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Comparing Hα and H I Surveys as Means to a Complete Local Galaxy Catalog in the Advanced LIGO/Virgo Era

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ABSTRACT

Identifying the electromagnetic counterparts of gravitational wave (GW) sources detected by upcoming networks of advanced ground-based interferometers will be challenging due in part to the large number of unrelated astrophysical transients within the $\sim 10 - 100$ deg^2 sky localizations. A potential way to greatly reduce the number of such false positives is to limit detailed follow-up to only those candidates near galaxies within the GW sensitivity range of ~ 200 Mpc for binary neutron star mergers. Such a strategy is currently hindered by the fact that galaxy catalogs are grossly incomplete within this volume. Here we compare two methods for completing the local galaxy catalog: (1) a narrow-band Hα imaging survey; and (2) an H I emission line radio survey. Using Hα fluxes, stellar masses ($M_\star$), and star formation rates (SFR) from galaxies in the Sloan Digital Sky Survey (SDSS), combined with H I data from the GALEX Arecibo SDSS Survey and the Herschel Reference Survey, we estimate that a Hα survey with a luminosity sensitivity of $L_{\rm H\alpha} = 10^{40}$ erg s^{-1} at 200 Mpc could achieve a completeness of $f^{\rm H\alpha}_{\rm SFR} \approx 75\%$ with respect to total SFR, but only $f^{\rm H\alpha}_{\rm M_\star} \approx 33\%$ with respect to $M_\star$ (due to lack of sensitivity to early-type galaxies). These numbers are significantly lower than those achieved by an idealized spectroscopic survey due to the loss of Hα flux resulting from resolving out nearby galaxies and the inability to correct for the underlying stellar continuum. An H I survey with sensitivity similar to the proposed WALLABY survey on ASKAP could achieve $f^{\rm HI}_{\rm SFR} \approx 80\%$ and $f^{\rm HI}_{\rm M_\star} \approx 50\%$, somewhat higher than that of the Hα survey. Finally, both Hα and H I surveys should achieve $\gtrsim 50\%$ completeness with respect to the host galaxies of short duration gamma-ray bursts, which may trace the population of binary neutron star mergers.

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1. Introduction

The inspiral and coalescence of neutron star binaries (NS-NS) are the most likely astrophysical sources for direct detection with the upcoming advanced networks of ground-based gravitational wave (GW) interferometers, such as Advanced LIGO and Virgo (hereafter aLIGO/Virgo; Abramovici et al. 1992; Caron et al. 1999; Acernese et al. 2009; Abadie et al. 2010). Maximizing the science achievable from such detections will require the identification and localization of an associated electromagnetic (EM) counterpart (e.g., Bloom et al. 2009; Phinney 2009; Metzger & Berger 2012, hereafter MB12). The EM-GW link is crucial for identifying the host galaxy and distance of the merger, for placing the mergers in an astrophysical context, for studying the hydrodynamics of matter during the merger process, and potentially for lifting degeneracies associated with the inferred binary parameters (e.g., Hughes & Holz 2003, Kelley et al. 2012).

One commonly-discussed EM counterpart of NS-NS mergers is a short-duration gamma-ray burst (GRB); see Fong et al. (2010) and Berger (2011) for evidence favoring this association. Unfortunately, on-axis short GRBs occur at a low rate of $\lesssim 1$ yr^{-1} within the ~ 200 Mpc range for NS-NS detections by aLIGO/Virgo (Nakar et al. 2006; Fong et al. 2010; MB12), so the joint detection of a short GRB with a GW event is expected to be rare. More isotropic optical counterparts, such as an off-axis GRB afterglow (Coward et al. 2011; van Eerten & MacFadyen 2011; MB12) or supernova-like emission powered by the decay of radioactive ejecta ("kilonova"; Li & Paczyński 1998; Metzger et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Rosswog et al. 2012), may instead represent more promising counterparts for the bulk of GW-detected events (MB12); the typical timescale for these counterparts is a few days. Delayed radio emission, powered by the interaction of (non-)relativistic ejecta with the surrounding environment, may also be detectable if the merger occurs in a sufficiently dense medium, with a timescale of months to decades (Nakar & Piran 2011; Piran et al. 2012).

Regardless of physical origin, a major challenge to identifying EM counterparts is the expected poor sky localizations of $\sim 10-100$ deg^2 for networks of GW detectors (Fairhurst 2009; Nissanke et al. 2011, 2012). In the optical band, this large area will necessitate deep and rapid follow-up with wide-field survey instruments. Still, an even greater challenge may be the large number of false positives in these wide fields (e.g., background supernovae, M dwarf flares, shock break-out events, AGN flares; see Kulkarni & Kasliwal 2009; MB12;

Nissanke et al. 2012). Given the rapid evolution of the predicted optical signal, such false positives need to be quickly eliminated so that candidate counterparts could be followed up with deeper photometry or spectroscopy before the transient fades. Although rapid follow-up is not as essential at radio frequencies, false positives could also be of concern in this case (e.g., radio supernovae, tidal disruption events, AGN flares), given the poorer angular resolution of wide-field radio survey instruments and our lack of knowledge about the transient radio sky on the timescales and depths of the expected merger counterparts (e.g., Frail et al. 2012).

The contamination from false positives could be reduced by restricting the search volume to locations near[1] galaxies within the sensitivity range of aLIGO/Virgo ($z \lesssim 0.046$; e.g., Abadie et al. 2010). This approach has the potential to reduce the search area from tens of square degrees to $\lesssim 0.5$ deg^2, and hence to reduce the number of false positives by a factor of $\sim 10^3$ (Kulkarni & Kasliwal 2009). However, to implement this strategy with success, the census of local galaxies must be reasonably accurate and complete. Unfortunately, this is currently not the case: the galaxy catalogs used for recent LIGO/Virgo GW follow-up (Abadie et al. 2012; Evans et al. 2012) are estimated to be only $\approx 60\%$ complete (with respect to B-band luminosity) at 100 Mpc (Kopparapu et al. 2008; White et al. 2011), in which case the true counterpart (most likely at a larger distance) could easily be missed. Furthermore, although B-band completeness is a reasonable proxy for the NS-NS merger population if the latter traces current star formation (e.g., Belczynski et al. 2002), completeness with respect to stellar mass is also relevant if a sizable fraction of mergers occur in early-type galaxies with older stellar populations (e.g., O'Shaughnessy et al. 2008).

In this paper we compare two approaches for completing the local galaxy catalog. The first strategy is a narrow-band Hα survey (§2), an idea that has been discussed previously (e.g., Rau et al. 2009) but is fleshed out in detail here. The other strategy, explored here for the first time, is a wide-field H I survey (§3), as is already being planned as a main science driver for future wide-field radio arrays. Our main conclusion is that neither Hα nor H I surveys of planned sensitivity are sufficient to fully complete the galaxy catalog, especially with respect to stellar mass. However, even with respect to star formation completeness, an Hα survey suffers from a significant loss of flux (and hence sensitivity and completeness) from spatially resolving the disks of the galaxies and from the effects of Balmer absorption in the underlying stellar continuum. In §4 we discuss the merits of combining Hα and H I

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[1] Although it is possible that some mergers will occur far outside of the host galaxy of their stellar progenitors (e.g., Narayan et al. 1992; Kelley et al. 2010), even offsets as large as tens of kpc (as characterize the observed offsets of short GRBs; Berger 2010; Fong et al. 2010) would still reduce the required search area substantially as compared to a search conducted with no information on sky position.

surveys, and explore the relevance of our results in the context of the host galaxies of short GRBs (§4.1).

2. Narrow-Band Hα Imaging Survey

Most studies in the past have assumed that the rate of NS-NS mergers in the local universe traces B-band luminosity (Phinney 1991; Kopparapu et al. 2008), as would be expected if the rate of mergers is proportional to the current star formation rate (SFR). This naturally led to consideration of narrow-band Hα imaging surveys to complete the local galaxy catalog since Hα emission is closely tied to on-going star formation activity (e.g., Kennicutt 1992; Gallagher & Gibson 1994; Gallego et al. 1995; Kennicutt 1998; Fujita et al. 2003) and imaging surveys can efficiently identify and help characterize galaxies in a given redshift range (Dale et al. 2008, 2010; Ly et al. 2011). In this section we address the completeness of such a survey as a function of depth in terms of star formation and stellar mass, and discuss the associated challenges.

We first note that while SFR is certainly an important quantity, it is also possible that a sizable fraction of mergers instead trace total stellar mass, as determined by the distribution of merger times and the star formation history (Belczynski et al. 2002, 2006; see Figure 11 of O'Shaughnessy et al. 2008). Leibler & Berger (2010) find evidence from the host galaxies of short GRBs that mergers may track a combination of SFR and stellar mass, in rough analogy with Type Ia SNe (e.g., Scannapieco & Bildsten 2005). Given this possibility, in what follows we explore completeness with respect to both stellar mass and SFR independently.

In addressing the issue of Hα completeness we pursue an empirical approach, rather than directly making use of derived relations between Hα luminosity and various galaxy properties. Our primary source of data are galaxy catalogs with measured Hα fluxes ($F_{\mathrm{H}\alpha}$) provided by the MPA-JHU emission line analysis[2] from the Sloan Digital Sky Survey (SDSS) Data Release 7 (e.g., Strauss et al. 2002; Abazajian et al. 2009). Each galaxy is characterized by a stellar mass (determined by photometric modeling; Kauffmann et al. 2003; Salim et al. 2007) and SFR (determined from emission lines; Brinchmann et al. 2004). We correct the measured Hα fluxes to account for the finite angular size of the spectroscopic fiber relative to the galaxy by scaling the fluxes by the difference of the total r-band magnitude (keyword `r_petro`) to that contained in the spectroscopic fiber (keyword `r_fiber`), as described in Hopkins et al. (2003) and Brinchmann et al. (2004). This assumes uniform Hα surface brightness (see below for further discussion) and allows us to study the completeness achieved by an idealized survey

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[2] `http://www.mpa-garching.mpg.de/SDSS/DR7/`

that picks up the entire Hα flux from the galaxy. We also increase the quoted flux errors by a factor of 2.47 (as suggested by the MPA-JHU pipeline) and set a conservative threshold on the signal-to-noise ratio of $\mathrm{S/N} \gtrsim 5$ for an Hα detection; values with $\mathrm{S/N} \lesssim 5$ are treated as upper limits. Finally, we remove all galaxies with "flagged" SFRs (keyword `flagSFR` = 0) or redshifts (keyword `z_warning` = 1).

Figure 1 shows our results for the fraction ("completeness") of the total stellar mass (*red*) and SFR (*blue*) within 200 Mpc as a function of the survey flux depth[3] ($F_{\mathrm{lim,H}\alpha}$) for an idealized spectroscopic survey. Completeness is calculated as the fraction of the total SFR or the total stellar mass in all galaxies with $F_{\mathrm{H}\alpha} \gtrsim F_{\mathrm{lim,H}\alpha}$, normalized to the total SFR or mass of all galaxies in the redshift range $z < 0.046$. As the flux limit decreases below a few × 10^{-15} erg s^{-1} cm^{-2} the completeness becomes increasingly uncertain (shown by the hatched uncertainty bands), as increasing fractions of galaxies have only upper limits on $F_{\mathrm{H}\alpha}$. The miminum (maximum) completeness in this case is calculated by assuming that none (all) would be detections at $F_{\mathrm{H}\alpha} < F_{\mathrm{lim,H}\alpha}$.

An idealized survey to a depth $F_{\mathrm{lim,H}\alpha} = 2 \times 10^{-15}$ erg s^{-1} cm^{-2} (a luminosity of $L_{\mathrm{lim,H}\alpha} = 10^{40}$ erg s^{-1} at 200 Mpc), as could be reached with a few minute integration per pointing on a meter-class telescope such as the Palomar Transient Factory (Law et al. 2009), could achieve a completeness of $f^{\mathrm{H}\alpha}_{\mathrm{SFR}} \approx 97\%$ with respect to SFR, but only $f^{\mathrm{H}\alpha}_{\mathrm{M}_\star} \approx 60 - 80\%$ with respect to total stellar mass. It is not surprising that $f^{\mathrm{H}\alpha}_{\mathrm{SFR}} > f^{\mathrm{H}\alpha}_{\mathrm{M}_\star}$ given the known correlation between Hα luminosity and SFR (Kennicutt 1998; Kewley et al. 2002). Lower completeness with respect to stellar mass is consistent with the fact that $\approx 60\%$ of mass in the local universe is in early-type galaxies (Bell et al. 2003), while they account for only $\approx 10\%$ of the Hα luminosity density at $z \lesssim 0.046$ (e.g. Nakamura et al. 2003).

For comparison in Figure 1 we also plot the completeness with respect to B-Band luminosity using data from the 11HUGS survey of galaxies at < 11 Mpc (Lee et al. 2007; Kennicutt et al. 2008), and with respect to total Hα luminosity (using the $z = 0$ Hα luminosity function from Gallego et al. 1995; cf. Ly et al. 2007; Dale et al. 2010). B-Band completeness ($f^{\mathrm{H}\alpha}_{B}$) tracks closer to SFR than to stellar mass, with $f^{\mathrm{H}\alpha}_{B} \approx 87\%$ completeness at $L_{\mathrm{H}\alpha} = 10^{40}$ erg s^{-1}. This is not unexpected, as blue light tracks ongoing star formation, although not as tightly as Hα luminosity.

The estimates of mass and SFR completeness in Figure 1 are only appropriate for an idealized survey, such as that realized through direct spectroscopy of the target galaxies

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[3] We do not discuss here whether the Hα survey should be framed as being defined by a flux or equivalent width threshold (e.g., see the discussion in Steidel et al. 2000). This distinction will have a minor effect on our conclusions.

(as in SDSS), but with infinite aperture. For an actual imaging surveys, absorption in the underlying stellar continuum can reduce the perceived Hα flux when integrated over a filter (e.g., Meurer et al. 2006). While for young star-forming galaxies this will generally be a minor correction (Brinchmann et al. 2004; Meurer et al. 2006), the correction can be significant for early-type galaxies. In Figure 2 we show a comparison between the SDSS spectra of three galaxies with similar Hα fluxes, but where the integrated flux in a narrow-band Hα filter is reduced by increasing amounts of Balmer absorption from the stellar continuum. In the bottom spectrum, the Hα equivalent width (EW) is much greater than the correction due to stellar absorption ($\mathrm{EW}_\star$), in which case the galaxy would be detected regardless of the effects of stellar absorption. However, in the top spectrum EW and $\mathrm{EW}_\star$ are comparable, and the galaxy might escape detection in a narrow-band imaging survey.

To explore what completeness could be achieved by an actual imaging survey that cannot correct the Hα fluxes for stellar absorption, we recalculated the minimum mass and SFR completeness using the fluxes from SDSS which are instead calculated from the line equivalent widths computed via integration over broad wavelength ranges. The results are shown with dashed lines in Figure 1. Although the effect on SFR completeness $f_{\mathrm{SFR}}^{\mathrm{H}\alpha}$ is relatively minor (less than a few percent, and comparable to the corrections considered in Meurer et al. 2006), the completeness with respect to stellar mass decreases to $f_{\mathrm{M}_\star}^{\mathrm{H}\alpha} \approx 47\%$. This difference arises because Balmer absorption is strong and Hα is weak in galaxies with relatively old stellar populations and low levels of star formation activity, i.e., those that contribute to stellar mass but not SFR completeness.

Another challenge of a realistic survey is that nearby galaxies generally have angular sizes larger than the typical point-spread-function of a ground-based imaging survey. This effect can reduce the effective survey sensitivity compared to that for point sources (i.e., the survey is actually defined by a limiting surface brightness instead of a limiting flux). The actual correction between limiting surface brightness and limiting flux depends on the background noise level, the typical seeing, and the distribution of galaxy sizes. In Figure 3 we show the distribution of effective angular radii ($\mathcal{R}_{\mathrm{eff}} \equiv \mathcal{R}_{\mathrm{ap,SDSS}} \times 10^{(\mathtt{r\_fiber}-\mathtt{r\_petro})/5}$) of all galaxies in our sample, where $\mathcal{R}_{\mathrm{ap,SDSS}}$ is the $1.5''$ radius spectral aperture of SDSS. A significant number of sources have radii of $\gtrsim 5''$, meaning that they will cover $\gtrsim 10$ seeing disks for typical conditions, although this will be somewhat mitigated by the fact that Hα typically comes from localized H II regions which have higher-than-average surface brightnesses.

We include the effects of Balmer absorption and the galaxy size distribution to determine more realistic completeness fractions. We use the uncorrected SDSS Hα fluxes (i.e., not scaling the Hα fluxes by the total r-band magnitude, as described above). This gives an effective seeing disk of 1.5″, comparable to typical ground-based observing conditions, and basically assumes that the Hα flux outside the central portion is below the detectability threshold. We recompute the stellar mass and SFR completeness using this pessimistic ("imaging") scenario, and the resulting minimum completeness are shown with solid lines in Figure 1. For a (point source) luminosity $L_{\rm H\alpha} = 10^{40}$ erg s^{-1}, the SFR completeness is reduced to $f^{\rm H\alpha}_{\rm SFR} \approx 76\%$, while the stellar mass completeness is $f^{\rm H\alpha}_{\rm M_\star} \approx 33\%$.

In Table 1 we summarize the relevant completeness values. We give three values for the Hα survey, as discussed above. The first corresponds to our ideal survey, where there is no Balmer absorption and all of the flux from extended sources is recovered. The other two (realistic) sets include Balmer absorption, with the optimistic version still assuming that all of the flux from extended sources is recovered, and the pessimistic version assuming that none of the flux from extended sources is recovered; the true value likely is between these last two versions, i.e. $f^{\rm H\alpha}_{\rm SFR} \approx 75-95\%$ and $f^{\rm H\alpha}_{\rm M_\star} \approx 30-45\%$

3. H I Survey

Another strategy to complete the local galaxy catalog is via a wide-field H I (21 cm) emission line survey, looking for neutral rather than ionized gas. We are motivated in particular by the planned Widefield ASKAP *L*-band Legacy All-Sky Blind surveY (WALLABY; e.g., Duffy et al. 2012a), which plans to observe $\approx 75\%$ of the sky[4] (declination of $-90°$ to $+30°$) over a timescale of ~ 1 year and detect about a half-million galaxies to $z \approx 0.26$ with an estimated rms sensitivity (over a 100 kHz bandwidth) of ≈ 0.7 mJy. Below we examine to what extent WALLABY will be effective at completing the local galaxy catalog. Throughout we assume that H I luminosity ($L_{\rm H\,I}$) scales with gas mass ($M_{\rm H\,I}$) as $L_{\rm H\,I} = 2 \times 10^{25}(M_{\rm H\,I}/M_\odot)\,{\rm erg\,s^{-1}}$ (Duffy et al. 2012a), neglecting H I self-absorption (a good approximation; Zwaan et al. 1997). Determining the threshold for a given survey also requires assumptions about the velocity widths and inclinations of the galaxies. For our purposes we assume the limiting flux density and linewidth above, which are sufficient to detect $M_{\rm H\,I} \approx 10^9 M_\odot$ at a distance of 200 Mpc at 5σ significance (Duffy et al. 2012a,b).

As in the case of Hα, we opt for an empirical approach to estimate the achievable completeness with respect to stellar mass and SFR. We are limited by the absence of a single large sample of galaxies with measured H I masses (or upper limits), stellar masses, and SFRs, yet which is unbiased with respect to galaxy population. For this reason, we use

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[4] WALLABY may be complemented by similar surveys in the north, such as the proposed Westerbork Northern Sky H I Survey; see `http://www.astron.nl/{~}jozsa/wnshs/survey_layout.html`.

several different H I catalogs to explore completeness with respect to stellar mass and SFR (see Figure 4 for the H I masses and stellar masses).

To study completeness among star forming galaxies, we use H I masses from the Arecibo Legacy Fast ALFA Survey (ALFALFA; Giovanelli et al. 2005) with SDSS counterparts (for which stellar mass and SFR are available as described in §2) in the redshift range $z < 0.046$. Although the entire ALFALFA sample is large (about 9000 galaxies) and covers a wide range in stellar mass ($M_\star \approx 10^{7.5} - 10^{11.5}$ M$_\odot$) it is biased towards star forming galaxies and contains only SDSS counterparts with H I detections. A complementary data set is the GALEX Arecibo SDSS Survey (GASS; Catinella et al. 2010, 2012), which is much smaller (≈ 200 galaxies following our cuts) but also contains deep H I upper limits (down to HI masses of a few percent of the stellar mass). Unfortunately, even GASS does not represent a fair sample of the entire galaxy population since it is restricted to massive galaxies ($M_\star \gtrsim 10^{10}$ M$_\odot$), which for example only account for about half of the short GRB hosts (Leibler & Berger 2010); see Figure 4. For this reason, we also use H I masses and upper limits from the Herschel Reference Survey (HRS; Cortese et al. 2012), a volume limited sample at < 20 Mpc (Boselli et al. 2010) that covers a relatively broad range in stellar masses ($M_\star \approx 10^{8.5} - 10^{11.5}$ M$_\odot$), covering most of the short GRB host galaxies.

In Figure 5 we show our results for the completeness achievable by an all-sky H I survey with respect to total SFR $f^{\rm H\,I}_{\rm SFR}$ (*blue*) and stellar mass $f^{\rm H\,I}_{\rm M_\star}$ (*red*), as a function of survey limiting flux ($F_{\rm lim,H\,I}$), calculated using the GASS sample (also see Table 1). For mass completeness, we also show the HRS sample (*orange*). Note that as in the case of Hα, completeness is uncertain at low fluxes as the result of H I upper limits, as indicated by the hatched regions.

We find that a survey similar to WALLABY could achieve an SFR completeness of $f^{\rm H\,I}_{\rm SFR} \approx 93 - 98\%$, but only $f^{\rm H\,I}_{\rm M_\star} \approx 44 - 50\%$ with respect to total stellar mass. For mass completeness we quote numbers from HRS instead of GASS, since HRS samples a wider range of galaxy masses (Fig. 4). Again, a high SFR completeness is expected given the correlation between cold gas mass and SFR (Bigiel et al. 2011). Lower completeness with respect to stellar mass is expected since early-type galaxies are typically deficient in H I (Sage et al. 2007; Oosterloo et al. 2010) yet they contain $\approx 60\%$ of mass in the local universe (Bell et al. 2003). For comparison, we also shows completeness with respect to total H I mass (as determined from the local H I luminosity function of Zwaan et al. 2005), which is found to lie between that of stellar mass and SFR (Fig. 5; Table 1).

As we discussed in the context of Hα surveys, for H I surveys we should also consider the possible detrimental effect of spatially resolving the galaxies. However, the poorer angular resolution of ASKAP ($10 - 30''$) makes this less of an issue than for an optical survey, and the expected effect on detectability is anticipated to be minimal (see Figure 5 of Duffy et al. 2012a). The limited angular resolution of the H I surveys will not affect the follow-up of GW triggers, as a $\pm 30''$ position would be quite sufficient and the H I centroid will be known to even better precision. Ideally, candidate galaxies detected by WALLABY will also be followed up to obtain optical counterparts by wide-field survey instruments such as VISTA Hemispheric Survey (Arnaboldi et al. 2007), VST ATLAS (Capaccioli et al. 2005), or SkyMapper (Keller et al. 2007).

4. Discussion

Table 1 compares the minimum completeness to SFR and stellar mass achieved by our fiducial Hα and H I surveys based on Figures 1 and 5. Overall we find that when considering realistic surveys including the effects of Balmer absorption and finite source sizes, an H I survey can achieve a somewhat better completeness in both SFR and $M_\star$ compared to Hα.

It is clear from our results that neither the proposed Hα or H I surveys will produce a local galaxy catalog that is entirely complete with respect to stellar mass out to 200 Mpc. Fundamentally, both Hα and H I trace gas, while $\approx 60\%$ of stellar mass in the local universe is in early-type galaxies (Bell et al. 2003) with little gas. However, even completeness with respect to SFR is unlikely to reach 100% from either survey due to the issues discussed in §2 and §3.

A remaining question is whether there are any advantages to combining the results of separate Hα and H I surveys. In Figure 6 we show $L_{\mathrm{H}\alpha}$ versus $M_{\mathrm{H\,I}}$ from the ALFALFA-SDSS sample of star forming galaxies. We note that an obvious correlation exists between $M_{\mathrm{H\,I}}$ and $L_{\mathrm{H}\alpha}$ since both trace star formation, but there is also a large scatter (≈ 1 dex) in the correlation where the sensitivity threshold of WALLABY ($M_{\mathrm{H\,I}} \approx 10^9$ M$_\odot$ at 200 Mpc) intersects that of our fiducial Hα survey ($L_{\mathrm{H}\alpha} \approx 10^{40}$ erg s^{-1} at 200 Mpc). This scatter implies that some fraction of galaxies which are just below the detection threshold in H I will be detectable in Hα and vice versa. Therefore the SFR completeness attained by combining the results of both Hα and H I surveys together should be more than that of either individually.

If one were to combine H I and Hα surveys, which individually achieve a similar completeness (as is the case for WALLABY and our 'ideal' spectroscopic Hα survey)[5], then

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[5] The fact that a smaller fraction of sources lie in the top-left quadrant (detected in Hα but not H I) of Figure 6 than in the bottom-right (detected in H I but not Hα) appears at odds with the comparable

from the SDSS-ALFALFA sample we estimate that $f_{\rm SFR}$ could be increased from $\sim 95\%$ to $\sim 98\%$. Mass completeness could be increased by a somewhat greater amount (changing by up to $\approx 10-20\%$), however $f_{\rm M_\star}$ is ultimately limited to a value $\lesssim 60\%$ due to the fraction of early-type galaxies which possess neither detectable H I or Hα emission. We conclude that combining surveys provides the greatest benefit if both H I and Hα surveys separately achieve a similar completeness, however even in this case the gains will be relatively modest.

4.1. Connection to Short GRB Hosts

So far we have focused on completeness with respect to SFR and stellar mass separately. However, it is also of interest to investigate how complete the Hα or H I surveys will be with respect to the known population of short GRB host galaxies. We attempt to answer this question empirically by investigating the fraction of galaxies with properties (SFR or stellar mass $M_\star$) similar to those of the short GRB hosts that would be detected in Hα or H I.

In our calculation we use short GRB host galaxy masses from Leibler & Berger (2010) and SFRs (or upper limits) from Berger (2009), resulting in a sample of 11 galaxies. We define the 'short GRB host completeness' as the fraction of galaxies in our sample that have masses (and in some cases SFRs) within a factor of ± 0.5 dex of those of each short GRB host and that are detectable at a given Hα or H I flux, the result of which is then averaged over the short GRB hosts. In the case of Hα, the galaxy masses, SFRs, and Hα fluxes are again taken from the SDSS sample (§2), the latter of which are not corrected for stellar absorption or galaxy size (as would characterize a purely imaging survey). In the case of H I we use galaxy masses from the HRS sample, but we cannot make a cut on the SFR since these data are not available.

Figure 7 shows our results for completeness as a function of Hα or H I flux, normalized to the sensitivity of our fiducial surveys. In the case of Hα, results are shown for two cases: (1) in which the galaxy samples are chosen to match both the masses and SFRs of the short GRB hosts, and (2) in a case for which the samples are chosen based just on sharing similar stellar masses with the short GRB hosts. By this criteria, we find that our fiducial Hα imaging survey could achieve a short GRB host completeness of $f^{\rm H\alpha}_{\rm SGRB} \approx 50\%$ and $\approx 25\%$ in cases (1) and (2), respectively. Case (1) is more realistic and results in a higher completeness because most of the short GRB hosts (9 of 11) are star-forming galaxies, so the SFR cut preferentially picks out Hα-luminous galaxies. In both cases the minimum completeness

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completeness attained by our fiducial H I and spectroscopic Hα surveys (cf. Fig. 1, 5); however, the ALFALFA sample includes only H I detections and hence overestimates the fraction of H I-detected galaxies.

asymptotes to $\approx 80\%$ at low fluxes since 2 of 11 of the short GRB hosts are early-type galaxies, for which there are only upper limits on their SFRs and Hα luminosities.

In the case of H I, we find that our fiducial survey similar to WALLABY could achieve a completeness of $f^{\rm H\,I}_{\rm SGRB} \approx 45\%$. However, this probably underestimates the true completeness for the same reason as with Hα: most of short GRB hosts are star-forming and there is a correlation between SFR and H I mass (Bigiel et al. 2011), yet no cut was made on SFR.

We conclude that both Hα and H I surveys could achieve at least $\sim 50\%$ completion with respect to GRB host galaxies, although this number is likely to be substantially higher in the case of an H I survey. There is room to increase the completeness by performing a deeper search than our fiducial survey, potentially approaching the $\sim 80\%$ maximum completeness expected if one could detect all 9 of 11 star-forming short GRB hosts at ~ 200 Mpc.

5. Conclusions

We used observed samples of nearby galaxies, drawn from SDSS and augmented by H I data from several surveys, to estimate the completeness of fiducial Hα and H I surveys to SFR and stellar mass out to a distance of 200 Mpc. We conclude that neither H I nor Hα surveys to proposed depths will be entirely effective at completing the local galaxy catalog with respect to stellar mass within 200 Mpc, but that we can expect reasonable completenesses of $f^{\rm H\alpha}_{\rm SFR} \approx 76\%$, $f^{\rm H\alpha}_{\rm M_\star} \approx 33\%$, $f^{\rm H\,I}_{\rm SFR} \approx 93\%$, and $f^{\rm H\,I}_{\rm M_\star} \approx 44\%$. At this point neither the large-scale Hα nor H I surveys discussed here are underway, and it may be possible to alter the strategy (i.e., survey depth) to increase the completeness. For instance, halving the survey threshold of the fiducial Hα imaging survey results in a substantial increase in the completenesses to $f^{\rm H\alpha}_{\rm SFR} \approx 90\%$, $f^{\rm H\alpha}_{\rm M_\star} \approx 49\%$, but for H I only results in a modest increase to $f^{\rm H\,I}_{\rm SFR} \approx 95\%$, and $f^{\rm H\,I}_{\rm M_\star} \approx 50\%$. For H$\alpha$, these increases are comparable to that achieved by pursuing a spectroscopic survey (Fig. 1). Such a deeper survey would also increase the completeness with respect to short GRB host galaxies by $\gtrsim 10\%$ (Fig. 7).

If the survey thresholds remain as discussed here, assessing whether or not this is a concern for aLIGO/Virgo follow-up largely depends on the fraction of mergers that occur in early-type galaxies. If the host galaxies of short GRBs indeed represent a faithful sampling of the merger population, then the current census of about a 5 to 1 ratio of star forming to elliptical hosts (Berger 2011) would suggest that incompleteness of early-type galaxies is not a major concern. On the other hand, it is also possible that short GRBs do not represent all mergers, or that the short GRB host population is biased against early-type galaxies. Current population synthesis models do allow for a sizable fraction $\gtrsim 20-50\%$ of elliptical hosts at $z = 0$ (O'Shaughnessy et al. 2008).

We note that our treatment of the surveys used simply-defined empirical data sets, and some secondary effects may change the results slightly. For instance, neither the Hα flux nor the Balmer absorption is expected to be distributed uniformly within the galaxies. While we do not think that effects such as these will greatly change our conclusions, future studies could be done with more carefully constructed samples or could make use of observed semi-empirical correlations between galaxy properties to directly calculate the completeness.

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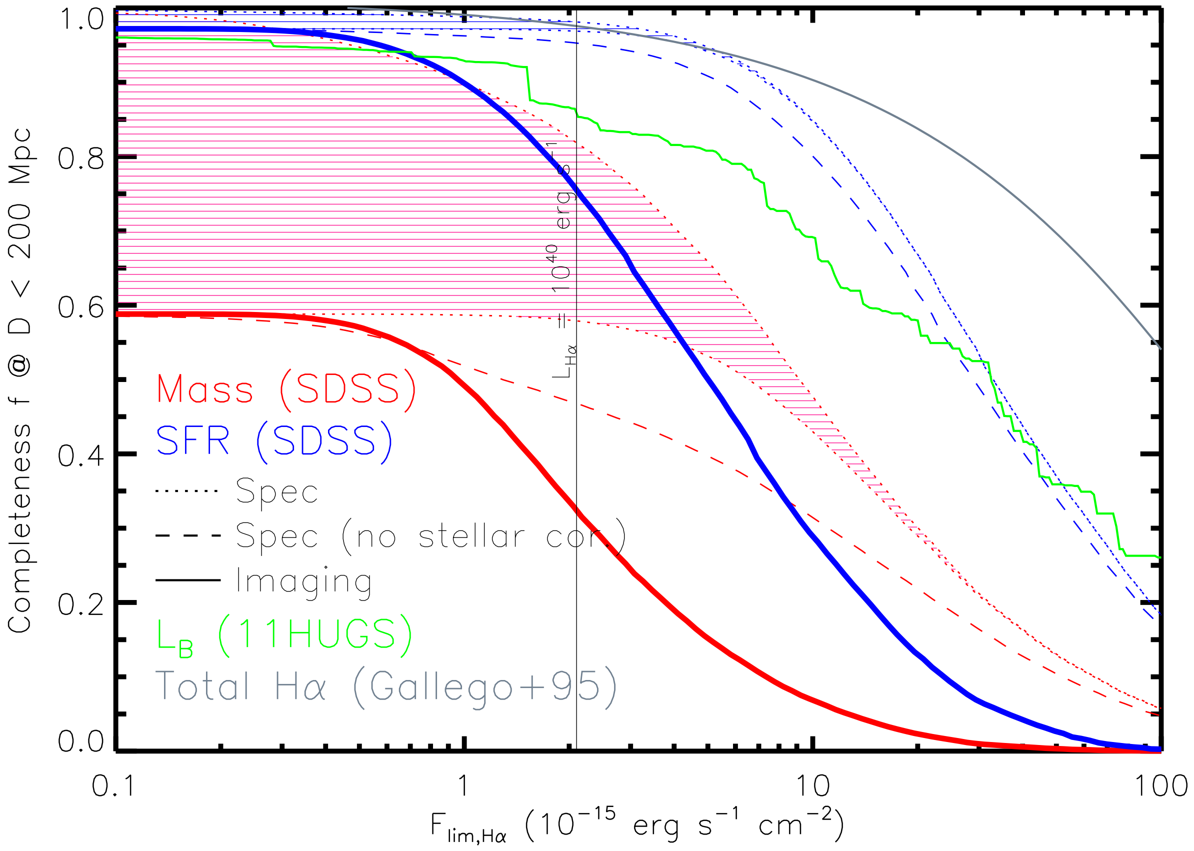

Fig. 1.— Estimated completeness of an all-sky, narrow-band Hα survey with respect to total stellar mass (*red*) and total star formation (*blue*) as a function of survey depth, $F_{\rm lim,H\alpha}$, calculated using Hα fluxes and galaxy properties derived from SDSS (see text). Dotted lines show the completeness of an idealized spectroscopic survey which measures the entire Hα luminosity of the galaxy (infinite aperture) and corrects the Hα flux for stellar absorption; the cross-hatched region represents the uncertainties due to Hα upper limits. Dashed lines show how the minimum completeness decreases when one does not correct Hα fluxes for the underlying stellar Balmer continuum, as appropriate for narrow-band imaging. Solid lines show the minimum completeness when the Hα fluxes are also not corrected for the finite angular size of the galaxy (assuming a 1.5″ radius aperture). These last two cases likely bracket the completeness provided by a purely imaging survey. Also shown for comparison is completeness with respect to B-band luminosity (*green*) of the local (< 11 Mpc) 11HUGS survey (Kennicutt et al. 2008) and with respect to total Hα luminosity (*gray*; using the Gallego et al. 1995 luminosity function).

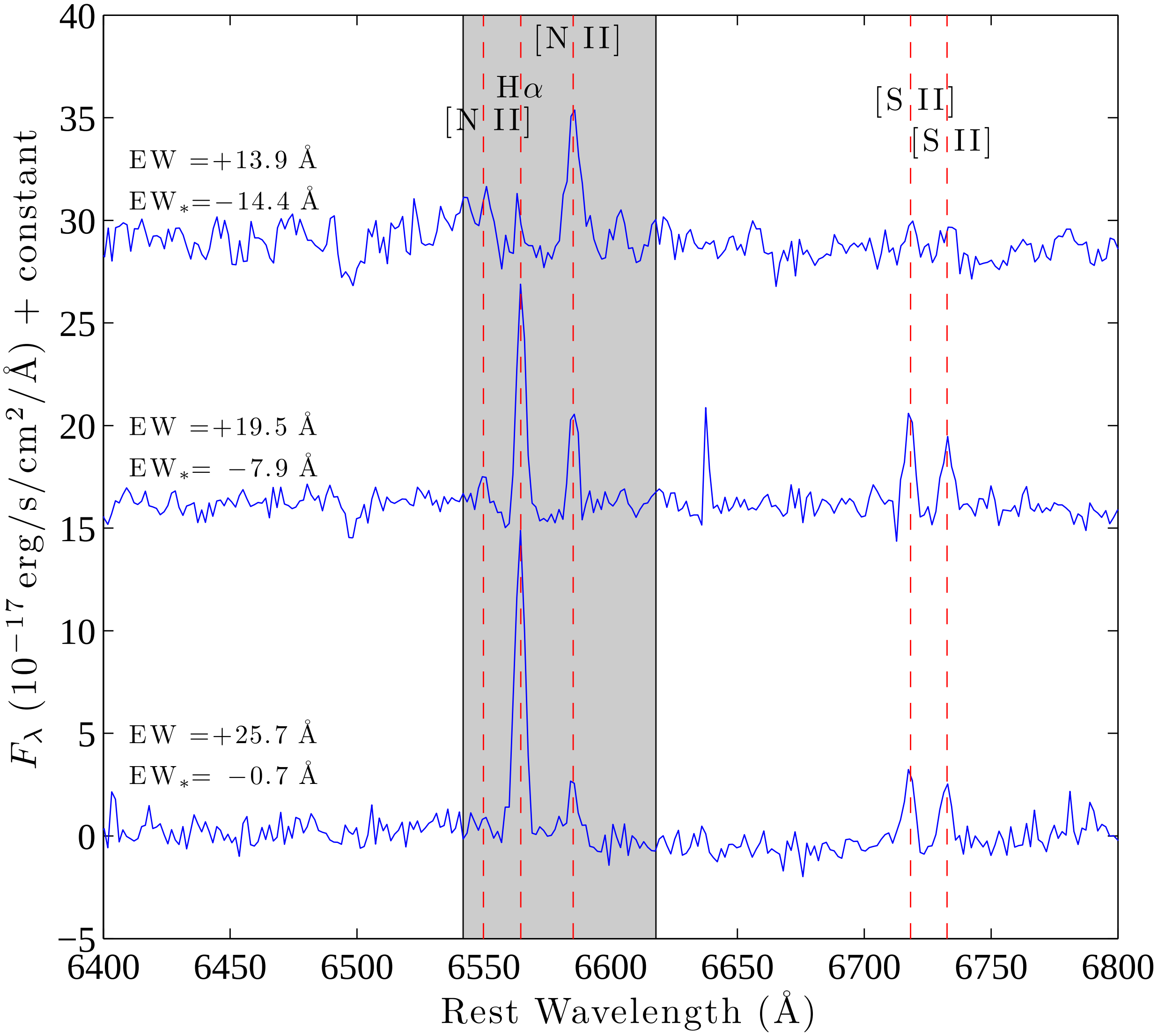

Fig. 2.— Spectra of three galaxies from our SDSS sample which illustrate, from bottom to top, the effect of increasing stellar absorption on the measured Hα equivalent width (EW) in a narrow-band survey. The line centers of the Hα, [N II], and [S II] lines are shown with red vertical dashed lines (wavelengths are shifted to the rest frame). The gray shaded region represents the approximate bandwith of a $z = 0 - 0.01$ Hα filter. For each galaxy we give the EW of the Hα emission line and the EW of the Balmer absorption (EW$_*$), with positive values indicating emission; all values have been scaled to have the same continuum. The Hα fluxes (from the MPA-JHU emission line analysis) are $72 \times 10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$, $58 \times 10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$, and $37 \times 10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$, from bottom to top. It is clear that the Hα EW in the bottom galaxy greatly exceeds the Balmer absorption (by a factor of > 30), while in the upper galaxies the Balmer absorption is 30% and 100% of the Hα emission, even as the line flux changes by only a factor of 2. This would make detecting the top galaxy in a narrow-band survey difficult, although the [N II] doublet will generally provide a minimum flux of $\approx$ 10% of the original Hα flux (dependent on metallicity, among other factors; Pettini & Pagel 2004).

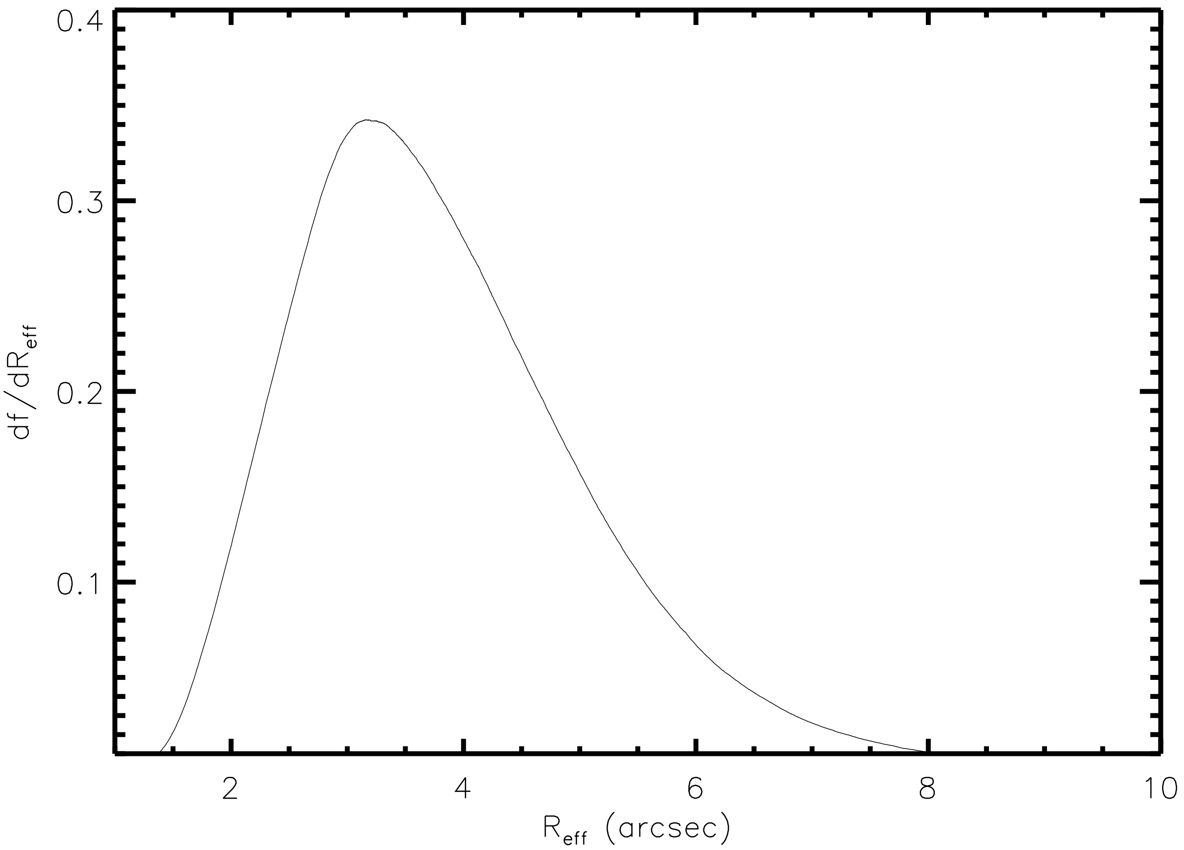

Fig. 3.— Normalized distribution df/d$\mathcal{R}_{\rm eff}$ of effective angular radii $\mathcal{R}_{\rm eff}$ of galaxies in our SDSS sample at redshift $z < 0.046$ (containing 103,025 sources). The effective radius is defined as $\mathcal{R}_{\rm eff} \equiv \mathcal{R}_{\rm ap,SDSS} \times 10^{(\texttt{r\_fiber}-\texttt{r\_petro})/5}$, where `r_fiber` and `r_petro` are the fiber and Petrosian r-band magnitudes and $\mathcal{R}_{\rm ap,SDSS}$ is the $1.5''$ spectral aperture of SDSS. To the extent that Hα and r-band have the same surface brightness distribution, the flux sensitivity to an extended Hα source is reduced by a factor $\sim (\mathcal{R}_{\rm eff}/\mathcal{R}_{\rm app})^2$ compared to a point source.

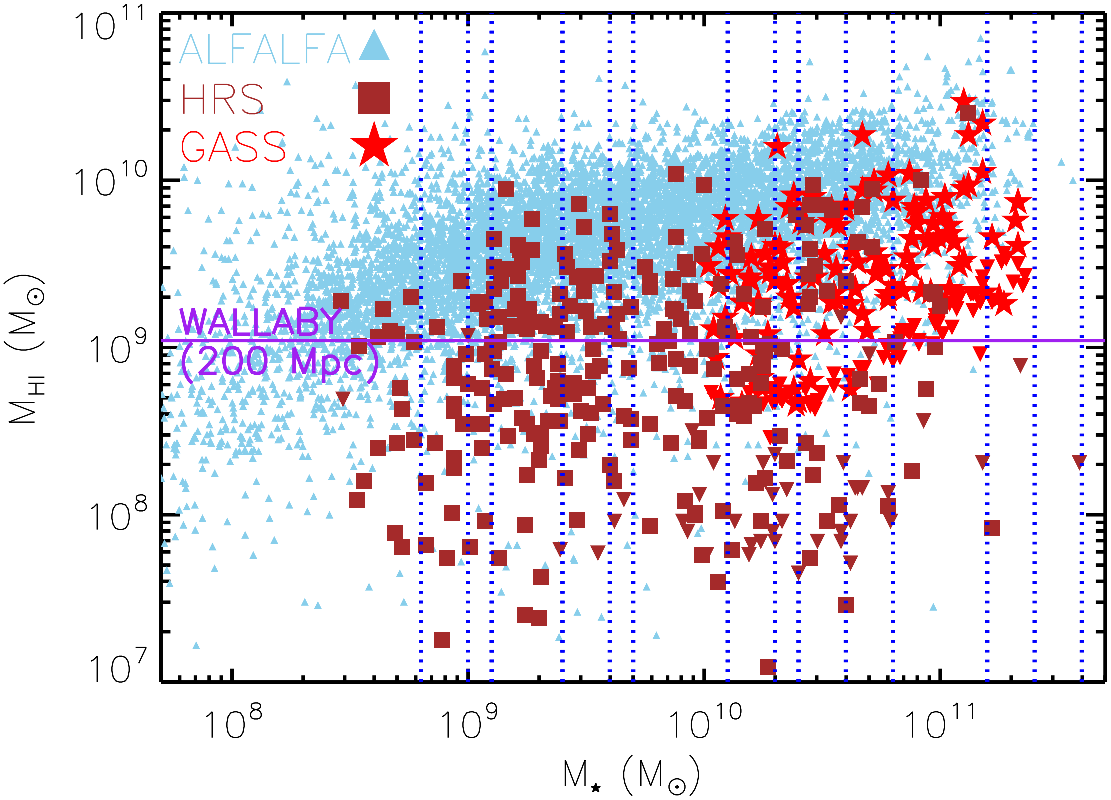

Fig. 4.— Stellar mass $M_\star$ versus H I mass $M_{\rm H\,I}$ from samples of galaxies used in estimating H I completeness: ALFALFA (*light blue points*, detections only); HRS (*brown*, both detections [*squares*] and upper limits); and GASS (*red*, both detections [*stars*] and upper limits); see text for references. Vertical blue lines show the masses of short GRB host galaxies from Leibler & Berger (2010), while the horizontal purple line shows the approximate H I sensitivity threshold of WALLABY at 200 Mpc.

Table 1. Galaxy Completeness within 200 Mpc

Survey Type	Proposed Depth	min($f_{\rm SFR}$)	min($f_{\rm M_\star}$)
Hα (ideal spectroscopic[a])	2×10^{-15} erg cm^{-2} s^{-1}	97%	58%
-	1×10^{-15} erg cm^{-2} s^{-1}	97%	59%
Hα (realistic imaging, optimistic[b])	2×10^{-15} erg cm^{-2} s^{-1}	95%	47%
-	1×10^{-15} erg cm^{-2} s^{-1}	96%	52%
Hα (realistic imaging, pessimistic[c])	2×10^{-15} erg cm^{-2} s^{-1}	76%	33%
-	1×10^{-15} erg cm^{-2} s^{-1}	90%	49%
H I	0.7 mJy × 100 kHz	93%	44%
-	0.35 mJy × 100 kHz	95%	49%

Note. — We give the minimum completeness to SFR and stellar mass based on our strawman Hα and H I surveys. The Hα flux limit corresponds to a luminosity of $L_{\rm H\alpha} = 10^{40}$ erg s^{-1} at 200 Mpc. The H I flux limit corresponds to a luminosity of $L_{\rm H\,I} = 3 \times 10^{31}$ erg s^{-1}, or an H I mass of $M_{\rm H\,I} \approx 10^9$ M$_\odot$.

[a] This scenario assumes no Balmer absorption and that all of the flux from extended sources is recovered (dotted line in Fig. 1).

[b] This scenario includes the effects of Balmer absorption, but assumes that all of the flux from extended sources is recovered (dashed line in Fig. 1).

[c] This scenario includes the effects of Balmer absorption, but assumes that none of the flux from extended sources is recovered (solid line in Fig. 1).

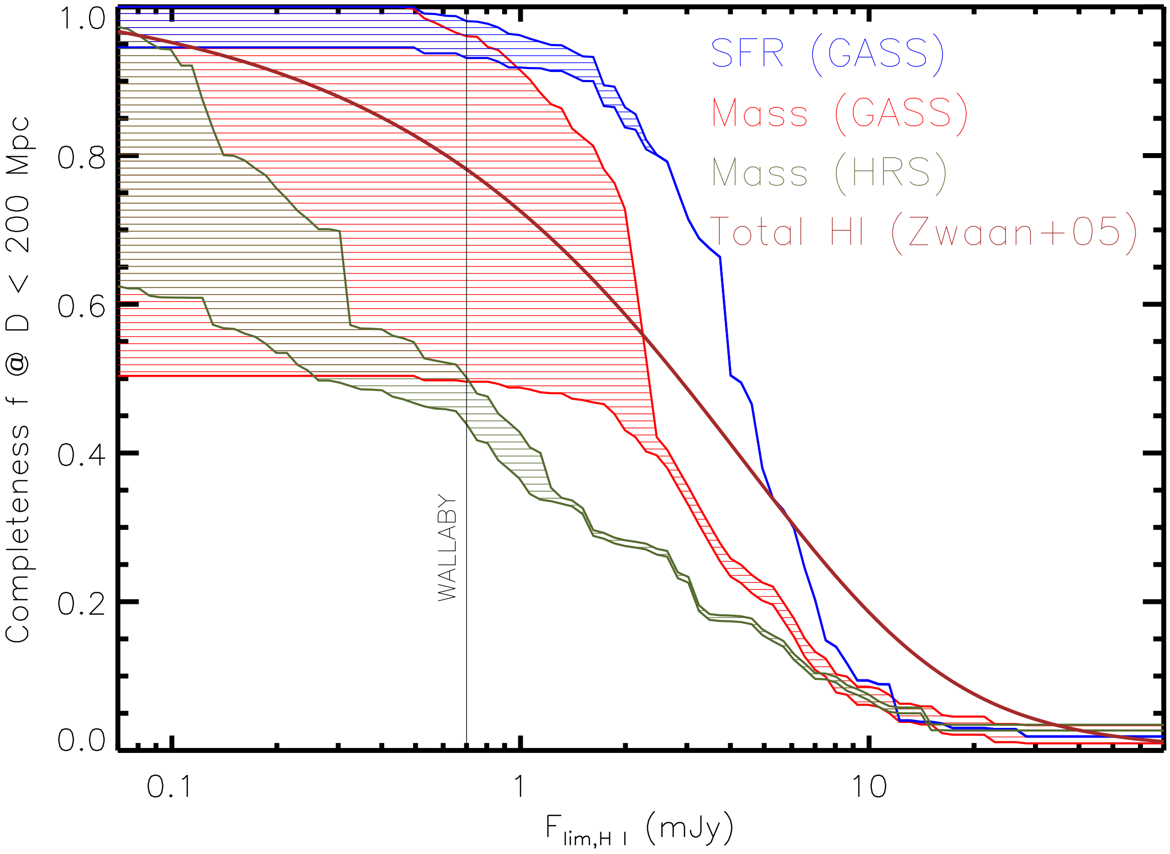

Fig. 5.— Estimated completeness of an all-sky H I survey with respect to total stellar mass (*red*) and total star formation (*blue*) as a function of survey depth ($F_{\rm lim,H\,I}$), calculated using H I fluxes from the GASS sample and galaxy properties derived from the SDSS catalog (see Fig. 4 text). Survey depth is calculated as the 5σ rms sensitivity over an assumed 100 kHz bandpass (see text). We also show the mass completeness calculated using H I masses from the Herschel Reference Survey (HRS; *orange*) and the completeness with respect to total H I mass (*brown*) calculated using the local H I luminosity function from Zwaan et al. (2005). The hatched regions indicate the range of uncertainty in completeness at low flux due to H I upper limits.

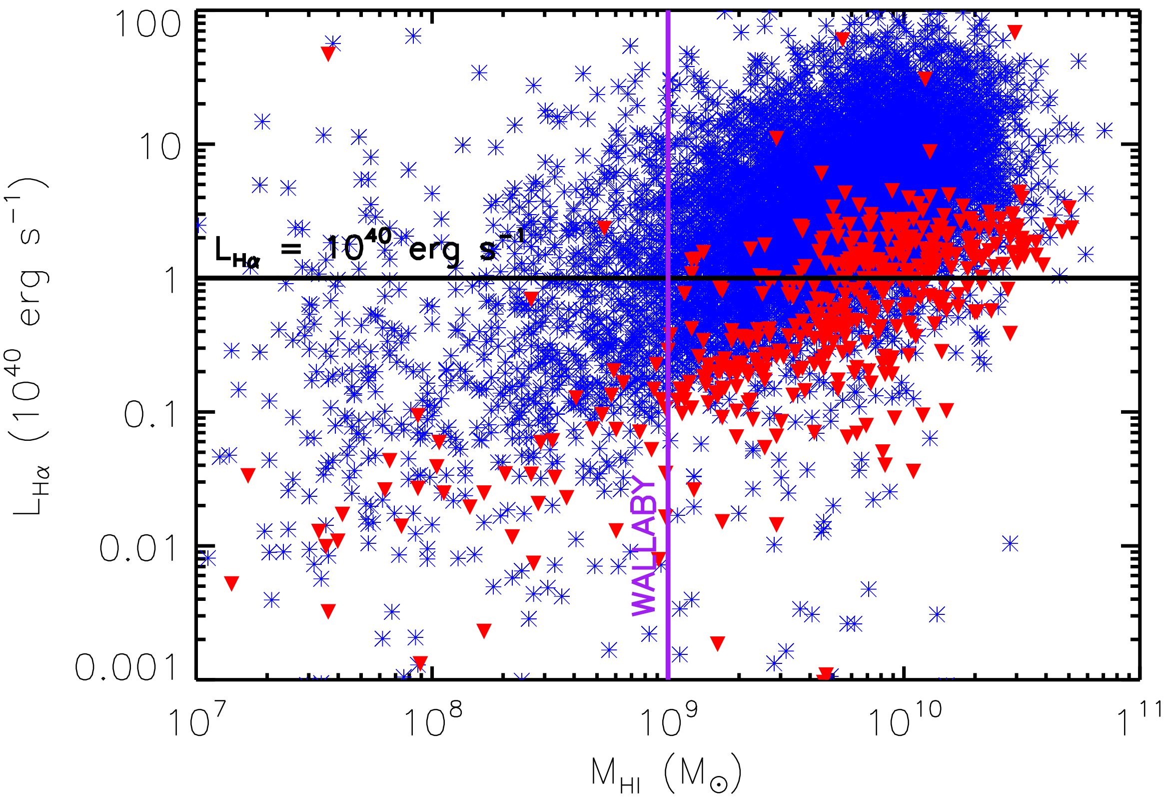

Fig. 6.— Hα luminosities $L_{\mathrm{H}\alpha}$ versus H I masses $M_{\mathrm{H\,I}}$ from the ALFALFA-SDSS sample of star-forming galaxies, showing both Hα detections (*blue stars*) and upper limits (*red triangles*). Although a clear correlation exists between $L_{\mathrm{H}\alpha}$ and $\mathrm{M}_{\mathrm{H\,I}}$ (since both trace star formation), the scatter in $L_{\mathrm{H}\alpha}$ is significant (≈ 1 dex) near the sensitivity threshold of an H I survey similar to WALLABY (*purple line*). The SFR completeness obtained by combining Hα and H I surveys may thus be increased somewhat compared to that obtained by either individually.

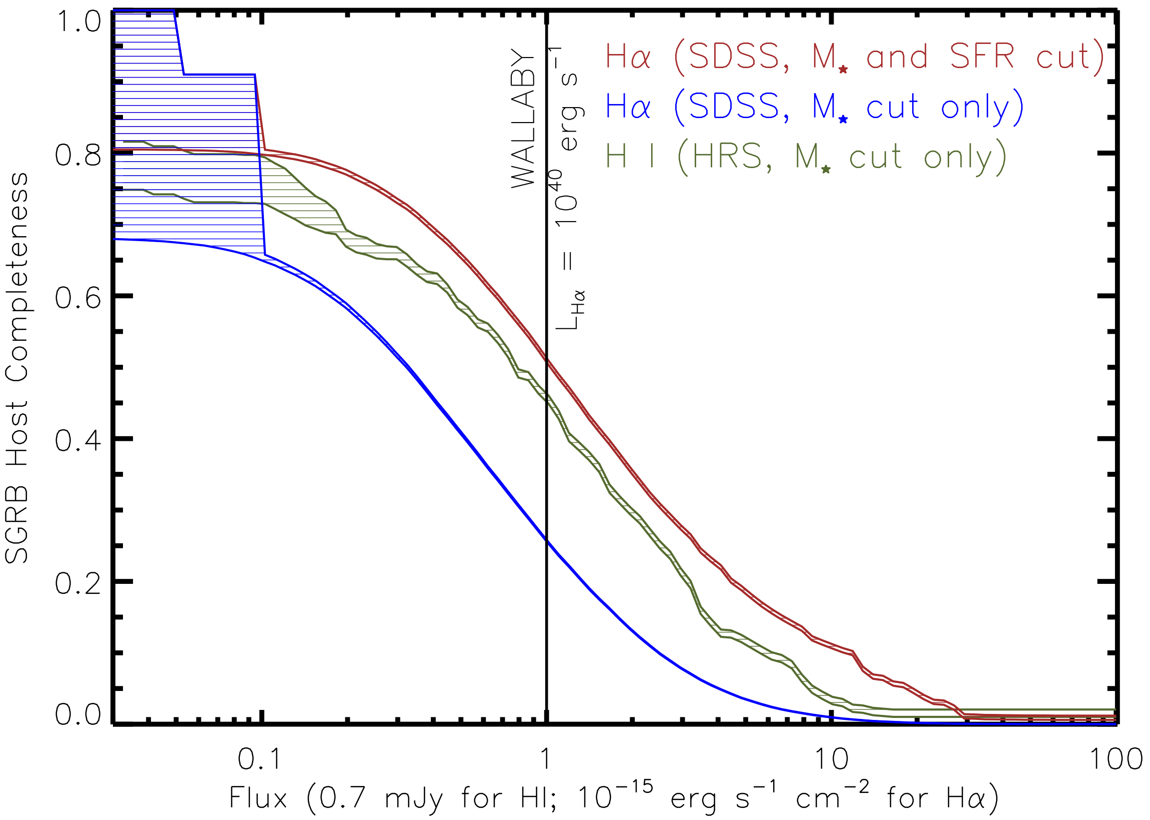

Fig. 7.— Completeness of Hα and HI surveys with respect to galaxies with properties (SFR and $M_\star$) similar to those of the host galaxies of short GRBs, normalized to the sensitivity of our fiducial Hα imaging survey and to that of WALLABY. In the case of Hα, the SDSS galaxy sample is used; results are shown both using a subsample of galaxies selected based on similar stellar masses and SFRs to the short GRB hosts (*brown*), as well as subsamples chosen based just on similar stellar masses (*blue*). In the case of H I, the HRS sample is used and results are shown just for the subsample with similar stellar masses (*orange*); since most SGRB hosts are star forming, the completeness achievable by H I is probably underestimated by this figure (see text).

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