Hydrogen 21-cm Intensity Mapping at redshift 0.8

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Observations of 21-cm radio emission by neutral hydrogen at redshifts $z \sim 0.5$ to $\sim 2.5$ are expected to provide a sensitive probe of cosmic dark energy\cite{1,2}. This is particularly true around the onset of acceleration at $z \sim 1$, where traditional optical cosmology becomes very difficult because of the infrared opacity of the atmosphere. Hitherto, 21-cm emission has been detected only to $z=0.24$\cite{3}. More distant galaxies generally are too faint for individual detections but it is possible to measure the aggregate emission from many unresolved galaxies in the 'cosmic web'. Here we report a three dimensional 21-cm intensity field at $z=0.53$ to 1.12. We then co-add HI emission from the volumes surrounding about ten thousand galaxies (from the DEEP2 optical galaxy redshift survey\cite{4}). We detect the aggregate 21-cm glow at a significance of $\sim 4$ sigma.

The DEEP2 optical redshift survey\cite{4} provides a rich sample for study of the Universe at redshifts near one. The team recorded optical spectra for 50,000 faint galaxies out to redshift $z = 1.4$, utilizing the DEIMOS spectrograph on the Keck II telescope. The DEEP2 sample consists of four survey fields, each $\sim 120' \times 30'$ in size. Roughly 10,000 of the DEEP2 galaxies fall in the
redshift range which overlaps the range of the radio data described below.

Using the Green Bank Telescope (GBT), we recorded radio spectra across two of the DEEP2 fields. We are searching for redshifted HI 21-cm emission, and for such emission the radio spectra span the redshift range $0.53 < z < 1.12$. This corresponds to a comoving distance 1400 to 2600 $h^{-1}$ Mpc assuming a $\Lambda$CDM cosmology\(^5\). The full-width-half-maximum GBT beam is about 15’, which corresponds to 9 $h^{-1}$ comoving Mpc at $z = 0.8$ so the angular resolution falls far short of that needed to separate one galaxy from the next. In the redshift dimension the spatial resolution is much higher than the transverse resolution. To keep the data set manageable we average in frequency to a resolution 430kHz, or 2$h^{-1}$ comoving Mpc. Unlike the optical survey we make no attempt to detect individual galaxies with the radio data. More observational details can be found in the Supplementary Information Section 1.

We have two goals for the radio observations. First, we examine whether it is possible to map the cosmic web in three dimensions, without detecting individual galaxies, a technique called ‘intensity mapping’. Second, we measure the 21 cm brightness and neutral gas density at high redshift. To accomplish the first goal we study the 21 cm data by itself. For the second goal we draw on the DEEP2 galaxy positions as guides, using them to locate likely bright spots of the 21 cm glow. If sufficient gas is present, and if the intensity mapping technique is viable, it will be possible to use this technique to economically map over 50 times the volume that has so far been surveyed.

To get to the 21 cm signal we must remove two much brighter sources of flux from the
data, Radio Frequency Interference (RFI) from terrestrial transmitters and broadband (continuum) emission by astronomical sources within and outside of the Milky Way.

We use polarization to identify and excise unwanted signals. Television, mobile telephone transmitters, and other terrestrial sources produce strongly polarized flux which remains polarized even after scattering. The GBT has two linearly polarized feed antennas at the focus of the parabolic reflector. RFI entering the feed antenna sidelobes produces signals in the data stream that correlate between the two polarization channels. 21-cm emission is not polarized, so we calculate the cross-correlation coefficient between the two polarizations and cut any flux with coefficient greater than 2%. This removes \(\sim 5\%\) of the data. The radio data, after this cut, is shown in the top panel of Figure 1. At this stage of the analysis astronomical continuum sources present a fluctuation of brightness temperature across the sky of rms amplitude \(\sim 125 \text{ mK}\), which is about a thousand times larger than the HI signal.

We remove astronomical continuum flux using a new matrix-based method. After a calibration procedure described in the Supplementary Information we arrange the data into a matrix in which the row index represents celestial coordinates, and the column index represents the observation frequency (redshift). All three panels in Figure 1 show such matrices. Continuum sources, including bright radio sources, blends of weak extragalactic sources, and Galactic synchrotron sources, extend across all columns of the matrix. They show up as horizontal stripes in the top panel of Figure 1. In contrast, 21-cm sources are tightly localized to a few columns. Within this matrix, a continuum source can be factored into a product of a function of position (for an isolated
point source this is the beam pattern of GBT), and a low order function of frequency (the smooth spectrum), $T(x, \nu) = f(x)g(\nu)$. The functions $f(x)$ and $g(\nu)$ are singular eigenmodes of the matrix, so we perform a singular-value decomposition (SVD) to detect continuum flux, which we subtract. We are then left with the brightness temperature field $\delta T_b$, shown in the middle panel of Figure 1. The SVD technique is non-parametric. No particular mathematical form for the spectra of the continuum sources is assumed.

We next examine the radio data without referring to the optical survey. After foreground subtraction, keeping only the component that is consistent over several days, we find the intensity field has a temperature fluctuation $464 \pm 277 \mu K$, on pixel scales of $(2 h^{-1})^3$ comoving Mpc$^3$. Note that our resolution element, $(9 h^{-1})^3$ comoving Mpc$^3$, is larger than the pixel. The noise in this measurement exceeds that expected from the antenna temperature and is likely due to residuals of emission by terrestrial transmitters and errors in the astronomical continuum removal process. Because of the weak statistical significance, this fluctuation amplitude should be treated an upper limit to the 21-cm brightness auto-correlation, rather than a detection of cosmic structure.

To further reduce uncertainty we proceed with the cross-correlation (stacking) technique. Cross-correlation reduces the error because terrestrial RFI and residuals of the continuum sources are randomly located compared to the locations of optically bright galaxies. To carry out the cross correlation we arrange the DEEP2 data in the same matrix as the radio data, as shown in Figure 1. We calculate the weighted cross correlation $\zeta$ between the data in the bottom two panels of the figure, producing the correlation function in Figure 2. We detect significant cross-correlation
power out to lag $\sim 10 \, h^{-1}$ comoving Mpc.

To check this cross-correlation result we carry out a statistical null test. We randomize the optical redshifts many times, each time repeating the correlation calculation. We find no significant correlation in the randomized sets and we use the bootstrap variance to estimate the uncertainties in our measurements. The null test confirms that the residual RFI and astronomical continuum sources are unlikely to cause false detection of 21-cm emission.

The measured cross correlation can be compared to a model prediction. Locations of optically cataloged galaxies are known to be correlated amongst themselves, and 21-cm emission is also thought to originate in galaxies. We therefore model the cross-correlation by adopting the DEEP2 optical galaxy auto-correlation power law $^6$$^7$, $\xi(R) = (R/R_0)^{-1.66}$, where $R_0 = 3.53 \, h^{-1}$ Mpc at $z=0.8$, which we convolve with the telescope primary beam in the transverse direction. In the radial direction we must account for peculiar velocities. The pairwise velocity distribution is modeled as a Gaussian with standard deviation $\sigma_{12} = 395$ km/sec, using the relation $\sigma_{12} \sim H(z) \, R_0 \, ^{2}$.$^9$. The expected correlation, calculated using this model, is plotted in Figure 2 using the best fit value of the correlation amplitude.

We use the correlation amplitude to constrain the neutral hydrogen density at redshift 0.8. The cross-correlation $\zeta$ between the optical galaxy density field and the neutral hydrogen temperature field is related to the density structure by (e.g., $^1$)

$$\zeta = \langle \Delta T_b \delta_{opt} \rangle = 284 \, b \, r \, \delta_{opt}^2 \left( \frac{\Omega_{HI}}{10^{-3}} \right) \left( \frac{h}{0.73} \right) \left( \frac{\Omega_m + (1 + z)^{-3}\Omega_{\Lambda}}{0.37} \right)^{-0.5} \left( \frac{1 + z}{1.8} \right)^{0.5} \mu\text{K}. \quad (1)$$
where $\Delta T_b$ is the neutral hydrogen 21-cm brightness temperature fluctuations, $T_b = 284 \, \mu K$ is the 21-cm mean sky brightness temperature at $z = 0.8$, $\Omega_{HI} \equiv \rho_{HI}/\rho_{c,0}$ is the HI density over the present-day critical density, $\Omega_m$ the matter density, and $h$ is the current expansion rate in units of $100 \, \text{km/s Mpc}^{-1}$. $\delta_{opt}$ is the optical density field, which is related to the neutral hydrogen density field, $\delta_{HI} = b\delta_{opt}$, where $b = \langle \delta_{HI}^2 \rangle^{1/2} / \langle \delta_{opt}^2 \rangle^{1/2}$ is the bias factor, and $r = \langle \delta_{HI}\delta_{opt} \rangle / (\langle \delta_{HI}^2 \rangle \langle \delta_{opt}^2 \rangle)^{1/2}$ is the stochasticity. Note that $|r| \leq 1$, and our data show $r$ to be positive. The effective $\delta_{opt}^2$ values for DEEP2 Field-3 and Field-4 calculated with simulations described in Supplementary Information are 2.3 and 3.3, respectively. A cosmic hydrogen fraction of $\rho_H/\rho_b = 0.75$ is assumed.

The correlation function at zero lag has a 21-cm brightness temperature $157 \pm 42 \mu K$ at a mean effective redshift of $z = 0.8$, from which we infer a value of $\Omega_{HI} = (5.5 \pm 1.5) \times 10^{-4} \times (1/rb)$. Combining all data in Figure 2, the statistical significance of the detection is at the four sigma level.

The cross correlation technique measures only the 21-cm component that clusters near optically bright galaxies. There may be additional neutral gas at high redshift that is more broadly distributed, or the gas may be clumped, but at locations not near the DEEP2 galaxies. If so, our fitting of the optical galaxy correlation function to the data underweights this component. Our detection should therefore be treated as a lower bound to the total neutral gas density.

We estimate the contribution of the DEEP2 galaxies to the total zero-lag 21-cm flux variance is $\sim 20\%$ of the total. The radio data has many galaxies in each independent resolution element
so we can not separate flux in the zero-lag bin due to the 21-cm emission of the DEEP2 galaxies themselves from that due to aggregate emission of other galaxies concentrated nearby. The effective resolution element in this survey is \((9 h^{-1} \text{Mpc})^3\), determined by the telescope angular resolution and pairwise velocity dispersion. On average there are five DEEP2 galaxies in each resolution element. We assume these have 21 cm luminosities similar to low redshift galaxies in estimating their contribution.

At \(z \sim 1\), the neutral gas density \(\Omega_{HI}\) is particularly difficult to measure. At low redshifts (using HST), \(\Omega_{HI}\) has been measured via the Lyman-alpha-line absorption of ultraviolet light from distant quasars. Extrapolating to redshift 1.2, \(\Omega_{HI} = 7.2 \pm 2.2 \times 10^{-4}\) is found\(^9\). Similar observations can also be made with ground based telescopes at redshifts above two, since these wavelengths penetrate the atmosphere. However at redshift \(z = 2.2\), a substantially lower neutral hydrogen content \(\Omega_{HI} = 3.9 \pm 0.7 \times 10^{-4}\) is found\(^10\). Despite the high redshift, the ground based measurement is consistent with the measured present day value\(^11\). This implies little evolution of the average gas density, at conflict with the clear evolution of star formation rate. Our data constrain the combination \(\Omega_{HI}rb\), but there is so far no observational constraint on the 21-cm stochasticity \(r\) or the bias \(b\). Theoretical estimates of \(rb\) lie in the range 0.5 to 2, a range too wide for the 21 cm data to weigh in. With further 21 cm observations \(r\) can be measured by detecting both the auto and cross correlations, and \(b\) can be determined by measuring velocity space distortions\(^12\). This in turn would allow measurement of the neutral gas density at \(z \sim 1\) via 21 cm intensity mapping.

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Acknowledgements We are grateful to the GBT support staff, in particular Toney Minter and Paul Ruffle, for their generous help with the observation. We thank Kevin Blagrave, Olivier Doré, Patrick McDonald, Jonathan Sievers, Kris Sigurdson, Renbin Yen for many useful discussions. We acknowledge financial support by NSERC, NSF, and NRAO. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Author Contribution T.-C. and U.-L.P. analyzed and interpreted the data. K.B. conducted the remote observations. J.B.P. was in charge of the paper writing. All authors were present at the telescope for the on-site observations and contributed to the writing of the manuscript and Supplementary Information.

Competing Interests The authors declare that they have no competing financial interests.

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Figure 1 Spectra of DEEP2 Field-4. The top two panels show radio flux arranged with redshift horizontal and right ascension vertical. Each panel contains data collected in two declination bins, separated by 15’, roughly one GBT beam width. The higher declination strip occupies the top half of each panel. The pixels are 2 h$^{-1}$ comoving Mpc in size in each dimension. The top panel shows measured flux after the polarization cut has removed the brightest terrestrial emission. The rms fluctuation of the map is 128mK. Vertical structures in the top panel are due to residual RFI: the wide stripes are digital television signals and narrow vertical features are analog television carriers. Redshift windows free of RFI are rare on the right side of the plot, which corresponds to greater redshift and lower frequency. The horizontal bright stripes are due to continuum emissions by astronomical sources (NVSS J022806+003117 and NVSS J022938+002513), and the width of these stripes shows the GBT beam width. The middle panel shows the inverse-variance-weighted radio brightness temperature, after subtraction of continuum sources. The weighted rms fluctuation is 3.8mK. Even though the standard deviation of the flux values in this images has been reduced by more than a factor of 30 compared to the top panel, residual RFI and continuum emission dominates the overall variance. The bottom panel shows the optical galaxy density in the DEEP2 catalog, smoothed to match the resolution of the radio data. The rms fluctuation of the map is 1.8. The cross correlation function in Figure 2 is calculated by multiplying the middle and bottom panels with a relative displacement (lag) in redshift, then calculating the variance of the product map.

Figure 2 The cross correlation between the DEEP2 density field and GBT HI brightness
temperature. The crosses are the measured cross-correlation temperature, while error bars are the $1\sigma$ bootstrap errors generated using randomized optical data, and the diamonds are the mean null-test values over 1,000 randomizations as described in SI; the same bootstrap procedure performed on randomized radio data returns very similar null-test values and error bars. The solid line is a DEEP2 galaxy correlation model which assumes a power law correlation and includes the GBT telescope beam pattern as well as velocity distortions, and uses the best-fit value of the cross-correlation amplitude.
Supplementary Information

1 Observation details

We use the Green Bank Telescope (GBT) in drift scan mode to record spectra on Fields 3 and 4 of the DEEP2 survey area. We park the telescope and let the sky drift through the beam of GBT. Each scan takes about six minutes. The telescope is then moved to the leading edge of the field at a new declination and parked, again letting the sky drift across the beam. Six such scans are used to cover the field at a series of declinations separated by 0.05°. Since the GBT beam size is approximately 0.25° at these frequencies, the scan pattern creates a raster of overlapping beams. Averaged spectra for each polarization are saved every 0.5 seconds. We recorded a total of 10.5 hours of integration time on Field-3 and 4.8 hours on Field-4. A noise source at the feed point is switched on and off every 0.5s, increasing the system temperature by 10% while on. We find gain fluctuations cause apparent flux changes over the drift scan period that exceed real sky signal variations. Rapid calibration using the noise source is required to measure sky flux variations, which are used in the sky maps shown in this paper. The noise source is only used to calibrate the average gain, not the spectral structure. Since our signal is spectral in nature, the low level of the noise source does not introduce substantial additional noise in the map.

2 Radio Frequency Interference (RFI) Removal

Although there is a radio quiet zone in the immediate vicinity of GBT, in the surrounding area these frequencies are used for television transmission as well as mobile telephone service. These terrestrial sources are single-mode and therefore 100% polarized at the source. The GBT has two linearly polarized feed antennas at the prime focus of the parabolic reflector. The feed system is about 150 meters above the ground, so high that flux from transmitters outside the radio quiet zone enters the sidelobes of the two feed antennas. This produces signals in the data stream that strongly correlate between the two polarization channels. Some astronomical sources are partially polarized, particularly pulsars, however 21-cm emission is not polarized. We therefore use polarization as a discriminating factor allowing identification and removal of terrestrial flux, to which we give the name Radio Frequency Interference (RFI).

For each time and frequency we calculate the inter-feed cross-correlation coefficient $q$, which is the ratio of the cross-polarized flux to the unpolarized flux. We flag as RFI, and discard, data that has $q > 0.02$. This procedure removes ~ 5% of the data. The $q$ cut removes RFI that arrives at the feed at high signal to noise ratio, however lower level RFI remains. While this residual RFI raises the noise level in the DEEP2-21-cm cross-correlation there is no reason to think that DEEP2 galaxy redshifts are correlated with the frequencies of terrestrial television transmitters and the low-level
RFI should therefore not provide a spurious apparent cross-correlation signal. The success of the null test described below shows the absence of such spurious correlation.

In addition to the $q$ cut we subtract the mean flux in each spectral channel. The assumption here is that any flux localized in frequency, but present for all telescope pointings, is likely terrestrial.

3 Calibration

The flux calibration is carried out by observing the bright radio source 3C48. Alternating the telescope pointing on source and then off source allows measurement of the response to 3C48 compared to the noise source, which is continuously switching throughout. The presence of 3C48 in the beam changes the total system temperature by a factor of two, which allows an accurate calibration while avoiding error due to non-linearities in the correlator sampling system.

4 Foreground (Continuum) Removal

At these frequencies the primary broadband emission mechanism in astronomical sources is widely accepted to be synchrotron radiation by relativistic electrons. This mechanism generically produces a very smooth spectrum with at most a gentle slope across our frequency range. Sources in the Milky Way, as well as extragalactic sources contribute to the continuum flux and our procedure treats all such sources as equivalent. We call the composite broadband flux ‘foreground’ emissions even though studies of extragalactic radio sources typically show that many have redshift greater than one.

In contrast to the foregrounds, the 21-cm brightness should be highly structured in its spectrum. However, the variation from pixel to pixel due to the foregrounds is three orders of magnitude larger than the 21-cm signal, so it is challenging to calibrate the spectral response with sufficient accuracy, especially for an instrument that has time variable gain. Fortunately, we find that instrumental gain fluctuations are primarily achromatic, and any chromatic variation we do see are fit by low order polynomials in frequency. We are searching for 21cm signal fluctuations that span few-percent frequency ranges. The spectral stability provided by the noise source is sufficient across such a span. Often one subtracts a low order polynomial in frequency to remove the tendency of drift of the spectral calibration to create foreground residuals. However, since the RFI cutting generates a complicated window structure in the spectrum, we instead developed a novel non-parametric technique based on singular-value-decomposition (SVD).

We arrange the data into a matrix in which the row index represents celestial coordinates of the telescope pointings and the column index represents the observation frequency (redshift). All three panels in Figure 1 of the main text show such matrices. Continuum sources extend across all columns of the matrix. In contrast, 21-cm sources are tightly localized to a few columns. Continuum sources can be factored into a product of a function of position and a low order function of frequency. That is, we assume the brightness temperature $T$ is a separable function of space $x$ and frequency $\nu$, $T(x, \nu) = f(x)g(\nu)$. Then the product functions $f(x)$ and $g(\nu)$ are singular eigenmodes of the matrix. We perform a singular-value decomposition (SVD) on the matrix to find these modes. The dominant right eigenvector $g_1(\nu)$ provides a correction to the gain calibration in this model. For each raster, we tag the ten eigenmodes with the largest singular eigenvalues as contribution from the foregrounds, accounting for a spectrally smooth component and variations
to that. We remove these eigenmodes. To this point the procedure is carried out on individual drift scan rasters, matrices arranged as a function of drift scan time (spatial sampling) and redshifts. Next we accumulate all data for each field into a six-declination spatial and redshift map. Large-spatial-scale fluctuations remain in this data, so we remove three more SVD modes. We are then left with the brightness temperature field $\delta T_b$, shown in the middle panel of Figure 1.

Visual inspection of the foreground subtracted maps indicates that the residual arises from time and frequency variable RFI, which does not take the factorization form that we assumed for the foregrounds. Work is in progress to test active noise cancellation, which may allow for cleaner foreground subtraction.

In principle, one might also worry about frequency dependence of telescope beams. The observations were scanned at very fine spatial sampling, which would allow us to degrade the resolution at all frequencies to the lowest common denominator. Unfortunately, the foreground residual appear RFI dominated, so the beam compensation was not implemented.

5 Cross Correlation

We calculate the cross-correlation between the HI and optical three-dimensional density fields, as a function of separation in the redshift direction. The DEEP2 density, $\rho_{opt}$, is estimated directly from the DEEP2 catalog; galaxies are binned into a cube with a 3D cell size of $3' \times 3' \times 2 \, h^{-1} \, \text{Mpc}$, according to their 3D optical positions. For every $370 \, h^{-1} \, \text{Mpc}$ in the redshift direction, the mean 3D optical galaxy density $\bar{\rho}$ is computed. The optical density contrast is then given by $\delta_{opt} = \rho_{opt}/\bar{\rho} - 1$.

We further subtract off the mean value of $\delta_{opt}$ in each redshift interval, to match the analysis of the radio data cube. This optical density field $\delta_{opt}$ is further convolved with the GBT primary beam response, a Gaussian function with FWHM of $15'$.

The cross-correlation signal is then the weighted sum of the products of the two fields, $\zeta(d) = \sum_{x,z} \left[ w_{opt}(x) w_{HI}(x) \, w_{HI}(z + d) \, \delta_{opt}(x, z) \, \delta_{HI}(x, z + d) \right] / \sum_{x,z} \left[ w_{opt}(x) w_{HI}(x) w_{HI}(z + d) \right]$, summed over all spatial $x$ and redshift $z$ pixels, where $w_{HI}(x)$ is given by the number of observations in a spatial pixel, summed over all redshifts. $w_{HI}(z)$ is given by the inverse-variance of $\delta_{HI}(x, z)$ at a given redshift bin, and $w_{opt}(x)$ is obtained by collapsing the redshift direction such that the 2D weights represents the optical survey masks, and $d$ is the separation in redshift space. The weighting functions effectively put our cross-correlation measurement at mean redshift $z = 0.8$.

At our spatial resolution, there are 10 NVSS radio sources per beam. Most of these radio sources are AGN's; in comparison, there are 500 DEEP2 galaxies per beam. It is really the redshift resolution that results in any meaningful signal, and we can see that the correlation indeed drops to zero at large lags, meaning we are not measuring the correlation of AGN continuum emission with galaxies. Radio continuum emission is not correlated spectrally.

6 Auto Correlation

We attempted to measure the auto-correlation of the HI temperature field after the RFI and foreground removal. Our foreground-subtracted maps contain residual RFI, which has a time variable component. In addition, the (time variable) RFI cuts affect the quality of our measurement of the gain versus frequency, and therefore limit the precision of foreground removal. The 21-cm signal should however be constant from day to day. We therefore calculate the auto-correlation of a given
field by cross-correlating radio data obtained on different observing dates. The correlation values calculated this way are lower than the rms of the intensity map shown in Figure 1. The mean HI auto-correlation of Field-3 and Field-4 is measured to be $464 \pm 277\mu$K, which should be interpreted as an upper limit.

The cross-correlation technique can only find 21-cm concentrations that happen to cluster around optically bright galaxies. The auto correlation, if detected, would additionally include 21-cm structures that are not near bright galaxies. In other words the stochasticity $r$ (in Eqn. (1) in the main text) is less than one and we expect the auto-correlation to be larger than the cross-correlation. The auto-correlation uncertainty is about a factor two larger than the cross-correlation, so despite the RFI and gain fluctuations at GBT, we come very close to an auto-correlation detection. This is important because it implies that using a 100 m telescope at a quieter site, it should be possible to detect high redshift 21-cm structure directly, without use of an optical redshift survey catalog.

7 Error Estimation and Null Tests

To study the error in our determination of the cross-correlation we test the (null) hypothesis that there is no real correlation in the data. This requires generating a large ensemble of random data sets with the same statistical distribution as the data from the sky. Since this distribution is not a priori known, we need to estimate it from our data. Bootstrap sampling provides such a procedure.

The bootstrap error is calculated as follows: for every 3D position we assign an HI brightness temperature in the redshift direction drawn randomly from the radio cube, generating an example of a randomized HI temperature field. Repeating this process many times, the resulting cross-correlation values serve as null tests and the distribution an error estimator. The optical galaxy angular position information is retained in this exercise, as are the optical survey masks.

We repeat this procedure, this time keeping the HI temperature field fixed and randomizing the optical density field in the redshift direction, retaining the optical survey masks. We find for both versions of the randomization the null tests succeed, and the variances in the cross-correlation values are very similar with 1,000 random samplings; these are used to generate our error estimate on the cross-correlations, and the null tests values are plotted in Figure 2 in the main text.

8 Adjustment for 21-cm signal loss

To determine how much the foreground removal process attenuates the 21-cm signal, we generate a simulated 21-cm sky. We start with the DEEP2 density field, smooth it with the GBT beam pattern as described in Section 5 and multiply it by 21-cm brightness temperature 100$\mu$K.

First, we cross-correlate this simulated 21-cm field with the optical density field using all the weighting functions derived from the data, as described in Section 5. Because both parts of the correlation product contain the field $\delta_{\text{opt}}$, the calculation yields the effective (weighted) variance $\delta_{\text{opt}}^2$ of each of the DEEP2 fields. We use this to solve for the normalized correlation function in Figure 2 as well as the mean hydrogen density. We use this procedure because it accounts for the complex weighting functions produced by RFI cuts, inverse-variance weighting, and the optical survey masks. The effective $\delta_{\text{opt}}^2$ calculated using this procedure for Field-3 and Field-4 are 2.3 and 3.3, respectively.
To measure the loss of 21-cm signal due to the SVD process we add the simulated 21-cm field to the original drift-scan-raster radio data and pass this through the entire analysis process. After foreground removal using the SVD procedure described in Section 4, we calculate the cross-correlation of the simulation-added data, $\zeta(d + s)$, where $d$ denotes actual radio data and $s$ the simulation, and compare to the cross-correlation of data alone, $\zeta(d)$. We compute the retention factor $h = [\zeta(d + s) - \zeta(d)] / \zeta_0(s)$ as a function of subtracted SVD modes. Here $\zeta_0(s)$ is the cross-correlation of the simulated 21-cm field without going through the SVD process, while both $\zeta(d+s)$ and $\zeta(d)$ experience the SVD process.

We find the signal loss increases with the number of subtracted SVD modes, as expected, although after the first few SVD modes both the correlation values and the signal loss level off with number of SVD modes, suggesting a converging value for the cross-correlation. For the 13 SVD modes we settled on, the loss is $\sim 30\%$ and we scale the correlation signal and error accordingly.

9 Volume and Mass Scales

We recast our results in units of hydrogen mass, which may be more familiar to some than brightness temperature. The GBT angular resolution, along with the galaxy pairwise velocity dispersion, define an effective resolution volume element $dV = (9h^{-1}\text{Mpc})^3$. The whole survey, including both fields, has 2000 such volume elements. These cells contain on average five DEEP2 galaxies since there are about 5000 galaxies per DEEP2 field. The total volume is about $126 \times 18 \times 740(h^{-1}\text{Mpc}^3)$.

The average optical luminosity per volume element is $L = Vj_B = 3.5 \times 10^{11}L_\odot$ [13]. The galaxies in the DEEP2 catalog account for more than half the light in this wavelength range. Integrating the best fit luminosity function for the optical galaxies, the total number of galaxies formally diverges.

Considering the component of hydrogen that correlates with optical galaxy position, the average hydrogen mass per resolution element is $M_{HI} = \Omega_{HI} \rho_{crit} V = 1.2 \times 10^{11}M_\odot$. We are therefore reporting the detection of an aggregate $2 \times 10^{14}M_\odot$ of HI-emissive gas. This is more than the sum of all previously detected hydrogen in the universe. It is this large mass that allows the detection of the 21-cm flux at a luminosity distance an order of magnitude further than the furthest previous HI detection. This illustrates the impact of Intensity Mapping technique.

References

[13] Willmer, C. N. A. et al. The Deep Evolutionary Exploratory Probe 2 Galaxy Redshift Survey: The Galaxy Luminosity Function to $z\sim 1$. ApJ 647, 853–873 (2006).