The Gas Mass of Star-Forming Galaxies at $z \sim 1.3$

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OUTLINE

- Galaxy evolution: The big questions.
- High-redshift galaxies: The "deep fields".
- Stacking of HI 21cm emission lines.
- The DEEP2 survey.
- A GMRT HI 21cm emission survey of the DEEP2 fields.
- The future.

Galaxy Evolution: The Big Questions

- Galaxy sizes and luminosities: Luminosity functions.
- Star formation rates and star formation efficiencies.
- The nature of star formation: Quenched, steady, starburst ?
- Stellar, gas, and dynamical masses: Mass functions.
- Kinematics (rotating disk or random motions).
- The ISM phases: Cold or warm HI, diffuse or dense H_2.
- ...

HIGH-REDSHIFT GALAXIES: DEEP FIELDS

- *Emission-selected* galaxies from fields with deep multi-band optical imaging (e.g. GOODS-N, GOODS-S, COSMOS, etc). Typically, follow-up imaging in radio, UV, X-ray, near-IR, mid-IR, … wavebands, follow-up optical spectroscopy on galaxy sub-samples.

- Selection methods: magnitude-limited, Lyman-break, BzK, Gunn-Petersen break, Lyman-α emitters, spectroscopic samples...

- Estimates of luminosities, SFRs, stellar masses, kinematics.

- Redshift evolution of the cosmological SFR density!

(e.g. Hopkins & Beacom 2006, ApJ; Bouwens et al. 2011, 2015, ApJ)

- "Main sequence", with SFR roughly proportional to stellar mass!

(e.g. Brinchmann et al. 2004, MNRAS; Noeske et al. 2007, ApJL)

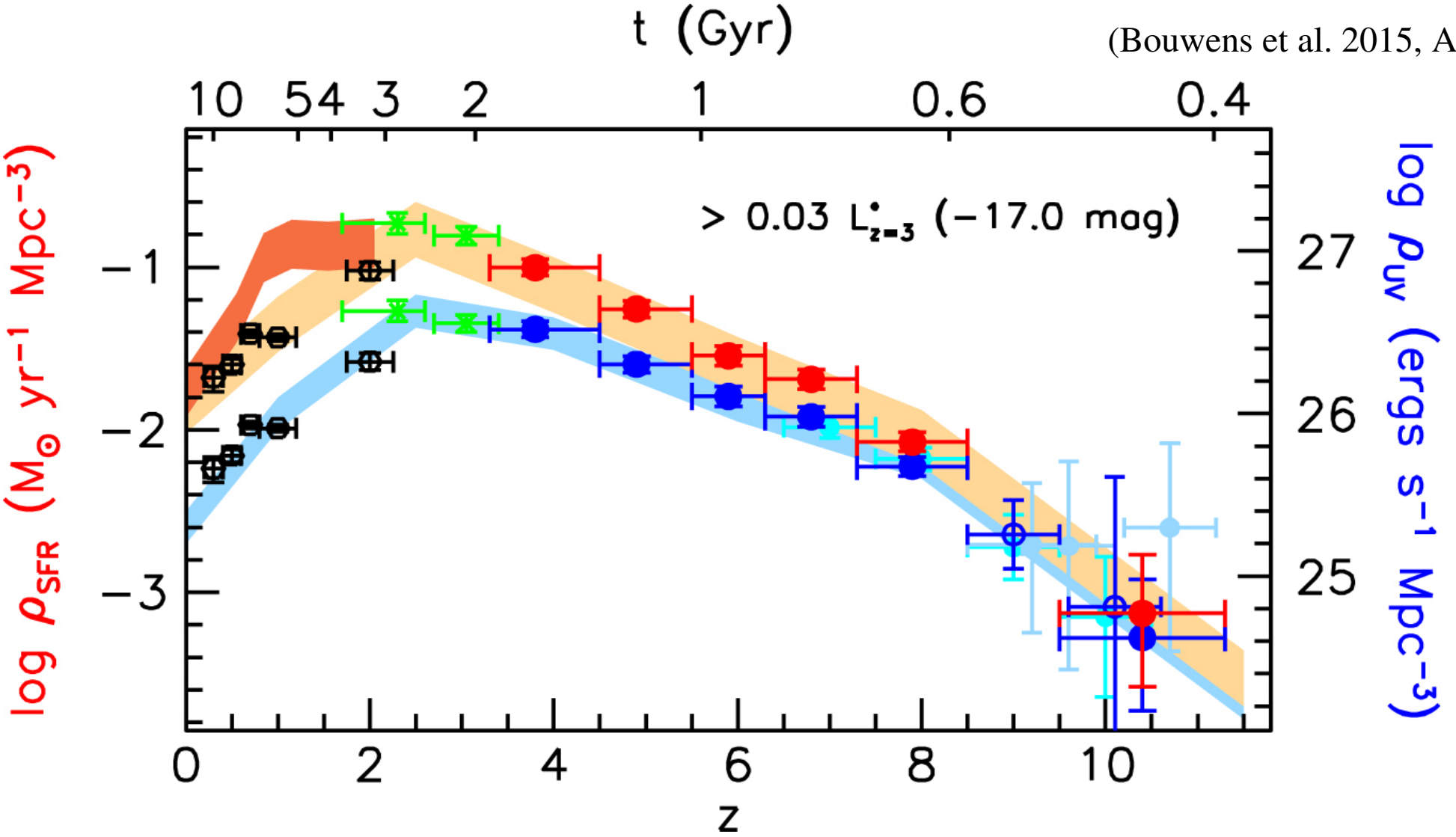
- CO studies: Large molecular gas reservoirs, evidence for rotation.

(e.g. Tacconi et al. 2013, ApJ)

- But... No information whatsoever on the neutral atomic gas!

The Star Formation Rate Density

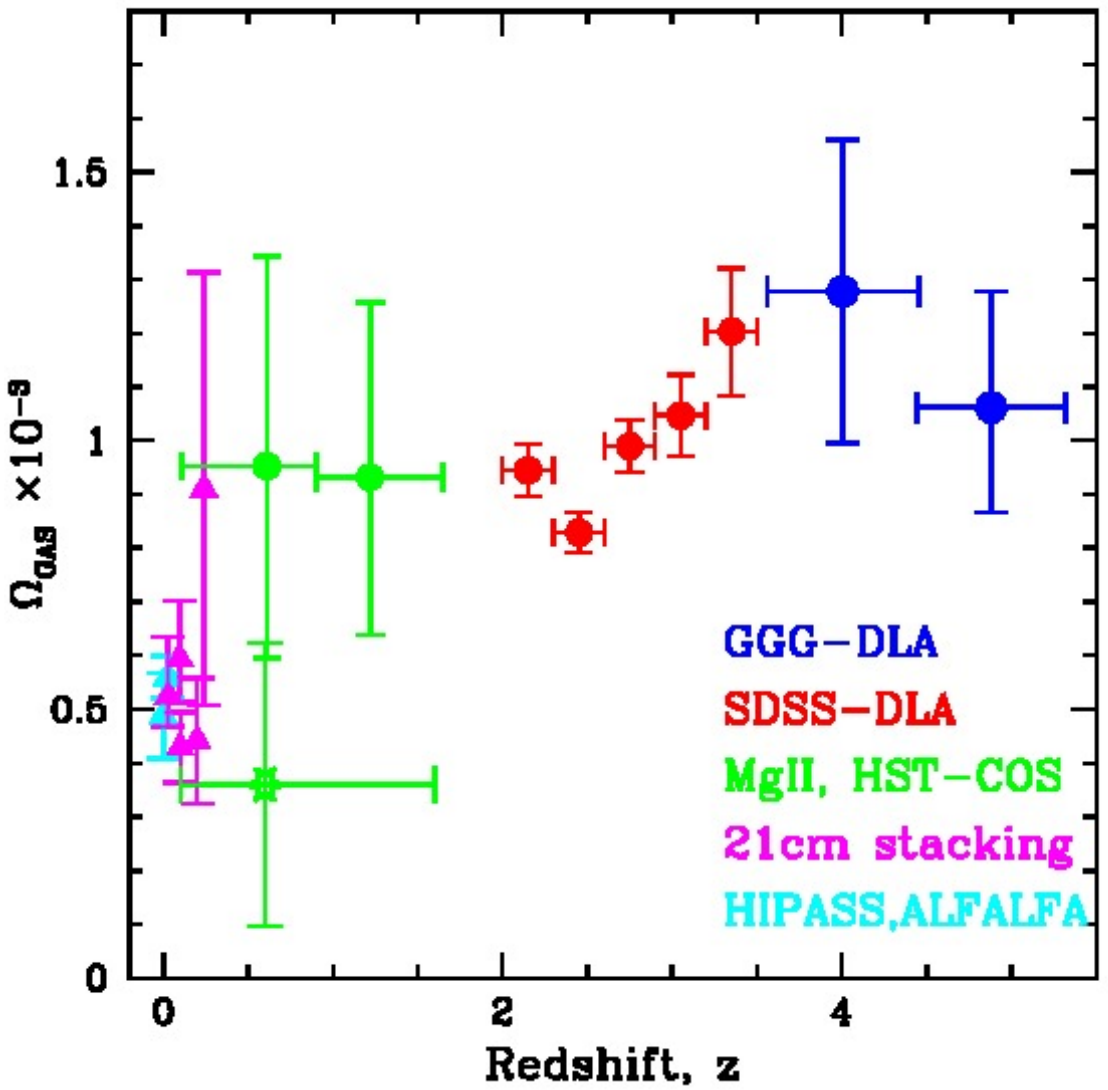
(Bouwens et al. 2015, ApJ)



- The SFR density increases by an order of magnitude over $z \sim 0-1$, is flat at $z \sim 1-4$, declines at $z > 4$, and declines steeply at $z \sim 8$.

(e.g. Hopkins & Beacom 2006, ApJ; Schiminovich et al. 2005, ApJL; Magnelli et al. 2009, 2011, A&A; Bouwens et al. 2011, 2015, ApJ)

The Cosmological Gas Mass Density



(e.g. Zwaan et al. 2005;
Rao et al. 2006;
Lah et al. 2007;
Martin et al. 2010;
Prochaska et al. 2005;
Noterdaeme et al. 2012;
Delhaize et al. 2013;
Rhee et al. 2013;
Crighton et al. 2015;
Neeleman et al. 2016)

- From HI 21cm emission at $z \sim 0$, damped Ly-α absorption at $z > 2$.
- Cosmological gas mass density declines by a factor of ~ 2 from $z \sim 3$ to $z \sim 0$. Little information in the redshift range $z \sim 0.2 - 2$.

HI 21CM EMISSION STACKING

- The HI mass $M(HI) = 2.35 \times 10^5 \times [D_L^2 / (1+z)] \times \int S_{21}\, dV$

- HI 21cm emission is tough to detect ($z_{MAX} \sim 0.36$)! *Very* deep integrations needed to reach even to $z \sim 0.4$, e.g. JVLA-CHILES.

(e.g. Catinella & Cortese 2015, MNRAS; Fernandez et al. 2016, ApJL)

- *Stacking* of HI 21cm emission signals from galaxies with known redshifts ⇨ The average HI mass of the stacked galaxies!

(Zwaan 2000, Ph.D.; Chengalur et al. 2001, A&A)

- HI 21cm emission stacking of ALFALFA galaxies: Reproduces dependences of average properties on stellar mass, environment.

(Fabello et al. 2011, 2012, MNRAS)

- HI 21cm stacking at $z \sim 0.1 - 0.37$, for field and cluster galaxies.

(e.g. Lah et al. 2007, 2009, MNRAS; Rhee et al. 2013, 2016, MNRAS)

- To push to $z > 1$: The GMRT 610 MHz band: $z \sim 1.15 - 1.45$.

- Need a galaxy sample in a region within the telescope beam, with accurate redshifts and positions, and at the "right" redshifts.

The Galaxy Sample: The DEEP2 Survey

- Few spectroscopic surveys cover $z \sim 1 - 1.5$: The "redshift desert", as the strong optical Hα-λ6563, OII-λ3727, OIII-λ5007 lines are redshifted to spectral regions containing numerous night sky lines.

- DEEP2 survey: 3.5 sq. degrees of multi-band optical imaging, in 4 fields, 3 of size $2^o \times 0.5^o$, & the Extended Groth Strip ($2^o \times 0.25^o$).

(Coil et al. 2004, ApJ)

- Spectroscopy with the DEIMOS multi-object spectrograph on Keck-II: a spectral resolution of ~ 5900 and covering wavelengths ~ 6500 – 9100 Å (i.e. the OII-λ3727 doublet for $z \sim 0.7 - 1.45$).

(Davis et al. 2007, ApJ; Newman et al. 2013, ApJS)

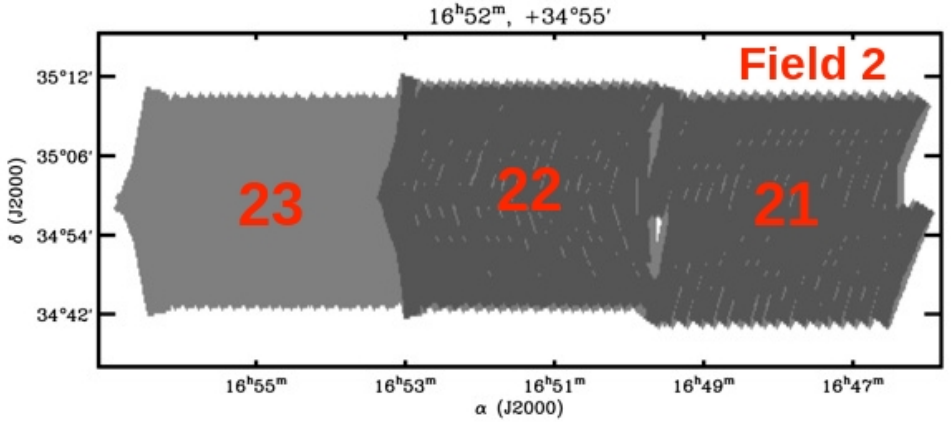
- BRI photometry used to exclude galaxies at $z < 0.7$. Slitmasks used to cover other galaxies with $R < 24.1$, with 1-hr Keck integrations.

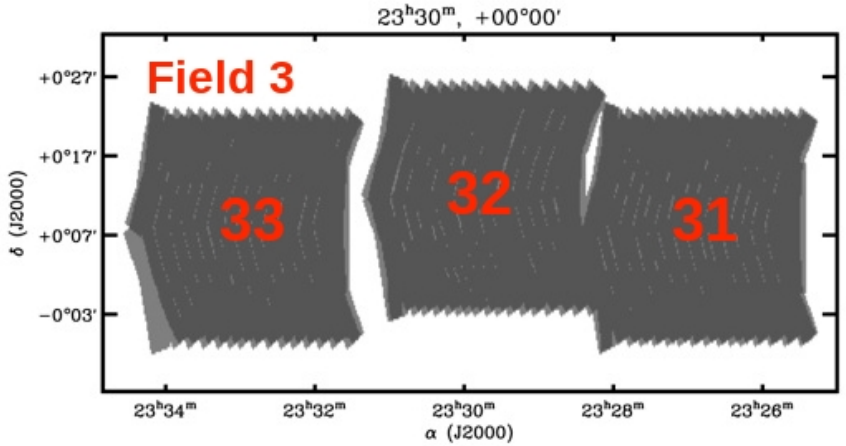
- 38,000 galaxies with redshifts. Redshift accuracy ~ 30 km/s: Good for HI 21cm stacking!

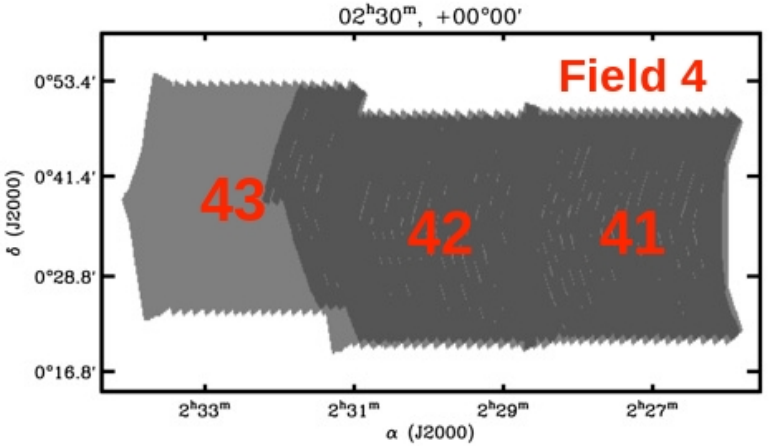
(e.g. Maddox et al. 2013, MNRAS; talks by Chengalur, Elson)

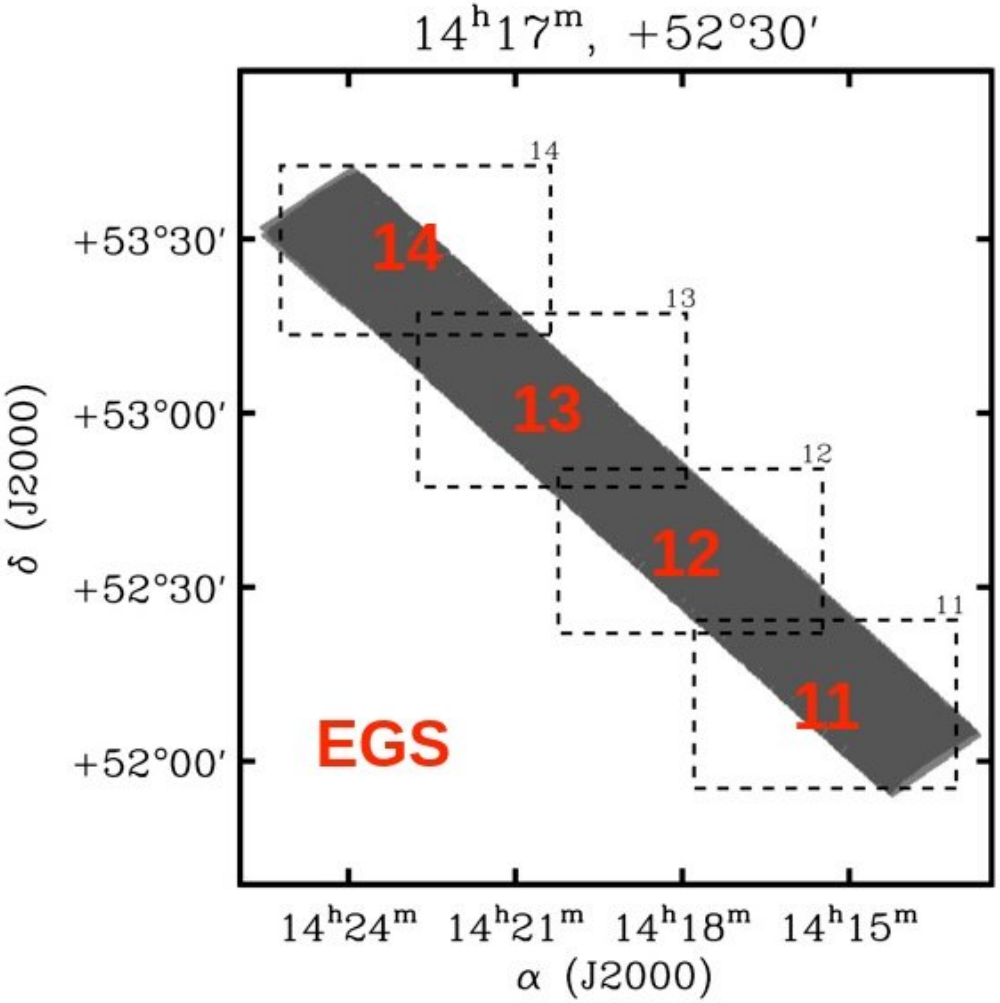
THE DEEP2 SURVEY

(Newman et al. 2013, ApJS)









THE GMRT DEEP2 PILOT SURVEY

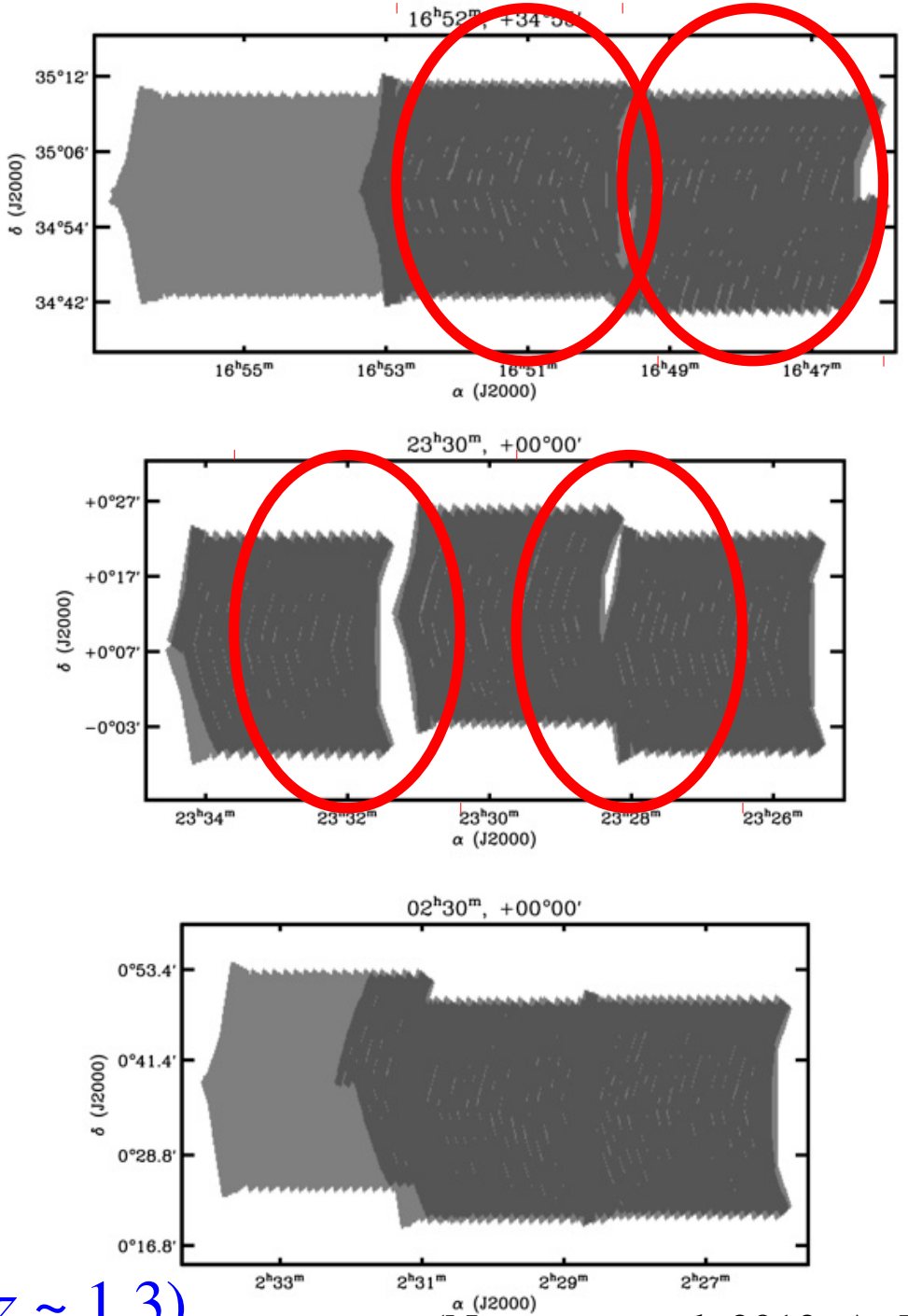
- DEEP2 sub-fields ~ 36′ × 30′:
  Excellent match to 43′ GMRT 610 MHz primary beam.

- Accurate redshifts, z ~ 0.7 – 1.45:
  Upper end matched to GMRT's 610 MHz frequency coverage.

- 12 – 18 on-source hours per field;
  33 MHz bandwidth, 512 channels, centred at 617 and 637 MHz.
  HI 21cm line from z ~ 1.18 – 1.36.

- 4 pointings to test dynamic range.
  2 frequencies to test for RFI.

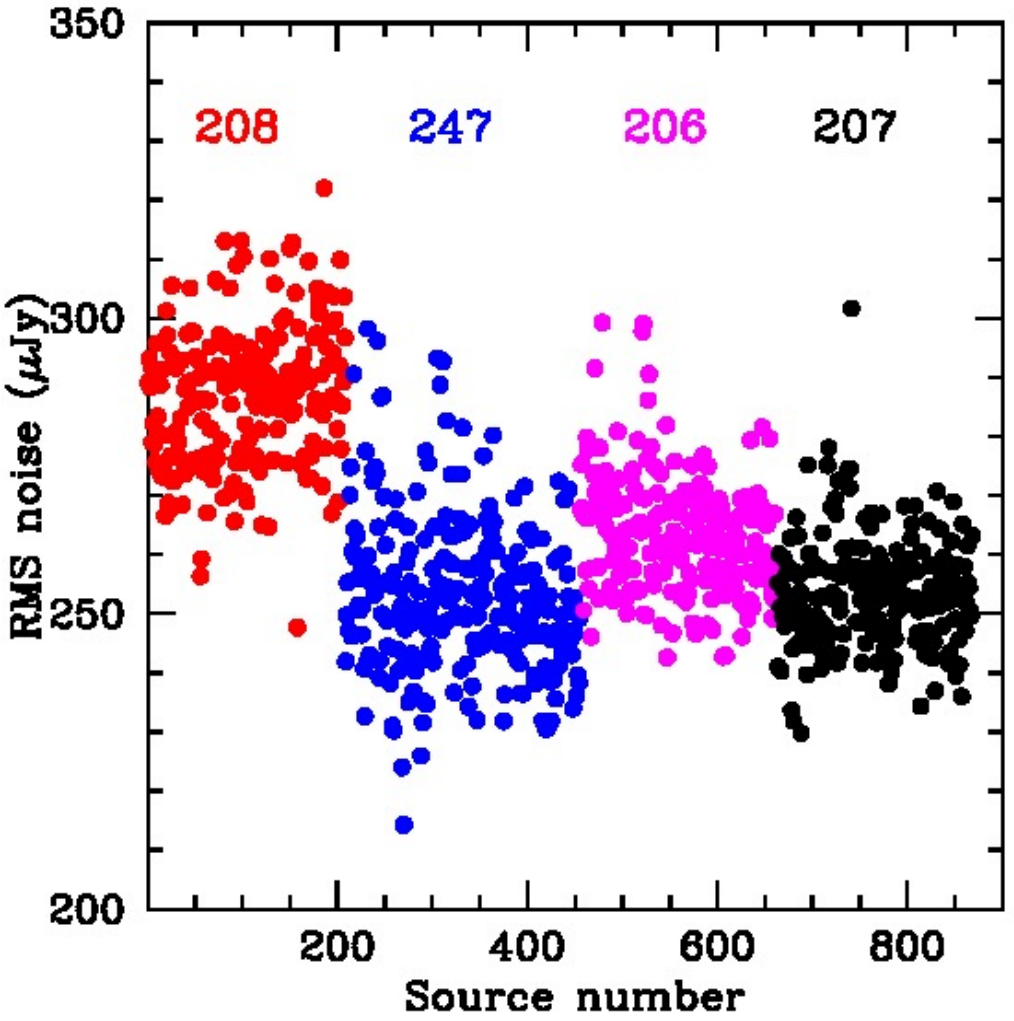
- Angular resolution ~ 6″: ~ 50 kpc (z ~ 1.3).

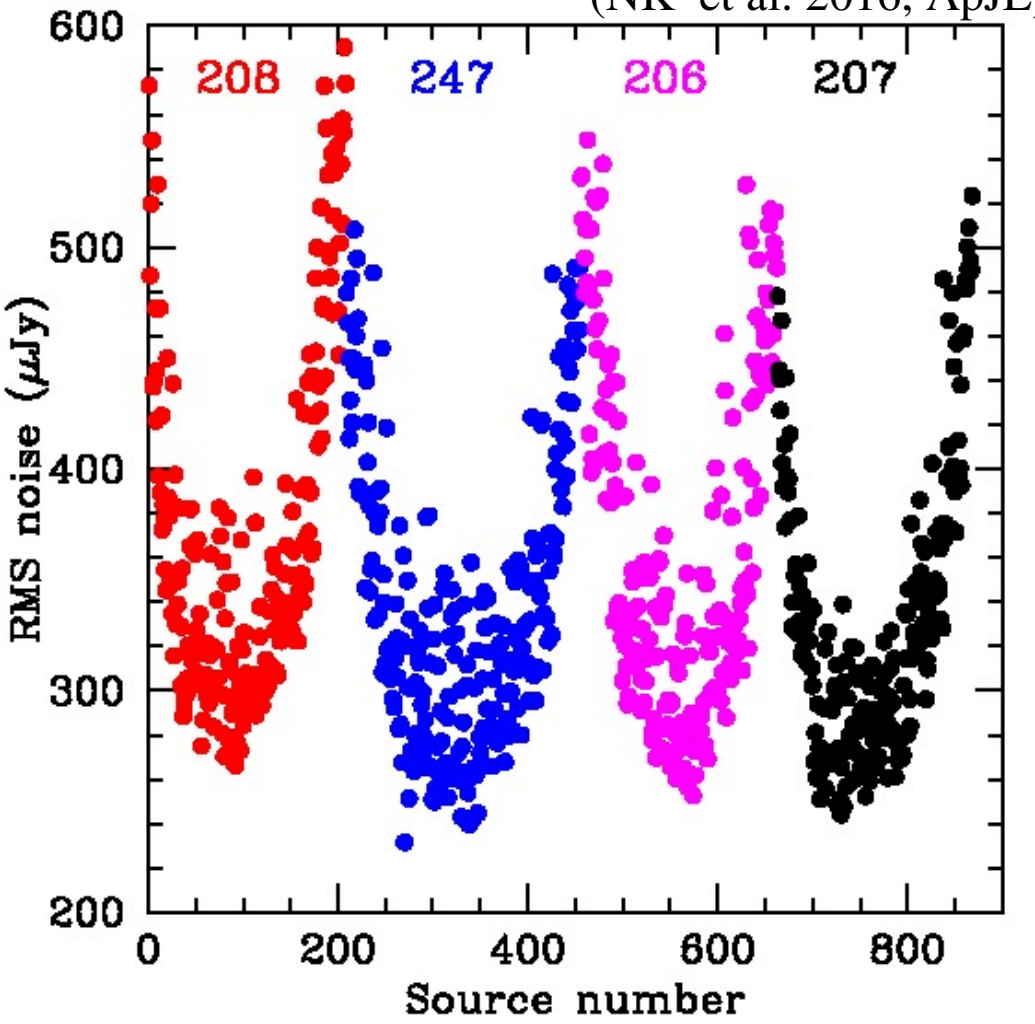


(Newman et al. 2013, ApJS)

HI 21CM LINE STACKING

(NK et al. 2016, ApJL)



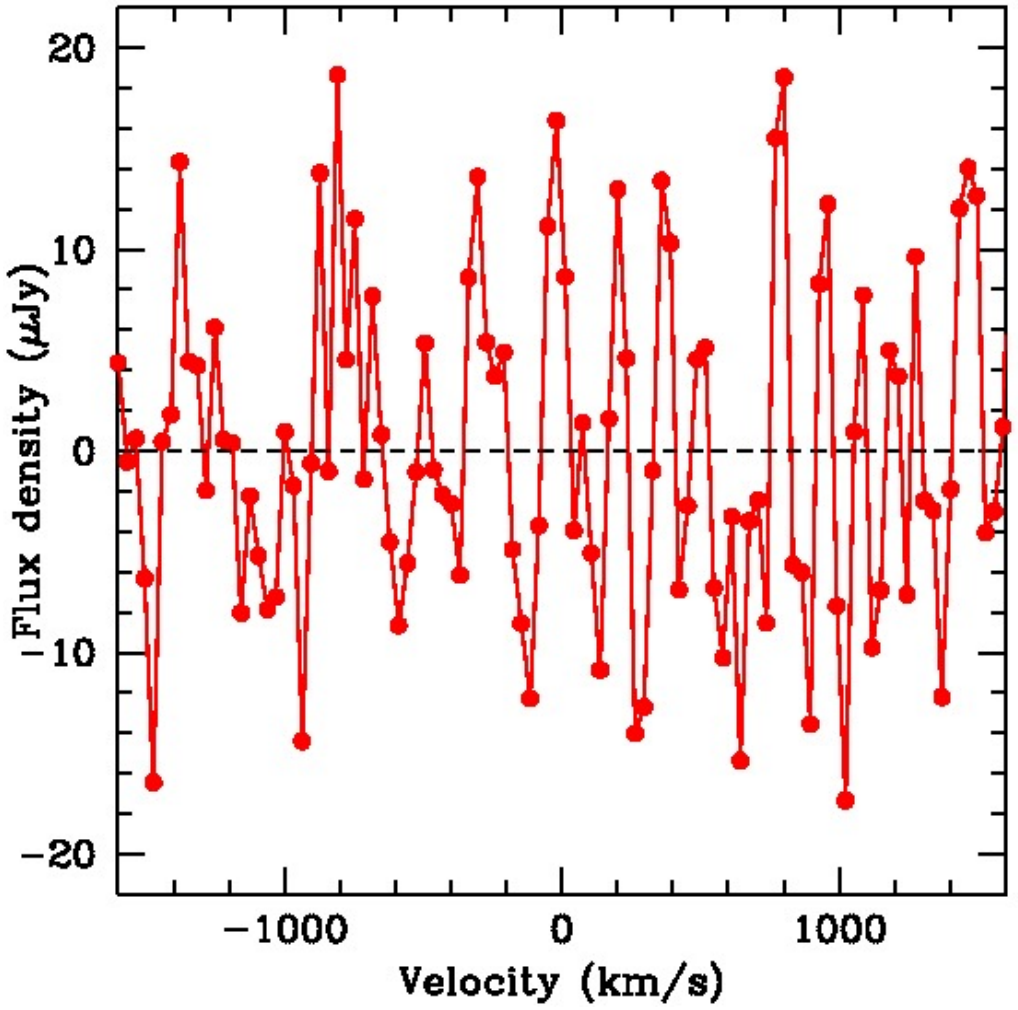


- Spectral RMS noise of ~ 240 – 300 μJy per 31 km/s channel.

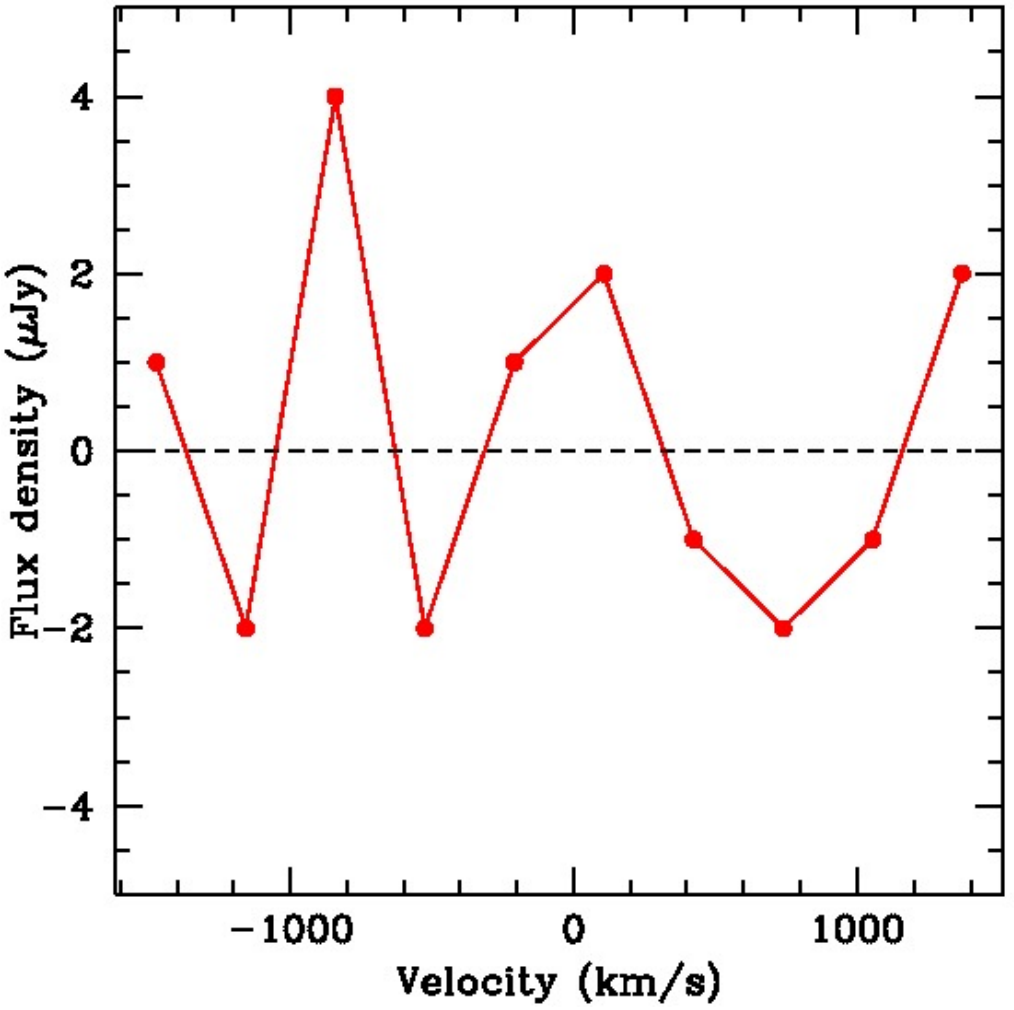
- 868 DEEP2 galaxies within the beam FWHM, and with redshifts placing the HI 21cm line within 1500 km/s of the band edge. 857 spectra were stacked, after aligning in velocity space.

HI 21CM LINE STACKING

Resolution ~ 31.5 km/s



Resolution ~ 315 km/s



- Final stacked RMS noise: 2.5 μJy per 315 km/s channel. Deepest "HI 21cm spectrum" ever obtained.

(NK et al. 2016, ApJL)

HI 21CM LINE STACKING: RESULTS

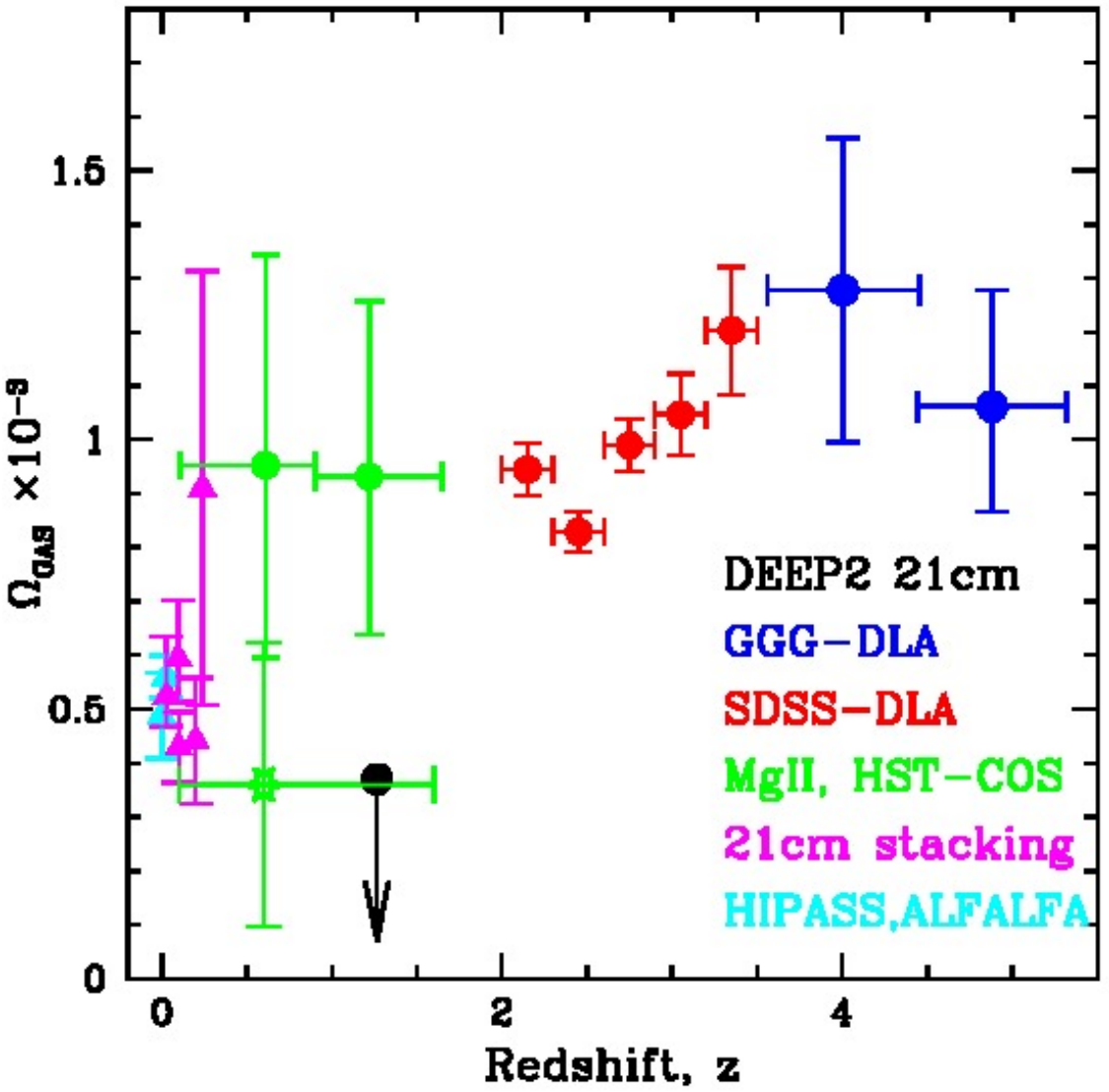
(NK et al. 2016, ApJL)

- Final stacked RMS noise: 2.5 μJy per 315 km/s channel.
- Average HI mass of the 857 galaxies $\leq 2.1 \times 10^{10}\,M_{\odot}$ (3σ).
- Average stellar mass of the 857 galaxies $\sim 5.6 \times 10^{10}\,M_{\odot}$.
  ⇨ Ratio of atomic gas mass (including He) to stellar mass < 0.5.
- Very surprising as galaxies at $z > 1$ are expected to be gas-rich, to fuel their higher star formation activity.
- Possible caveats: Incorrect redshifts, resolved galaxies, gas stripping, large velocity widths, …? Unlikely to be important.
- CO emission detected in a sub-sample of the DEEP2 galaxies: Ratio of molecular gas mass to stellar mass ~ 0.33.

(Tacconi et al. 2013 ApJ)

Could the bulk of the gas be in molecular form?

THE COSMOLOGICAL GAS MASS DENSITY



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Rhee et al. 2013;
Crighton et al. 2015;
Neeleman et al. 2016)

- The gas mass density in star-forming galaxies at $z \sim 1.3$ is $\Omega_{GAS}(SF) < 0.00037$, lower than the total Ω_{GAS} at $z \sim 0-4$!

  ⇨ The bulk of the atomic gas is *not* in star-forming galaxies ??!!

(NK et al. 2016, ApJL)

THE "FUTURE"

- Pilot 30-hour GMRT 610 MHz survey of the EGS: Wide-band data recorded with new correlator, with better redshift coverage.

- Completed the observations of a 400-hour GMRT project to observe the seven DEEP2 sub-fields with spectroscopy to improve the HI mass sensitivity by a factor of ~ 3, to $< 10^{10}\,M_{\odot}$.

- 125 GMRT hours allocated to observe the EGS, covering 1000 – 1400 MHz, i.e. $z = 0.0 - 0.4$ for the HI 21cm line. Should yield detections of both individual and stacked HI 21cm emission.

(see talk by Jasjeet Bagla)

- New GMRT 550 – 900 MHz receivers will yield coverage of $z \sim 0.7 - 1.5$ ⇨ Large survey of the DEEP2 fields from 2018.

SUMMARY

- Possible to measure the *average* gas mass of galaxies at $z > 1$ with the GMRT via HI 21cm emission stacking!

- DEEP2 survey fields: Excellent match to the GMRT primary beam width and the redshift coverage in the 610 MHz band.

- Stacked spectra of 857 DEEP2 galaxies: No detection of emission!
  ⇨ Average HI mass $\leq 2.1 \times 10^{10}\,M_\odot$ (3σ) at $z \sim 1.3$.
  ⇨ Gas fraction < 0.5 at $z \sim 1.3$ for galaxies with SFRs $> 30\,M_\odot$/yr.

- The cosmological atomic gas mass density in star-forming galaxies $\Omega_{GAS}(SF) < 0.00037$ at $z \sim 1.3$, lower than the total Ω_{GAS} at $z \sim 0 - 4$! ⇨ The bulk of the gas is *not* in star-forming galaxies!

- Large GMRT project now under way to determine the gas masses of star-forming galaxies at $z \sim 1.3$.