A blind H\textsc{i} Mass Function from the Arecibo Ultra-Deep Survey (AUDS)

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ABSTRACT

The Arecibo Ultra Deep Survey (AUDS) combines the unique sensitivity of the telescope with the wide field of the Arecibo L-band Feed Array (ALFA) to directly detect 21 cm H\textsc{i} emission from galaxies at distances beyond the local Universe bounded by the lower frequency limit of ALFA ($z = 0.16$). AUDS has collected 700 hr of integration time in two fields with a combined area of 1.35 deg$^2$. In this paper we present data from 60\% of the total survey, corresponding to a sensitivity level of 80$\mu$Jy. We discuss the data reduction, the search for galaxies, parametrisation, optical identification and completeness. We detect 102 galaxies in the mass range of $\log(M_{\text{HI}}/M_\odot) - 2 \log h = 5.6 - 10.3$. We compute the H\textsc{i} mass function (HIMF) at the highest redshifts so far measured. A fit of a Schechter function results in $\alpha = -1.37 \pm 0.03$, $\Phi^* = (7.72 \pm 1.4) \times 10^{-3} h^3 \text{Mpc}^{-3}$ and log($M_{\text{HI}}^*/M_\odot$) = $(9.75 \pm 0.041) + 2 \log h$. Using the measured HIMF, we find a cosmic H\textsc{i} density of $\Omega_{\text{HI}} = (2.33 \pm 0.07) \times 10^{-4} h^{-1}$ for the sample ($z = 0.065$). We discuss further uncertainties arising from cosmic variance. Because of its depth, AUDS is the first survey that can determine parameters for the H\textsc{i} mass function in independent redshift bins from a single homogeneous data set. The results indicate little evolution of the comoving mass function and $\Omega_{\text{HI}}$ within this redshift range. We calculate a weighted average for $\Omega_{\text{HI}}$, in the range $0 < z < 0.2$, combining the results from AUDS as well as results from other 21 cm surveys and stacking, finding a best combined estimate of $\Omega_{\text{HI}} = (2.63 \pm 0.10) \times 10^{-4} h^{-1}$.

Key words: galaxies: evolution – galaxies: ISM – galaxies: luminosity function, mass function – radio lines: galaxies – surveys

1 INTRODUCTION

Understanding how and at what rate stars form from cool atomic and molecular gas ($< 10^4$ K) is one of the crucial questions of modern astrophysics. The star formation rate (SFR) is well measured from UV, optical, infrared and radio continuum observations, and is found to increase by an order of magnitude over the redshift interval of $0 < z < 2.5$ (Hopkins & Beacom 2006). By comparison, the evolution of the atomic and molecular cosmic gas density appears to be less dramatic with recent galaxy evolution models suggesting that there may only be a weak evolution of cosmic gas density at $z < 2$ if there exists a self-regulated equilibrium between the inflow of gas into galaxies and the SFR (Obreschkow & Rawlings 2009; Lagos et al. 2011; Power et al. 2010). However, better observations are necessary to further develop these models and to better understand the balance between gas accretion, star formation and feedback.

Measurements of the H$_2$ density (e.g. Keres et al. 2003) are unfortunately not easy, as the molecule does not possess a low-energy rotational transition. Instead, we are dependent on the use of CO as a proxy, with its uncertain dependence on optical depth, metallicity and the radiation field. More accurate observations are available for atomic hydrogen via Damped Lyman-\alpha (DLA) systems at high redshift or via the 21 cm line in the local Universe.
DLAs are wide absorption features caused by high column densities of H\textsc{i} (> 2 x 10^{19}\text{atoms cm}^{-2}) normally associated with galaxies. DLAs can be observed against bright background sources such as QSOs and appear to represent objects which contain the majority of H\textsc{i} at redshifts 1.6 < z < 5.0. [Wolfe et al. 2005] and Prochaska & Wolfe (2009) find a 50\% decrease to occur at lower redshifts 2.3 < z < 5.5. However, Noterdaeme et al. (2012) use a larger Sloan Digital Sky Survey (SDSS) Data Release (DR) 9 sample and only find a 20\% decrease over a similar range. Measurements using Mg\textsc{ii} systems at low-redshift DLA proxies are consistent with the latter [Rao et al. 2006], though selection effects are uncertain and errors are high. Nevertheless evolution in \(\Omega_{\text{H}_1}\), above redshift \(z > 0.5\) appears significantly lower than the corresponding evolution in the star formation rate.

Interpretation of 21 cm observations is more robust, but sensitivity considerations mean that observations are mainly limited to the local Universe. Examples of 21 cm surveys are summarised in Table 1. Extensive mapping of the sky has been done since the installation of multi-beam receivers on the Arecibo, Parkes and Effelsberg telescopes, which transformed these telescopes into powerful survey facilities. This resulted in a significant increase in the area surveyed and the number of galaxies detected. In terms of redshift, however, these surveys are still limited to \(z \approx 0\). The two largest H\textsc{i} surveys are the H\textsc{i} Parkes All-Sky Survey (HIPASS) (\(z < 0.04\)) [Meyer et al. 2004], Wong et al. [2006] and the Arecibo Legacy Fast ALFA (ALFALFA) \((z < 0.06)\) [Giovanelli et al. 2005]. HIPASS detected 5,317 galaxies in the southern and the northern sky up to a declination of \(\delta = +25.5\). ALFALFA observed an area of \(\sim 7000\text{deg}^2\) with the target of detecting about 30,000 galaxies at 21 cm.

Direct detections of galaxies beyond the local Universe are not only limited by sensitivity, but also by radio frequency interference (RFI) and receiver bandwidth. Target galaxies for deep 21 cm observations are therefore normally preselected. For example, Catinella et al. (2008) targeted galaxies up to \(z = 0.25\) to look for the most H\textsc{i}-massive objects, selecting them by their H-\(\alpha\) emission. [Zwaan et al. 2001] and [Verheijen et al. 2007] targeted clusters with redshifts about \(z \approx 0.2\) to increase the chance of detection. Such a strategy leads to samples that are biased towards galaxies with high surface brightness in optical bands. Furthermore, in order to extend beyond the local Universe, such surveys need to be very sensitive. With that in mind, we commenced the Arecibo Ultra Deep Survey (AUDS) - a blind 21 cm survey with the Arecibo L-band Feed Array (ALFA) to search for 21 cm H\textsc{i} line emission at redshifts between 0 and 0.16, the limit of the receiver. The AUDS precursor observations [Freudling et al. 2011] were an important test of the feasibility of such a survey. The precursor survey detected 18 galaxies in the redshift range 0.07 < z < 0.16 with a total integration time of 53 hr. While this provided a measurement of \(\Omega_{\text{H}_1}\) in good agreement with measurements in the local Universe, the AUDS precursor was limited to a very small region with few detections and covered only a limited range of redshifts. Small number statistics and cosmic variance were therefore problems, resulting in large errors.

In this paper, we present results of 60\% of the data from the full survey. It is a fully sampled and a significantly more sensitive data set than the precursor observation, providing a larger sample of direct 21 cm detections. The total integration time is eight times larger than that of the precursor survey. This paper allows a preliminary release for galaxies so far detected, and makes significant advances in the understanding of the evolution of the H\textsc{i} mass function (HIMF).

Throughout this paper we use \(H_0 = 100h\text{km s}^{-1}\text{Mpc}^{-1}\), \(\Omega_M = 0.3\) and \(\Omega_{\Lambda} = 0.7\).

**1.1 Survey Strategy**

The primary goal of AUDS is to systematically survey the cosmic H\textsc{i} density (\(\Omega_{\text{H}_1}\)) in a volume that is beyond the local Universe to a sensitivity that has not been probed before. The strategy of the survey is therefore orthogonal to other current single-dish H\textsc{i} surveys in the sense that AUDS covers a very small area on the sky using the most sensitive 21 cm system currently available and using a very long integration time. Our goal was to achieve an exposure time of about 40 hr per pointing, and a total of 1000 hr of observing time (including overheads) were assigned to this project. To cover the field in the most uniform and sensitive way, we used the “drift and chase” mode which we extensively tested and refined during our precursor observations [Freudling et al. 2011]. The basic strategy was to carry out repeated drift scans over the same field. To optimise uniformity of the sky coverage, the feed array was rotated to ensure equal spacing between the beams. Due to the elliptical projection of the array onto the sky the rotation angle varies between 15° and 23°. The orientation of the array relative to the scan direction is shown in Figure 1.

One major difference with the precursor observations was that, with significantly more observing time available, we were able to Nyquist-sample the sky using short adjacent drift scans that were offset in declination by 0.1 of the beam size. This enabled much more accurate determination of source positions (limited only by signal-to-noise ratio) and source fluxes.

All observations were carried out at night time to

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achieve the best baselines and lowest system temperature. In order to be able to schedule observations for the project throughout the year, we elected to divide the total area into two fields at opposite right ascension within the SDSS footprint. The size of the individual field areas was determined by science goals and telescope limitations. A small area is required to go deep. On the other hand, the upper redshift limit of ALFA means that once sufficient sensitivity to low-mass galaxies is obtained, it is then better to go wide. Edge effects such as loss of sensitivity make it inefficient to consider fields which are smaller than half a square-degree in size. Telescope start-up delays make it inefficient to consider fields which are smaller than half a square-degree in size. Telescope start-up delays make it inefficient to consider fields which are smaller than half a square-degree in size.

### 1.2 Target Selection and Observations

The goal of AUDS is to carry out an unbiased, sensitive survey outside the local Universe. Our original goal was to be able to detect galaxies with $\sim 0.1 M_{\odot}$ of neutral hydrogen at the frequency limit of the ALFA receiver ($f = 1225$ MHz). In order to sample independent volumes, we chose to observe two independent fields that contain no known clusters. Because of the long necessary integration times, the surveyed fields are necessarily small $\sim 67 \times 44'$ each, corresponding to a total volume of $V \approx 10^{3.9}$ Mpc$^3$. For efficient surveying, the two regions should differ in right ascension as much as possible, and be located at a declination where they can be tracked for the maximum time possible at Arecibo. Another criterion for the selection of our fields was that they were within the SDSS survey region. We also tried to avoid bright continuum sources as much as possible. The brightest continuum source in Field 1 is 43.9 mJy and in Field 2 196.9 mJy.

We used a “drift and chase” mode for the observations. Each AUDS scan consists of 230 individual spectra for each beam and polarisation, with each successive spectrum integrated over 1 s while the telescope covers 1 s in right ascension. The spectra from the seven ALFA beams were recorded using the Mock Spectrometer dividing each spectra into two intermediate frequency (IF) sub-bands, each 172 MHz wide. The high frequency IF is centred at $f = 1450$ MHz and the low frequency IF is centred at $f = 1300$ MHz. Combined they cover the whole bandpass range of the ALFA receiver of 300 MHz with a spectral resolution of $\Delta f = 0.02$ MHz.

### 1.3 Data Processing

The bandpass removal and calibration was done using the multi-beam single-dish data reduction software [livedata]. Details of the steps of the reduction process are described in [Barnes et al. (2001)]. As [livedata] was originally developed to reduce data from the Parkes telescope for HIPASS, the program was adapted to suit the different settings of the Arecibo telescope including the handling of different types of FITS files and other Arecibo specific issues such as calibration.

Each individual spectrum with 1 s integration time has a root mean square (RMS) of about 50 mJy. To convert the individual spectra into regular gridded position-position-velocity cubes we use the software [gridzilla] for the final gridded data cubes, data from all beams and polarisations were combined.

[gridzilla] calculates the contribution of every individual spectrum to each pixel of the grid and calculates the final value of the pixel based on the contributing spectra and the assigned weights. The weights were determined by the distance of spectra from the beam centre. We used a weighted median statistic to combine the spectra. The data values were first sorted, and their weights were summed. The weighted median is then the data value for which the sum of the weights is half the total weights. [Barnes et al. (2001)] have shown that using a median estimator was very successful for HIPASS in removing small amounts (less then 40%) of bad data (caused by RFI etc) with the downside of increasing the noise level by at least 25.3%.

However, on occasion, the AUDS data show much more significant levels of bad data (Figure 2), especially in the frequency range of $f = 1220 \text{ to } 1350$ MHz, necessitating further measures. Several sources of strong RFI, like the radar in Punta Salinas and transmissions from the nearby airport interfere in this frequency range. Additionally, several satellites (e.g. GPS, Galileo and GLONASS) transmit in this frequency range. While the RFI emitted from the radar are narrow in frequency and pulsed in time, the RFI from the satellites span a wide frequency range, but do not occur at all times.

To further mitigate against the RFI problem, we used

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1 [http://www.atnf.csiro.au/computing/software/livedata]
a flagging routine applied to the bandpass-corrected data as follows:

(i) The RMS in a RFI-free region is estimated. The RFI free region was chosen by examination of several time-frequency images.
(ii) A 3.5σ mask is created where zero corresponds to valid pixels and one to masked pixels.
(iii) The mask is grown by smoothing it with a Hanning kernel of the size 5×5 pixel (time-frequency domain) which results in values between zero and one. Pixels where the values of the mask is above 0.1 are flagged and ignored during the gridding of the data.

This process is repeated three times before the data is gridded into data cubes. An example of the mask and flagging is shown in Figure 2.

2 AUDS SAMPLE

2.1 Galaxy Catalogue

To search for galaxies, position-velocity images were searched by eye to create a list of galaxy candidates. Due to the varying noise and strong RFI at higher redshift, available automated source finders were not able to create a usefully short candidate list. To create the source list the cubes were searched by three members of the AUDS team. Each tried to identify every possible candidate, even those that were unlikely to be significant detections. Together, 294 unique candidates were identified and a preliminary source list was created. In a second step, a single person inspected each spectrum and image in position-velocity space from the merged list. Spectra were extracted and fitted and a shorter source list created based on the final inspection of each candidate. It was important to carefully distinguish between real galaxies and spurious detections based on their signal-to-noise ratio (SNR), their spectral line shape and the shape of the detections in the image plane. Special attention was taken to distinguish between real sources and RFI. In many cases a clear distinction was possible given their very different signatures in the position-velocity plane, RFI often being narrow in frequency and visible over large ranges in right ascension/declination. However, at low SNR, the distinction is not as clear. Candidates close to, or overlapping with known RFI were treated especially carefully to ensure they were real and that the bandpass was fitted correctly. This resulted in a shorter list of 133 likely candidates, five of which were common between the overlapping bands leaving 128 candidates.

We then used the completeness coefficient \( C \), derived from the simulation discussed in Section 2.3, to create a final source list. \( C \) uses the integrated flux \( S_{\text{int}} \), the velocity width \( W \) and the RMS \( \sigma \), of each galaxy to calculate the probability of detecting a galaxy in the survey. If \( C > 0 \), the galaxy was retained in the sample.

The final sample consists of 102 galaxies. A selection of spectra of AUDS galaxies is presented in Figure 3. Parameterisation of the galaxies was performed using the task \texttt{mbspect} which is part of the radio astronomy data reduction package \texttt{miriad} (Sault et al., 1995). The galaxy position estimated from the manual search was more precisely determined by fitting a Gaussian to the velocity integrated image (0th moment) over a width of 5-9 arcmin around the input position assuming the galaxies are point sources. This is a good approximation as the beam size at the mean redshift of the galaxies in the sample \((z = 0.065)\) is about 190 \( h^{-1} \) kpc in diameter. Additionally we also looked at the optical diameter (Petrosian diameter in the r-band) of the AUDS galaxies we could cross match to SDSS galaxies (details are given in Section 2.2) and found that 95\% of galaxies are smaller than 1.2 arcmin. This would allow the H I disk to exceed the optical diameter by up to three times and still be within the ALFA beam.

Next the spectra were optimally extracted, also using the \texttt{miriad} function \texttt{mbspect}, at the new position using a window of 5-9 arcmin, weighing neighbouring pixels by the beam shape. The velocity range occupied by the detected galaxy was masked out, before a polynomial was fitted to the baseline. The spectral width \( W \) and the central velocity of the profiles were measured. The fit also provided \( S_{\text{int}}, S_{\text{peak}} \) and the peak SNR. The fluxes were measured assuming the galaxies are point sources. Using \( S_{\text{int}} \) and the luminosity distance \( D_L \) of the galaxies we calculate \( M_{\text{HI}} \):

\[
M_{\text{HI}} = 49.8 \left( \frac{D_L}{\text{Mpc}} \right)^2 \left( \frac{S_{\text{int}}}{\text{Jy Hz}} \right).
\]  

The \( \text{H} I \) masses of the AUDS galaxies as a function of their distance is presented in Figure 4.

The bivariate distributions as well as single parameter histograms of the galaxy parameters \((z, S_{\text{int}}, S_{\text{peak}}, W)\) are shown in Figure 4. The redshift histogram shows that we did not detect any galaxies with \( z > 0.13 \). Detecting \( \text{H} I \) galaxies at high redshift proved challenging as the RFI environment at Arecibo is very hostile, especially for \( f < 1290 \) MHz.

\[2 \text{ http://www.atnf.csiro.au/computing/software/miriad/} \]

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2.2 Optical Counterparts

Both AUDS fields were chosen to overlap with the SDSS footprint. Searching the SDSS DR7 catalogue we find Field 1 has 25 galaxies and Field 2 has 56 galaxies with spectroscopic redshifts in the redshift range of AUDS. Additionally there are 11588 galaxies with only photometric redshifts in Field 1 and 9932 galaxies in Field 2.

We used the SDSS to find optical counterparts for the AUDS galaxies and found that 36 out of 102 have spectroscopically confirmed counterparts and that at least one of the AUDS galaxies is a pair. Optical galaxies are identified as matches when they are within a two arcmin radius around the H I position and the difference with the spectroscopic redshift is smaller than 150 km s$^{-1}$. Taking the position (inside the beam), the size, inclination and colour of the galaxy into account we identify another 18 likely optical counterparts. Figure 7 (left panel) shows the offset between the position of the optical counterparts as given by the SDSS and the positions measured from the H I data for both the galaxies with optical counterparts with spectroscopic redshift as well as the galaxies with likely counterparts with photometric redshifts. We also show the difference between the optical redshift and H I redshift in the right panel of the same figure.

Even though the overall number of galaxies with reliable optical information is small, some trends are clearly visible (Figure 8). There is a correlation between the detectability of a galaxy and its $r$-band luminosity as the SDSS is a magnitude but not volume-limited sample. This also becomes evident when one compares the luminosity of the optical counterparts with and without spectroscopic redshifts. Galaxies with higher masses at a certain redshift are more likely to have spectroscopic counterparts.

The second trend is that lower mass galaxies are predominantly blue galaxies ($g-r<0.7$) and less likely to have spectroscopic information. Redder galaxies are only found at large $M_{HI}$. This is expected as bluer galaxies tend to be more gas rich. Red galaxies on the other hand tend to have lower gas mass fractions but are significantly more massive and luminous. That makes them easier to detect in optical surveys especially at higher redshift where the survey volume is larger. This means that non-volume limited H I surveys tend to be biased against red galaxies with increasing redshift.
Figure 4. Selection of AUDS spectra. The black dashed vertical lines indicate the spectral range in which the line is fitted. This spectral region is excluded for the fit of the baseline, marked with the blue dashed line. The completeness coefficient for each galaxy is given in the upper right hand corner. The top panels show the three lowest mass galaxies detected in the survey. The central panels shows three galaxies at intermediate redshift with high SNR. The lowest panels are the three highest redshift galaxies.

Figure 6. Log-log bivariate distribution of measured parameters of AUDS galaxies: redshift $z$, 50% velocity width $W_{50}$, peak flux $S_{\text{peak}}$ and integrated flux $S_{\text{int}}$. On the diagonal the single-parameter histograms are plotted.
We leave the more detailed discussion of optical properties as well as a stacking analysis for a later paper.

### 2.3 Survey Completeness

The completeness of a survey is defined as the fraction of a certain type of galaxy which can be detected by a survey from the underlying distribution of objects down to the detection limit of the survey. Estimating the completeness of AUDS is a crucial step to understand the underlying galaxy population.

A good way to determine the completeness of the sample is to insert synthetic galaxies into the data and test the rate with which these galaxies are detected. This allows us to determine a completeness limit as a function of $S_{\text{int}}$ as well as $W$ and the single pixel noise $\sigma$. To take the noise into account we defined a noise weighted integrated flux $S_{\text{int}}^\prime = S_{\text{int}}/\sigma$.

To insert the galaxies we chose three representative subregions in the data cube of Field 1: one RFI free region (1381 MHz); one region moderately affected by RFI (1325 MHz); and one region with high RFI occupancy (1231 MHz). Each region is 20 MHz wide. In total 356 synthetic galaxies were inserted into the subcubes. The parameters for the synthetic galaxies were randomly chosen from an integrated flux range of $S_{\text{int}} = 0$ to 1.5 mJy MHz and a...
Completeness essentially becomes zero. To detect) and (3) the flux value at which the completeness decreases for smaller fluxes for all values of \( W \), (2) \( W \) influences the steepness of the decrease of the completeness to zero (narrow profiles are easier to detect) and (3) the flux value at which the completeness essentially becomes zero.

The errorbars in Figure 9 indicate the 1 \( \sigma \) binomial confidence interval given by \( n_d/n_s = \sqrt{p(1-p)/n_b} \) = \( p \) with \( n_d \) being the number of detected synthetic galaxies in a bin, \( n_s \) the number of all synthetic galaxies in that bin and \( p \) the upper/lower limit of the confidence interval. Binning data in intervals of \( \Delta S_{\text{int}} = 0.1 \) mJy MHz and \( \Delta W = 0.4 \) MHz and fitting equation 2 gives the best-fit parameter of \( \alpha = 28.95, \beta = -0.08, \gamma = -5.21 \) and \( \delta = 0.29 \). Using the noise weighted flux (\( \Delta S_{\text{int}} = 0.2, \Delta W = 0.4 \) MHz) and fitting equation 3 gives the best-fit parameter of \( \alpha = 68.39, \beta = 0.45, \gamma = -0.52 \) and \( \delta = 0.030 \). Since the noise changes throughout the cube, we found that equation 3 is the better way to minimise the effect of the different noise levels and we therefore used \( C(S_{\text{int}}, W) \) when calculating the HIMF. For each galaxy in the sample we calculate the completeness coefficient by inserting the value for \( S_{\text{int}} \), \( \sigma \) and \( W \) into equation 3 giving us a specific value for that galaxy which represents the probability of detecting this galaxy in the sample. Additionally we give the integrated flux at which a galaxy of a certain width reaches a completeness limit of 95%, 90% and 65%.

### Table 2.

| Width (MHz) | Width (\( z = 0 \)) | \( S_{\text{int}} \) (mJy MHz) | \( C = 0.95 \) | \( C = 0.90 \) | \( C = 0.65 \) |
|------------|---------------------|-------------------------------|----------------|----------------|----------------|
| 0.22       | 46                  | 0.76                          | 0.49           | 0.18           |
| 0.62       | 131                 | 0.81                          | 0.58           | 0.28           |
| 1.02       | 215                 | 0.87                          | 0.65           | 0.35           |
| 1.42       | 300                 | 0.93                          | 0.71           | 0.40           |
| 1.82       | 384                 | 0.98                          | 0.77           | 0.45           |

The shapes of the galaxy spectra were described by a busy function ([Westmeier et al. 2014](#)).

The data cubes were searched blindly in the same way as the original data cubes and 256 of the galaxies in the mock sample could be recovered. From the ratio of the number of detected galaxies (\( n_d \)) to the number of all galaxies (\( n_s \)) the completeness in logarithmic flux and linear \( W \) bins can be computed.

The dependency of the completeness on \( W \) and \( S_{\text{int}} \) as well as \( W \) and \( S_{\text{int}} \) shown in Figure 9 resembles an error function shifted along the flux axis. We chose to describe the completeness function with the following analytic model:

\[
C = \max \left( \text{erf} \left( \alpha W^n (S_{\text{int}} - \beta W - \gamma) \right), 0 \right) \quad (2)
\]

\[
C = \max \left( \text{erf} \left( \alpha W^n (S_{\text{int}} - \beta W - \gamma) \right), 0 \right) \quad (3)
\]

The four independent parameters in equation 2 and 3 were chosen to fit the features in the binned completeness data namely: (1) the completeness decreases for smaller fluxes for all values of \( W \); (2) \( W \) influences the steepness of the decrease of the completeness to zero (narrow profiles are easier to detect) and (3) the flux value at which the completeness essentially becomes zero.

The completeness is well described by an error function shifted along the horizontal axis. The grey shaded area indicates the completeness for the maximum and minimum width in the bin. The completeness as a function of \( S_{\text{int}} \) and \( W \). The dashed line is the best-fit to the data using equation 2. The red dashed line indicates a nominal completeness limit of \( S_{\text{int}} = 0.8 \) mJy MHz. Right panel: The completeness as a function of \( S_{\text{int}}^* \) and \( W \). The dashed line is the best-fit to the data using equation 3.

The central width of each bin is given in the upper left hand corner. The completeness is well described by an error function shifted along the horizontal axis. The grey shaded area indicates the completeness for the maximum and minimum width in the bin. Left panel: The completeness as a function of \( S_{\text{int}} \) and \( W \). The dashed line is the best-fit to the data using equation 2. The red dashed line indicates a nominal completeness limit of \( S_{\text{int}} = 0.8 \) mJy MHz. Right panel: The completeness as a function of \( S_{\text{int}}^* \) and \( W \). The dashed line is the best-fit to the data using equation 3.
2.4 Reliability

One method of estimating the reliability of an \HI\ survey is to use optical information provided by other large surveys, e.g. SDSS. Another possibility is to re-observe parts of the survey area to assess the reliability of their sources and the measured parameters, done for example by HIPASS (Zwaan et al. 2004). However, neither of these methods are feasible for AUDS. The spectral density of SDSS in the area of the survey is too low to systematically cross-match all the optical and \HI\ selected galaxies (Section 2.2) and using additional telescope time for re-observations is not practical.

As a first step to estimate the reliability we therefore looked at the overlap regions between the low and the high frequency bands. The cubes overlap in the frequency range of 1368 – 1382 MHz. In this overlapping region we find 5 galaxies which are individually detected in both the high and the low frequency bands. There are two additional galaxies in the source list which are only detected in the high frequency bands. However, both these galaxies have a completeness coefficient $C < 0.3$.

Next, we estimated the reliability of our survey re-using the list of possible detections created from the data cubes with inserted synthetic objects (see Section 2.3). Of the total of 330 detected sources, 256 turned out to be synthetic, and 12 were previously detected AUDS galaxies. Of the 62 unidentified source candidates, about 10 passed the criteria for being included in our first cut candidate list as described in Section 2.1. None of them passed our criteria to be included in the final catalog, otherwise they would be considered as one of the detected AUDS galaxies. We find that the number of such false detections is roughly proportional to the number of confirmed detections in any of the volumes. Therefore, we conclude that first cut catalogues contain on the order of 10/256 $\approx$ 4\% false detections, and the number of false detections in the final catalogue will be lower than that. We therefore consider 96\% as a lower limit for the reliability of AUDS. The impact of false detections in AUDS is negligible for all results presented in subsequent sections.

2.5 Cosmic Variance

Measurements of the galaxy density in a finite volume are affected by the large scale structure of the Universe causing a bias in measurements in small volumes like AUDS. The sample variance originating from a finite volume is called cosmic variance. In order to quantify the cosmic variance of the density measurement, a quantity $\xi$ can be defined as $\xi[\%] = 100 \times \sigma_{\text{var}} / \langle N \rangle$ with the variance $\sigma_{\text{var}}^2 = \sum_i (N_i - N) / n$ with $\langle N \rangle$ being the mean galaxy count in the selected volume, $N_i$ the number of galaxies in the volume $i$, and $n$ the total number of selected volumes.

To estimate $\xi$ in our sample, we selected 100 random fields in the SDSS North Galactic Pole field (using DR7) with the same size and redshift range as one of the AUDS fields. We then calculated the mean and standard deviation of the number of galaxies in these fields. To estimate the sampling error in $\xi$ and $\sigma_{\text{var}}$, we repeated that procedure 1000 times. The number of galaxies per random field var-
Table 3. To correct our HIMF for the effect of cosmic variance we calculated the relative density in redshift bins for both AUDS fields individually. We compared the number of galaxies per deg$^2$ in redshift bins in the small fields ($S1, S2$) around the AUDS fields and a large field ($L1$) to detect over- or under-dense regions in $S1$ and $S2$. We derive the density ratio $p_S/p_L$ of the AUDS field (Field 1, Field 2) in relation to a representative SDSS galaxy sample and its dependence on the redshift.

| $z$ | $p_S/p_L$ | $p_S/p_L$ |
|-----|-----------|-----------|
| 0.0 − 0.02 | 0.316 | 3.754 |
| 0.02 − 0.04 | 1.004 | 0.264 |
| 0.04 − 0.06 | 1.835 | 0.363 |
| 0.06 − 0.08 | 0.147 | 0.249 |
| 0.08 − 0.10 | 0.430 | 3.216 |
| 0.10 − 0.12 | 0.453 | 1.422 |
| 0.12 − 0.14 | 0.439 | 0.424 |
| 0.14 − 0.16 | 0.230 | 0.380 |
| 0.16 − 0.18 | 0.350 | 1.783 |

ied between 10 and 335 galaxies with an average number of $54 \pm 2 \pm 23 \pm 3$ galaxies or a sample variance of $\xi = 42 \pm 5 \%$. Doing the same test, selecting two AUDS sized fields as in the survey reduces the cosmic variance to $\%$. The decrease in cosmic variance corresponds to a reduction in the survey reduces the cosmic variance to $\%$.

We compared the number of galaxies per deg$^2$ in redshift bins in the small fields ($S1, S2$) of the DR7 SDSS in the redshift range of $\xi$ and $\xi = 33 \%$ for both fields, or $\xi = 46 \%$ which is within $1\sigma$ of our result.

The sample variation in the AUDS fields suggest that any density result will be correspondingly biased. However, a correction is possible as follows:

(1) We selected a large sub-sample from the spectroscopic DR7 SDSS galaxy sample ($L1$). $L1$ is in the main SDSS field ($130^\circ < \alpha < 236^\circ$, $0^\circ < \delta < 58^\circ$) selected to maximise the area ($5150$ deg$^2$) but to avoid the complex shape of the edges of SDSS (see Driver & Robotham 2010). Even though SDSS is not completely immune to cosmic variance itself, $L1$ is large enough that the expected difference between the mean density of $L1$ and that of the Universe is $\sim 7\%$ based on the results of Driver & Robotham (2010).

(2) We selected all SDSS galaxies in small fields surrounding each of the AUDS fields. We name these smaller SDSS fields $S1$ and $S2$. The area of $S1$ and $S2$ needs to be larger than the area of the original AUDS fields to reduce Poisson noise due to the small number of galaxy counts, but small enough such that their density remains correlated with the density of galaxies in the AUDS fields.

To find the optimum size of $S1$ and $S2$, we placed 100 AUDS-like volumes at random positions within SDSS. We then computed the average galaxy density of each AUDS-like volume. Around each of these 100 AUDS-like fields we placed another field of a larger size. For each field, we calculated the ratio of the density of the AUDS sized field to the larger field surrounding it. Repeating this procedure for differently sized field 250 times, we found that the standard deviation of the density ratio is minimised (at $11\%$) when the size of the surrounding field is $4.2$ deg$^2$. That is, the quadrature sum of Poisson noise and cosmic variance are lowest for this field size. Furthermore, the density ratio itself indicates that $S1$ and $S2$ are representative of the structure in the smaller field.

(3) We compared the number of galaxies per area in redshift bins in the small fields ($S1, S2$) and the large field ($L1$) to detect over- or under-dense regions in $S1$ and $S2$ (Figures 10 Table 3). It is important to note that we make the assumption that the optically selected fields ($S1, S2$ and $L1$) have the same distribution of galaxies as the $H\alpha$ selected AUDS sample. Looking at the respective redshift bins for each field we find the relative density of the small fields to vary between being $4.3$ times under-dense and $3.8$ times over-dense in comparison to the representative SDSS field ($L1$). Tracing the relative density in the AUDS fields in redshift bins allows us to correct for the effect of the HIMF as described in Section 3.1.

For this correction we make the assumption that optical data and the $H\alpha$ data correlate. To test this assumption we compare the bias factor for the SDSS fields ($S1, S2, L1$) with derived bias parameters for $H\alpha$ selected surveys, Seiják et al. (2005) measured the bias parameter for optical galaxies as a function of luminosity. Using their bias factors we find that the average bias factor of the galaxies in the $4.2$ deg$^2$ regions around the AUDS fields are: $<b_{S1, S2}> = 0.97 \pm 0.11$ while the $L1$ field has an average bias of $<b_{L1}> = 0.99 \pm 0.06$. Observations as well as numerical simulations estimate local bias parameters of the neutral hydrogen relative to the dark matter between 0.7 and 1.0, with a typical uncertainty of $\pm 0.2$ (Basilakos et al. 2007, Martin et al. 2012, Davé et al. 2013, see also Padmanabhan et al. 2015 for review). This shows that the clustering between optical selected galaxies and dark matter, and $H\alpha$ selected galaxies and dark matter are very similar on the spatial scales probed here, therefore allow to use the optical data to correct for over-/under-densities in the $H\alpha$ selected galaxies.

3 H I MASS FUNCTION (HIMF)

3.1 Methods

The HIMF $\Phi(M_{H\alpha})$ is a measure of the number of galaxies per unit volume dV for a given $M_{H\alpha}$ and is crucial input parameter for models and simulations describing galaxy formation and evolution. We derived the HIMF in co-moving coordinates to avoid changes in the measured densities purely caused by the expansion of the Universe.

The HIMF is often parameterised by a Schechter function defined as:

$$\Phi(M_{H\alpha}) = \Phi^* \left( \frac{M_{H\alpha}}{M^*} \right)^{-\alpha - 1} e^{-\frac{M_{H\alpha}}{M^*}},$$

with the faint end slope $\alpha$, the characteristic mass $M^*$, and the normalisation $\Phi^*$.

We use two different methods to derive the HIMF: The
\sum 1/V_{\text{max}}\text{ method }^{[\text{Schmidt}1968]}\text{ and the 2D stepwise maximum likelihood (SWML) }^{[\text{Zwaan et al.2003}].}

The basic $1/V_{\text{max}}$ method assigns each galaxy a weighting factor which corresponds to the inverse maximum volume ($V_{\text{max}}$) in which a galaxy can be detected inside the survey volume.

We adapt this method to compute the maximum search volume using the relation for completeness in equation [3]. The completeness for a galaxy changes if the galaxy is shifted to a different part of the cube as the noise changes within the field and with frequency.

We therefore create two additional data cubes of the same size as the original cubes. In the first one, each pixel value corresponds to the co-moving volume in Mpc$^3$ corresponding to that pixel. In the second data cube each pixel value corresponds to the RMS noise of neighbouring pixels. We compute the expected completeness $C_i$ if that galaxy were placed at any of the pixels within the survey volume using equation [3]. For that purpose, we scaled $S_{\text{int}}$ and $W$ to the distance corresponding to each pixel, and used the RMS of the noise in the pixel cube. The effective volume per pixel is then the product of completeness and volume $V_i$ for each galaxy.

The volume in which a given galaxy is detectable, hereafter called the “detectable volume” is then the sum over the effective volume of each pixel

$$V_{\text{max}} = \sum_j C_i \times V_i.$$  \hfill (5)

The co-moving HIMF is then defined as the sum over the $M_{\text{HI}}$ range of all galaxies $j$ in a $M_{\text{HI}}$ bin with the bin size $\Delta M_{\text{HI}}$,

$$\Phi(M_{\text{HI}}) = \sum_j \frac{1}{V_{\text{max},j}}.$$  \hfill (6)

In addition to the volume cube, we also created a cosmic-variance-corrected volume cube. For the cosmic-variance-corrected cube we multiplied each volume pixel in a redshift bin with the relative density of that redshift bin found in the optical sample (Table [3])

$$V_{\text{max,CV}}[z_1, z_2] = \frac{\rho_{\text{opt}}[z_1, z_2]}{\rho_{L}[z_1, z_2]} \times V_{\text{max}}[z_1, z_2].$$  \hfill (7)

That means that the volume of a pixel in an under-dense region is “shrunk” while the volume of a pixel in an over-dense regions is “enlarged”. The $1/V_{\text{max}}$ method has the advantage of being fast and simple to implement as well as producing a normalised HIMF.

The second method to calculate the HIMF is the stepwise maximum likelihood method developed by Estathiou et al. [1988] as a superior tool to derive the luminosity functions of galaxies. The idea behind the SWML technique is to find the function $\Phi(M_{\text{HI}})$ that yields maximal joint probability of detecting all galaxies in the sample. It has the advantage over the $1/V_{\text{max}}$ method because the results are independent variables of density. In the SWML method the galaxy mass distribution is split into bins assuming a constant distribution in each bin. It is not necessary to assume a functional form for the HIMF. Based on SWML method, Zwaan et al. [2003] developed the 2 dimensional - SWML method which solves for the space density of $M_{\text{HI}}$ and $W$ at the same time.

\begin{table}[h!]
\centering
\caption{Comparison of different results for the HIMF from 21 cm surveys.}
\begin{tabular}{|l|l|c|c|c|}
\hline
Survey & Reference & $\alpha$ & $\log(M_{\text{HI}}^*/M_\odot)$ & $\Phi^*$ \\
& & & $+2 \log h$ & $(10^{-3} h^3 \text{Mpc}^{-3})$ \\
\hline
AHISS & Zwaan et al. [1997] & -1.2 & 9.55 & 14 \\
ADBS & Rosenberg & Schneider [2002] & -1.53 & 9.63 & 11.9 \\
HIPASS & Springob et al. [2005] & -1.24 & 9.68 & 9.3 \\
ALFALFA & Zwaan et al. [2005] & -1.37 $\pm$ 0.03 & 9.55 $\pm$ 0.02 & 14.2 $\pm$ 1.9 \\
AUDS & This work & -1.33 $\pm$ 0.02 & 9.71 $\pm$ 0.01 & 14.0 $\pm$ 0.9 \\
\hline
\end{tabular}
\end{table}
steady, we used a single value for the RMS for each detected galaxy.

We recovered the normalisation for the HIMF using the mean galaxy density \( n \). \( n \) is calculated by correcting the measured distribution of galaxies with the selection function \( S(D) \) (Section 3.3.1) [Davis & Huchra (1982)] presented several estimators to calculate \( n \). We choose the \( \Pi = N_{\text{total}}/\int S(D)\,dV \) estimator as it is the most stable one for small numbers even though it has a slight dependency on large scale structure.

Figure 12 compares the 2DSWML HIMF and the \( \Sigma \) 1/\( V_{\text{max,CV}} \) HIMF. We find that the data points for both methods are in reasonably good agreement at the high mass end (\( M_{\text{HI}}>10^{5.5} M_\odot \)) with each other. At lower masses the slope of the 2DSWML (red dashed line) is less steep. Even though most of the data points agree with each other within the 1\( \sigma \) errorbar the 2DSWML HIMF points are systematically lower causing a significant difference in the fitted slope. The best-fit to the 2DSWML HIMF function yields \( \Phi^* = (9.82 \pm 5.40) \times 10^{-3} \, h^3 \, Mpc^{-3} \), \( \log(M_{\text{HI}}/M_\odot) = (9.70 \pm 0.07) + 2 \log h \) and \( \alpha = -1.14 \pm 0.10 \). The good agreement between the normalisation of the 2DSWML and the \( \Sigma \) 1/\( V_{\text{max,CV}} \) HIMF is encouraging, as the normalisation for the 2DSWML HIMF was calculated independently.

### 3.3.1 Selection Function
The selection function \( S(D) \) is the probability that a galaxy at a distance \( D \) is detected by the survey. We calculate \( S(D) \) for the 2DSWML and the \( \Sigma \) 1/\( V_{\text{max}} \) HIMF as described in Zwaan et al. (2003).

Assuming a homogeneous space distribution of galaxies, the number of galaxies observed in a distance bin of the size \( \Delta D \) at the distance \( D \) is \( n(D) = \Omega D \Delta D \pi S(D) \) with the solid angle \( \Omega \) and the average number of galaxies \( \bar{n} \). Figure 12 compares the 2DSWML with the 1/\( V_{\text{max}} \) HIMF showing that they are not in good agreement.

The galaxy numbers derived by the selection function give lower numbers of nearby galaxies while overestimating galaxies at larger distances in comparison to the detected galaxy distribution. The effects could be caused by large scale structure which are not traced by the selection function. A good example is the over-density at \( D \approx 270 \, Mpc \) in the AUSN histogram which does not show up in the prediction. A possible explanation for the over-estimation of high redshift galaxies lies in the general limitation of AUS to pick up galaxies at high redshift largely caused by RFI, as described in Section 2.1.

### 3.4 Influence of Completeness
We rate the quality of our detected galaxies by their completeness coefficient \( C \) and only include galaxies with \( C>0 \), excluding the lowest mass galaxy for the HIMF fit. In Figure 13 we compare the 1/\( V_{\text{max,CV}} \) HIMF for different cuts in the completeness coefficient (\( C = 0.4, 0.5, 0.6 \)). The plot shows the lower mass galaxies (\( M < 10^{9.5} M_\odot \)) are excluded first causing the slope to flatten. High completeness cutoffs (\( C > 0.5 \)) exclude galaxies with masses around the knee of the HIMF resulting in smaller values for the normalisation \( \Phi^* \). The change in the HIMF with completeness
is an intriguing result as unlike HIPASS and ALFALFA, the low-mass AUDS galaxies are located well beyond the local volume and may represent more typical volumes in the Universe.

3.5 Evolution of the HIMF

The redshift range of AUDS allows us to split the sample into redshift bins to see evolutionary trends. We split our sample at the mean redshift of our sample (z = 0.065). This creates a lower redshift bin with 52 galaxies and a mean redshift of z = 0.036 and higher redshift bin with 50 galaxies and a mean redshift of z = 0.095. The binning by redshift indirectly means we divide the galaxies by their mass, as the faint galaxies can only be detected close by while rarer, massive galaxies need the large volume of the high redshift bin to be found.

However, there is some overlap in a mass range of $10^8$ to $10^{10} M_\odot$ as can be seen in Figure 14. There appears to be evidence for only a modest change in the HIMF. Formally, if $\alpha$ and $M_{50}$ are held fixed at their best-fit value for the whole sample, $\Phi^*$ is $\sim 16\%$ lower for the higher redshift sample. Any change in the density of galaxies with H I mass $> 10^{10}$ or $<10^8 M_\odot$ cannot be explored. The full AUDS sample will provide tighter limits on the amount of evolution that can arise from feedback processes in galaxies over this redshift range (Kim et al. 2013).

3.6 Comparison of HIMF

The HIMF is a useful tool to describe how much H I is locked up in galaxies. The slope of the HIMF gives the relative importance of low mass and high mass galaxies. An early HIMF measured from the AHISS survey (Zwaan et al. 1997) found a flat faint end slope of $\alpha = -1.2$. The Arecibo Dual-Beam Survey (ADBS) (Rosenberg & Schneider 2002) found a much steeper slope of $\alpha = -1.53$. However, both these surveys suffer from small numbers and small volumes.

The two largest blind H I surveys HIPASS and ALFALFA (40%) find slopes $\alpha = -1.37 \pm 0.03$ (Zwaan et al. 2005) and $\alpha = -1.33 \pm 0.02$ (Martin et al. 2010) respectively. The good agreement between the two surveys seems to suggest that the slope of the HIMF in the local Universe is well defined. However, at the high mass end the ALFALFA survey reveals a larger number of galaxies than HIPASS (Figure 15). Martin et al. (2010) explains this difference with the higher upper redshift limit and larger volume in comparison to HIPASS.

The AUDS sample allows us to construct an HIMF for the first time which is independent of the local volume and at much higher redshifts and to higher sensitivities than previous surveys. Figure 15 compares the results from AUDS with the best-fit of HIPASS and ALFALFA. AUDS measures a slightly steeper slope $\alpha$ than HIPASS or ALFALFA, but overall the surveys agree well with each other. We find a tentative rise at very low masses caused by faint, low-mass galaxies detected in our survey, which might have been missed in previous, less sensitive surveys. Twice as many galaxies are detected compared to the prediction from the
extrapolated HIMF. Unfortunately the overall small-number statistics make it necessary to interpret this result with caution. Although the detected faint galaxies are well beyond the Local Group, the volume sampled at this mass level is only about $8 \, h^{-3} \, \text{Mpc}^3$, so the cosmic variance is high.

Figure 14. Top panel: Comparison between the HIMF derived from the low redshift (red diamonds) and high redshift (black triangles) sub-sample. The blue dashed line is the fit to the complete AUDS sample (Figure 11). In the mass range of $10^8 - 10^{10} h^{-2} M_\odot$ the low redshift HIMF is significantly higher than the high redshift HIMF. The discrepant high redshift bin at $10^{9.75} h^{-2} M_\odot$ only contains one galaxy. Lower panel: The number distribution of the low redshift sample $(z = 0.036)$ in red and the high redshift sample $(z = 0.094)$ in black.

Figure 15. Comparison between the AUDS HIMF (red diamonds and red dashed line) and the best-fit Schechter functions from HIPASS (blue solid line) and ALFALFA (green dot dashed line). The individual data points of the HIMF agree (within the error-bars) with the two surveys in the local Universe, apart from a small number of low $\text{H} \, \text{i}$ mass AUDS galaxies.

Figure 16. The distribution of the $\text{H} \, \text{i}$ mass density as a function of $M_{\text{HI}}$. The $\text{H} \, \text{i}$ mass density is derived by multiplying the HIMF by the centre of each $M_{\text{HI}}$, mass bin. The red diamonds and dashed line show the mass density derived from the $\Sigma 1/V_{\text{max, CV}}$ method and the black diamonds and dashed line correspond to the $\Sigma 1/V_{\text{max}}$ method. The blue line indicates the $\text{H} \, \text{i}$ mass density from HIPASS. The comparison shows that for AUDS there is a slightly higher contribution from both faint and bright galaxies to the overall $\text{H} \, \text{i}$ density.

4 COSMIC $\text{H} \, \text{i}$ DENSITY $\Omega_{\text{H} \, \text{i}}$

4.1 $\text{H} \, \text{i}$ Mass Density ($\rho_{\text{HI}}$) and Cosmic $\text{H} \, \text{i}$ Density ($\Omega_{\text{H} \, \text{i}}$)

Figure 16 shows the $\text{H} \, \text{i}$ mass density $\rho_{\text{HI}}$ for different $\text{H} \, \text{i}$ masses; we compare the results before and after cosmic variance correction. The lines indicate the best-fit to $\rho_{\text{HI}}$ using equation 4. The measured slope of the HIMF has important implication for the contribution to the $\text{H} \, \text{i}$ mass density $\rho_{\text{HI}}$ of low-mass galaxies. The measured slope of the AUDS sample that the gas mass density is dominated by galaxies with masses around $10^{9.7} h^{-2} M_\odot$ corresponding to the knee of the HIMF. Comparing the results of AUDS and HIPASS (Figure 16) shows differences between the two surveys. AUDS detects more galaxies at the low mass end and also detect slightly more galaxies at the very high mass end.

The total $\text{H} \, \text{i}$ mass density can then be computed by integrating the best Schechter fit using $\rho_{\text{HI}} = \Gamma (\alpha + 2) \times \Phi^* M_{\text{HI}}^{\alpha}$, where $\Gamma$ is the Euler Gamma function and $\alpha$, $\Phi^*$ and $M_{\text{HI}}$ the fit parameters from the Schechter fit. This gives $\rho_{\text{HI}} = (6.24 \pm 0.20) \times 10^7 h M_\odot \text{Mpc}^{-3}$ for the $\Sigma 1/V_{\text{max}}$ method and $\rho_{\text{HI}} = (6.53 \pm 0.31) \times 10^7 h M_\odot \text{Mpc}^{-3}$ for $\Sigma 1/V_{\text{max, CV}}$. We estimated the error using the jackknifing technique as with the HIMF calculation (Section 4.2).

In addition to this, we can also calculate $\rho_{\text{HI}}$ by summing over individual data points in the $\text{H} \, \text{i}$ density distribution. The results are $\rho_{\text{HI}} = (4.46 \pm 0.21) \times 10^7 h M_\odot \text{Mpc}^{-3}$ and $\rho_{\text{HI}} = (5.78 \pm 0.20) \times 10^7 h M_\odot \text{Mpc}^{-3}$ for the uncorrected and corrected values respectively. The results of the summation and integration of $\rho_{\text{HI}}$ agree within the $1\sigma$ error-
bars indicating that our survey was able to adequately probe below the knee of the HIMF to capture most of $\Omega_{HI}$. To compare our results to other measurements we compare the co-moving $H$ density, $\rho_{HI}$, to the current ($z = 0$) critical density of the Universe, $\rho_{c,0}$, to derive the cosmic $H$ density

$$\Omega_{HI} = \frac{\rho_{HI}}{\rho_{c,0}} = \frac{8\pi G}{3H_0} \rho_{HI}, \quad (8)$$

where $G$ is the Gravitational constant and $H_0$ is the Hubble constant at $z = 0$. Note that the definition of $\Omega_{HI}$, consistent with previous work, simply scales the co-moving density by the current critical density and not by the co-moving, redshift dependent critical density. We find $\Omega_{HI} = (1.63 \pm 0.08) \times 10^{-4} h^{-1}$ before correction and $\Omega_{HI} = (2.33 \pm 0.07) \times 10^{-4} h^{-1}$ after cosmic variance correction, summing up the data points. As noted in Section 4.2, the cosmic variance correction has formal uncertainties of 8% in piggy-backing to the larger 4.2 deg$^2$ SDSS field (11% for a single field, 8% for two fields) and 7% for SDSS as a whole (Driver & Robotham 2010), giving rise to a combined systematic uncertainty of 11%. However, there are additional factors due to differing bias factors for $H$ and optical surveys, and unknown stochasticity factors which may raise this overall uncertainty (see Chang et al. 2010) which are neglected in this paper.

### 4.2 Evolution of the Cosmic $H$ Density $\Omega_{HI}$

To trace the evolution of cool gas with cosmic time we split our sample in different bins of redshift. For each sub-sample we derived the HIMF and calculated $\Omega_{HI}$. As the number of the galaxies in the redshift bins are relatively small we decided to fit the HIMF with a Schechter function keeping $M_{HI}$ and $\alpha$ fixed using the results we found for the $\sum 1/V_{max,CV}$ and only fit the normalisation $\Phi_*$. $\Omega_{HI}$ is then calculated by integrating over the Schechter function. First we split the sample in two redshift bins at the mean redshift of the sample ($z = 0.065$), creating two samples with mean redshifts of $(z) = 0.036$ and $(z) = 0.095$. We find $\Omega_{HI} = (3.68 \pm 0.39) \times 10^{-4} h^{-1}$ for the low redshift sample and $\Omega_{HI} = (1.93 \pm 0.19) \times 10^{-4} h^{-1}$ for the high redshift sample. The results indicate a possible decrease in $\Omega_{HI}$ towards the upper end of the redshift range of the sample.

Next we selected the 8 highest redshift galaxies between the redshifts of 0.119 and 0.132 to probe the high redshift end of our sample. Integrating over the Schechter function we find $\Omega_{HI} = (2.05 \pm 0.78) \times 10^{-4} h^{-1}$. Due to the small numbers of galaxies in this bin Poisson scatter is the dominant source of error. We also selected a low redshift with the 8 lowest redshift galaxies. The result is $\Omega_{HI} = (3.03 \pm 1.89) \times 10^{-4} h^{-1}$ agreeing well with results from HIPASS and ALFALFA as well as the AUDS lower redshift bin.

The results for $\Omega_{HI}$ for different redshift bins are summarised in Figure 17 as well as Table 7. Note that the measurements of the 8 high and 8 low-redshift galaxies are not independent of the data binned at the mean redshift of the sample. It appears likely from this comparison that the low redshift points are high compared with those at higher redshift. The HIPASS result agrees better with the high redshift points suggesting that there is no evolution detected and that the low redshift results may be subject to cosmic variance errors.

### 4.3 Discussion

Measuring $\Omega_{HI}$ and its evolution with redshift has long been an important scientific question. 21 cm measurements at low redshift provide a good constraint for $\Omega_{HI}$ in the local Universe. Beyond that measurements have been more difficult. Until very recently there has been a huge gap between these local measurements and measurements at high redshift $z > 1.5$ using DLA measurements. Moreover, this period is marked by a significant change in star formation rate and therefore interesting for galaxy evolution studies. Successful attempts have been made using the stacking technique to
Table 7. Results for $\Omega_{H_1}$ binning the sample in different redshift bins for AUDS.

| $\Delta z$ | $z$ | Number | $\log(\frac{M_{H_1}}{M_\odot}) + 2\log h$ | $\Omega_{H_1}$ |
|-----------|-----|--------|---------------------------------------------|----------------|
| 0 - 0.013 | 0.009 | 8      | 6.3 - 9.3                                   | 5.33 ± 1.89 |
| 0 - 0.065 | 0.036 | 52     | 6.3 - 9.5                                   | 3.68 ± 0.39 |
| 0.065 - 0.132 | 0.095 | 53 | 8.4 - 10.3 | 1.93 ± 0.19 |
| 0.119 - 0.132 | 0.127 | 8 | 8.9 - 10.3 | 2.24 ± 0.78 |
| 0 - 0.132 | 0.065 | 102    | 6.3 - 10.3                                  | 2.33 ± 0.07 |

*a* Errors derived using Poisson statistics.

*b* Errors derived using jackknifing.

bridge that intermediate redshift gap [Rhee et al. 2013; Delhaize et al. 2013] as well as the intensity mapping technique (Chang et al. 2010; Masui et al. 2013) at higher redshift (Figure 18).

ALFALFA. These observations constitute strong evidence that the HIMF did not rapidly evolve in the last billion years.

At redshifts up to 0.005, AUDS probes the HIMF at masses as low as log($M_{H_1}/M_\odot$) = 5.6 + 2 log h. We detected twice as many galaxies as predicted from the local HIMF for log($M_{H_1}/M_\odot$) < 7 + 2 log h. This might be an indication that the HIMF rises more steeply than previously thought at the very low mass end. If correct, this finding implies that the fraction of $M_{H_1}$ contributed by low mass galaxies may be more significant than previously appreciated.

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**References**

Abazajian K. et al., 2004, The Astronomical Journal, 128, 502

Auld R. et al., 2006, Monthly Notices of the Royal Astronomical Society, 371, 1617

Barnes D. G. et al., 2001, Monthly Notices of the Royal Astronomical Society, 322, 486

Basilakos, S., Plionis, M., Kovač, K., & Voglis, N. 2007, Monthly Notices of the Royal Astronomical Society, 378, 301

Catinella B., Haynes M. P., Giovanelli R., Gardner J. P., Connolly A. J., 2008, The Astrophysical Journal Letters, 685, L13

Chang T.-C., Pen U.-L., Bandura K., Peterson B. J., 2010, Nature, 466, 463

Dave, R., Katz, N., Oppenheimer, B. D., Kollmeier, J. A., & Weinberg, D. H. 2013, Monthly Notices of the Royal Astronomical Society, 434, 2645

Davis M., Huchra J., 1982, The Astrophysical Journal, 254, 437

Delhaize J., Meyer M. J., Staveley-Smith L., Boyle B. J., 2013, Monthly Notices of the Royal Astronomical Society, 433, 1398

Driver S. P., Robotham A. S. G., 2010, Monthly Notices of the Royal Astronomical Society, 407, 2131

Elstathieu G., Ellis R. S., Peterson B. A., 1988, Monthly Notices of the Royal Astronomical Society, 232, 431

Fernández X. et al., 2013, The Astrophysical Journal Letters, 770, L29

Freudling W. et al., 2011, The Astrophysical Journal, 727, 40

Giovanelli R. et al., 2005, The Astronomical Journal, 130, 2598

Haynes M. P. et al., 2011, The Astronomical Journal, 142, 170

Henning P. A. et al., 2010, The Astronomical Journal, 139, 2130

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Figure 18. Evolution of the cosmic $\Omega_{\text{HI}}$ density with redshift. The colour corresponds to the type of measurement. Blue: blind 21 cm surveys, Magenta: $\text{HI}$ stacking, Cyan: Intensity mapping, Green: Measurements from Ly-$\alpha$ absorption spectra, Red: AUDS. We present the result using the complete AUDS sample (single thick diamond) as well as the binned results (thin diamonds). Observations show no significant evolution in $\Omega_{\text{HI}}$ out to $z = 0.2$. Calculating the best combined estimate based on all measurements of $\Omega_{\text{HI}}$ out to this redshift we find the 1σ interval marked in grey. The black dashed line is the prediction presented by Lagos et al. (2014), using semi-analytic models described in Lagos et al. (2012).
Staveley-Smith L., 2014, Monthly Notices of the Royal Astronomical Society, 438, 1176
Wolfe A. M., Gawiser E., Prochaska J. X., 2005, araa, 43, 861
Wong O. I. et al., 2006, Monthly Notices of the Royal Astronomical Society, 371, 1855
Zwaan M. A., Briggs F. H., Sprayberry D., Sorar E., 1997, The Astrophysical Journal, 490, 173
Zwaan M. A., Meyer M. J., Staveley-Smith L., Webster R. L., 2005, Monthly Notices of the Royal Astronomical Society, 359, L30
Zwaan M. A. et al., 2004, Monthly Notices of the Royal Astronomical Society, 350, 1210
Zwaan M. A. et al., 2003, The Astronomical Journal, 125, 2842
Zwaan M. A., van Dokkum P. G., Verheijen M. A. W., 2001, Science, 293, 1800