# Low to Intermediate redshift HI Stacking Studies

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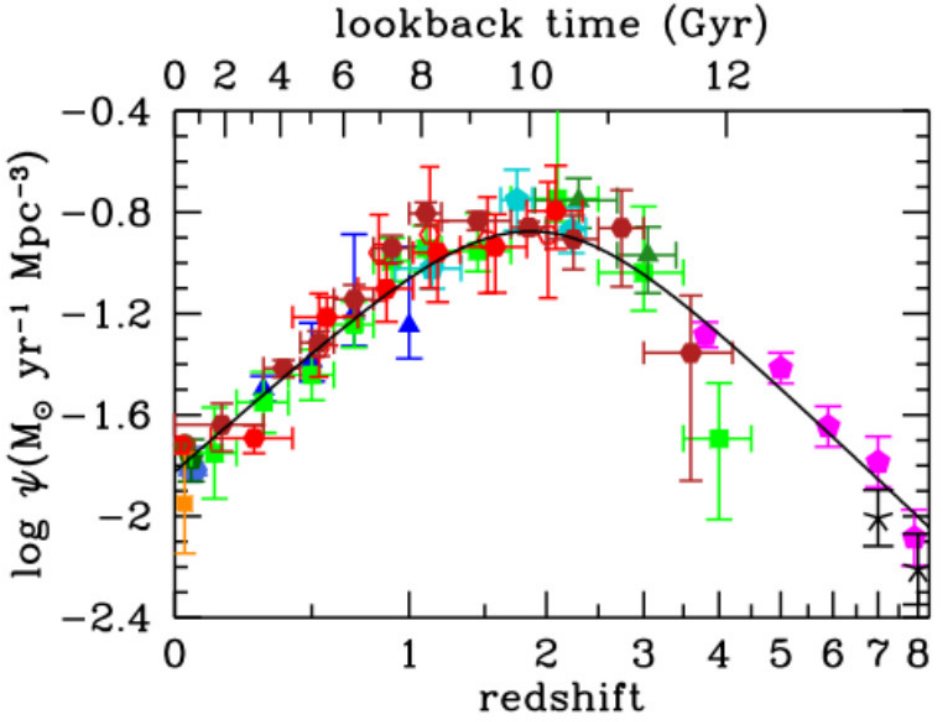
# Observing HI in high redshift star forming galaxies





The time required to make a 3σ detection of the HI emission of an $M_{HI}^{*}$ galaxy at z ~ 1 with the GMRT is

$$\tau = 10000\,hr\left(\frac{T_{sys}/70\,K}{(N/30)(G/0.25\,K/Jy)}\right)^{2}\left(\frac{200\,km/s}{\Delta V}\right)$$

Clearly a much larger sensitivity is needed ***i.e. the SKA***

# What can one do “now”?

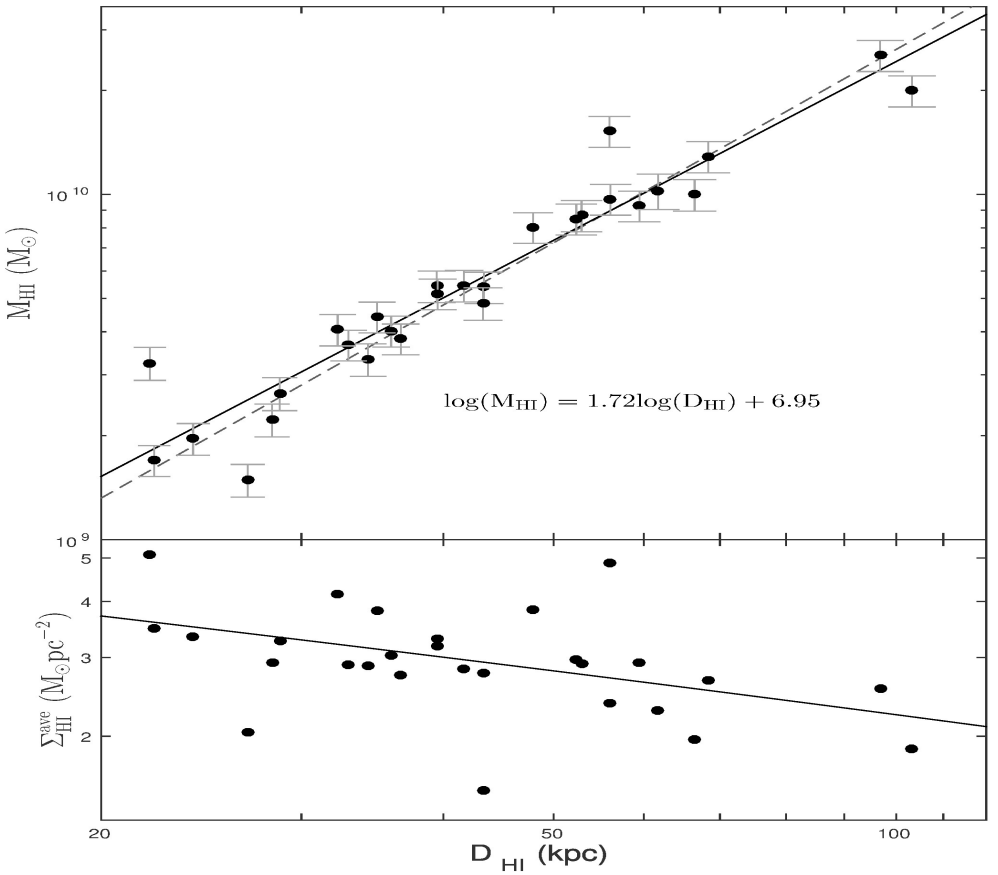
- The volume of space observed in a single setting ~ (FoV x Bandwidth) would contain 100s of bright galaxies

- One could try to detect the average HI emission of all of these galaxies by aligning the spectra and adding (“stacking”)
  - Chengalur, Braun Wieringa A&A 372, 768, 2001, Martin Zwaan Ph.D. Thesis 2000

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

# SNR increase with stack size

- Naively if one co-adds the HI emission signal from N galaxies, the SNR should improve by $N^{½}$
- BUT
  - Sensitvity varies across the field of view of the telescope
  - Variation in  velocity widths results in varying snr per channel
  - Unknown HI extent of each galaxy also leads to non optimal SNR.
  - Redshift measurement errors lead to errors in aligning HI spectra

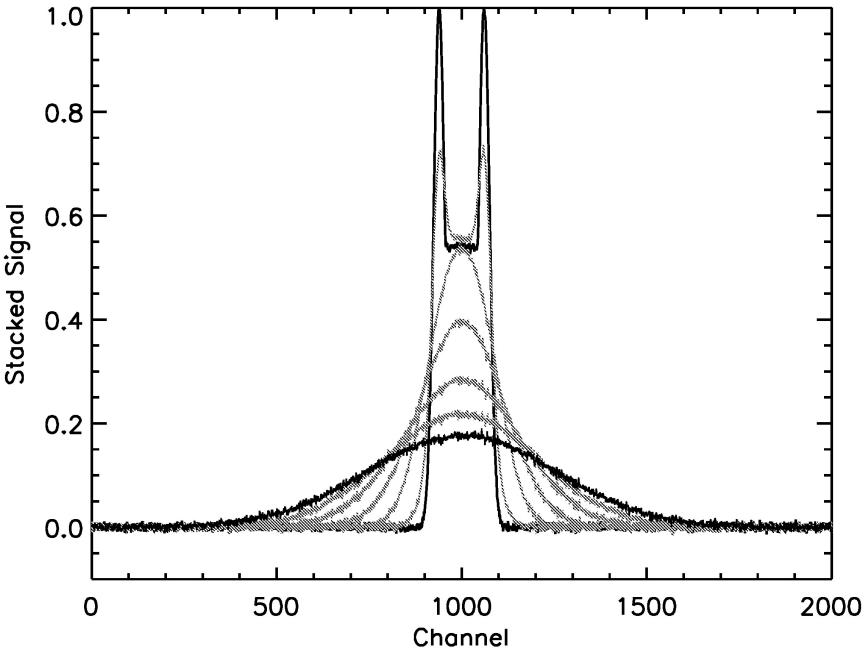


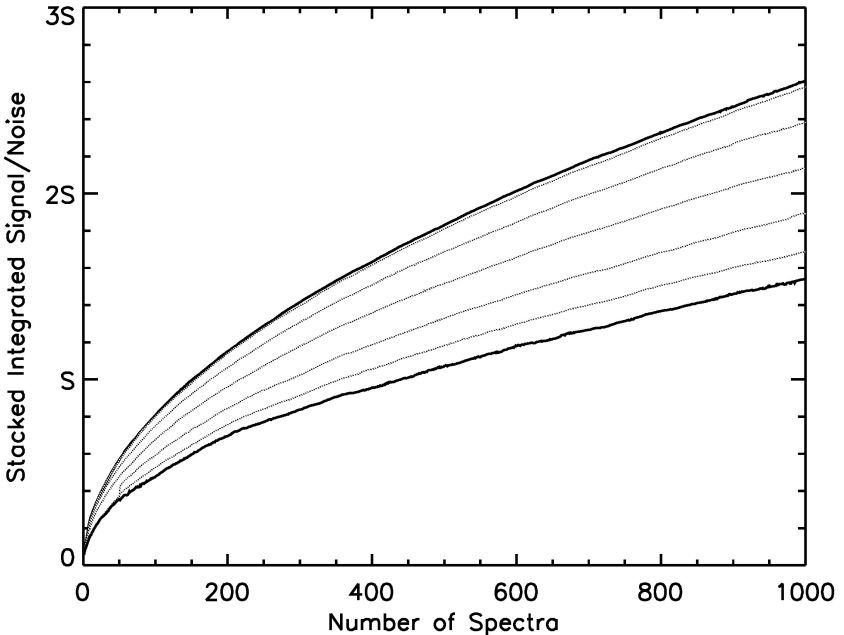

Martinsson et al.  A&A 585, 99 (2016)

Maddox et al. MNRAS 433, 2613 (2013)

# Effect of redshift errors

- Comparison of HI and SDSS redshifts show that negligible systematic offsets
  - Velocity erors lead to a broadening of the stacked profile
    - Since the noise in different channels is independent this leads to a loss in snr
    - Loss can be significant at rms errors of ~ 100 km/s
  - Increasing velocity error does not bias the avegage integrated flux



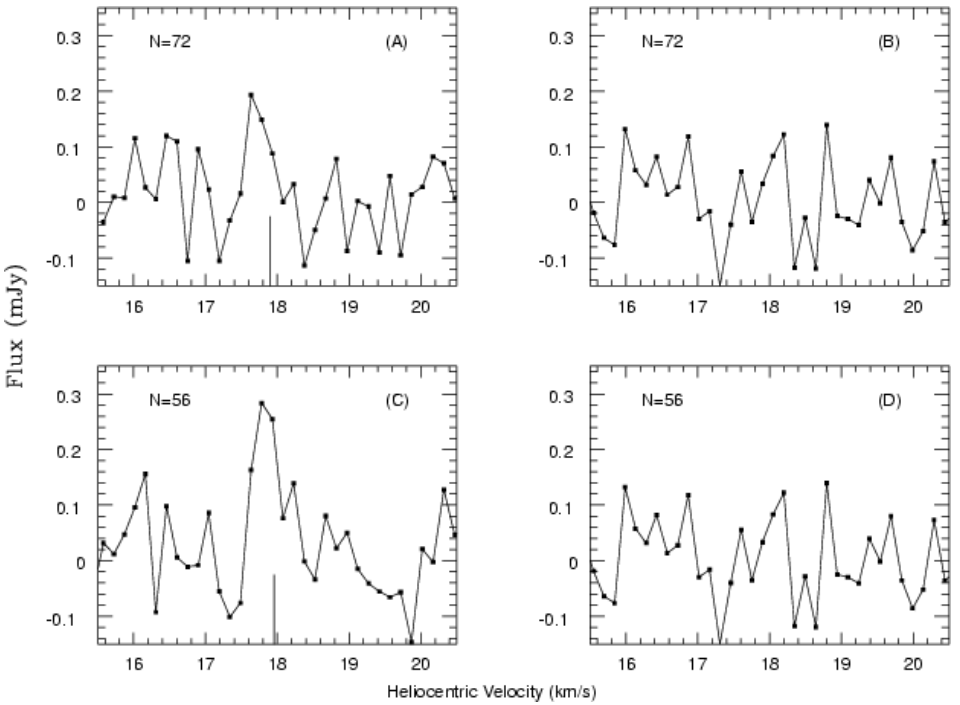
*Chengalur et al. A&A 372, 768 (2001)*

# Proof of Concept: A3128

- A 3128 is a z ~ 0.06, richness class 3, Bautz-Morgan type I-II cluster
- Shallow ATCA observation made of the cluster region
  - Redshifts were available for 193 galaxies, of which 148 lay inside the ATCA cube
- Co-added emission detected from cluster galaxies.
- Signal detected from late type galaxies that lie outside the cluster core

All late types

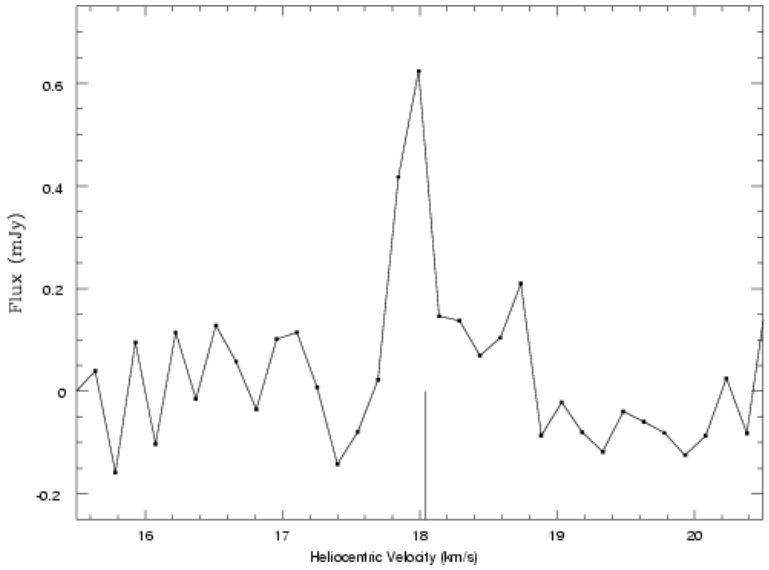
Control Sample



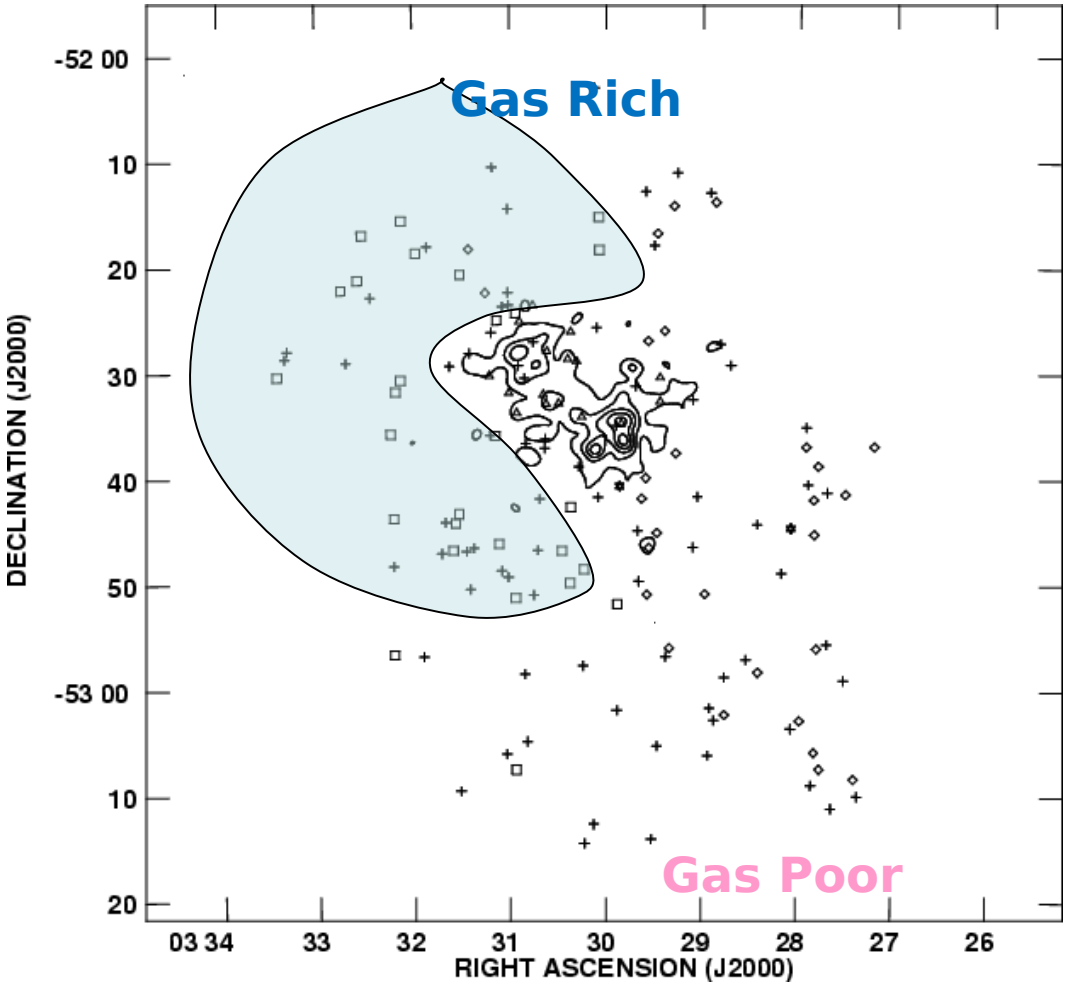

Late types outside X-ray contours

*Chengalur et al. A&A 372, 768 (2001)*

# Gas rich galaxies in AbeII 3128




Co-added spectra of the most gas rich group



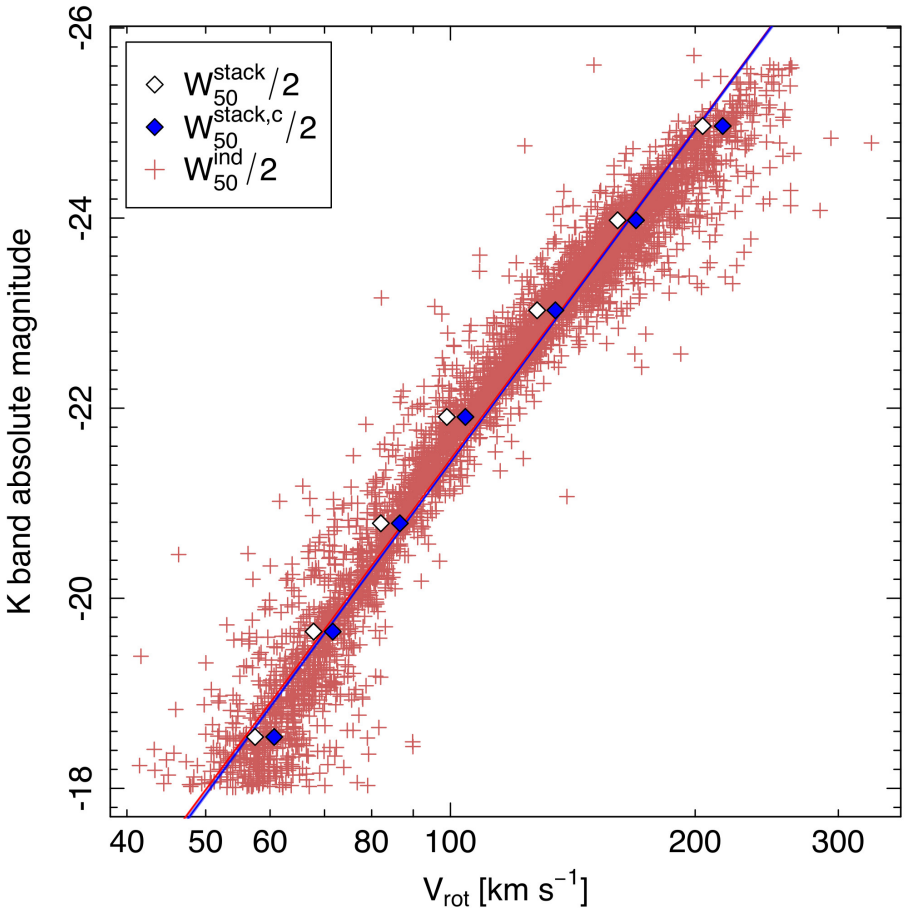
*Meyer et al. MNRAS 445, 3136, (2016)*

# Tully-Fisher measurements from stacked profiles

- The stacked profile also can be used to measure the TF relation
  - Assuming that the stack is done without redshift errors
  - i.e. does not need information on the individual galaxies inclination etc.

- Stack the observed HI lines from galaxies with the same absolute magnitude
  - Stacked profile width tracks the deprojected and dedispered input profiles

- Ratio of the width of the stack to that of the deprojected/dedispered input lines ~ 0.93
  - Very little dependence on the galaxy mass, gas dispersion, galaxy morpholgy..



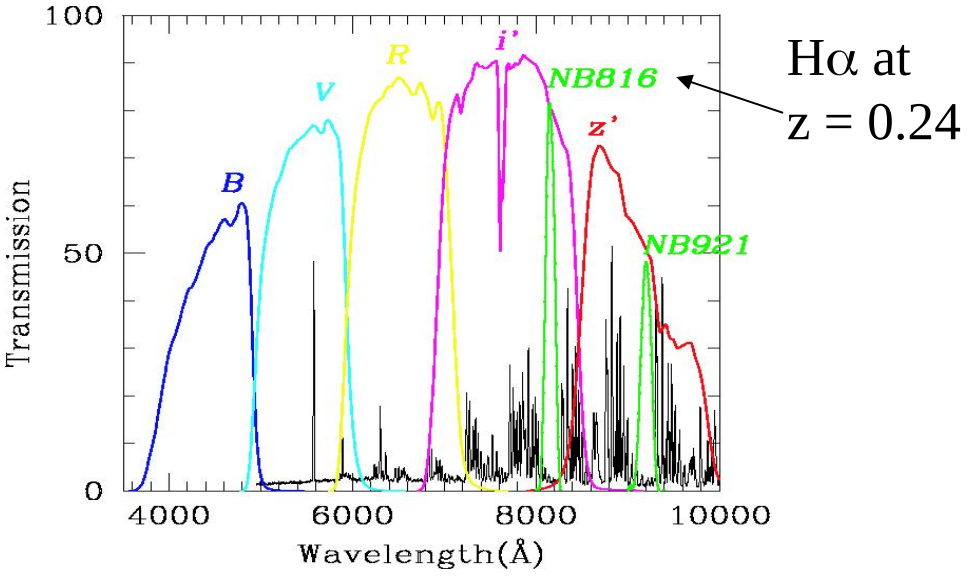
Lah et al. MNRAS 376,1357,2007

# Narrow band Hα selected galaxies

**24’ × 30’**

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

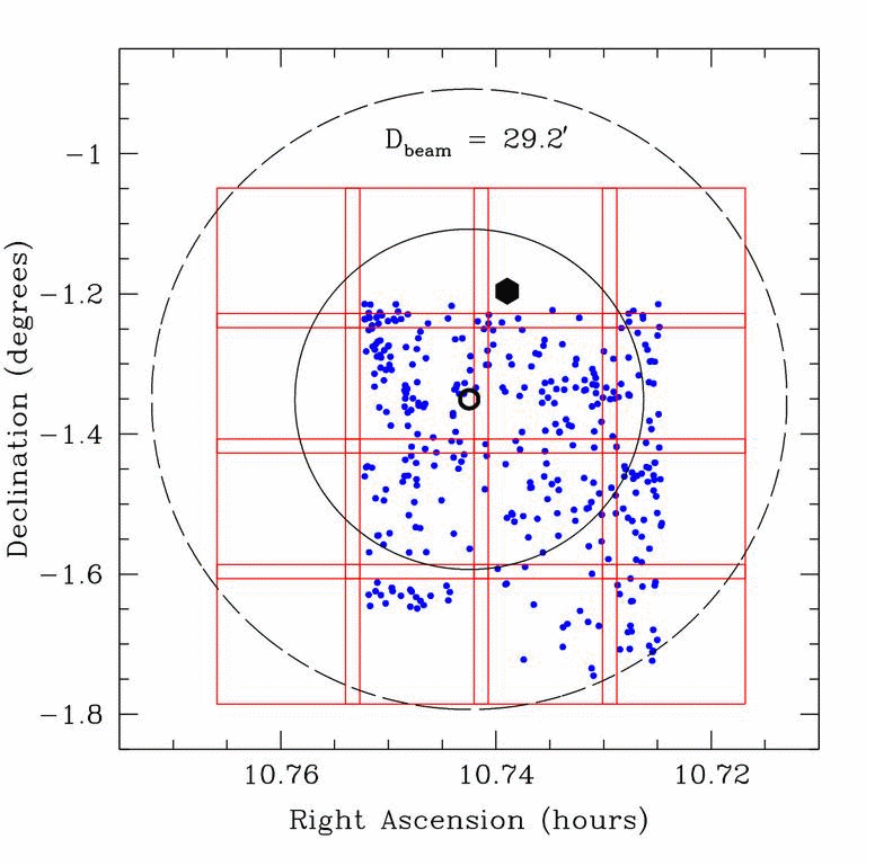
Total of 348 galaxies in the sample



Lah et al. MNRAS 376,1357,2007

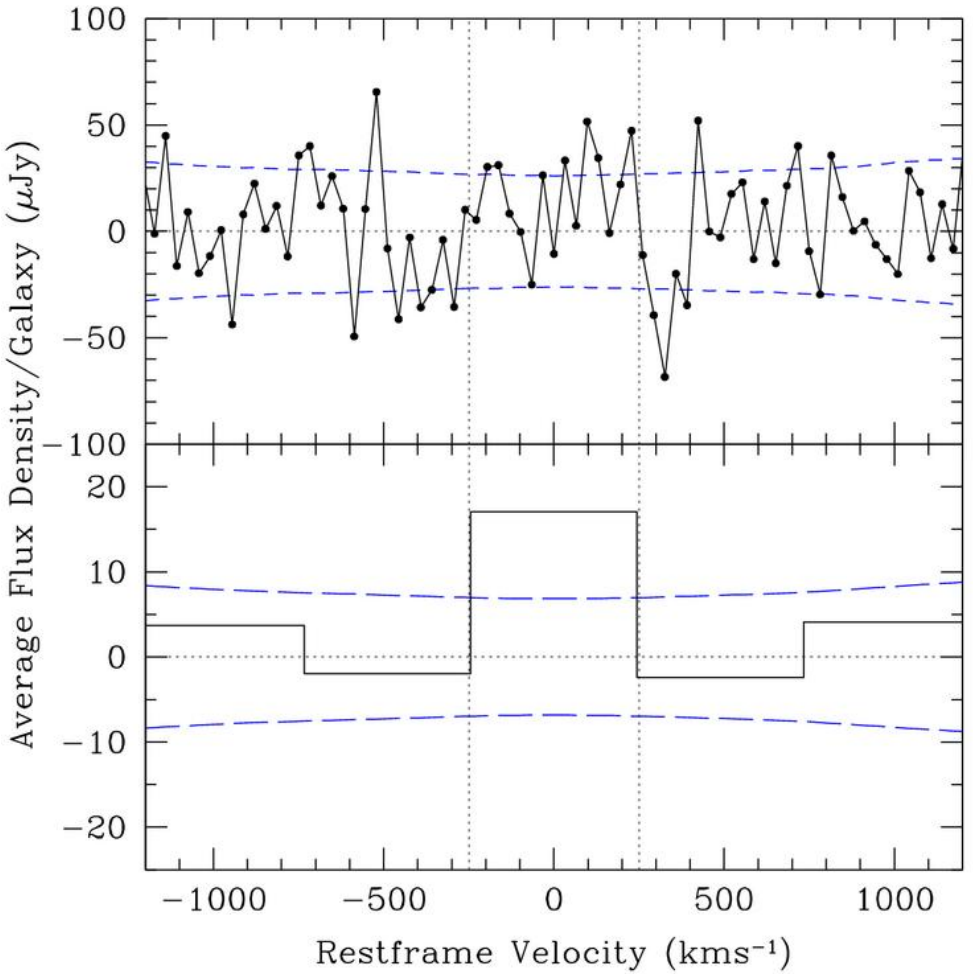
# GMRT Observations

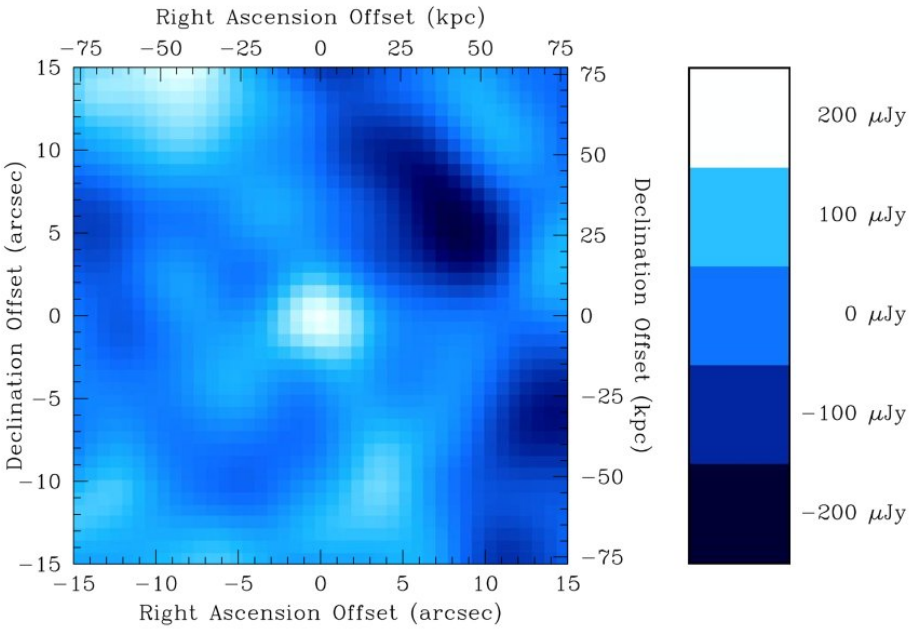
- 121 galaxies within the GMRT data cube
  - Total of ~ 40 hours of on source time
- Most of these galaxies are fainter than $L_*$ (i.e. low HI mass)
- Redshifts obtained using the 2dF instrument on the AAT
- Optical imaging with the ANU 40” telescope.
- Smoothing sized fixed using $D_{HI}$ -$D_{opt}$ relation from Broeils & Rhee (1997)



Lah et al. MNRAS 376,1357,2007

# Stacked HI signal at z ~ 0.2

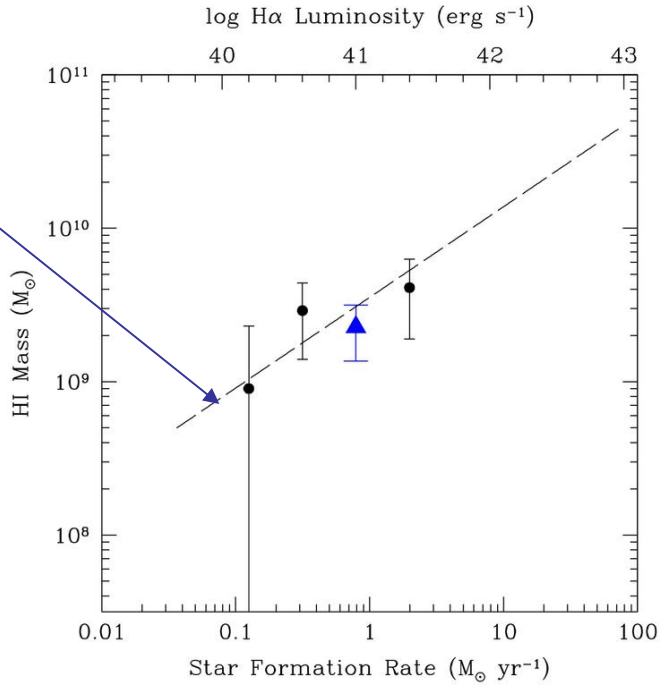



$M_{HI} = (6.3 \pm 0.9) \times 10^9\ M_\odot$

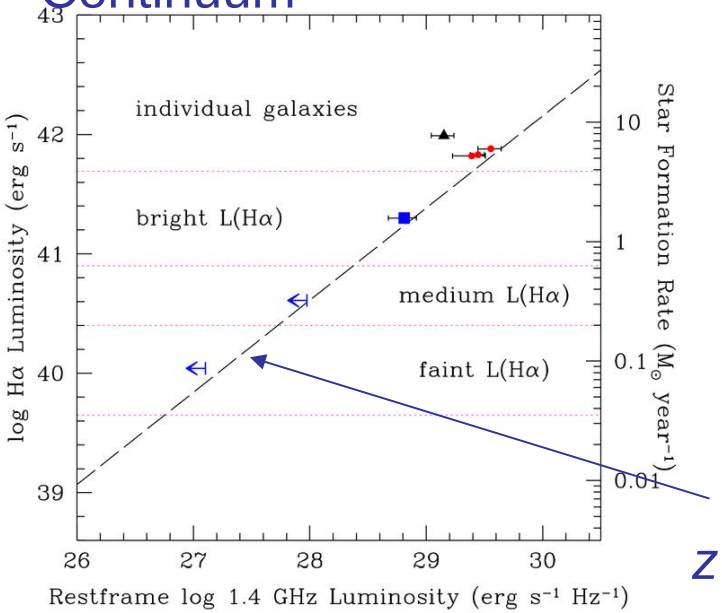
# Star Formation Rate at z = 0.2 shows same correlations as for z=0 galaxies

SFR vs $M_{HI}$




*z = 0 relation from Doyle & Drinkwater (2006)*

SFR vs Radio Continuum



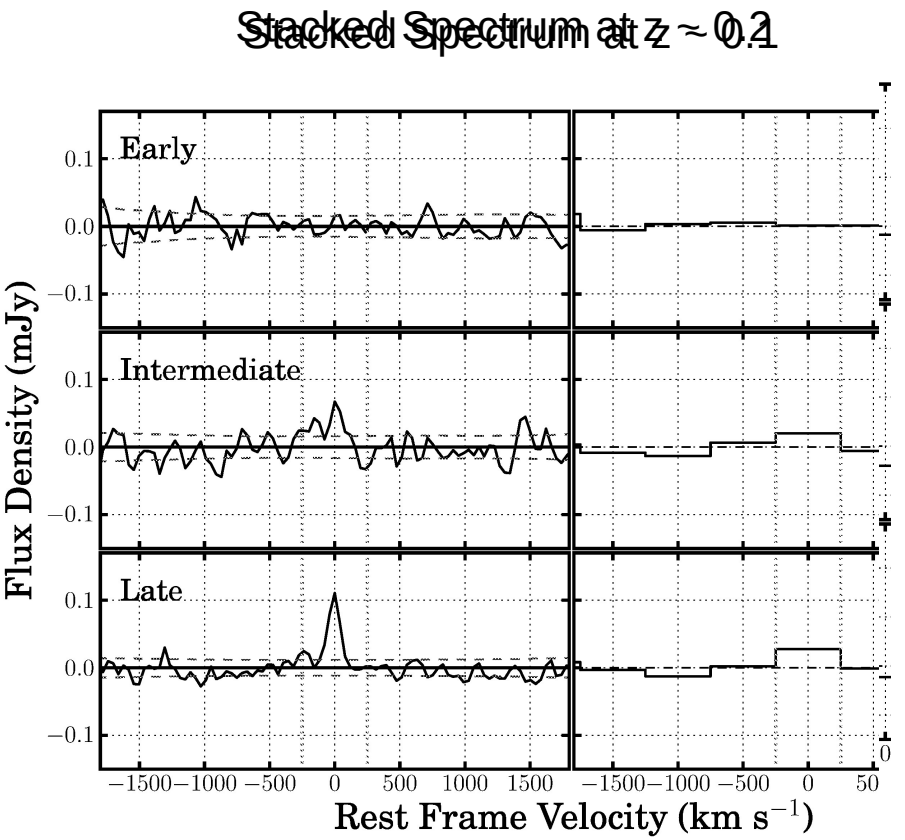

*z = 0 relation from Sullivan (2001)*

Lah et al. MNRAS 376,1357,2007

Rhee et al. MNRAS 435, 2693 (2013)

# HI in the CNOC2 fields

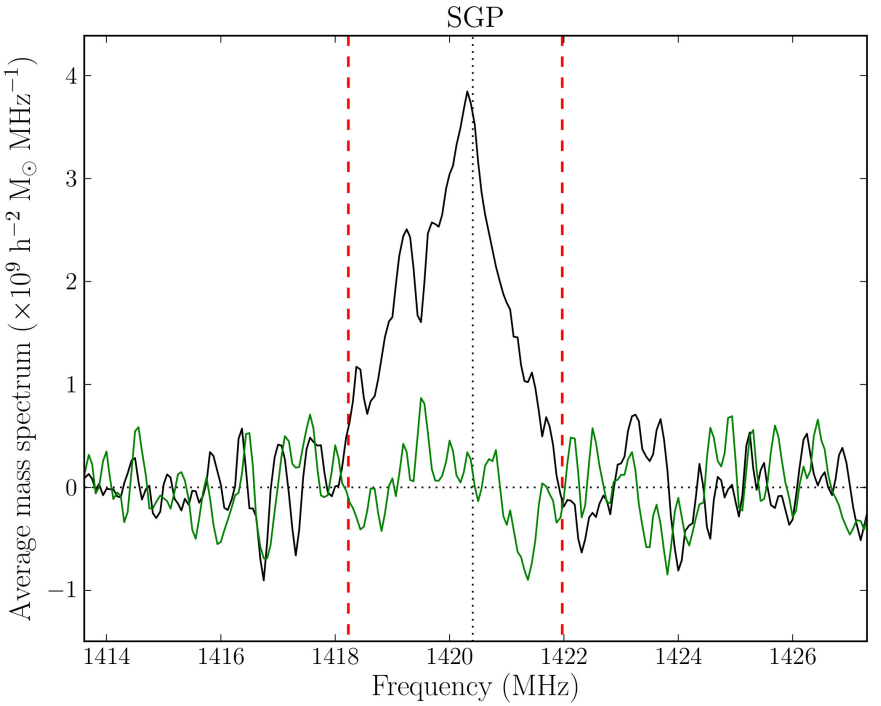
- Radio observations were made using the WSRT
  - Optical redshifts from the CNOC2 survey
- Correlator covered two subbands, one centered around z ~ 0.1 and the other z ~ 0.2
  - A total of 115 galaxies with known redshifts lay within the observation volume
- A total of ~ 105 hours of on source time
  - Stacked emission clearly detected at both z ~ 0.1 and z ~0.2
- $\Omega_{HI}(0.1) \sim (0.33 \pm 0.05)\times10^{-3}$ , $\Omega_{HI}(0.2) \sim (0.34 \pm 0.09)\times10^{-3}$
- No evidence for the evolution of $\Omega_{HI}$



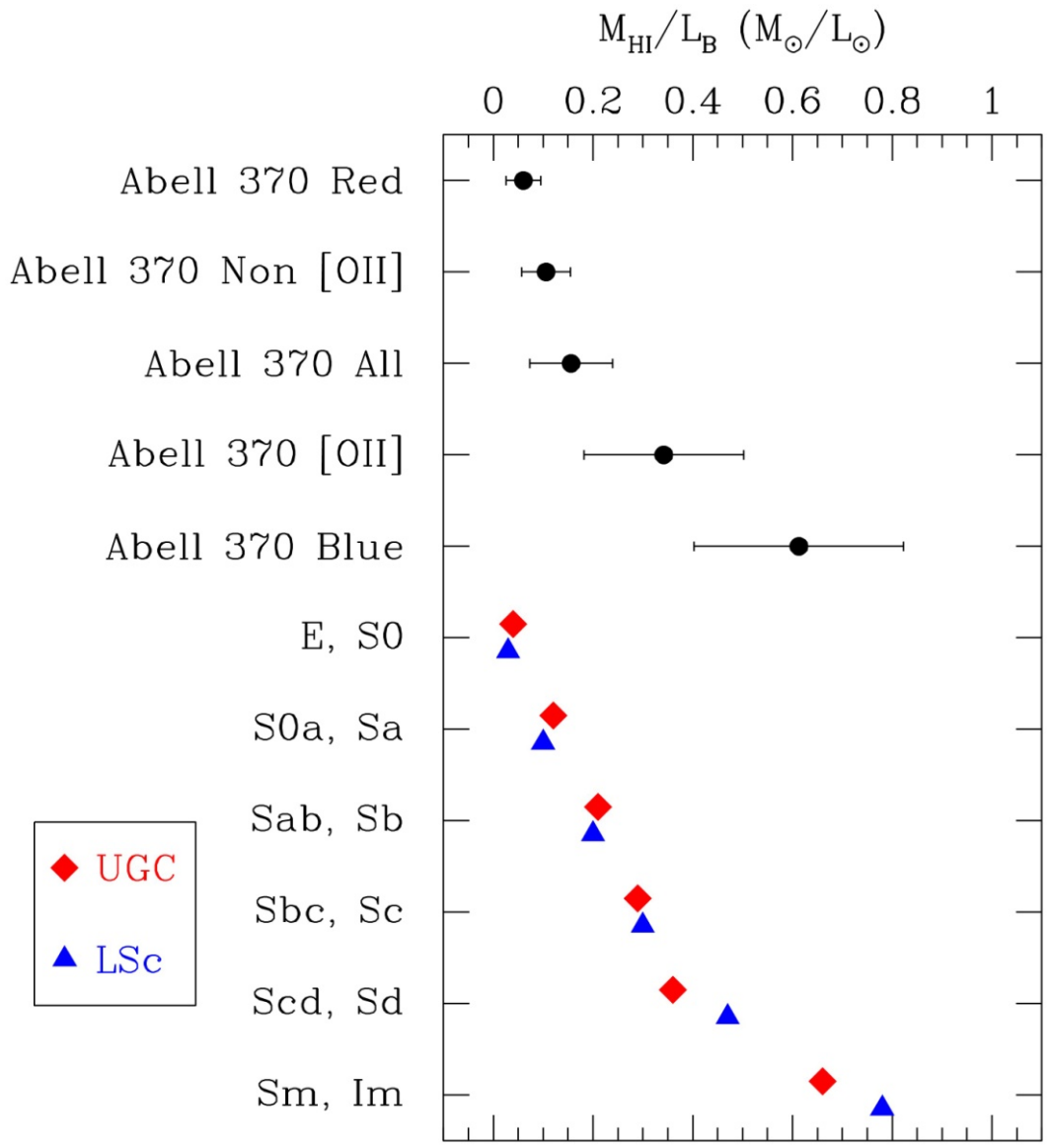
Delhaize et al.MNRAS 433, 1398 (2013)

# Stacks at z ~ 0.13 with the Parkes Telescope

- HI in galaxies with 0.04 < z < 0.13 studied using observations of 42 $deg^2$ field near the SGP
  - Optical positions and redshifs taken from the 2dFGRS
- Stacking ~ 12000 galaxies gives a ~ 12σ detection
- Given the large beam (~ 15') source confusion is siginficant
  - See also (Jones et al. MNRAS, 455, 1574, 2016; Elson et al. MNRAS, 460, 4366, 2016)
- After correction for source confusion, $\Omega_{HI} \sim 3.19^{+0.43}_{-0.59} \times 10^{-4}\ h^{-1}$
  - i.e. no evidence for evolution
  - Given the large sample size, trends in HI mass with Luminosity, color etc. could be measured



# HI mass to luminosity ratios in A 370 (z ~ 0.37)




HI mass to optical *B* band luminosity for Abell 370 galaxies

Uppsala General Catalog

Local Super Cluster

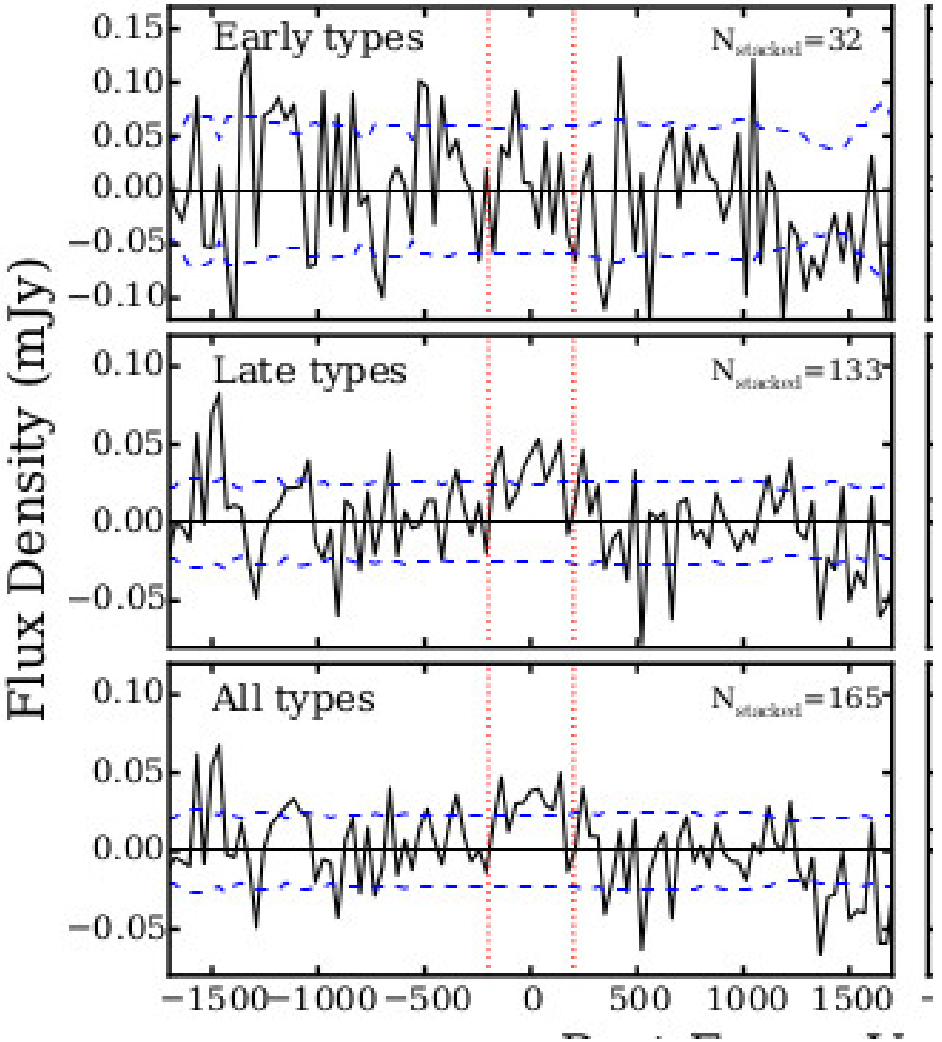
(Roberts & Haynes 1994)

Lah et al. MNRAS 399,1447,2009

Rhee et al. MNRAS (submitted)

# HI at z ~ 0.3 (VVDS field)

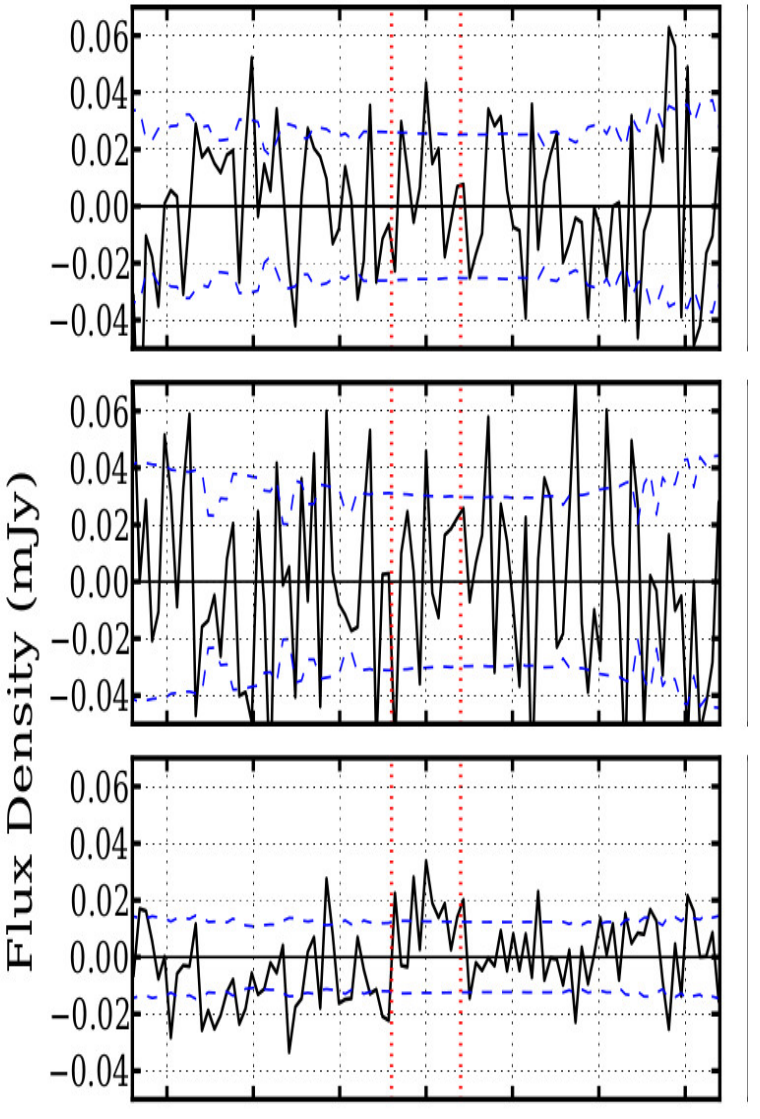
- VVDS field (z ~ 0.32), [Rhee (MNRAS, submitted)]
- 
- Radio observations made with the GMRT (old hardware correlator)
  - Optical data from the SDSS, as well as fresh AAO & MMT observations
  - Total of 165 galaxies that lie within the observed volume
- Data analyzed in AIPS/CASA after preprocessing through flagcal [Prasad & Chengalur Exp Astr, 33,157,2012].
- $\Omega_{HI}(0.3) \sim (0.5 \pm 0.18) \times 10^{-3}$



Rhee et al. MNRAS 460 2675 (2016)

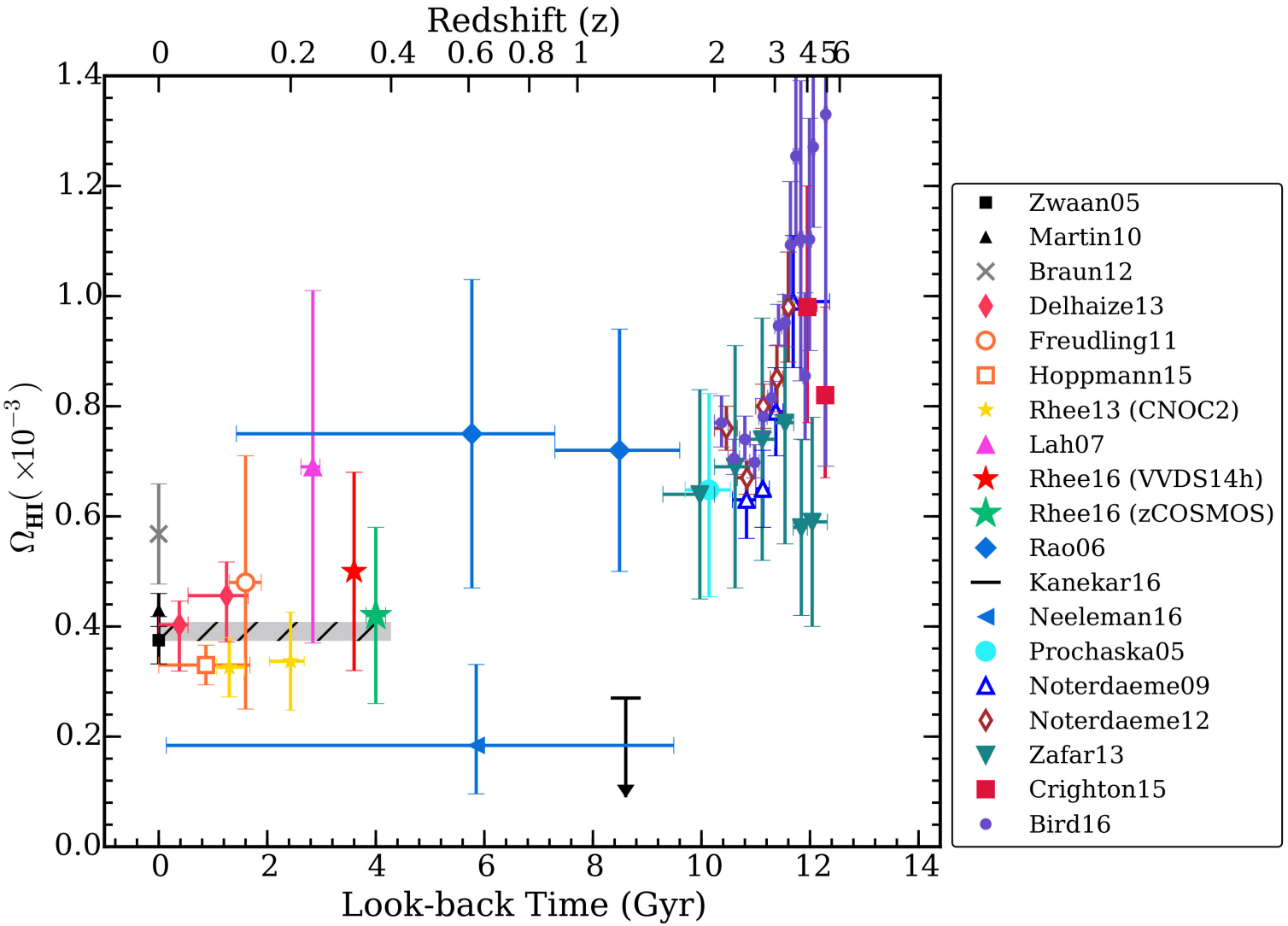
# HI at z ~ 0.4 (Cosmos field)

- Observations made with the GMRT (old hardware correlator)
  - Total observation time of ~ 135 hours
  - However significant fraction of data had to be flagged because of the low receiver dynamic range at that time
- Redshifts taken from the z COSMOS survey
  - Total of ~ 500 galaxies in the observed volume
- $\Omega_{HI}(0.4) \sim (0.42 \pm 0.16) \times 10^{-3}$



Rhee et al. MNRAS (submitted)

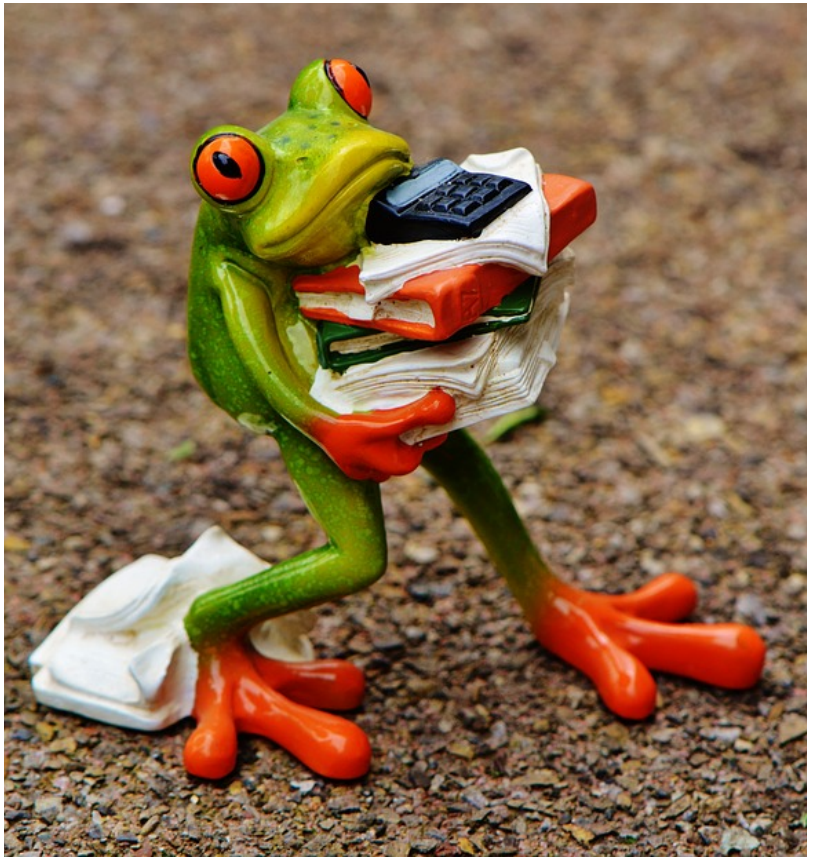
# $\Omega_{HI}$ in star forming galaxies



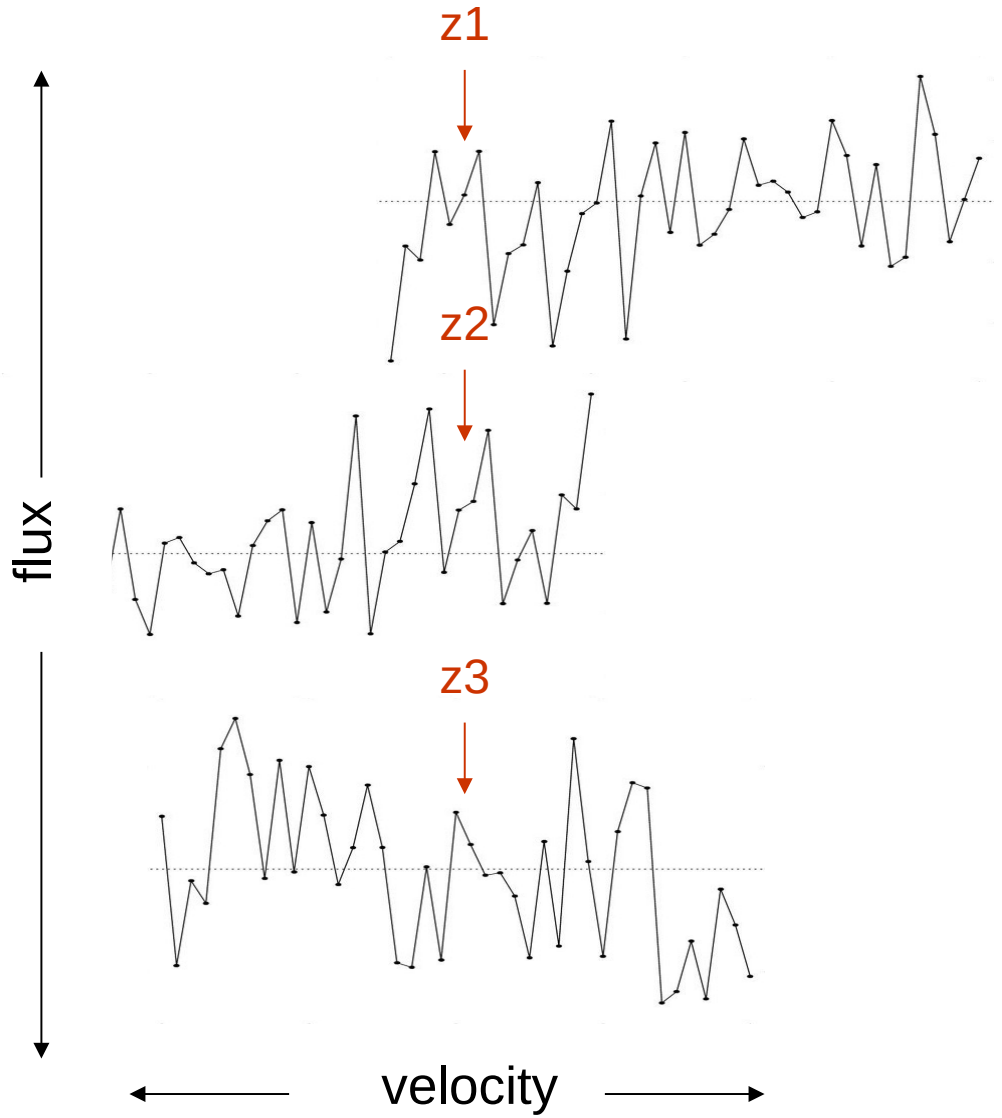

- No evidence for evolution of $\Omega_{HI}$ from z ~ 0 to z -0.4

# Summary

- HI stacking studies are a powerful way of studying the average HI content of galaxies
  - At redshifts where it is difficult to detect emission from single galaxies
- Given large enough sample sizes one can determine dependence of HI content on
  - Environment, luminosity, color, etc.
- Observations indicate no evolution in $\Omega_{HI}$



# Coadding HI signals




z1, z2 & z3
optical redshifts of
galaxies

Slide from P. Lah's thesis presentation

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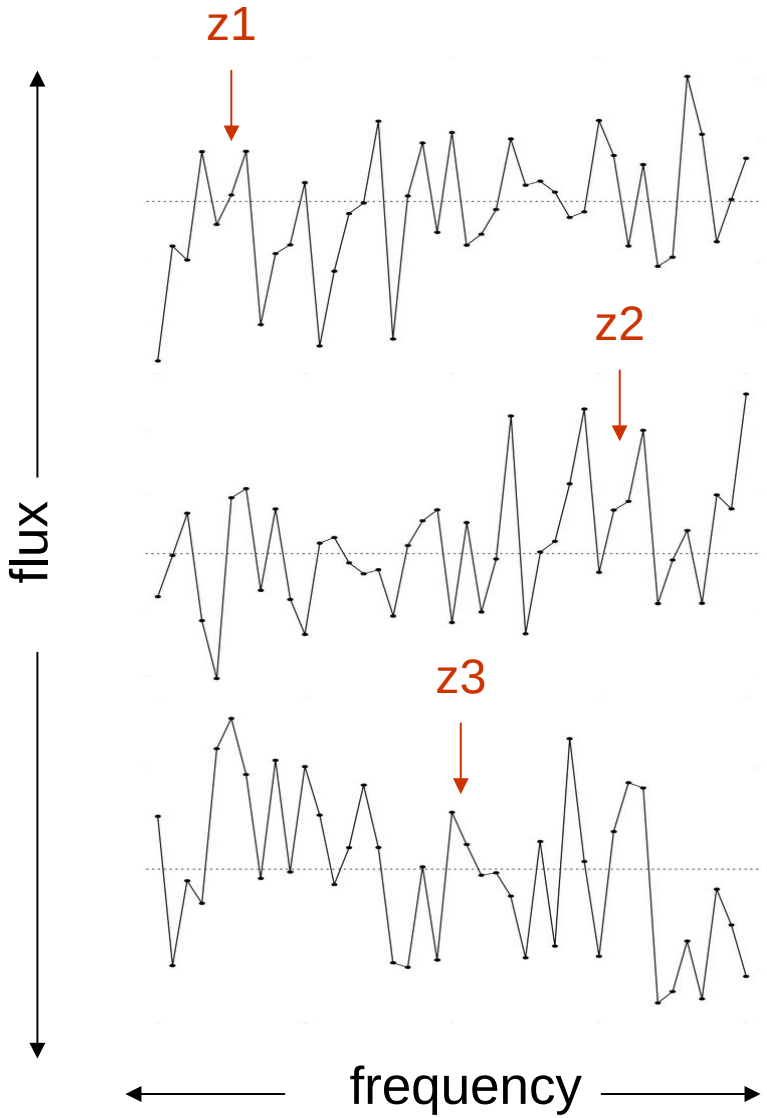


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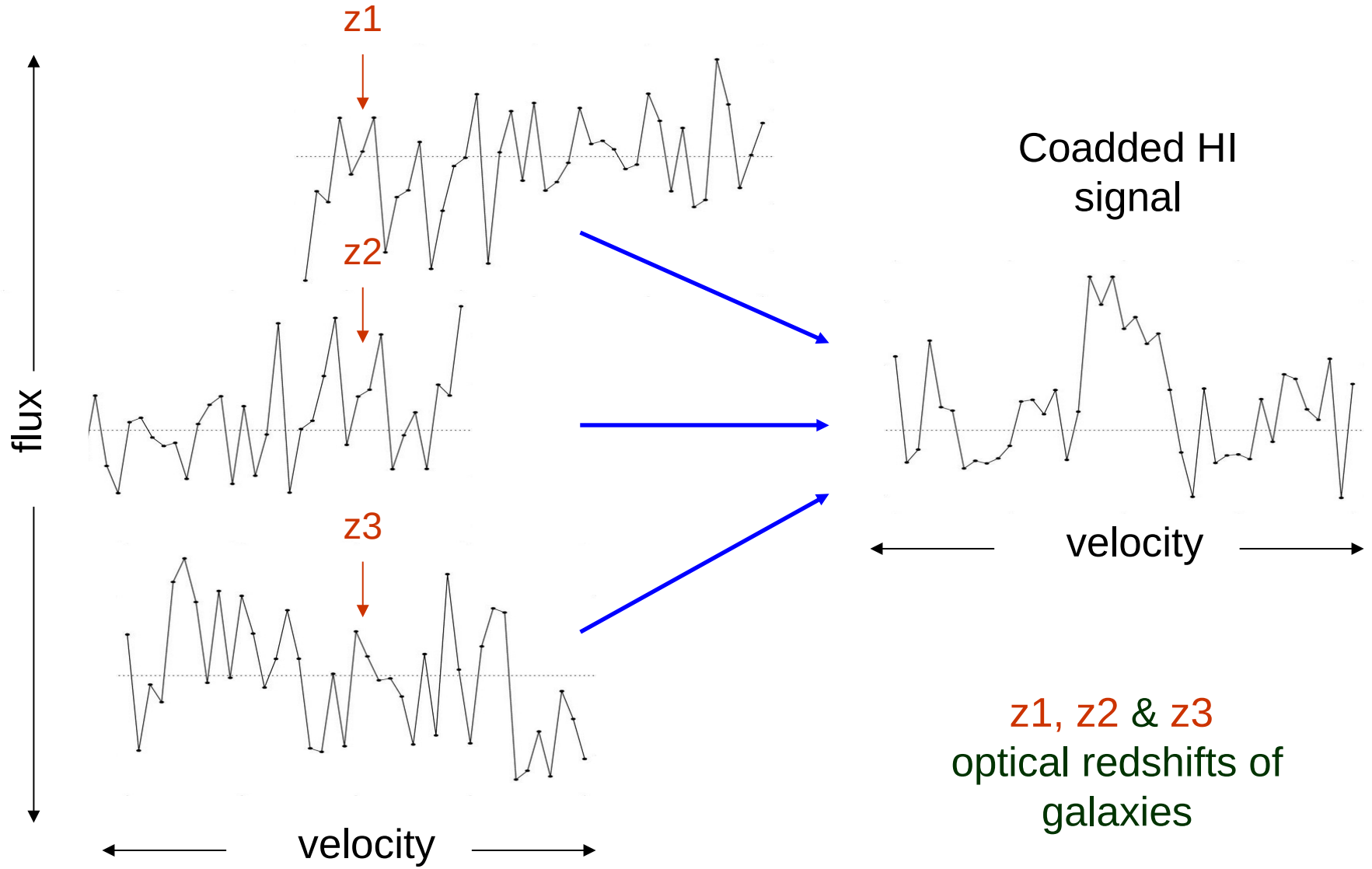


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