We report a wide-bandwidth search for H I 21-cm emission from star-forming galaxies at redshifts of about one, obtained by stacking their individual H I 21-cm emission signals. We obtain an average H I mass similar to the average stellar mass of the sample. We also estimate the average star-formation rate of the same galaxies from the 1.4-gigahertz radio continuum, and find that the H I mass can fuel the observed star-formation rates for only 1 to 2 billion years in the absence of fresh gas infall. This suggests that gas accretion onto galaxies at redshifts of less than one may have been insufficient to sustain high star-formation rates in star-forming galaxies. This is likely to be the cause of the decline in the cosmic star-formation rate density at redshifts below one.

Baryonic processes in galaxy evolution include the infall of gas onto galaxies to form neutral atomic hydrogen, which is then converted to the molecular state (H₂), and, finally, the conversion of H₂ to stars. Understanding galaxy evolution thus requires an understanding of the evolution of stars and of neutral atomic and molecular hydrogen. For the stars, the cosmic star-formation rate density is known to peak at redshifts from 1 to 3, and to decline by an order of magnitude over approximately the subsequent 10 billion years; the causes of this decline are not known. For the gas, the weakness of the hyperfine transition of H I at 21-centimetre wavelength—the main tracer of the H I content of galaxies—means that it has not hitherto been possible to measure the atomic gas mass of galaxies at redshifts higher than about 0.4; this is a critical gap in our understanding of galaxy evolution. Here we report a measurement of the average H I mass of star-forming galaxies at a redshift of about one, obtained by stacking their individual H I 21-centimetre emission signals. We obtain an average H I mass similar to the average stellar mass of the sample. We also estimate the average star-formation rate of the same galaxies from the 1.4-gigahertz radio continuum, and find that the H I mass can fuel the observed star-formation rates for only 1 to 2 billion years in the absence of fresh gas infall. This suggests that gas accretion onto galaxies at redshifts of less than one may have been insufficient to sustain high star-formation rates in star-forming galaxies. This is likely to be the cause of the decline in the cosmic star-formation rate density at redshifts below one.
star-forming galaxies of the sample, covering the velocity range ±135 km s⁻¹ around the galaxy redshift (see Methods). The circle at bottom left indicates the size of the 60-kpc beam (that is, the spatial resolution). The contour levels are at 3σ and 4.2σ statistical significance, where σ is the r.m.s. noise on the image. The stacked H i 21-cm emission signal is clearly detected in the centre of the image, at approximately 4.5σ significance, and is statistically consistent with it arising from an unresolved source.

$L_{\text{HI}} = (6.37 \pm 1.42) \times 10^{5} \text{Jy Mpc}^{-2} \text{km s}^{-1}$, at the average galaxy redshift of $(z) = 1.03$. This implies an average H i mass of $(M_{\text{HI}}) = (1.19 \pm 0.26) \times 10^{10} \text{M}_\odot$ (Table 1 provides a summary of our results).

We used simulations to estimate the possible contamination in the above estimate of the average H i mass due to ‘source confusion’, that is, companion galaxies lying within the uGMRT synthesized beam (see Methods). We find that this contamination is negligible, being ≤2% for even very conservative assumptions. This is due to the compact uGMRT synthesized beam used for the H i 21-cm stacking, which has a full-width at half-maximum (FWHM) of just 60 kpc, similar to the size of an individual galaxy.

The mean stellar mass of the galaxies in our sample is $(M) = 9.4 \times 10^{9} \text{M}_\odot$ (see Methods5), yielding a ratio of average H i mass to average stellar mass of $(M_{\text{HI}})/(M) = 1.26 \pm 0.28$ at $(z) = 1.03$, that is, an average H i mass that is comparable to, and possibly larger than, the average stellar mass. This is very different from the situation in star-forming galaxies with a similar stellar mass distribution in the local Universe, for which the average H i mass is only about 40% of the average stellar mass5. The ratio of H i mass to stellar mass in star-forming galaxies thus appears to evolve from $z = 1$ to the present epoch.

Most star-forming galaxies have been shown to lie on a so-called main sequence—a power-law relationship between the SFR and the stellar mass—at $z = 0$–2.5, with the amplitude of the power law declining with time13,14. Such main-sequence galaxies form stars in a steady regular manner, and dominate the cosmic SFR density at all redshifts15. However, the time for which a galaxy can continue to form stars at its current SFR depends on the availability of neutral gas. This is quantified by the gas depletion time, $t_{\text{dep}}$, which is the ratio of the gas mass (either H₂ or H i) to the SFR. The H₂ depletion timescale $t_{\text{dep}, \text{H}_2}$ gives the time for which a galaxy could sustain its present SFR without additional formation of H₂. Conversely, the H i depletion time, $t_{\text{dep}, \text{HI}} = M_{\text{HI}}/\text{SFR}$, gives the timescale on which the H i in a galaxy would be exhausted by star formation (with an intermediate conversion to H₂). This would result in quenching of the star-formation activity if the H i is not replenished in the galaxy, via accretion from the circumgalactic medium or minor mergers.

We estimated the average SFR of our 7,653 main-sequence galaxies by stacking their rest-frame 1.4-GHz continuum emission (see Methods) to measure the average rest-frame 1.4-GHz luminosity. We then combined this 1.4-GHz luminosity with the radio–far-infrared correlation6 to derive an average SFR of $(7.72 \pm 0.27) \text{M}_\odot \text{yr}^{-1}$ (refs. 17,18). Combining this with our average H i mass estimate of $(1.19 \pm 0.26) \times 10^{10} \text{M}_\odot$, yields an average H i depletion time of $(t_{\text{dep}, \text{HI}}) = (1.54 \pm 0.35) \text{Gyr}$ for star-forming galaxies at $(z) = 1.03$. The H i depletion time is even shorter for the brighter galaxies of the sample, those with absolute B-band magnitude $M_B \leq -21$. To estimate this, we stacked the H i 21-cm emission with $M_B \leq -21$ from the 3,499 galaxies with $M_B \leq -21$ to obtain an average H i mass of $(1.70 \pm 0.43) \times 10^{10} \text{M}_\odot$, and also stacked their rest-frame 1.4-GHz continuum emission to derive an average SFR of $(16.37 \pm 0.43) \text{M}_\odot \text{yr}^{-1}$. Combining these measurements, we find that galaxies with $M_B \leq -21$

![Image](84x592 to 233x741)

**Fig. 1** The final stacked H i 21-cm emission image. This image of the stacked H i 21-cm line luminosity was obtained by stacking the corresponding spatial and velocity pixels of the sub-cubes centred on each of the 7,653 blue, star-forming galaxies of the sample, covering the velocity range ±135 km s⁻¹ around the galaxy redshift (see Methods). The circle at bottom left indicates the size of the 60-kpc beam (that is, the spatial resolution). The contour levels are at 3σ and 4.2σ statistical significance, where σ is the r.m.s. noise on the image. The stacked H i 21-cm emission signal is clearly detected in the centre of the image, at approximately 4.5σ significance, and is statistically consistent with it arising from an unresolved source.

![Image](243x592 to 251x742)

**Fig. 2** The final stacked H i 21-cm spectrum. This was obtained via a cut through the location of the peak H i 21-cm line luminosity in Fig. 1, at a velocity resolution of 90 km s⁻¹. The dashed curve indicates the 1σ r.m.s. noise on the spectrum in each of the 90 km s⁻¹ velocity channels. The stacked H i 21-cm emission signal is clearly detected, at about 4.5σ significance.

**Table 1 | Details of the sample and our key results**

| Number of galaxies | 7,653 |
|--------------------|-------|
| Redshift range     | 0.74–1.45 |
| Mean redshift, $(z)$ | 1.03 |
| Mean stellar mass, $(M)$ | $9.4 \times 10^{9} \text{M}_\odot$ |
| Mean H i mass, $(M_{\text{HI}})$ | $(1.19 \pm 0.26) \times 10^{10} \text{M}_\odot$ |
| $(M_{\text{HI}})/(M)$ | $1.26 \pm 0.28$ |
| Radio-derived SFR, $(L_{\text{HI}})$ | $(7.72 \pm 0.27) \text{M}_\odot \text{yr}^{-1}$ |
| H i depletion timescale, $(t_{\text{dep}, \text{HI}})$ | $(1.54 \pm 0.35) \text{Gyr}$ |
| $D_{\text{H}_2 \text{Hi}}$, at $(z) = 1.06$ | $(2.31 \pm 0.58) \times 10^{4}$ |
| Total $D_{\text{H}_2}$ at $(z) = 1.06$ | $(4.5 \pm 1.1) \times 10^{4}$ |

Rows are as follows: (1) the number of galaxies whose H i 21-cm spectra were stacked to detect the average H i 21-cm emission signal; (2) the redshift range of the stacked galaxies; (3) their mean redshift; (4) their mean stellar mass; (5) the mean H i mass; (6) the ratio $(M_{\text{HI}})/(M)$; (7) the SFR derived from the rest-frame average 1.4-GHz radio luminosity density; (8) the H i depletion timescale; (9) the co-moving cosmological H i mass density in bright galaxies with $M_B < -20$ at $(z) = 1.06$; and (10) the total $D_{\text{H}_2}$, in star-forming galaxies at $(z) = 1.06$. 

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symbols are measurements from DLAs (triangles)23,27 or Mg ii absorbers of similar redshifts, only the most sensitive result has been included. The green ≈ 2.15 from DLA surveys 23.

The purple circles are from low-

Ω formation. In the local Universe, mergers), resulting in a paucity of neutral gas to fuel further star formation.

dependence on redshifts. This indicates that the quenching of star-formation activity at z < 1 is likely to arise owing to insufficient gas infall (from the circumgalactic medium or via minor mergers), resulting in a paucity of neutral gas to fuel further star formation.

Measurement of the redshift evolution of the co-moving cosmological H i mass density in galaxies (ΩHi) is important for understanding the global flow of gas into galaxies. In the local Universe, ΩHi can be measured from unbiased H i 21-cm emission surveys28, whereas at high redshifts, z ≥ 2, ΩHi has been measured from damped Lyman-α absorbers (DLAs) detected in quasar absorption spectra29. These studies have shown that ΩHi declines by a factor of about 2 from z = 2.2 to z = 0 (ref. 30).

However, the nature of the evolution of ΩHi between z = 0.4 and z = 2.2 remains unclear, owing to the difficulty of carrying out both H i 21-cm emission studies28 and direct DLA surveys28 at these redshifts.

Our measurement of the average H i mass in a sample of blue, star-forming galaxies allows us to measure ΩHi at z = 1 (see Methods). For this purpose, we use a subsample of galaxies with M_B ≤ −20, for which the DEEP2 survey is expected to be spectroscopically complete at z = 1 (ref. 4). To estimate ΩHi, we used the known B-band luminosity function for blue galaxies at z = 1 (ref. 26) and the relation between M_B and ΩHi from the local Universe (which we find to be consistent with our measurements for galaxies with M_B ≤ −20; see Methods).

We find that blue, star-forming galaxies with M_B ≤ −20 contribute Ω_R,HI,HI = (2.31 ± 0.38) × 10^{-4} to the total co-moving H i mass density at z = 1.06. We emphasize that this estimate is a lower limit to the total ΩHi in galaxies at z ≥ 1, as contributions from H i in faint blue galaxies (and red galaxies) could only increase the total ΩHi. Extrapolating this estimate to all blue galaxies, again using the B-band luminosity function at z = 1 and the M_B–ΩHi relation of the local Universe, we obtain Ω_Hi = (4.5 ± 1.1) × 10^{-4} in blue galaxies at z = 1.06 (see Methods).

Figure 3 shows a compilation of ΩHi measurements at different redshifts. Our measurement of ΩHi at z = 1.06 is consistent within the uncertainties with all measurements at ΩHi at z ≤ 1, but is lower (at about 3σ significance) than the DLA measurement of ΩHi at z = 2.15 (ref. 35).

Our results thus indicate that the cosmic H i mass density in galaxies declines substantially by z = 1, and then remains unchanged at later times. This also indicates that H i in star-forming galaxies is not sufficiently replenished to fuel star-formation at the same level after the peak of star-formation activity.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-020-2794-7.

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Methods

Cosmological parameters
Throughout this work, we use a flat Λ-cold dark matter (ΛCDM) cosmology, with \((H_0, \Omega_m, \Omega_\Lambda) = (70 \text{ km s}^{-1} \text{ Mpc}^{-1}, 0.3, 0.7)\).

The initial mass function
The stellar mass and SFR estimates in this work assume a Chabrier initial mass function (IMF). Measurements from the literature that assume a Salpeter IMF have been converted to a Chabrier IMF by subtracting 0.2 dex (ref. 1). All magnitudes are in the AB system.

Observations and data analysis
We used the uGMRT Band-4 550–850 MHz receivers to observe five sub-fields of the DEEP2 galaxy redshift survey\(^3\) in October–November 2018, with a total observing time of about 90 h (see Extended Data Table 1). These five sub-fields are in DEEP2 fields 3 and 4, at declination -0°. The total on-source time was about 900 min for four of the pointings, and about 450 min for the fifth pointing. A bandwidth of 400 MHz was used for the observations, sub-divided into 8,192 spectral channels, and centred at 730 MHz. The GMRT wideband backend was used as the correlator. Observations of one or more of the standard calibrators \(3C\) 48, \(3C\) 147 or \(3C\) 286 were used to calibrate the flux density scale, while regular observations of nearby compact sources were used to calibrate the antenna gains and the antenna bandpass shapes.

The data were analysed in the Common Astronomy Software Application (CASA, version 5.4) package\(^4\), with the AOFlagger package\(^5\) additionally used for the detection and excision of radio frequency interference (RFI). The uGMRT has a hybrid antenna configuration with 14 antennas located in a ‘central square’, of approximate area 1 km\(^2\), and the remaining 16 antennas lying along the three arms of a ‘Y’, providing baselines out to about 25 km. The hybrid configuration provides some insurance against RFI, as RFI decorrelates on the longer baselines. We took advantage of this by entirely excluding the 91 central-square baselines from our analysis, working with only the 344 long (that is, \(\geq 1\) km) baselines of the array.

The antenna-based complex gains and system bandpasses were estimated from the data on the calibrator sources, with our own custom routines developed within the CASA framework. The algorithms used in these routines are more robust to the presence of RFI in the data, and thus yield a more accurate calibration than the standard CASA routines. After applying these initial calibrations, the target-source visibilities were smoothed to a spectral resolution of 0.488 MHz for the purpose of continuum imaging; this reduces the data volume by a factor of 10 while avoiding bandwidth smearing of source structures. On each field, we performed multiple iterations of the standard imaging and self-calibration procedure (again using our calibration routines), along with RFI excision, until no further improvement was seen in the continuum image. The imaging at each self-calibration iteration was done using the tclean routine, with w-projection\(^6\), and multi-frequency synthesis (second-order expansion)\(^7\).

At the end of the self-calibration procedure, the fraction of target-source data lost to all-time-variable issues within a run (for example, RFI, temporarily malfunctioning antennas, and power failures, but excluding entirely non-working antennas and the 91 central-square baselines that were excised at the outset) is about 20%–30% for each field. Extended Data Fig. 1 shows the fraction of data excised due to such time-dependent issues as a function of observing frequency for the entire 4,004 min of observation; the median fractional data loss across our observing band is about 20%.

The final continuum image of each field was created using the tclean routine, with Briggs weighting of 0.5, w-projection\(^8\), and multi-frequency synthesis (second-order expansion)\(^7\). A region of radius 0.75° was imaged for each field, extending far beyond the null of the uGMRT primary beam at our observing frequencies. The r.m.s. noise on our continuum images is about 5–8 μJy per beam away from bright continuum sources, with synthesized beam (FWHM) widths of about 5° (see Extended Data Table 1).

We used the uvsub routine to subtract all detected radio continuum emission from each self-calibrated visibility data set before making the spectral cubes. The cubes were made in the barycentric frame (after applying a correction for the shape of the primary beam), using natural weighting. Each cube has a channel resolution of 48.83 kHz, corresponding to velocity resolutions of 18–25 km s\(^{-1}\) across the frequency band (820–580 MHz). The large frequency range implies that the FWHMs of the synthesized beam of each cube are different at different frequencies, about 3.8°–7.5°, corresponding to a physical size of 30–70 kpc for the redshift range 0.74–1.45.

Sample selection
The DEEP2 survey used the DEIMOS spectrograph on the Keck II telescope to accurately measure the spectroscopic redshifts of 38,000 galaxies at \(z = 0.70–1.45\), in four regions of the sky\(^9\). The redshifts were measured from the \(\text{[O} \text{II}] \lambda = 3,727 \text{ Å} \) doublet, with a high spectral resolution \(R = 6,000\). Both the large number of galaxies and the excellent redshift accuracy (corresponding to a velocity uncertainty of \(< 53 \text{ km s}^{-1}\) of the DEEP2 survey\(^9\) are critical to our aim of detecting the stacked \(\text{H} \text{I} 21\)-cm emission signal. The large number of galaxies increases the signal-to-noise ratio of the stacked \(\text{H} \text{I} 21\)-cm emission signal, while a redshift accuracy \(< 100 \text{ km s}^{-1}\) is important to prevent the stacked signal from being smeared in velocity (see, for example, refs. 12,13). The DEEP2 survey targeted galaxies for spectroscopy to a completeness limit of \(R_{\text{AB}} = -24.1\) (ref. 1). This selection criterion favours blue, star-forming galaxies at \(z = 0.70–1.45\) (ref. 18).

Our sample consists of galaxies in the redshift range \(z = 0.74–1.45\), for which the rest-frame velocity range of \(\pm 1,500 \text{ km s}^{-1}\) for the redshifted \(\text{H} \text{I} 21\)-cm line lies in the frequency range of about 580–820 MHz, that is, in the sensitive part of the uGMRT band. For the five DEEP2 sub-fields, there are 11,370 DEEP2 galaxies in the redshift range 0.74–1.45 with reliable redshifts (quality code, \(Q \geq 3\)) lying within the half-power point of the uGMRT primary beam at the galaxy’s redshifted \(\text{H} \text{I} 21\)-cm line frequency. We initially rejected red galaxies, with colour \(C > 0\), where \(C\) is a combination of the rest-frame B-band magnitude \(M_B\) and rest-frame \(U\) – \(B\) colour\(^10\): \(C = U - B + 0.032(M_B + 21.63) - 1.014\). C is defined such that the \(C = 0\) line passes through the green valley that separates the blue galaxies from the red ones in the colour–magnitude diagram. We note that the R-band selection criterion for the DEEP2 survey preferentially picks out blue galaxies at \(z = 1\) (ref. 17). As a result, only 1,469 galaxies, that is, about 13% of the galaxies of our sample, are red systems, with most of these at the lower end of the redshift coverage. After applying the colour selection, there are 9,901 blue galaxies in the sample.

Next, any sample of star-forming galaxies contains contamination from active galactic nuclei (AGNs), which form a different population from main-sequence galaxies. The presence of AGNs in the DEEP2 sample is likely to affect both our SFR and \(\langle \text{SFR} \rangle\) estimates. Studies of radio sources have found that AGNs typically have rest-frame 1.4-GHz luminosity densities \(L_{\text{1.4GHz}} \gtrsim 2 \times 10^{25} \text{ W Hz}^{-1}\) (ref. 14). We used this luminosity threshold to exclude possible AGNs from the DEEP2 sample. This was done by using the measured flux density of each DEEP2 galaxy in our continuum images, along with the galaxy redshift and an assumed spectral index \(\alpha = -0.8\), to estimate its rest-frame 1.4-GHz luminosity density. All DEEP2 galaxies detected at \(\leq 4\sigma\) significance in our continuum image, with \(L_{\text{1.4GHz}} \gtrsim 2 \times 10^{25} \text{ W Hz}^{-1}\), were excluded from the sample. 435 objects were identified as likely AGNs using this criterion, leaving us with a sample of 9,466 blue, star-forming galaxies.

\(\text{H} \text{I} 21\)-cm sub-cubes and spectra
We extracted three-dimensional \(\text{H} \text{I} 21\)-cm sub-cubes around the spatial position and redshifted \(\text{H} \text{I} 21\)-cm frequency of each galaxy, covering the rest-frame velocity range \(\pm 1,500 \text{ km s}^{-1}\), and an angular range of
±38.4 arcsec. Each sub-cube was then convolved with a two-dimensional Gaussian function to obtain a synthesized beam of angular FWHM corresponding to a physical size of 60 kpc at the galaxy’s redshift. In other words, we took into account the relation between angular diameter distance and redshift to produce sub-cubes with the same spatial resolution (60 kpc) around each target galaxy.

The naturally-weighted synthesized beam of each sub-cube deviates substantially from a Gaussian beam. This needs to be accounted for while scaling the convolved maps by beam area ratios to ensure that these maps are in the correct Jy per beam unit. This correction, for each frequency channel in a sub-cube, was applied by (a) convolving the point spread function with the same kernel as was done for the sub-cube, (b) computing the inverse of the value of the central pixel in the convoluted point spread function, and (c) multiplying the frequency channel of the sub-cube by this factor. The above procedure ensures that the central pixel of the convolved point spread function is correctly normalized to unity.

After convolution to the same physical scale with a synthesized beam FWHM of 60 kpc, we regridded each sub-cube to a uniform physical pixel size of 5.2 kpc and a spatial range of ±260 kpc. Next, we fitted a second-order spectral baseline to each spatial pixel and subtracted it out. This was done to remove the effects of low-level deconvolution errors from continuum sources, as well as any residual errors from bandpass calibration. Following this, we interpolated the spectral axis in each sub-cube to a single rest-frame velocity grid with a velocity resolution of 30 km s⁻¹.

Next, the H I 21-cm spectrum for each galaxy was obtained by taking a cut through the galaxy’s location in its sub-cube, covering a velocity range of ±1,500 km s⁻¹ around the galaxy redshift, with a uniform velocity resolution of 30 km s⁻¹. These spectra were used to further screen the range of ±1,500 km s⁻¹ around the galaxy redshift, with a uniform velocity resolution of 30 km s⁻¹. A spectrum is rejected if it fails either of the tests at any of the three resolutions, with a P value < 0.0002.

After excising spectra based on the above tests, our sample contains 7,925 galaxies. Finally, in order to stack in the image plane at a physical resolution of 60 kpc, we excluded galaxies for which the naturally weighted synthesized beam at the galaxy’s redshift H I 21-cm frequency corresponds to a physical size >60 kpc. This was found to be the case for 272 galaxies whose redshifted H I 21-cm frequencies lie beyond the beam of the longest uGMRT baselines. We hence chose a spatial resolution of 60 kpc for our final spectral cube. In passing, we note that 60 kpc is the typical diameter of galaxies in the local Universe with an H I mass of \( M_{\text{HI}} = 10^{10} M_\odot \) (ref. 10), the H I 21-cm spectra from individual galaxies are typically slightly higher than the noise in other regions. This is due to the fitting of a second-order baseline to the final spectrum excluding this velocity range, which has the effect of marginally increasing the noise in the line region. We note that we also estimated the r.m.s. noise on the stacked H I 21-cm spectrum via a Monte Carlo approach, where the systemic velocity of each galaxy in our sample was shifted by a random offset in the range −1,500 km s⁻¹ to ±1,500 km s⁻¹ before their H I 21-cm spectra were stacked; the error obtained from this approach is consistent with that obtained from bootstrap resampling (with replacement).

In H I 21-cm stacking experiments (except for a uGMRT experiment at \( z = 0.34; \) ref. 19), the H I 21-cm spectra from individual galaxies are typically weighted by the inverse of their variance before stacking them in flux density, to optimize the r.m.s. noise on the final stacked spectrum. However, our observations span a large redshift range, 0.74 ≤ \( z \) ≤ 1.45; stacking in flux density would have the unwanted effect of a bias towards galaxies at the low-redshift end of our coverage. We hence carried out the stacking in H I 21-cm luminosity density, instead of H I 21-cm flux density. Further, the r.m.s. noise on the individual H I 21-cm luminosity density spectra would also be higher for the higher-redshift galaxies, by a factor of about 2, owing to their larger luminosity distances. Hence, the standard approach of weighting by the inverse of the variance would again bias the stacked spectrum towards lower-redshift galaxies. To avoid this, we stacked the H I 21-cm luminosity density spectra without any weights. Finally, we note that the results obtained on weighting the spectra by the inverse of the variance of the H I 21-cm luminosity density are consistent (within 1σ significance) with the results obtained without weighting. Our conclusions thus do not depend on whether we stack with equal weights or use an inverse-variance weighting scheme.

We also carried out a median stack of the H I 21-cm emission signals of the 7,653 galaxies in our sample, obtaining an average H I mass estimate.
Data quality and systematic effects

We compared the r.m.s. noise on the H i 21-cm spectrum of each of the 7,653 galaxies of the final sample to the theoretical r.m.s. noise, based on the sensitivity of the uGMRT receivers. The predicted r.m.s. noise was calculated using the sensitivity curve provided by the uGMRT observatory, after taking into account the average flagged fraction, and the effects of spectral and spatial smoothing. Extended Data Fig. 2 shows (blue dots) the r.m.s. noise per 30 km s$^{-1}$ channel for each galaxy, plotted against the observing frequency. The red curve shows the theoretical sensitivity curve for a galaxy at the centre of the field (the theoretical sensitivity would be worse for a galaxy away from the field centre, due to the telescope primary beam response). It is clear that the theoretical sensitivity provides a lower envelope to the observed r.m.s. noise values, and that the spread in the r.m.s. noise values is a factor of about 2 at any given frequency. The spread in the observed r.m.s. noise values is because we have included galaxies out to the half-power point in the telescope primary beam, whose spectra would have an r.m.s. noise two times worse than that of galaxies at the field centre. We thus find that the observed r.m.s. noise values on the individual H i 21-cm spectra are consistent with the predicted r.m.s. noise.

Next, when stacking a large number of spectra to search for a faint signal, it is important to test whether there are low-level correlations between the spectra, arising from systematic non-Gaussian effects (for example, deconvolution errors from continuum sources, and unmodelled changes in the antenna bandpass shapes over time). If no correlations are present between the spectra, the r.m.s. noise of the stacked spectrum is expected to decrease as $\sqrt{N}$, where $N$ is the number of spectra that are stacked together. The presence of any correlations between the spectra would cause the r.m.s. noise of the stacked spectrum to decline more slowly than $\sqrt{N}$. We tested for such low-level correlations between the spectra by stacking smaller subsamples of galaxies, randomly drawn from the full sample of 7,653 galaxies, and determining the dependence of the r.m.s. noise on the number of stacked spectra. Specifically, we stacked random subsamples containing 100, 200, 400, 800, 1,600, 3,200 and 6,400 galaxies and estimated the r.m.s. noise on the H i mass, for an assumed channel width of 270 km s$^{-1}$. For each subsample, the r.m.s. noise is computed in the same way as for the main stacked spectrum, that is, by making 10,000 realizations of the stacked spectrum, using bootstrap re-sampling (with replacement) of the $N$ individual H i 21-cm spectra. The results are shown in Extended Data Fig. 3, which plots the r.m.s. noise on the stacked H i 21-cm spectrum against the number of stacked spectra. It is clear from the figure that the r.m.s. noise on the stacked spectrum indeed decreases as $\sqrt{N}$, indicating that there is no evidence for the presence of correlations between the H i 21-cm spectra.

Red galaxies and AGNs

We also stacked the H i 21-cm spectra from the sample of red DEEP2 galaxies, which were excluded from our main stack, to estimate their H i mass. As noted earlier, the DEEP2 selection criteria preferentially picks out blue galaxies. There are only 1,469 red DEEP2 galaxies with reliable redshifts that lie within the spatial and spectral coverage of our uGMRT observations. After excluding AGNs and applying the same quality controls (described earlier) to the H i 21-cm spectra, we obtain a sample of 1,053 red galaxies. We stacked the H i 21-cm spectra of these 1,053 red galaxies, following the approach described earlier, and find no evidence for a detection of H i 21-cm emission. This implies a 3$\sigma$ upper limit of $1.8 \times 10^{10}$ M$_\odot$, on the average H i mass of red galaxies at $z = 0.95$. We note that this upper limit is larger than our estimate of the average H i mass of blue star-forming galaxies, $(M_{\text{H}i}) = (1.19 \pm 0.26) \times 10^{10}$ M$_\odot$. We also combined the 1,053 red galaxies with the 7,653 blue galaxies to measure the average H i mass of all galaxies in our sample. Stacking the H i 21-cm spectra of these 8,726 galaxies yields an H i mass of $(M_{\text{H}i}) = (0.97 \pm 0.24) \times 10^{10}$ M$_\odot$, consistent (within 1σ significance) with our result for the blue star-forming galaxies alone. The relatively small number of red galaxies due to the DEEP2 selection criteria implies that their inclusion in the stacking process does not appreciably affect our results.

Finally, we examined the effect of including the 435 radio-bright AGNs on our estimate of the average H i mass. After again applying the above quality controls to the H i 21-cm spectra of the 435 AGNs (yielding 368 usable spectra), we stacked the H i 21-cm spectra of the 7,653 blue galaxies and the 368 AGNs, obtaining an average H i mass $(M_{\text{H}i}) = (1.02 \pm 0.26) \times 10^{10}$ M$_\odot$. This is again consistent, within statistical uncertainties, with our measurement of the average H i mass of the blue galaxies alone. Again, the small number of AGNs in the DEEP2 sample implies that their retention in the sample does not substantially affect our results.

The effect of source confusion

For low angular resolution, the average H i 21-cm signal in a stacking experiment can include, in addition to the H i 21-cm emission from the target galaxies, H i 21-cm emission from gas in companion galaxies, lying within the synthesized beam and emitting at the same velocities as the target galaxy. Such ‘source confusion’ can result in an over-estimation of the average H i mass of the target galaxies. Simulations of H i 21-cm stacking experiments at $z = 0.7$–0.758 have found that source confusion does not dominate the signal from the target galaxies even with a resolution of 18″ (corresponding to a physical size of approximately 130 kpc), with only about 31% of the stacked H i 21-cm signal arising from companion galaxies. Our spatial resolution of 60 kpc is substantially smaller than this, and the effect of source confusion will thus be much lower.

We used the S$^2$SAX-Sky simulations to estimate the contamination in our detected H i 21-cm signal due to source confusion. The S$^2$SAX-Sky simulation is based on semi-analytical models of galaxy evolution and provides a catalogue of galaxies (including the H i mass) out to $z = 20$ (ref. 35). We retrieved the galaxies from the simulated catalogue over a 1.2 square degree region and at redshifts $z = 0.74$–1.45, matched to the volume covered by our uGMRT observations; there are 657,421 galaxies in this volume. The effect of source confusion is expected to be largest around massive galaxies, owing to the strong clustering around these galaxies. Therefore, to get an upper limit on the effect of source confusion, we selected 7,653 galaxies with the largest H i masses from the 657,421 simulated galaxies. The average H i mass of these 7,653 simulated galaxies is 1.2 $\times 10^{10}$ M$_\odot$, in excellent agreement with our estimate of the average H i mass, $(M_{\text{H}i}) = (1.19 \pm 0.26) \times 10^{10}$ M$_\odot$. Next, for each of these 7,653 simulated galaxies, we identified companion galaxies in the simulated catalogue within the spatial and spectral resolution of our final stacked spectral cube, that is, galaxies lying within 60 kpc and within 270 km s$^{-1}$ of the target galaxy. We assume that the H i 21-cm emission from the entire H i mass of such companion galaxies will contribute to the stacked H i 21-cm signal. Even with these conservative assumptions (that would certainly over-estimate the contribution of source confusion to the measured H i mass), we find that the companion galaxies contribute only about 2% of the average H i mass measurement. We thus conclude that the high spatial resolution (60 kpc) of the final spectral cube implies that our measurement of the average H i mass of galaxies at $z = 0.74$–1.45 is not appreciably affected by source confusion.

Determination of the SFR

We initially convolved the radio continuum images of the five uGMRT pointings to a uniform beam of FWHM = 5.5″ $\times$ 5.5″. We then followed the convolution of the H i 21-cm sub-cubes, in order to take into account any deviations of the synthesized beam of each image from
a Gaussian beam, so as to ensure that the convolved maps are in the correct units of Jy per beam. We hence convolved the point spread function of the continuum maps with the same kernel that was used in the images, and checked that the central pixel of the convolved point spread function was correctly normalized to unity. From these convolved images, we extracted $25^\prime\times25^\prime$ cutouts around the location of each of our 7,653 galaxies. For each galaxy, the flux density at each pixel was converted to its rest-frame 1.4-GHz luminosity density $\left(L_{1.4\,\text{GHz}}\right)$ at the galaxy’s redshift, assuming a spectral index of $-0.8$ (ref. $38$). These 1.4-GHz luminosity densities of the 7,653 galaxies were then stacked together, using a ‘median stacking’ approach, computing the median 1.4-GHz luminosity density in each pixel from the galaxy sample. Such a median stacking procedure has been shown to be more robust to outliers (for example, undetected AGNs in the sample) and deconvolution errors in the continuum images$^2$. Further, in cases (such as ours) of low signal-to-noise ratio ($\lesssim 1$) of the signal from individual objects of the sample, the median-stacking procedure yields the mean of the distribution$^2$. We also applied the above procedure to locations offset by $100^\prime$ from the true position of each galaxy, to search for possible systematic effects. The median-stacked 1.4-GHz luminosity density images, at the position of each DEEP2 galaxy and at the offset position, are shown in Extended Data Fig. 4. The median-stacked 1.4-GHz luminosity density image at the position of the DEEP2 galaxies shows a clear detection of an unresolved continuum source at the centre of the image, with a 1.4-GHz luminosity density $L_{1.4\,\text{GHz}} = (2.09 \pm 0.07) \times 10^{22}$ W Hz$^{-1}$. No evidence is seen for systematic patterns in the offset stack. We converted our measured rest-frame 1.4-GHz luminosity density to an SFR estimate via a calibration derived from the radio–far-infrared correlation (but assuming a Chabrier IMF)$^9$; SFR (in $M_\odot$ yr$^{-1}$) $\approx 3.71 \times 10^{-22} \times L_{1.4\,\text{GHz}}$ (in W Hz$^{-1}$). This yields an average SFR of $7.72 \pm 0.27 M_\odot$ yr$^{-1}$ for the 7,653 galaxies of our sample.

Stellar masses for the DEEP2 galaxies

The stellar masses of the DEEP2 galaxies of our sample were inferred from a relation between the $U-B$ colour and the ratio of the stellar mass to the B-band luminosity, calibrated at $z=1$ using stellar masses estimated from K-band observations of a subset of the DEEP2 sample$^{13}$. The r.m.s. scatter of individual galaxies around the above relation is about $0.3$ dex (ref. $11$).

Reference sample at $z=0$

A fair comparison of our results to those from the local Universe requires a uniformly selected sample of nearby galaxies. The xGASS sample is a stellar-mass-selected sample of galaxies at $z=0$ with stellar mass $M>10^9 M_\odot$, and with deep H I 21-cm emission studies yielding either a detection of H I 21-cm emission or, for non-detections, an H I mass fraction relative to the stellar mass of $<0.1$ (ref. $12$). We use our measurements of the average H I mass estimate for galaxies with spectroscopic redshifts; further, these galaxies are typically the brighter members of the population. In such experiments, the cosmological H I mass density is usually computed using $\rho_{\text{HI}}(z) = \int \Phi(M_{\text{HI}})dM_{\text{HI}}$, where $\Phi(M_{\text{HI}})$, the ‘H I mass function’, is the number density of galaxies per unit H I mass at a given $M_{\text{HI}}$ (ref. $39$). However, in H I 21-cm stacking studies, we only have an estimate of the average H I mass estimate for galaxies with spectroscopic redshifts; further, these galaxies are typically the brighter members of the population. In such experiments, the cosmological H I mass density is usually computed using $\rho_{\text{HI}}(z) = \int \Phi(M_{\text{HI}})dM_{\text{HI}}$, where $\Phi(M_{\text{HI}})$ is the H I mass of a galaxy at a given absolute magnitude $M_B$ in the optical K-band (and $\Phi(M_{\text{HI}})$, the ‘H I mass function’, is the number density of galaxies per unit absolute magnitude $M_B$ at a given $M_{\text{HI}}$). The luminosity function, $\phi(M_B)$, is usually known from optical redshift surveys. The dependence of $\rho_{\text{HI}}$ on $M_B$ is either (a) characterized directly from the H I 21-cm stacking experiment by dividing the sample of galaxies in multiple subsamples in $M_B$ and finding the average H I mass of galaxies in each of these subsamples$^{39}$, or (b) assumed to be a power law, where only the normalization is constrained by the average H I mass measured in the experiment$^{40}$. We measure $\Omega_{\text{HI}}$ in blue galaxies at $z=1$ by using a combination of these two approaches.

The DEEP2 galaxy sample is statistically unbiased up to a rest-frame B-band magnitude $M_B < -20$ at $z = 1$ (ref. $1$). We used this absolute-magnitude-limited sample to estimate $\Omega_{\text{HI}}$. There are 6,620 galaxies with $M_B < -20$ at a mean redshift of $\langle z \rangle = 1.06$ in our main sample of 7,653 blue star-forming galaxies.

The computation of H I mass density, $\rho_{\text{HI}}(z) = \int \Phi(M_{\text{HI}})dM_{\text{HI}}$, requires a knowledge of the dependence of $M_{\text{HI}}$ on the B-band magnitude, $M_B$, of the galaxies at $z=1$. In order to characterize the dependence of $M_{\text{HI}}$ on $M_B$, we split our sample of 6,620 galaxies with $M_B < -20$ into two subsamples separated by the median value of the distribution, $M_B = -21.042$, and stacked the H I 21-cm emission from the galaxies in each subsample to estimate the dependence of $M_{\text{HI}}$ on $M_B$. We find that the subsample of fainter galaxies, $M_B > -21.042$, has an average H I mass of $\langle M_{\text{HI}} \rangle = (5.38 \pm 3.75) \times 10^9 M_\odot$, while the subsample of brighter galaxies, $M_B < -21.042$, has an average H I mass of $\langle M_{\text{HI}} \rangle = (18.02 \pm 4.39) \times 10^9 M_\odot$. Studies in the local Universe have found a relation between $M_{\text{HI}}$ and $M_B$ of the form

$$\log[M_{\text{HI}}(M_B)] = K - \beta M_B,$$

where $K = 2.89 \pm 0.11$ and $\beta = 0.34 \pm 0.01$ at $z = 0$ (ref. $40$). Assuming the same value of the slope, $\beta = 0.34$, at $z = 1$, we use our measurements of $\langle M_{\text{HI}} \rangle$ of galaxies in the two subsamples to find the normalization of the relation to be $K = 2.89 \pm 0.11$; this is consistent, within statistical uncertainties, with the value of $K = 2.89 \pm 0.11$ measured at $z = 0$. Extended Data Fig. 5 shows the relation between $M_{\text{HI}}$ and $M_B$ at $z = 0$ (equation (1), with $K = 2.89$ and $\beta = 0.34$; ref. $40$) overlaid on our measurements of the average H I mass of galaxies in the two $M_B$ subsamples at $z = 1$. Our measurements of the average $M_{\text{HI}}$ in the two subsamples are consistent with the $M_{\text{HI}} - M_B$ relation measured at $z = 0$. In passing, we note that our observations find evidence that the ratio of average H I mass to stellar mass in blue star-forming galaxies changes from $z = 1$ to $z = 0$, whereas the relation between $M_{\text{HI}}$ and $M_B$ appears to not change over the same redshift range. This could arise because $M_B$ is not a direct tracer of the stellar mass in galaxies.

We used the Schechter function fit to the B-band luminosity function of blue galaxies, $\phi(M_B)$, obtained from the DEEP2 survey$^{40}$ to estimate the number density of galaxies at a given $M_B$. The Schechter function fits are available for three independent redshift bins: $0.8 < z < 1.00$, $1.00 < z < 1.20$ and $1.20 < z < 1.40$. These bins are well matched to the redshift coverage of our observations and we thus take the mean of the three B-band luminosity functions to estimate the mean number density of galaxies at a given $M_B$ at $z = 0.8-1.4$. Combining this with the $M_{\text{HI}} - M_B$ relation of equation (1) with $K = 2.88 \pm 0.11$ and $\beta = 0.34$, we obtain
The above estimate of $\Omega_{\text{HI,Bright}}$ does not include contributions from galaxies fainter than $M_B = -20$. To include these contributions, we assume that the relation between $M_B$ and $M_\text{HI}$ for galaxies with $M_B \leq -20$ at $z = 1.06$ can be extrapolated to fainter galaxies, with $M_B > -20$. With this extrapolation and the average $B$-band luminosity function at $z = 0.9-1.4$, we obtain $\rho_{\text{HI}} = (4.5 \pm 1.1) \times 10^{-4}$, including contributions from all blue galaxies at $z = 1.06$.

**Data availability**

The raw data reported in this paper are available through the GMRT archive (https://naps.ncra.tifr.res.in/goa) with project code 3S_087. The analysed data files are large and are available from the corresponding author on reasonable request. The data displayed in Fig. 1 are publicly available at https://github.com/chowdhuryaditya/DEEP2_nature as a FITS file. Source data are provided with this paper.

**Code availability**

The custom code used to calibrate the GMRT data is publicly available at https://github.com/chowdhuryaditya/calR.
Extended Data Fig. 1 | The fraction of data excised across the observing band. This includes all data lost due to time-variable effects, including RFI, malfunctioning antennas and power failures. The plotted fraction of lost data was obtained by averaging over the approximately 67 h of on-source time on the five DEEP2 sub-fields.
Extended Data Fig. 2 | Distribution of the spectral r.m.s. noise for the 7,653 target galaxies. Shown is the r.m.s. noise per 30 km s\(^{-1}\) channel on the H\(\text{I}\) 21-cm spectra of the 7,653 galaxies of the final sample. Left panel, results for the galaxies in fields 31–33 and 42, each of which have about 900 min of on-source time. Right panel, results for field 41, where the on-source time was about 450 min. The red curve in each panel shows the predicted r.m.s. noise for the uGMRT array, after accounting for (1) the on-source time, (2) the fraction of data lost due to RFI and other effects, and (3) the smoothing of the H\(\text{I}\) 21-cm cubes to the same spatial resolution at all redshifts, that is, to coarser angular resolutions at higher frequencies.
Extended Data Fig. 3 | Dependence of the stacked r.m.s. noise on the number of galaxies, \(N\). The figure shows the r.m.s. noise (in units of H\textsubscript{i} mass sensitivity) on the stacked H\textsubscript{i} 21-cm spectrum as a function of the number of galaxies whose H\textsubscript{i} 21-cm spectra have been stacked together, assuming a velocity width of 270 km s\(^{-1}\). Each red dot shows the r.m.s. noise from the spectrum of \(N\) galaxies (with \(N\) = 100, 200, 400, 800, 1,600, 3,200 and 6,400), randomly drawn from the full sample of 7,653 galaxies. The magenta star shows the r.m.s. noise on the final stacked spectrum of 7,653 galaxies. The dashed blue line indicates the relation r.m.s. noise \(\propto N^{-0.5}\) (normalized to pass through the point with \(N\) = 100), as expected if the 7,653 H\textsubscript{i} 21-cm spectra contain no correlations. The relation r.m.s. noise \(\propto N^{-0.5}\) is an excellent match to the data points, implying that the H\textsubscript{i} 21-cm spectra show no evidence for the presence of systematic correlated non-Gaussian effects.
Extended Data Fig. 4 | The stacked 1.4-GHz continuum emission from our galaxies and offset positions. a, b. The average rest-frame 1.4-GHz luminosity density of the 7,653 main-sequence DEEP2 galaxies, obtained by median-stacking the 1.4-GHz radio continuum emission at the location of each individual galaxy (a), and at a location 100″ offset from each galaxy (b). Dec., declination; RA, right ascension. A clear (29σ significance) detection is visible at the location of the DEEP2 galaxies, while the stack at offset positions shows no evidence for either emission or any systematic patterns. The circle in the bottom left corner of each panel represents the final 5.5″ beam of the continuum images, after convolution. The patterns visible in a around the central bright source arise from the effective point spread function of the stacked image.
Extended Data Fig. 5 | The relation between H i mass and absolute blue magnitude. The figure shows the relation between average H i mass and absolute B-band magnitude for galaxies with $M_B \leq -20$ at $\langle z \rangle = 1.06$. The red points show the average H i mass, obtained by stacking the H i 21-cm emission, of blue galaxies in two $M_B$ bins (separated at the median, $M_B = -21.042$) at $\langle z \rangle = 1.06$. The solid blue curve shows the relation between $M_B$ and $M_{HI}$ in the local Universe40. Our measurements at $\langle z \rangle = 1.06$ are consistent with the $M_B$–$M_{HI}$ relationship at $z = 0$. 
Extended Data Table 1 | Summary of the uGMRT observations

| DEEP2 sub-field | Right Ascension (J2000) | Declination (J2000) | On-Source Time | Beam     | $\sigma_{\text{rms}}$ | Number of Galaxies |
|-----------------|-------------------------|---------------------|----------------|----------|------------------------|-------------------|
| Field-31        | 23h26m52.8s             | 00'08'25.7"        | 861 min        | 4.3" x 4.0" | 5.7 $\mu$Jy/Bm         | 1,353             |
| Field-32        | 23h29m49.9s             | 00'12'12.7"        | 872 min        | 5.4" x 4.5" | 5.2 $\mu$Jy/Bm         | 1,310             |
| Field-33        | 23h32m58.7s             | 00'08'22.7"        | 919 min        | 4.8" x 4.2" | 5.7 $\mu$Jy/Bm         | 1,283             |
| Field-41        | 02h28m24.0s             | 00'35'27.6"        | 450 min        | 4.8" x 4.7" | 8.0 $\mu$Jy/Bm         | 1,672             |
| Field-42        | 02h30m48.0s             | 00'35'15.0"        | 902 min        | 5.0" x 3.8" | 5.8 $\mu$Jy/Bm         | 1,835             |

For each DEEP2 sub-field that was observed with the uGMRT 550–850 MHz receivers (column 1), the following columns provide the J2000 coordinates of the uGMRT pointing (column 2, right ascension; column 3, declination), the total on-source time (in min; column 4), the synthesized beam obtained in the continuum image (column 5), the r.m.s. noise (in $\mu$Jy per beam) measured on the continuum image away from detected sources ($\sigma_{\text{rms}}$; column 6), and the number of galaxies from the sub-field that were included in the average $M_\text{HI}$ and SFR measurements (column 7).