Atomic Hydrogen in the Universe

A: Intermediate and high redshifts

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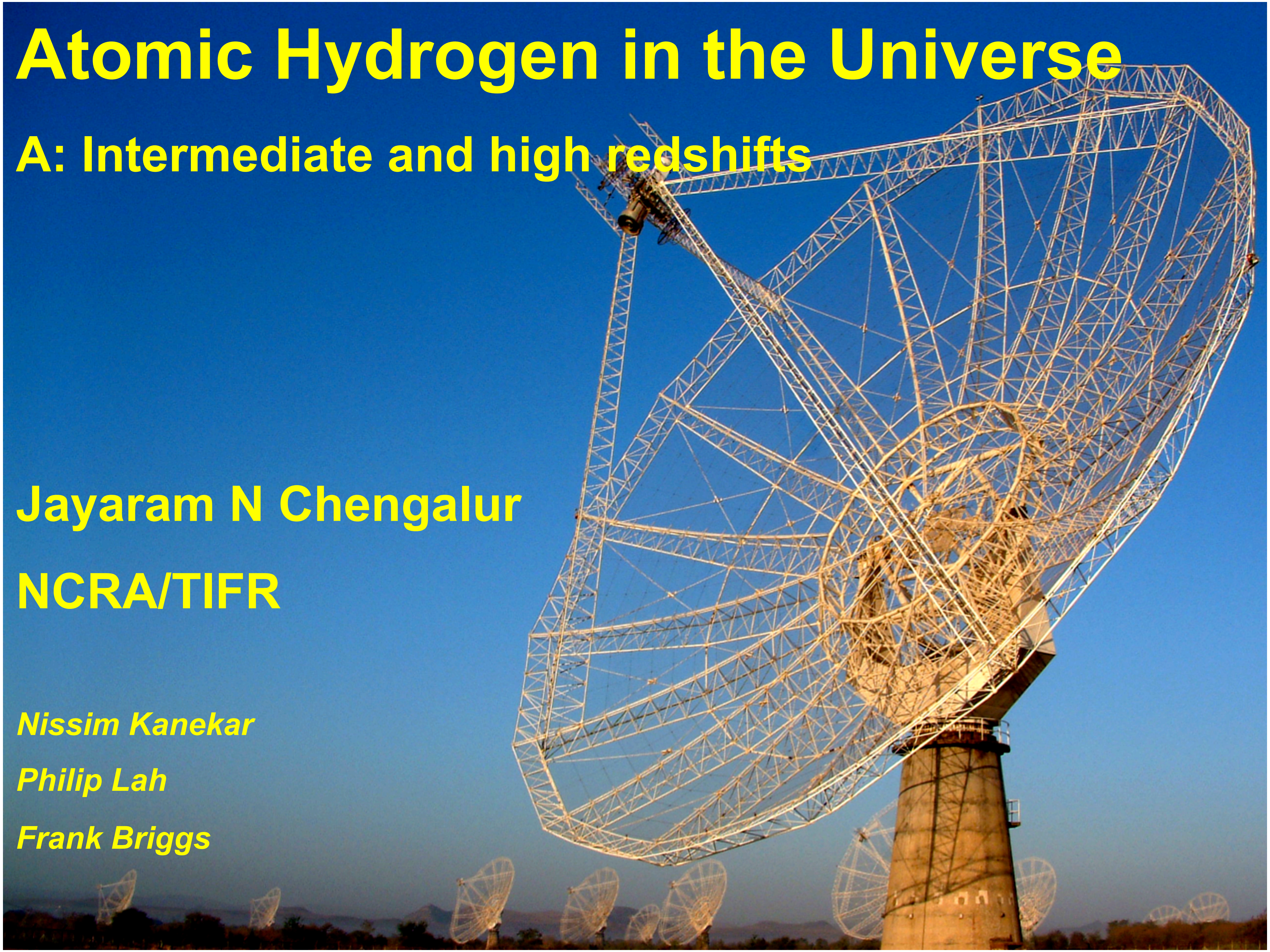


Atomic Hydrogen (HI) in the Universe

- Hydrogen is the dominant baryonic component of the universe

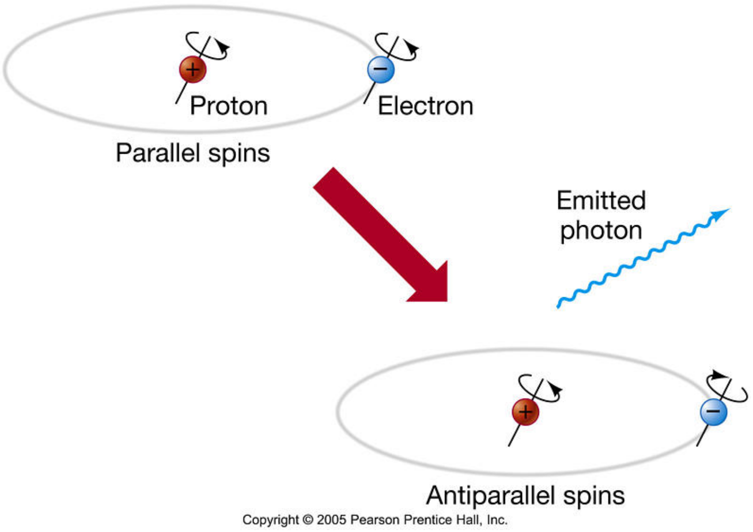
- From redshifts lower than ~ 10±3 most of the hydrogen is ionized

- At z ~ 0 essentially all of the HI is in galaxies (very few HI clouds without star-formation)

Zwaan et al. ApJ 490, 173, (1997)

- The HI mass of a typical spiral galaxy is ~ 10% of the stellar mass

The HI 21cm line



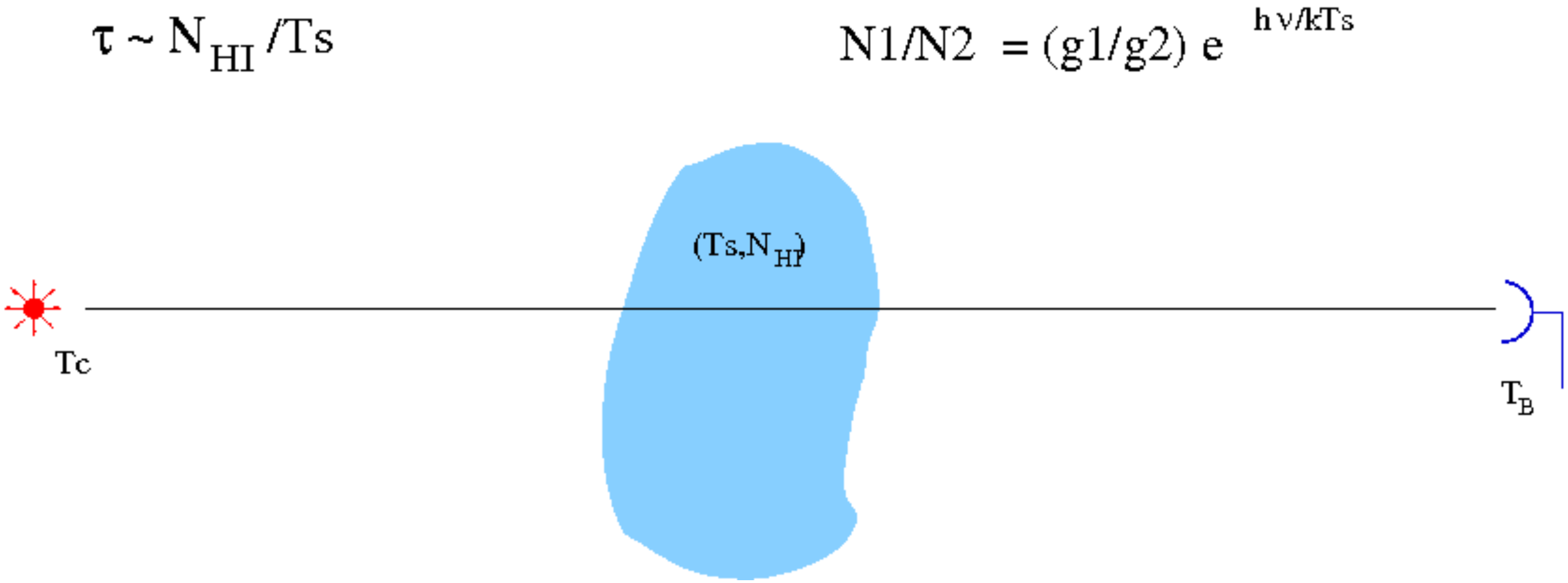
- The hydrogen atom has hyperfine structure
  - State with parallel electron and proton spins has higher energy than the state where spins are anti parallel

The wavelength of this transition corresponds to ~ 21cm.

The A coefficient is very small ~ 2.8 10^{-15} s
  - Characteristic transition time is ~ 10^7 yr

- Because of the large abundance of HI this is one of the strongest cm radio spectral lines

Radiative Transfer



$T_c >> T_s$ (Absorption)

$T_c \sim 0$, $\tau << 1$ (Emission)

- Rayleigh-Jeans limit $B(\nu) \sim 2\,kT\nu^2/c^2$
- $T_B = T_s(1\text{-}e^{-\tau}) + T_c e^{-\tau}$

$T_B = T_c e^{-\tau}$

$T_B \sim T_s \tau \sim N_{HI}$

From emission absorption experiments can measure both N_{HI} and T_s

Can measure gas column density or mass

Can measure τ or N_{HI}/T_s

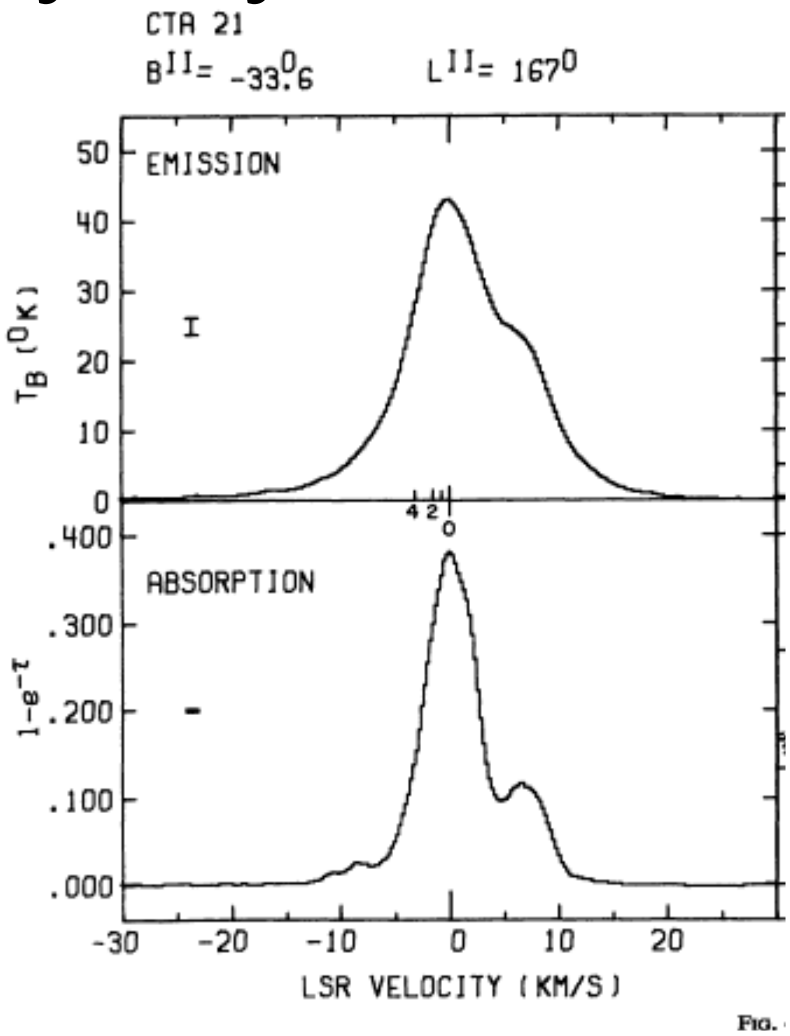
$\tau \sim N_{HI}/T_s$

HI in the Milkyway

- It has been known for long that the HI in the Milkyway has two phases
  - One which is seen in both emission and absorption
  - One which is seen in emission *but not* absorption
- The natural explanation is that the component not seen in absorption has a low optical depth because it's spin temperature is large

$$\tau \sim N_{HI}/Ts$$

Ts ≥ 5000 K would make τ too small to be observed



Dickey et al. ApJS, 36, 77 (1978)

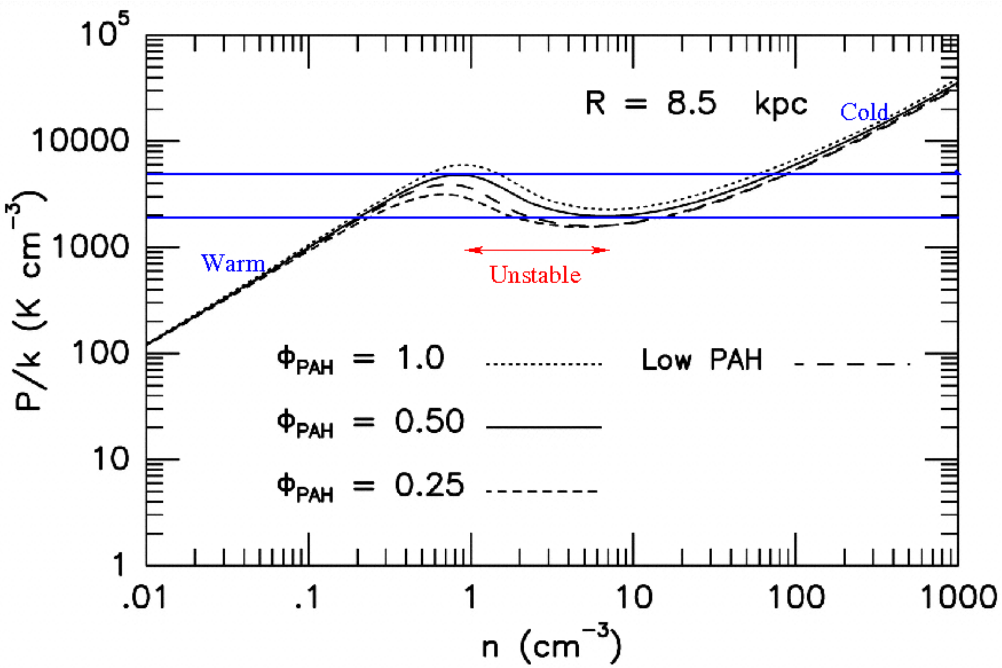
Two phase models

- At thermal steady state and constant pressure there are two stable phases of the ISM
  - *Warm Neutral Medium (WMN, Ts ~ 8000K, n ~0.1)*
  - *Cold Neutral Medium (CNM, Ts ~ 80 K, n~ 10)*

- Gas at intermediate temperatures is unstable and is not expected to be present
  - *However recent observations suggest that "unstable gas" may be ubiquitous*

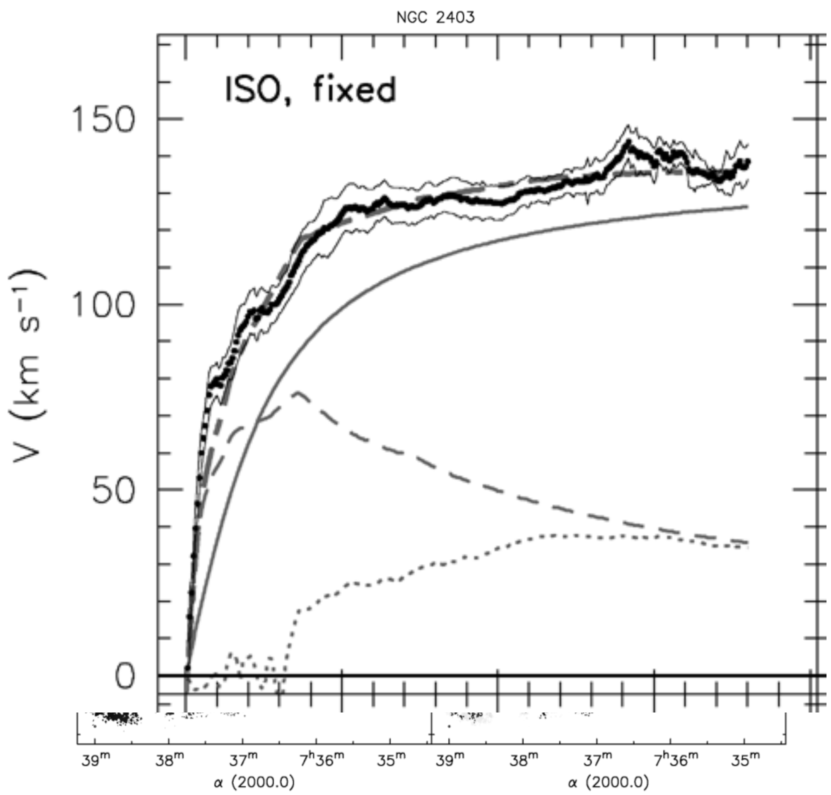
  (e.g. Heiles & Troland, 586, 1067, 2003)

Wolfire et al. ApJ, 587, 278 (2003)



HI in galaxies

- HI in galaxies is generally in the form of a thin disk
- The HI disk is extended compared to the stellar disk
- The HI disk shows differential rotation
- From radio observations one can determine
  - *Mass and distribution of HI in the disk*
  - *Kinematics of the gas in the disk ("rotation curves")*
  - *Total dynamical mass of the galaxy*



De Blok et al. AJ 136, 2648, (2008)

Walter et al. AJ 136, 2563, (2008)

The expanding universe

- The universe is expanding
- Light emitted at a wavelength λ_{src} in the earlier universe is stretched to a longer wavelength λ_{obs} by the time it reaches earth

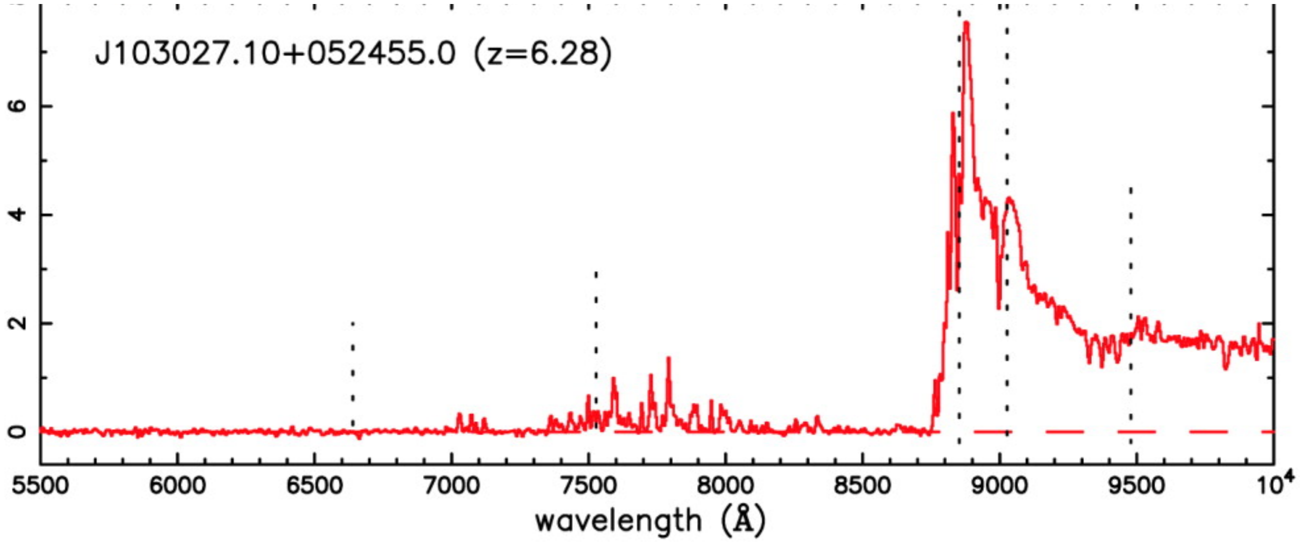
$$\lambda_{obs} = \lambda_{src}(1+z)$$

(1+z) - factor by which the universe has expanded

z is the "redshift"

High redshift (large z) → Early times

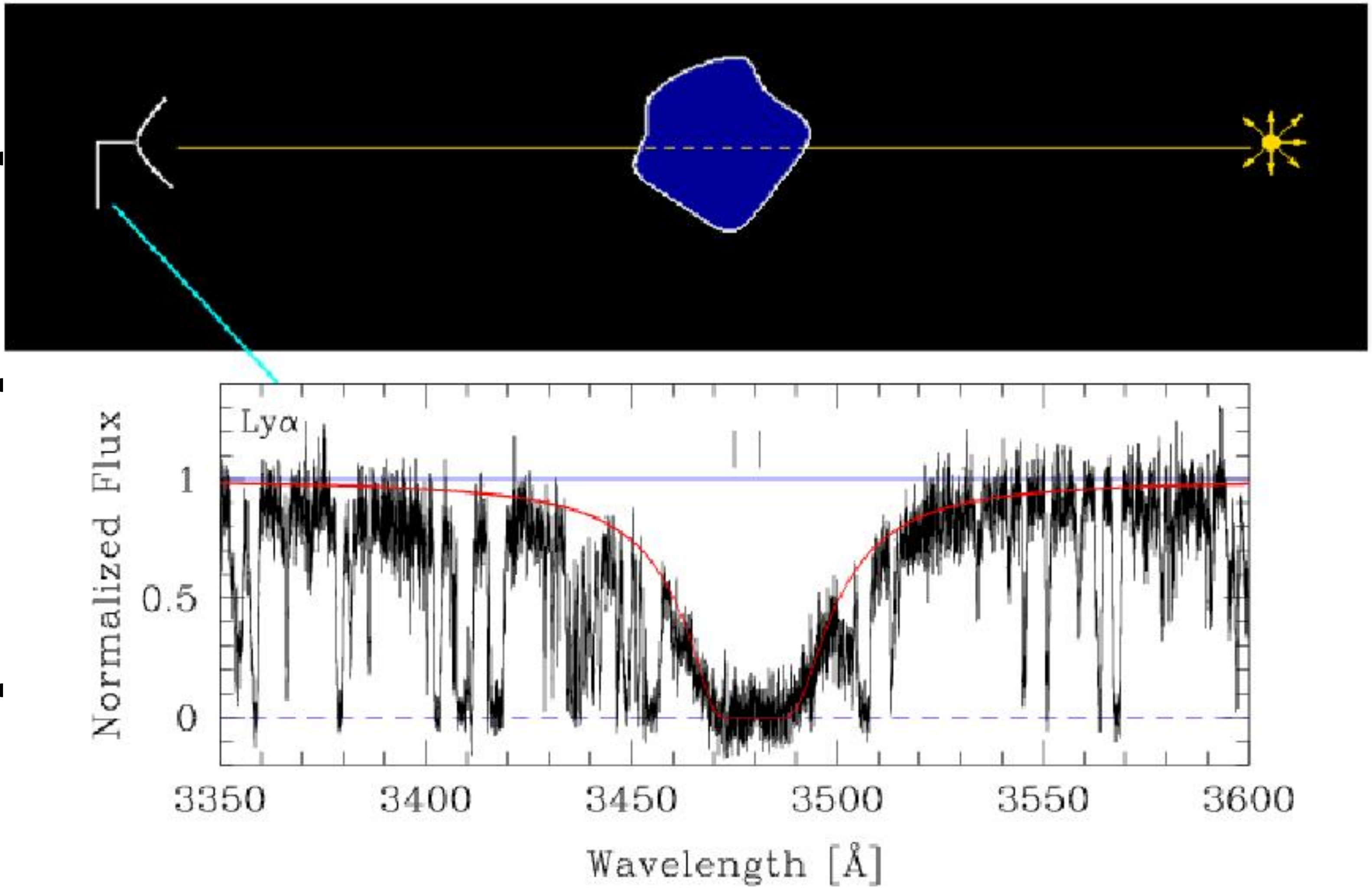
HI at high z: Ly-α absorption



Becker et al. AJ 122, 2850, (2001)

- HI has a very large cross section for absorption of Lyα
- Any HI in the IGM between us and a distant quasar will absorb Lyα
- If the IGM has atomic HI then one would see a broad absorption on the blue side of the quasar Lyα emission
- No such broad absorption seen till z ~ 6
  - *IGM is largely ionized at least till z ~ 6*
    - *Because of the large Lyα cross section even small neutral fraction leads to large optical depth*

Damped Ly-α systems



of

- $N_{HI} \propto EW^2$ ➔ N_{HI} is an observable

Cosmic Density of HI (Ω_{HI})

- The probability of finding a DLA in a given Δz interval

  Cross section X Number Density

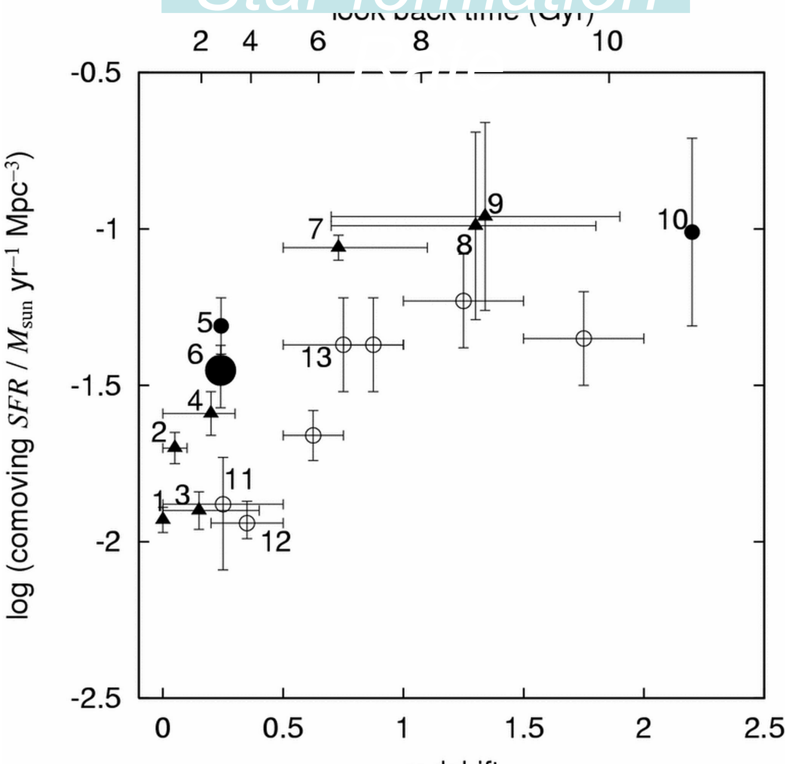
  Ω_{HI} *~ Cross section x Number Density X* N_{HI}

- From DLA observations one can determine Ω_{HI} as a function of redshift for $z > 1.6$

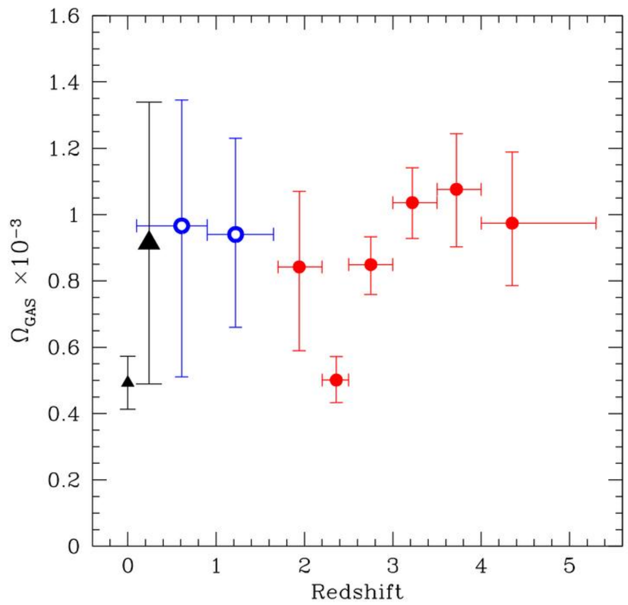
- Ω_{HI} at $z \sim 0$ can be determined by radio surveys of HI emission
  - *Radio telescopes lack sensitivity to detect HI emission at redshifts > 0.2*

Evolution of Ω_{gas}

Star formation



Cold gas



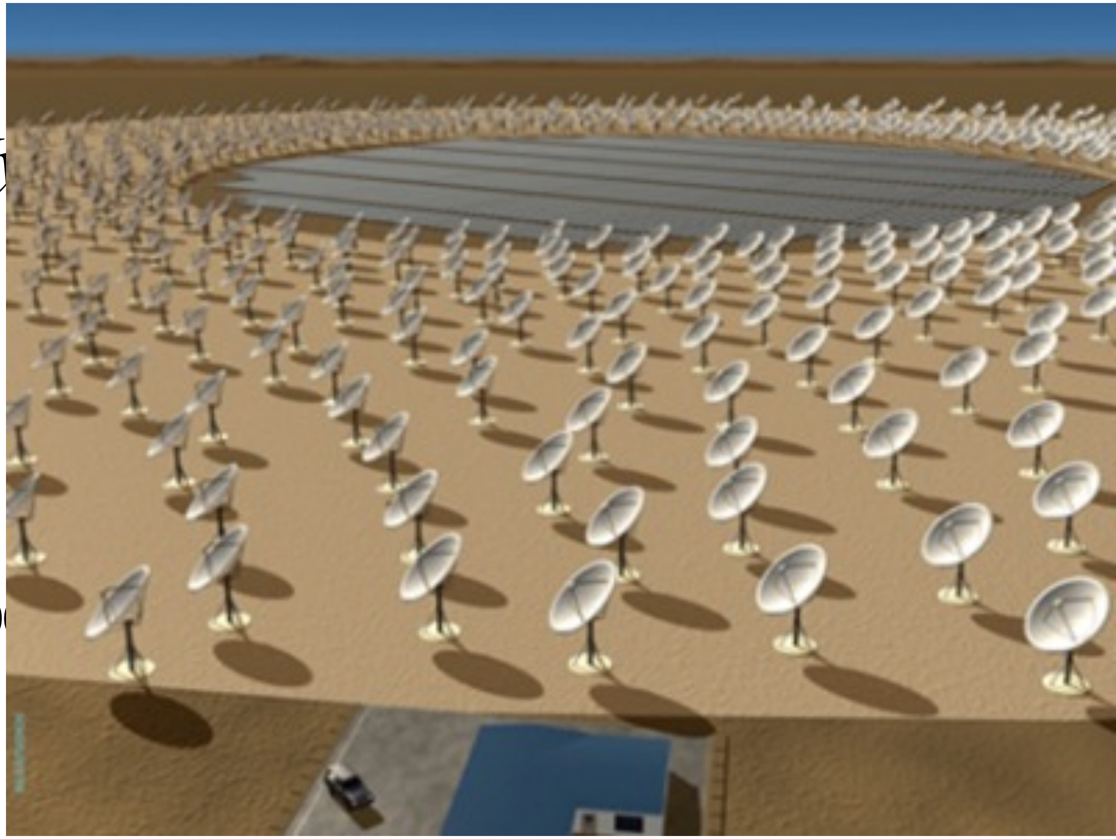
Lah et al., MNRAS. 376, 1357, (2007)

Very limited constraints on the gas content (i.e. raw material for star formation) exist in the redshift range in which the star formation rate shows very rapid evolution

Measuring the gas content of galaxies at intermediate redshifts

Sensitivity Issues – need for SKA

$S \approx 7\mu Jy$ … $\frac{+z}{2})$



$\tau = 900$ … $\frac{00km/s}{\Delta V})$

What can one do now?

- The volume of space observed by the GMRT telescope in a single observation ~ (FoV x Bandwidth) could contain ~ 100 or more bright galaxies

- One could try to detect the average HI emission of all of these galaxies by stacking

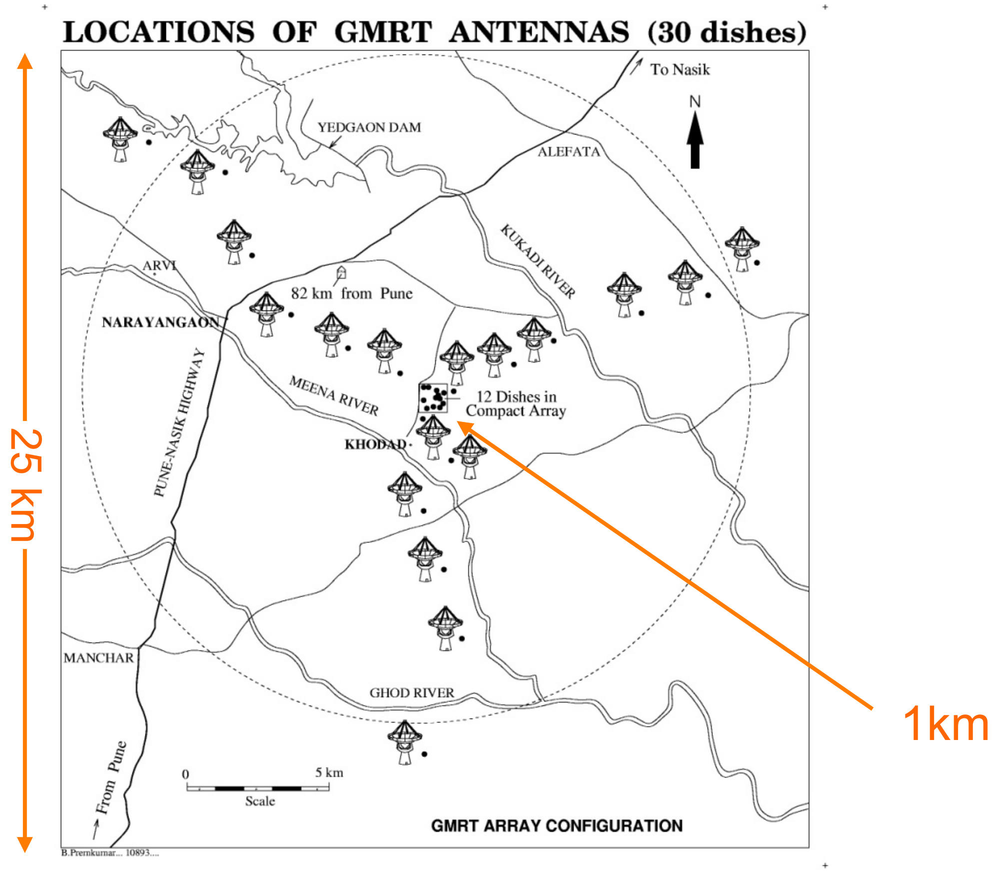
- Stacking requires one to know the *position* and *redshift* of all galaxies

The Giant Metrewave Radio Telescope

- The Giant Metre-wave Radio Telescope (GMRT) is a large aperture synthesis radio telescope optimized for operation at low frequencies
- Designed and built primarily by NCRA, a national centre of TIFR.
- Array telescope consisting of 30 antennas of 45 metres diameter
  - The most sensitive synthesis radio telescope in the world at most of its frequencies of operation,

GMRT Antenna Layout

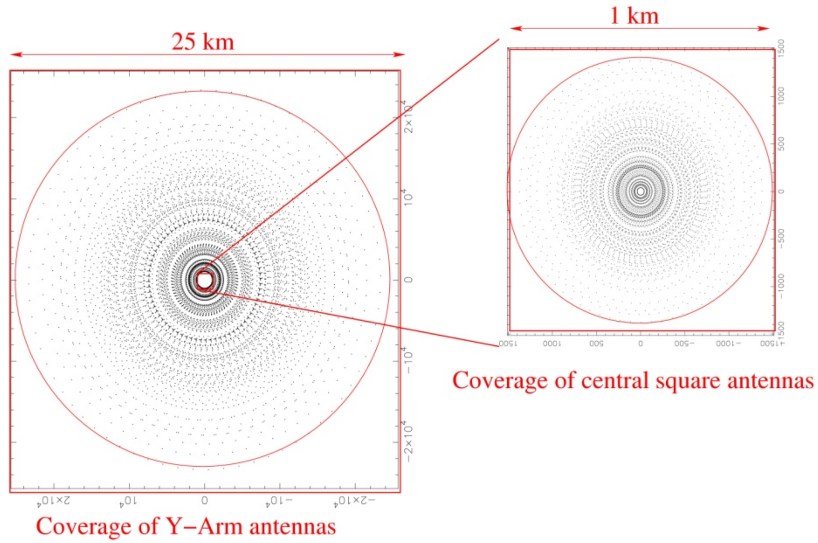
Unique hybrid configuration with mix of long and short baselines



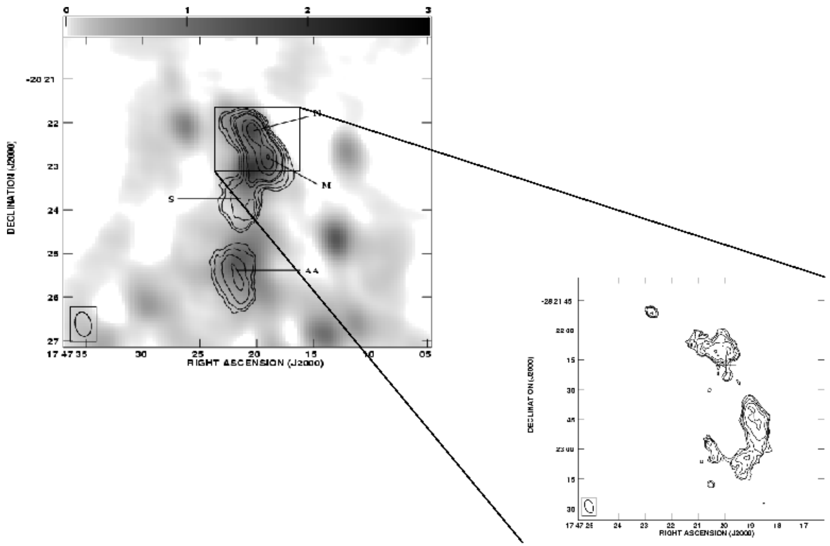
Imaging with the GMRT

Aperture Synthesis Arrays measure the Fourier Transform of the Sky Brightness distribution

Sensitivity to both extended emission (central square antennas) as well as fine structure (arm antennas)



Chengalur & Kanekar 2003,A&A,403,L43

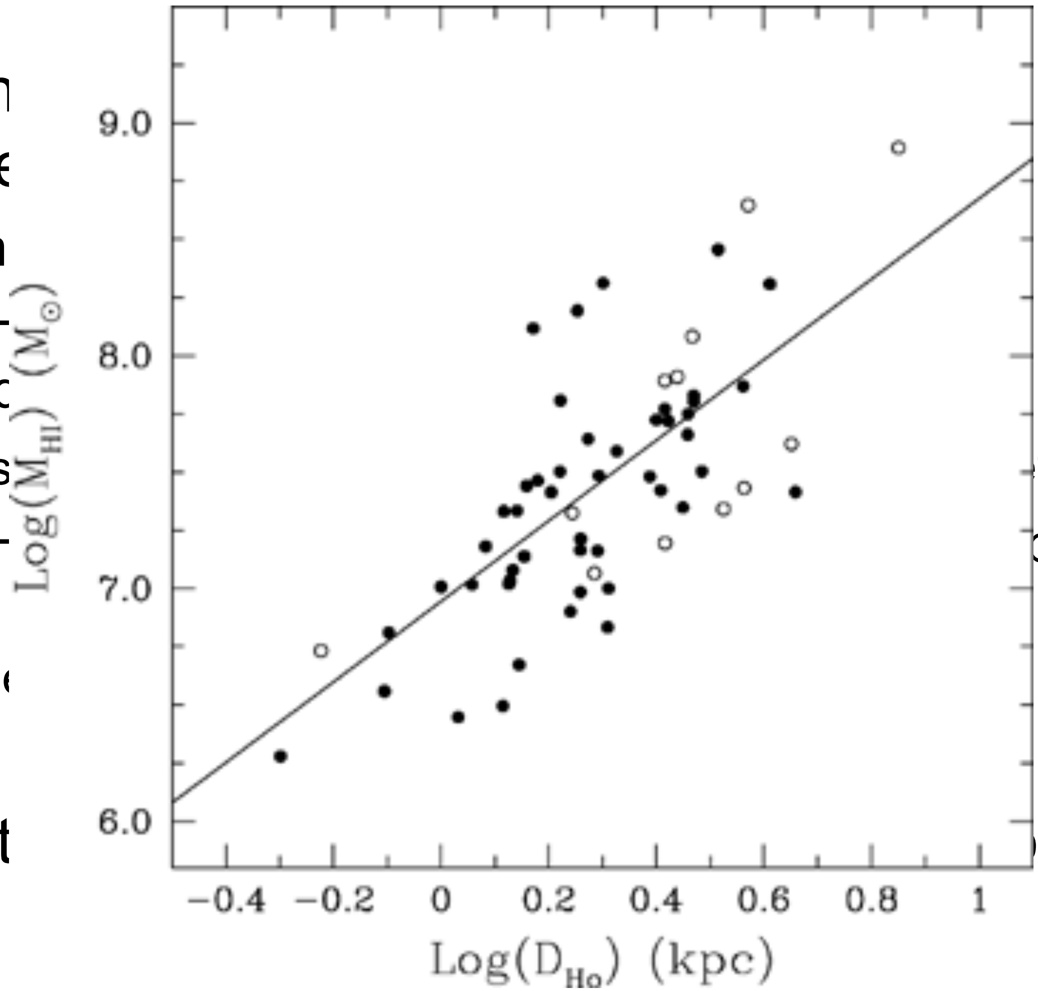


Low and high resolution images of CH_3CHO emission from SgrB2 made from a single GMRT observation

Proof of concept A3128

- Naively if on… m N galaxies, the…
  - Redshift m… HI spectra
  - Unknown H… weights while co-ad…
    - HI mass… ter.
  - Unknown H… ptimal SNR
    - HI diam…

- Low redshift… f "concept"



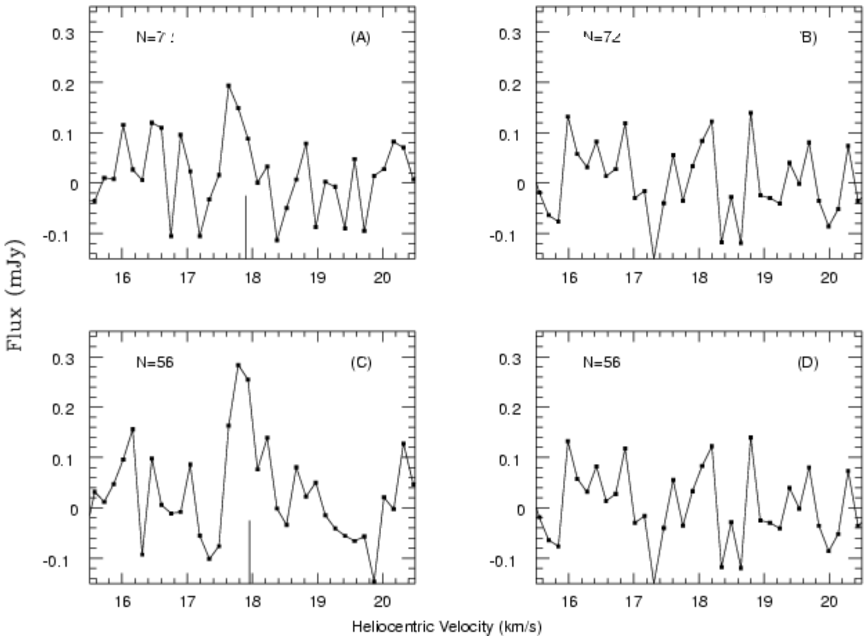
Karachentsev et al. (2008)

A3128

Chengalur et al. 2001

(also Zwaan et al. 2001

- A 3128 is a z ~ 0.06, richness class 3, Bautz-Morgan type I-II cluster
- Redshifts available for 193 galaxies, of which 148 lie inside the ATCA cube
- Co-added emission detected from cluster galaxies.
- Late type galaxies located outside the X-ray contours have the highest HI content
    - M_{HI} = 16.7 ± 2.6 (late type, outer)
    - M_{HI} = 8.6 ± 2 (all galaxies)



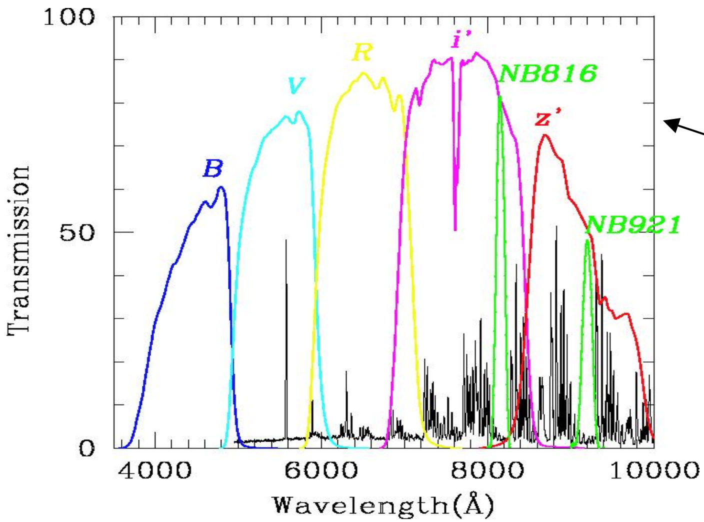
Late types outside X-ray contours

Measuring Ω_{HI} at z ~ 0.24

Fujita et al. 2003 did a narrow band imaging survey for Ha emission at z=0.24

FoV 24’x30’

Total of 348 galaxies in the sample



GMRT Observations

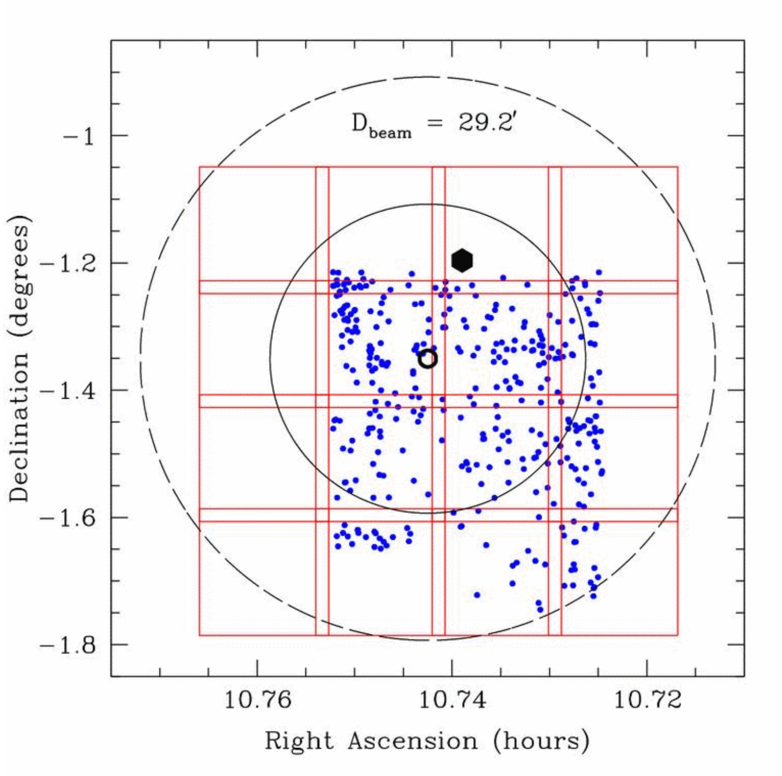
- 121 galaxies within the GMRT data cube
  - Total of ~ 40 hours of on source time

- Most of these galaxies are fainter than L_* (i.e. low HI mass)

- Redshifts obtained using the 2dF instrument on the AAT

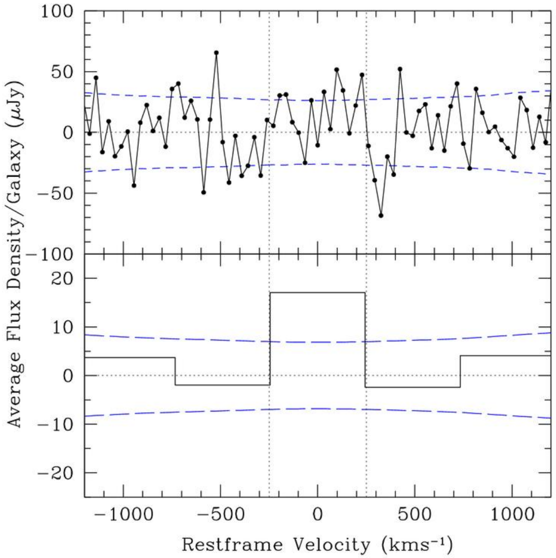
- Optical imaging with the ANU 40" telescope.

- Smoothing sized fixed using D_{HI} - D_{opt} relation from Broeils & Rhee (1997)



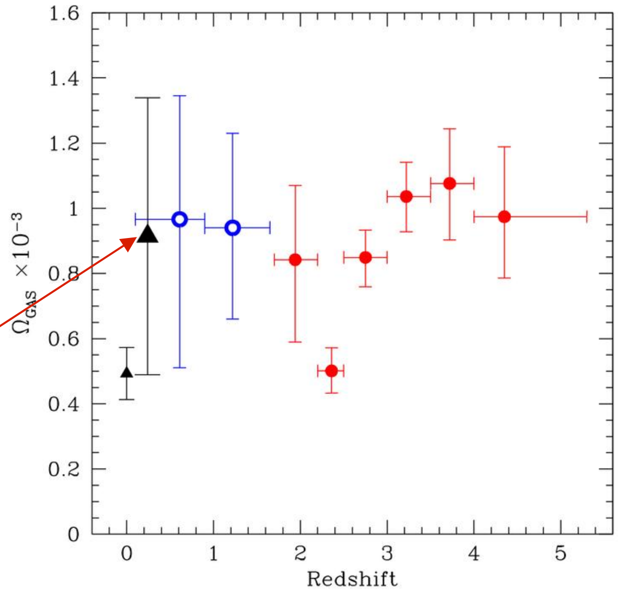
Lah et al. MNRAS. 376, 1357, (2007)

Stacked HI Spectrum and ΩHI



121 redshifts - weighted average

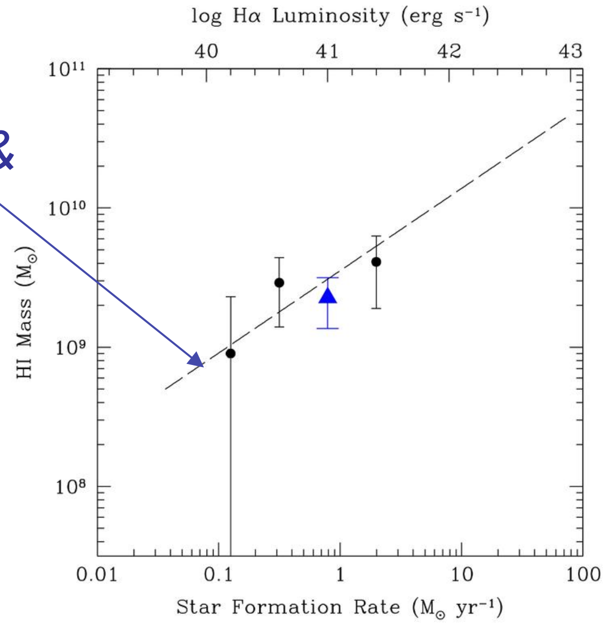
$M_{HI} = (2.26 \pm 0.90) \times 10^9\ M_\odot$



Lah et al. (MNRAS,376, 1357, 2007)

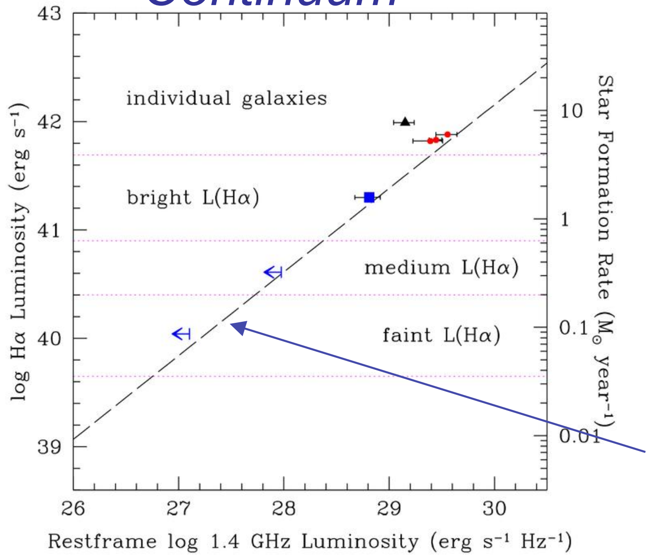
Star Formation Rate at z = 0.24 shows same correlations as for z=0 galaxies

SFR vs M_{HI}



z = 0 relation from Doyle & Drinkwater (2006)

SFR vs Radio Continuum



z = 0 relation from Sullivan (2001)

Abell 370

a Galaxy Cluster at $z = 0.37$

Abell 370, a galaxy cluster at z = 0.37

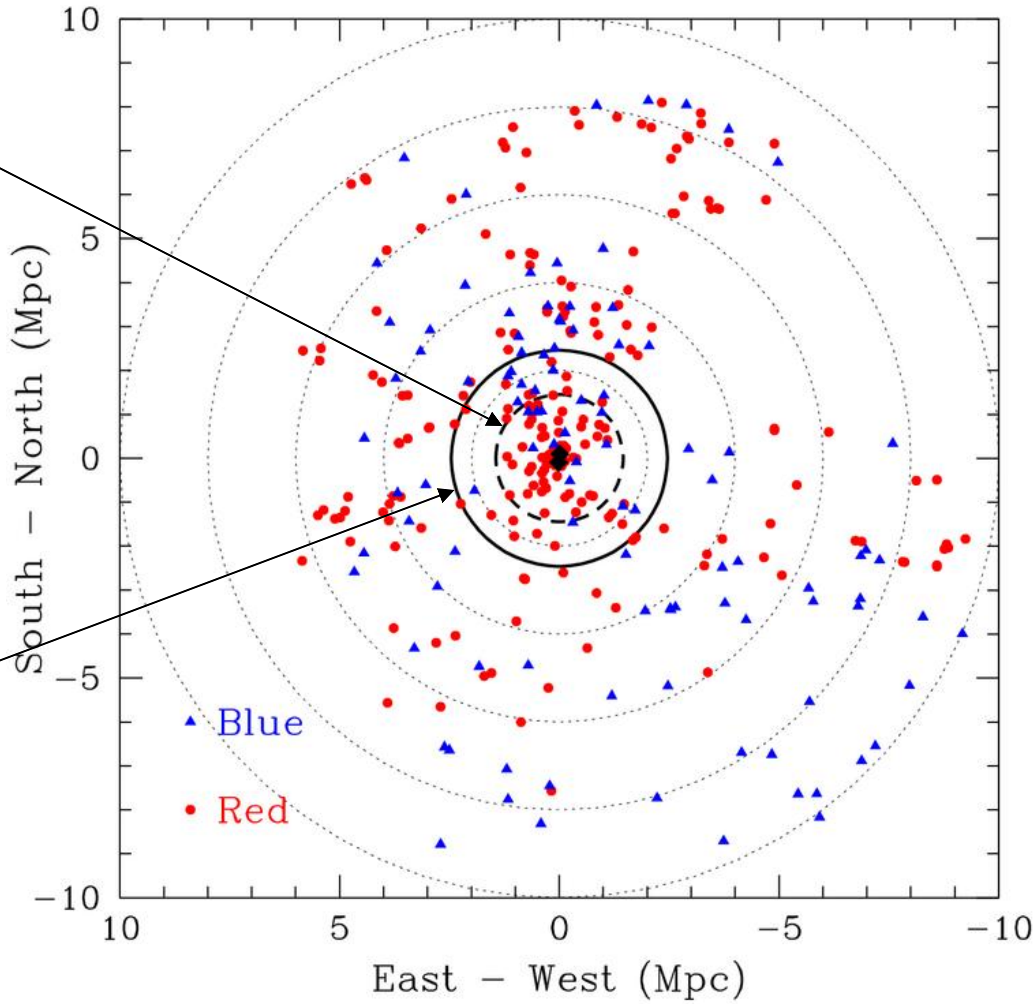
optical imaging

spectroscopic follow-up with the AAT

GMRT ~34 hours on cluster

Abell 370 galaxy cluster

Extent of X-ray gas



R_{200} ⇨ radius at which cluster 200 times denser than the general field

105 blue (B-V ≤ 0.57)

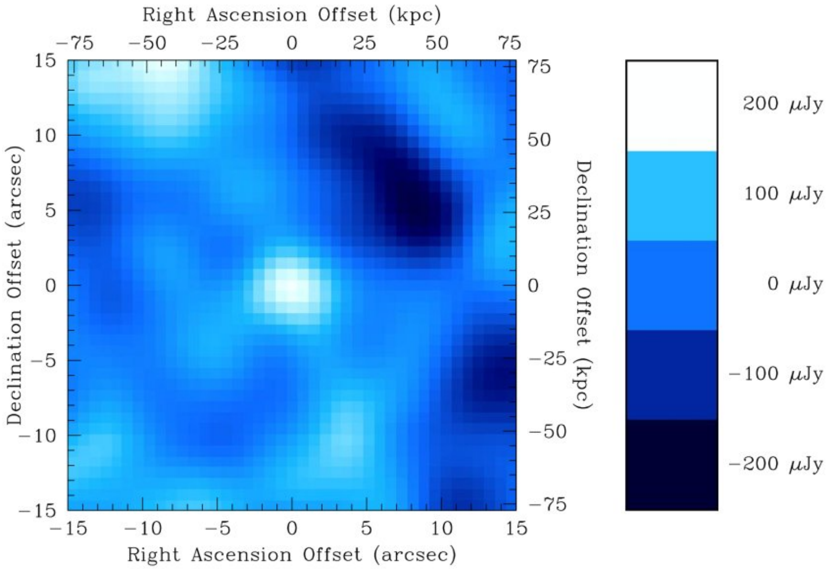
219 red (B-V > 0.57)

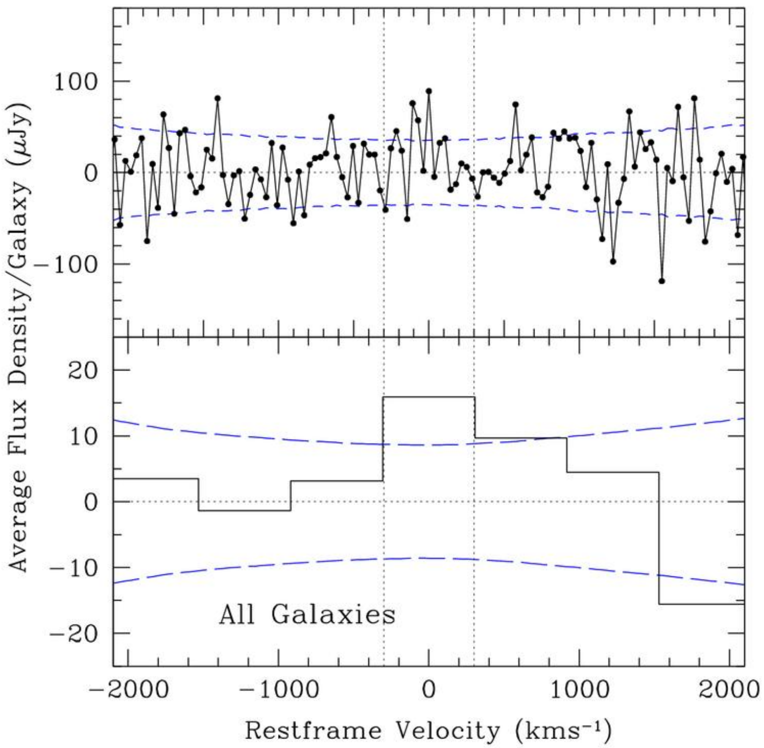
Lah et al., MNRAS, 399, 1447, (2009)

HI spectrum

Average HI mass ~ 8 times more than average HI mass of z ~0 Coma cluster

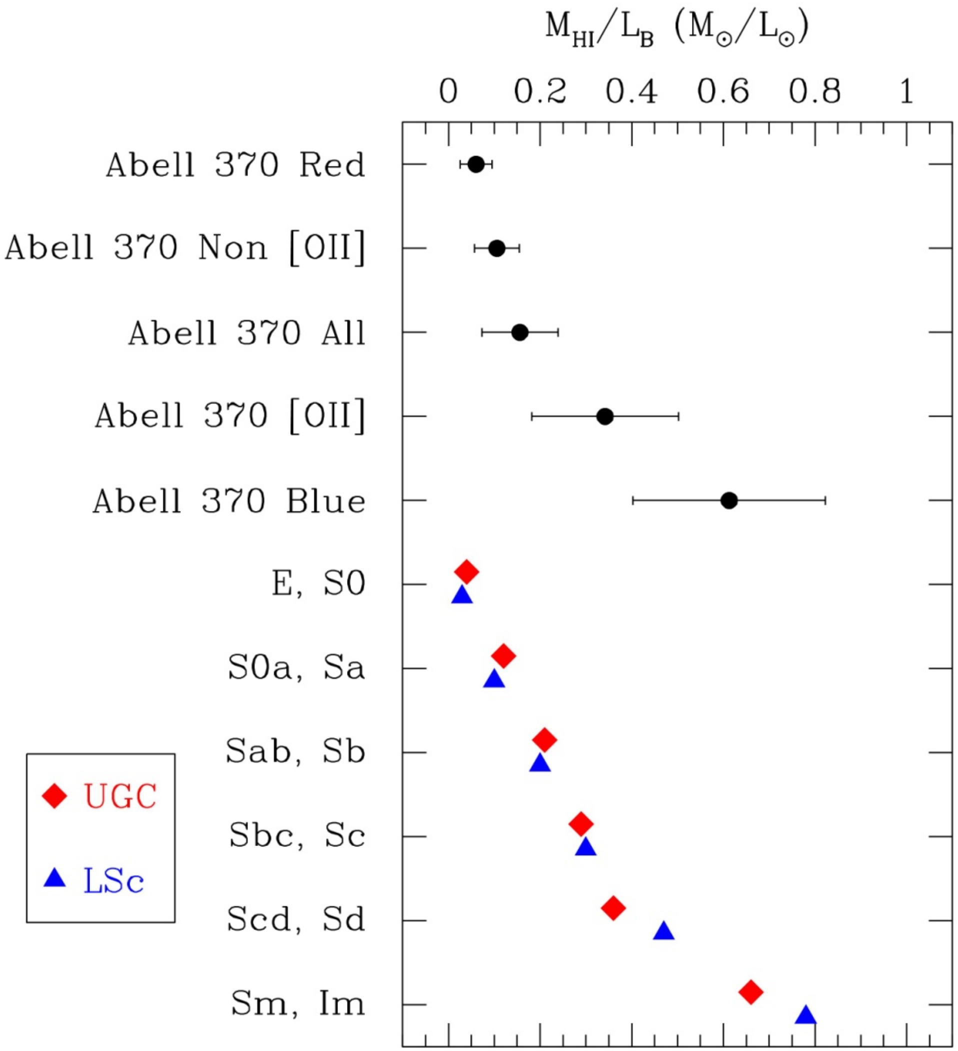
$M_{HI} = (6.6 \pm 3.5) \times 10^9 M_\odot$





Lah et al., MNRAS, 399, 1447, (2009)

HI mass to luminosity ratios



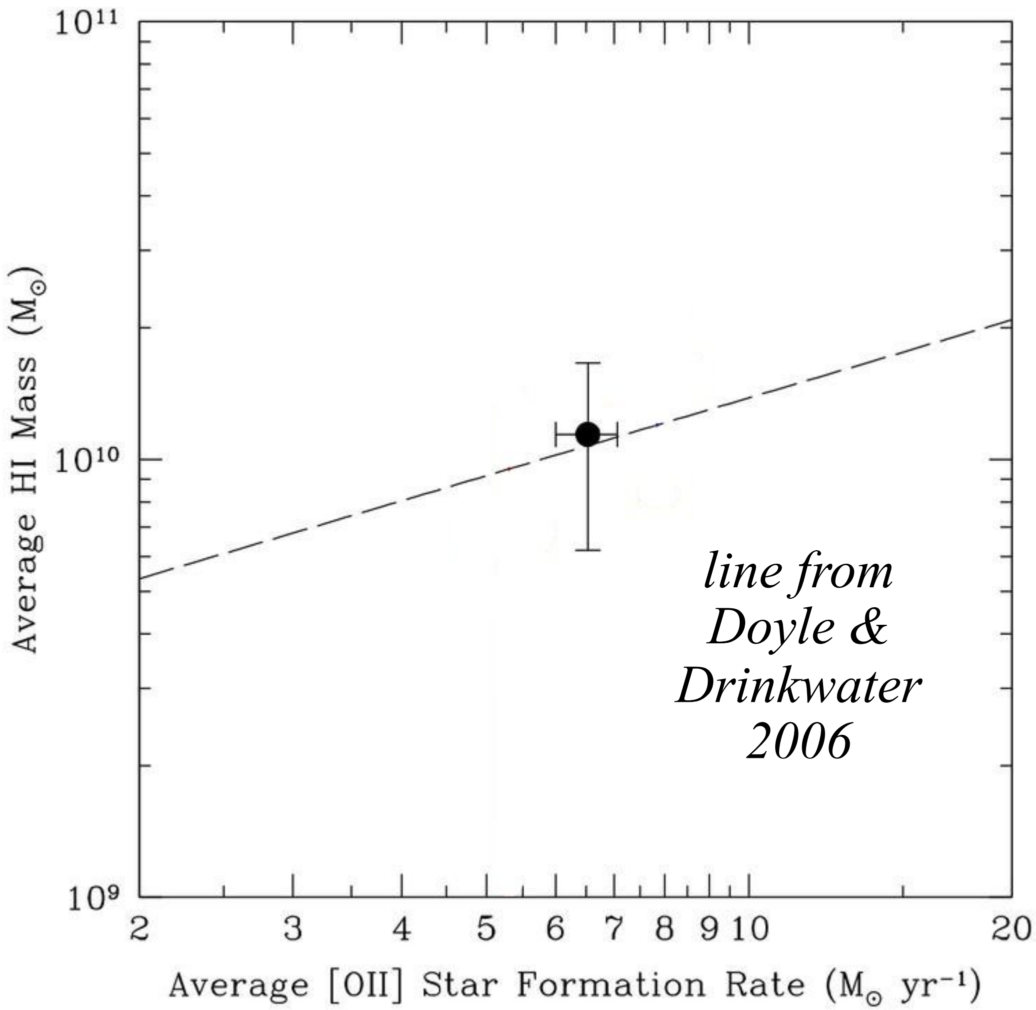
HI mass optical B band luminosity for Abell 370 galaxies

Uppsala General Catalog

Local Super Cluster

(Roberts & Haynes 1994)

HI Mass vs Star Formation Rate in Abell 370



Results for A370

- Galaxies in A370 are much more gas rich than those in Coma
  - Rapid evolution of galaxies in clusters

- A370 shows similar trends as for nearby clusters, e.g.
  - decrease in HI mass for central galaxies
  - Correlation of SFR with total HI content
  - Calibration between O[II] derived SFR and radio continuum derived SFR is the same as in the local universe

- At the observed SFR, A370 will evolve into a gas poor cluster like Coma by z ~ 0

Using Radio Observations to understand high redshift DLAs

HI 21 cm absorption

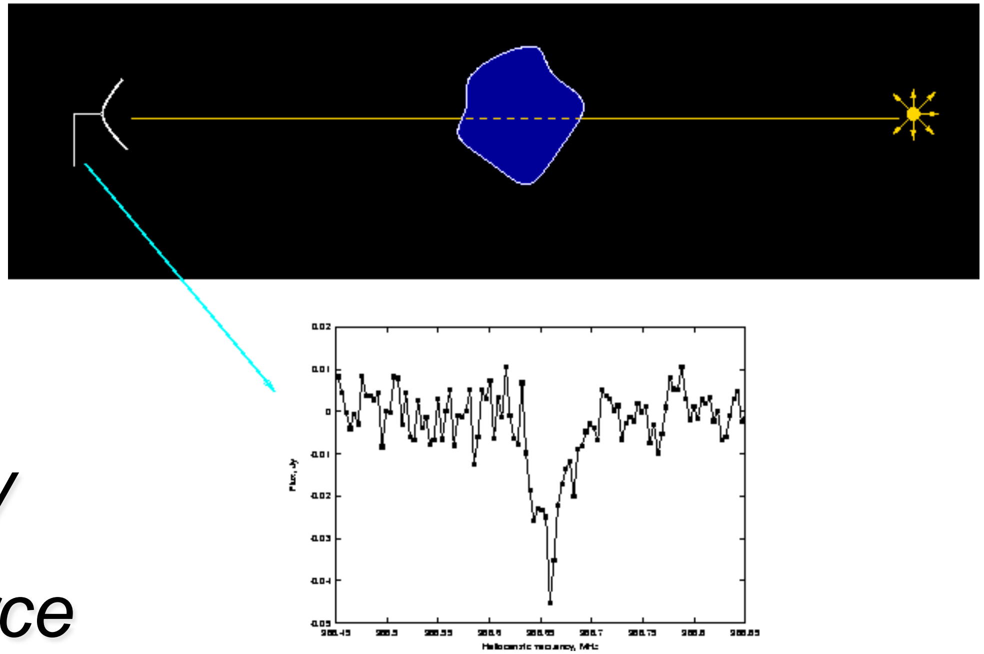
$N_{HI} = 1.8\times10^{18}\ T_s \int \tau(v)dv$

For an HI gas cloud with:

$N_{HI} \sim 2\times10^{20}$ *atoms/cm*^{2}

$T_s \sim 80$ *K*

$\Delta V \sim 20$ *km/s*



➡ *peak line depth ~ 7 mJy*

against a 100 mJy source

Radio Observations of DLAs

$$N_{HI} = 1.8\times10^{18}\ T_s/f \int\tau(v)dv$$

Optical (→ N_{HI}) ***Radio*** (→ $\int\tau(v)dv$)

- Given NHI and $\tau(v)$ Ts can be determined
  - Radio emission is generally more extended than the optical emission ➔ need to know the covering factor f
  - Need to assume that the N_{HI} measured towards the optical QSO applies across the absorbing cloud

- Best suited for observations against compact, core dominated sources

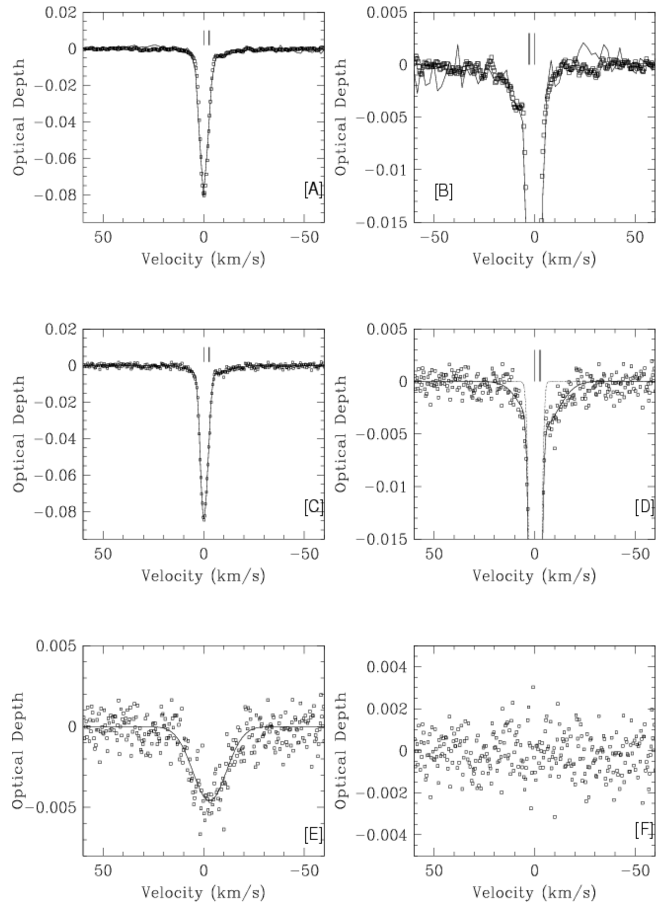
T_s in a Two Phase Medium

- HI in the Galaxy is often modeled as a two phase medium in rough pressure equilibrium
  - CNM (n ~ 1-10 cm^{-3}, T_k ~ 80 K), $T_s \sim T_k$
  - WNM (n ~ 0.1 cm^{-3}, T_k ~ 8000 K), $T_s \leq T_k$ (depending on Lyα flux)
- The observed T_s in a two phase medium is the column density weighted harmonic mean of the T_s in each phase
  - 50% CNM and 50% WNM ➔ Ts ~ 160 K (typical for the MW)
  - 10% CNM and 90% WNM ➔ Ts ~ 735 K
- T_s measurement hence gives information on the distribution of gas in the CNM and WNM phase

Two Phase Medium in a DLA

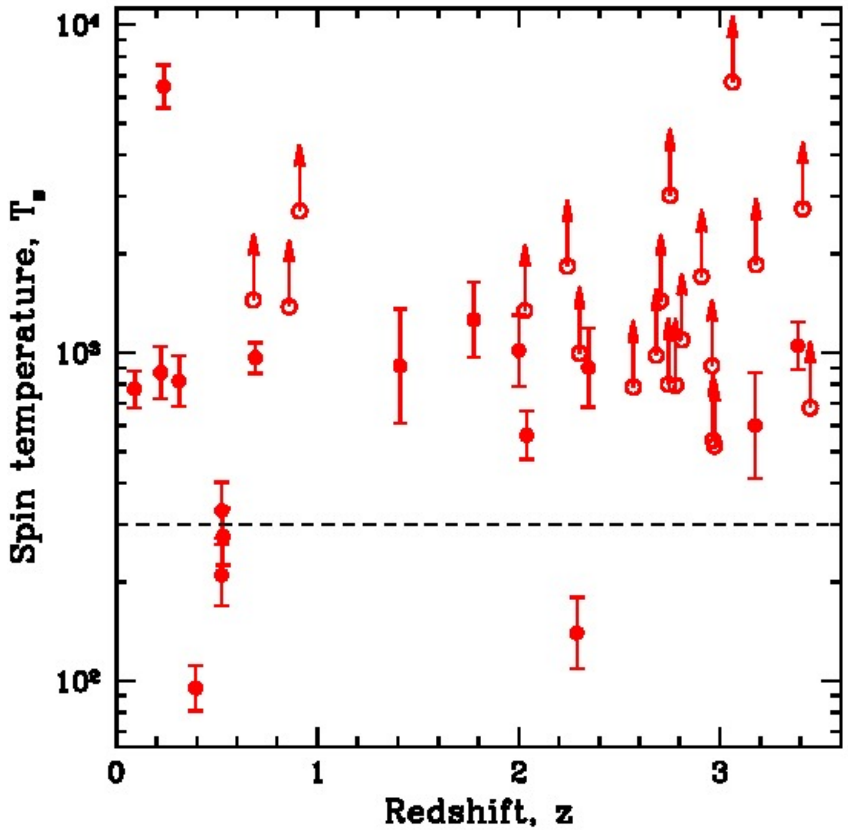
- The DLA at z ~ 0.22 towards B0738+313 shows two absorption components
  - *One narrow and deep*
  - *The other wide and shallow*
- These can be modeled as arising in the CNM and WNM respectively
  - *WNM fraction larger than typical for the Milkyway*
- The total column density predicted by the model matches that measured using Lyα absorption

Kanekar et al. A&A373,394 (2001)



Spin Temperature in DLAs

- T_s in DLAS generally higher than that in our own galaxy
- Low values of T_s seen only in those DLAs identified as large spirals
- Most of the gas in high z DLAs is in the WNM

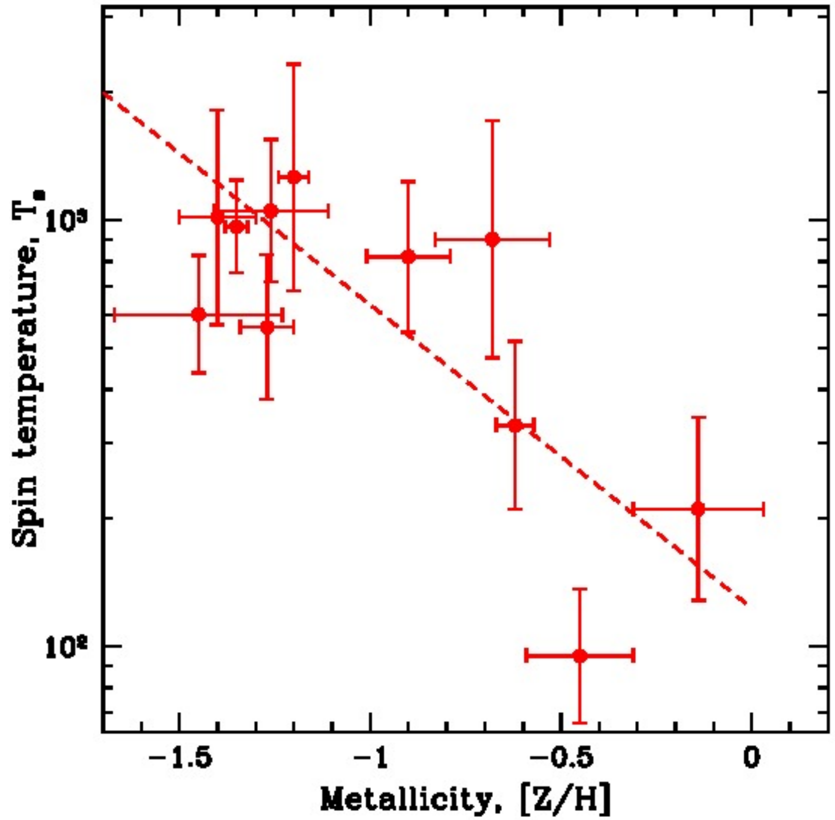


In contradiction to models of star formation in DLAs which predict that most of the gas is in the CNM (Wolfe et al. ApJ 235, 593 2003)

Are DLA hosts small galaxies?

- Small galaxies have low Z and low central pressures
- Both of these work against forming the CNM
- Observations of local dwarfs indicate that their WNM fraction is larger than typical in the Milkyway

Kanekar et al. ApJL,75,40,(2009)



Trying to measure the HI mass of very low z absorbers

- $z = 0.00632$, $N_{HI} \sim 2\times10^{19}$ (Trip et al. ApJ 619 714 2005)
- Gas has low metalicity [O/H] ~ -1.60
  - Typical of high redshift systems
- No bright galaxies nearby
  - Closest L_* galaxy is 246 kpc away in projection
  - Unlikely to be tidal debris

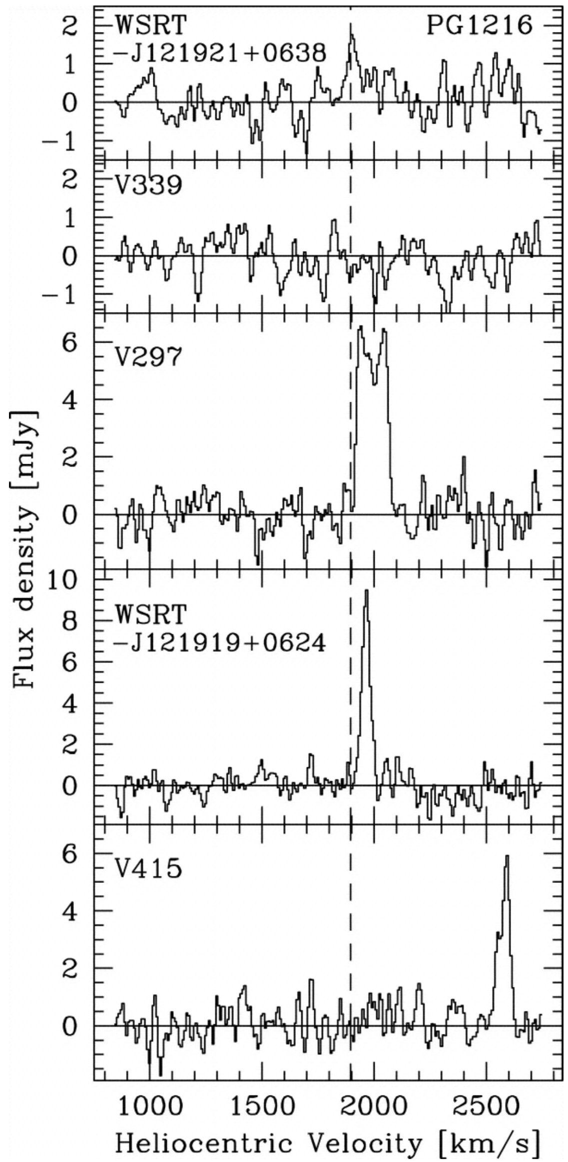
Searches for HI Emission

- No emission detected at GMRT (Kanekar & Chengalur A&A 429 L21 2005)

  M ≤ 10^7 Msun (40” resolution and 20 km/s

- Weak emission feature seen at WSRT (Briggs & Barnes ApJ 640, L127,2006)

  MHI ~ 5 -15 x 10^6



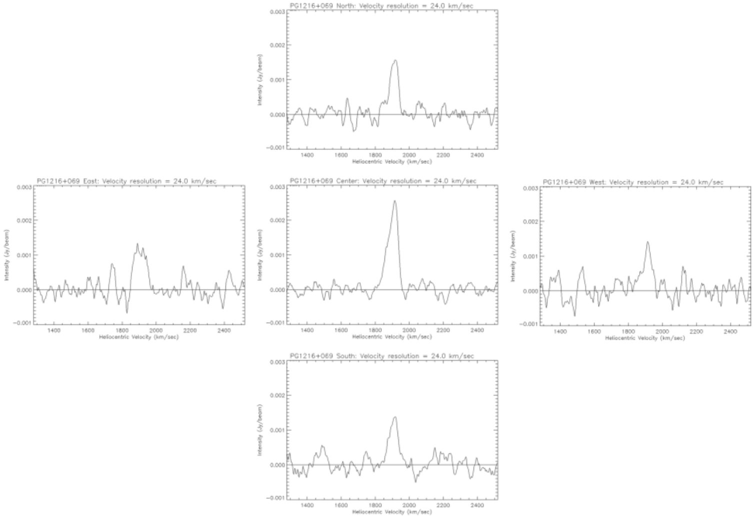
PG1216:Arecibo Observations

$M_{HI} \sim 3x10^7\ M_{sun}$

5 kpc < D < 15 kpc

Lowest mass absorber associated with damped absorption

HI mass ~ 1/100 that of the Milkyway



Ghosh et al., AAS, 208, 1503, (2006)

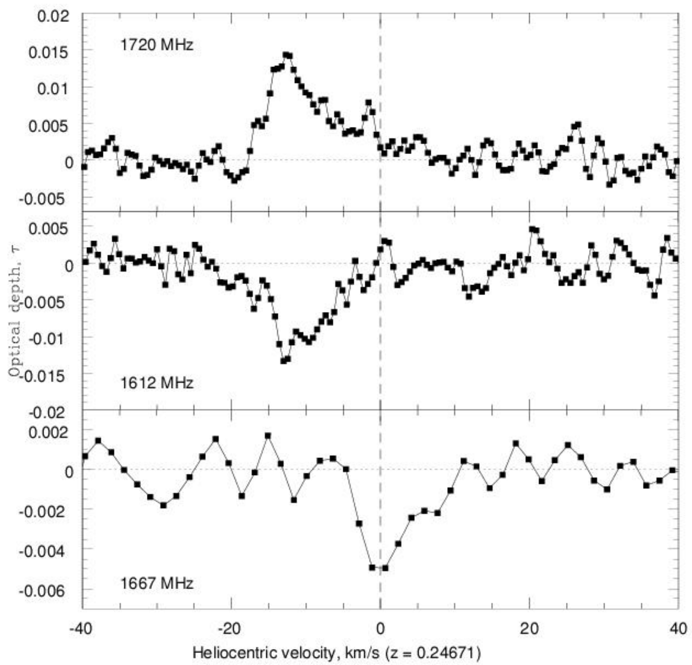

Thank you

Satellite lines in PKS1413+135

- Line profiles are exactly conjugate!
  - » because of competition between two decay routes to the ground state

- doppler shifts between the 1612 and 1720 lines can be ruled out

- If g_p, μ constant then $\Delta\alpha/\alpha$ = (0.6 ± 1)x10^{-5} between z=0.247 and now



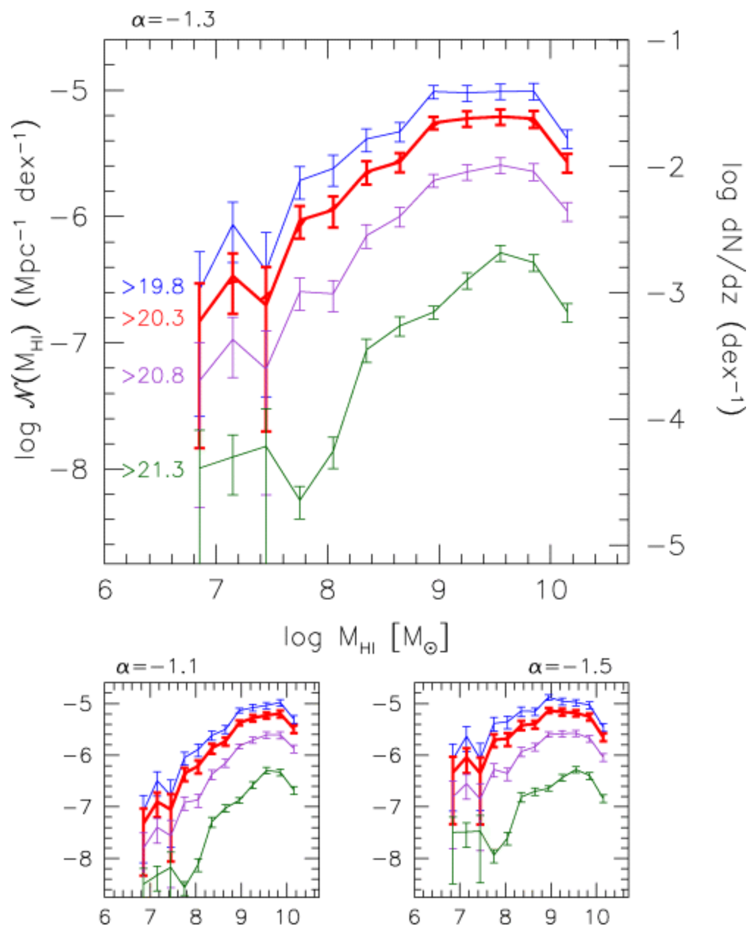
Kanekar, Chengalur & Ghosh PRL 93, 051302, (2004)

Low redshift DLA counterparts

- M_{HI}^* galaxies make the biggest contribution to the DLA cross-section

- BUT the distribution across M_{HI} is relatively broad
  - 68% of DLAs lie in $8.5 < \log(M_{HI}) < 9.8$

Zwaan et al. astro-ph/0510127



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