Giant Metrewave Radio Telescope Detection of HI 21 cm Emission from Star-forming Galaxies at $z \approx 1.3$

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ABSTRACT

We report a ≈ 400-hour Giant Metrewave Radio Telescope (GMRT) search for HI 21 cm emission from star-forming galaxies at $z = 1.18 - 1.39$ in seven fields of the DEEP2 Galaxy Survey. Including data from an earlier 60-hour GMRT observing run, we co-added the HI 21 cm emission signals from 2,841 blue star-forming galaxies that lie within the full-width at half-maximum of the GMRT primary beam. This yielded a 5.0σ detection of the average HI 21 cm signal from the 2,841 galaxies at an average redshift $\langle z \rangle \approx 1.3$, only the second detection of HI 21 cm emission at $z \geq 1$. We obtain an average HI mass of $\langle M_{HI} \rangle = (3.09 \pm 0.61) \times 10^{10}\ M_\odot$ and an HI-to-stellar mass ratio of 2.6 ± 0.5, both significantly higher than values in galaxies with similar stellar masses in the local Universe. We also stacked the 1.4 GHz continuum emission of the galaxies to obtain a median star-formation rate (SFR) of $14.5 \pm 1.1\ M_\odot yr^{-1}$. This implies an average HI depletion timescale of ≈ 2 Gyr for blue star-forming galaxies at $z \approx 1.3$, a factor of ≈ 3.5 lower than that of similar local galaxies. Our results suggest that the HI content of galaxies towards the end of the epoch of peak cosmic SFR density is insufficient to sustain their high SFR for more than ≈ 2 Gyr. Insufficient gas accretion to replenish the HI could then explain the observed decline in the cosmic SFR density at $z < 1$.

Keywords: Galaxy evolution — Radio spectroscopy — Neutral hydrogen clouds

1. INTRODUCTION

Understanding galaxy evolution requires us to understand the evolution of, and the interplay between, the two main baryonic components of galaxies, the stars and the interstellar medium (ISM). For most galaxies in the local Universe, the dominant component of the ISM, by mass, is neutral atomic hydrogen (HI), the primary fuel for star-formation. The HI mass of different types of galaxies, and the relations between the HI mass and the molecular gas mass, the stellar mass, and the star-formation rate (SFR), are thus critical inputs to studies of galaxy evolution. In the local Universe, the HI mass of galaxies has long been measured via emission studies in the HI 21 cm emission line. Unfortunately, the low Einstein A-coefficient of this transition has meant that it has not been possible to detect HI 21 cm emission from individual galaxies beyond even fairly low redshifts, $z \gtrsim 0.4$, with the highest-redshift detection till date at $z = 0.376$

ПРОБЛЕМА

- Over the last two decades, the contrast between the dramatic improvement in measurements of the stellar properties of high-z galaxies (e.g. Madau & Dickinson 2014) and the lack of information on their Hi properties has become more and more stark.
- It has not been possible to detect Hi 21 cm emission from individual galaxies beyond even fairly low redshifts, $z > 0.4$, with the highest-redshift detection till date at $z = 0.376$ (e.g. Fernandez et al. 2016).

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ПОЯВИЛАСЬ НОВАЯ ВОЗМОЖНОСТЬ:

A progress can be made by ‘’stacking" the Hi 21 cm emission signals of a large number of galaxies with known spectroscopic redshifts, that lie within the primary beam of a radio interferometer.

Цель работы

- Recently Chowdhury et al. (2020) used the new receivers and the new wideband correlator of the upgraded Giant Metrewave Radio Telescope (GMRT) to obtain the first detection of the stacked Hi 21 cm emission. They stacked the Hi 21 cm emission signals from 7,653 star-forming galaxies at z = 0.74 – 1.45 to measure the average Hi mass of star-forming galaxies at z~ 1.
- **In this Letter, we report an independent 400-hour GMRT search for Hi 21 cm emission from a sample of star-forming galaxies at z = 1.18-1.39.**

Использовался глубокий обзор DEEP2 Galaxy Redshift Survey. Its redshift coverage extends out to $z \approx 1.4$ (Davis et al. 2003; Newman et al. 2013), due to the use of the high spectral resolution ($R = 6000$) mode of the DEIMOS spectrograph on the Keck II Telescope, allowing the clear identification of the O IIλ3727 doublet out to $z \approx 1.4$.

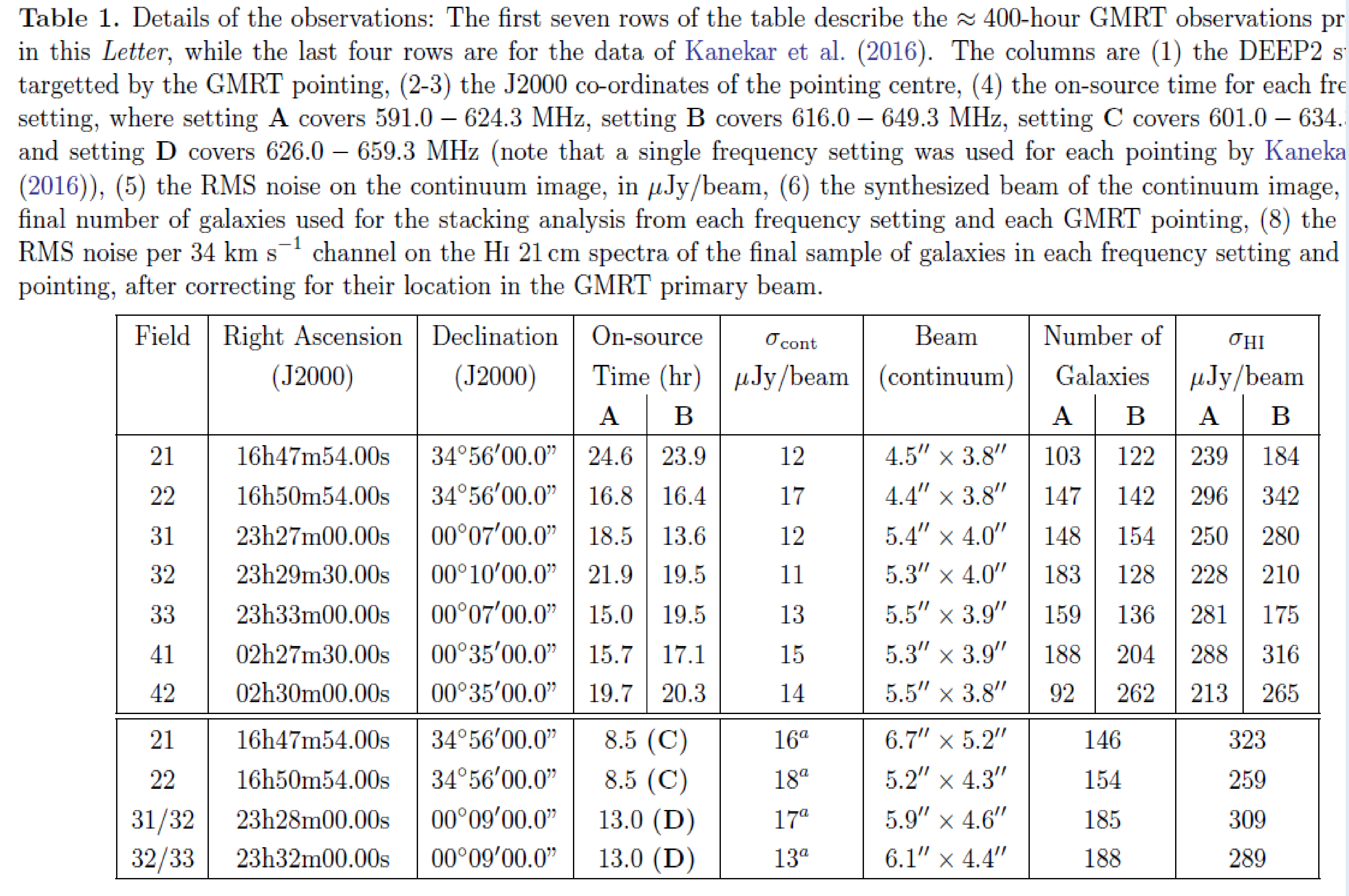


Table 1. Details of the observations: The first seven rows of the table describe the ≈ 400-hour GMRT observations pr in this *Letter*, while the last four rows are for the data of Kanekar et al. (2016). The columns are (1) the DEEP2 s targetted by the GMRT pointing, (2-3) the J2000 co-ordinates of the pointing centre, (4) the on-source time for each fre setting, where setting **A** covers 591.0 – 624.3 MHz, setting **B** covers 616.0 – 649.3 MHz, setting **C** covers 601.0 – 634. and setting **D** covers 626.0 – 659.3 MHz (note that a single frequency setting was used for each pointing by Kaneka (2016)), (5) the RMS noise on the continuum image, in μJy/beam, (6) the synthesized beam of the continuum image, final number of galaxies used for the stacking analysis from each frequency setting and each GMRT pointing, (8) the RMS noise per 34 km s^{-1} channel on the HI 21 cm spectra of the final sample of galaxies in each frequency setting and pointing, after correcting for their location in the GMRT primary beam.

Field	Right Ascension (J2000)	Declination (J2000)	On-source Time (hr)		$\sigma_{\rm cont}$ μJy/beam	Beam (continuum)	Number of Galaxies		$\sigma_{\rm HI}$ μJy/beam	
			A	B			A	B	A	B
21	16h47m54.00s	34°56′00.0”	24.6	23.9	12	4.5″ × 3.8″	103	122	239	184
22	16h50m54.00s	34°56′00.0”	16.8	16.4	17	4.4″ × 3.8″	147	142	296	342
31	23h27m00.00s	00°07′00.0”	18.5	13.6	12	5.4″ × 4.0″	148	154	250	280
32	23h29m30.00s	00°10′00.0”	21.9	19.5	11	5.3″ × 4.0″	183	128	228	210
33	23h33m00.00s	00°07′00.0”	15.0	19.5	13	5.5″ × 3.9″	159	136	281	175
41	02h27m30.00s	00°35′00.0”	15.7	17.1	15	5.3″ × 3.9″	188	204	288	316
42	02h30m00.00s	00°35′00.0”	19.7	20.3	14	5.5″ × 3.8″	92	262	213	265
21	16h47m54.00s	34°56′00.0”	8.5 (C)		16^a	6.7″ × 5.2″	146		323	
22	16h50m54.00s	34°56′00.0”	8.5 (C)		18^a	5.2″ × 4.3″	154		259	
31/32	23h28m00.00s	00°09′00.0”	13.0 (D)		17^a	5.9″ × 4.6″	185		309	
32/33	23h32m00.00s	00°09′00.0”	13.0 (D)		13^a	6.1″ × 4.4″	188		289	

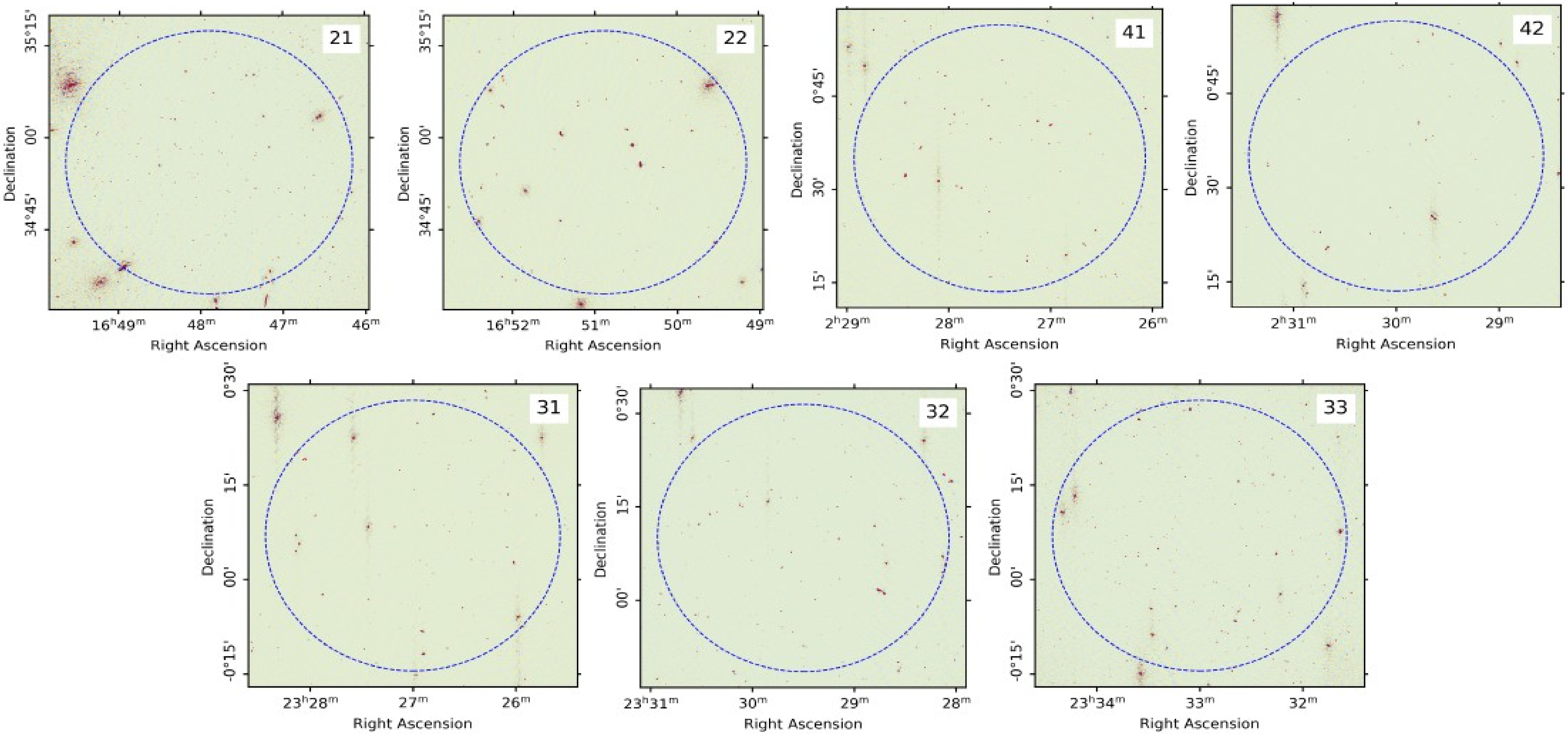


Figure 1. The GMRT 610 MHz continuum images of the seven DEEP2 sub-fields from the ≈ 400-hours of data presented here. The blue dotted circle in each panel marks the FWHM of the GMRT primary beam at 610 MHz.

Выборка

- The DEEP2 DR4 catalog contains 3,109 galaxies with accurate redshifts (Newman et al. 2013), for which the redshifted Hi 21 cm line frequency lies within our frequency coverage, and that lie within the FWHM of the GMRT primary beam at the redshifted Hi 21 cm line frequency.
- the DEEP2 selection criterion (R <24.1) preferentially picks out blue star-forming galaxies at z > 1 (e.g. Weiner et al. 2009).
- Для однородности выборки (starforming galaxies) исключались «красные» (для данного z) галактики(162) – по Willmer et al 2006 (the rest-frame M_B versus U-B color-magnitude diagram of DEEP2 galaxies shows that the color-magnitude bimodality seen in galaxies locally is still present at redshifts z>1)
- Исключались AGN (по континууму) (238).
- Складывались области ±1500 km/s вокруг каждой галактики (всего 3596 независимых спектров). **Размер области вокруг каждой галактики на z~1 – около 60 kpc.**
- After excluding galaxies that fail the Gaussianity tests, our sample contains 2,841 blue star-forming galaxies at z = 1.18-1.39.

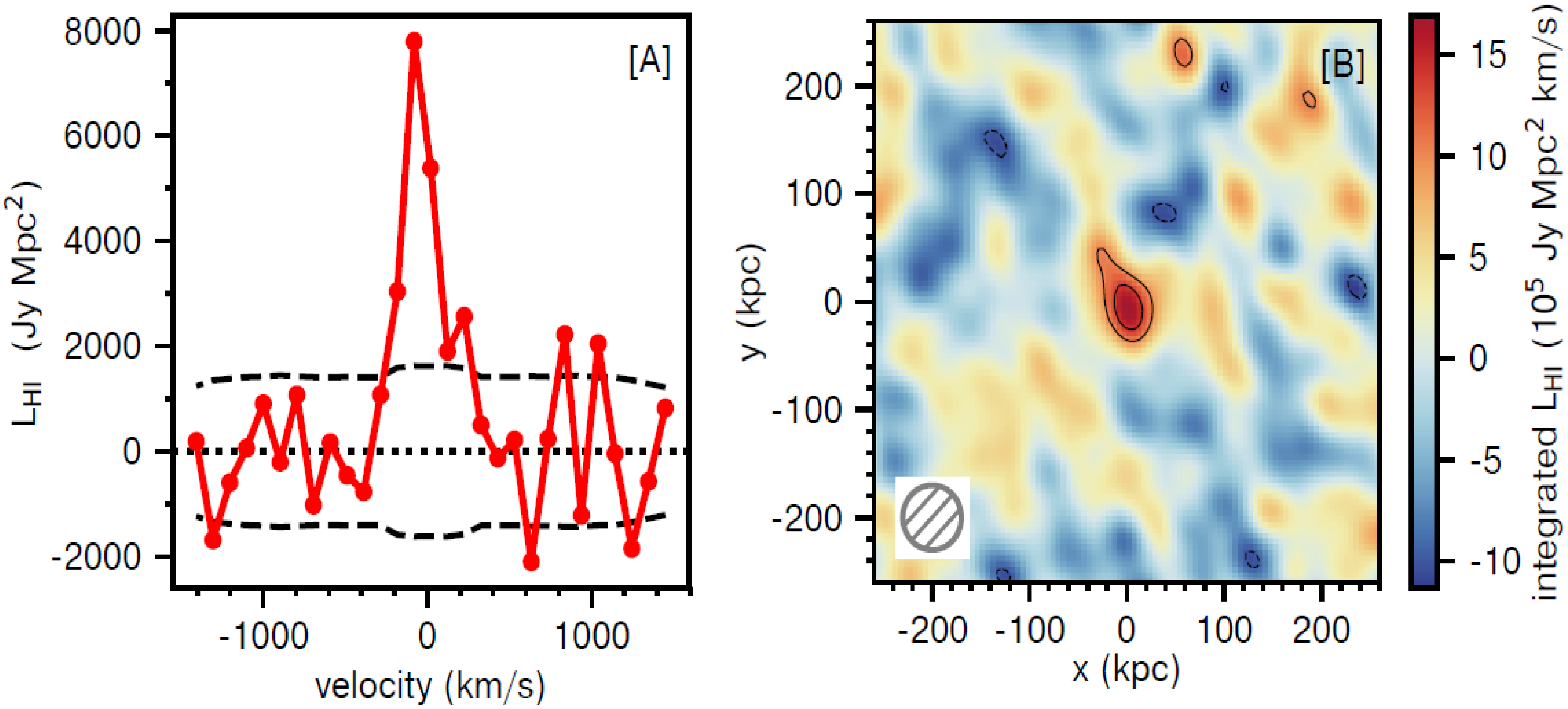
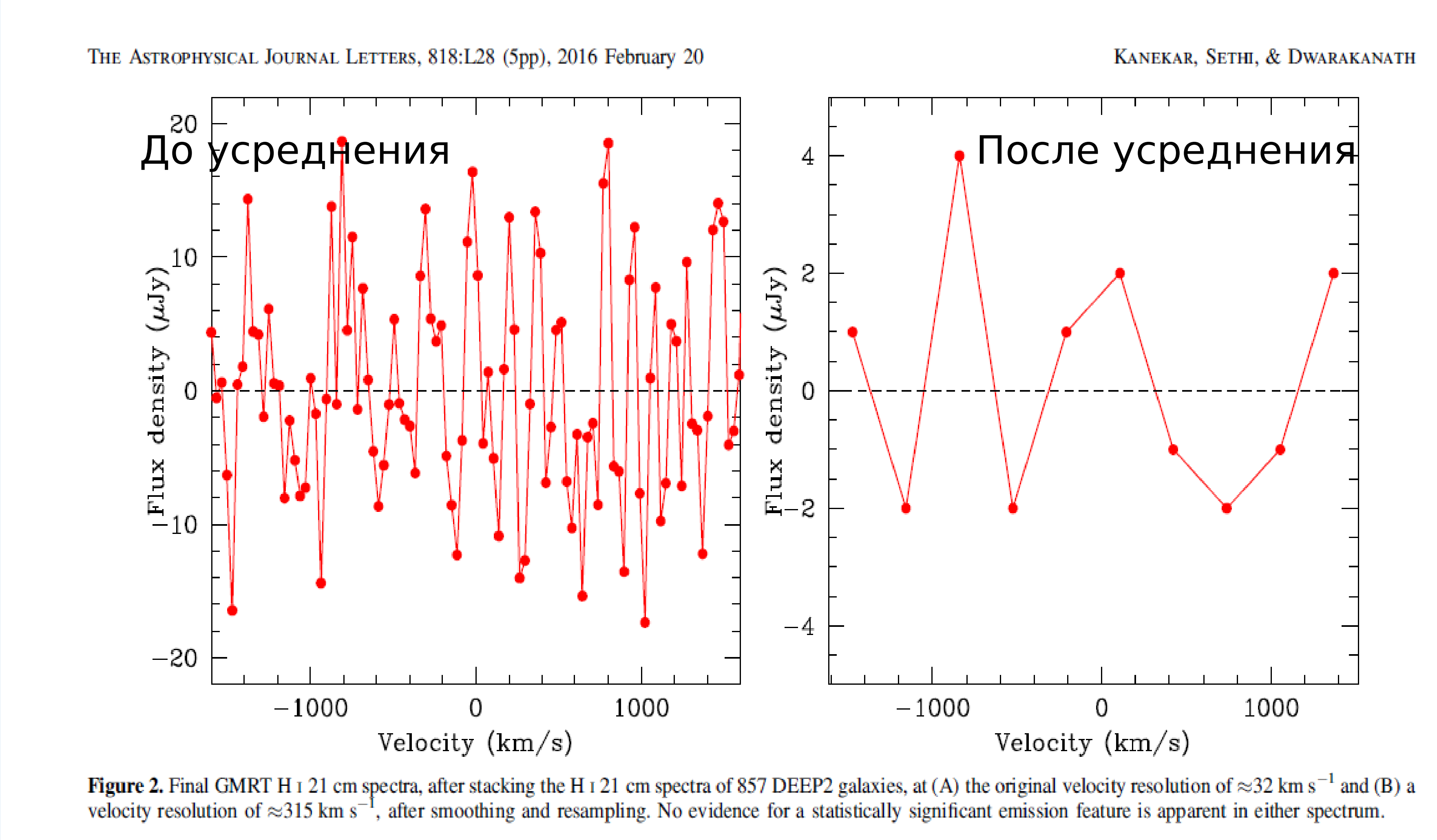


Figure 2. [A] The average HI 21 cm spectrum, at a velocity resolution of 102 km s^{-1}, obtained after stacking the individual HI 21 cm spectra at the location of the 2,841 blue star-forming galaxies at $z = 1.18 - 1.39$. The dashed lines show the 1σ uncertainty on the spectrum. A clear detection of the average HI 21 cm signal can be seen in the central velocity channels. [B] The average HI 21 cm emission image obtained by combining the central channels of the stacked cube. The circle at the bottom left indicates the 60 kpc resolution of the image. The contours are at $(-3, 3, 4.2) \times \sigma$ levels, dashed negative contours. A clear detection of the average HI 21 cm emission is obtained at the centre of the image.

Предыдущая работа на GMRT для 857 галактик обзора DEEP2 (наблюдения 2011 года)



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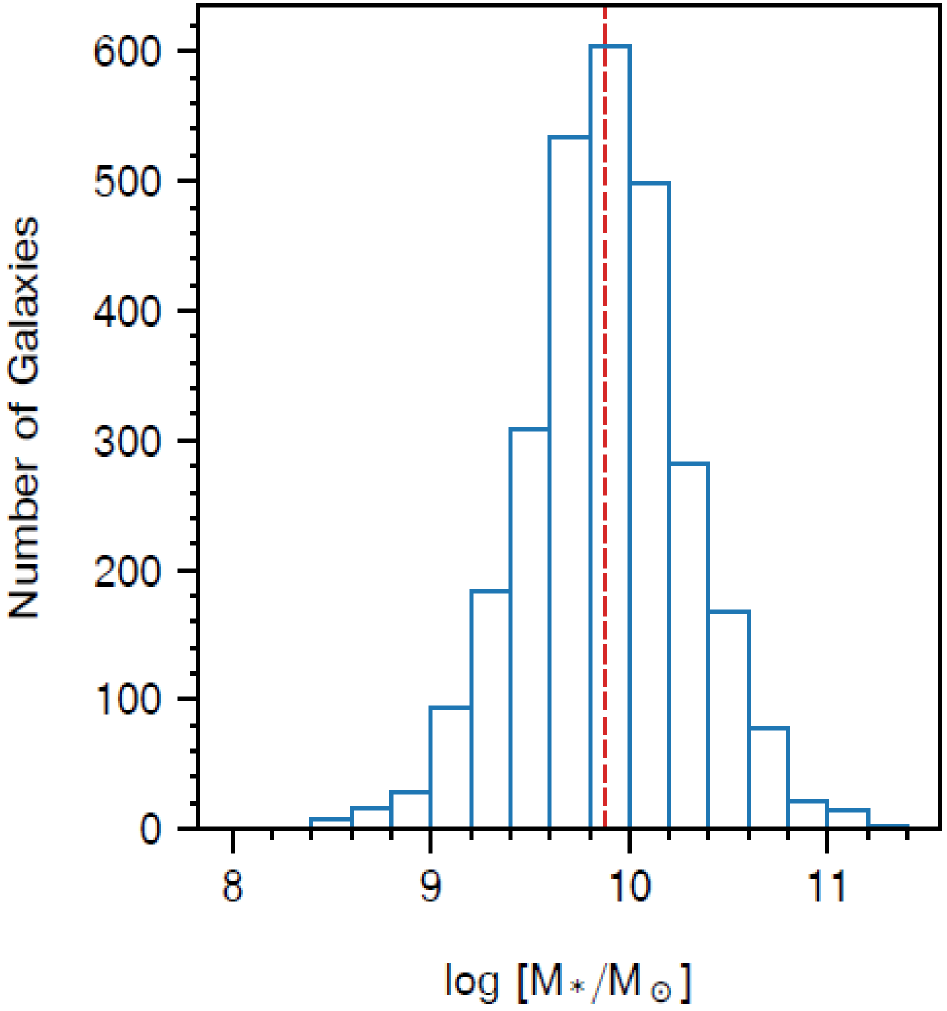
До усреднения

После усреднения

Figure 2. Final GMRT H I 21 cm spectra, after stacking the H I 21 cm spectra of 857 DEEP2 galaxies, at (A) the original velocity resolution of ≈32 km s^{-1} and (B) a velocity resolution of ≈315 km s^{-1}, after smoothing and resampling. No evidence for a statistically significant emission feature is apparent in either spectrum.

$$\langle \mathrm{M}_* \rangle = 1.2 \times 10^{10}\ \mathrm{M}_\odot$$



ure 3. The stellar mass distribution of our sample of 2,841 blue star-forming galaxies at $z \approx 1.3$. The dashed red vertical shows the median stellar mass of the sample.

РЕЗУЛЬТАТЫ по HI

- <Mhii> = (3.09 ± 0.61) 10^{10} Ms, for the 2,841 blue star-forming galaxies at <z> ~ 1.3.
- Increasing the size of the beam beyond 60 kpc does not result in a statistically-significant increase in the average Hi 21 cm emission signal. We thus find no evidence that the average Hi 21 cm emission from star-forming galaxies arises from a region larger than 60 kpc.

- We obtain a median rest-frame 1.4 GHz luminosity of $L_{1.4GHz}$ = (3.93 ±0.30) 10^{22} W Hz^{-1}. Using the SFR calibration of Yun et al. (2001), this implies a median SFR of (14.5± 1.1) Ms /yr

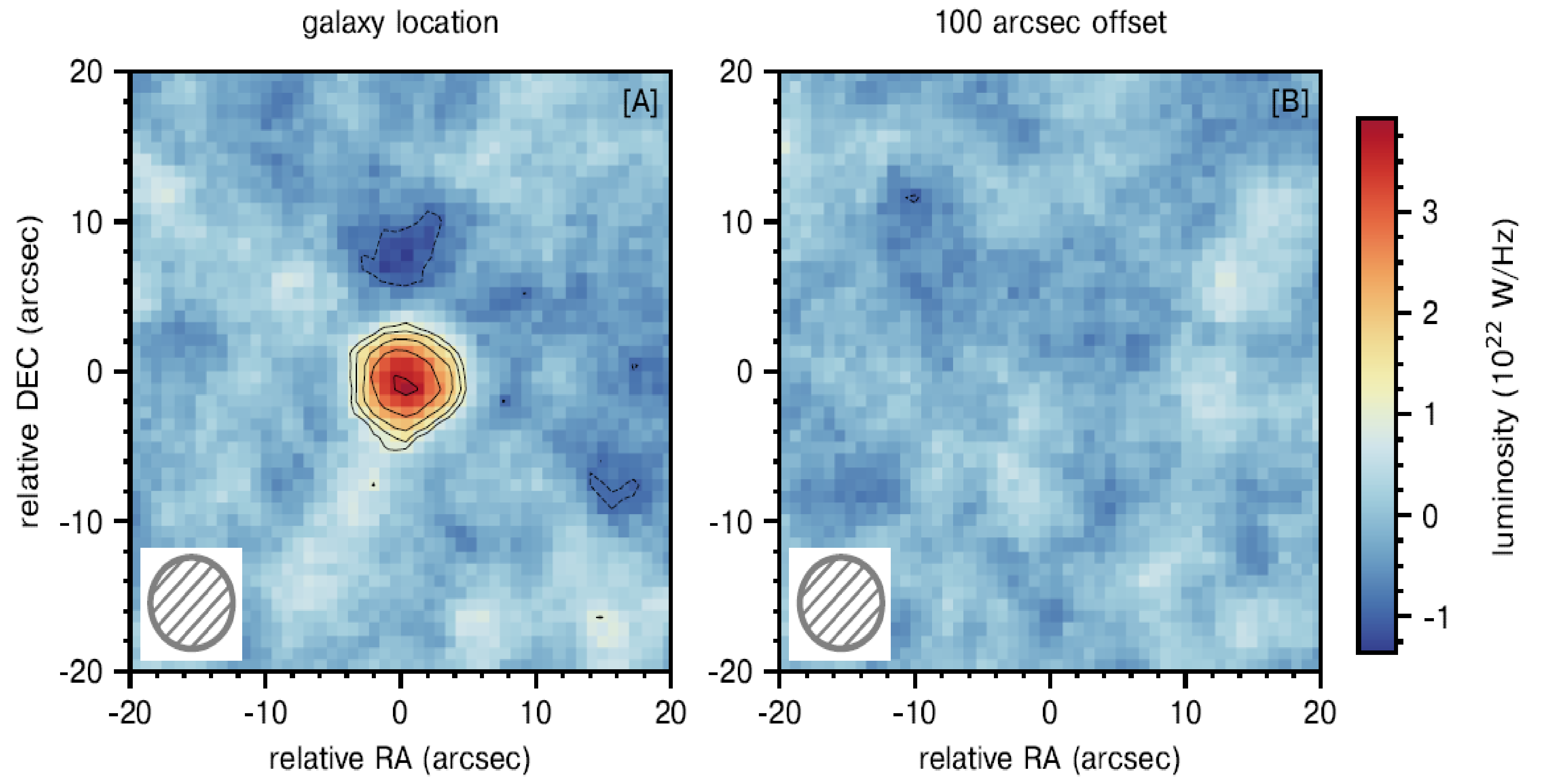


Figure 4. [A] The average rest-frame 1.4 GHz luminosity of our 2,841 star-forming galaxies, obtained from a weighted-median stack of their rest-frame 1.4 GHz emission. A clear ($\approx 12\sigma$ significance) detection of the median 1.4 GHz emission of the galaxies can be seen in the image. [B] The result of the offset stack, a weighted-median stack at locations 100″ offset from the above galaxies: no signal is seen in this image. The circle at the bottom left of each panel shows the 6.1” resolution of the images. The contours are at $(-3.0, 3.0, 4.2, 6.0, 8.4, 12.0) \times \sigma$, with dashed negative contours.

РЕЗУЛЬТАТЫ ПО ЭВОЛЮЦИИ

- The average properties of our galaxies are consistent with those of the star-forming main-sequence at $z \sim 1.3$ (e.g. Whitaker et al. 2012; Leslie et al. 2020).
- The typical Hi masses of main-sequence galaxies at $z \sim 1.3$ are significantly larger than their stellar masses, with an average Hi-to-stellar mass ratio <MHI/M*> of 2.6 ± 0.5. This is very different from the situation in the local Universe, where the Hi-to-stellar mass ratio is only 0.4, for blue star-forming galaxies with a similar stellar mass distribution.
- Менее массивная половина галактик (<M*>~4 10^9 Ms) имеют более высокое значение <MHI/M*> = 7.4±2.2, более массивная – 1.61±0.44 (это средне-взвешенные значения).

Сравнение с CO-газом

- CO emission studies of similar main-sequence galaxies at z ~1.2 have shown that their molecular gas mass is comparable to the stellar mass (e.g Tacconi et al. 2020). Our results thus indicate that the atomic gas content of star-forming galaxies at this epoch is larger than their molecular gas content.
- **ТАКИМ ОБРАЗОМ,**

at this epoch, star-forming galaxies contain nearly four times more cold gas, including both atomic and molecular gas, than stars, very different from the local Universe.

ГАЛАКТИКИ Z~1.3 –
В КОНЦЕ АКТИВНОЙ СТАДИИ ИСЧЕРПАНИЯ ГАЗА

The average Hi depletion timescale $<t_{\text{dep Hii}}>$= 2.13±0:45 Gyr. In the local Universe, the Hi depletion time for the main-sequence galaxies is 7 Gyr (e.g. Saintonge et al. 2017).

- **The short Hi depletion timescale is comparable to the timescale on which the cosmic SFR density declines after its peak at z~ 1 - 3.**

ТАКИМ ОБРАЗОМ,

- main-sequence galaxies in the local Universe can continue to quiescently form stars at their current SFR for 5 -10 Gyr without the need for fresh gas accretion, as long as there is efficient conversion of Hi to H2. Conversely, main-sequence galaxies at z ~1.3 can sustain their current SFR for only ~ 2 Gyr unless their Hi reservoir is replenished.
- Our results are thus consistent with the hypothesis of Bera et al. (2018) and Chowdhury et al. (2020) that

the quenching of star-formation activity at z < 1 may arise due to insufficient gas accretion, resulting in a paucity of neutral gas to fuel further star-formation.