Looking for needles in the HI-stack

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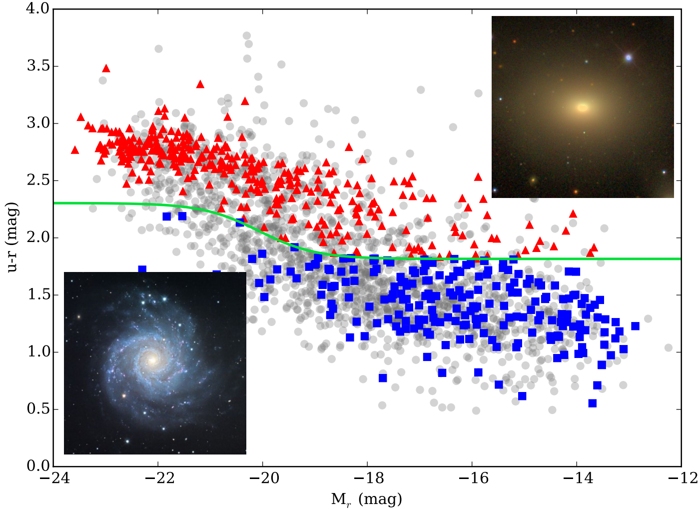
Current understanding of Galaxy Evolution

Colour bimodality: blue, mostly star-forming & old, red

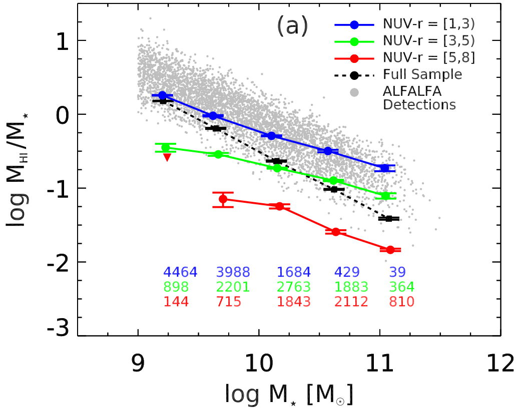


Baldry et al. (2004)

Probing the gas-richness of galaxies

Gas fractions ($f_{\mathrm{HI}} = \mathrm{M_{HI}}/\mathrm{M_\star}$) are useful to probe gas richness

- a volume-limited sample of ALFALFA galaxies
- Brown et al. (2015) explore what drives gas fraction relations
- gas fraction relations primarily driven by $NUV - r$, followed by $\mathrm{M_\star}$



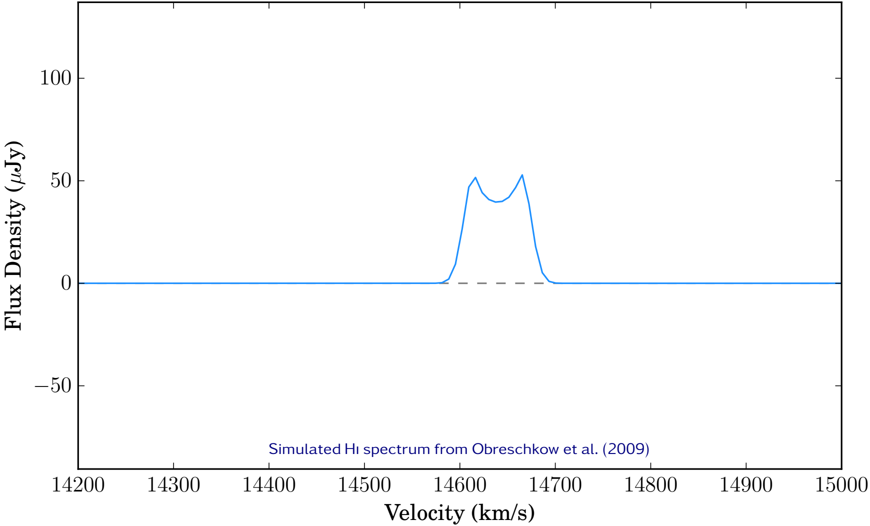
(Brown et al., 2015, Figure 5)

HI Studies

- Current challenges of HI studies:
  - limited by long integration times
  - deepest imaged HI at $z \sim 0.35$ (Fernández et al., 2016)
- Future Surveys using SKA and Pathfinders: LADUMA, APERTIF MDS, DINGO, etc
  - LADUMA aims to detect HI to $z \sim 0.6$
  - use stacking for high redshift ($0.4 \leq z \leq 1.4$)

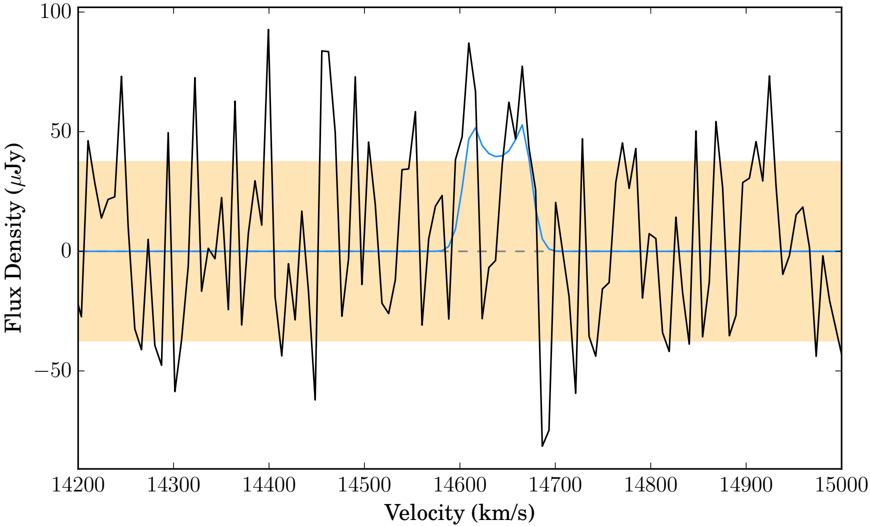
What is Stacking?

Detecting the HI signal from a distant galaxy

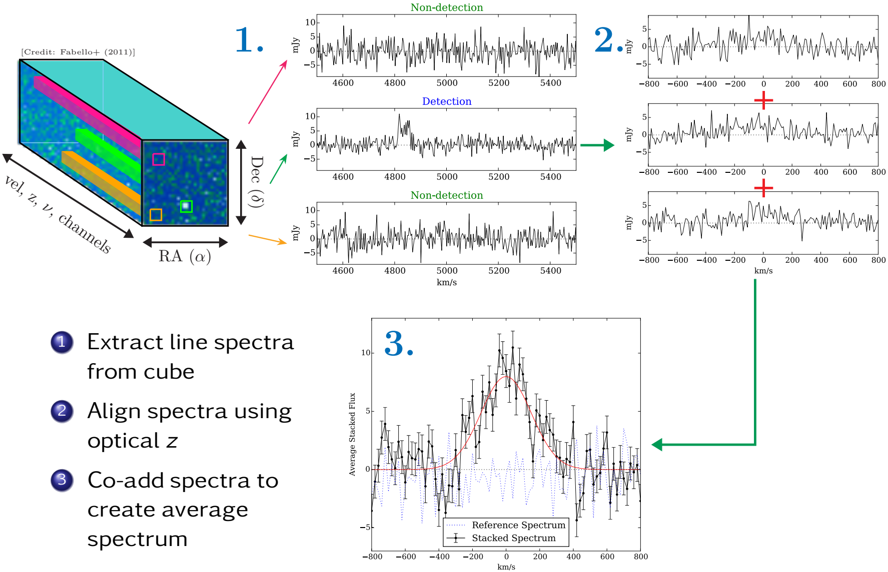


What is Stacking?

Most of the HI signal is buried in the noise



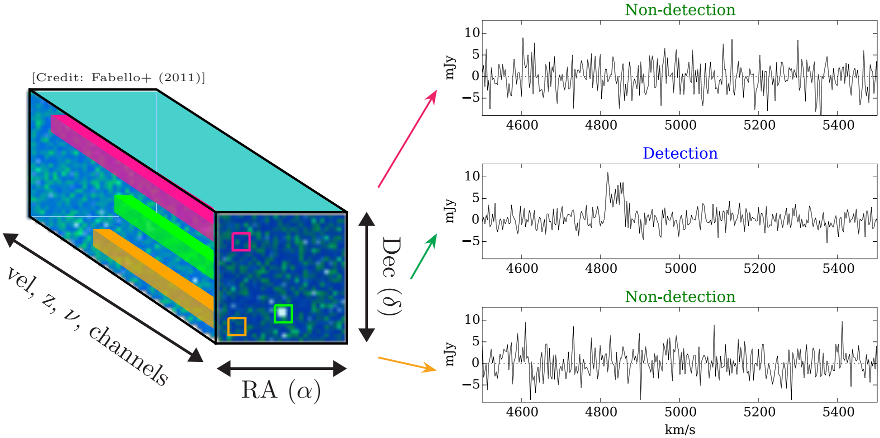
What is Stacking?



1. Extract line spectra from cube
2. Align spectra using optical z
3. Co-add spectra to create average spectrum

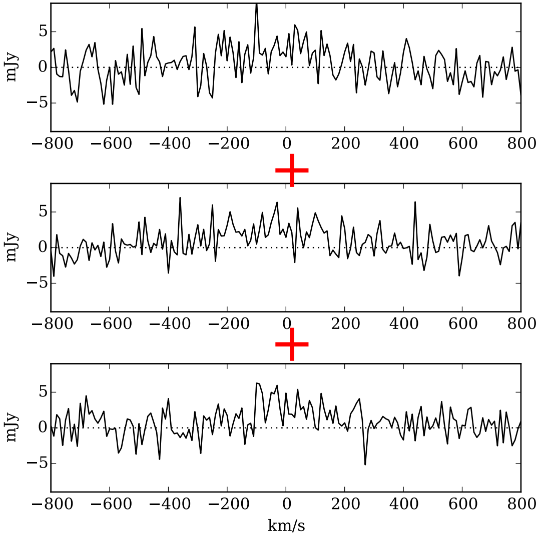
What is Stacking: 1. Extract spectra

1. Extract HI line spectra from cube



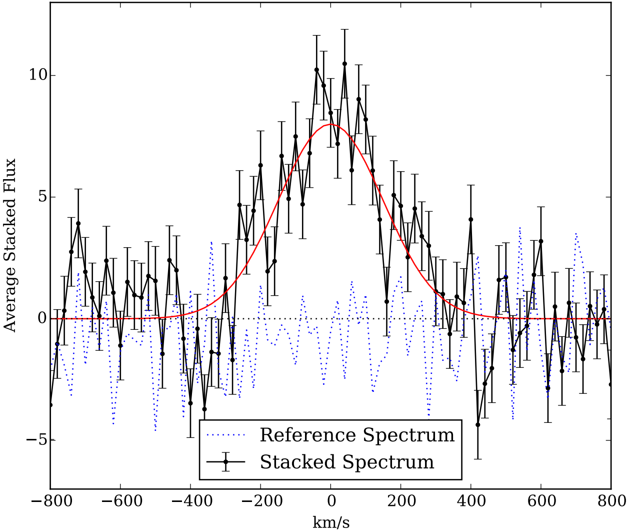
What is Stacking: 2. Align spectra

2. Align spectra using optical z



What is Stacking: 3. Co-add spectra

3. Co-add spectra to create average spectrum



My Masters Work

Two main goals:

1. Develop, test and implement an HI spectral line stacking package to be used by the Astronomy community
   - Serve a as a reference stacking tool
   - Free & accessible: Python-based
   - User friendly (use command-line or a graphical user interface)
   - Modular: easy to update & maintain
2. Use package to analyse spectra from the NIBLES Survey (van Driel et al., 2016)

Key Aspects of HI Stacker

- stack with different units
  - spectral units ($\mathrm{km \cdot s^{-1}}$ or Hz)
  - flux units ($M_\odot$, Jy, f_{HI})
- track stacking progress
- compute detection statistics (S/N, significance, etc.)
- characterise shape of stacked spectrum
- determine integrated flux of both individual spectra & stacked spectrum
- save all plots & calculated quantities to file
- display results

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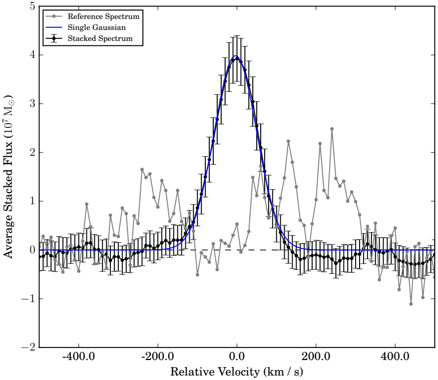
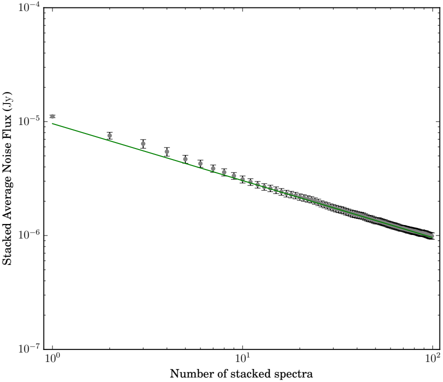


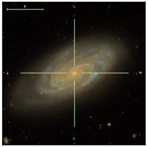


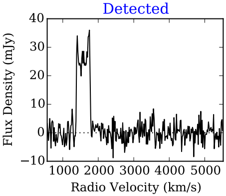
Number of galaxy profiles included in Stacked Spectrum: 99
Total flux of sample = 5.09×10^{10} $M_\odot$
The peak signal-to-noise ratio: 34
The significance of the peak: 8.2σ (p-value = 1.64×10^{-141})

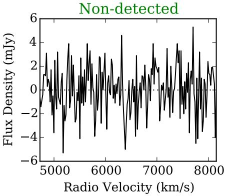
Fitted Function	**Integrated Flux ($M_\odot$)**	**Uncertainty Integrated Flux ($M_\odot$)**	**Fit RMS**	**Fit ChiSquare**
Single Gaussian	5.38×10^8	5.38×10^8	0.438	19.3
Summed Flux of Stacked Spectrum	5.40×10^8	1.13×10^7	0	0

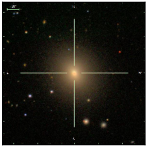
Stacking with NIBLES

- NIBLES: Nançay Interstellar Baryon Legacy Extragalactic Survey (van Driel et al., 2016)
- Aim to investigate galaxy properties as a function of stellar mass
- Galaxies selected by stellar mass, no colour selection
- Targeted HI survey of SDSS selected galaxies





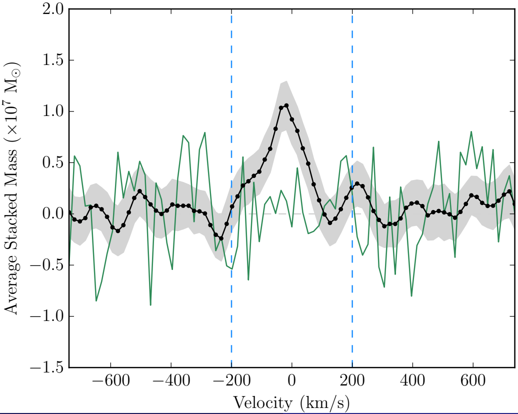




NIBLES: Stacking the Non-Detections

Stacking the non-detections to recover the HI content buried in the noise

- Stacked 361 profiles
- $\langle M_{HI} \rangle = (9.72 \pm 0.72) \times 10^{7}\ M_{\odot}$

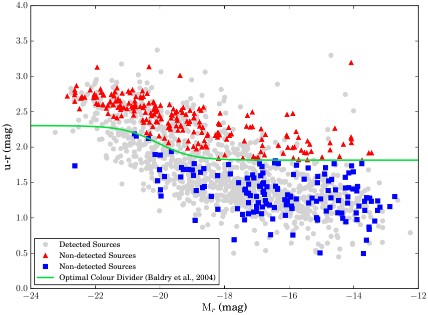


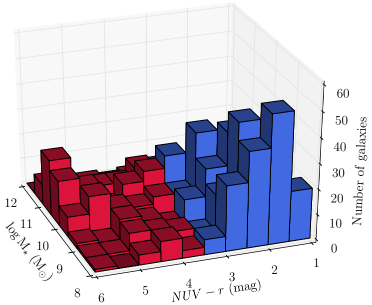
- black line: ave. stacked flux
- grey band: error on stacked flux
- green line: ave. reference spectrum

NIBLES: Stacking non-detections by Colour

Separate blue (mostly star-forming) and red (mostly non-starforming) populations using Baldry et al. (2004) SDSS optimal colour divider.

Find 147 (73) blue galaxies and 214 (191) red galaxies.

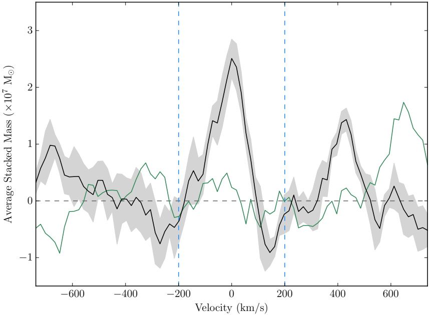




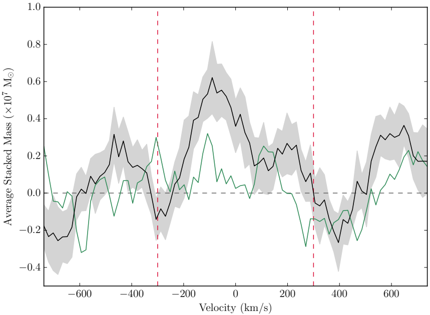
NIBLES: Stacking non-detections by Colour

Stacking all non-detections with $M_\star$ in two bins: blue & red

- The blue sample:
  - $\langle M_{HI} \rangle = (1.384 \pm 0.038) \times 10^8\ M_\odot$
  - $\langle f_{HI} \rangle = 0.1188 \pm 0.0059$
  - $\Delta v = 198\ \mathrm{km \cdot s^{-1}}$



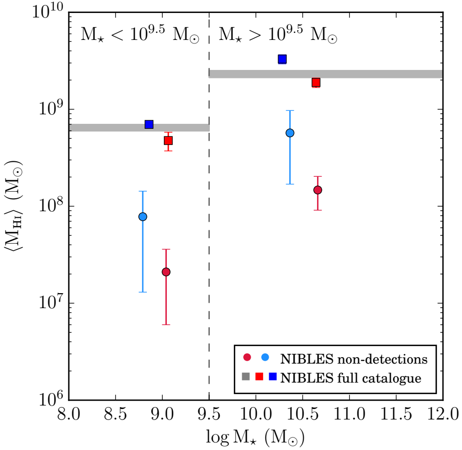
- The red sample:
  - $\langle M_{HI} \rangle = (8.301 \pm 0.065) \times 10^7\ M_\odot$
  - $\langle f_{HI} \rangle = 0.017190 \pm 0.000094$
  - $\Delta v = 306\ \mathrm{km \cdot s^{-1}}$



Probing the gas-richness scale with NIBLES

"gas-richness scale" ($M_\star \sim 10^{9.5}$ $M_\odot$): transition from gas-rich to gas poor (Kannappan et al., 2013)

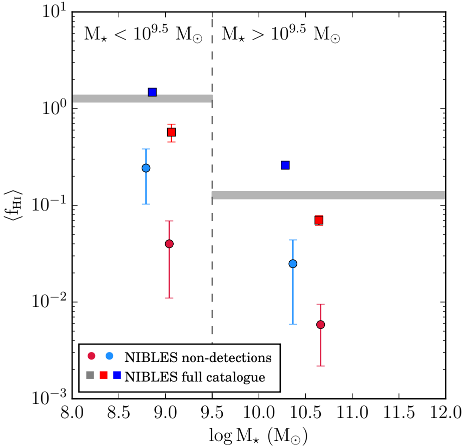
- non-detections only provide a limit
- blue, high $M_\star$ galaxies have more HI



Probing the gas-richness scale with NIBLES

"gas-richness scale" ($M_\star \sim 10^{9.5}$ $M_\odot$): transition from gas-rich to gas poor (Kannappan et al., 2013)

- high $M_\star$ galaxies more gas-poor
- blue, low $M_\star$ galaxies have higher f_{HI}



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Gas fractions ($f_{\rm HI} = M_{\rm HI}/M_\star$) are useful to probe gas richness

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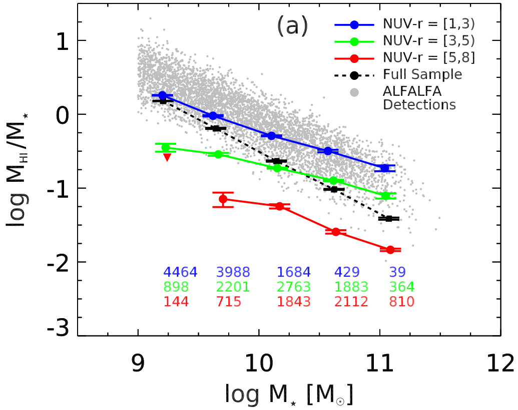
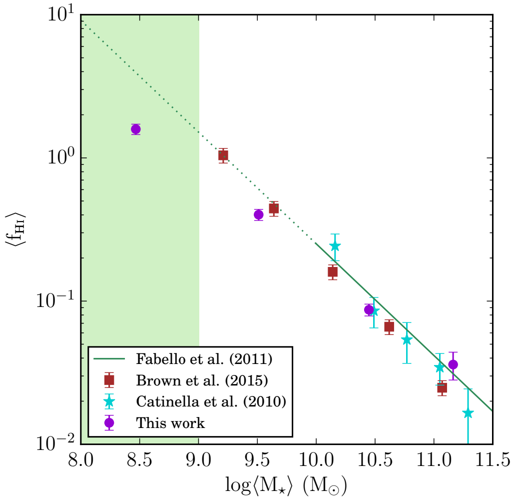
- gas fraction relations primarily driven by $NUV - r$, followed by $M_\star$



(Brown et al., 2015, Figure 5)

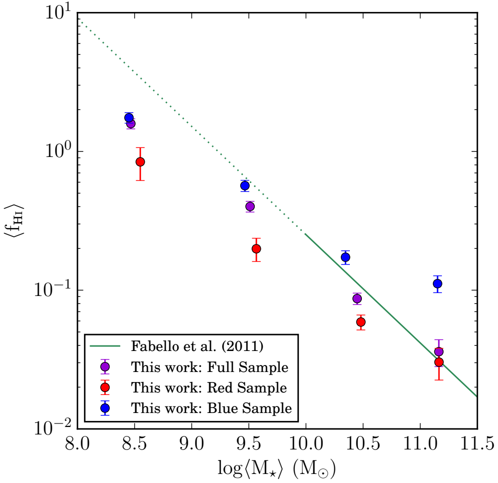
NIBLES: Extending published work with NIBLES sample

Find same f_{HI} vs $M_\star$ relation as Brown et al. (2015) to lower $M_\star$



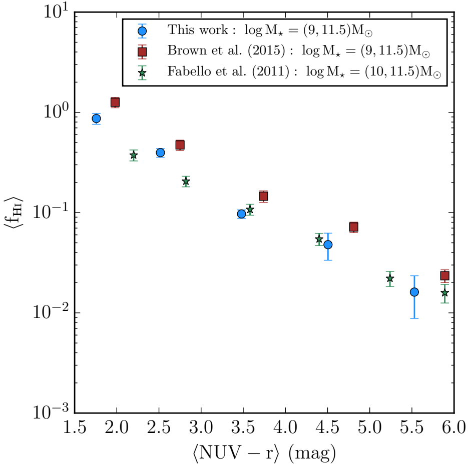
- This work: $10^8 < M_\star < 10^{11.5}\, M_\odot$
- Brown et al. (2015): $10^9 < M_\star < 10^{11.5}\, M_\odot$
- Catinella et al. (2010) & Fabello et al. (2011): $10^{10} < M_\star < 10^{11.5}\, M_\odot$

f_{HI} vs $M_\star$ for the red and blue galaxy samples



NIBLES: Extending published work with NIBLES sample

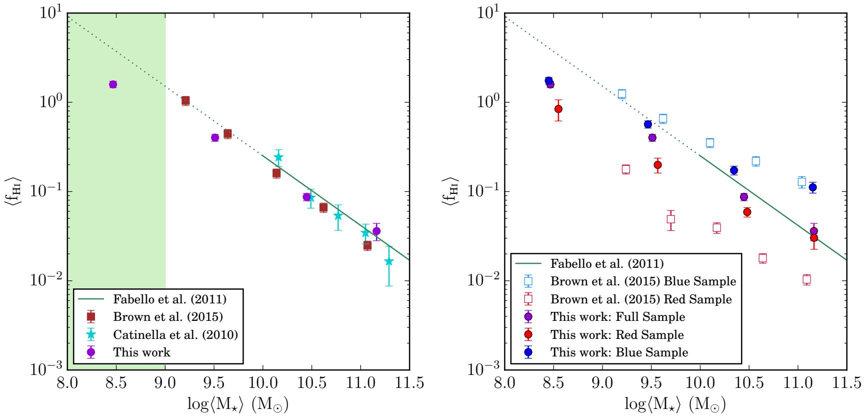
Investigate f_{HI} as function of colour: same trend as Brown et al. (2015)

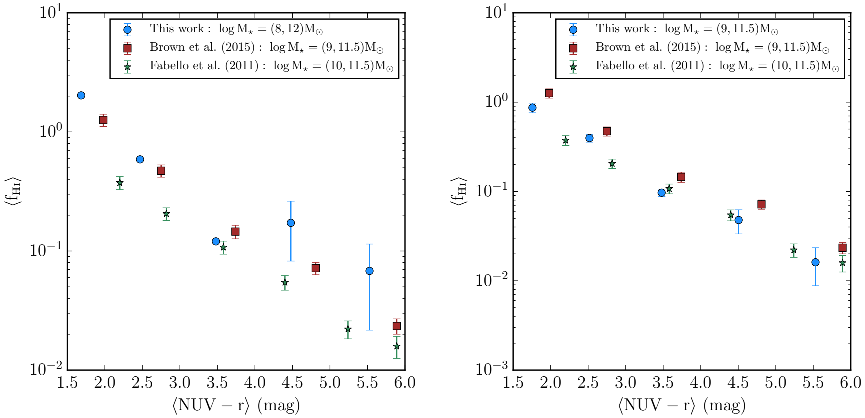


- Brown et al. (2015) find *NUV* – *r* better tracer of HI
- This work: $10^9 < M_\star < 10^{11.5}\,M_\odot$
- Brown et al. (2015): $10^9 < M_\star < 10^{11.5}\,M_\odot$

Ongoing work

- Recently submitted MSc thesis
- Stacking Package:
  - Construct the graphical user interface for the Stacking Package
  - Write User Manual
  - Make HiSS publicly available
- NIBLES Analysis:
  - Write up paper
  - Investigate $M_\star / NUV - r$ distribution for comparison samples
- Start PhD with Prof Marc Verheijen and Dr Sarah Blyth


Fabello et al. (2011)
Brown et al. (2015)
Catinella et al. (2010)
This work
Fabello et al. (2011)
Brown et al. (2015) Blue Sample
Brown et al. (2015) Red Sample
This work: Full Sample
This work: Red Sample
This work: Blue Sample
⟨f_HI⟩
log⟨M⋆⟩ (M⊙)


This work : log M⋆ = (8, 12)M⊙
Brown et al. (2015) : log M⋆ = (9, 11.5)M⊙
Fabello et al. (2011) : log M⋆ = (10, 11.5)M⊙
⟨f_HI⟩
⟨NUV − r⟩ (mag)
This work : log M⋆ = (9, 11.5)M⊙
Brown et al. (2015) : log M⋆ = (9, 11.5)M⊙
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⟨f_HI⟩
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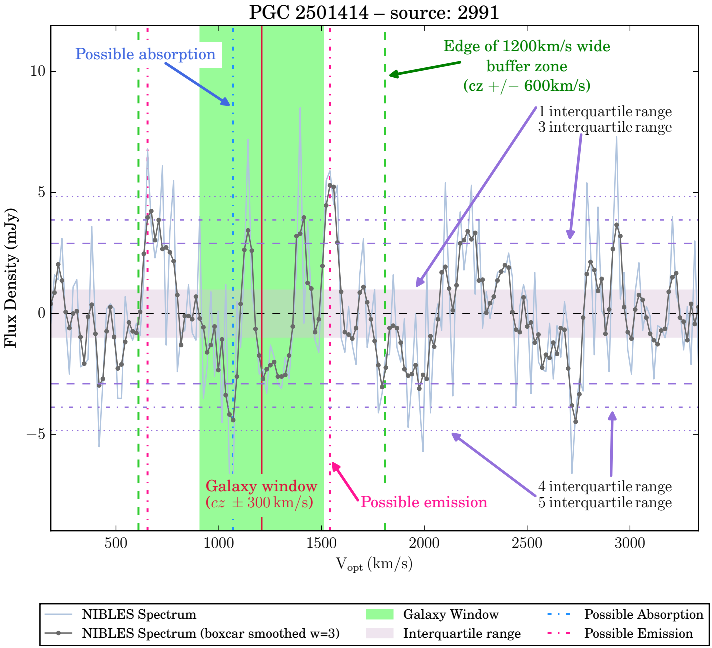
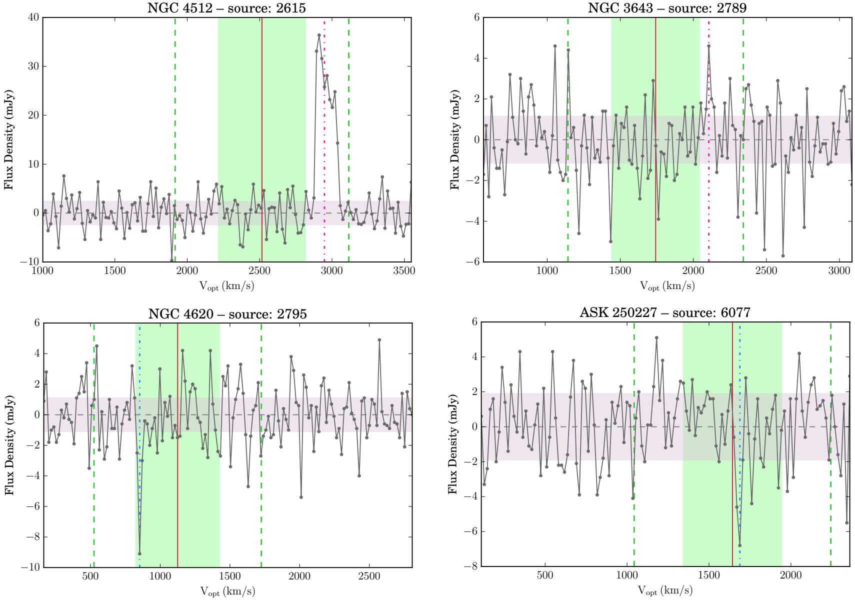
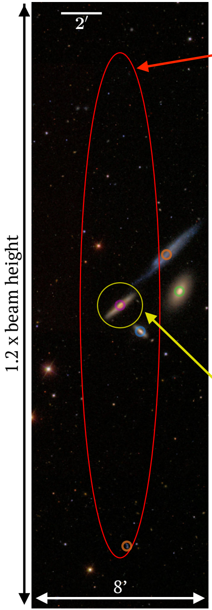


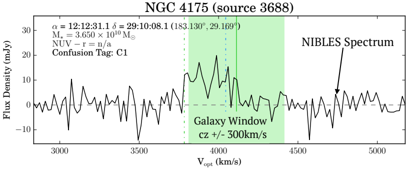
PGC 2501414 – source: 2991
Possible absorption
Edge of 1200km/s wide buffer zone (cz +/− 600km/s)
1 interquartile range
3 interquartile range
4 interquartile range
5 interquartile range
Galaxy window ($cz \pm 300$ km/s)
Possible emission
Flux Density (mJy)
V_{opt} (km/s)
10
5
0
−5
500
1000
1500
2000
2500
3000
NIBLES Spectrum
NIBLES Spectrum (boxcar smoothed w=3)
Galaxy Window
Interquartile range
Possible Absorption
Possible Emission


NGC 4512 – source: 2615
Flux Density (mJy)
V_{opt} (km/s)
NGC 3643 – source: 2789
Flux Density (mJy)
V_{opt} (km/s)
NGC 4620 – source: 2795
Flux Density (mJy)
V_{opt} (km/s)
ASK 250227 – source: 6077
Flux Density (mJy)
V_{opt} (km/s)

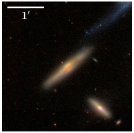


FWHM of Nançay beam (3.6’ x 22’-34’)

r-band Petrosian radius



Close-up of the target
(3.7’ x 3.7’)



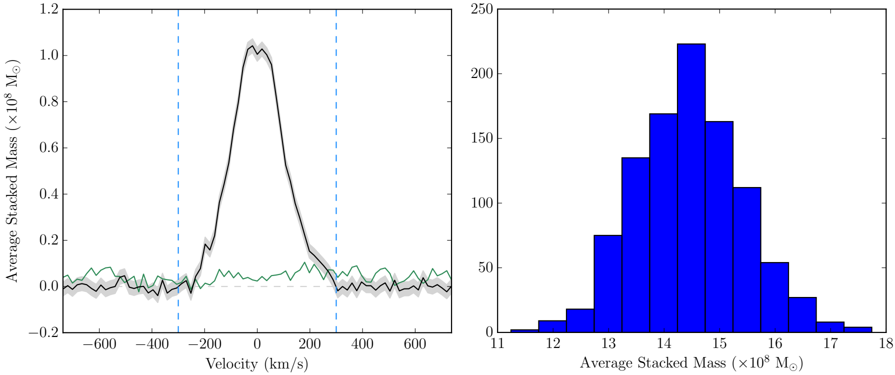
Gal. Identifier	cz km / s	Separation arcmin	Vel. Separation km / s
NGC 4175	4112	0	0
NGC 4174	4045	1.5	67
NGC 4169	3784	2.76	328
NGC 4173	1127	3.11	2985
KISSBx 37	10433	10.9	6320

Target galaxy

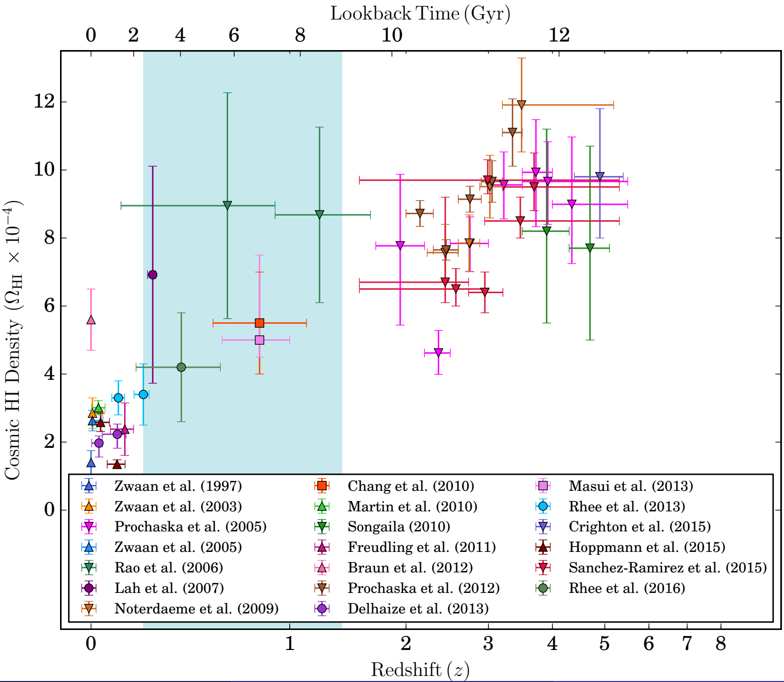
Galaxy in galaxy window

Galaxy in beam and spectrum, but not galaxy window

Galaxies in beam and survey volume, but not spectrum



1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
Average Stacked Mass ($\times 10^8$ M$_\odot$)
−600
−400
−200
0
200
400
600
Velocity (km/s)
250
200
150
100
50
0
11
12
13
14
15
16
17
18
Average Stacked Mass ($\times 10^8$ M$_\odot$)


Lookback Time (Gyr)
0 2 4 6 8 10 12
Cosmic HI Density $(\Omega_{\mathrm{HI}} \times 10^{-4})$
0 2 4 6 8 10 12
Zwaan et al. (1997)
Zwaan et al. (2003)
Prochaska et al. (2005)
Zwaan et al. (2005)
Rao et al. (2006)
Lah et al. (2007)
Noterdaeme et al. (2009)
Chang et al. (2010)
Martin et al. (2010)
Songaila (2010)
Freudling et al. (2011)
Braun et al. (2012)
Prochaska et al. (2012)
Delhaize et al. (2013)
Masui et al. (2013)
Rhee et al. (2013)
Crighton et al. (2015)
Hoppmann et al. (2015)
Sanchez-Ramirez et al. (2015)
Rhee et al. (2016)
0 1 2 3 4 5 6 7 8
Redshift (z)