Atomic Hydrogen at High Redshifts

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Outline

- Understanding galaxies: gas and stars.
- Atomic hydrogen gas: HI 21cm line.
- HI at low redshifts.
- HI at high z: stacking HI 21cm emission at z~1.
- The GMRT CATz1 survey.
- GMRT Band-4 survey of COSMOS.
- Summary.

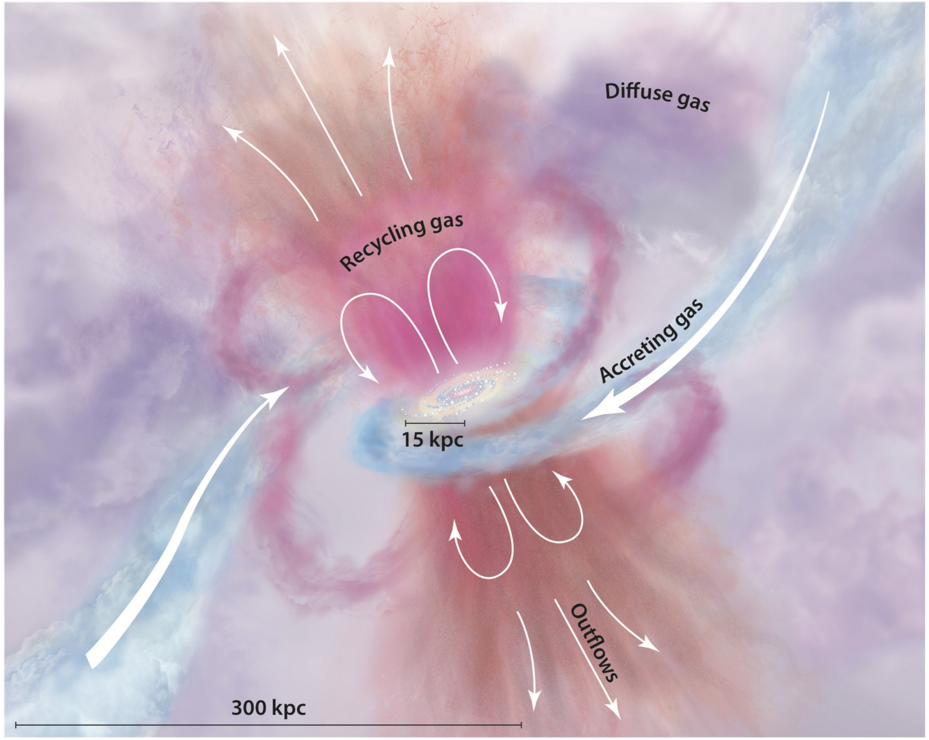
The Baryonic Composition of Galaxies

- Stars ➔ Stellar Mass, SFR,...
  Probes: UV, optical, IR, ...
  (e.g., Madau & Dickinson. 2014)

- Molecular gas ➔ Mass, CO excitation,..
  Probes: CO Rotational lines, ...
  (e.g., Tacconi et al. 2020)

- Neutral Atomic gas ➔ Mass, spin temperature,..
  Probes: HI 21 cm emission, HI 21cm absorption,
  (e.g.,Kanekar et al. 2014, Saintonge & Catinella 2022)

- Circumgalactic medium and Intergalactic Medium
  ➔ Gas inflow, outflow.
  Probes: UV absorption lines, X-ray emission, ...
  (e.g., Tumlinson et al. 2017)

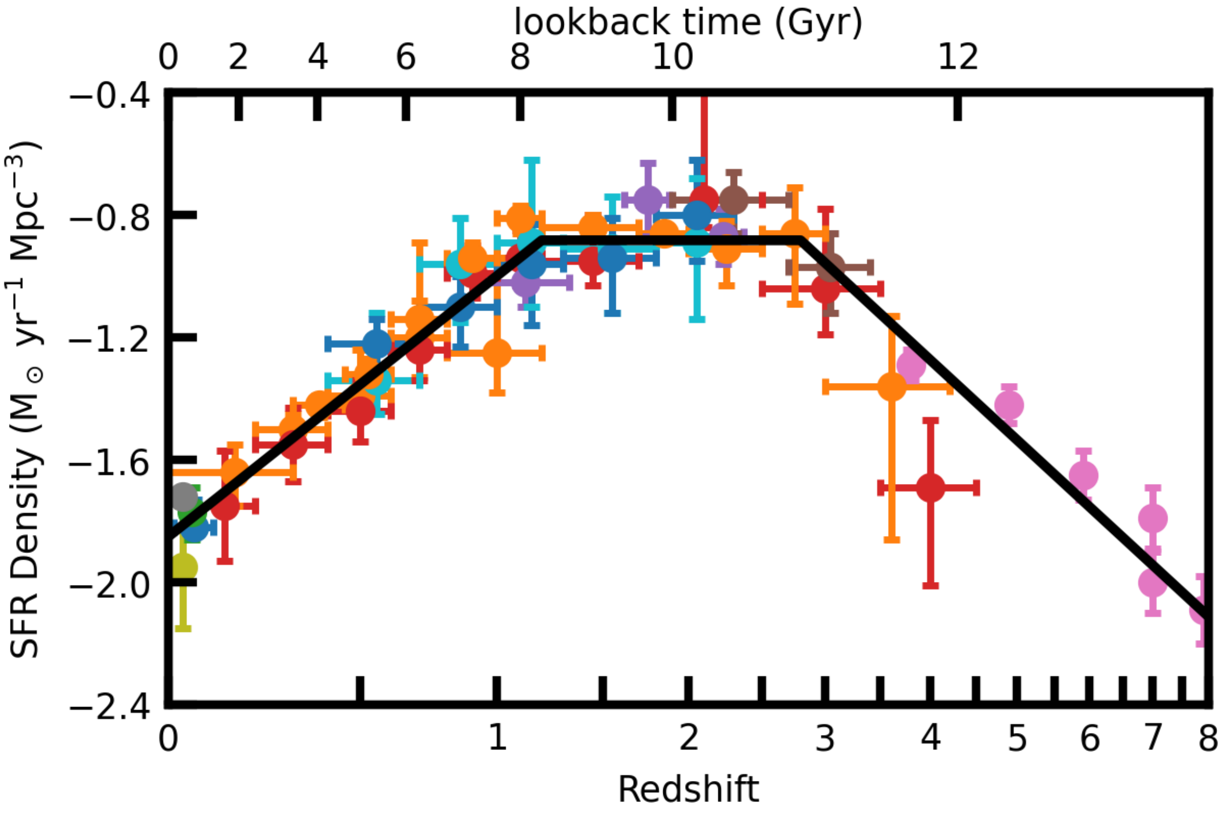


(e.g., Tumlinson et al. 2017)

Star formation in the Universe

- Galaxy formation and evolution ➔ Multiwavelength imaging, spectroscopic surveys.

- Star formation rate density peaked at *z* ~1–3, and declined at *z* < 1.

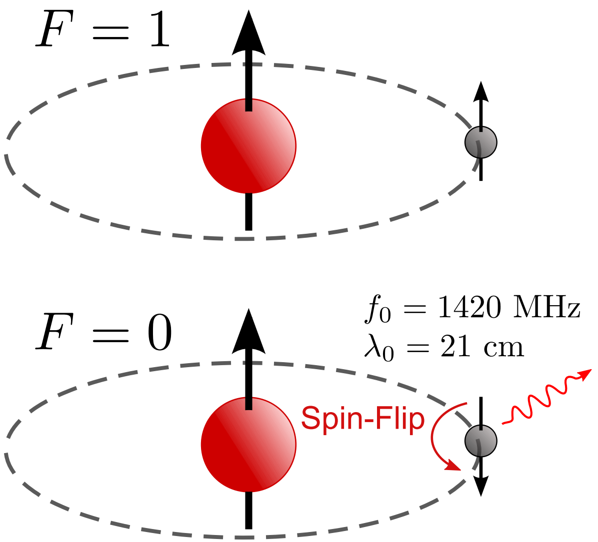


(Madau & Dickinson. 2014)

(Figure: Aditya Chowdhury)

Atomic hydrogen: HI 21 cm transition

- Atomic hydrogen is the primary fuel for star formation.
- Probed using HI 21 cm line ➔ Hyperfine transition.
- Total HI 21 cm line flux density $\propto$ HI mass of the galaxy.
- Low Einstein A coefficient ➔ Very weak line.

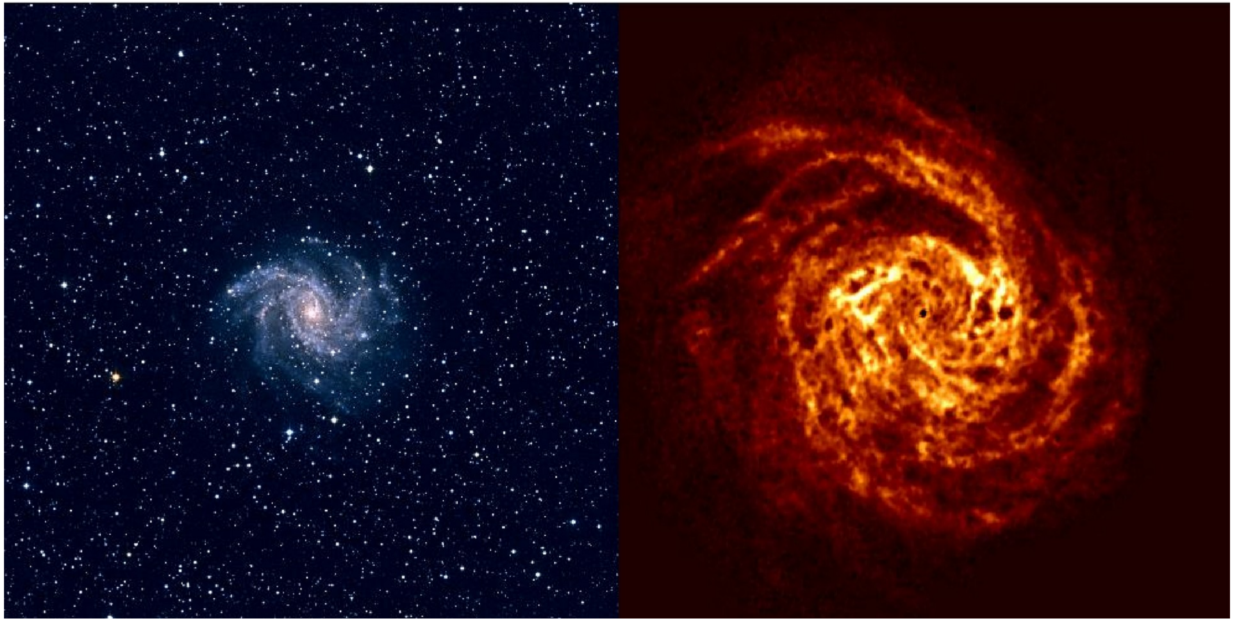


(Figure: Wikipedia)

Atomic hydrogen: HI 21 cm transition

- Galaxies have been extensively studied in the local universe using HI 21 cm line:
  - Total HI mass of the galaxy.
  - Kinematics, rotation curves.
  - Scaling relations, e.g., M_{HI}- M_*, M_{HI}- M_B,..
  - Dependence of HI content on morphology, environment,..

(e.g., Walter et al. 2008, Serra et al. 2012, Saintonge & Catinella 2022)



(Boomsma et al. 2008)

Atomic hydrogen: HI 21 cm transition

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  - Total HI mass of the galaxy.
  - Kinematics, rotation curves.
  - Scaling relations, e.g., M_{HI}-$M_{\ast}$, M_{HI}- M_B,..
  - Dependence of HI content on morphology, environment,..

- But HI 21 cm emission is weak ➔ Hard to detect at z>~0.2.

- Highest redshift detection of an unlensed galaxy at z = 0.376 with 180 hours of JVLA time.

(Fernandez et al. 2016)

HI 21 cm stacking

- Stacking HI 21cm signal from a large number of galaxies ➔ Average HI mass of the population.

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  - Accurate redshifts and positions.

(Zwaan 2000; Chengalur et al 2001)

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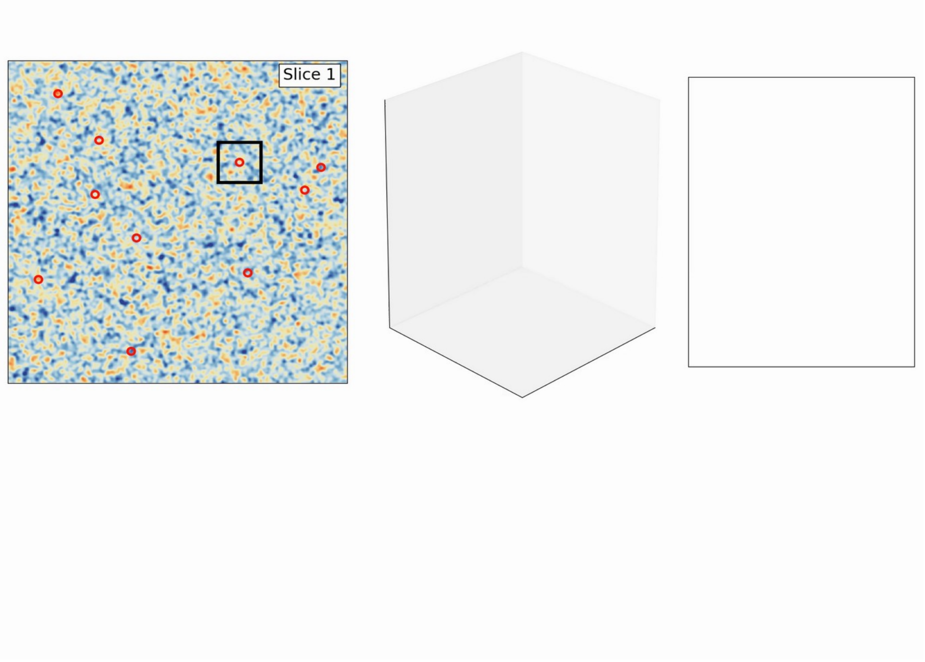
(Zwaan 2000; Chengalur et al 2001)



(Credit: Aditya Chowdhury)

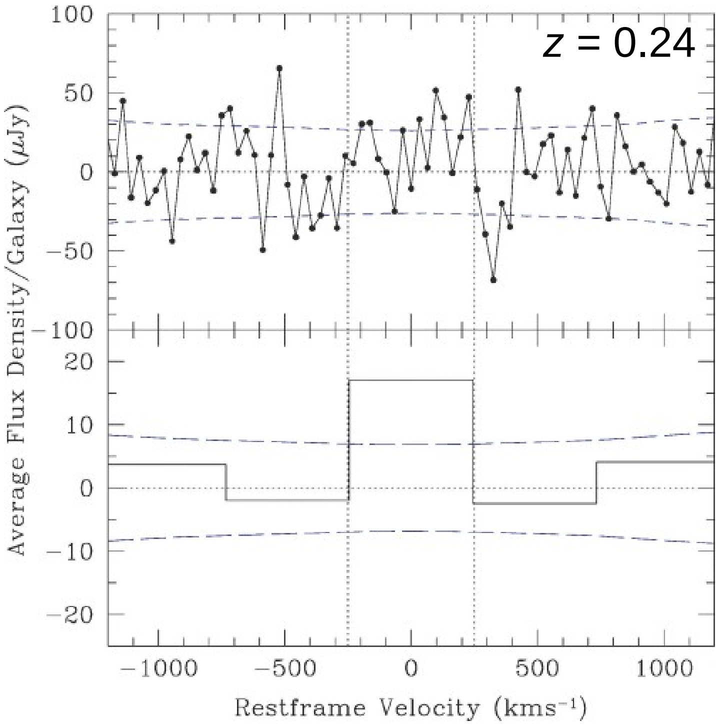
HI 21 cm stacking

- Several stacking attempts to measure average HI mass out to $z \sim 0.4$ using GMRT, WSRT.

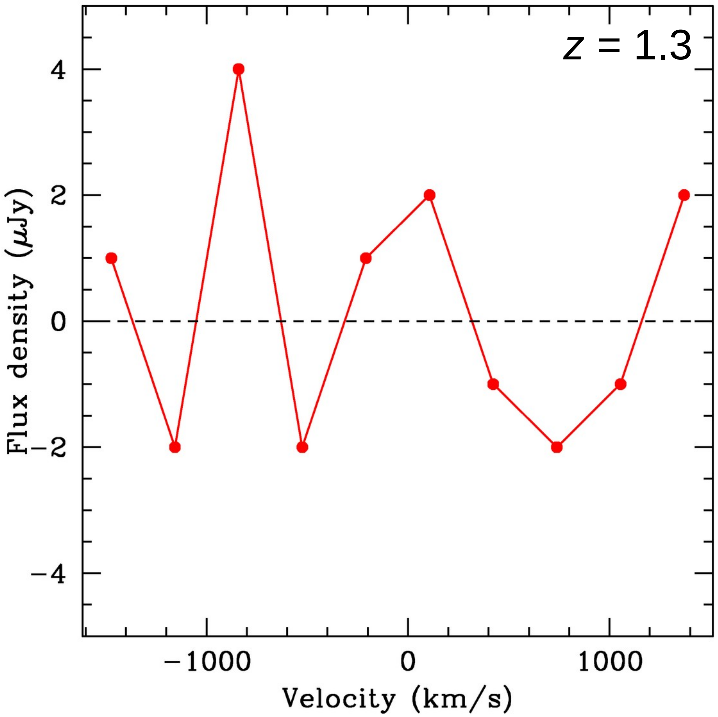
(e.g., Lah et al 2007, 2009; Rhee et al. 2016, 2018)

- First stacking study at $z > 0.4$ ➔ GMRT Upper limit on $\langle M_{HI} \rangle < 2.1 \times 10^{10}\ M_\odot$ at $z = 1.3$.

(Kanekar at al. 2016)



(Lah at al. 2007)

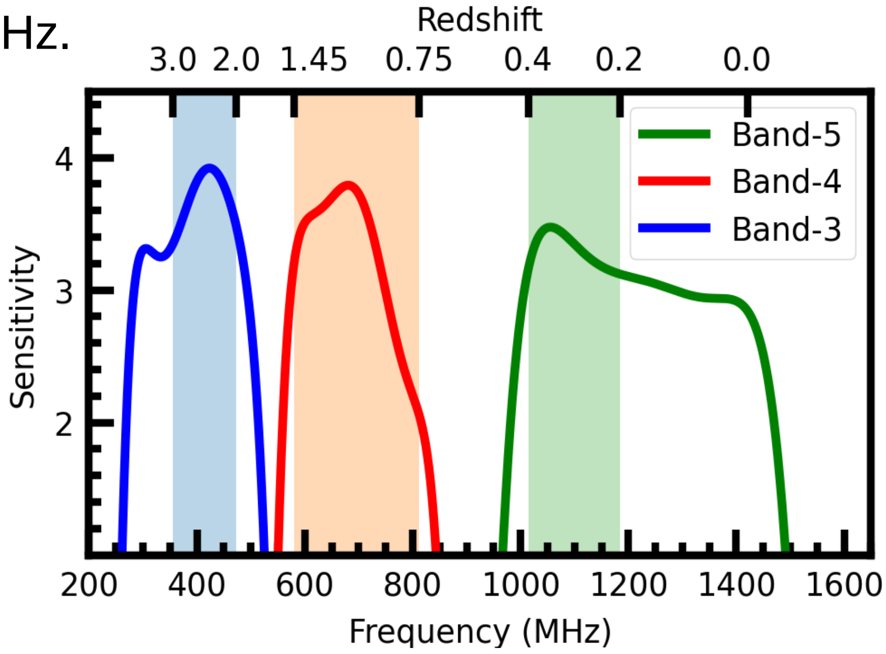


(Kanekar at al. 2016)

The upgraded GMRT

- uGMRT ➔ New correlator, receivers, improved sensitivity.
  - Increase in instantaneous bandwidth to 400 MHz.
  - Wide bandwidth receivers
    - Band 5 - 980–1500 MHz
    - Band 4 - 550–850 MHz
    - Band 3 - 250–500 MHz
    - Band 2 - 120–250 MHz

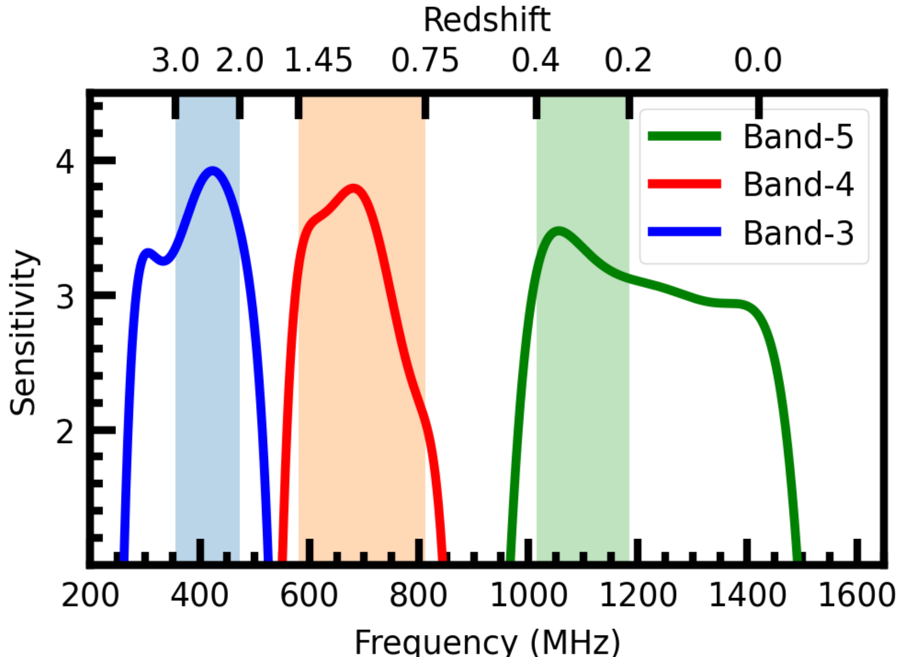
(Gupta et al. 2017)

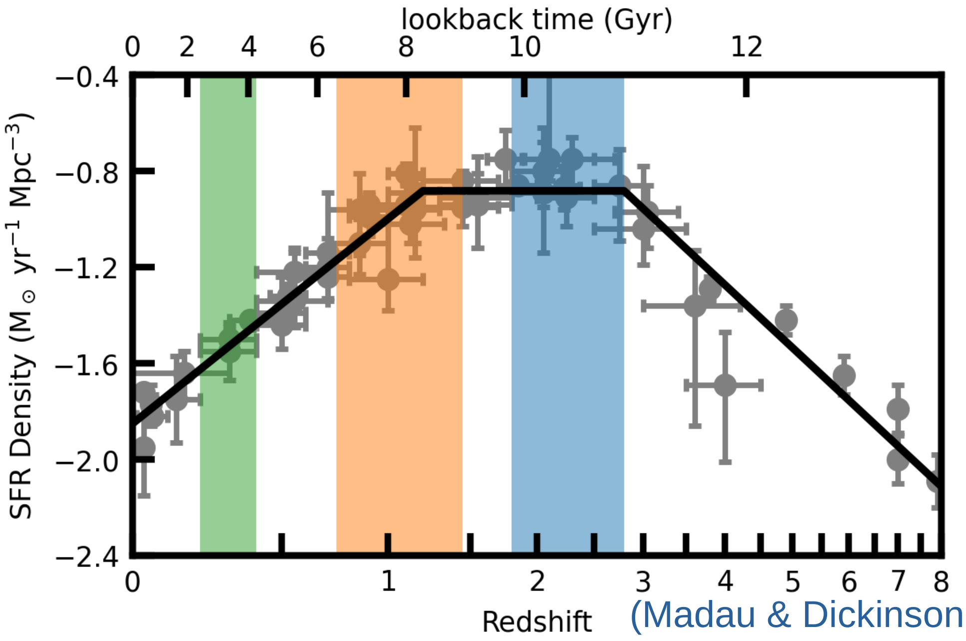


(Figure: Aditya Chowdhury)

Stacking projects with uGMRT

- 350 hr Band-5 survey at z = 0–0.4 of the EGS field. (Bera et al. 2019, 2022)
- 510 hr (+ 580 hr) Band-4 survey at z = 0.74–1.45 of the DEEP2 field. (e.g., Chowdhury et al. 2020, 2022a)
- 140 hr Band-4 survey at z = 0.7–1.4 of the COSMOS field. (This work)
- 200 hr (+ 325 hr) Band-3 survey at z = 1.8–3.3 of the COSMOS field. (Chowdhury 2022)





(Madau & Dickinson. 2014)

Stacking projects with uGMRT

- 350 hr Band-5 survey at z = 0.2–0.4 of the Extended Groth Strip. (Bera et al. 2019, 2022)
- **510 hr Band-4 survey at z = 0.74–1.45 of the DEEP2 field.** (e.g., Chowdhury et al. 2020, 2022a)
- **140 hr Band-4 survey at z = 0.7–1.4 of the COSMOS field.** (This work)
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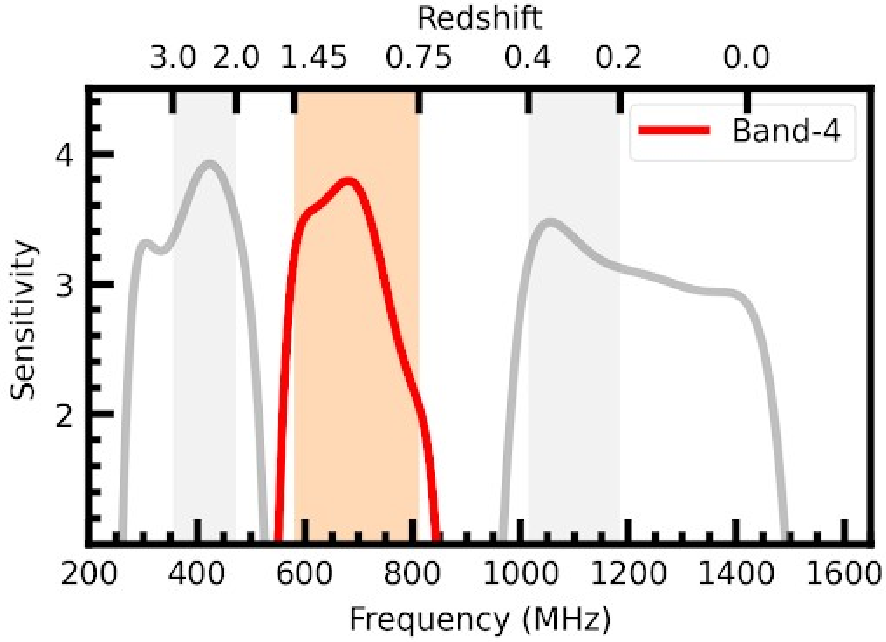
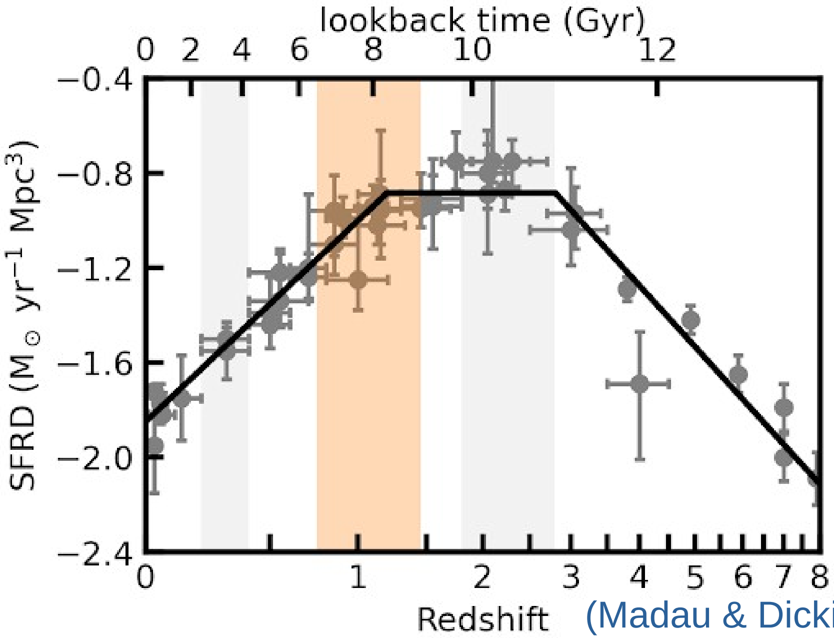


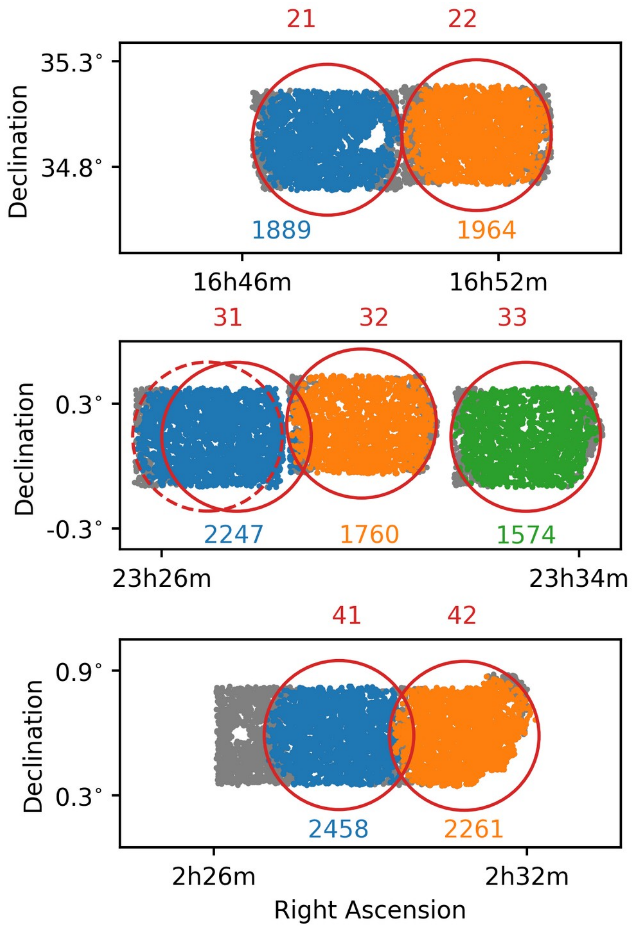


(Madau & Dickinson. 2014)

The GMRT Cold HI AT *z* ~ 1 (CATz1) Survey

- Requirements for stacking:
  - Large number of galaxies within the primary beam and redshift within the frequency coverage.
  - Accurate redshifts and positions.
- The DEEP2 Galaxy Redshift Survey
  - Well-matched to GMRT primary beam (43' at Band-4).
  - Redshifts for >28,000 galaxies at $0.7 < z < 1.45$.
  - Redshift accuracy ~ 62 km/s.

(Newman et al. 2013)

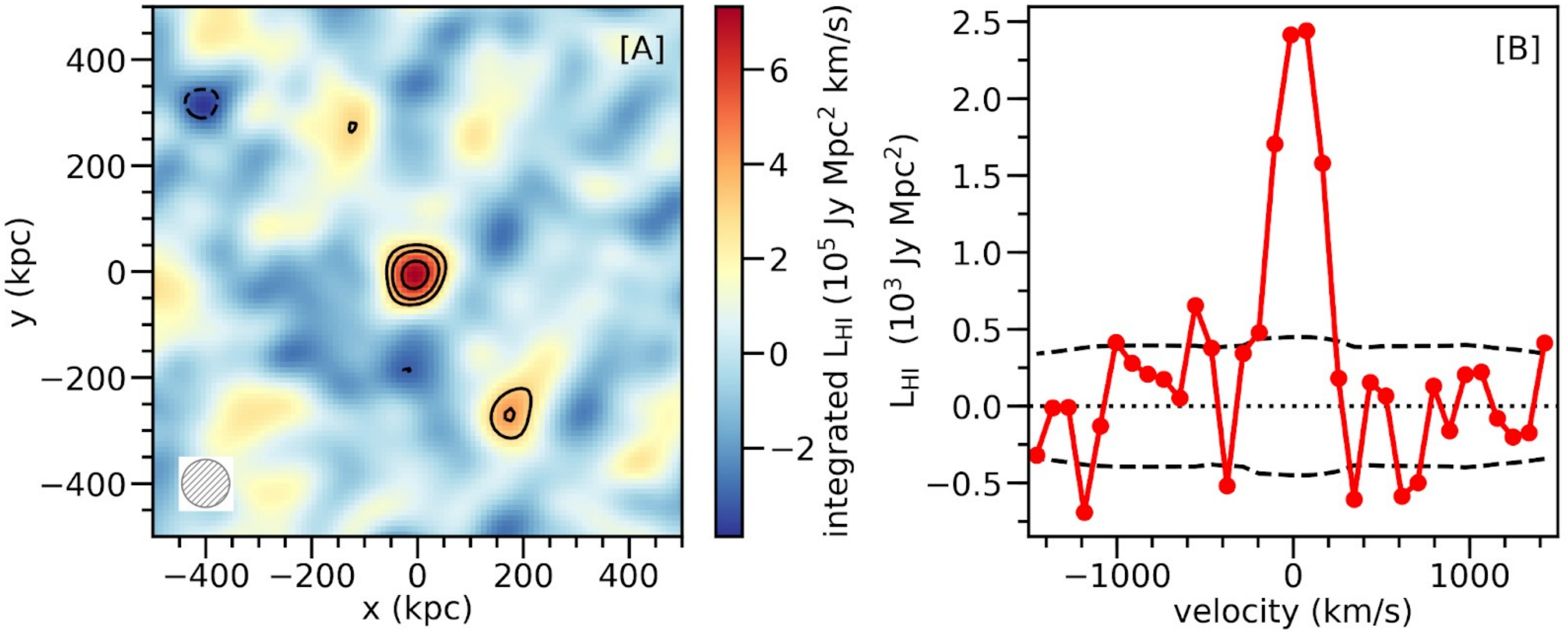


(Chowdhury et al. 2022a)

GMRT CATz1 survey

(Chowdhury et al. 2020,2022a)

- GMRT Band-4 HI 21 cm survey of 16,000 galaxies in the DEEP2 fields.

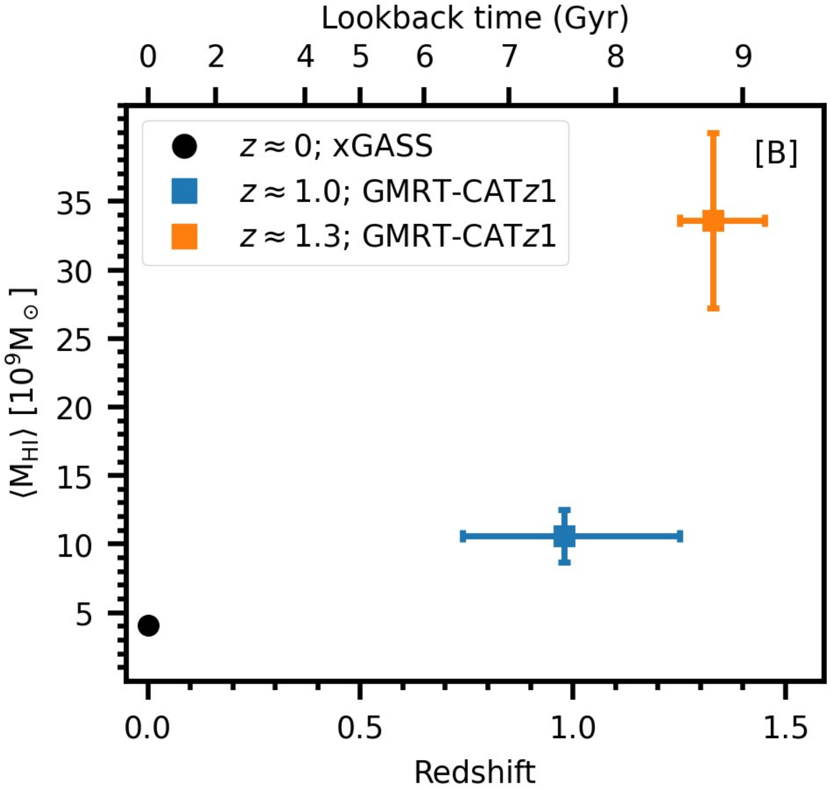


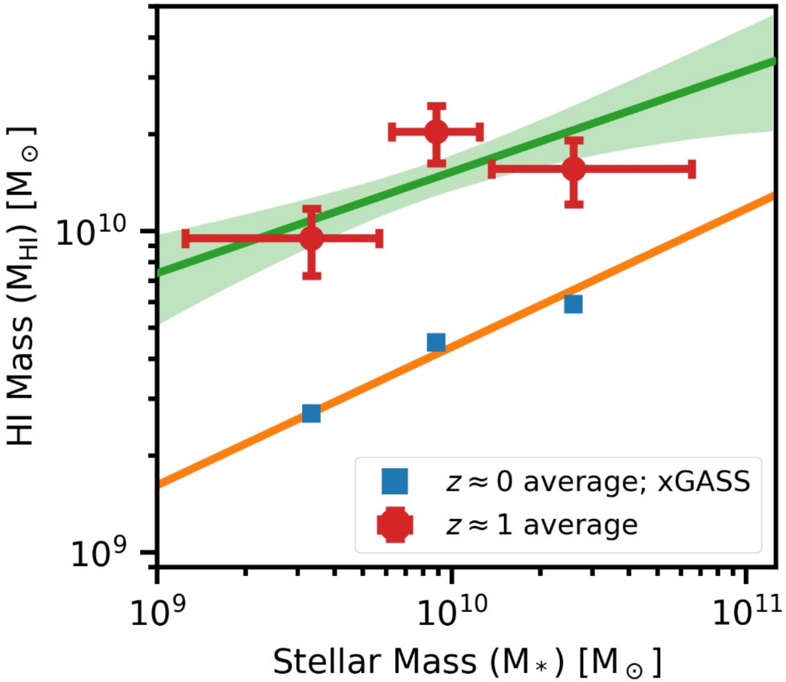
(Chowdhury et al. 2022a)

- First detection of HI 21cm emission at $z \sim 1$ ➔ $\langle M_{HI} \rangle = (1.37 \pm 0.19) \times 10^{10}\ M_{\odot}$

GMRT CATz1 survey

(Chowdhury et al. 2022b, 2022c)

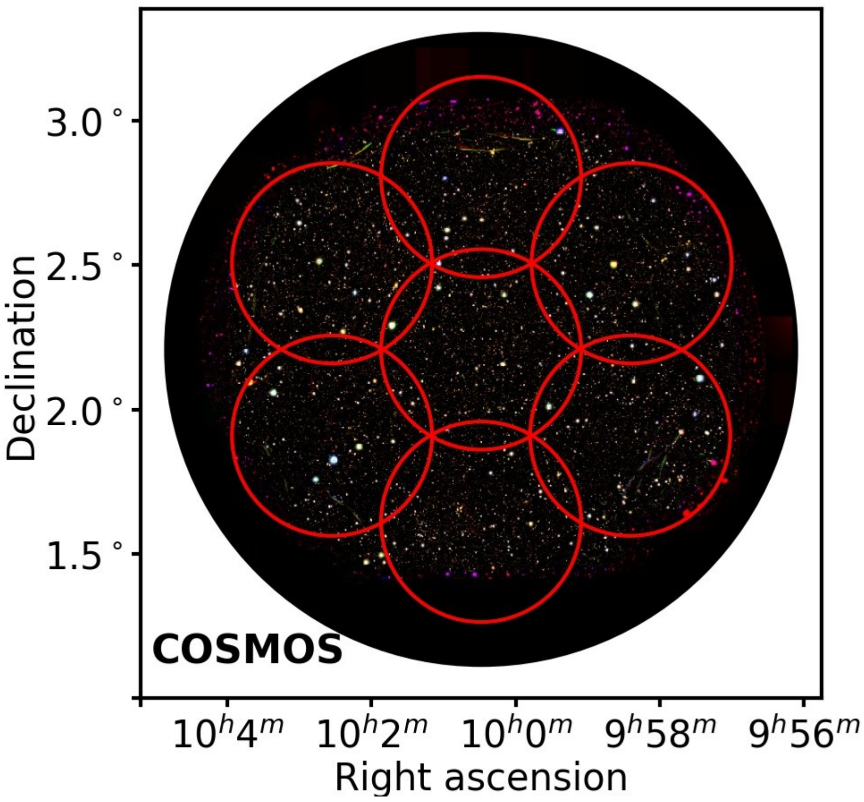




- Redshift evolution, M_{HI}–M_{*} and M_{HI}–M_{B} scaling relations, HI mass function, accretion rate, ...
- But no HST imaging of DEEP2 fields: Dependence on galaxy morphology? Relatively poor multi-wavelength coverage.

COSMOS: GMRT Band 4 survey

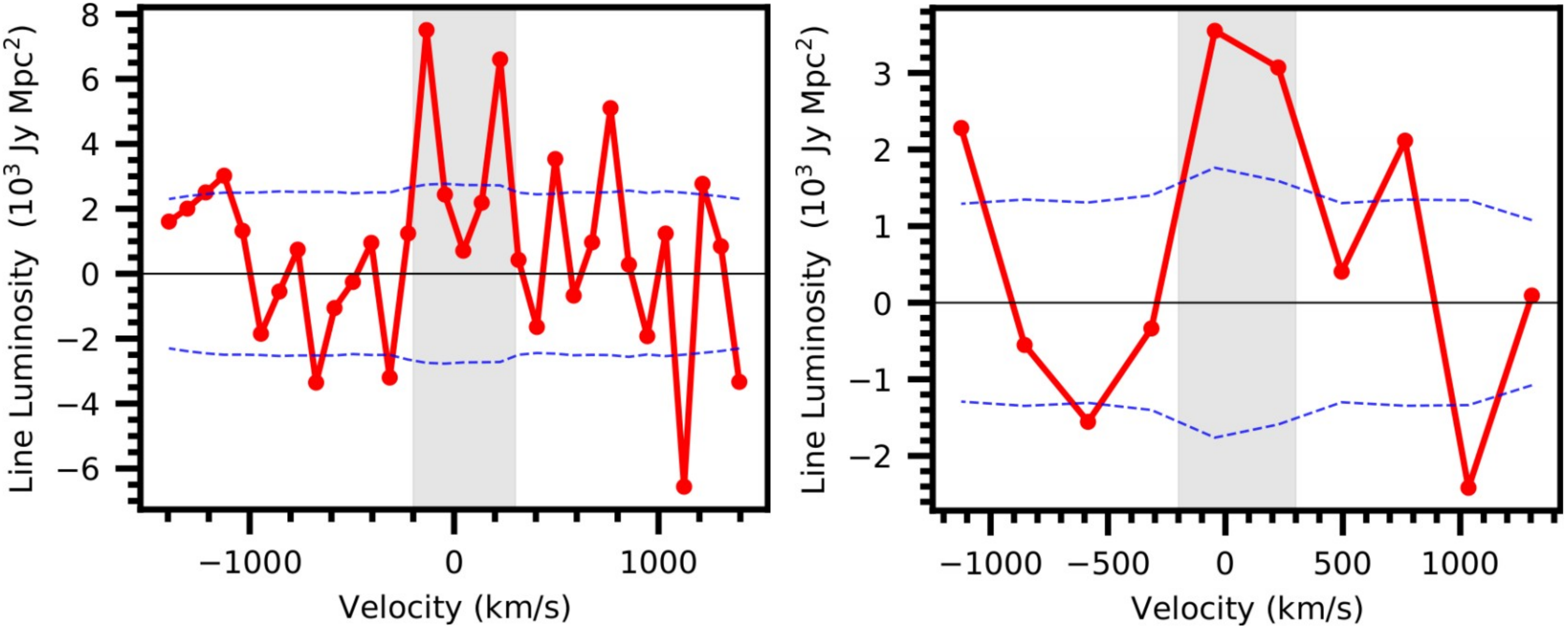
- Wide deep field, 2 sq. deg, uniform HST coverage.
  (e.g., Scoville et al. 2007a)
- Outstanding multiwavelength photometry.
  (e.g., Scoville et al. 2007b)
- VLT+Keck spectroscopic redshifts at z~0.7 – 1.4.
  (e.g., Lilly et al. 2009; Hasinger et al. 2018)
- GMRT Band-4 HI 21 cm survey ➔ 2.8 sq. deg, 7 pointings x 19 hrs.
- Two key science goals:
  - Average HI mass of star-forming galaxies at z~1.
  - Dependence on morphology, environment.
- Covered 550 – 850 MHz, with 16,384 channels.
  ~14 hours on-source per pointing.



(e.g., Aihara et al. 2019)

Stacking HI 21 cm emission from COSMOS

- So far, analysed GMRT data on the central pointing.
- Stacked HI 21cm emission from 824 blue galaxies.
- 2.5 sigma emission feature $\langle M_{HI} \rangle$ ➔ $(3.6 \pm 1.4) \times 10^{10}\ M_{\odot}$ at $z \sim 1.0$.



Summary

- Understanding galaxy evolution ➔ Understand stars and gas in high-z galaxies.
- Weakness of HI 21cm line ➔ HI 21cm stacking to measure $\langle M_{HI} \rangle$ of high-z galaxies.
- First detection of $\langle M_{HI} \rangle$ at z~1 in the DEEP2 fields ➔ $\langle M_{HI} \rangle = (1.37 \pm 0.19) \times 10^{10}\ M_{\odot}$.

(Chowdhury et al. 2020,2022a)

- Dependence of $\langle M_{HI} \rangle$ on redshift, M_{*} , M_B, ...

(Chowdhury et al. 2022b, 2022c)

- Outstanding multi-wavelength photometry and HST imaging of COSMOS
  - GMRT Band-4 HI 21 cm survey, 2.8 sq. deg, 133 hours.
    - Average HI 21 cm properties of star-forming galaxies in COSMOS at z~1.
    - Dependence on morphology, environment, ...
- Stacked HI 21cm emission from 824 galaxies from central pointing➔ 2.5σ feature ➔ $\langle M_{HI} \rangle = (3.6 \pm 1.4) \times 10^{10}\ M_{\odot}$ at $z \sim 1.0$.