The Neutral Hydrogen Content of Galaxies at $z \approx 0.75 - 1.45$

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Outline

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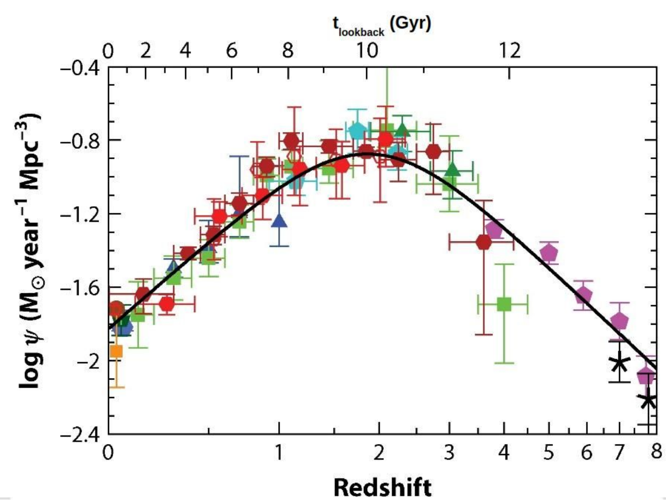
- HI21cm survey of DEEP2 fields at $z \approx 0.75 - 1.45$ using the uGMRT.
- The star formation rate of galaxies at $z \approx 1$
- The atomic hydrogen mass of galaxies at $z \approx 1$
- Conclusion
- Summary

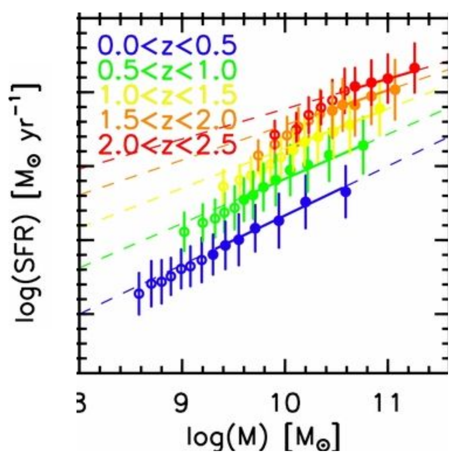
Introduction

Cosmic Evolution of Galaxies

- A clear picture of cosmic star-formation activity has evolved over the past decade from deep surveys in optical and infrared. (e.g. Madau & Dickinson, 2014)
- ~ 50 % of the stellar mass in the universe today created at the peak of cosmic star-formation between z=1~3. (e.g. Reddy et al., 2008; Marchesini et al., 2009)
- Peak SFR ~ 10 times than at the local universe.
- ~ 90% of cosmic star-formation activity over the past ~ 10 Gyr (z~2) occur on the almost linear "star-formation main sequence". (e.g. Whitaker et. al., 2012)
- Suggestive of a smooth mode of star-formation where galaxies move along the main sequence until their star-formation is quenched.



Madau & Dickinson, 2014



Whitaker et. al. 2012

Introduction

Cosmic Evolution of Galaxies and Cold Gas

- Star formation are formed out of cold molecular gas (e.g. McKee and. Ostriker, 2007)

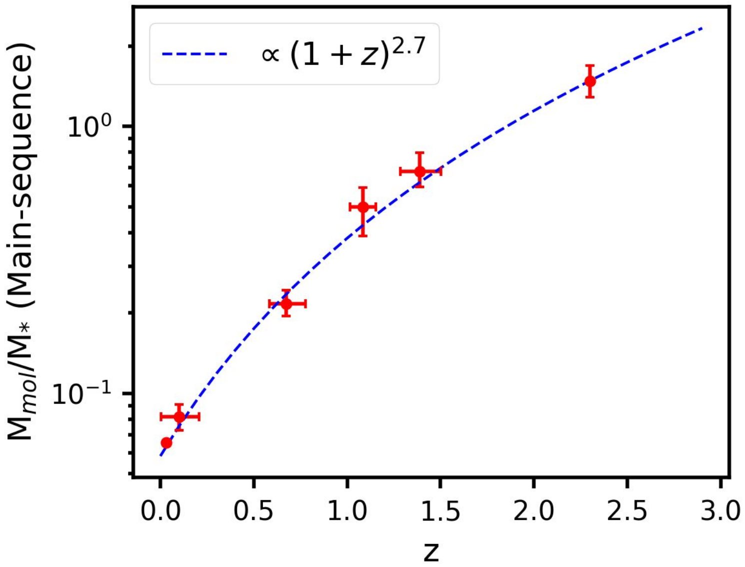
  HI → H_2 → Stars

- Understanding the cosmic evolution of these components critical to gain insights into the cosmic star-formation history.

- Observations suggest that the molecular gas fraction in main-sequence galaxies also goes up by a factor of 10 at the peak of star-formation. (e.g. Genzel et. al. 2015)

- Uncertainties in CO-to-H_2 conversion factor. (e.g. Carilli & Walter, 2013)

- What about HI?



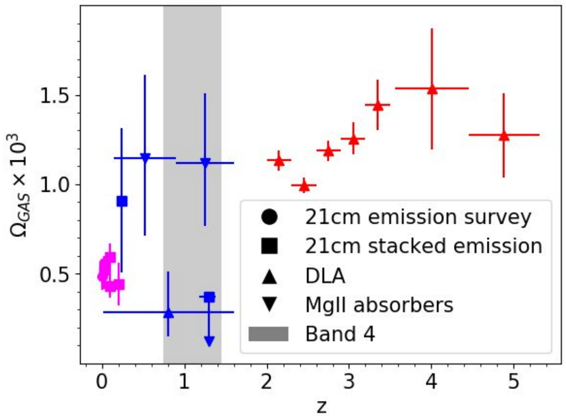
Genzel et. al. 2015

Introduction

HI21cm Emission from High Redshift Galaxies

- At high redshifts, 21cm absorption study of DLAs show that Ω_{gas} in galaxies a factor of 2 higher than in the local universe.

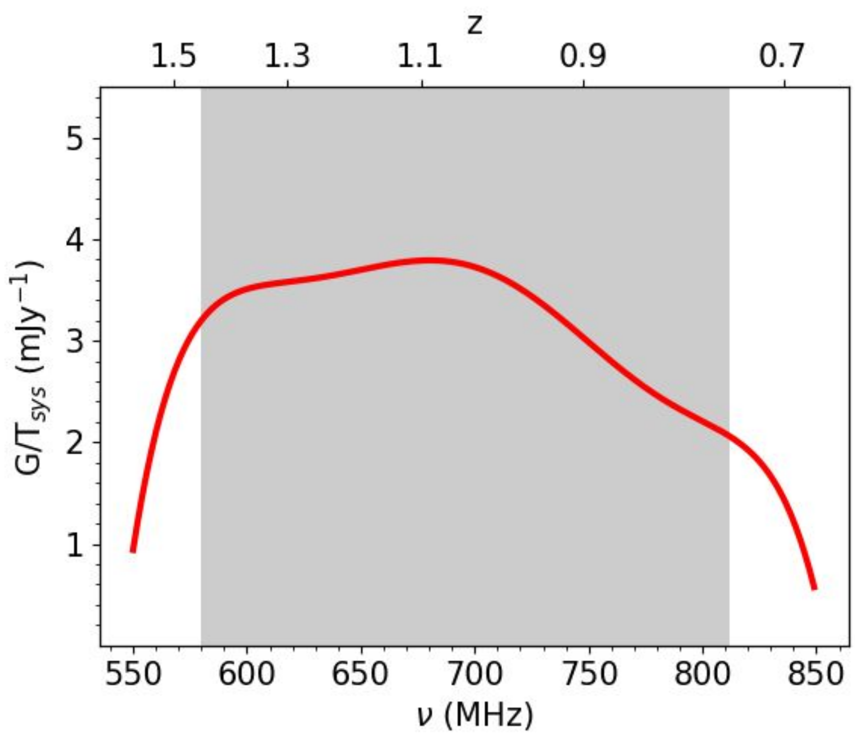
  (e.g. Noterdaeme et al., 2012; Crighton et al., 2015)
- HI21cm emission from individual high redshift galaxies difficult with current facilities.
- Highest redshift detection in emission at z=0.376 (M_{HI} ~ 3×10^{10} $M_{\odot}$) (Fernández et. al.)
- Individual detections at z ~ 1 possible only with next generation telescopes.
- Stacking or co-adding 21cm spectra to find the average HI content. (Chengalur et al., 2001)
  - z < 0.24 - Lah et. al., 2007 ; Rhee et. al. 2013 ; Delhaize et al., 2013
- Kanekar et. al. (2016) used the legacy GMRT 610 MHz system to place an upper limit of 2.1×10^{10} $M_{\odot}$ on the HI mass of star-forming galaxies at z ~ 1.3.



Noterdaeme et al., 2012; Crighton et al., 2015; Neeleman et al., 2016; Rao et. al. 2006; Lah et al., 2007; Kanekar et al., 2016; Zwaan et al., 2005; Martin et al., 2010

A Survey with the uGMRT

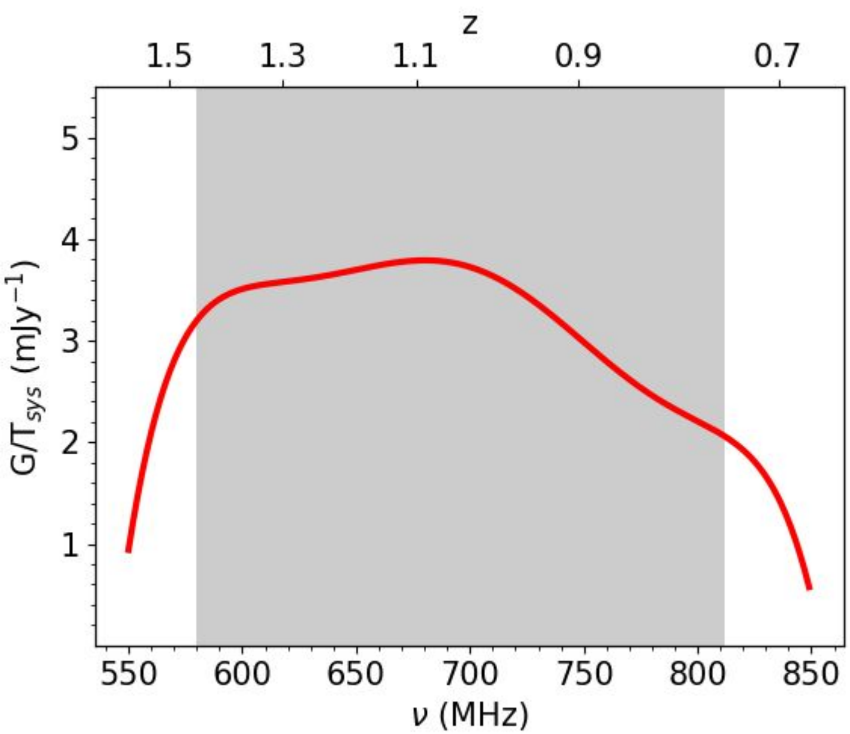
Redshift Coverage and Sensitivity



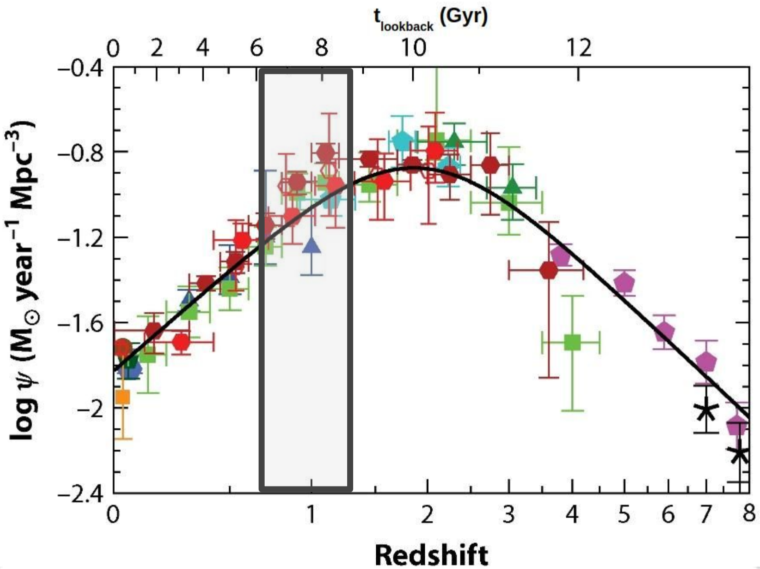
uGMRT Band 4 Sensitivity

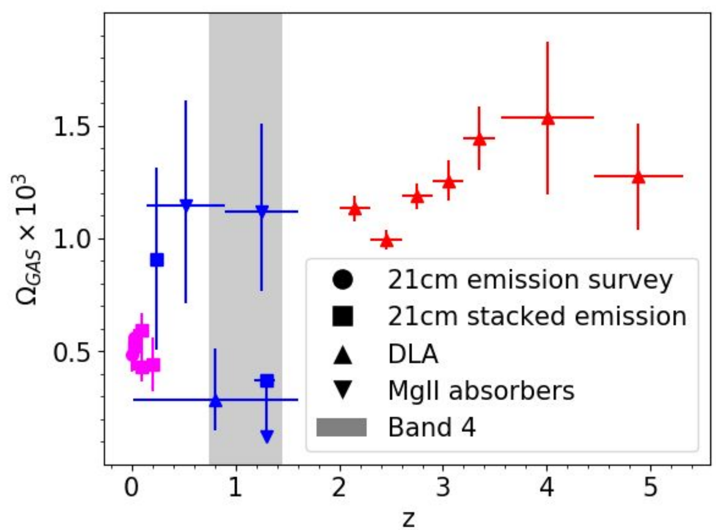
A Survey with the uGMRT

Redshift Coverage and Sensitivity



uGMRT Band 4 Sensitivity

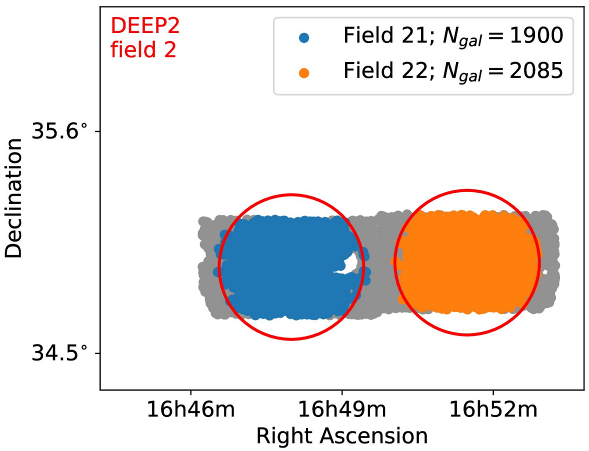


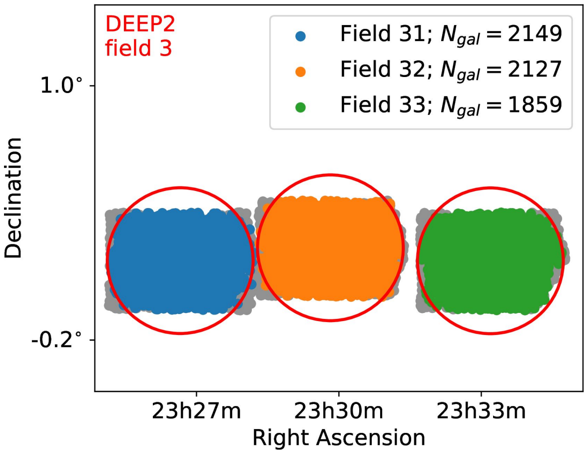


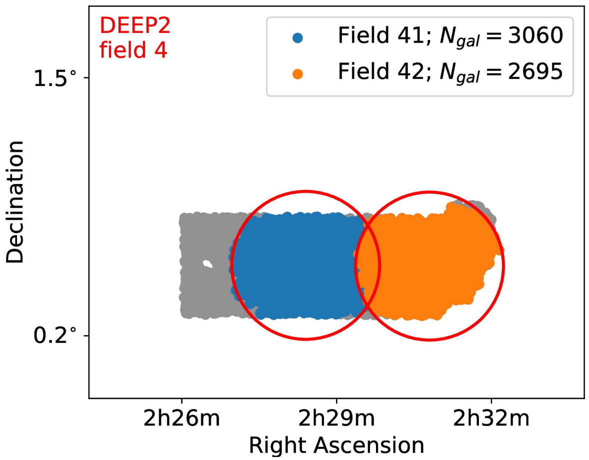
A Survey with the uGMRT

The DEEP2 Survey Fields

- Stacking spectra to detect the average 21cm emission from galaxies requires precise redshifts (Δv < 300km/s; Δz<0.002).
- The DEEP2 Survey : an unique spectroscopic survey with the DEIMOS spectrograph on the Keck Telescope. (Newman et al., 2013)
- Redshifts out to z ≈ 1.45 with Δv ~ 60 km/s.
- Three out of the four observed DEEP2 fields have sizes well matched to the GMRT primary beam at band-4.





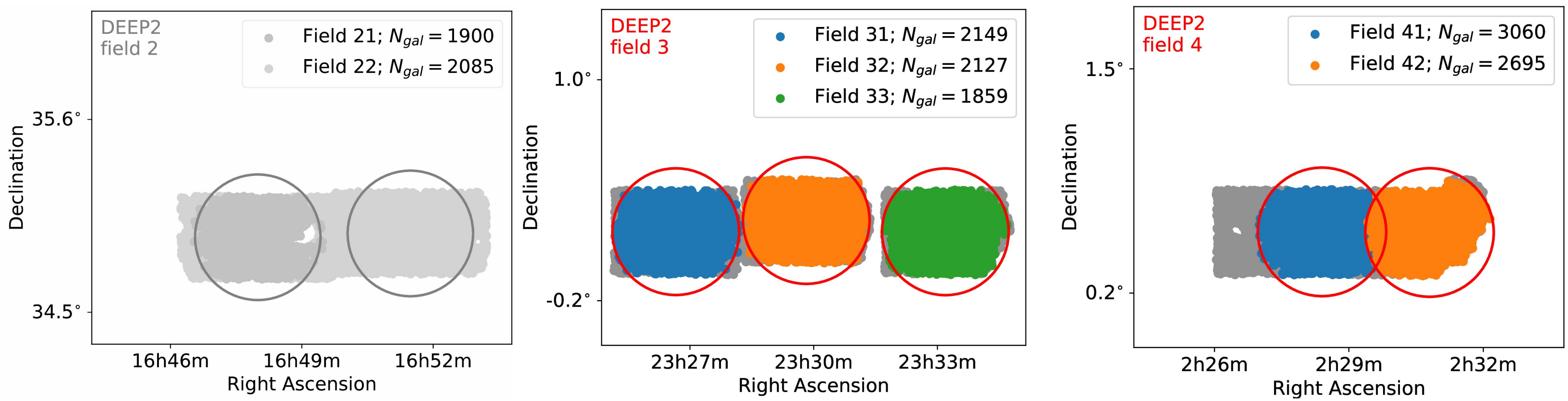


A Survey with the uGMRT

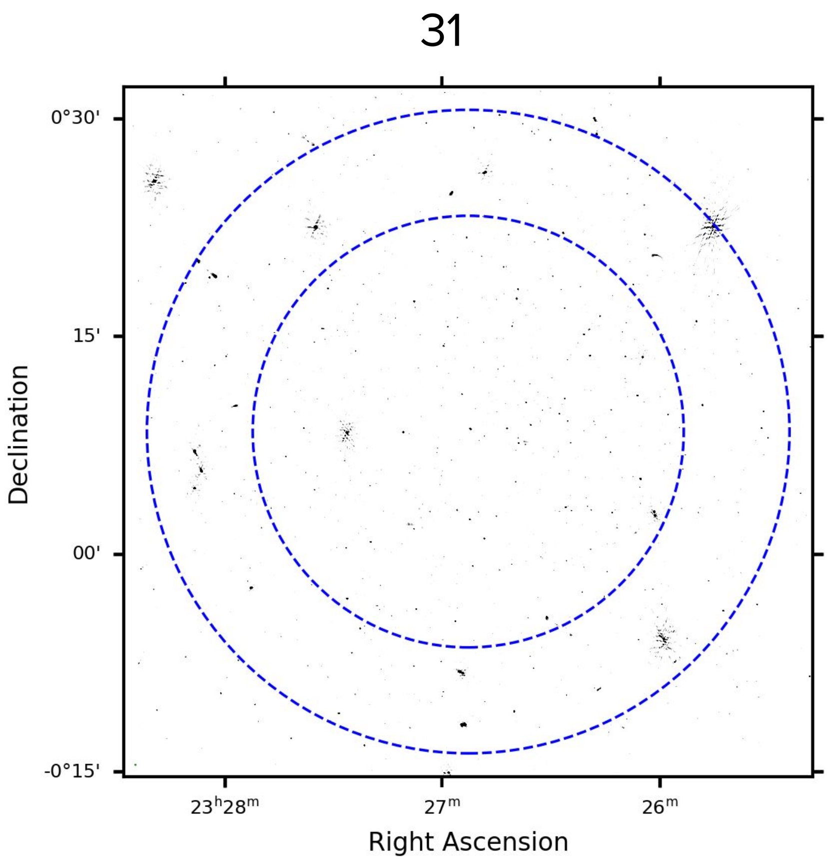
Observations in cycle 35

- Total time : 100 hours
- On DEEP2 fields (~ 64 hrs)
- Analysis progress: Field 31 (~ 14 hrs) and one night of Field 41 (~ 7 hrs).
    - CASA (McMullin et. al. 2007)
    - Robust versions of gaincal and bandpass developed : gaincalR, bandpassR (AIPS algorithm + minor enhancements)
    - Flagging : Manual + AOFLAGGER (Offringa et al. 2012)

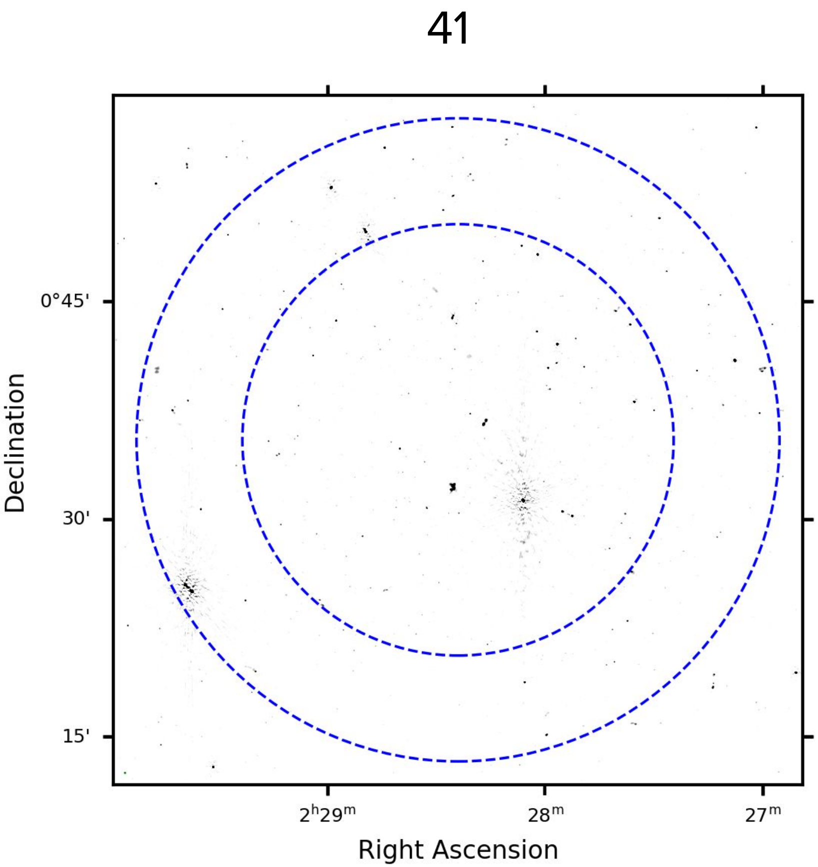
- Stacking of the continuum emission to estimate star formation rate of these galaxies.
- Stacking of the HI21cm emission to estimate the average HI mass of galaxies.



The Fields



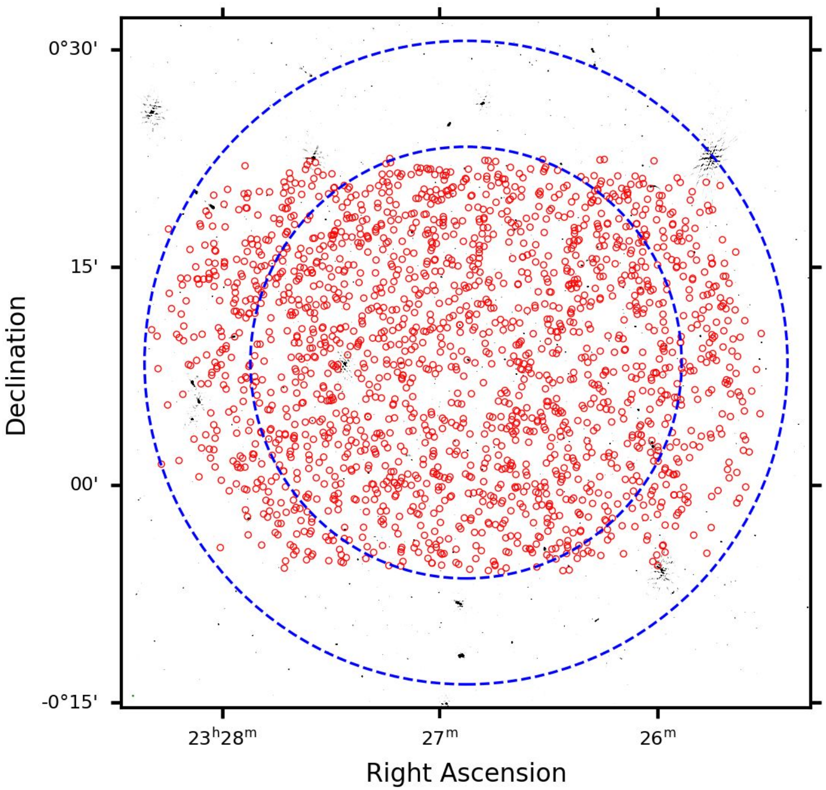
On Source : 13.5 hrs
RMS : ~ 5 µJy/bm



On Source : 7.5 hrs
RMS : ~ 7 µJy/bm

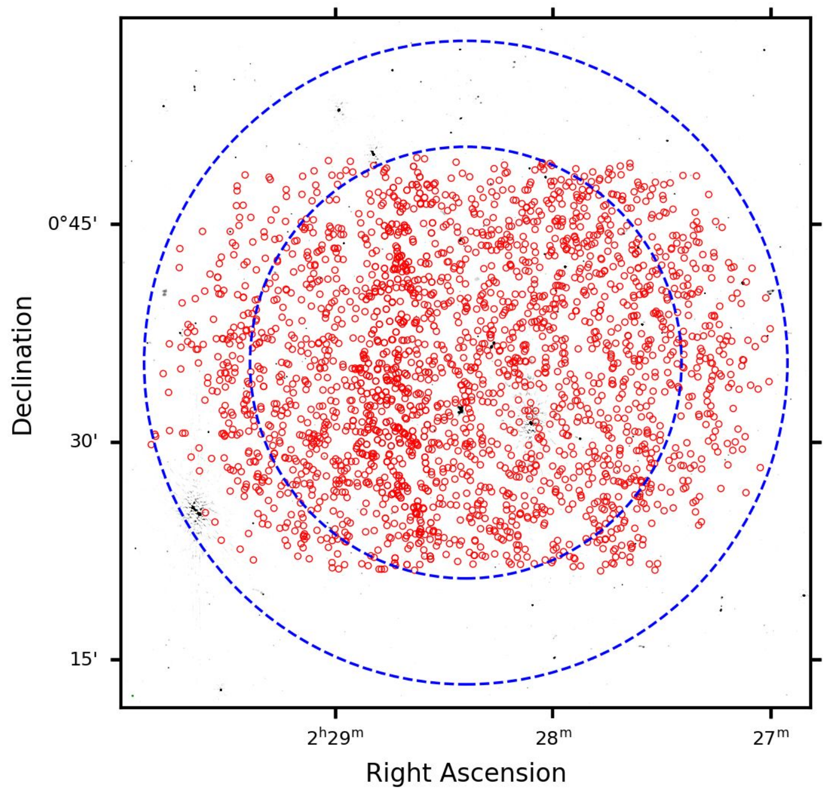
The Fields

31



On Source : 15 hrs
RMS : ~ 5 µJy/bm
1898 DEEP2 Galaxies

41

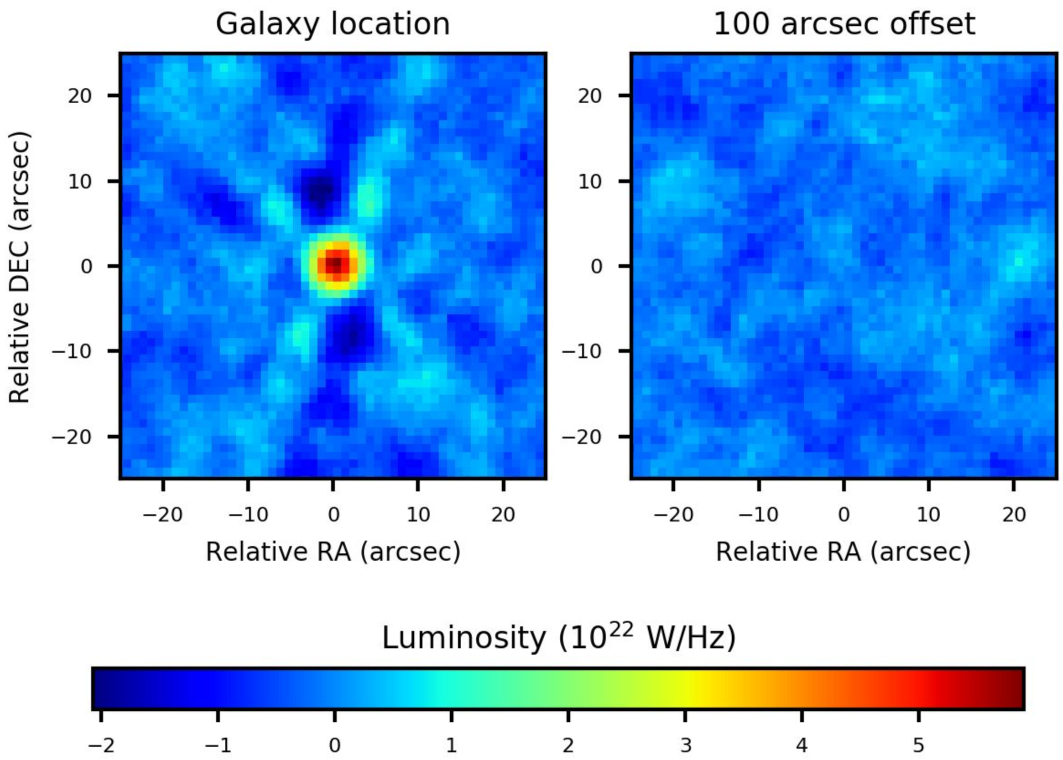


On Source : 7.5 hrs
RMS : ~ 7 µJy/bm
2531 DEEP2 Galaxies

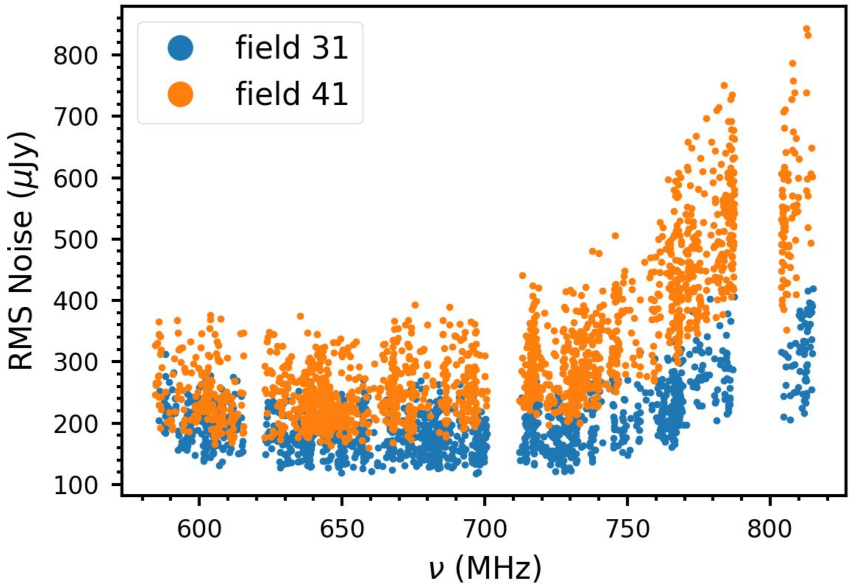
Star Formation Rate

- The rest frame 1.4 GHz luminosity can be used to derive star formation rate via the Radio-FIR correlation. (e.g, Bera et. al. 2018)
- Bera et. al. (2018) used observations using the legacy GMRT to find a star formation rate of 24.4 ± 1.4 at a median redshift $z = 1.1$
- Median stack of continuum emission from galaxies in our fields.

$$L_{1.4GHz} = (5.9 \pm 0.3) \times 10^{22}\ \mathrm{W/Hz}$$
$$\mathrm{SFR} \sim 34\ M_{\odot}/\mathrm{yr}$$



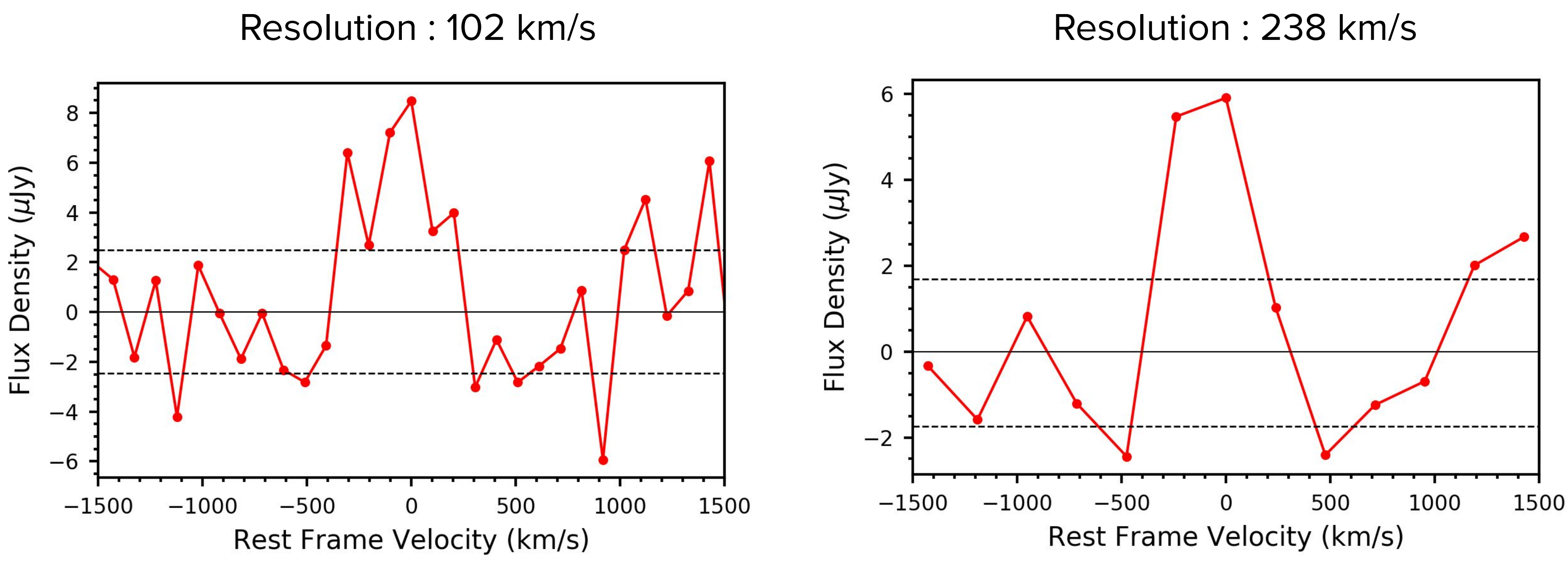
Stacking HI21cm Emission



Noise on the final set of spectra at 34 km s^{-1}

- Extract HI21cm spectrum at the location of each galaxy from continuum subtracted data cube.
- Interpolate all spectra to the same rest frame velocity grid with a resolution of 34 km s^{-1}.
- Fit second order baseline to each spectrum.
- Gaussianity tests to look for *bad* spectra.
- Co-add spectra with appropriate weights to minimize final rms.
- Smooth stacked spectra to various resolutions and search for a signal!

The HI Content of Galaxies at z ≈ 0.75 – 1.45



Integrated Flux Density: 2.9 ± 0.7 mJy km/s (4.1 σ detection)

HI Mass at median z:

$$\mathbf{M_{HI}\ (z=1.07) = (1.8 \pm 0.4) \times 10^{10}\ M_{\odot}}$$

Conclusion

- The median stellar mass of galaxies in our sample: $M_* = 10^{10}\ M_\odot$
- The detected HI mass of $(1.8 \pm 0.4) \times 10^{10}\ M_\odot$ implies an atomic mass fraction
  $M_{HI}/M_* \sim 1.8$
- In the local universe $M_* = 10^{10}\ M_\odot$ galaxies have a median $M_{HI}/M_* = 0.14$
  (The xGASS sample, Catinella et. al. 2018)
- Indicative of an order of magnitude increase in atomic gas fraction, similar to SFR density and molecular gas fraction.
  (Madau & Dickinson 2014; Genzel et. al. 2015)

- The median star formation rate of galaxies in our sample : ~ 34 $M_\odot$/yr
- An atomic gas depletion timescale (M_{HI}/SFR) of $t_{dep;\ HI}$~0.5 Gyr.
- Similar to molecular gas depletion timescale (at z ~1) $t_{dep;\ mol}$~0.7 Gyr.
  (Genzel et. al. 2015)
- Atomic to molecular gas transition at the same rate as molecular gas to stars.
- Not the case in local universe where atomic gas depletion timescale (~3 Gyr) is longer than that of molecular gas (~1 Gyr). (The Cold Gas Sample, Saintonge et. al. 2011)

Summary

- Surveyed the DEEP2 fields with uGMRT at 550-900 MHz to measure the atomic hydrogen mass of galaxies at $z \approx 0.75 - 1.45$.
- Stacked the continuum emission from DEEP2 galaxies to measure a median SRF of ~ 34 $M_{\odot}$/yr.
- Stacked and detected, for the first time, the HI21cm emission from galaxies at $z \approx 1$.
- Average HI mass of galaxies at z_{med}=1.07, $M_{HI} = (1.8 \pm 0.4) \times 10^{10}\ M_{\odot}$
- These galaxies have a atomic mass fraction of ~ 1.8 and a atomic hydrogen depletion timescale of ~ 0.5 Gyr.
- The future: We will look at the results more closely as well as analyze the data for the remaining three fields. By the end of it, we should have a lot more to say about the atomic gas in galaxies at the epoch of cosmic star formation.