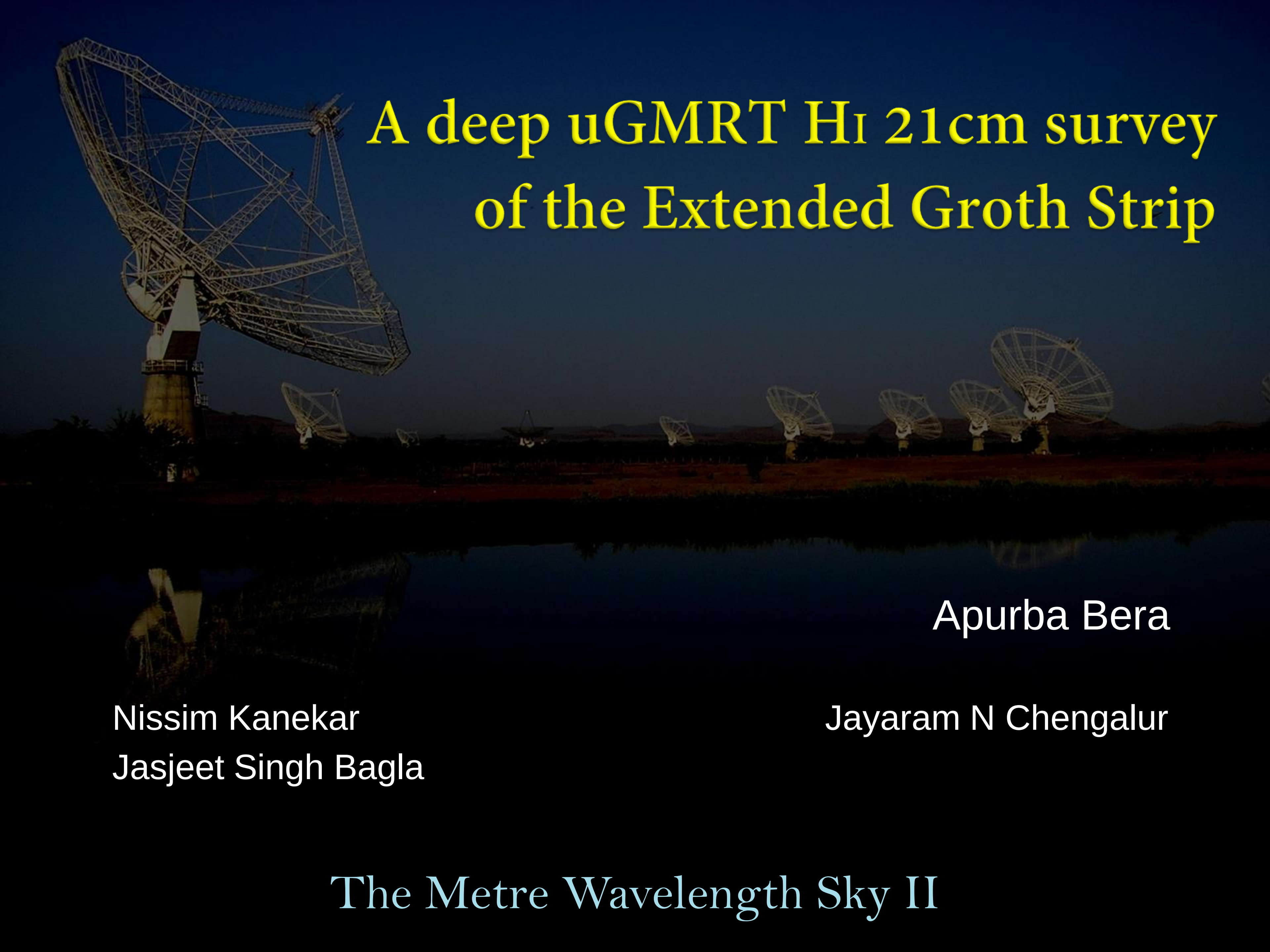

A deep uGMRT HI 21cm survey of the Extended Groth Strip

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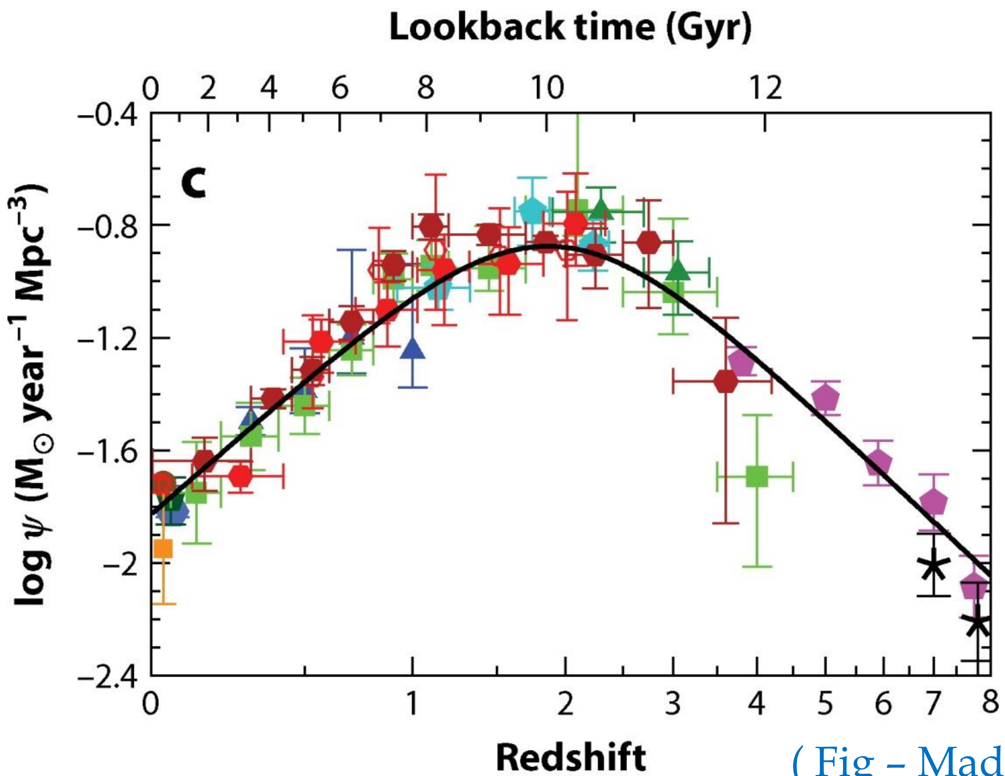
The Metre Wavelength Sky II

Outline

- Background
- HI 21 cm survey with the uGMRT
- Target field – Extended Groth Strip
- Survey plan & current status
- Preliminary results
- Summary

Cosmic star-formation history



(Fig – Madau & Dickinson, 2014)

- Comoving SFR density of the universe decreases by an order of magnitude from z~1 to z~0.

- Atomic gas (HI) in galaxies – fuels the star formation

  evolution with cosmic time not yet understood

Probing HI in distant galaxies

- HI content of galaxies – best probed by HI 21cm emission line
  - hyperfine transition, intrinsically weak
  - difficult to detect from distant galaxies ($z > 0.1$)

- Big and gas rich galaxies at $z{\sim}0.2$ detected in recent surveys

  (e.g. Catinella & Cortese 2015; Jaffe et al. 2012,2013)

- Only two detections at $z > 0.3$
  - CHILES detection at $z = 0.376$
  - tentative detection at $z = 0.407$

  (Fernandez et al. 2016, Blecher et al. 2019)

- HI 21 cm emission from smaller galaxies at $z > 0.2$
  - difficult to detect with currently operating radio telescopes in reasonable integration time

HI 21 cm stacking

- Average HI 21 cm emission from smaller galaxies can still be measured … by STACKING !

- "Stacking" HI emission from a large number of faint galaxies gives information of their average HI mass.

(Chengalur et al. 2001)

- Stacking can be done in bins of redshift, stellar mass, SFR, etc to probe the variation of average HI mass with redshift and the physical properties of the galaxies.

- Previous HI stacking experiments at $z > 0.2$
  - yielded some information on average HI mass of galaxies
  - provided estimates of cosmic HI density (Ω_{HI})
  - results had large uncertainties

(Rhee et al. 2018, 2016; Lah et al. 2007)

HI 21 cm survey with the uGMRT

- uGMRT band-5 receivers + 400 MHz bandwidth
  covers HI 21 cm from galaxies out to $z < 0.4$

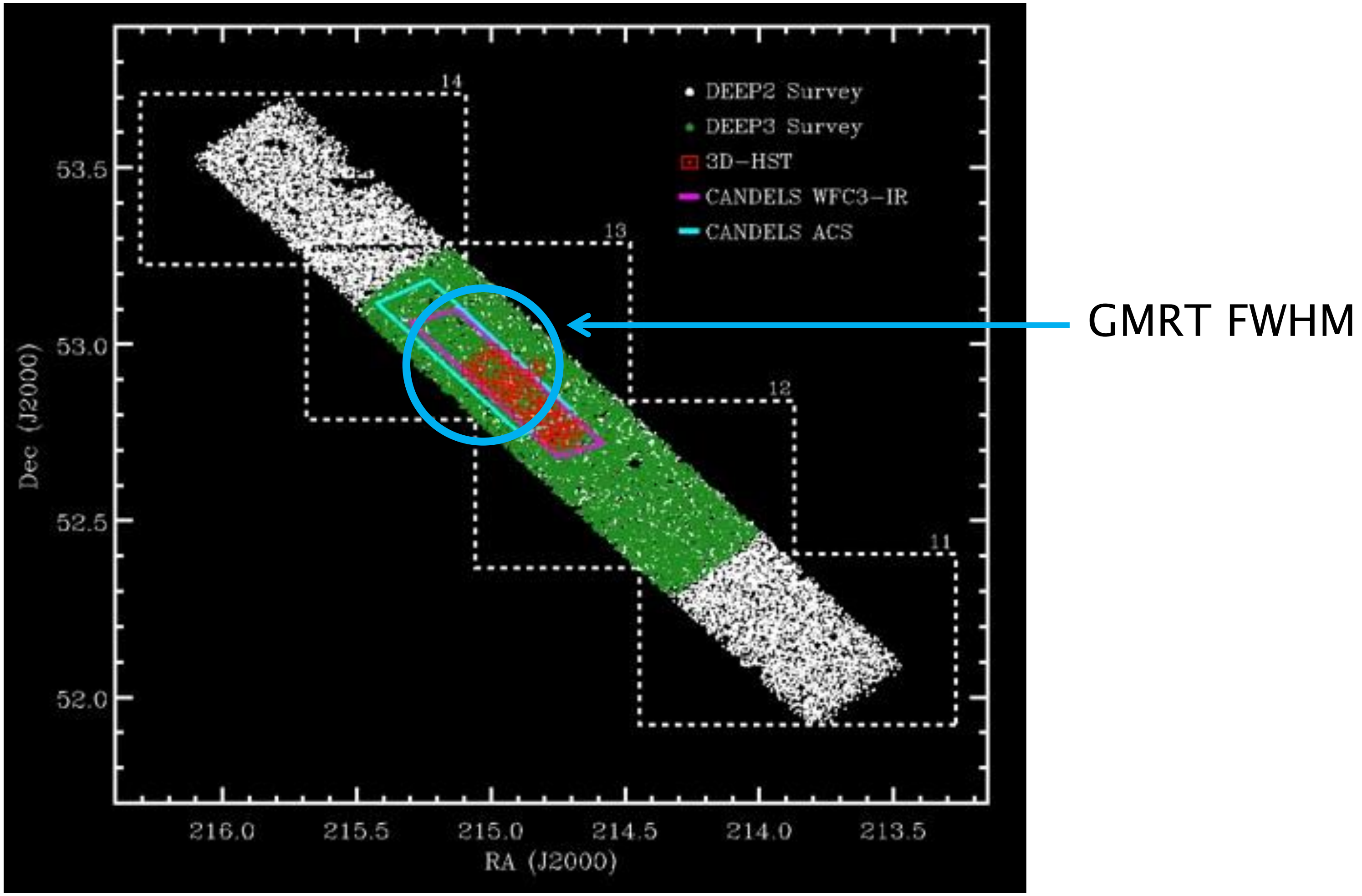
- Goals of uGMRT HI 21cm survey

  To probe atomic gas in individual star-forming galaxies out to $z < 0.4$ through their HI 21cm emission

  To measure the average HI mass of the galaxies with known spectroscopic redshifts by stacking their HI 21cm emission

  To produce a deep L-band continuum image of the field and obtain dust-free estimates of the total SFR of star-forming galaxies from their radio continuum emission.

Target field – Extended Groth Strip



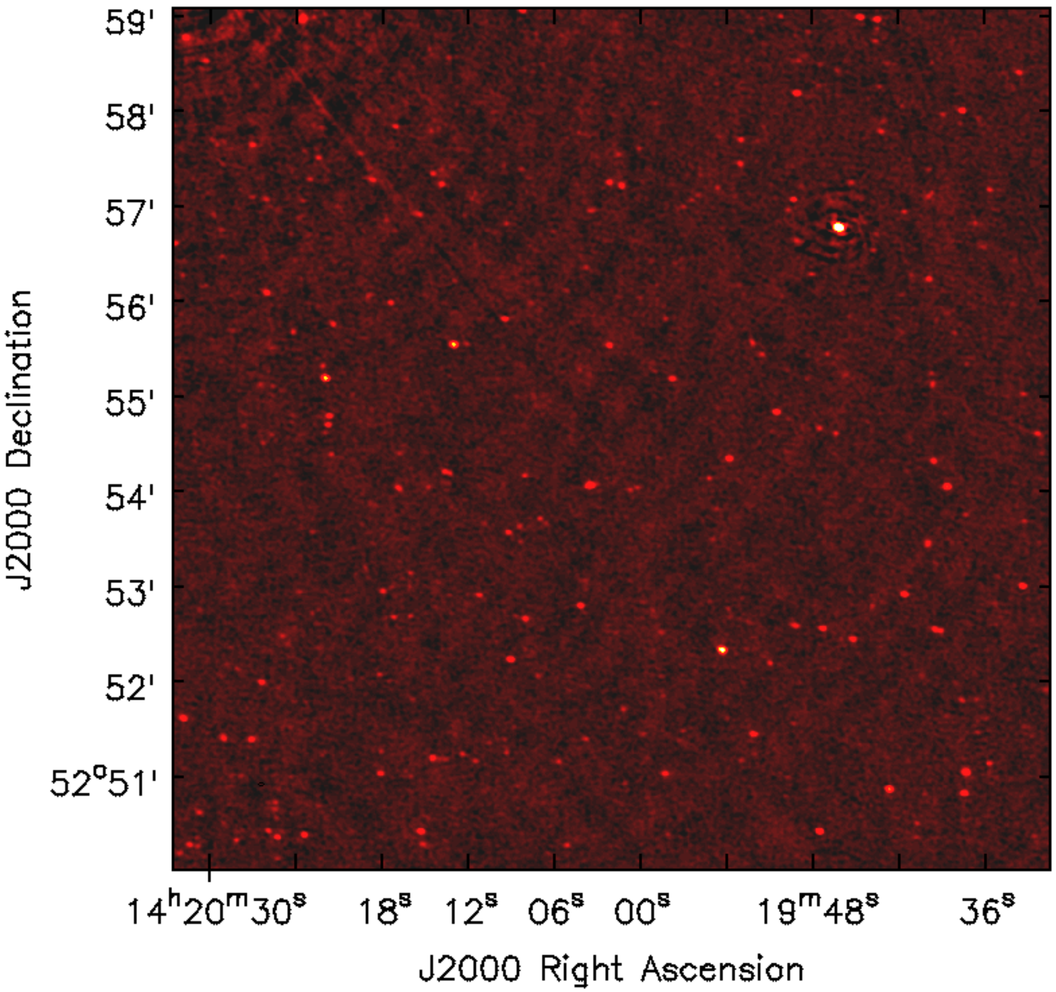
- DEEP2, DEEP3 surveys – Accurate spectroscopic redshifts.
- SFR, stellar mass estimates, etc are available.

(Newman et al. 2013, Mostek et al. 2012, Cooper et al. 2011)

Survey plan & current status

- Planned total on-source integration time = 250 hours
- Using uGMRT band-5 receivers (1000 MHz – 1400 MHz)
  400 MHz bandwidth with frequency resolution ~ 12 km/s
- Current status –
  Observation started in March 2017
  245 hours allocated so far, over three observing cycles
  yielded ~170 hours of on-source data
- Analysis done for 175 hours (~120 on-source hours) of data
- Preliminary results
  based on first 175 hours (~120 on-source hours) of data

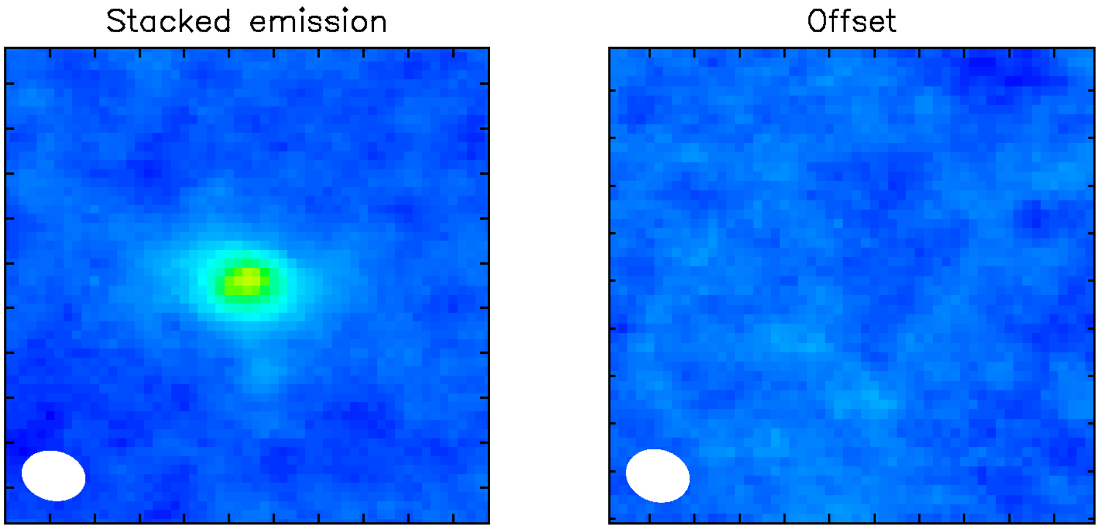
EGS continuum image



- RMS noise $\approx 2.3\ \mu$Jy/Beam, beam size $\approx 2.3''$
- Deepest image ever made with the GMRT.

SFR from the radio continuum

- Stacked radio continuum emission from ~200 blue star-forming galaxies with $M_B < -18$ at $0.2 < z < 0.4$



- Clear detection of stacked emission (12σ)

- Median radio derived SFR $= (2.56 \pm 0.21)\ M_\odot\ yr^{-1}$
- Median optical SFR $= 1.40\ M_\odot\ yr^{-1}$
- Median extinction factor ≈ 1.83

HI 21cm spectral line analysis

- Data cube from continuum subtracted visibilities
  Channel resolution 100 kHz (~25 km/s)

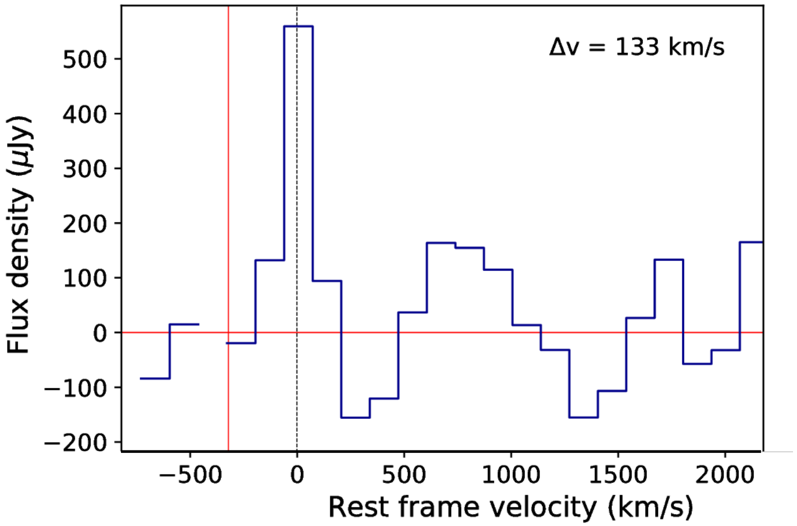
- Spectral line analysis done for DEEP2/DEEP3 sources at $0.2 < z < 0.4$
  Sub-cubes extracted around each target source
  spectra extracted after smoothing to different beam sizes
  each spectra searched for HI 21 cm emission feature

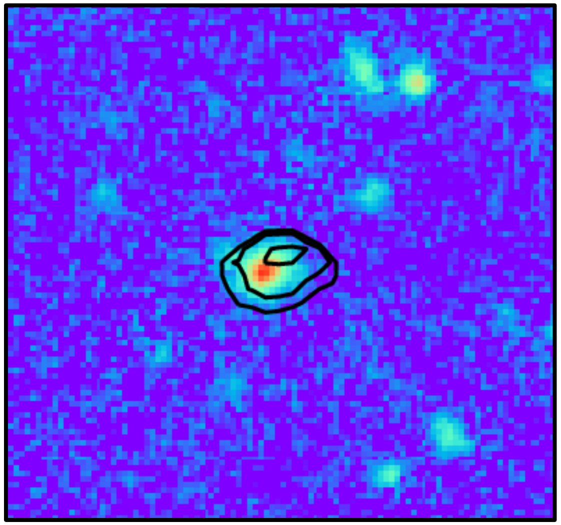
- Stacking analysis done for blue star forming galaxies at $0.2 < z < 0.4$
  excluded galaxies with unreliable redshifts
  excluded spectra failing statistical tests for Gaussianity
  stacking done for different spatial and velocity resolutions

- A blind search for HI 21cm emission in the entire cube will be carried out in future

HI 21 cm emission at $z \approx 0.387$

- Initially detected in the original survey well outside the FWHM detected again in a follow-up, with the source at the pointing centre





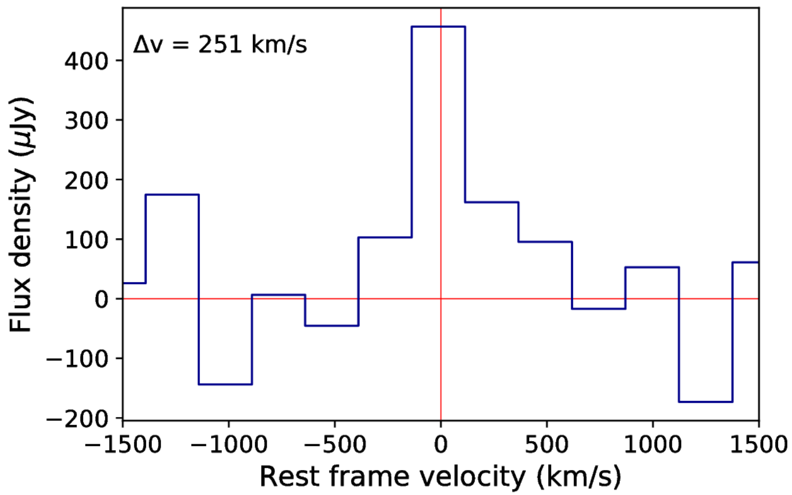
- Emission unresolved, inferred size $< 25\ kpc$

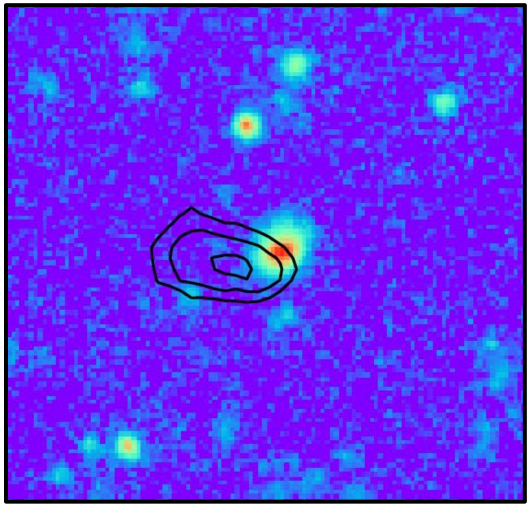
- $M_{HI} = (5.8 \pm 1.3) \times 10^{10} M_\odot$ ($\approx 4.5\sigma$), velocity width $\approx 130\ km/s$

- $M_* \approx 10^9 M_\odot$, $\mathrm{M_{HI}/M_*} \approx 60$
- $SFR\ (optical) \approx 0.5\ M_\odot\ yr^{-1}$, $SFR\ (radio) < 12\ M_\odot\ yr^{-1}$

Tentative detection at $z \approx 0.324$

- Detected outside the FWHM of the primary beam (sensitivity $\approx 25\%$)





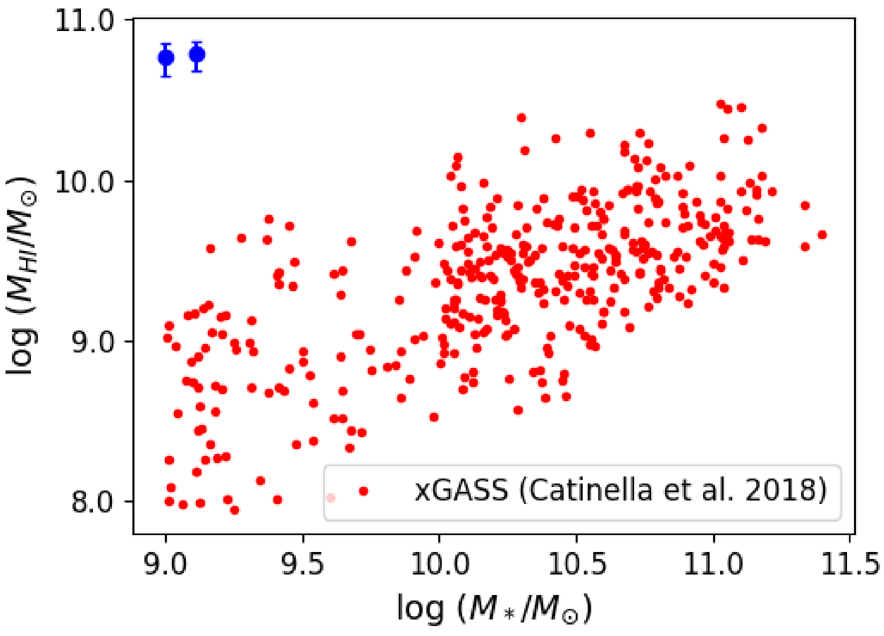
- Emission marginally resolved

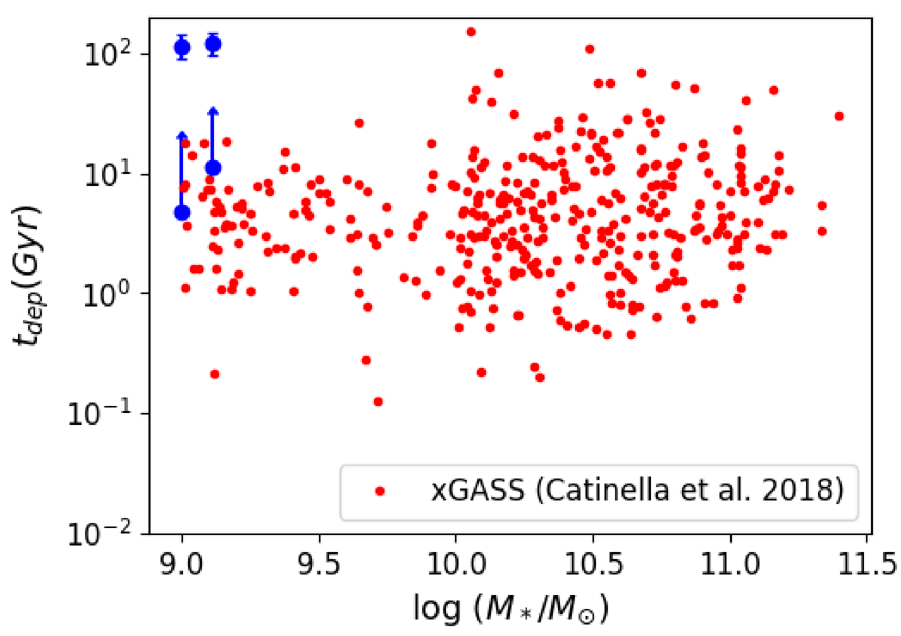
- $M_{HI} = (6.1 \pm 1.3) \times 10^{10} M_{\odot}$ ($\approx 4.6\sigma$) Velocity width $\approx 250\ km/s$

- $M_{*} \approx 1.3 \times 10^{9} M_{\odot}$ $\mathrm{M_{HI}/M_{*}} \approx 50$

- $SFR\ (optical) \approx 0.5\ M_{\odot}\ yr^{-1}$, $SFR\ (radio) < 5\ M_{\odot}\ yr^{-1}$

Comparison with local galaxies

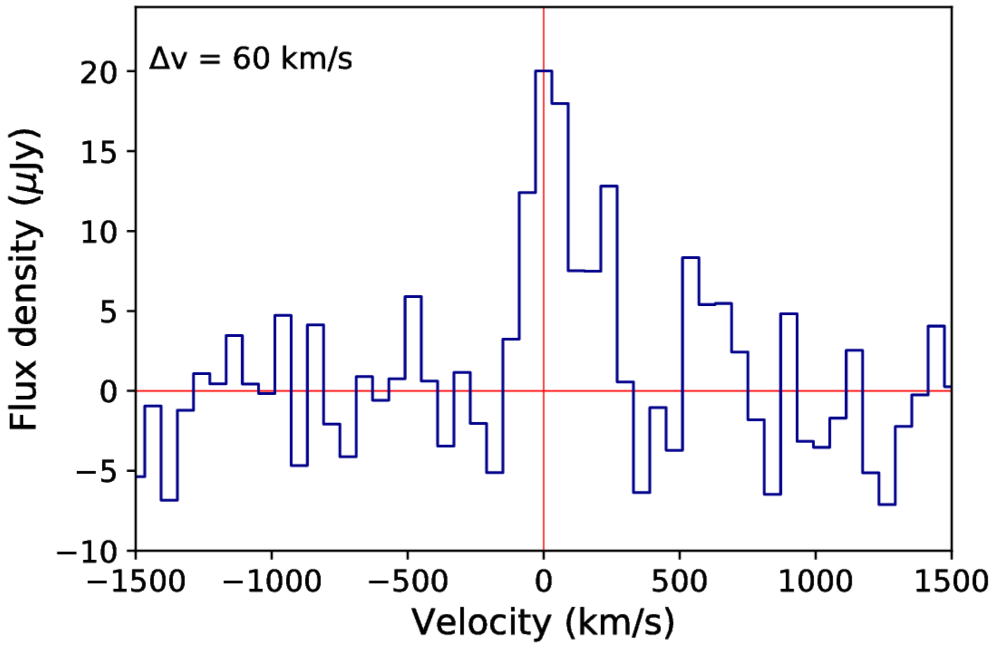




- **High gas-to-stellar mass ratio, large HI depletion time-scale !**

Stacked HI 21cm emission

- Stacked ~200 blue star-forming galaxies with $M_B < -18$ (brighter than the LMC) at $0.2 < z < 0.4$



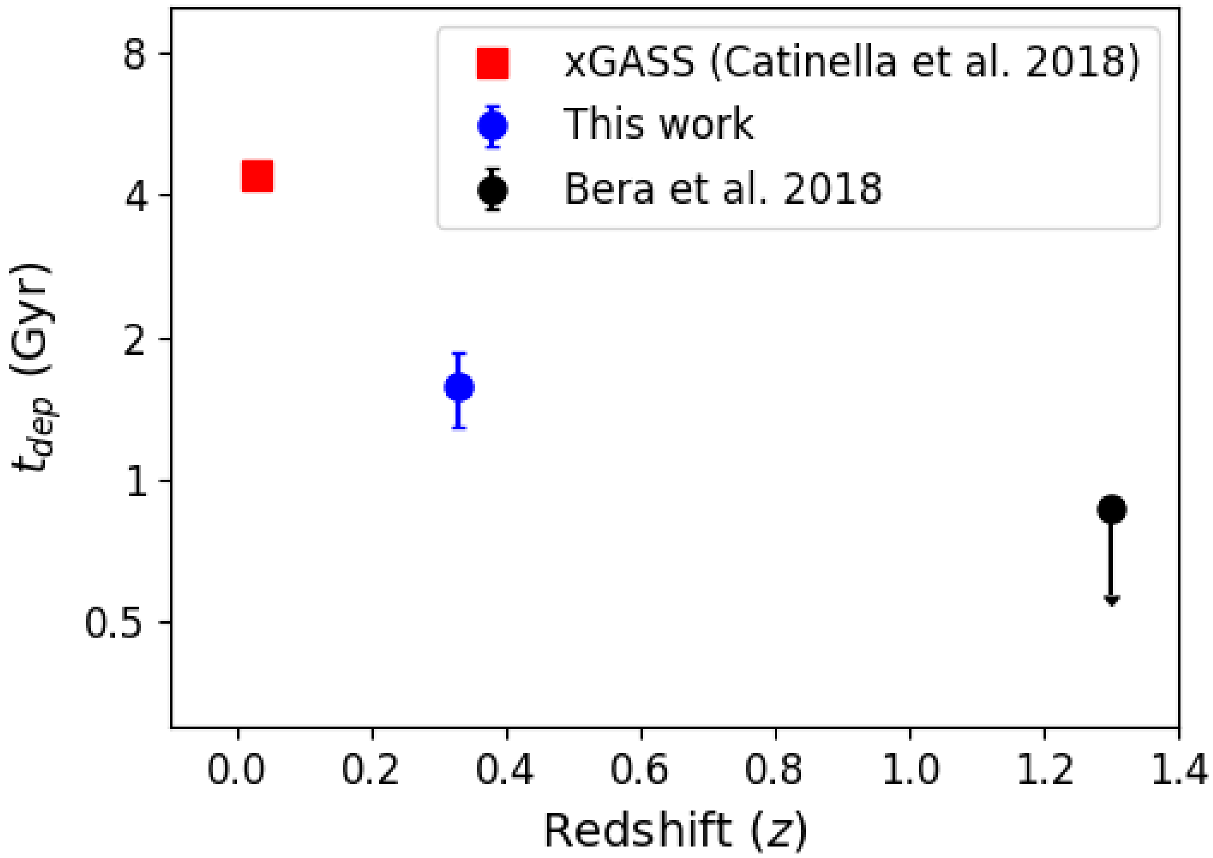
- Clear detection of average HI 21 cm emission (**$6.5\,\sigma$**)

$$< \mathrm{M_{HI}} > \; = (4.06 \pm 0.63) \times 10^9 \, M_\odot$$

$$< \mathrm{M_{HI}} >/< M_* > = 0.8 \pm 0.1$$

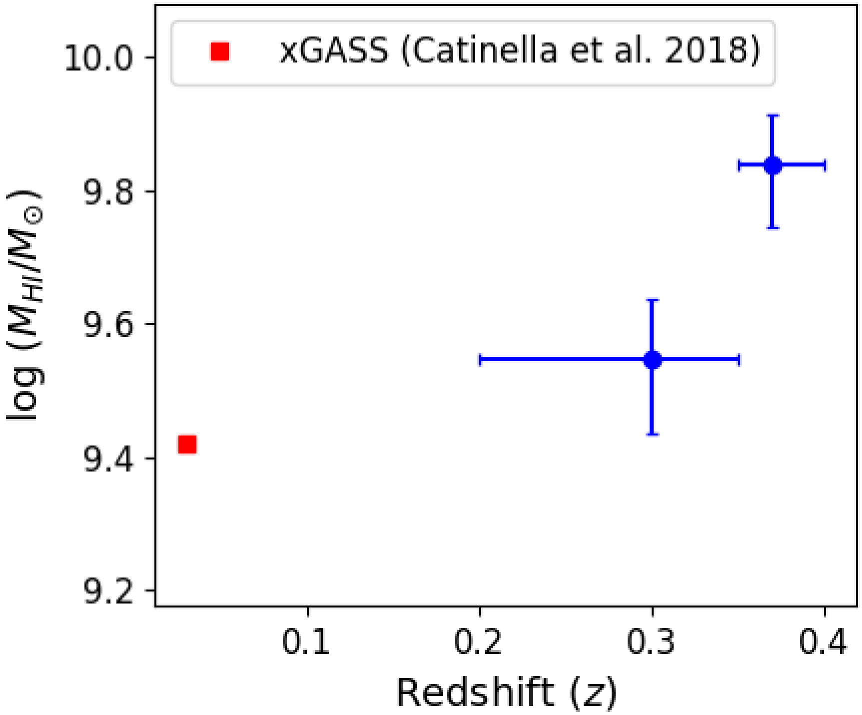
$$< t_{dep}(HI) > = 1.58 \pm 0.21 \, Gyr$$

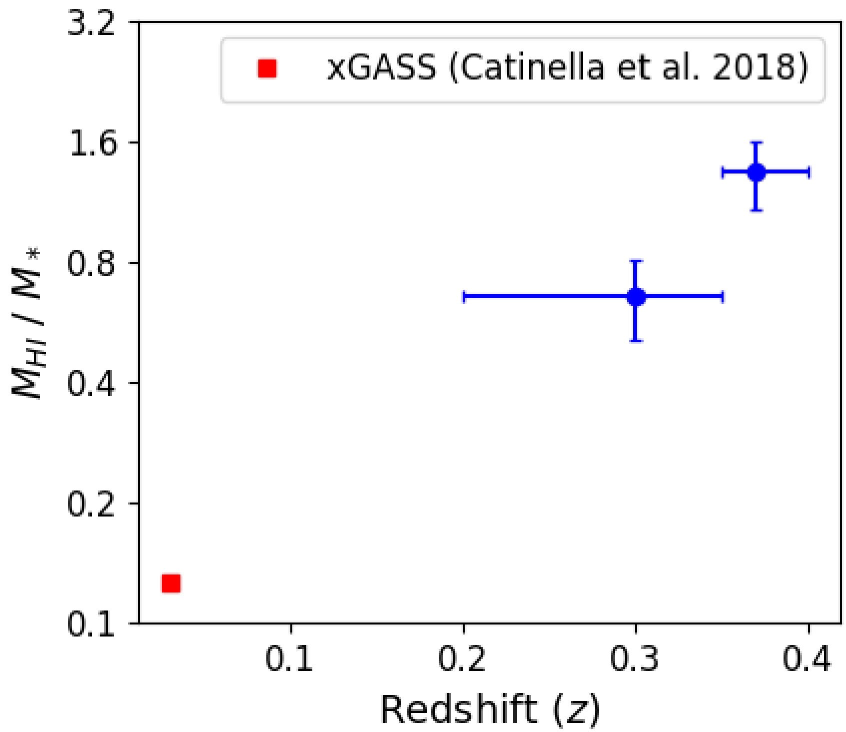
Atomic gas depletion time scale



- HI depletion time scale appears to decrease with increasing redshift.

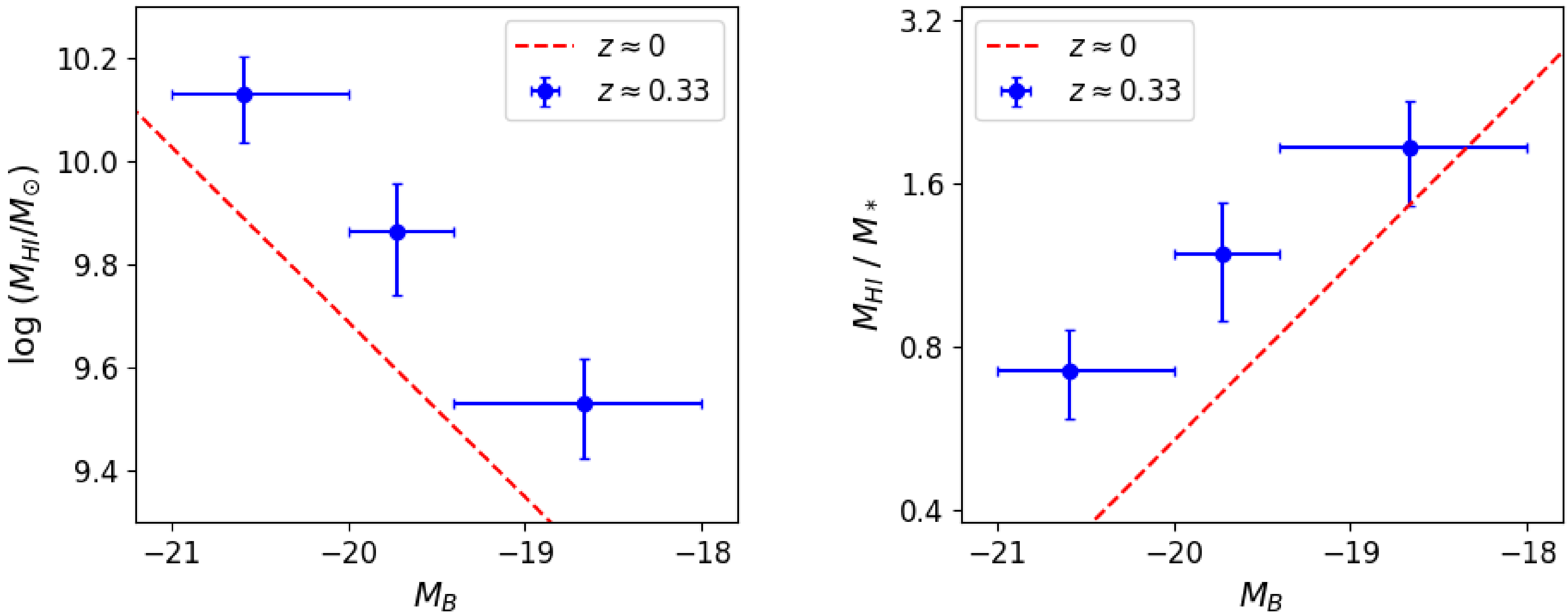
Redshift evolution of $< M_{HI} >$





- Average HI mass and gas-to-stellar mass ratio of star-forming galaxies appear to increase with redshift.

$M_{HI} - M_B$ scaling relation



- $M_{HI} - M_B$ scaling relation in the local universe

$$\log\left(\frac{M_{HI}}{M_\odot}\right) = \alpha - \beta M_B$$

(e.g. Dénes et al. 2014)

- **Scaling relation appears to shift upward from $z \approx 0$ to $z \approx 0.33$.**

Summary

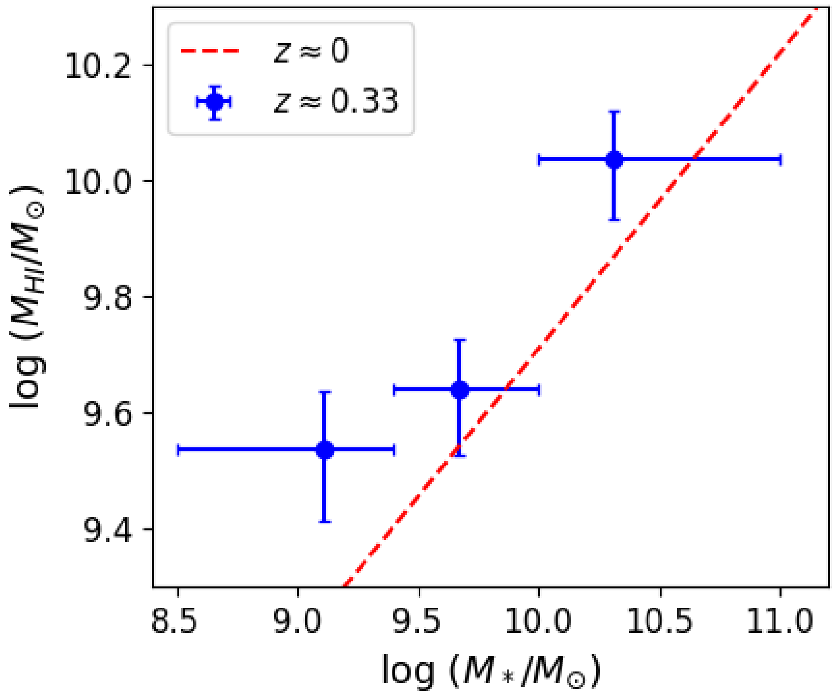
- We are carrying out a deep HI 21cm survey of the Extended Groth Strip with the uGMRT. So far analyzed 117 hours of on-source data.
- Deepest ever continuum image with the GMRT, used to estimate radio-derived SFR of star-forming galaxies.
- Two tentative detections at $z \approx 0.387$ and $z \approx 0.324$, with high gas-to-stellar mass ratio, large HI depletion time scale.
- HI mass of the star-forming galaxies at $z \approx 0.33$

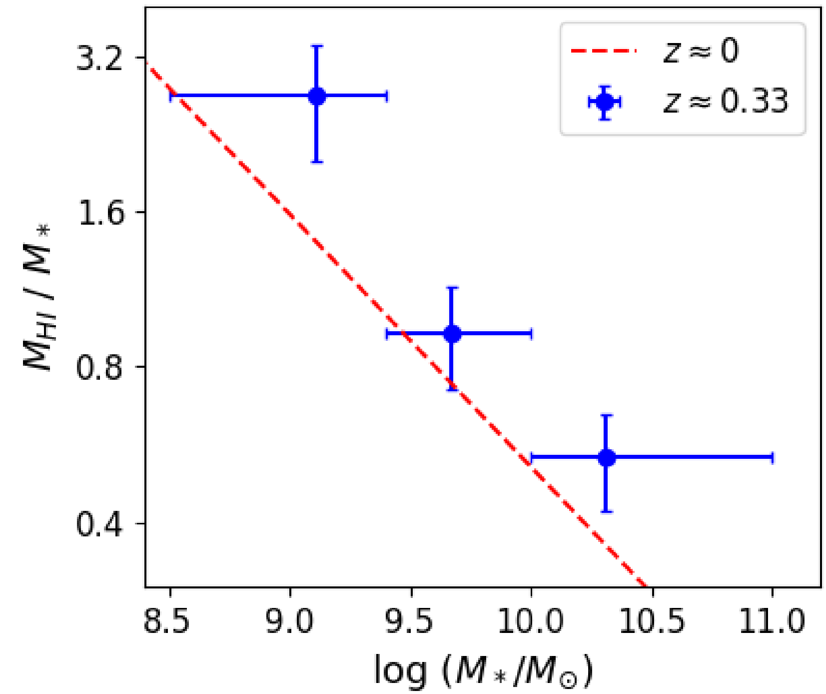
$$< \mathrm{M_{HI}} > \; = (4.06 \pm 0.63) \times 10^{9} \, M_{\odot}$$

$$< t_{dep}(HI) > = 1.58 \pm 0.21 \; Gyr$$

- $< \mathrm{M_{HI}} >$ of star-forming galaxies appears to increase with redshift.
- Atomic gas depletion time scale appears to decrease with redshift.

$M_{HI} - M_*$ scaling relation



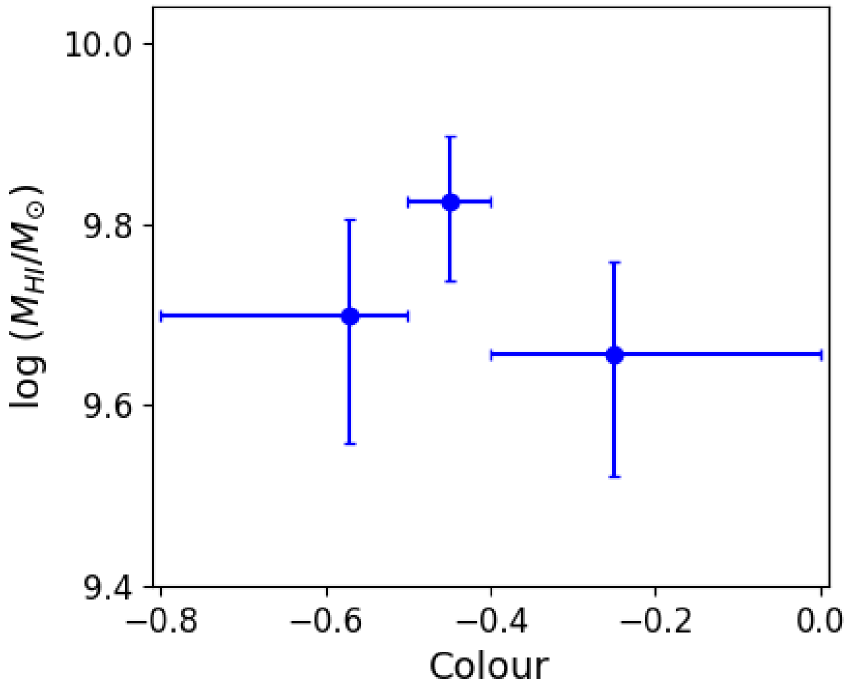


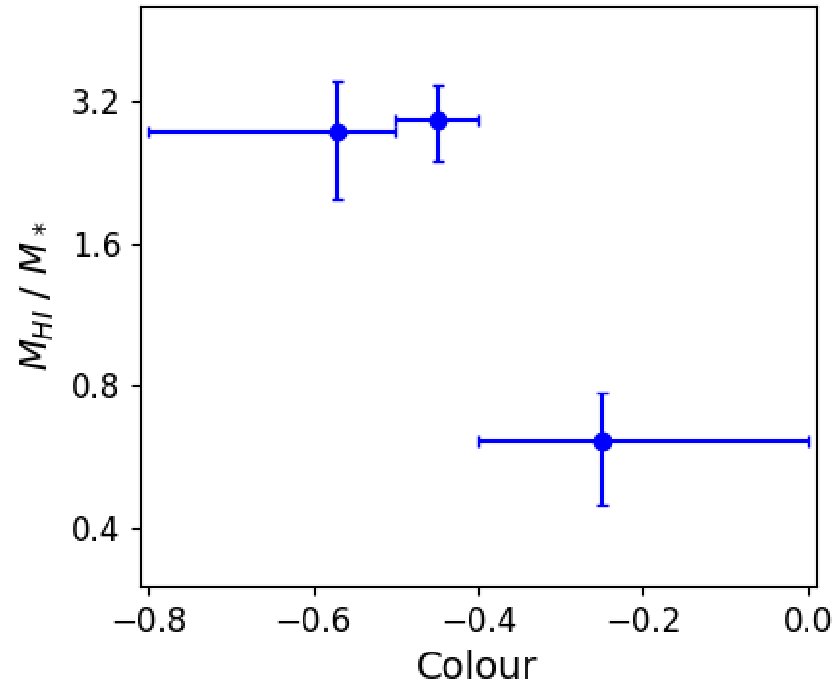
- Bigger galaxies -- more HI but less gas-to-stellar mass ratio (Similar to the local universe)
- In the local universe $\log(M_{HI}) = a + b\log(M_*)$

(e.g. Parkash et al. 2018)

- **$M_{HI} - M_*$ scaling relation shifts upward from $z \approx 0$ to $z \approx 0.33$.**

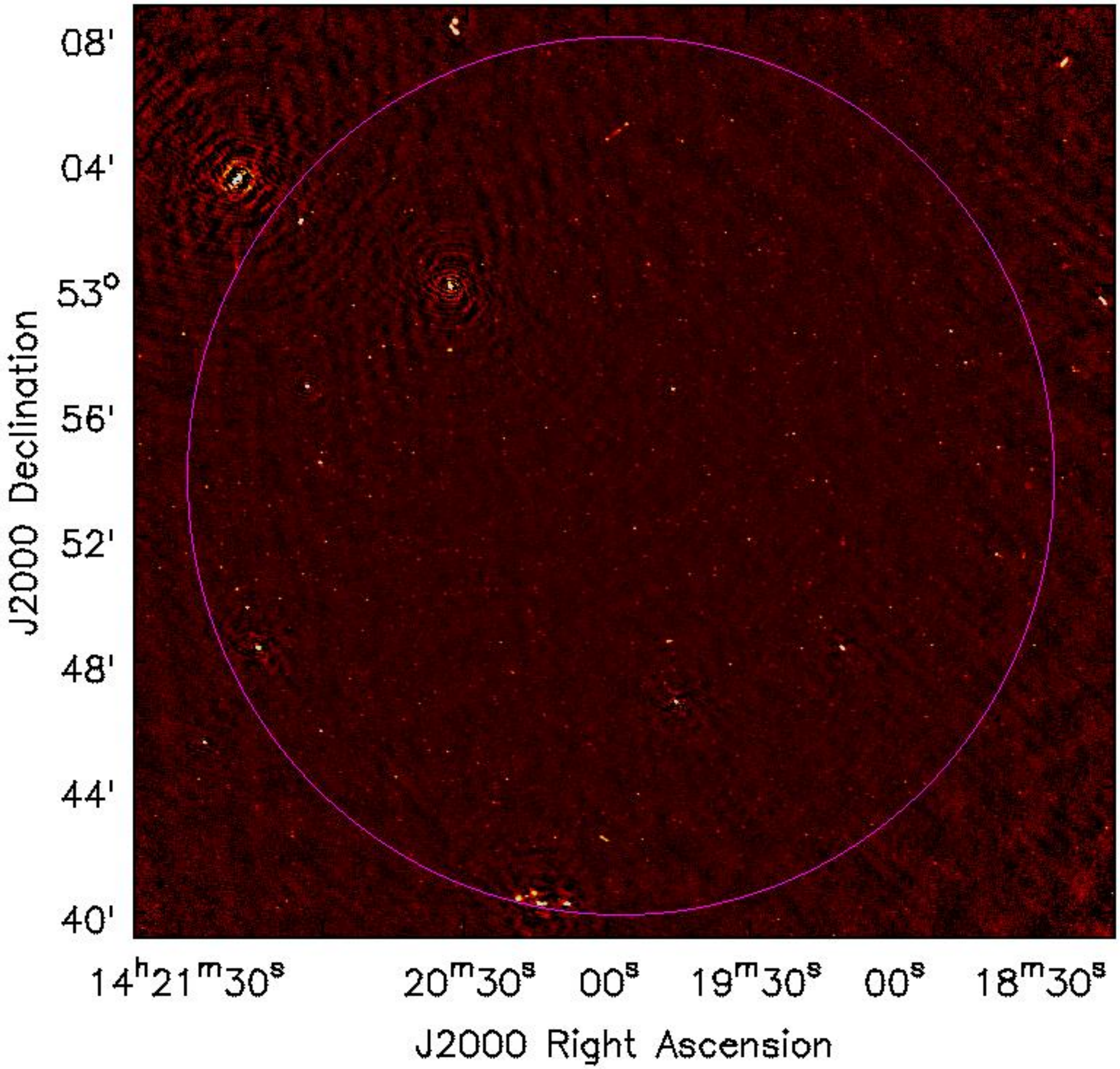
$< M_{HI} >$ vs galaxy colour

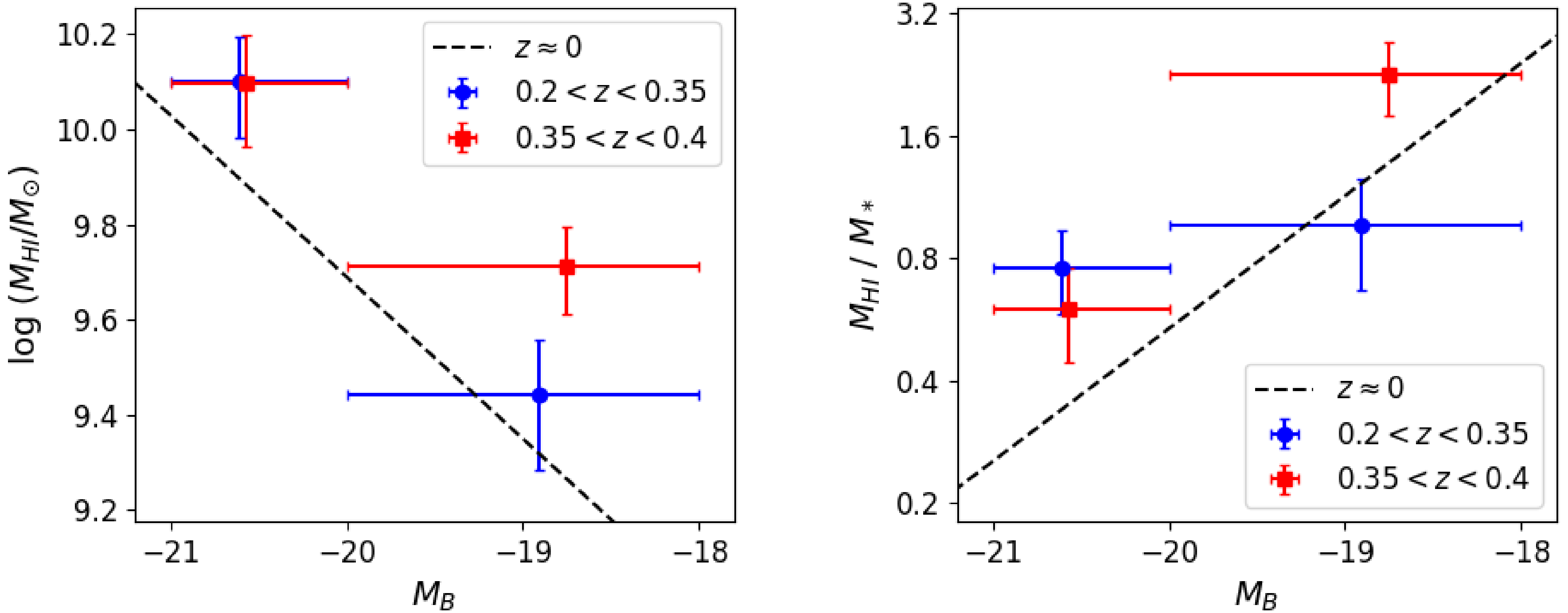




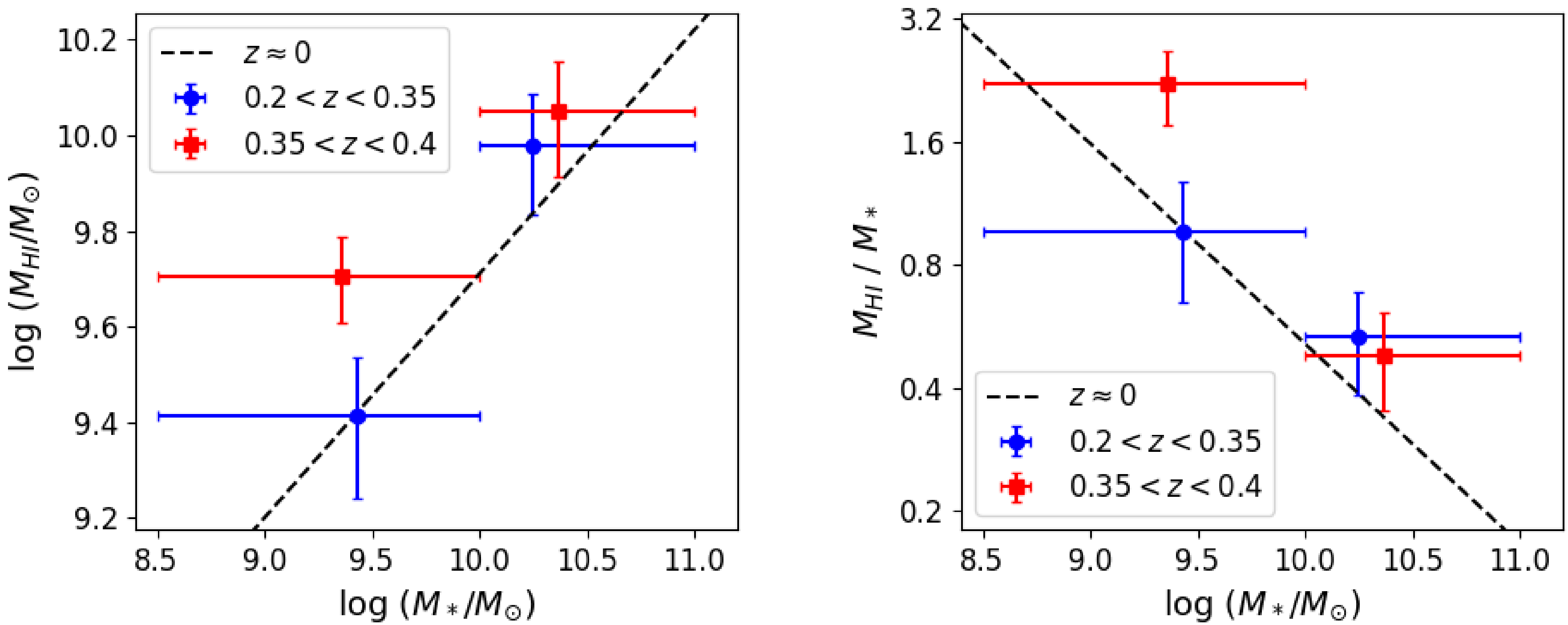
- No detectable dependence of total HI mass with galaxy colour.
- Bluer galaxies (more negative colour) – lighter in terms of stellar mass
  larger gas-to-stellar mass ratio

EGS continuum image

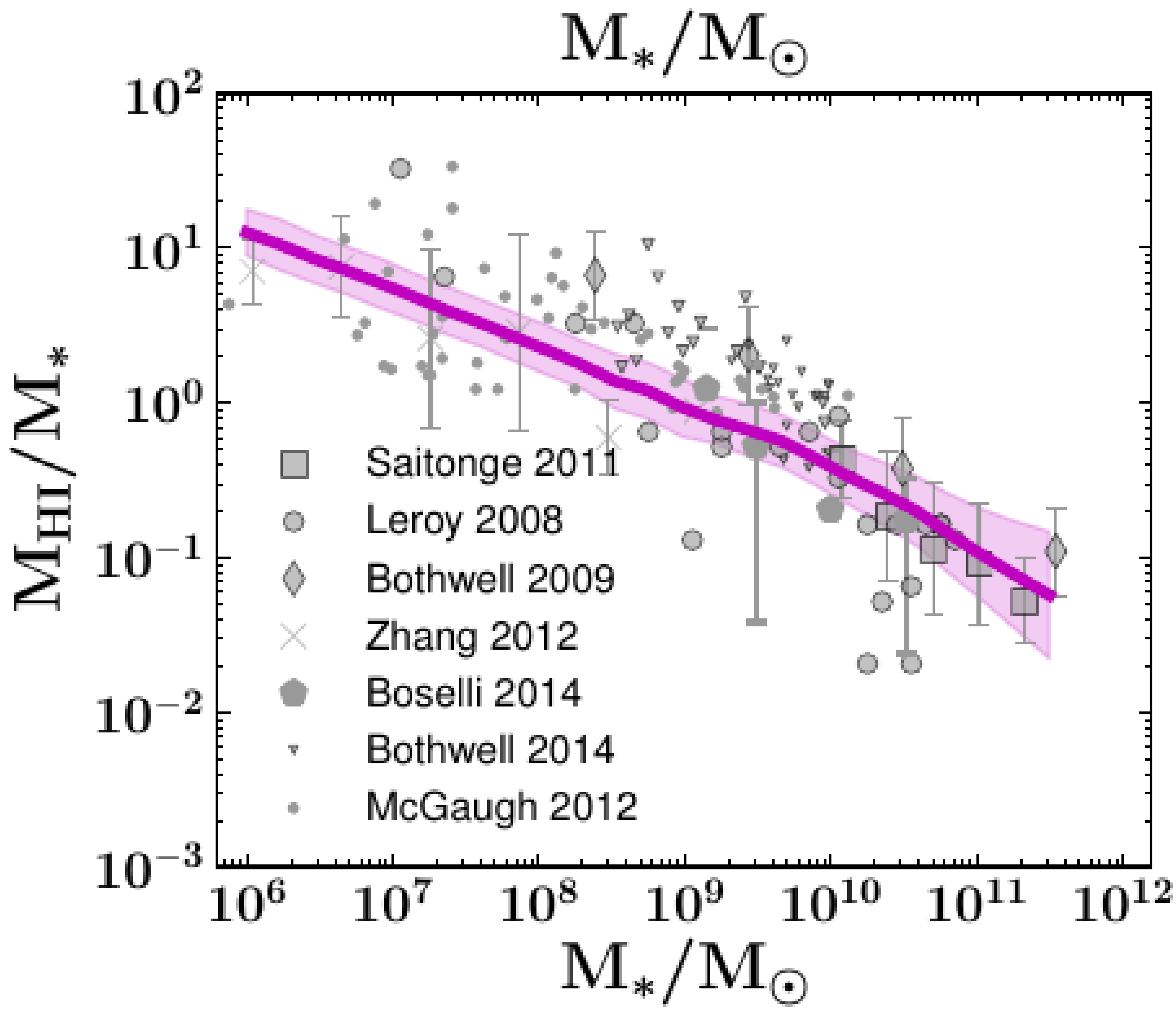




10.2
10.0
9.8
9.6
9.4
9.2
log ($M_{HI}/M_{\odot}$)
−21
−20
−19
−18
M_B
$z \approx 0$
$0.2 < z < 0.35$
$0.35 < z < 0.4$
3.2
1.6
0.8
0.4
0.2
M_{HI} / M_*
−21
−20
−19
−18
M_B
$z \approx 0$
$0.2 < z < 0.35$
$0.35 < z < 0.4$



10.2
10.0
9.8
9.6
9.4
9.2
log ($M_{HI}/M_\odot$)
8.5
9.0
9.5
10.0
10.5
11.0
log ($M_*/M_\odot$)
$z \approx 0$
$0.2 < z < 0.35$
$0.35 < z < 0.4$
3.2
1.6
0.8
0.4
0.2
M_{HI} / M_*



Popping et al. 2018