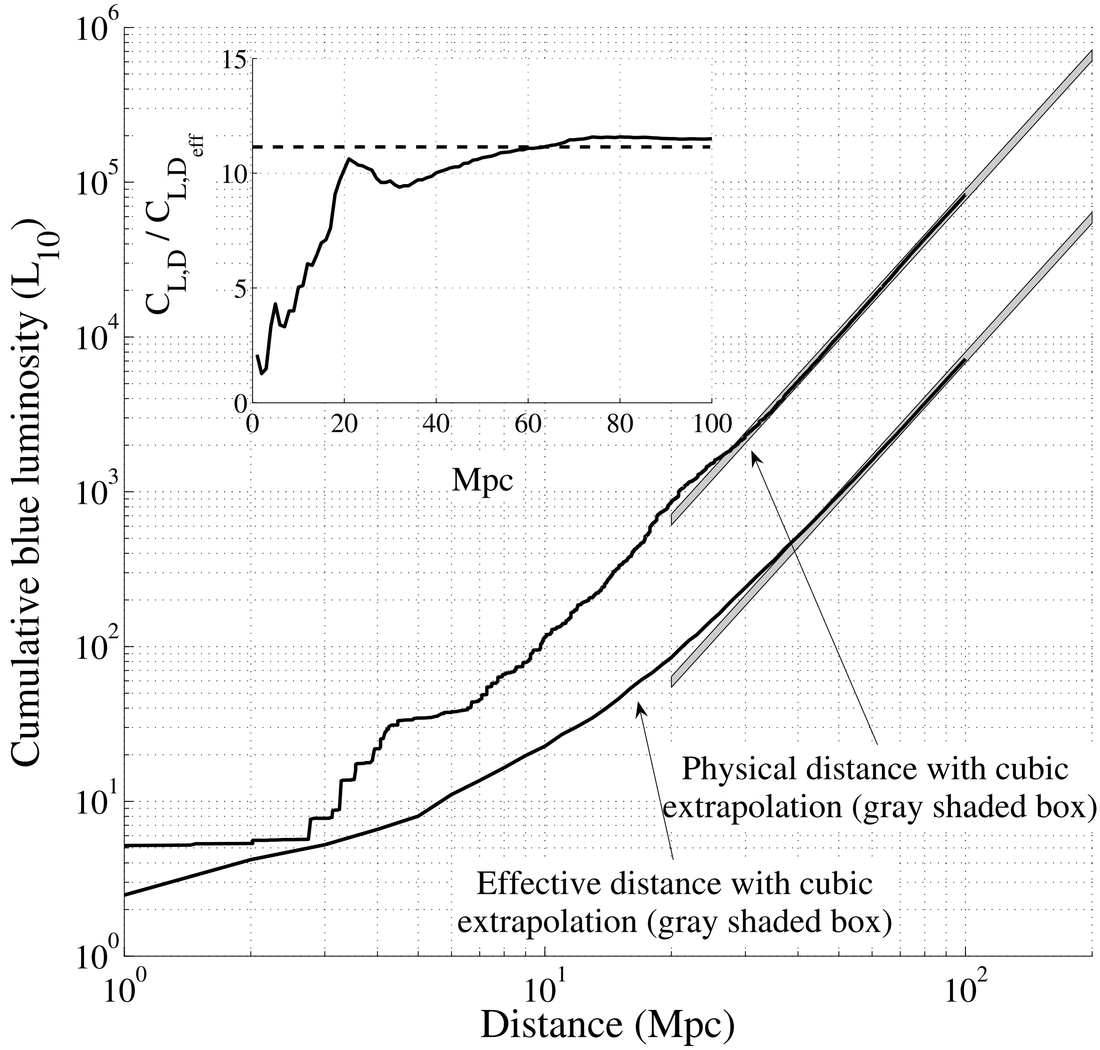

Fig. 7.— Cumulative luminosity as a function of physical distance (top line) and effective distance (bottom line). The gray shaded lines are cubic extrapolations (§3) derived for both cases. Given a LIGO horizon distance one can immediately get the cumulative blue luminosity from the bottom curve. To obtain an approximate rate upper limit one could calculate $\mathcal{R}_{90\%}\,[\mathrm{yr}^{-1}L_{10}^{-1}] = 2.3/(\mathcal{C}_L \times T)$ where $\mathcal{C}_L$ is taken from this plot at a given range in effective distance. *Inset:* Ratio of the cumulative luminosity for the physical and effective distance from the completeness corrected CBCG-catalog illustrates the non-uniform distribution at smaller ranges (< 20 Mpc) and asymptotes to the expected uniform distribution (dashed line) for larger distances.

number of compact binary merger events N detectable in a given LIGO search with an observation time T:

$$N = 10^{-3} \left(\frac{\mathcal{R}}{L_{10}^{-1}\ \mathrm{Myr}^{-1}} \right) \left(\frac{\mathcal{C}_L}{10^3 L_{10}} \right) \left(\frac{T}{\mathrm{yr}} \right) \tag{17}$$

If the horizon distance of a search is larger than 50 Mpc, we can use the following approximation, from a cubic law:

$$N \approx 10^{-3} \left(\frac{\mathcal{R}}{L_{10}^{-1}\ \mathrm{Myr}^{-1}} \right) \left(\frac{D_{\mathrm{horizon}}}{50\ \mathrm{Mpc}} \right)^3 \left(\frac{T}{\mathrm{yr}} \right) \tag{18}$$

Estimated rates of binary neutron star (BNS) mergers in our Galaxy are based on the observed sample of binary pulsars. The rates depend on the galactic distribution of compact objects. In Kalogera et al. (2004), the most recent reference estimating rates, the most likely galactic rate for their reference model 6 is $83\,\mathrm{Myr}^{-1}$, with a 95% confidence interval $17 - 292\,\mathrm{Myr}^{-1}$. The most likely rates for all the models used in Kalogera et al. (2004) are in the range $4 - 220\,\mathrm{Myr}^{-1}$ for the Milky Way.[4]

For the 4km LIGO detectors currently operating, $D_{\mathrm{horizon}} \approx 31$ Mpc for BNS. Thus, the predicted number of BNS events is in the range $N_6 \approx 2 - 30 \times 10^{-3}\ \mathrm{yr}^{-1}$ with the most likely number being $N_6 \approx 1/(100\ \mathrm{yr})$ [we use the subscript $_6$ to indicate these rates use reference model 6 from Kalogera et al. (2004)]. A search that reaches twice the distance (such as enhanced LIGO), yields a most likely rate $N_6 \approx 1/(10\ \mathrm{yr})$. And a search that would be 15 times more sensitive to coalescences of binary systems than the current LIGO detectors (such as Advanced LIGO) would yield a most likely rate of $N_6 \approx 40.0\ \mathrm{yr}^{-1}$.

5. CONCLUSION

Whether one wishes to compute expected detection rates for LIGO searches, or to interpret LIGO searches as rate upper limits (or eventually detection rates), we require at the simplest level accurate accounting of the total observable blue luminosity $\mathcal{C}_L$. As mentioned in the previous sections, a galaxy catalog complete with sky positions and distances is important for initial LIGO astrophysics because the blue luminosity is not uniformly distributed in the sky within the search range. For searches with ranges well beyond current sensitivity the universe is uniform and rate estimates depend primarily on accurate blue luminosity

[4]The rates quoted here are in units of rate per Milky Way per Myr; to get the rate per L_{10}, we divide by 1.7 which is the estimated blue luminosity of the Milky way in L_{10} units, assuming the blue absolute magnitude of the Milky Way to be -20.11 (Kalogera et al. 2001).

densities corrected for reddening. We have introduced a method to bridge the gap between the well known nearby galaxy distribution and the expected long range distribution through a completeness correction based on SDSS luminosity functions (Blanton et al. 2003).

This paper provides the most up to date accounting of nearby galaxies within 100Mpc as well as errors in the apparent magnitude (corrected for reddening) and distance and demonstrates how the errors propagate into rate calculations. We provide a way to easily account for the LIGO antenna pattern using effective distance and motivate the need to compute average cumulative blue luminosity found within a given effective distance sphere. For ranges within 50Mpc there is a nontrivial relationship between cumulative blue luminosity within an effective distance sphere and within a physical distance sphere. Beyond 50Mpc the relationship is well behaved leading to the simple scaling for the number of detected events N given in Eq.(18).

We provide adequate description of our methods for others to apply new rate models to future LIGO data. Although this catalog will serve as a reference for current and future LIGO data analysis, we look forward to future work that may transcend the simple blue light rate normalization that we have discussed. One way to go beyond blue light rate normalization, (necessary to ascertain the degree to which old stars contribute to present day mergers) is with multiband photometry of nearby galaxies which can reconstruct their mass, morphology and metallicity dependent star formation history. With this information in hand LIGO detections could be applied more stringently to assess the relative contribution that progenitors of different ages provide to the present day merger rate.

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Table 2: Table showing the cumulative blue luminosity $\mathcal{C}_L(D_{\rm horizon})$ accessible to a search with horizon distance $D_{\rm horizon}$ given in the first column.

$D_{\rm horizon}$ (Mpc)	$\mathcal{C}_L(D_{\rm horizon})$ (L_{10})
10	23
20	85
30	240
50	953
100	7200
200	59200
300	200000
500	926000