Neutral Hydrogen in Galaxies from Low to High z

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University of Cape Town

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In collaboration with:
A. Bouchard, K. van der Heyden, E. de Blok, W. van Driel, RC Kraan-Korteweg, D. Obreschkow

Outline

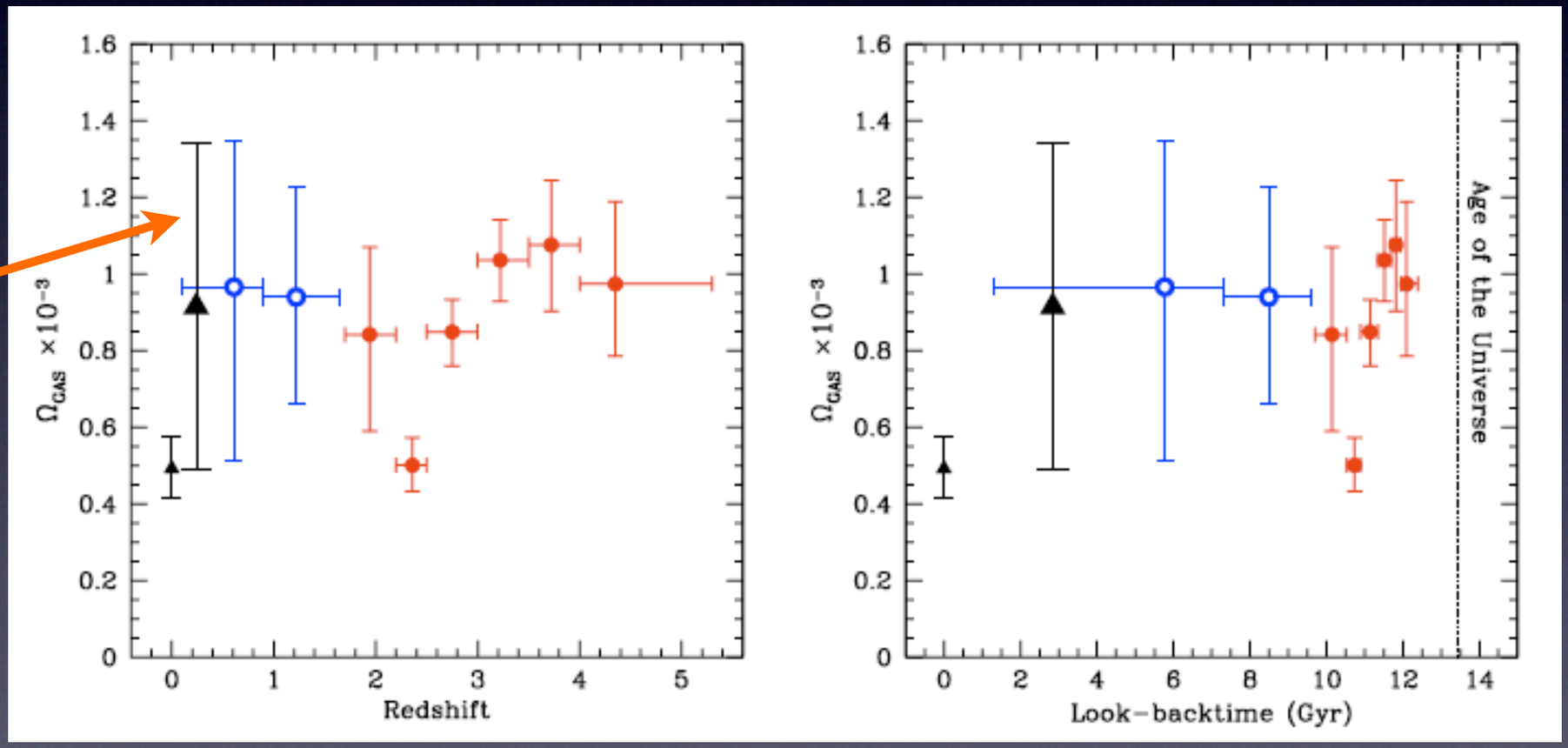
- HI-stacking techniques: measuring HI in galaxy surveys
- Application to the nearby Universe
- Probing higher *z* with MeerKAT
- Summary and Outlook

HI: Big Questions

How do galaxies evolve over cosmic time?

- How does Ω_{HI} evolve over time?
- How is HI distributed in galaxies, and how does this vary over time?

still large uncertainties



Lah et al., MNRAS 376: (2007)1357-1366

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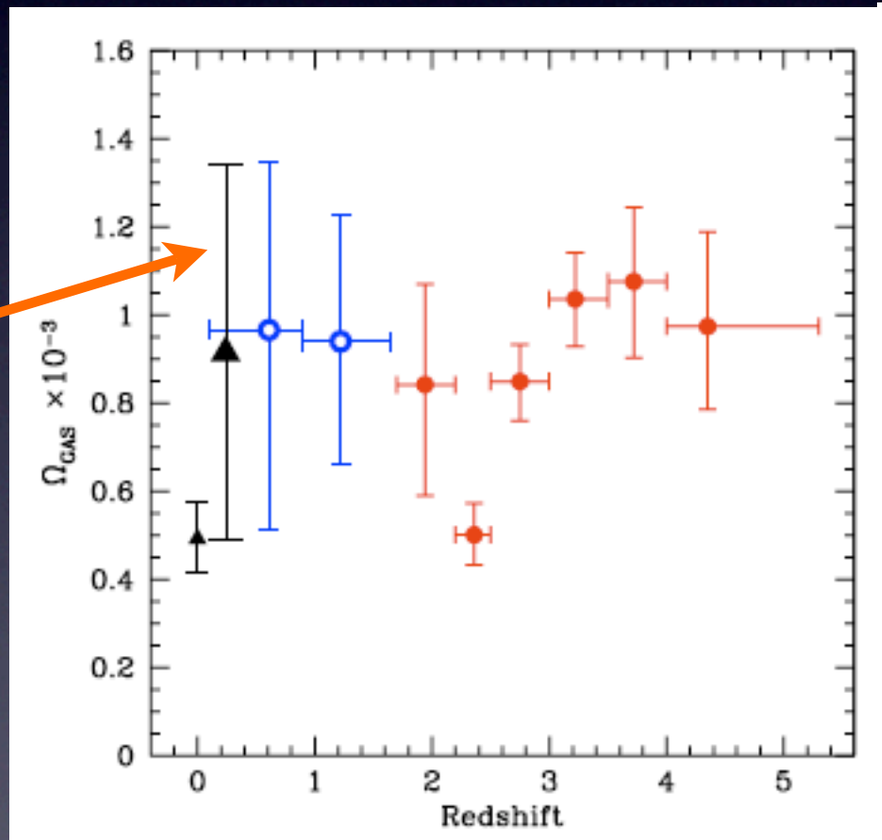

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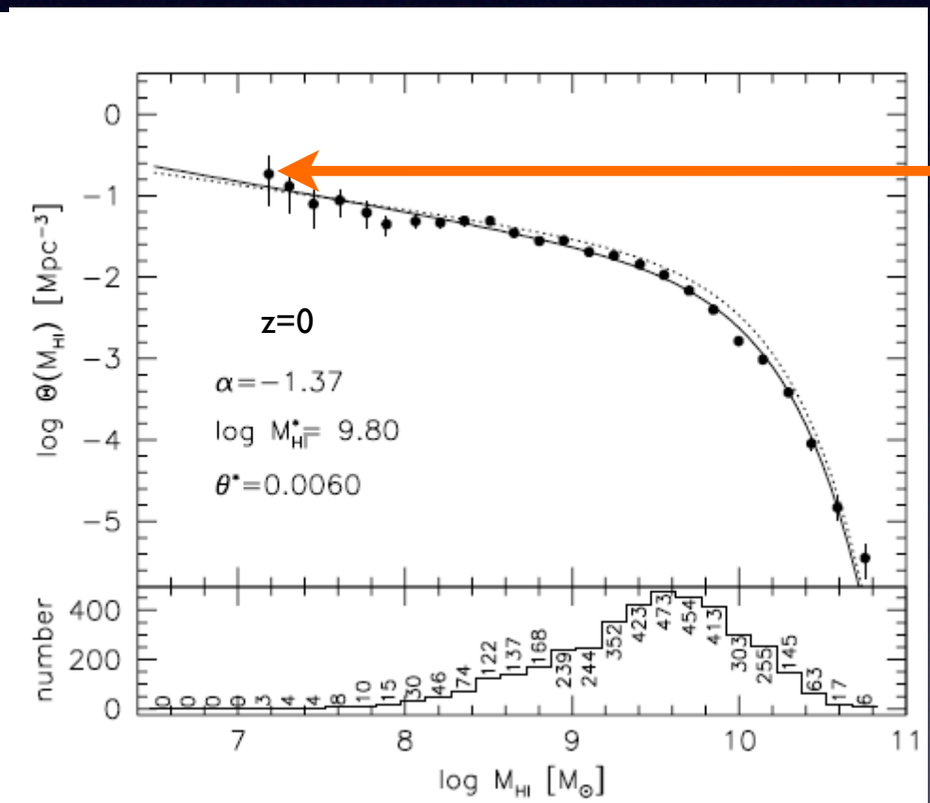
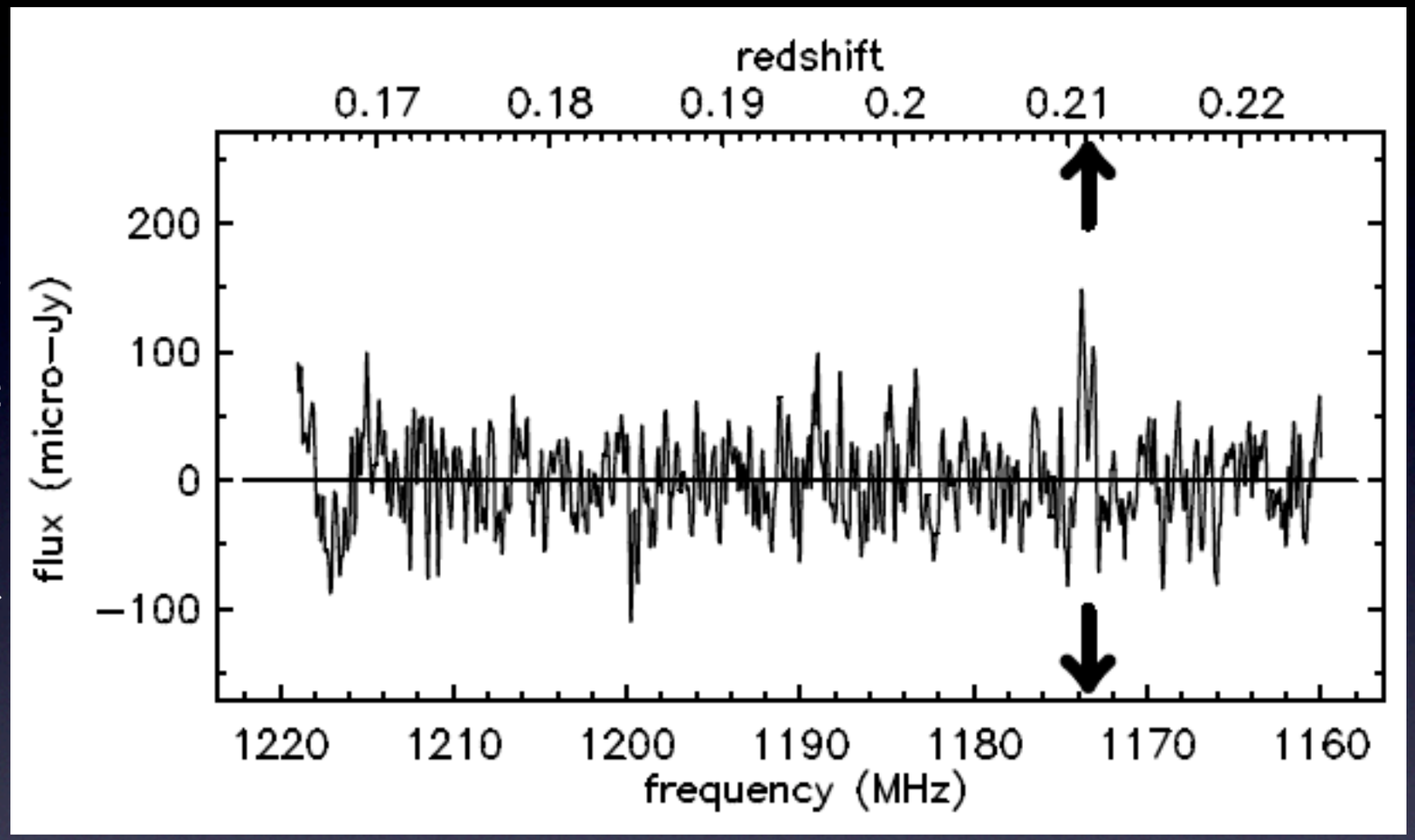


Zwaan et al., MNRAS 359 (2005) L30

not much known in this regime

Only known for z≈0 - how does it change with z?

How to Measure?



Galaxy in Abell 963, z = 0.21

Observing time: 20x12 hours on WSRT

How to Measure?

To measure HI at cosmological distances we need:

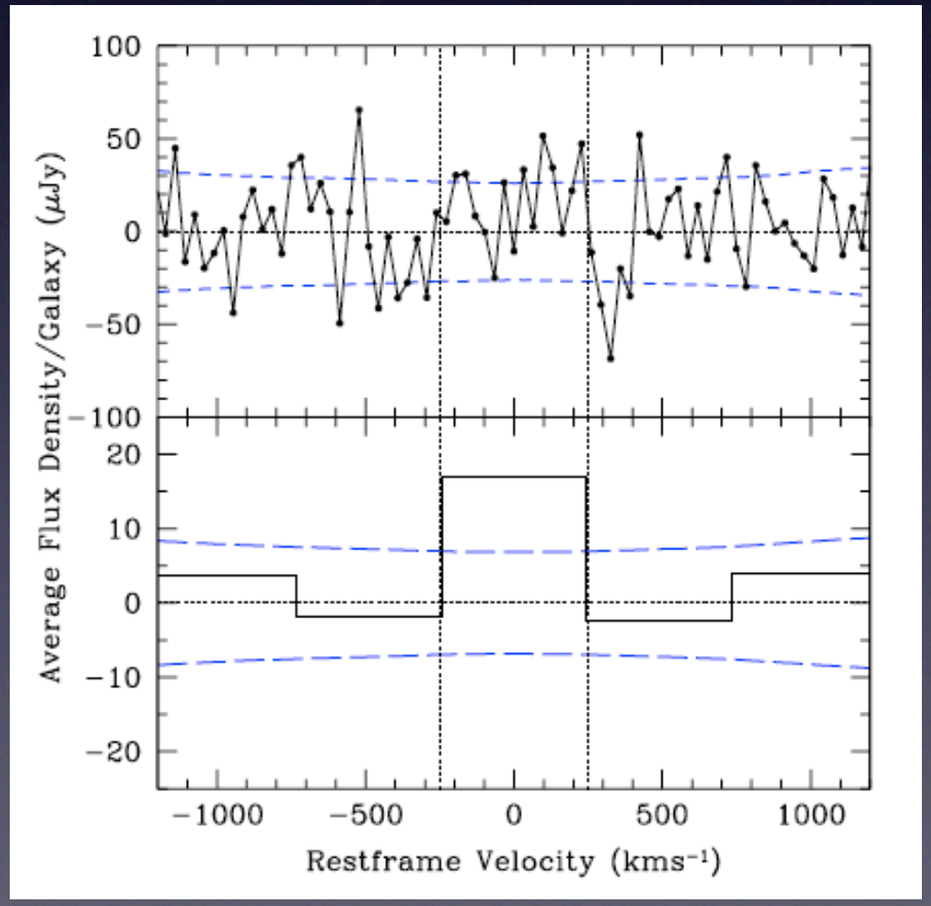
1. **Different techniques to optimise observation timing:**
   - measure the average HI content (Ω_{HI}) of galaxies for different z-ranges
   - co-add / stack individual spectra to increase S/N
     - (being used by various groups: Zwaan (2000), Chengalur et al. (2001), Lah et al. (2007), Verheijen et al. (2007)

State of the Art

With current telescopes, HI is hard to find at intermediate z, even with stacking...

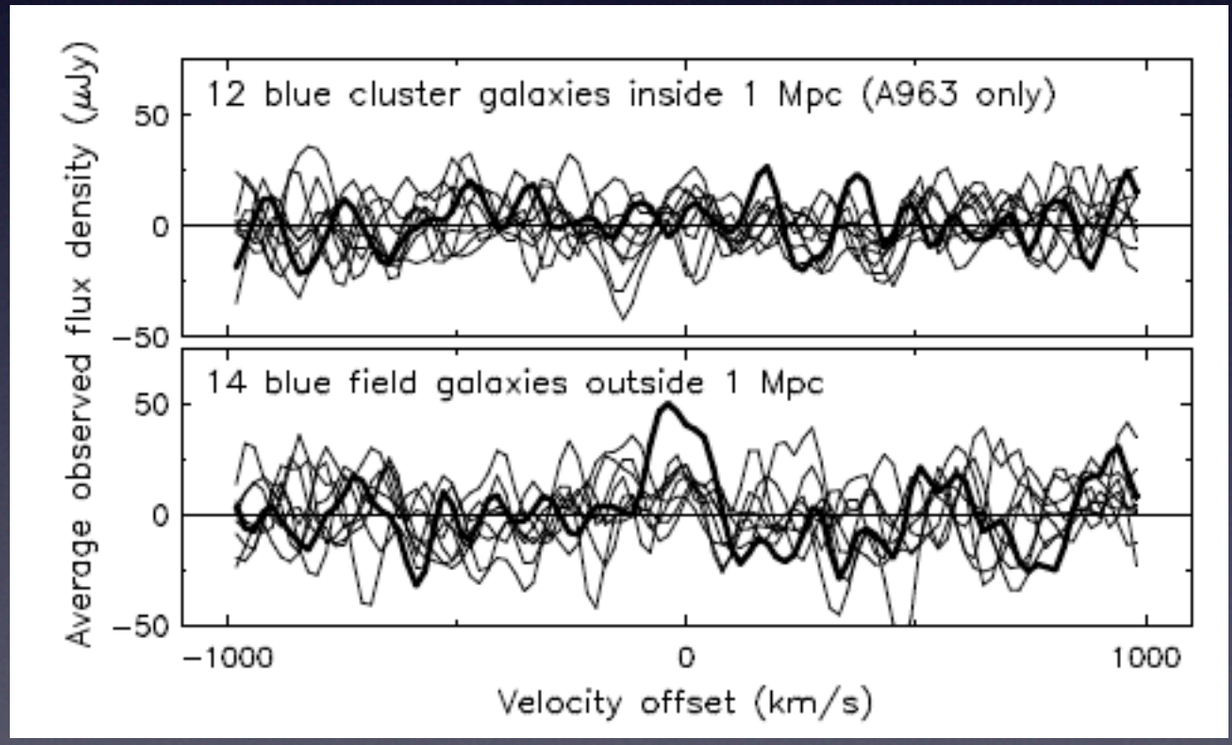
Lah et al. (2007)

z = 0.24, GMRT
signal: 2.6σ



Verheijen et al. (2007)

z = 0.206, WSRT
S/N not quoted



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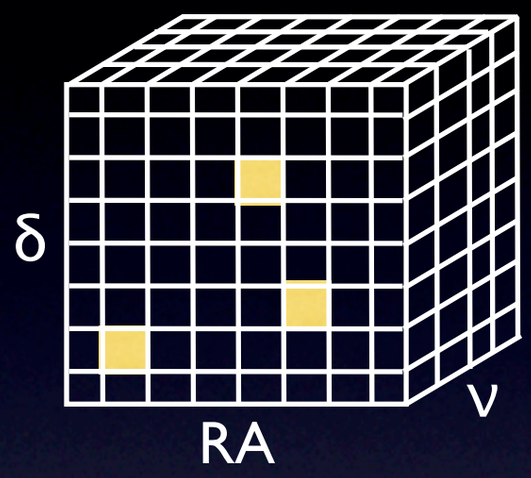
2. Larger more sensitive radio telescopes with large FoV and frequency coverage:

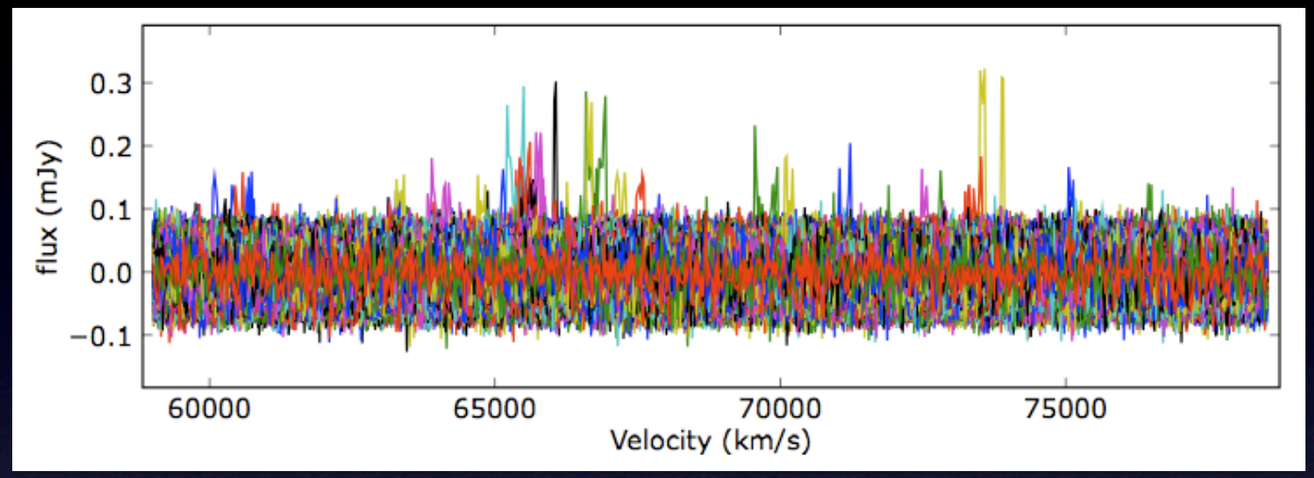
- SKA
- SKA pathfinders (MeerKAT, ASKAP ...)

HI Stacking/Co-adding

Since the HI signal is weak, we use independent measurements of galaxy z before stacking:

- STEP 1: extract spectra using known positions and z





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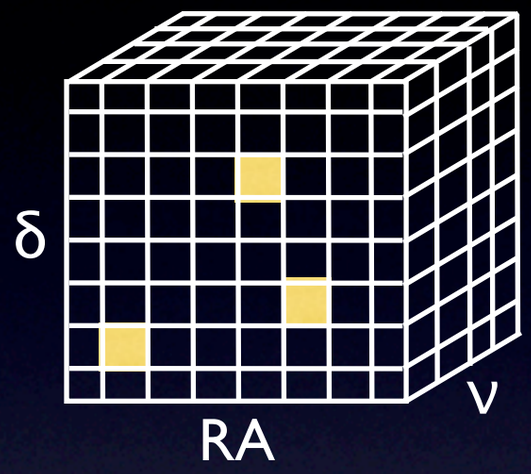
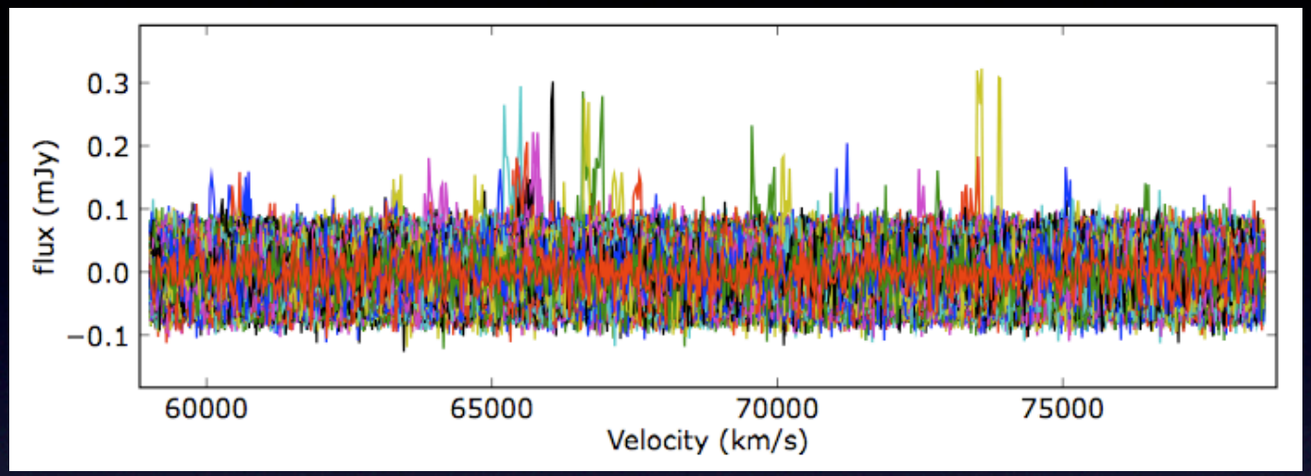
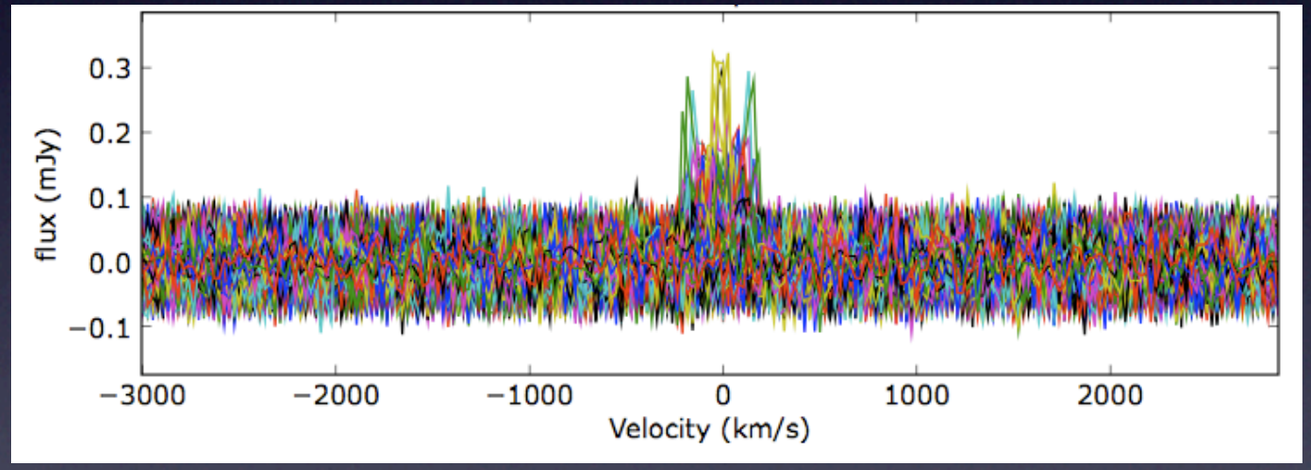




- STEP 2: Using *known* z values, shift all lines to common channel



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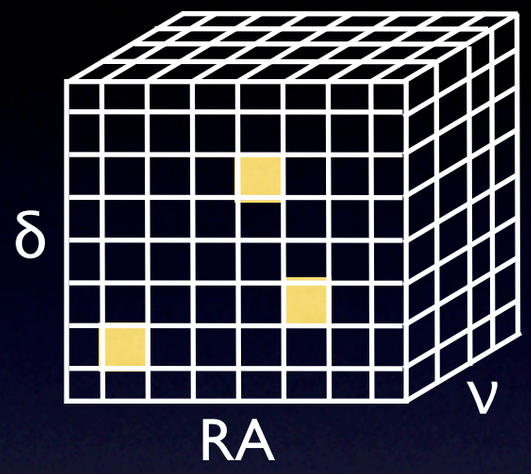

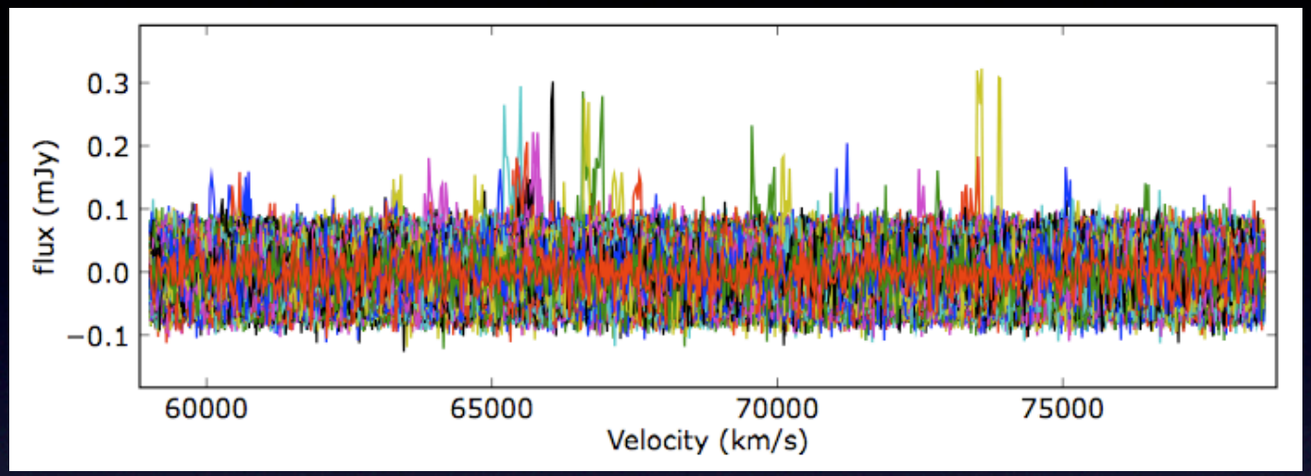

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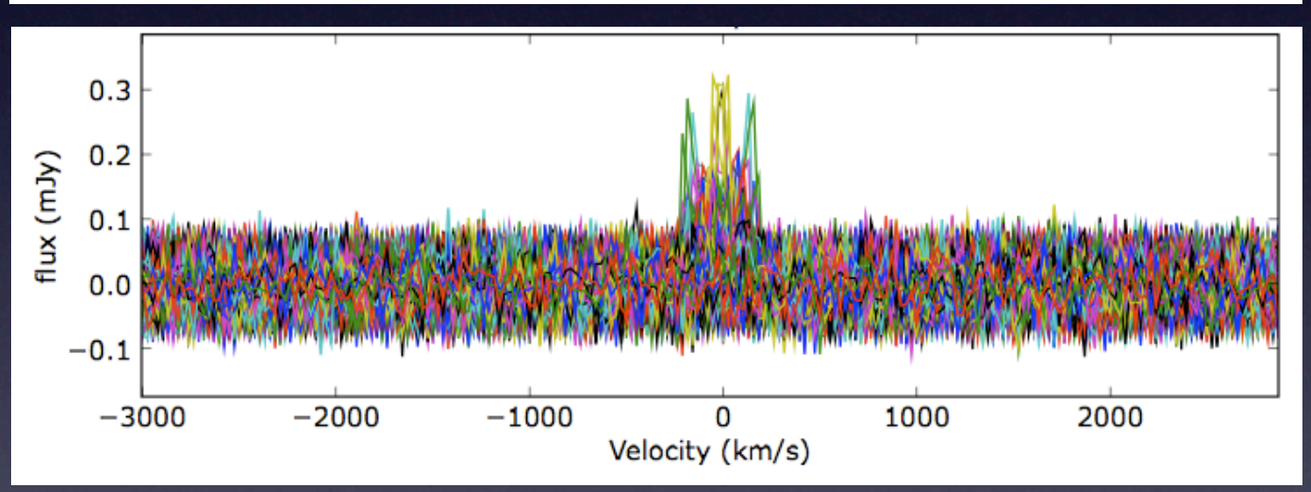
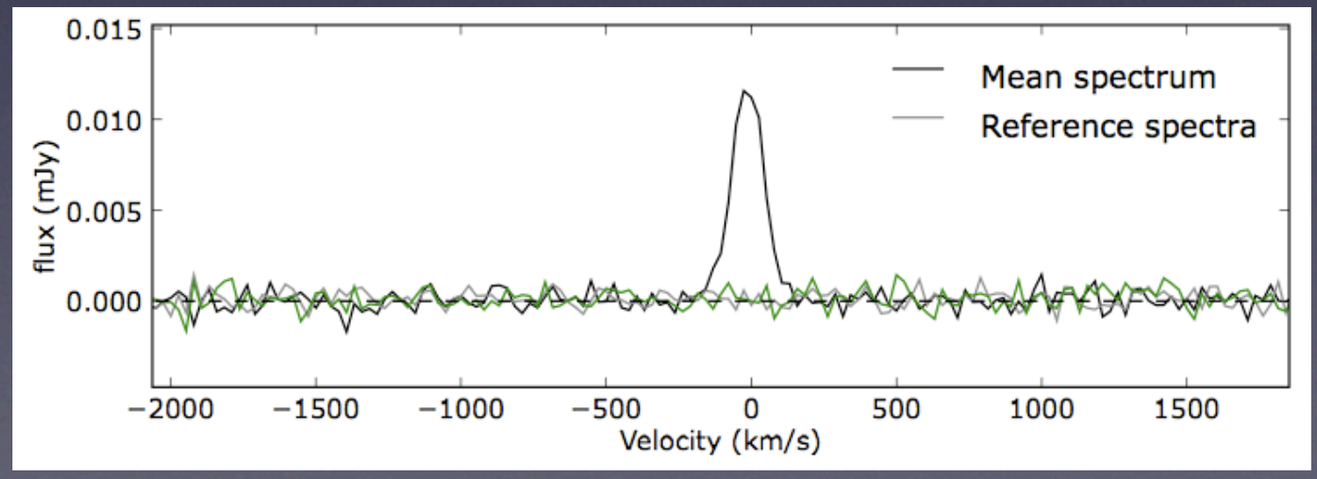


- STEP 3: Co-add spectra



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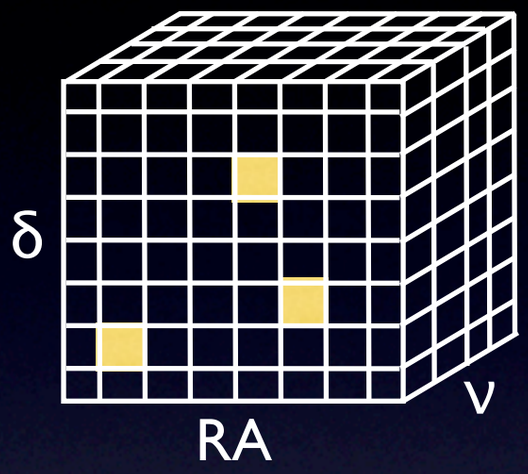

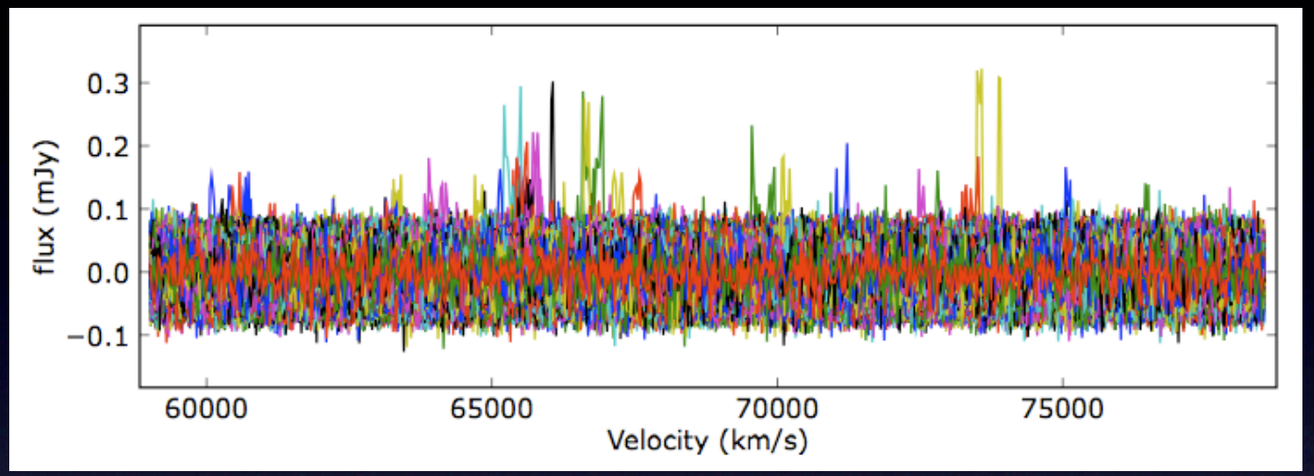

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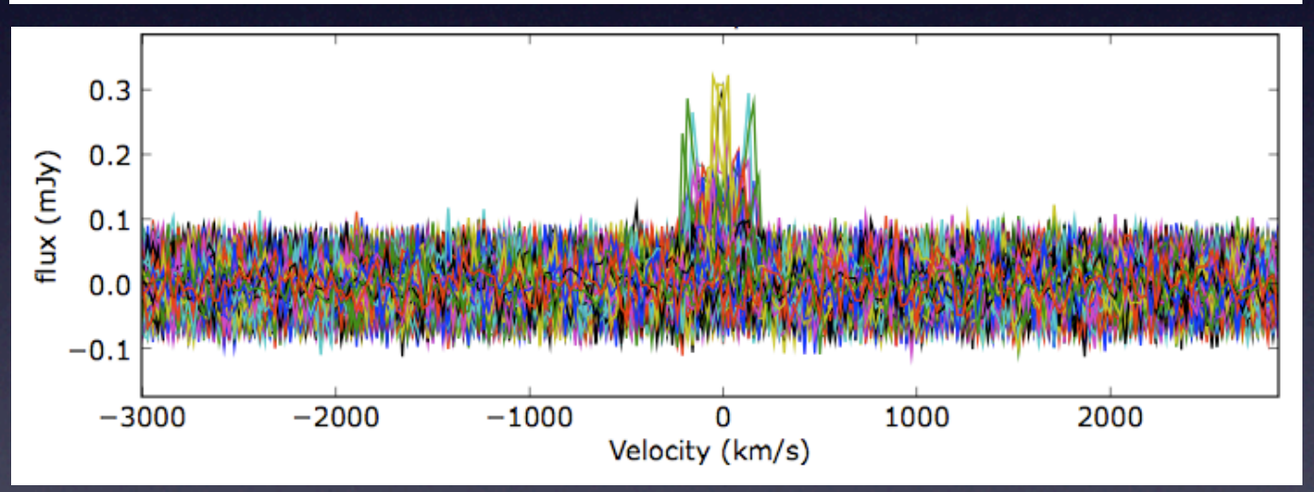

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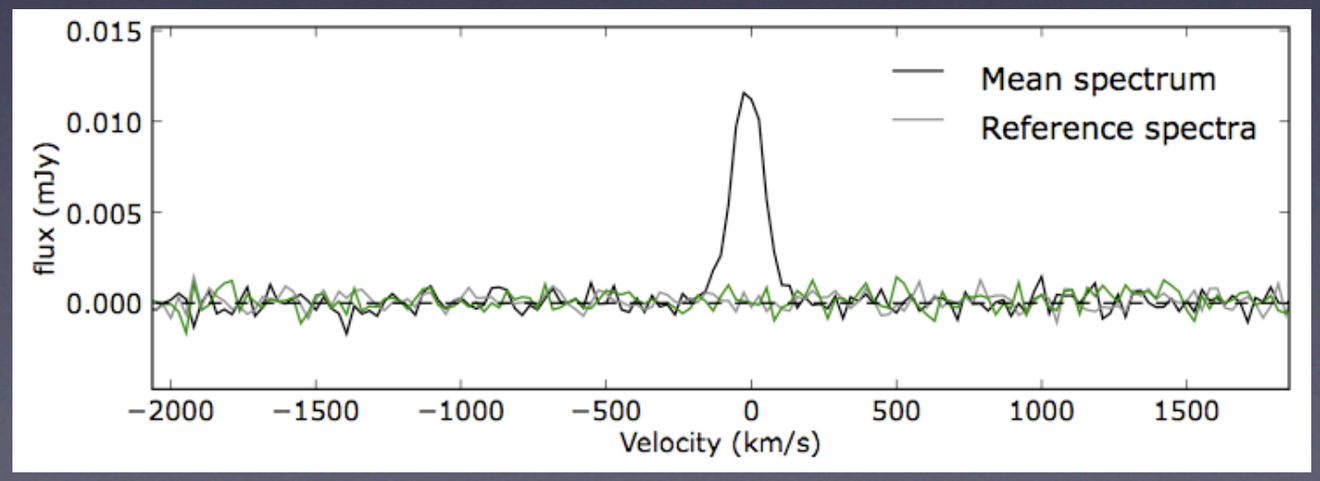
$$M_{HI} = \frac{236}{(1+z)} \left(\frac{S_\nu}{mJy}\right) \left(\frac{d_L}{Mpc}\right)^2 \left(\frac{\Delta V}{km\,s^{-1}}\right)$$



HI-stacking the Nearby Universe

NIBLES: W. van Driel et al.

- Nancay Interstellar Baryon Legacy Extragalactic Survey
- AIM: Find and quantify the density of baryons in the Local Universe
- Targeted survey of 3000 SDSS galaxies with ($900 < cz < 12\,000$ km/s)
- 0.5 M_z bins
- ~35 mins per pointing

CRUMBS: Blyth, Bouchard et al.

- Characterizing Radio-Undetected Masses in Baryonic Surveys
- AIMS: 'Squeeze' any/all remaining 'drops' of HI information out of the NIBLES non-detections
- Inform NIBLES observing strategy
- non-detections = all NIBLES spectra with < 3σ HI lines

Picking up the CRUMBS...

Preliminary results based on 884 NIBLES galaxies:

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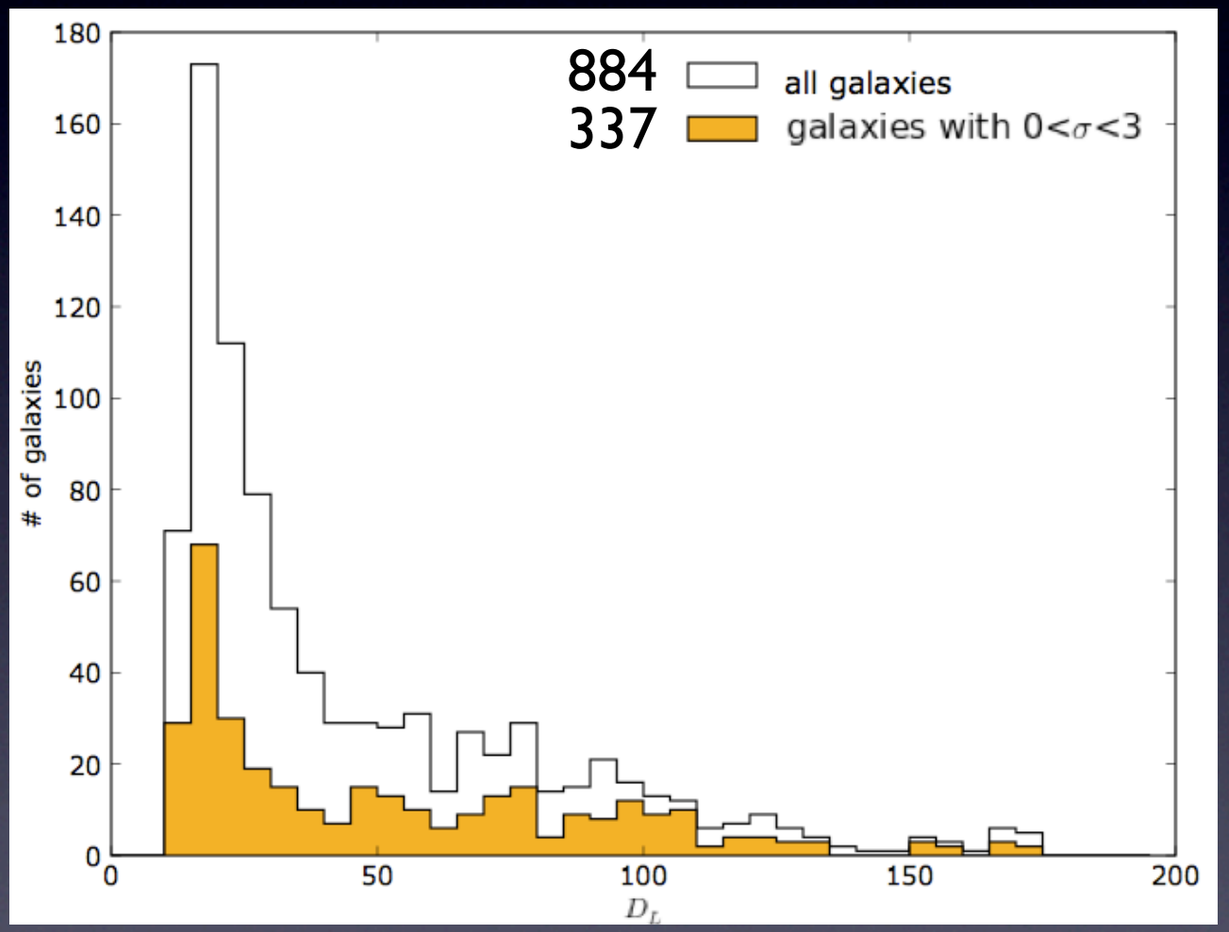
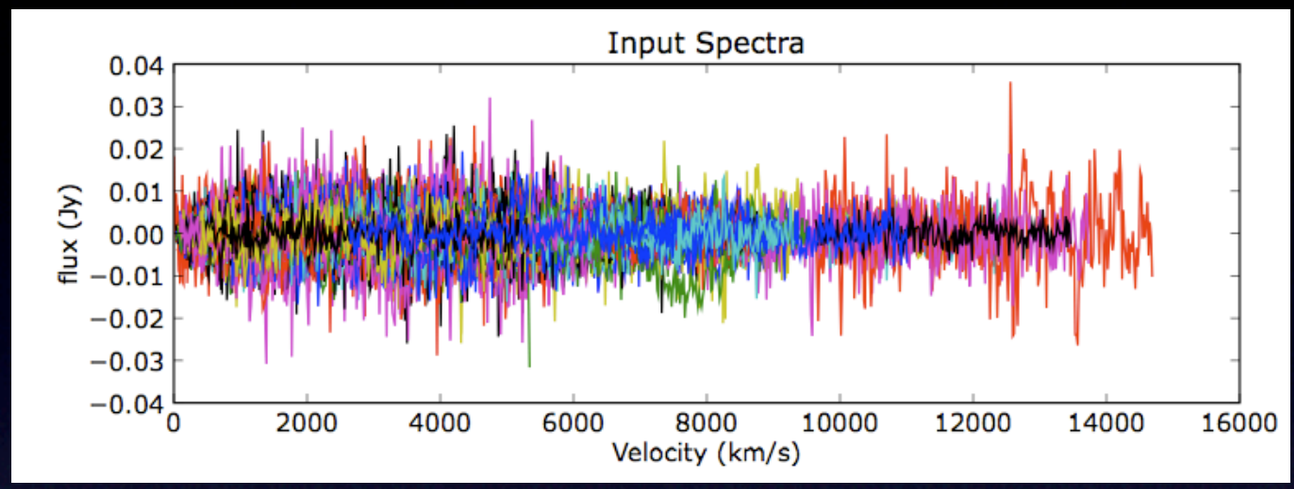


NIBLES data:



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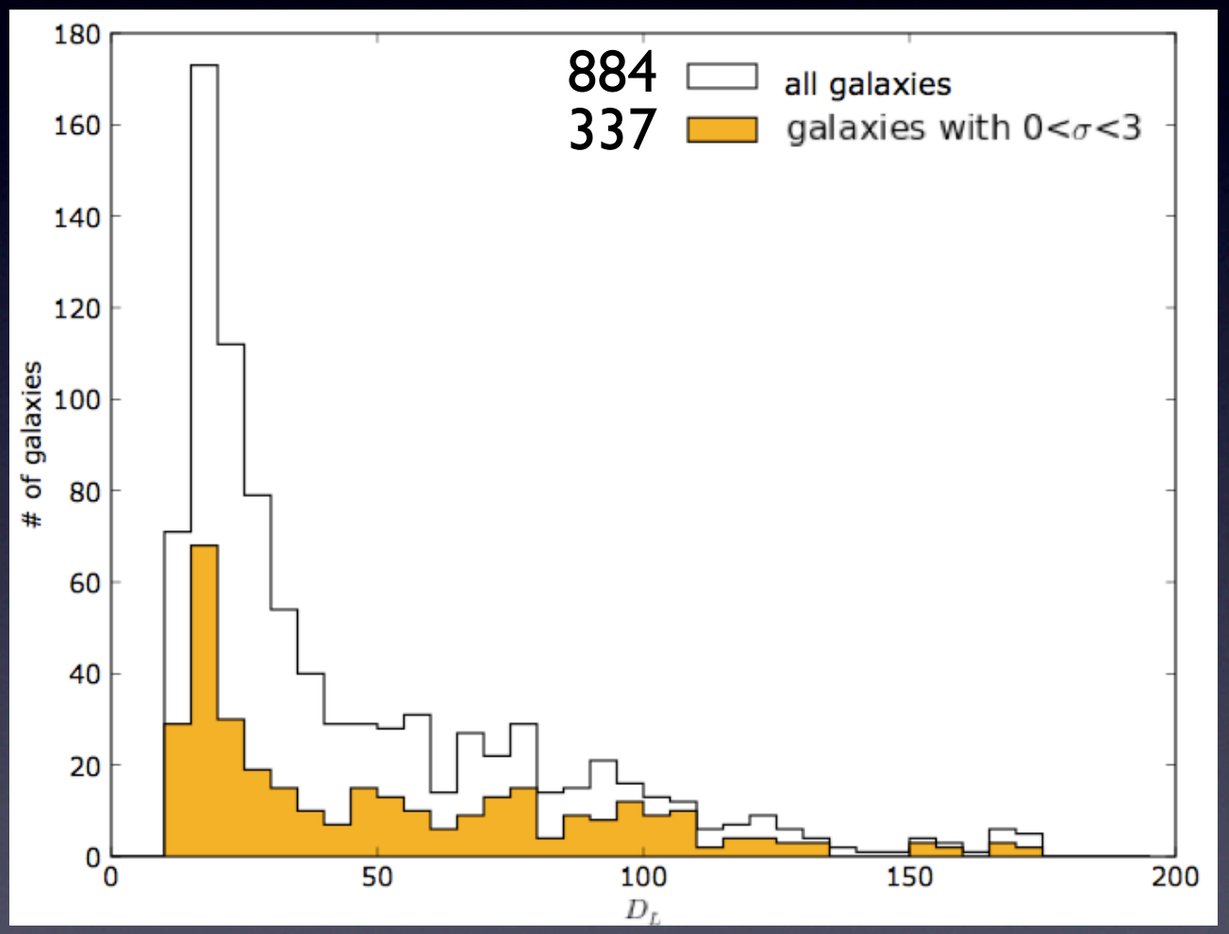

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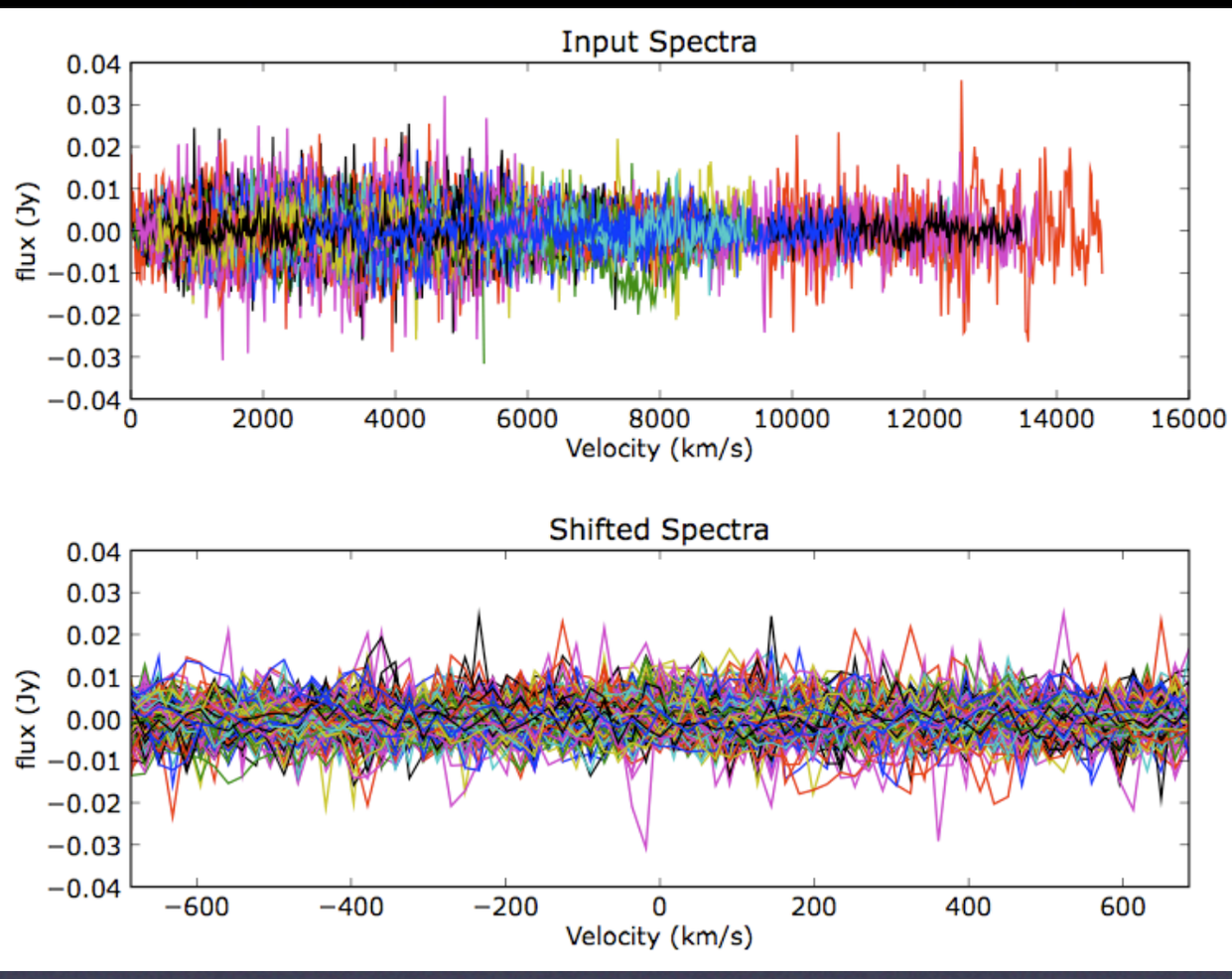

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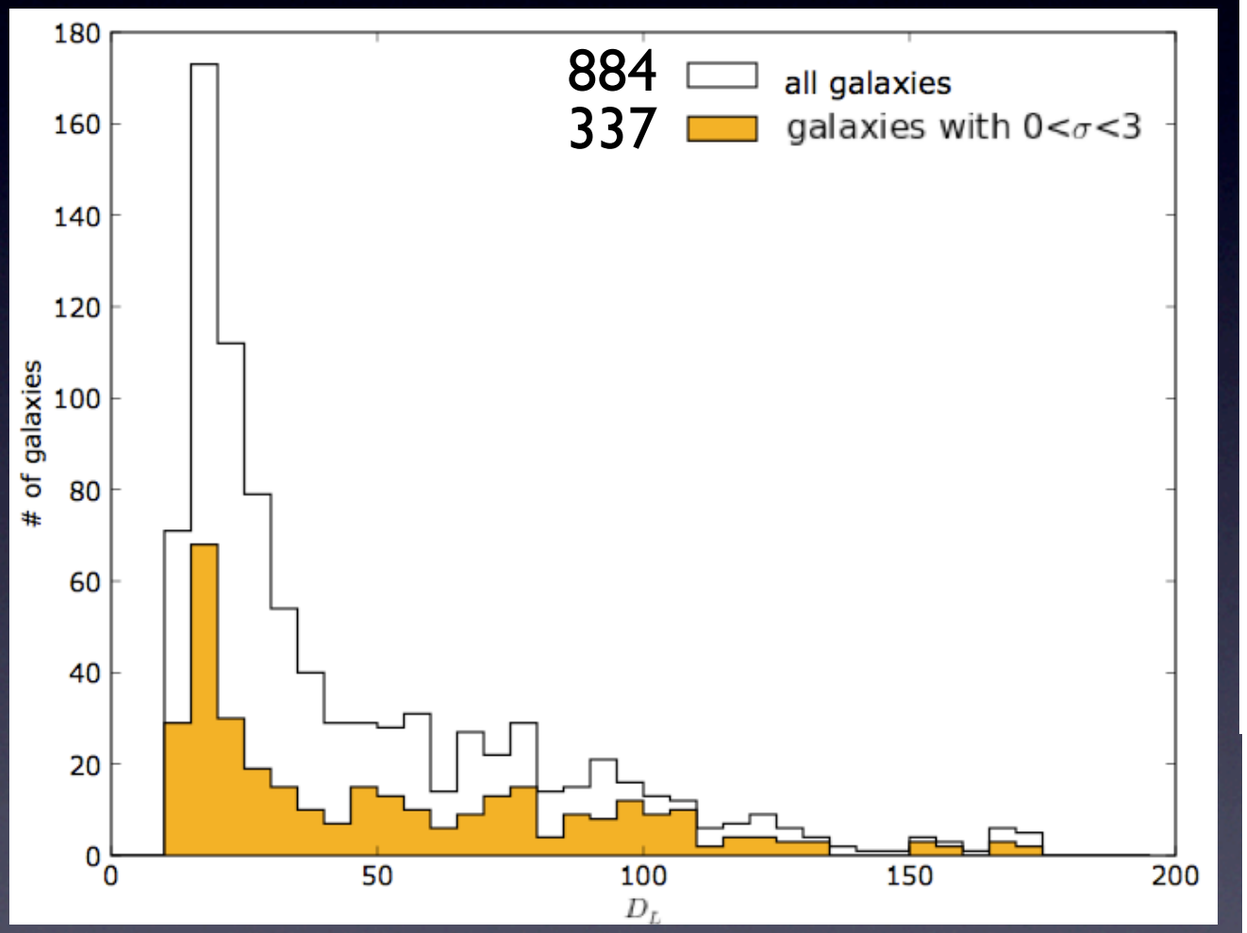

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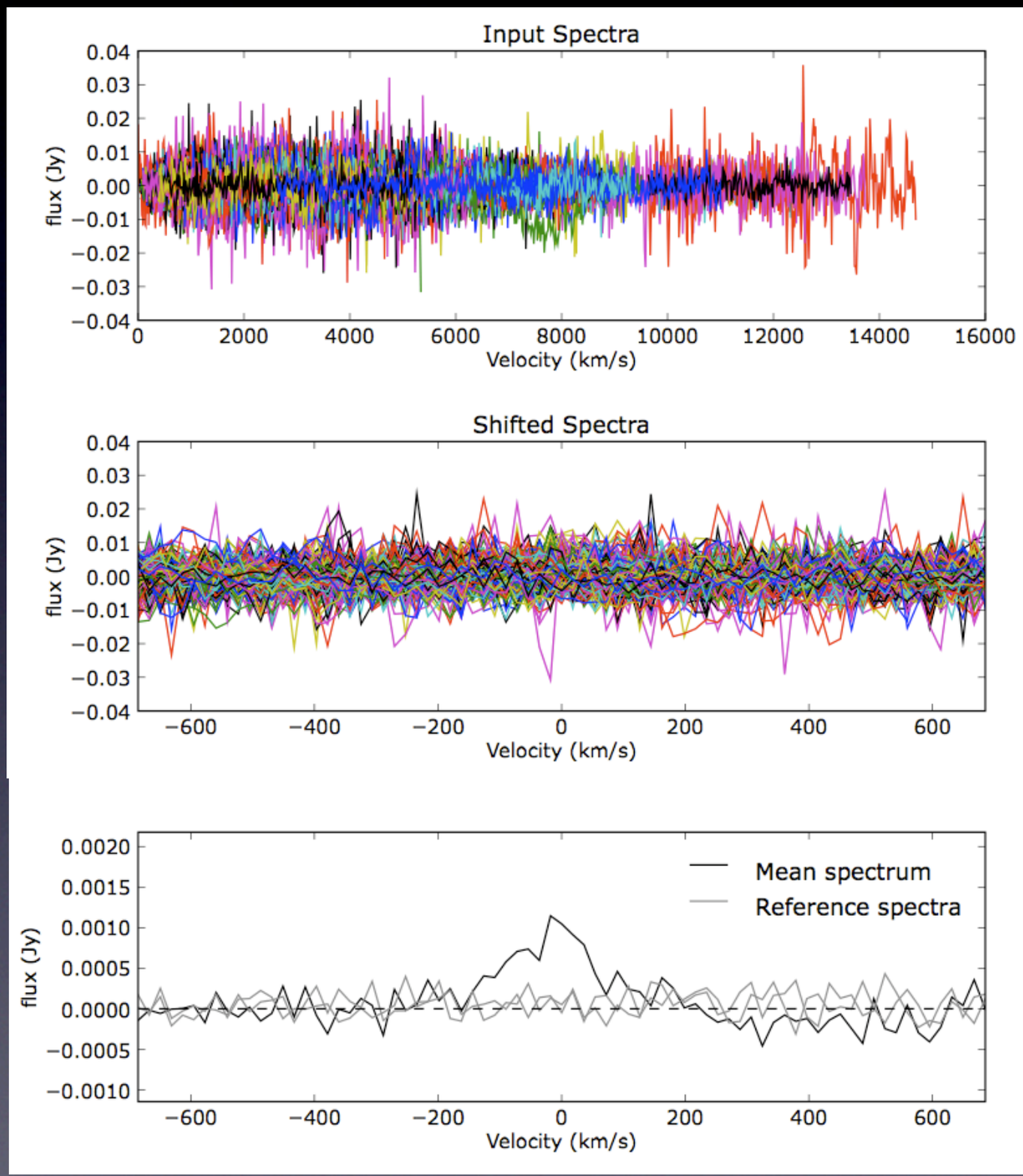

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S/N	galaxies	$\langle S_{HI} \rangle$ (mJy)	$\langle M_{HI} \rangle$ (M_{sun})	$\langle D_L \rangle$ (Mpc)	S/N stack.
<3	337	8.96 ± 0.03	$1.03 \times 10^8 \pm 8.22 \times 10^6$	52 ± 2	13.8
<2.5	304	5.63 ± 0.04	$6.46 \times 10^7 \pm 5.38 \times 10^6$	52 ± 2	9.1
<2.0	241	2.51 ± 0.02	$2.87 \times 10^7 \pm 2.74 \times 10^6$	52 ± 2	4.2
<1.5	140	0.5 ± 0.02	...	48 ± 3	...

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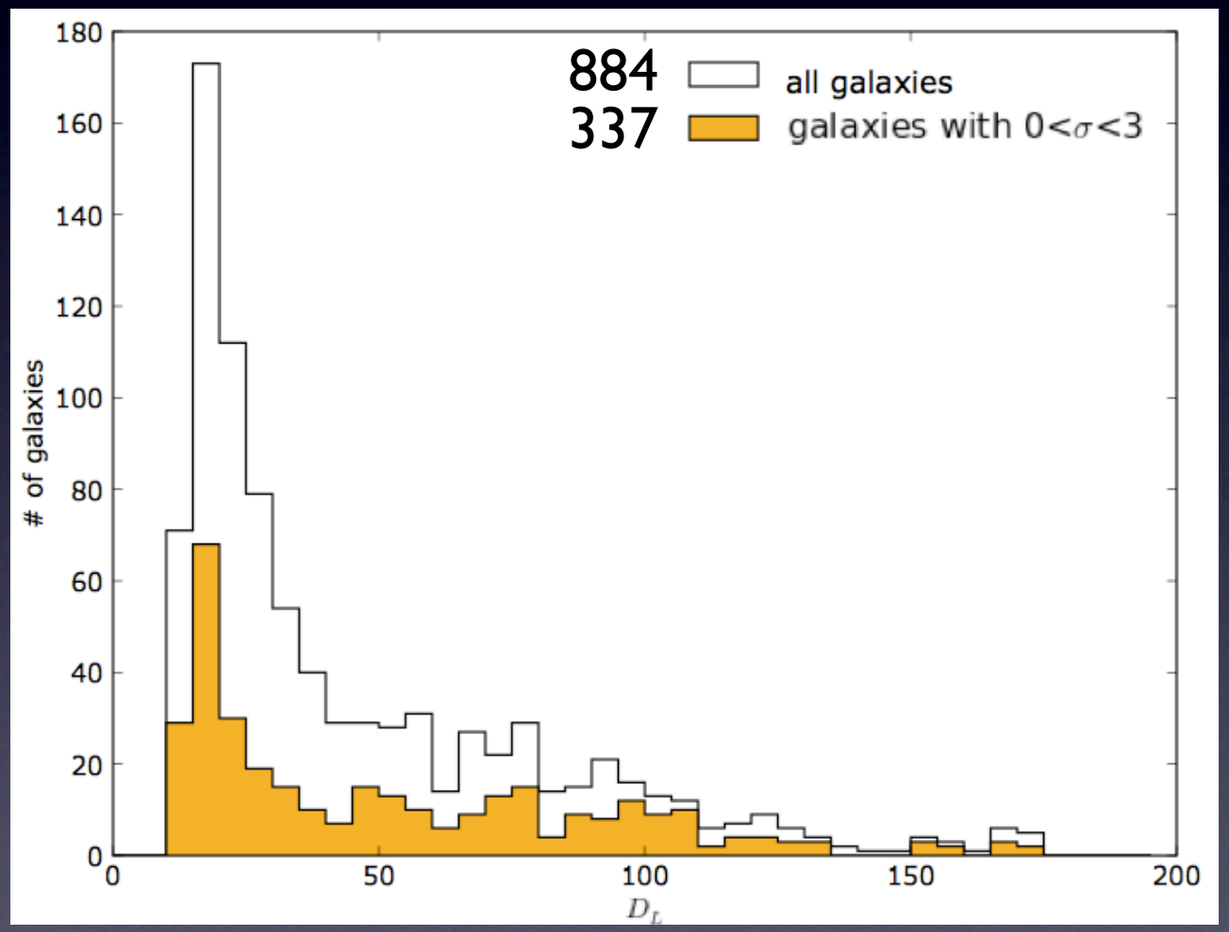

Picking up the CRUMBS...

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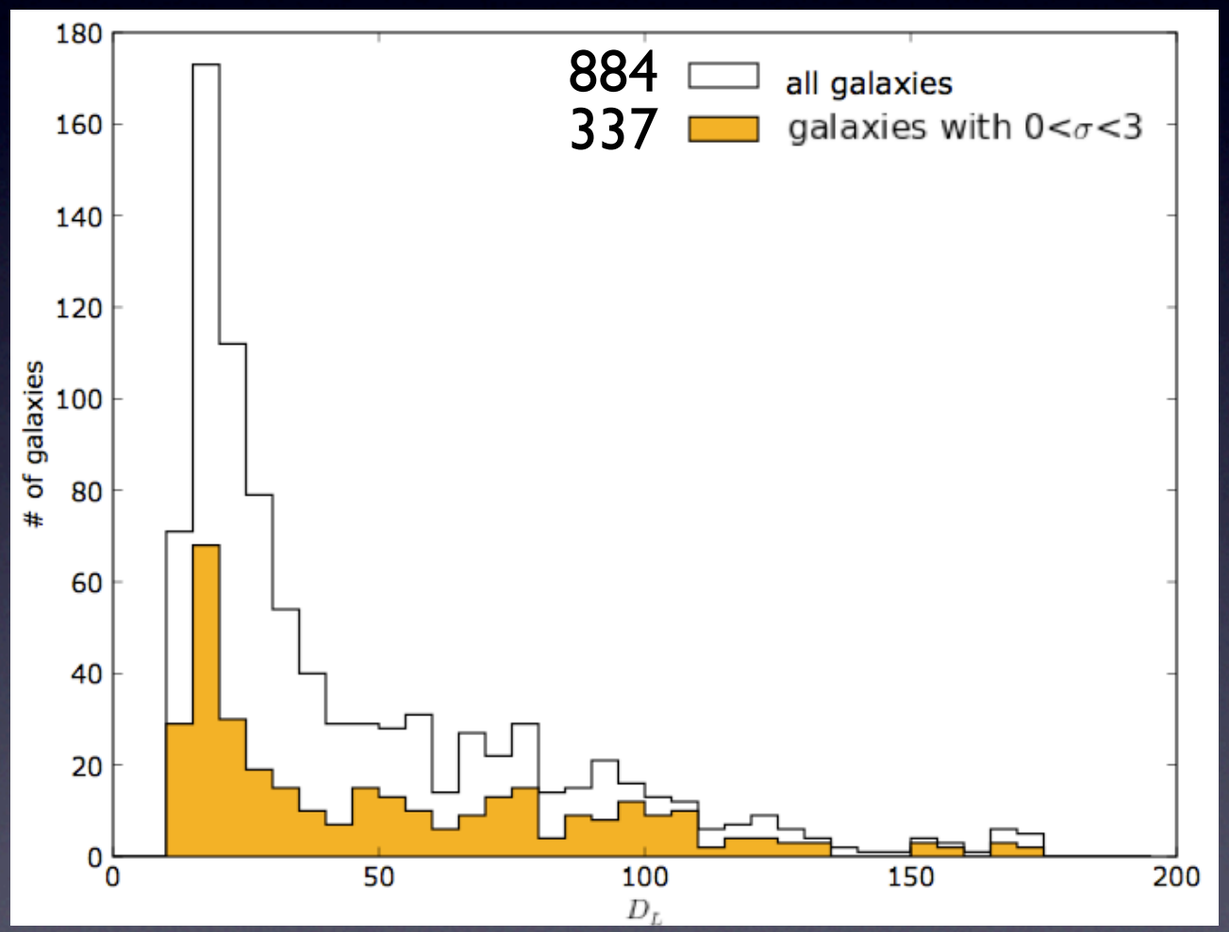
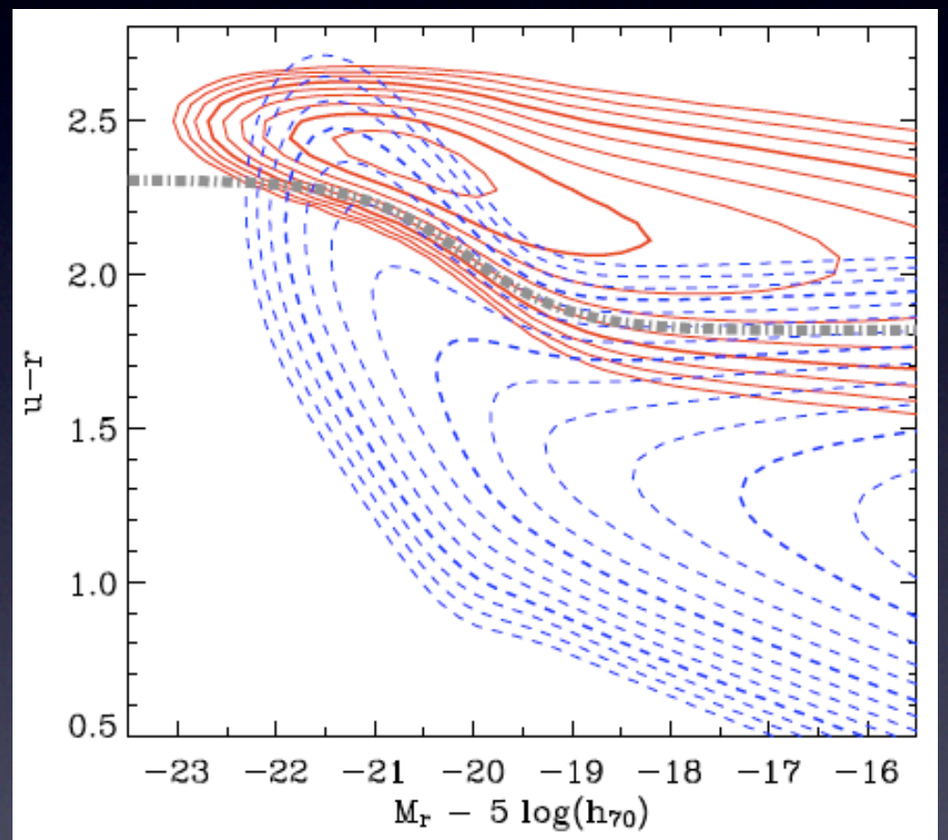
To understand how the non-detections were distributed, we implemented a red-blue colour cut as a morphology handle:





$$C'_{ur}(M_r) = 2.06 - 0.244\tanh\left[\frac{M_r + 20.07}{1.09}\right]$$

Baldry et al., ApJ 600 (2004) 681

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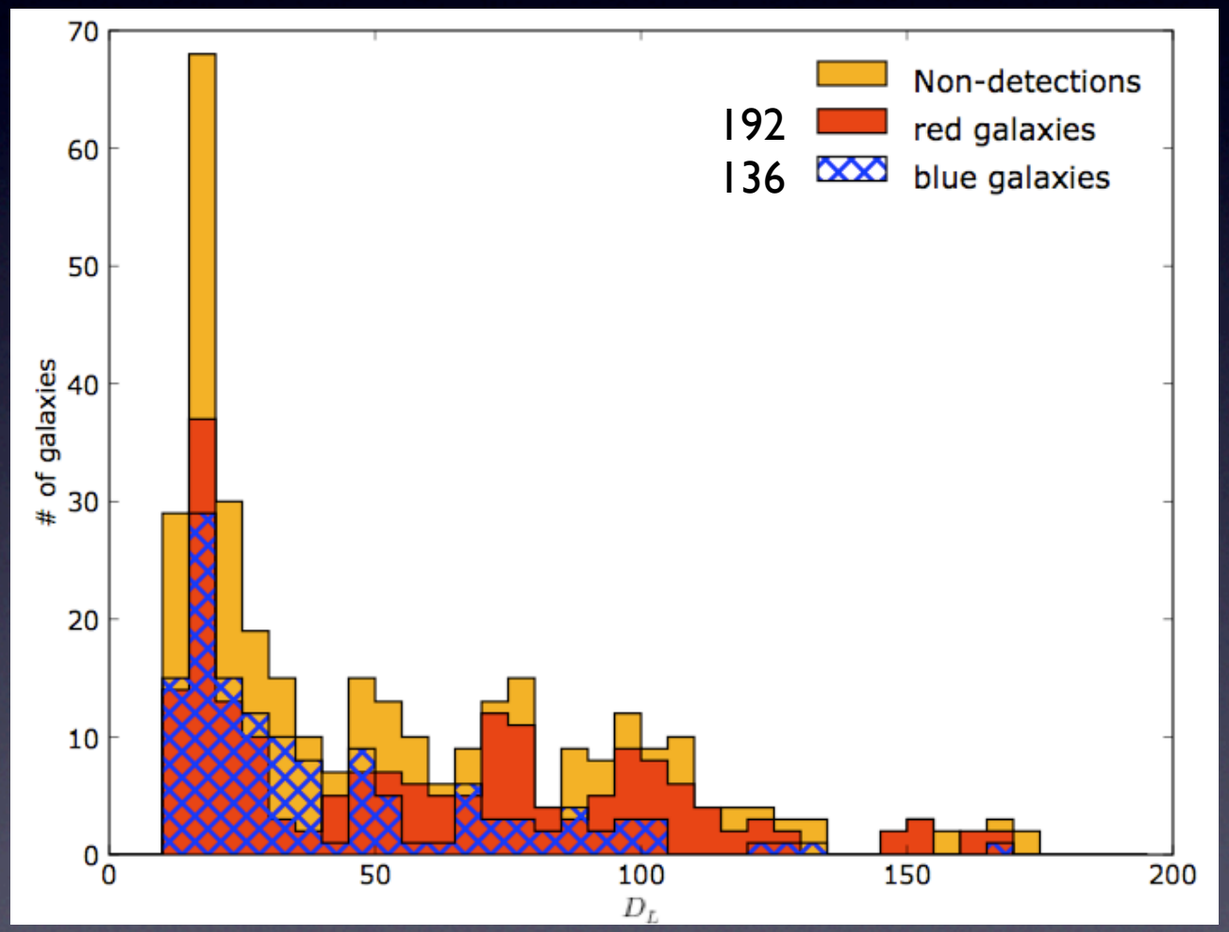

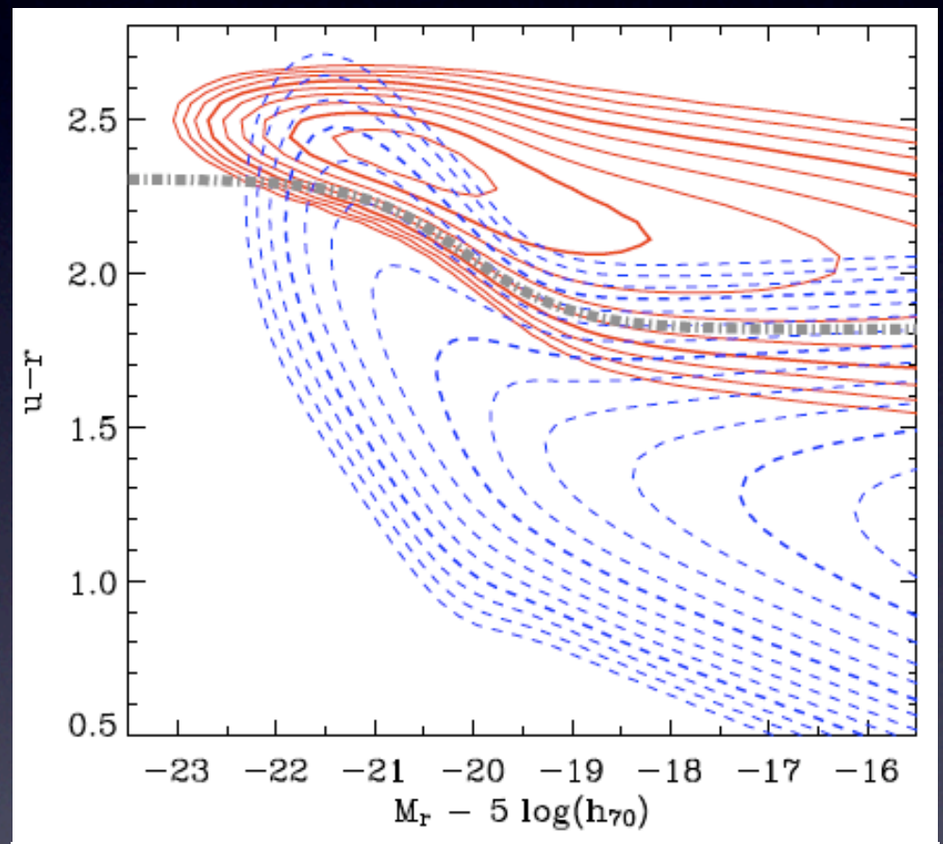

$$C'_{ur}(M_r) = 2.06 - 0.244\tanh\left[\frac{M_r + 20.07}{1.09}\right]$$

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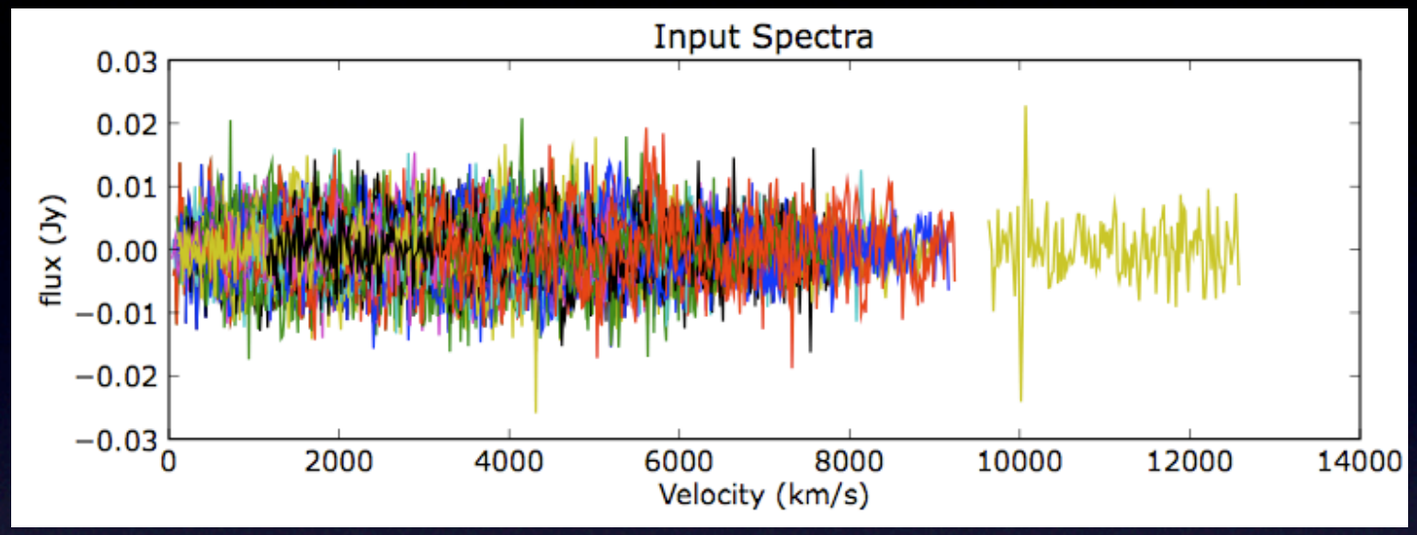
- # of blue galaxies drops off with distance
- red non-detections mostly more distant

Stacking results

e.g. blue non-detections:



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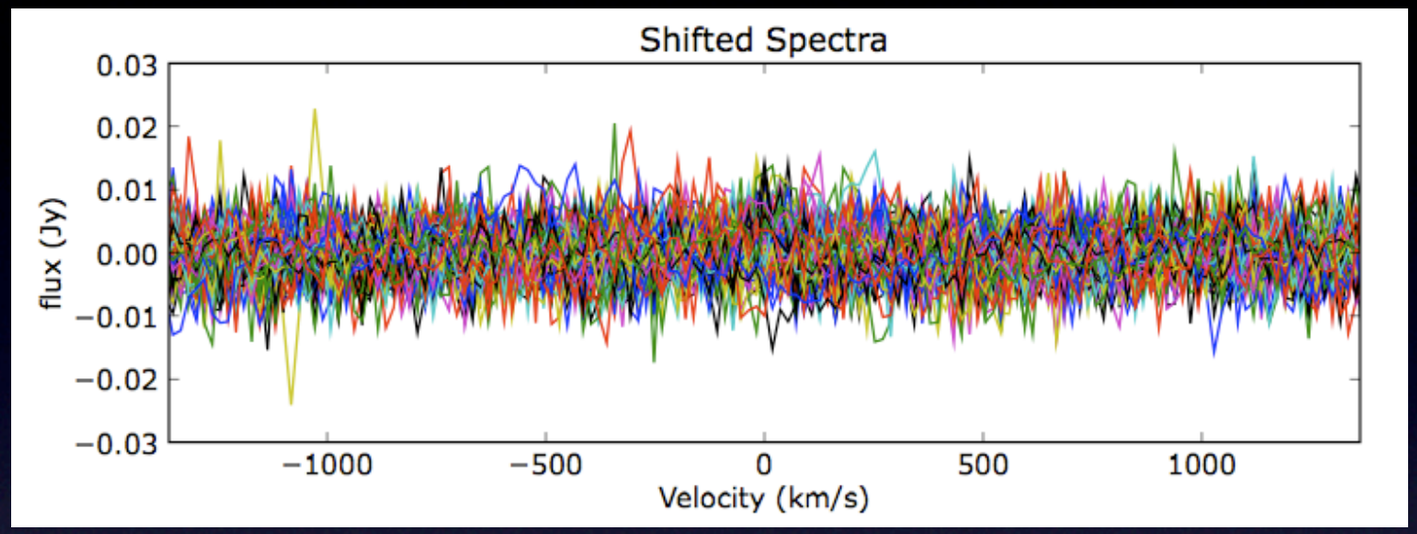

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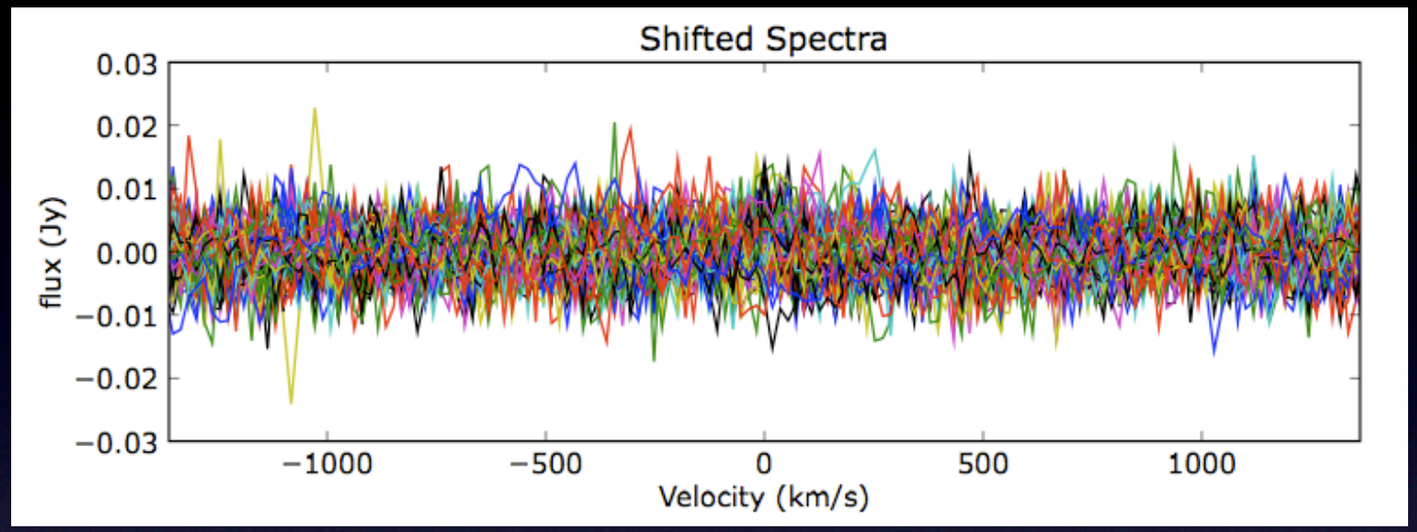

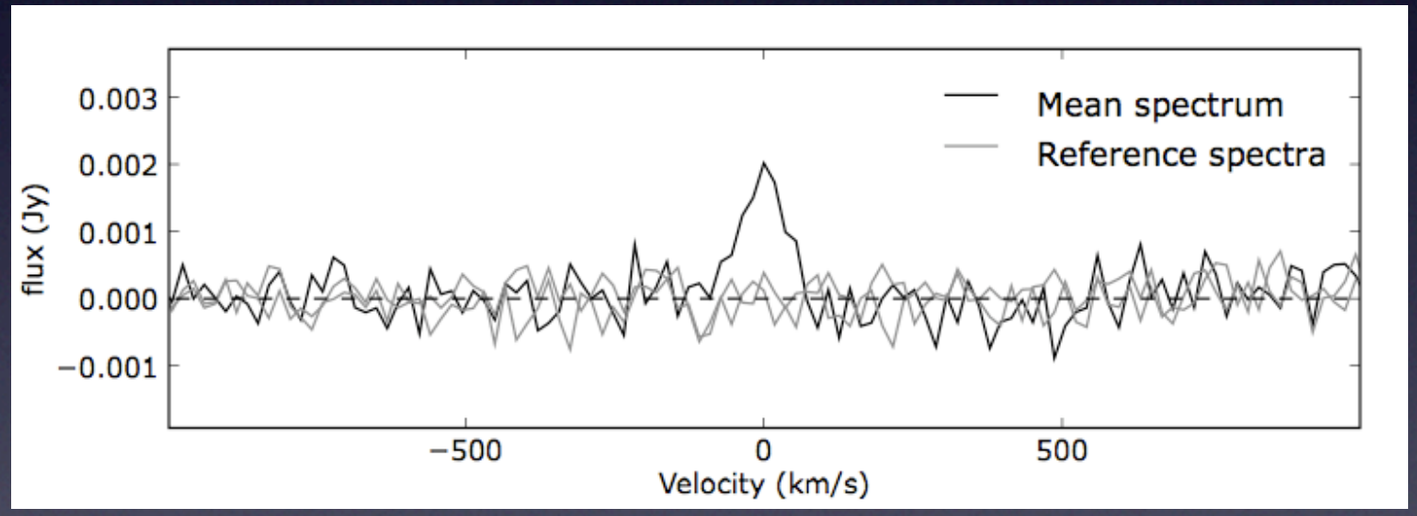

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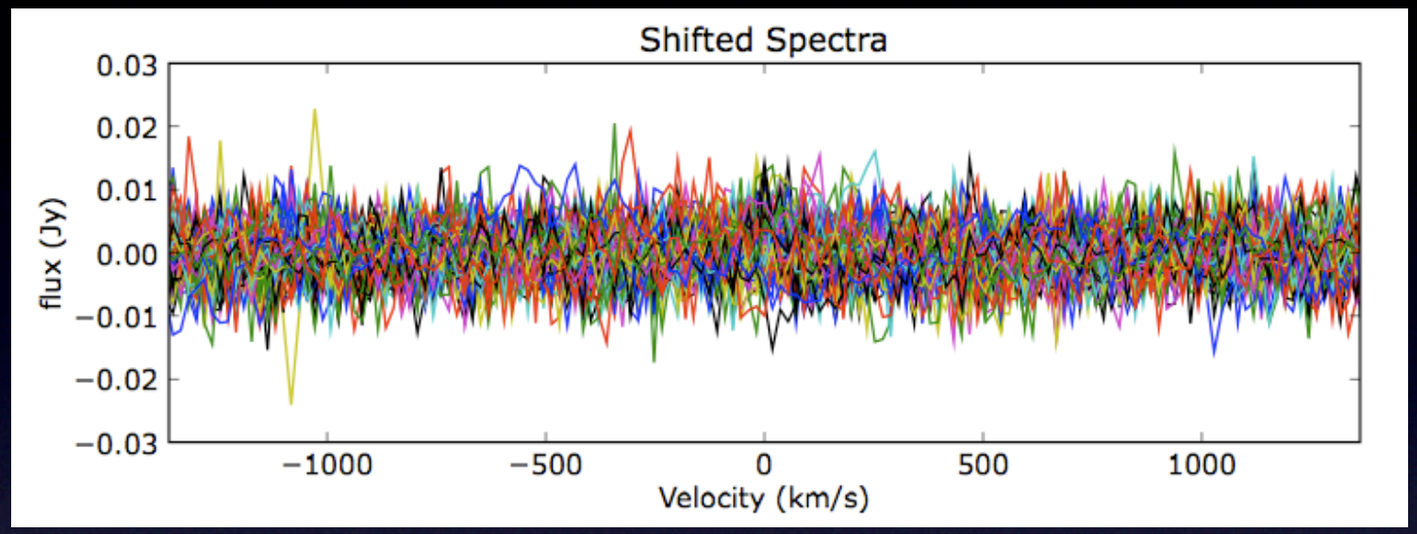

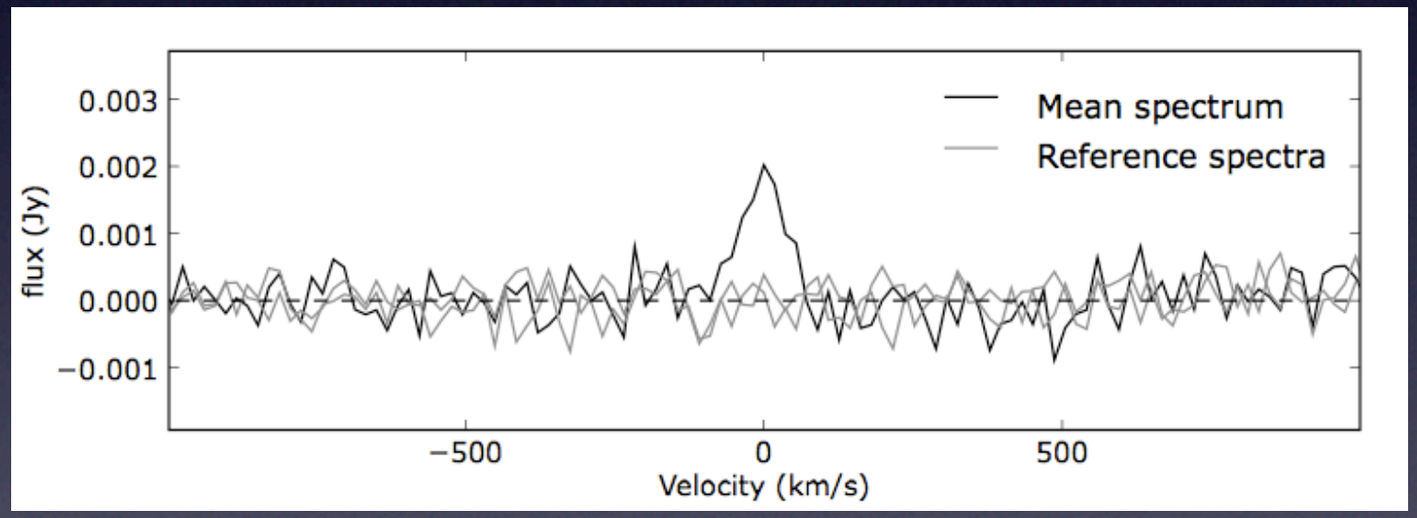

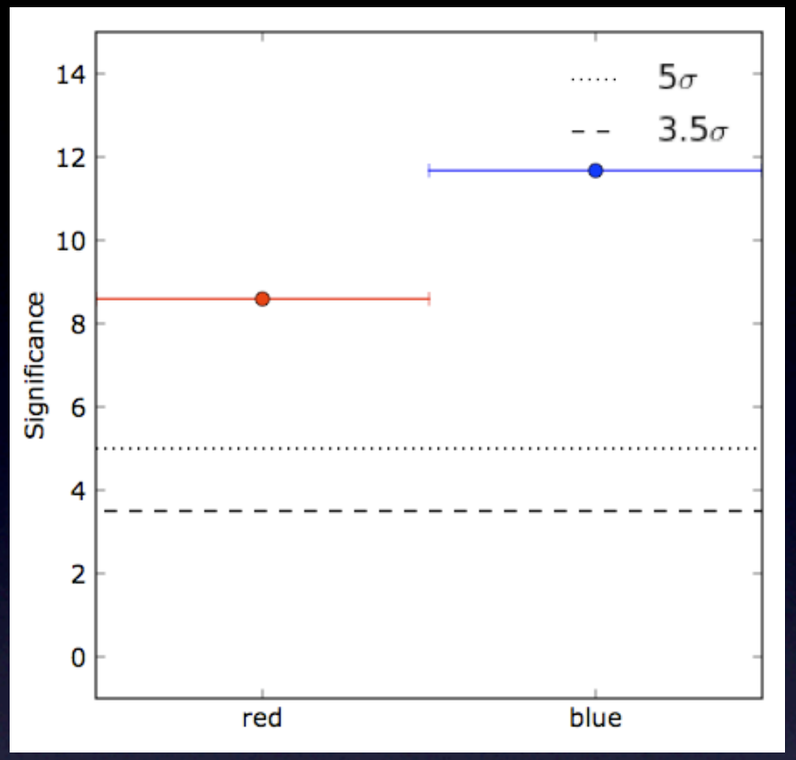

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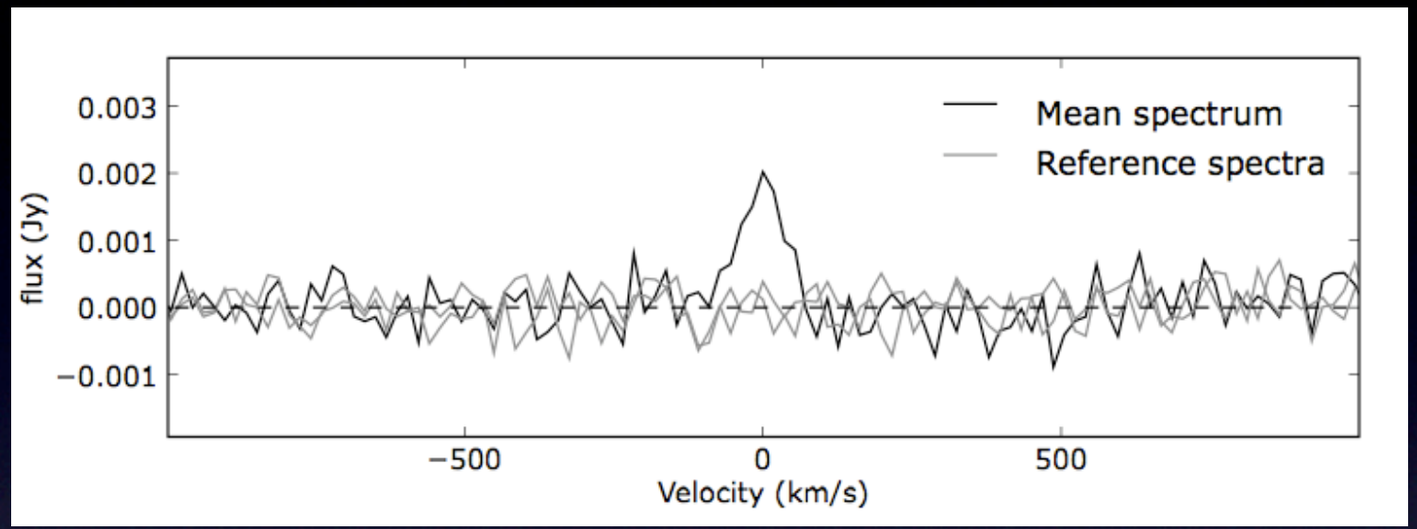
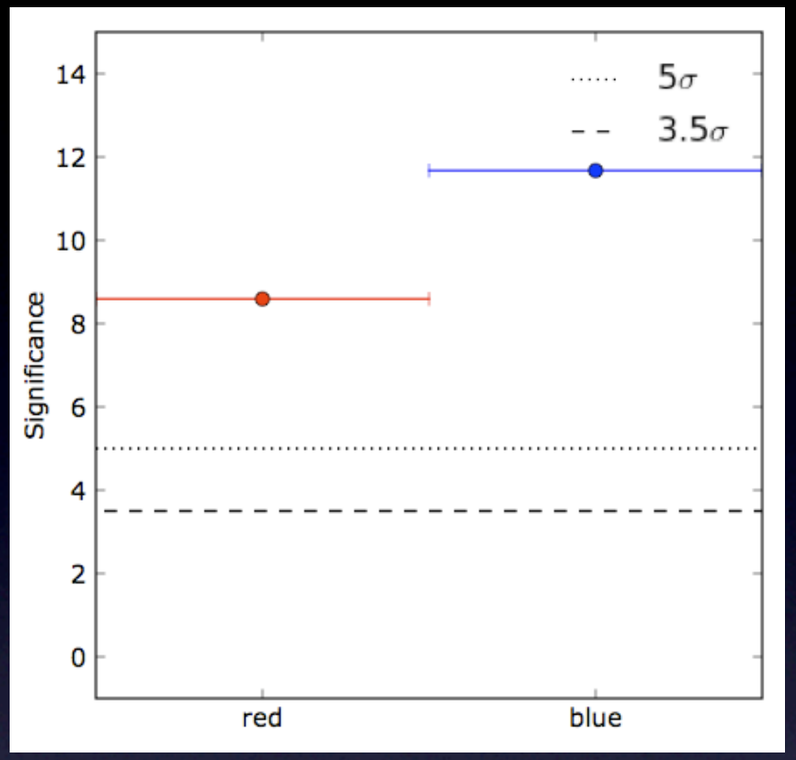
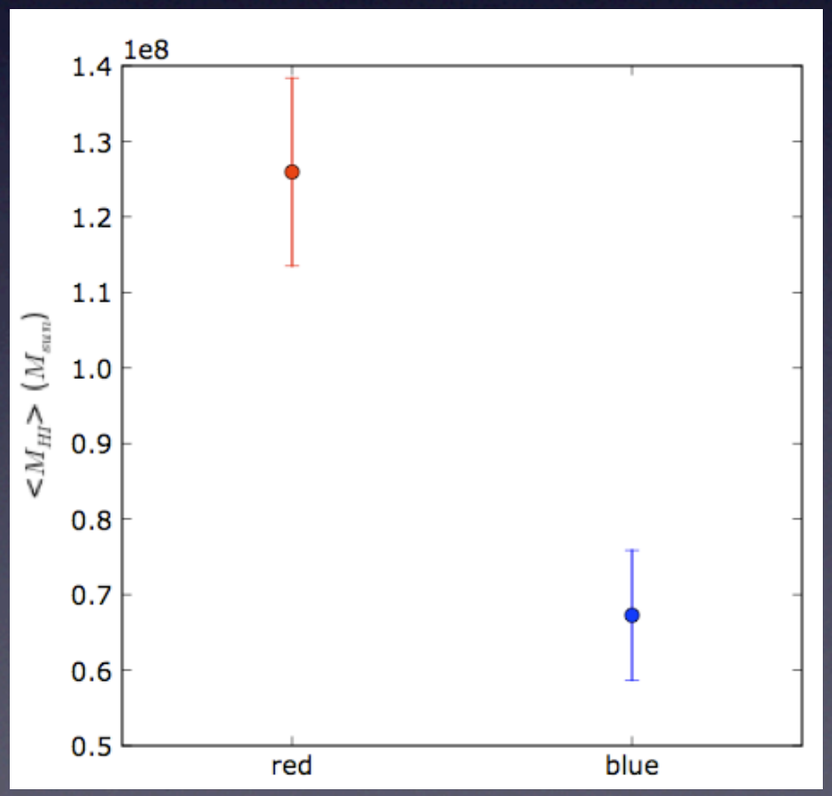




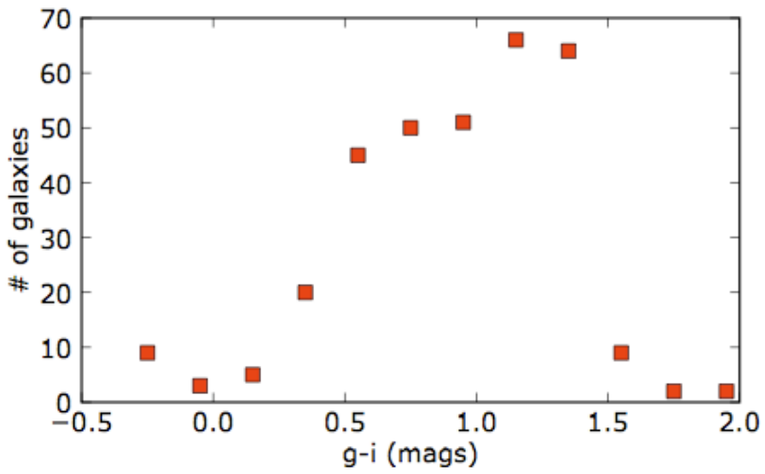


$\langle M_{HI\_red} \rangle = 1.26 \times 10^8 \pm 1.24 \times 10^7\ M_{sun}$

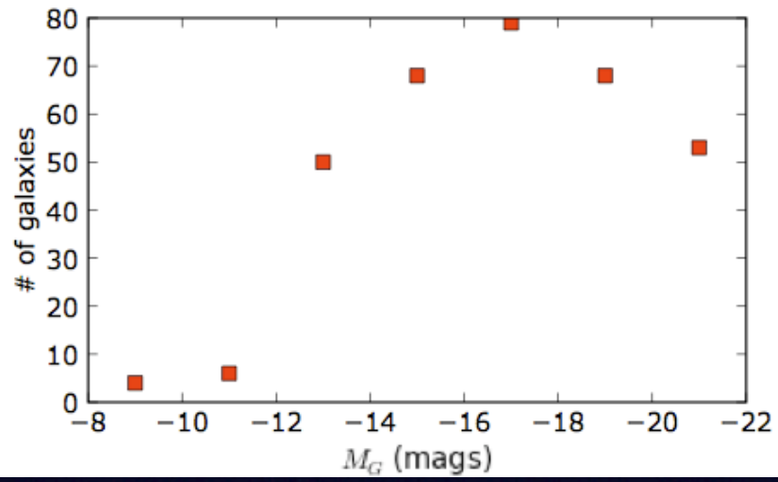
$\langle M_{HI\_blue} \rangle = 6.73 \times 10^7 \pm 8.59 \times 10^6\ M_{sun}$

More preliminary results...

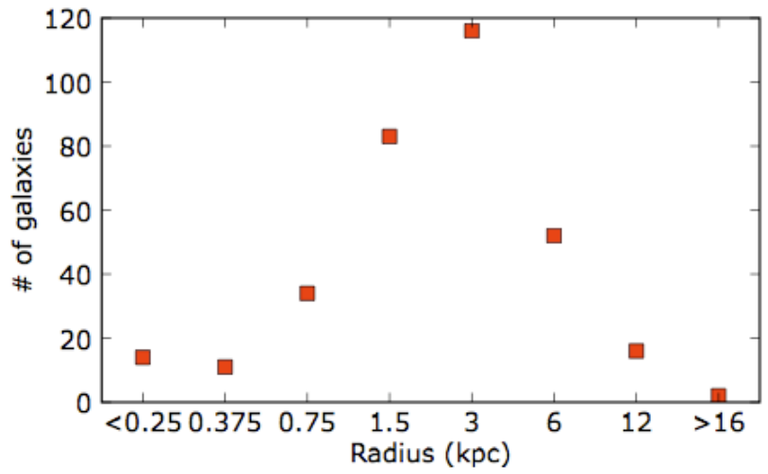
Colour



Magnitude



Radius



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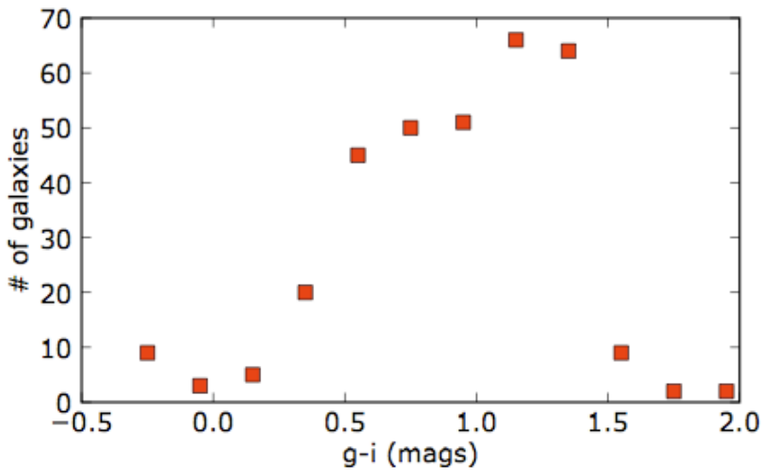
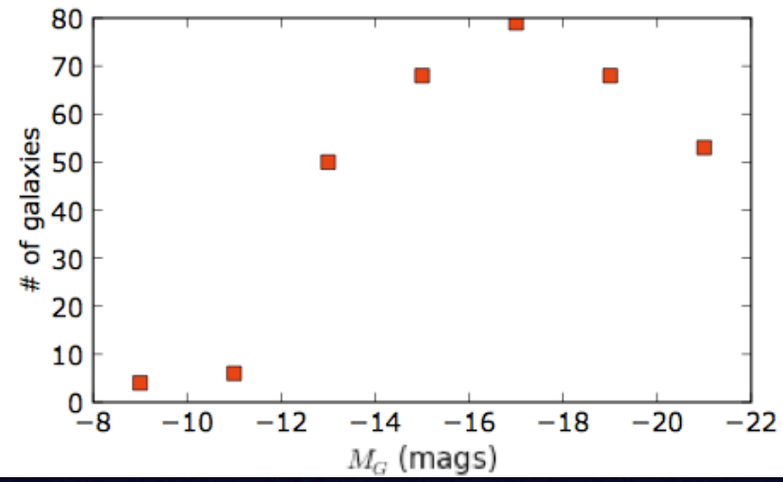
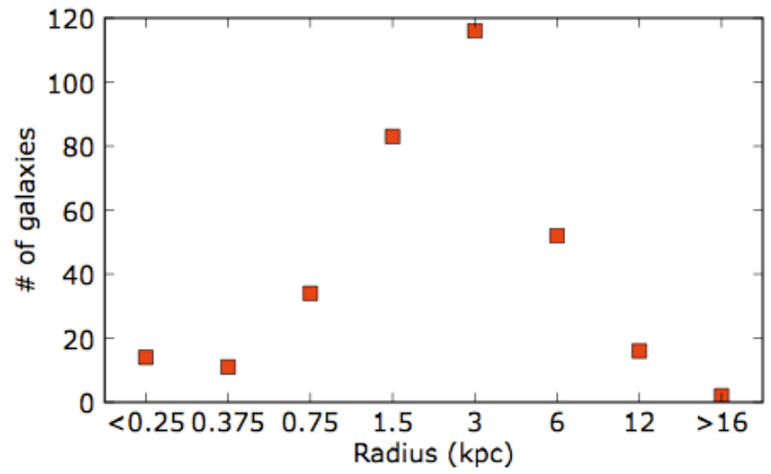
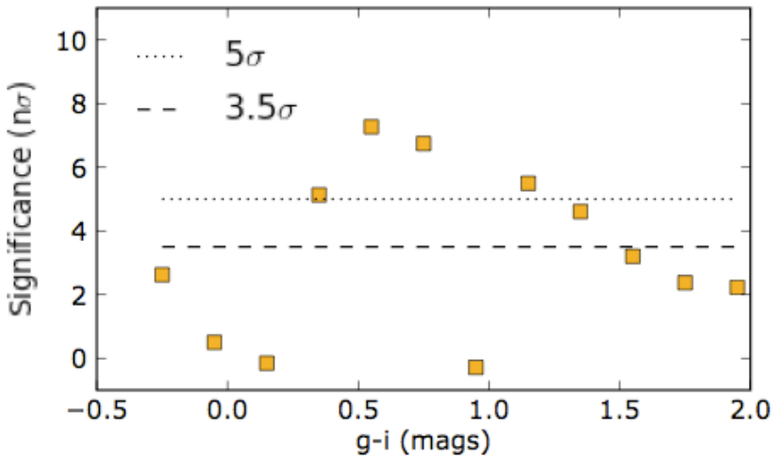
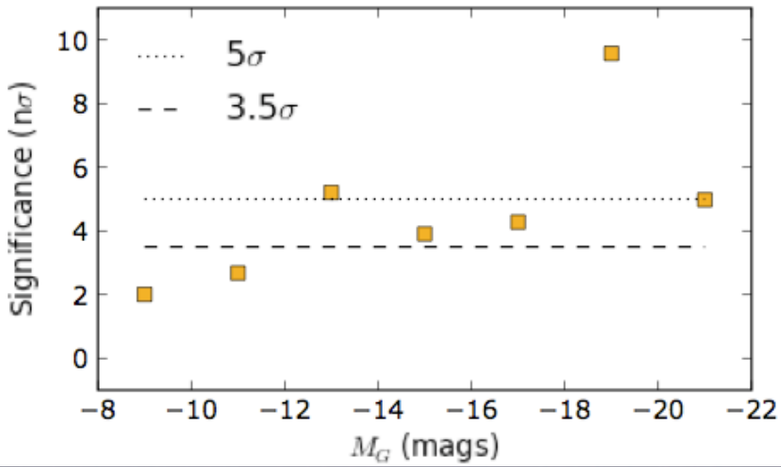
Colour **Magnitude** **Radius**

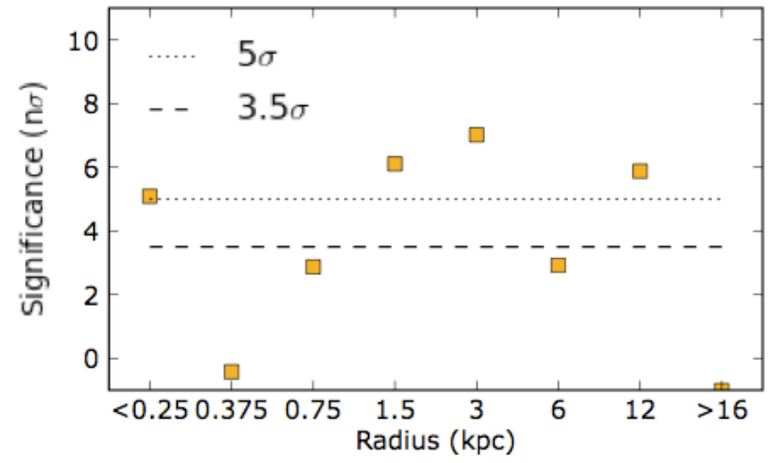






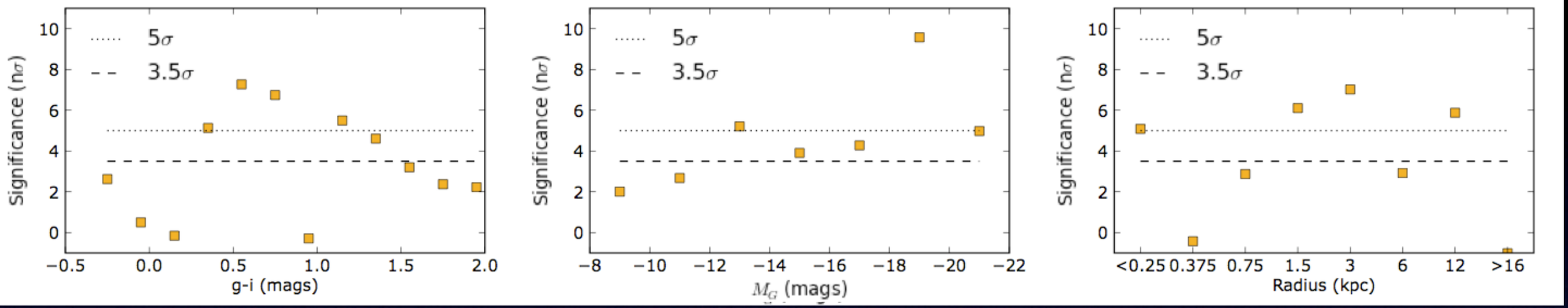


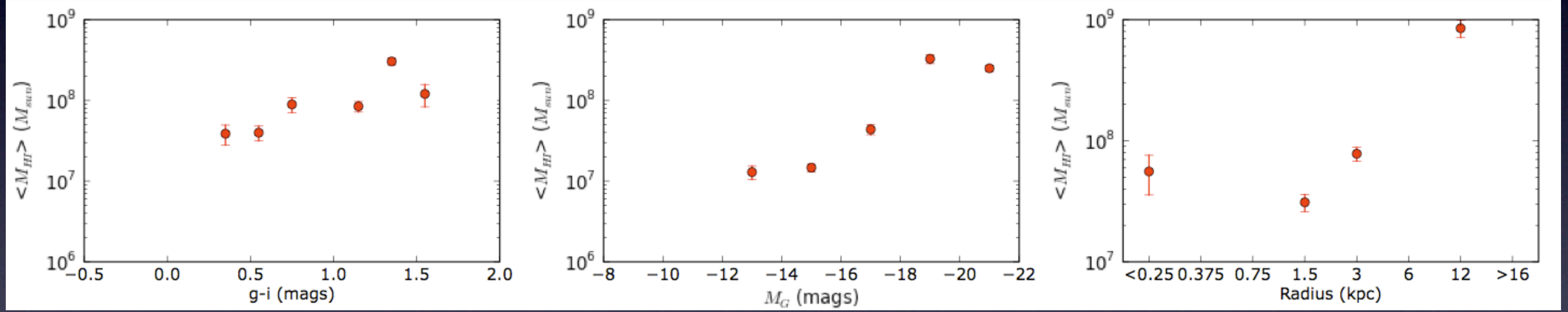




More preliminary results...

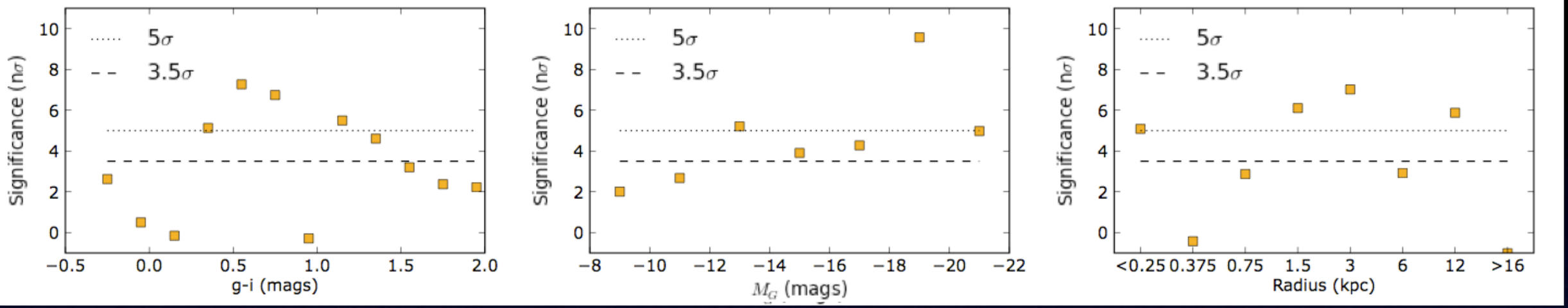
Colour **Magnitude** **Radius**

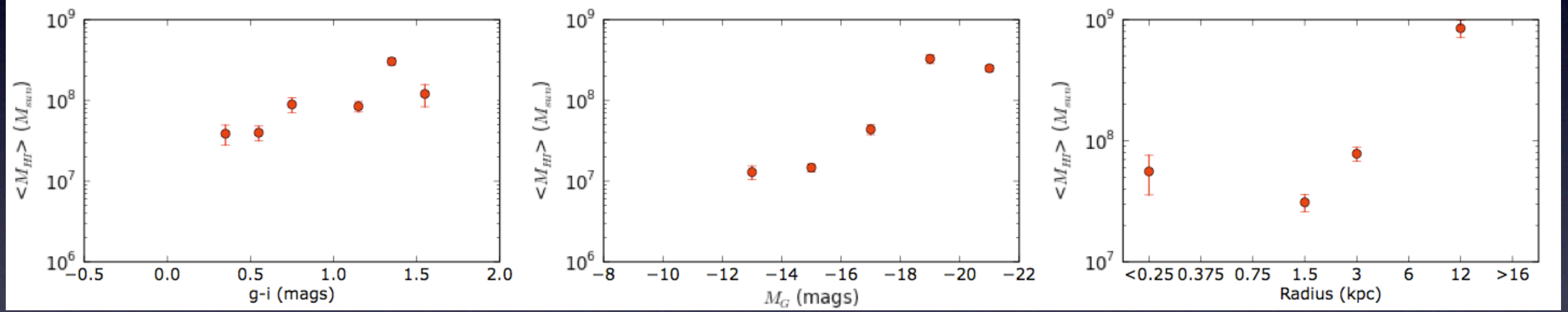




More preliminary results...

Colour **Magnitude** **Radius**

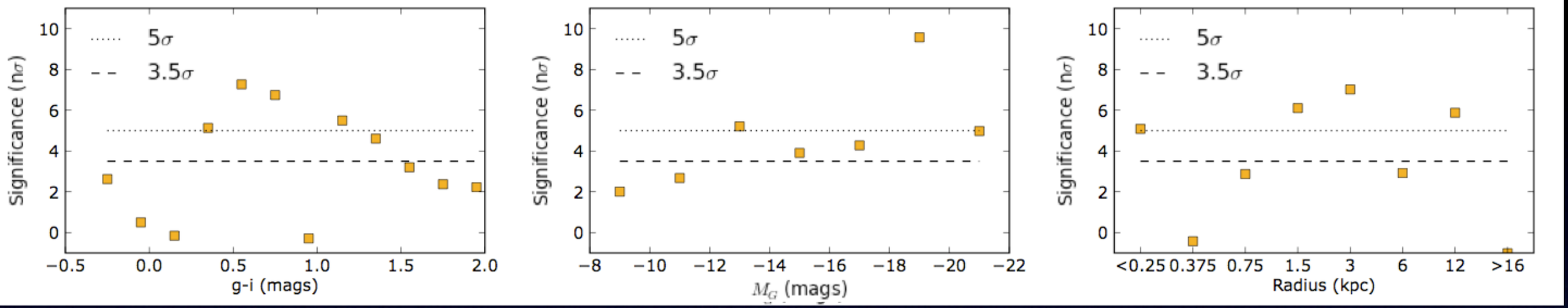


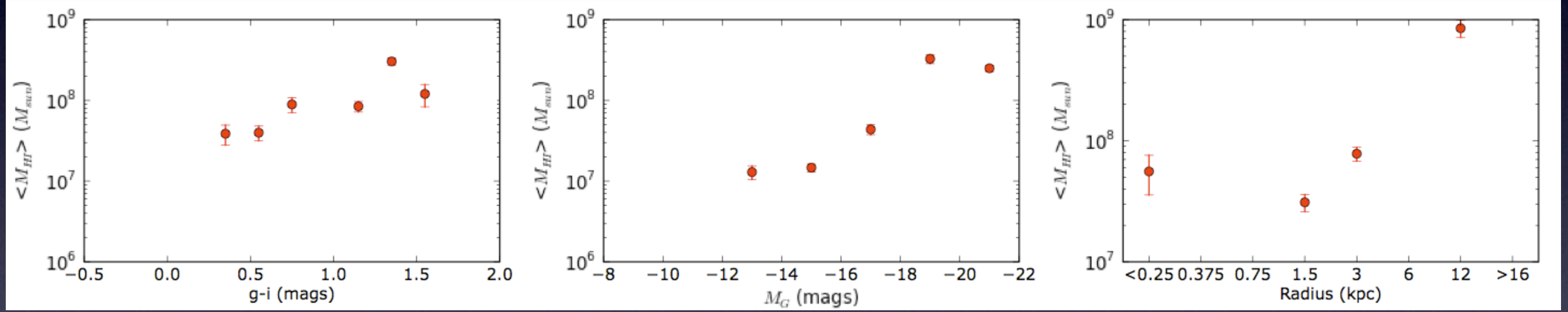


- $<M_{HI}>_{red}$ > $<M_{HI}>_{blue}$
- Non-detection bias:
  - sampling HI-poor blue galaxies
  - sampling bright red galaxies

More preliminary results...

Colour **Magnitude** **Radius**





- $<M_{HI}>_{red}$ > $<M_{HI}>_{blue}$
- Non-detection bias:
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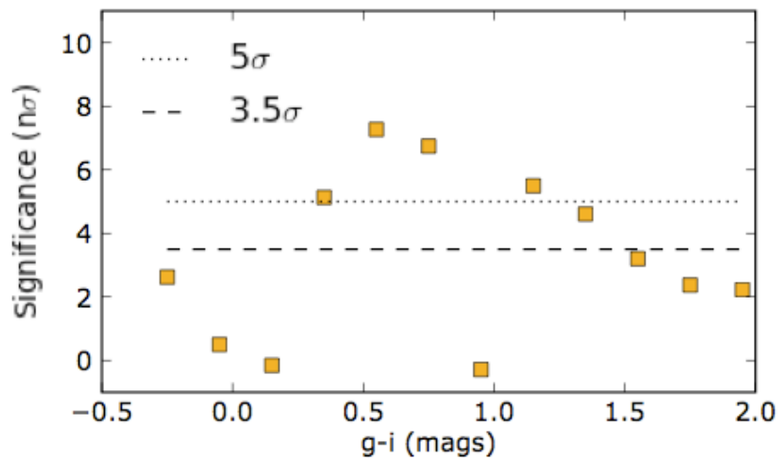
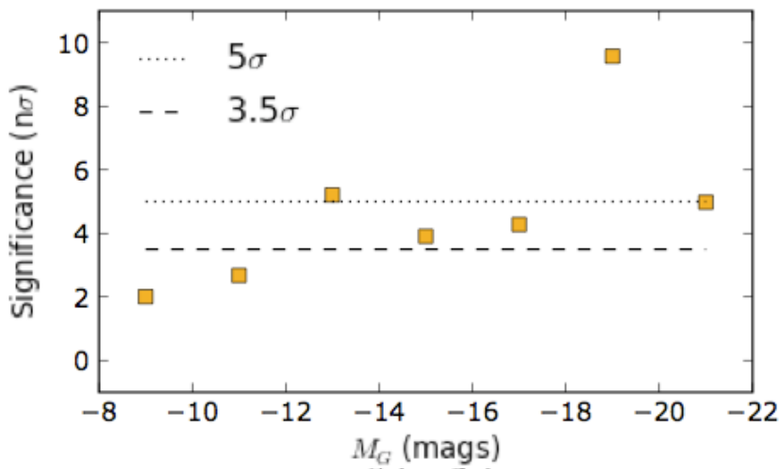
- Brighter galaxies: larger $<M_{HI}>$
- expect drop-off for M_G fainter than ~ -19

More preliminary results...

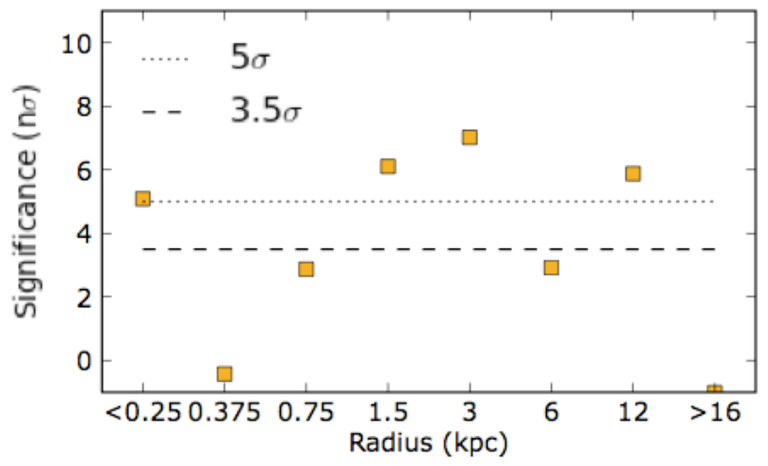
Colour

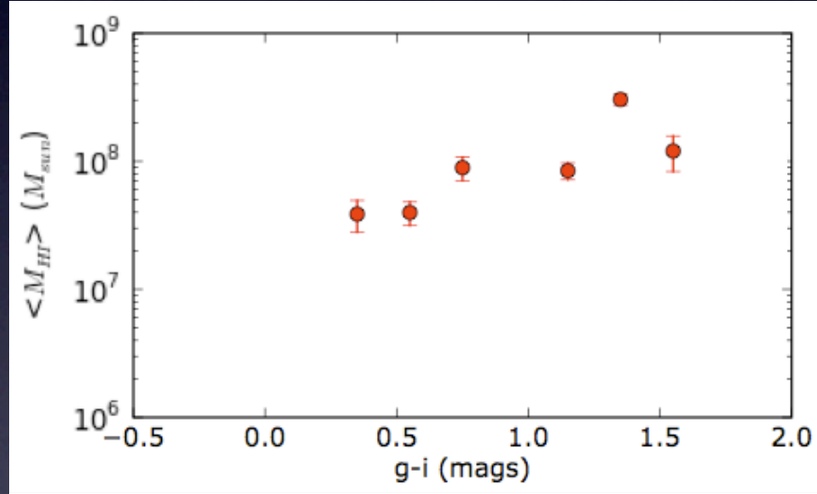


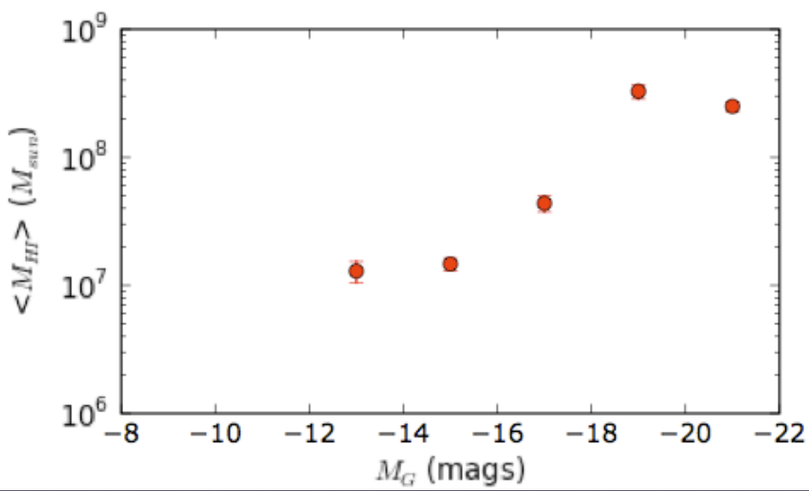
Magnitude

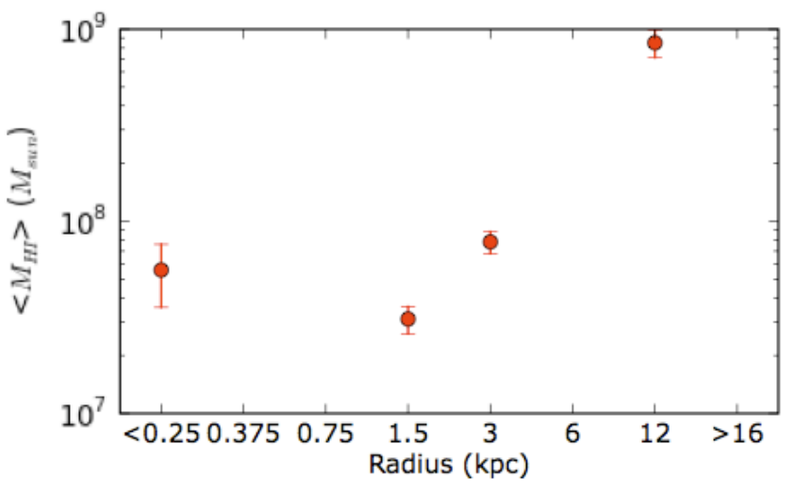


Radius









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- Non-detection bias:
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  - sampling bright red galaxies

- Brighter galaxies: larger $<M_{HI}>$
- expect drop-off for M_G fainter than ~ -19

- Bigger galaxies: larger $<M_{HI}>$

Outline

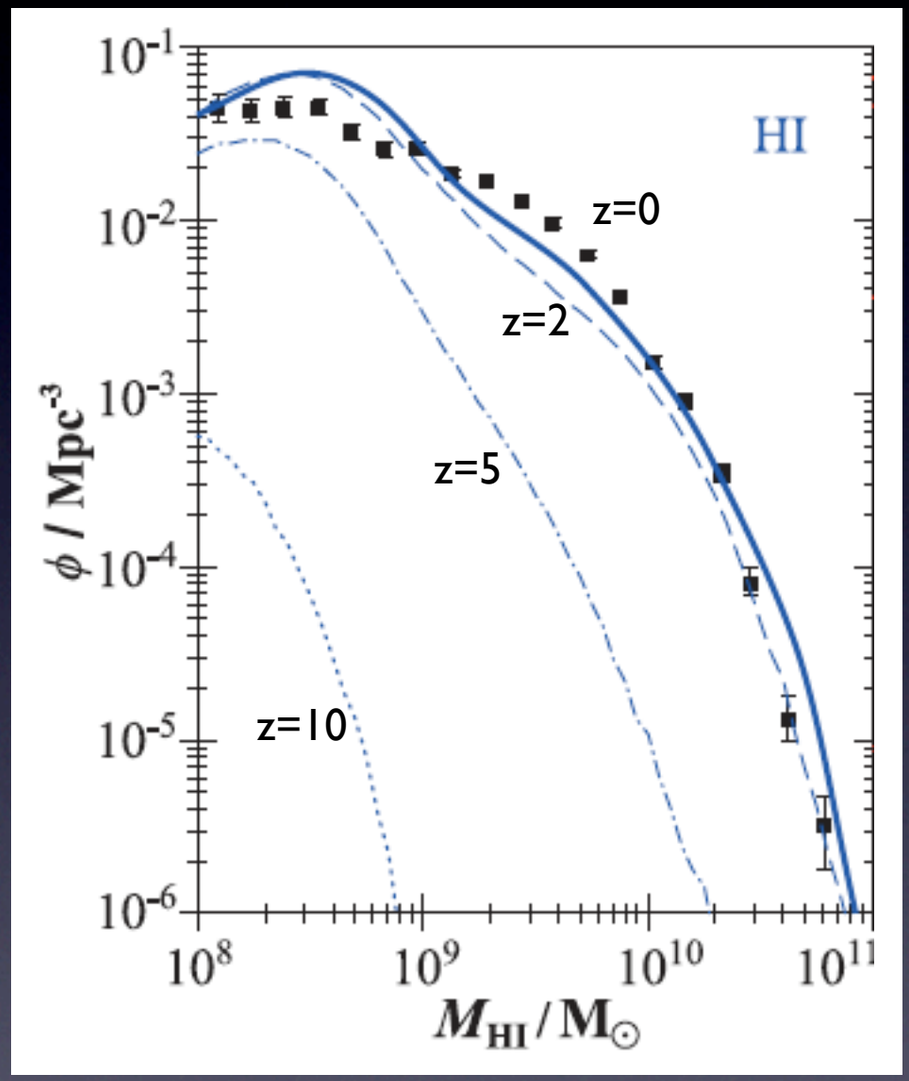
- HI-stacking techniques: measuring HI in galaxy surveys
- Application to the nearby Universe
- **Probing higher z with MeerKAT**
- Summary and Outlook

Simulations Input for Stacking

We have used a simulated galaxy catalogue from Obreschkow & Rawlings et al., (arXiv:0904.2221v2):

- Obreschkow et al. simulate cosmic evolution of neutral gas (HI and H_2) based on the virtual galaxy catalogue by De Lucia on Millenium simulation (Springel et al., 2005)

- Produce catalogue of 6 x10^7 galaxies ($0 < z < 9.7$) , complete for $M_{(HI+H2)}$ >10^8 M_{sun}
  - galaxy properties incl. parameters of realistic velocity profiles, (W_{20}, W_{50}, F_{peak} etc.)



D. Obreschkow & S. Rawlings, arXiv:0904.0213v3

Includes evolving HIMF

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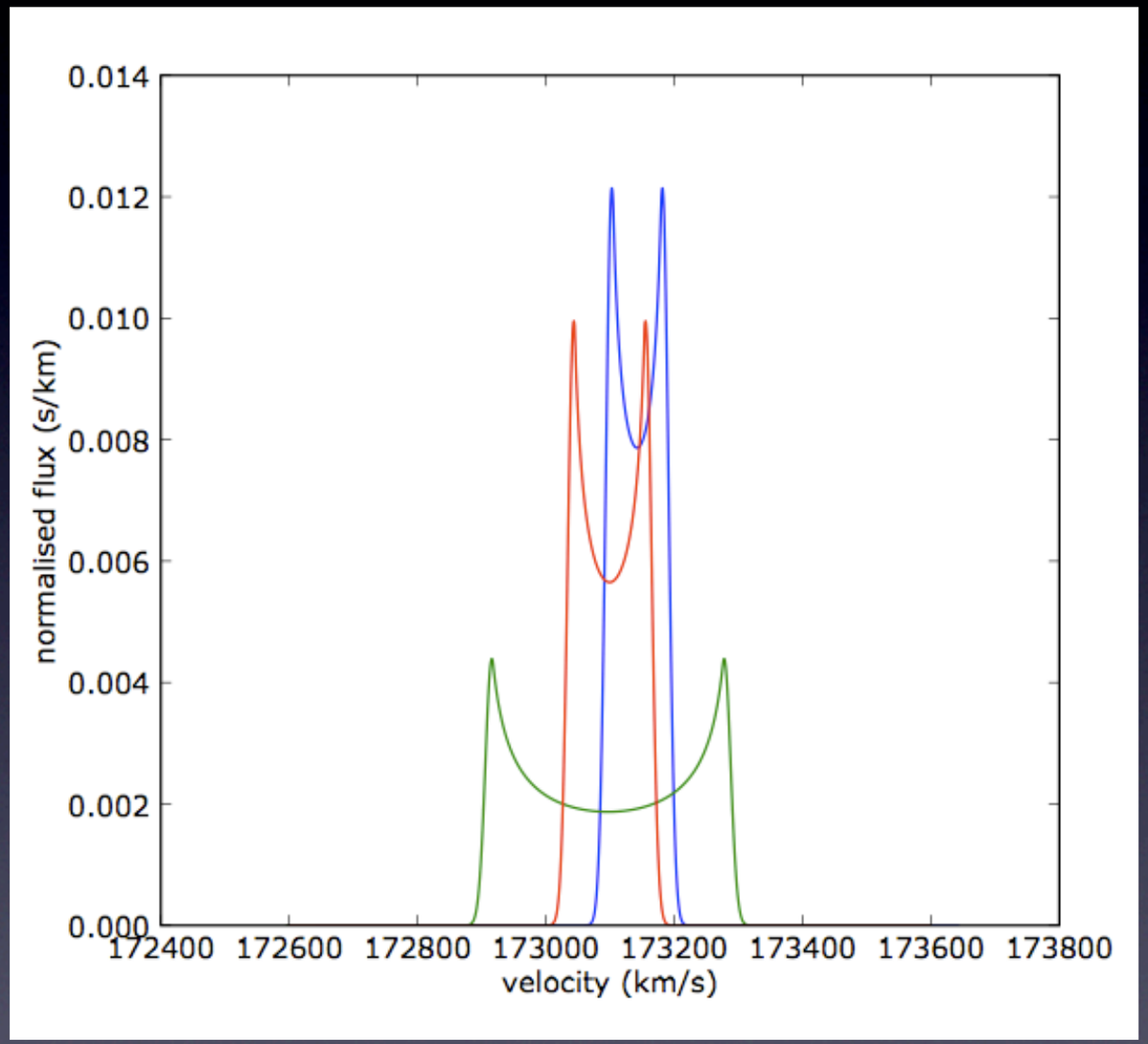


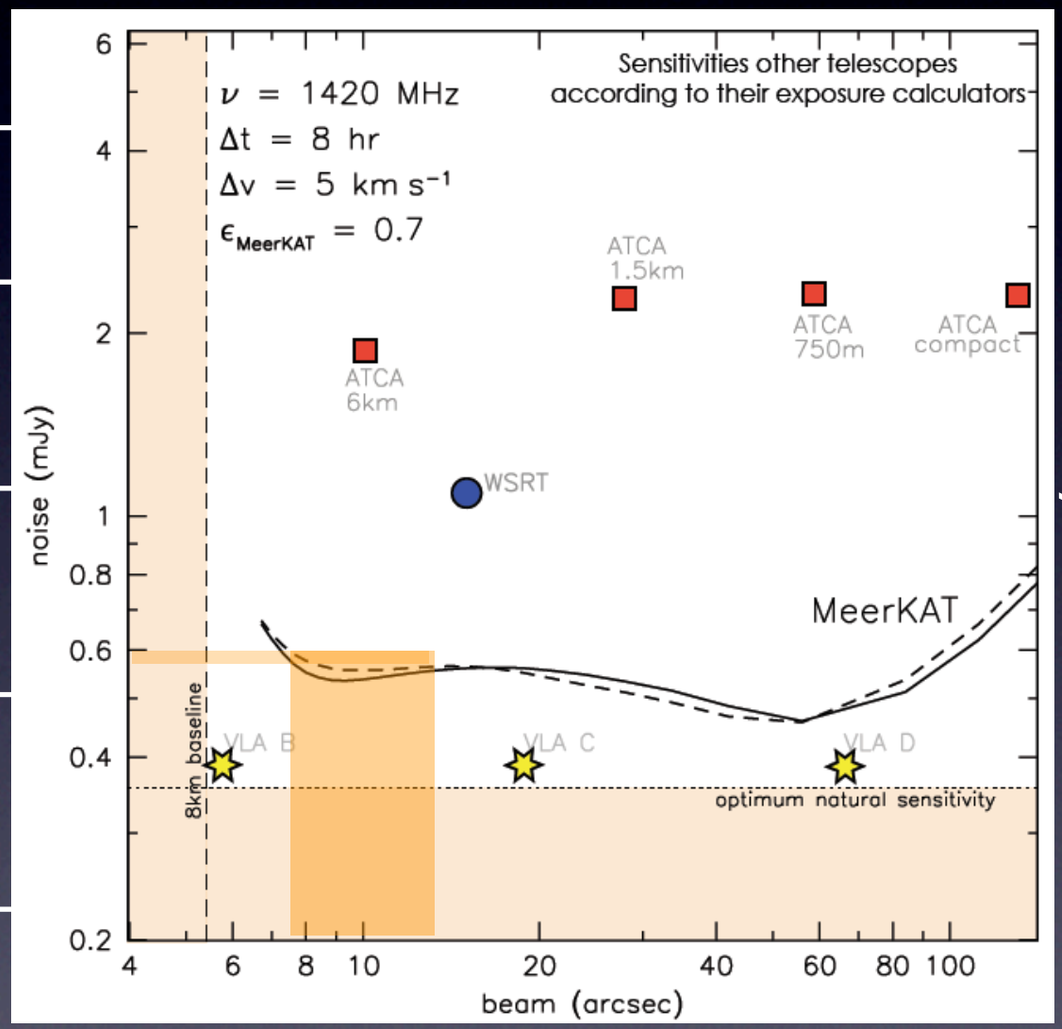
Includes evolving HIMF

Stacking Experiments for MeerKAT

We have simulated 3 survey scenarios for a single pointing observation with MeerKAT:

- Using sensitivities based on MeerKAT, 80 dish layout (E. de Blok's talk)

Survey Scenario
S1: 3 months (90 days x 12 hours)
S2: 6 months (180 days x 12 hours)
S3: 1 year (365 x 12 hours)



see talk by E. de Blok

- Set channel width = 0.096 MHz:
  - 22.3 km/s at z = 0.1
  - 38.5 km/s at z = 0.9

Stacking Experiments for MeerKAT

We have simulated 3 survey scenarios for a single pointing observation with MeerKAT:

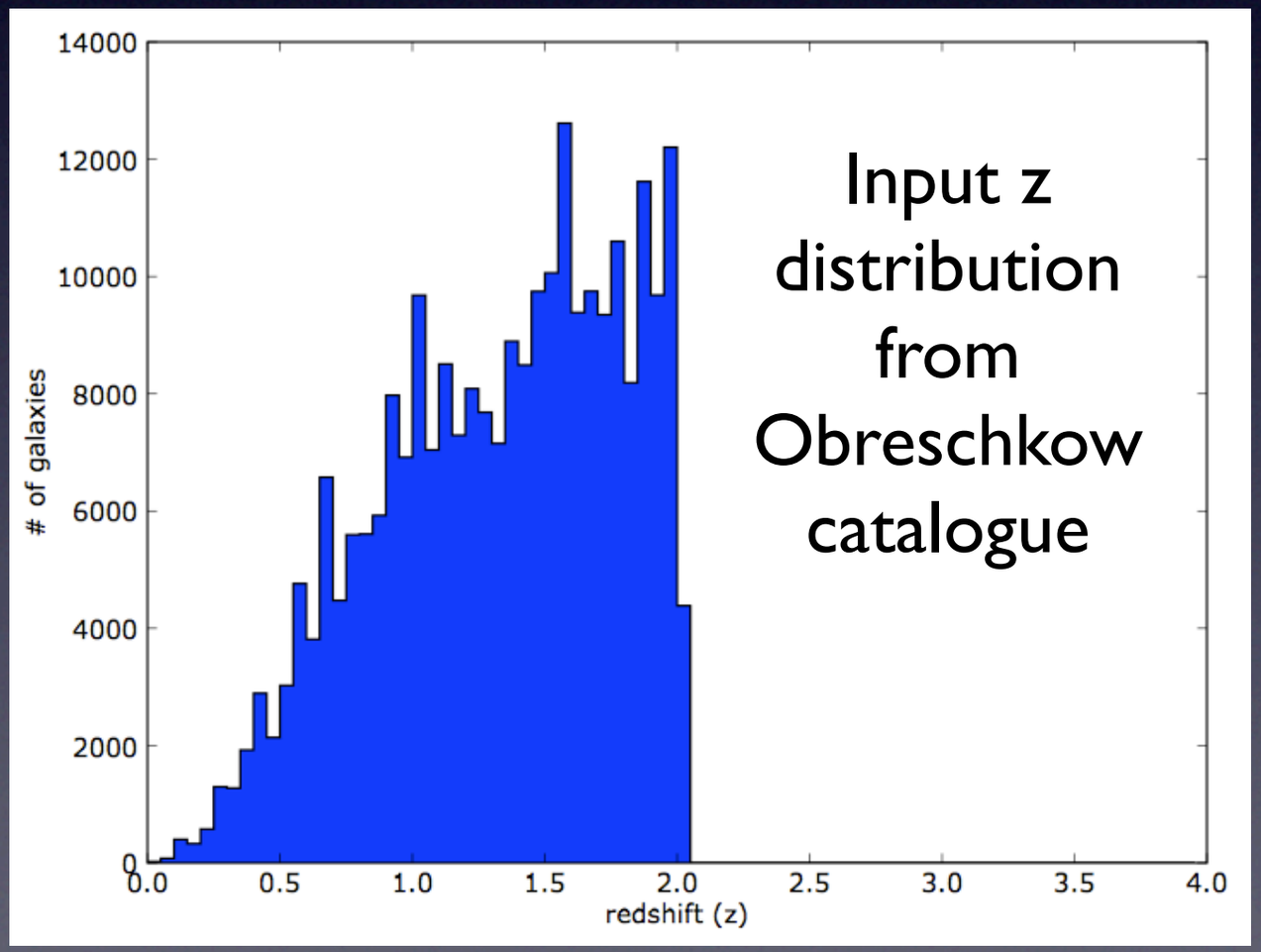
- Using sensitivities based on MeerKAT, 80 dish layout (E. de Blok's talk)

Survey Scenario	Expected noise rms
S1: 3 months (90 days x 12 hours)	2.55×10^{-2} mJy
S2: 6 months (180 days x 12 hours)	1.807×10^{-2} mJy
S3: 1 year (365 x 12 hours)	1.269×10^{-2} mJy

- Set channel width = 0.096 MHz:
  - 22.3 km/s at z = 0.1
  - 38.5 km/s at z = 0.9

Simulation parameters

- FoV = 0.47 deg x 0.47 deg (**= 25% MeerKAT FoV**)
- Simulate 'real' MeerKAT bandwidth of 512 MHz & 16k channels
- Set channel width = 0.096 MHz:
  - 22.3 km/s at z = 0.1 & 38.5 km/s at z = 0.9
- Binned galaxies in z = 0.1 chunks



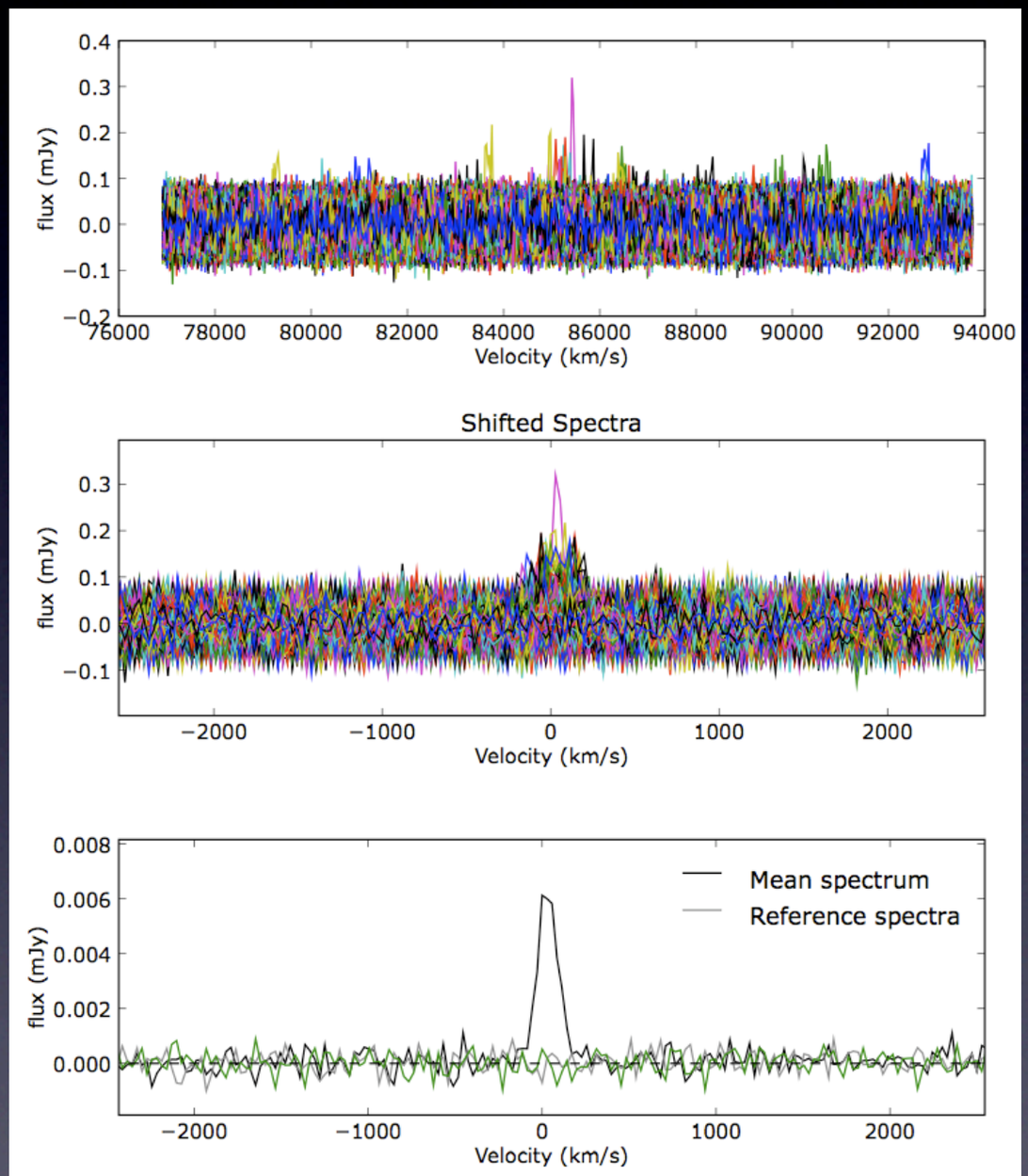
Input z distribution from Obreschkow catalogue

Caveat:

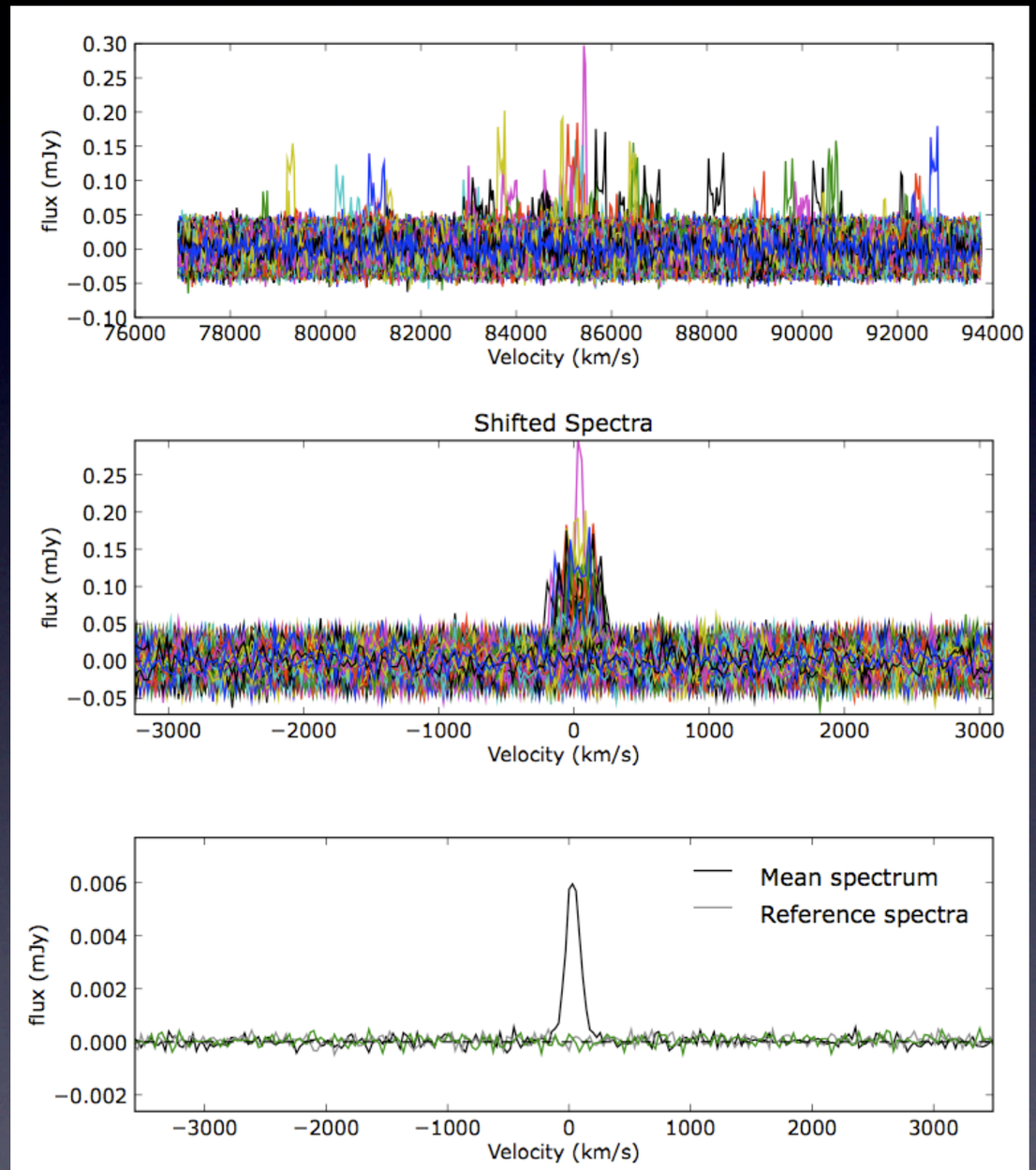
- Assume ALL galaxy redshifts known (i.e. 'perfect' optical data)

Quick comparison at z=0.4

S1: 3 month, single pointing

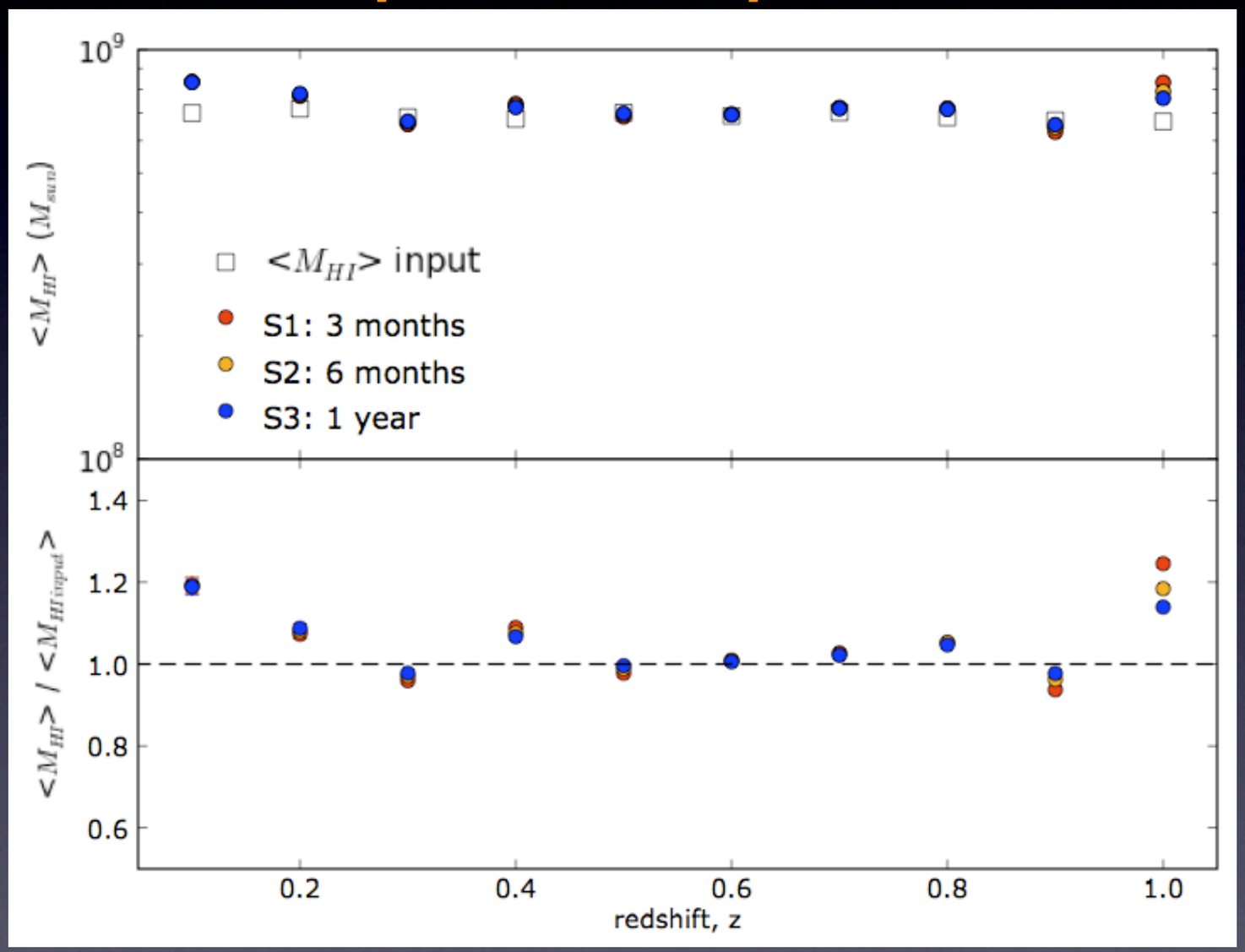


S3: 1 year, single pointing



Preliminary results: towards Ω_{HI}

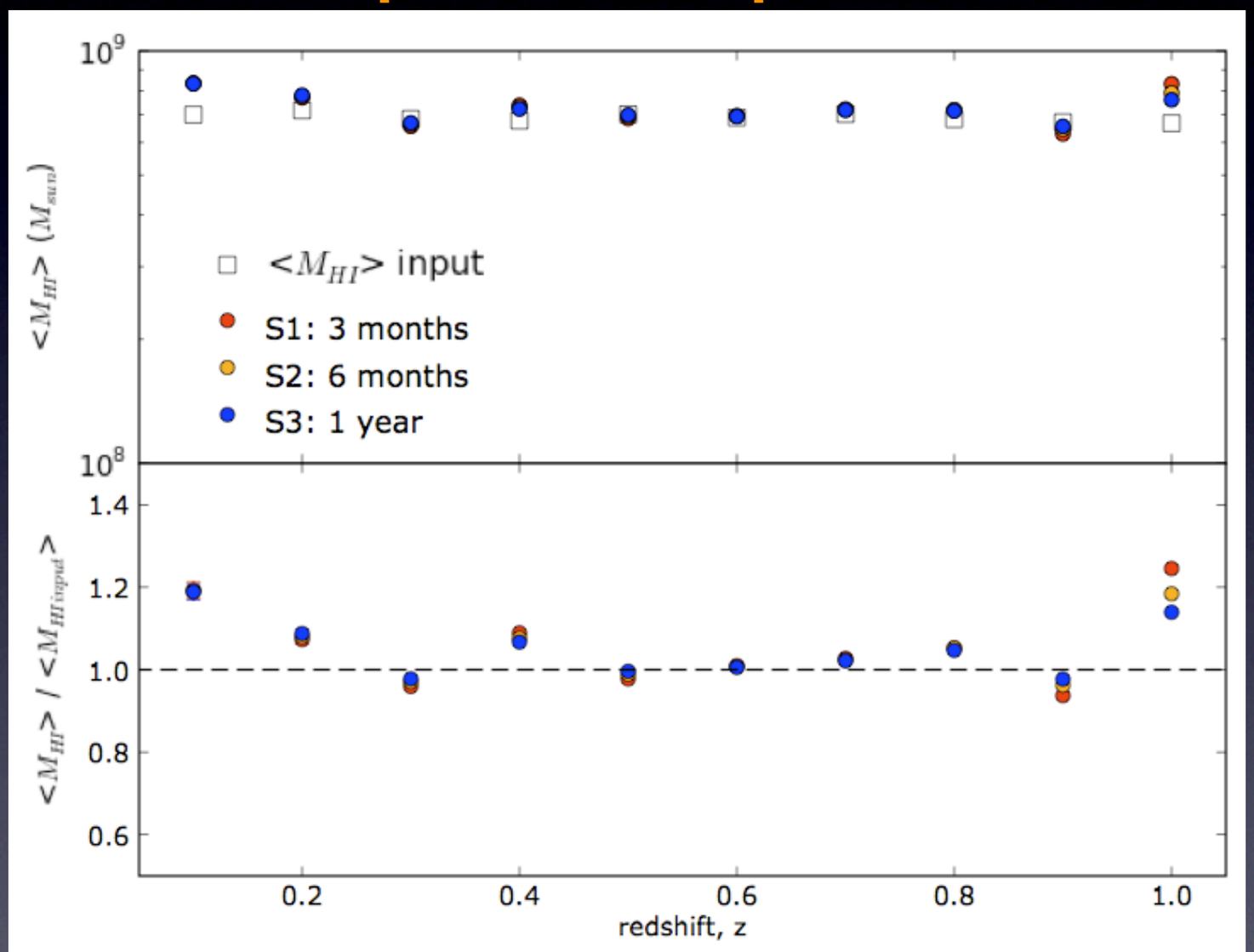
Output <M> vs. Input <M>



- Stacking technique recovers input <M> well

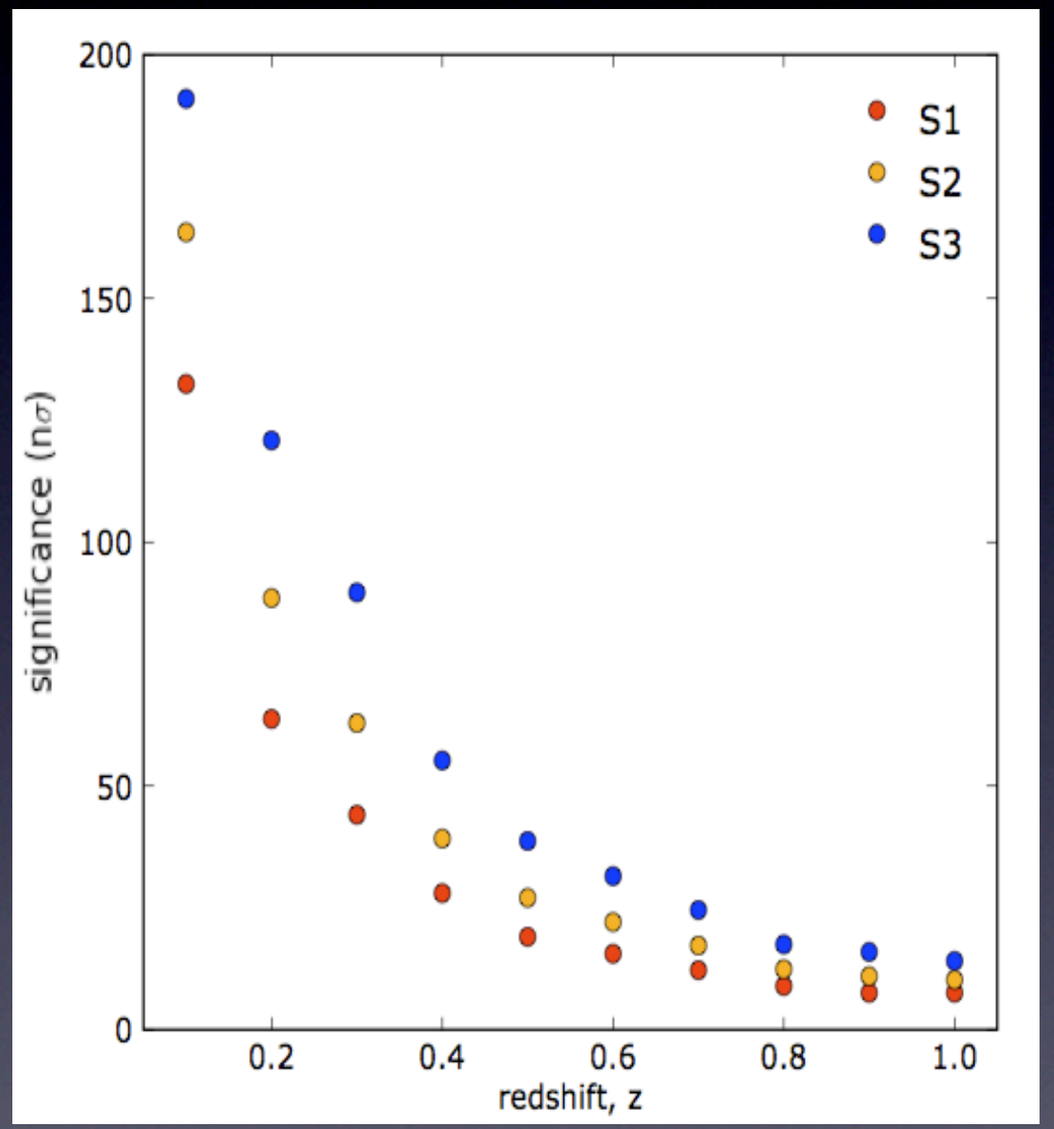
Preliminary results: towards Ω_{HI}

Output <M> vs. Input <M>



- Stacking technique recovers input <M> well

S/N vs. z



- More refinements yet to come, but looking promising!

Summary & Outlook

- HI-stacking is a promising technique to use for targeted HI surveys to ‘squeeze’ out additional information from non-detections

- HI-stacking will be useful technique to use for high-z surveys with MeerKAT

Next Steps

- Scale CRUMBS up to the full NIBLES dataset
- Stack non-detections from other surveys...

- Refine simulations for MeerKAT planning:
  - investigate luminosity cuts / biases
  - inclinations, etc.

Thank you to:

W. van Driel & the NIBLES team (especially to T. Joseph and M. Ramatsoku at UCT for data reduction)

D. Obreschkow & Oxford team for the use of their galaxy simulations catalogue

My UCT colleagues for all your input

Extra slides

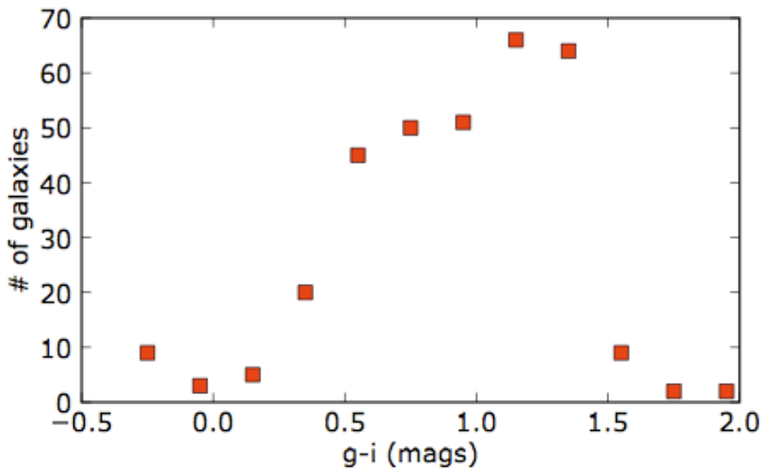
Picking up the CRUMBS...

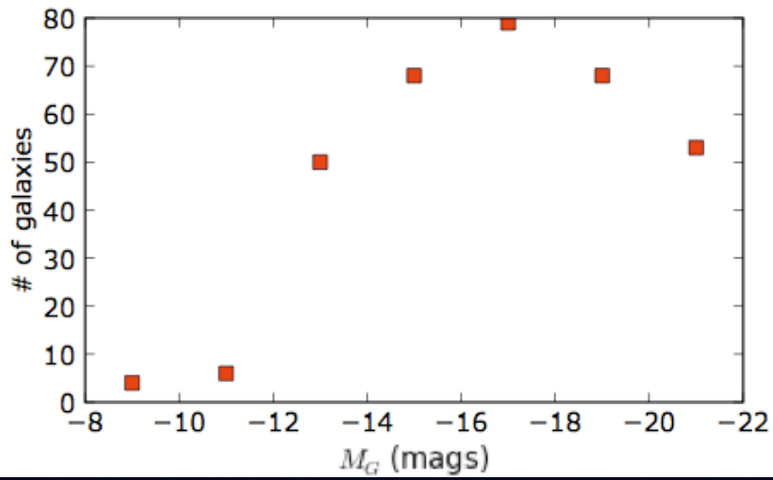
Preliminary results based on 884 NIBLES galaxies:

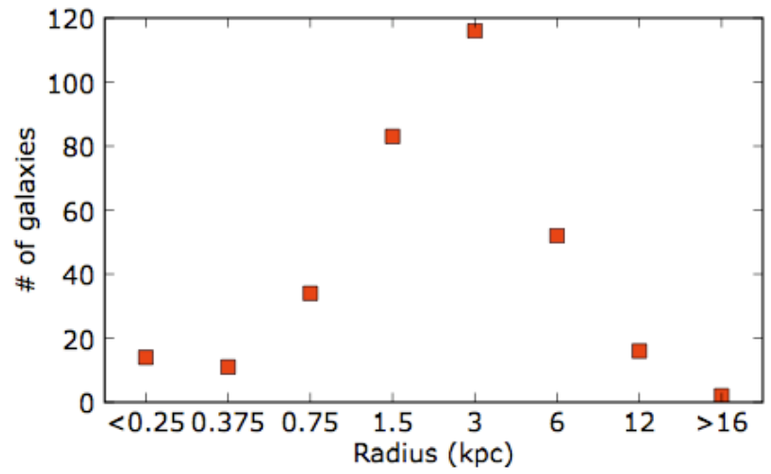
S/N	galaxies	$\langle S_{HI} \rangle$ (mJy)	$\langle M_{HI} \rangle$ (M_{sun})	M_{HI_Lim} (M_{sun})	$\langle D_L \rangle$ (Mpc)	S/N stack.
<3	337	8.96 ± 0.03	$1.03 \times 10^8 \pm 8.22 \times 10^6$	6.4×10^7	52 ± 2	13.8
<2.5	304	5.63 ± 0.04	$6.46 \times 10^7 \pm 5.38 \times 10^6$	7.1×10^7	52 ± 2	9.1
<2.0	241	2.51 ± 0.02	$2.87 \times 10^7 \pm 2.74 \times 10^6$	3.6×10^7	52 ± 2	4.2
<1.5	140	0.5 ± 0.02	...	4.5×10^7	48 ± 3	...

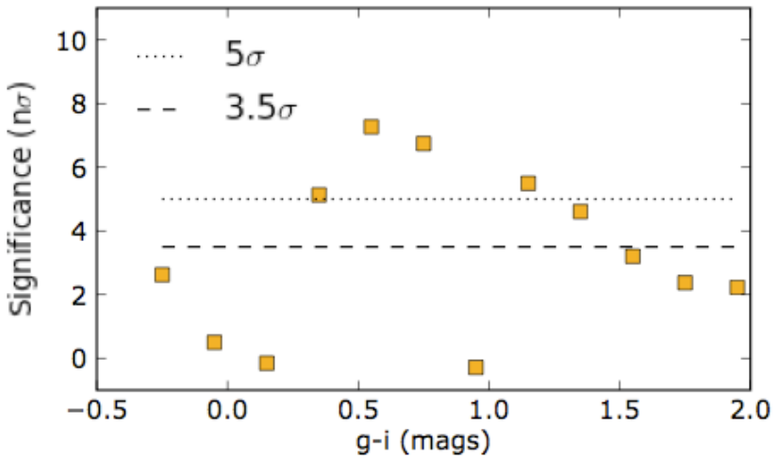
More preliminary results...

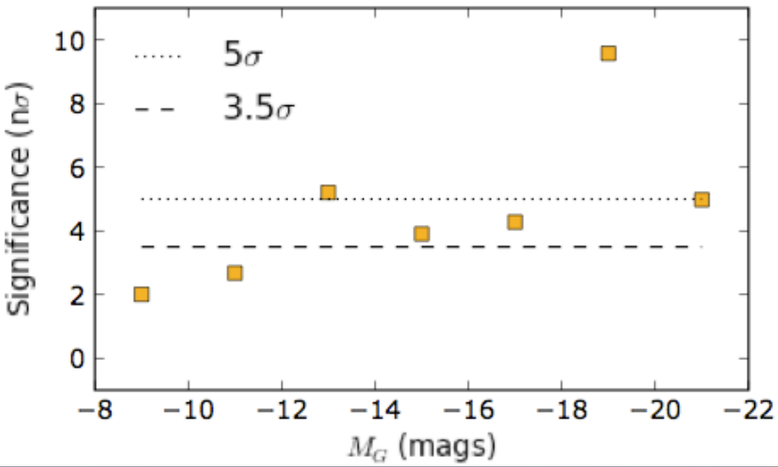
Colour **Magnitude** **Radius**

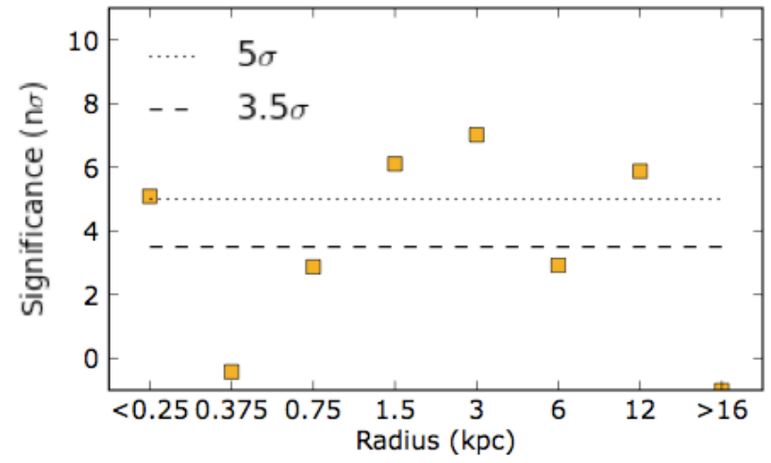


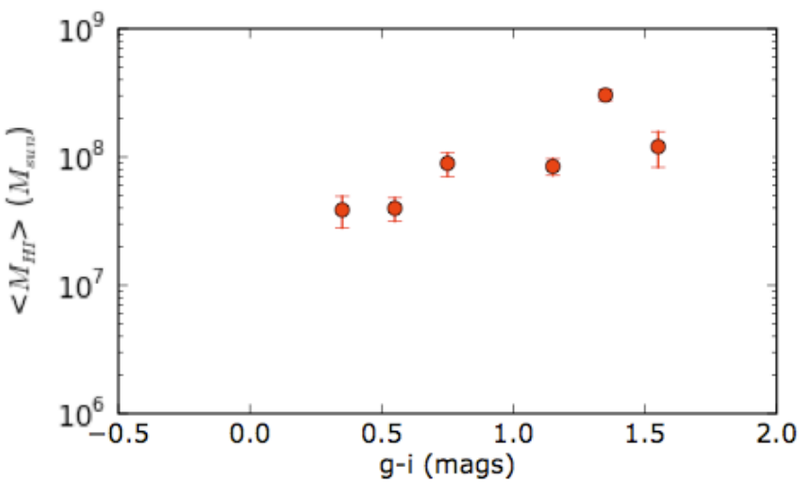


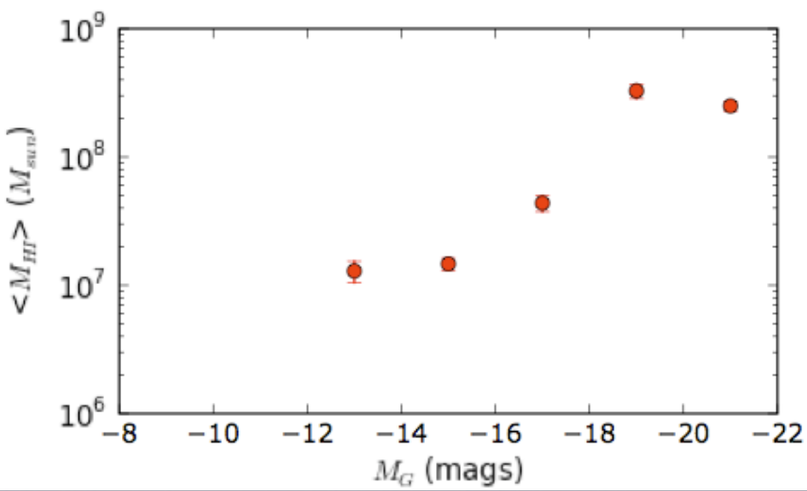


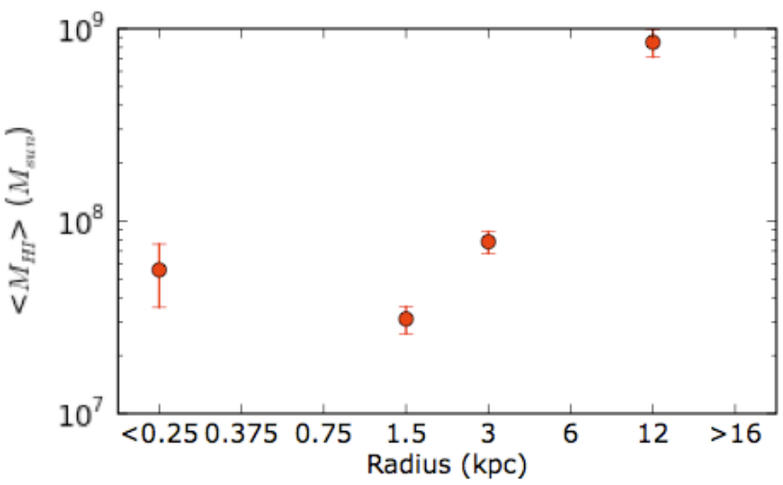






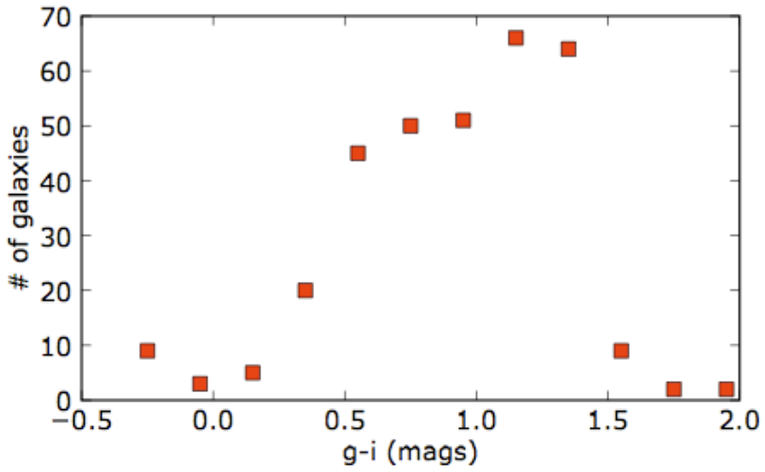


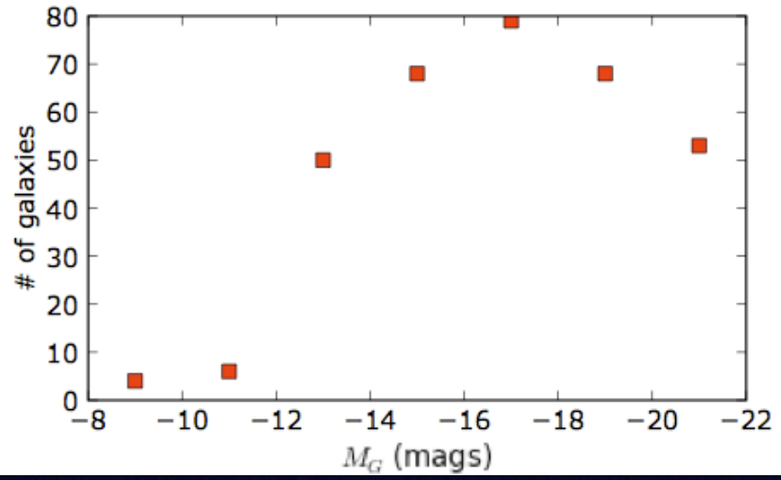


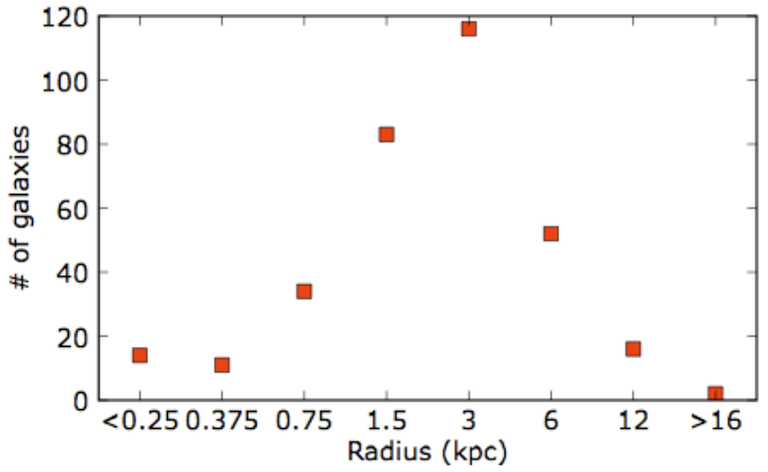


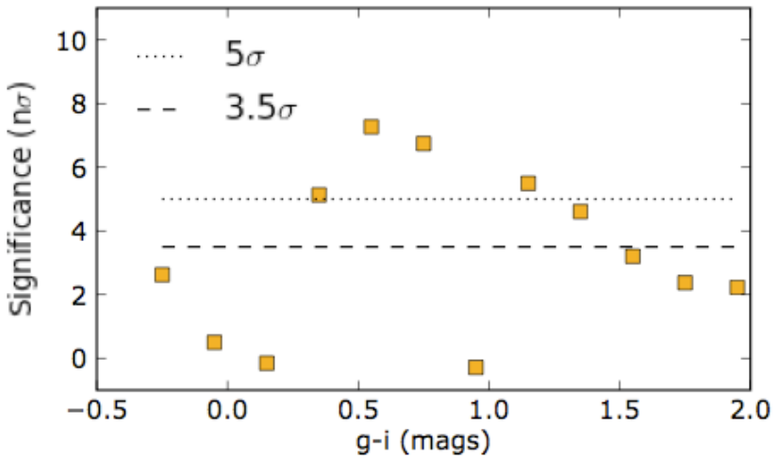
More preliminary results...

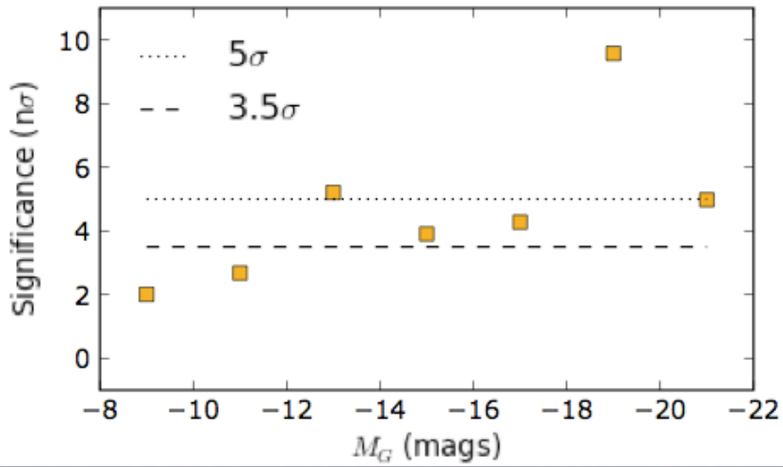
Colour **Magnitude** **Radius**

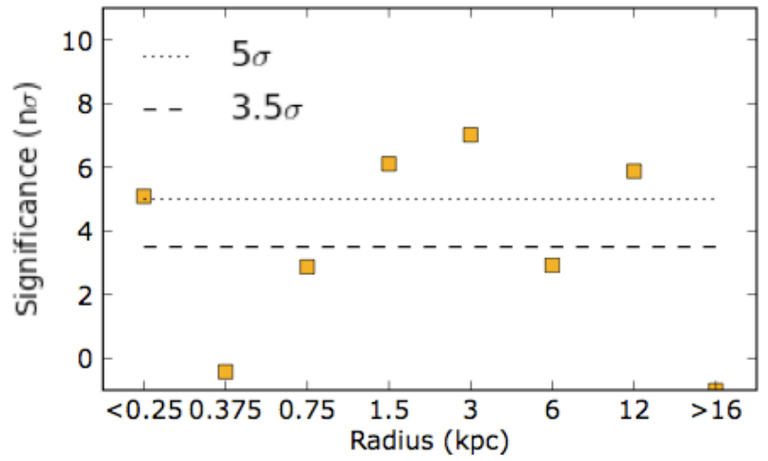


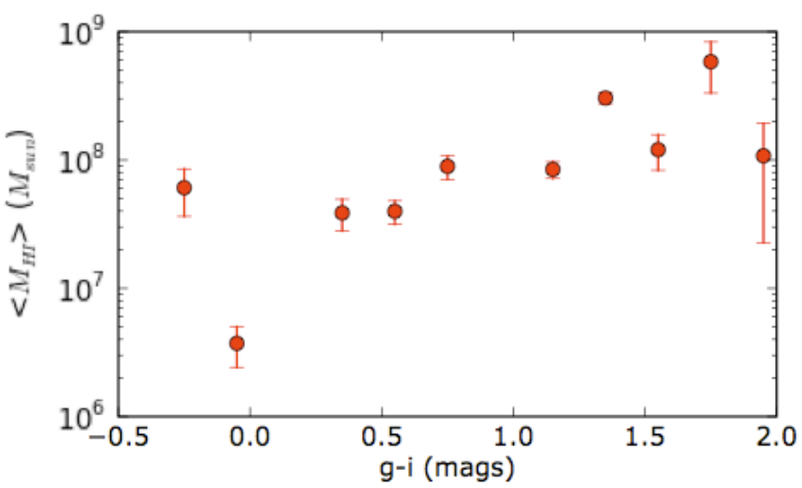


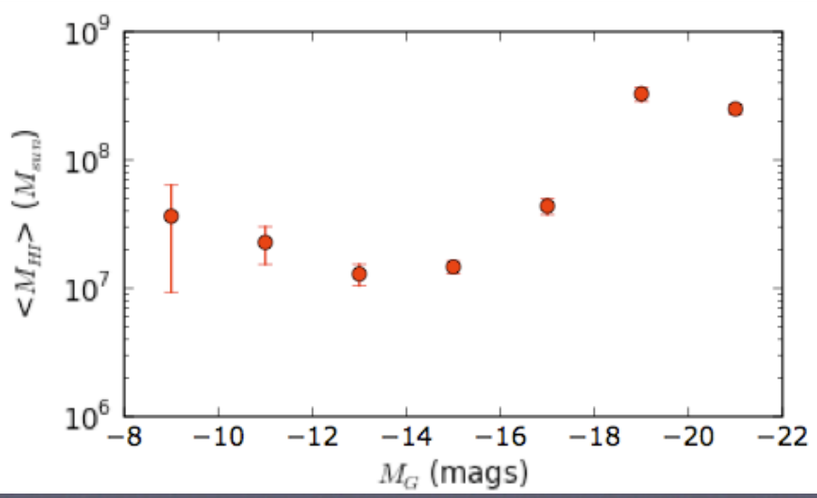


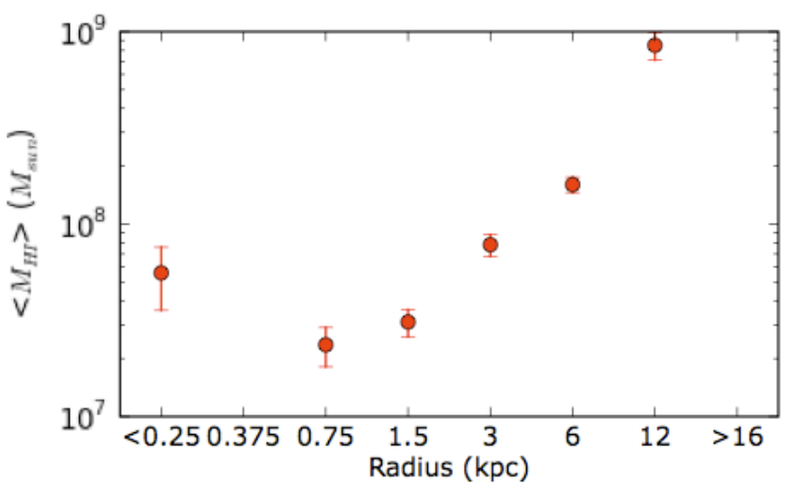


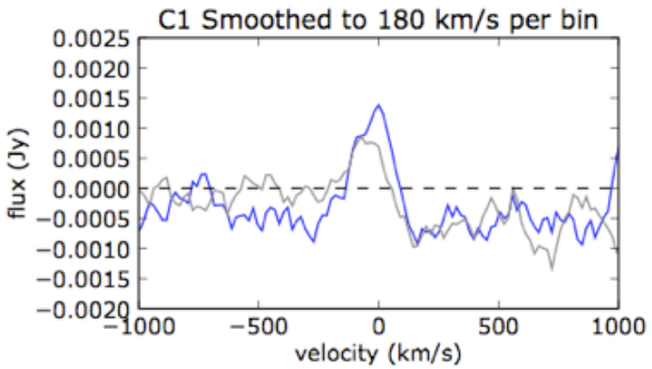


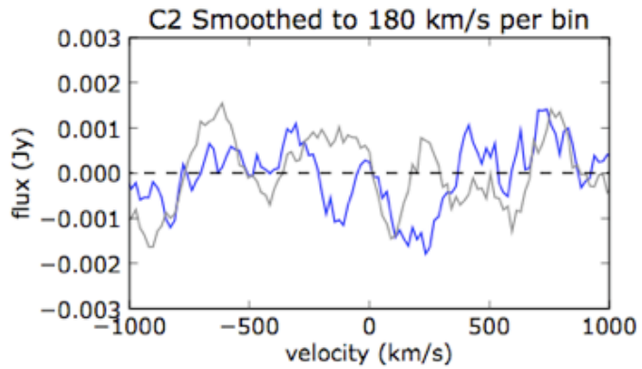


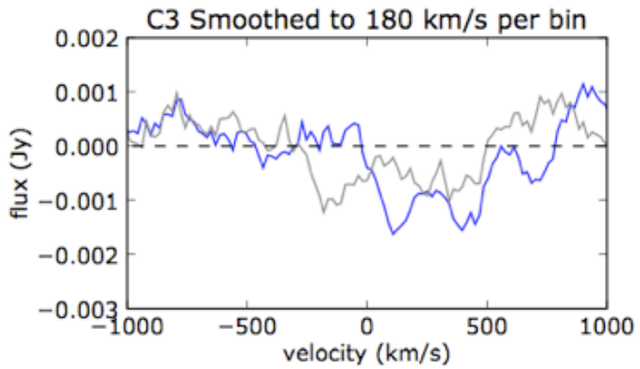


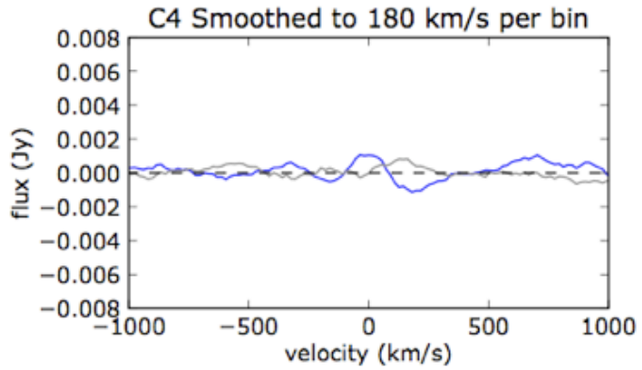


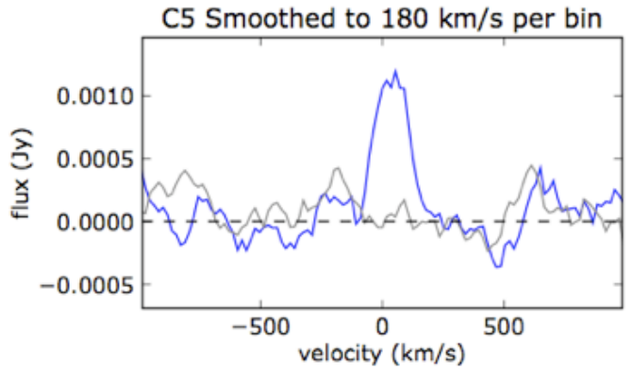


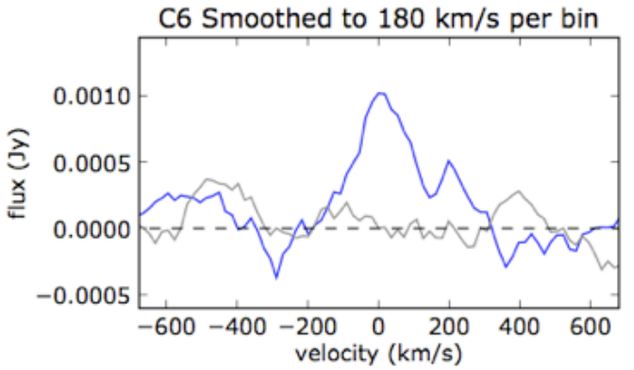

C1 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

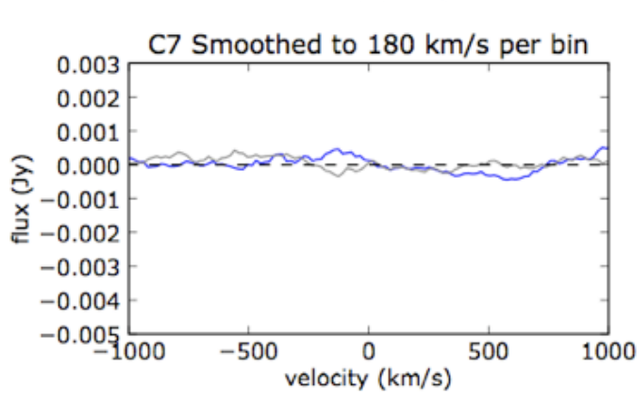

C2 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

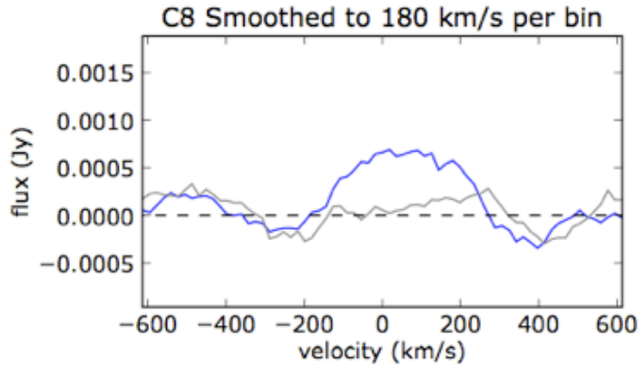

C3 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

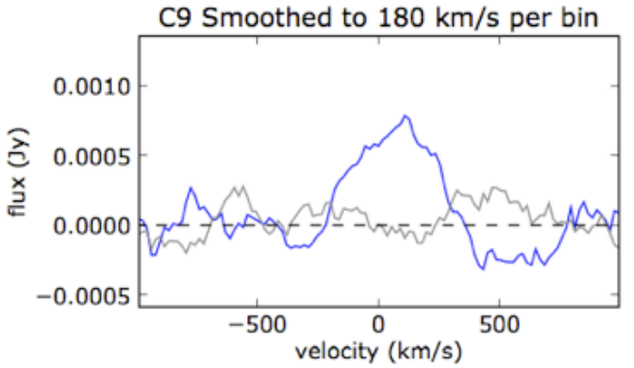

C4 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

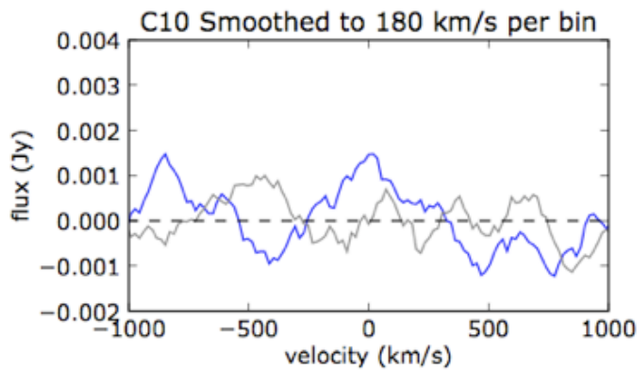

C5 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

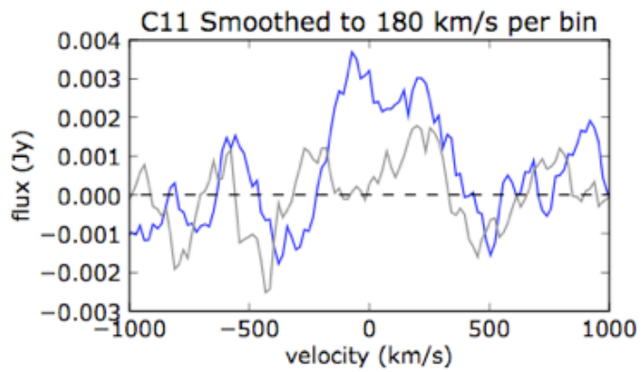

C6 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

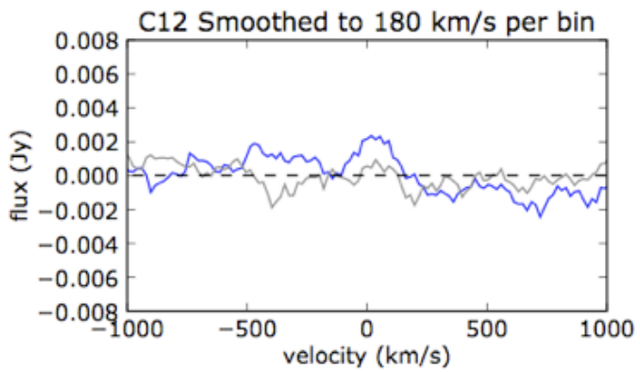

C7 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

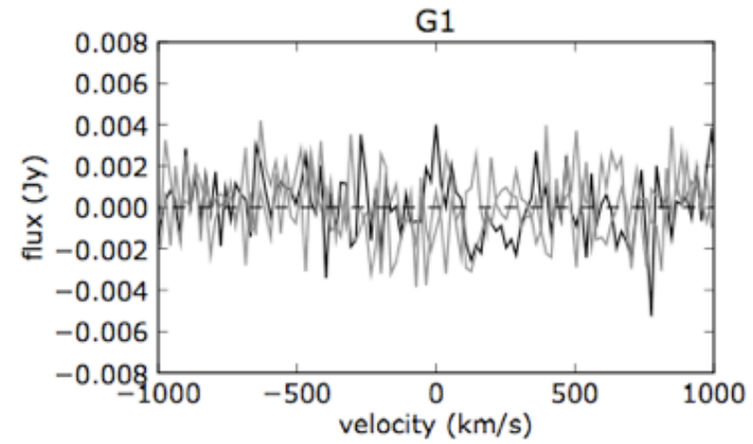

C8 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

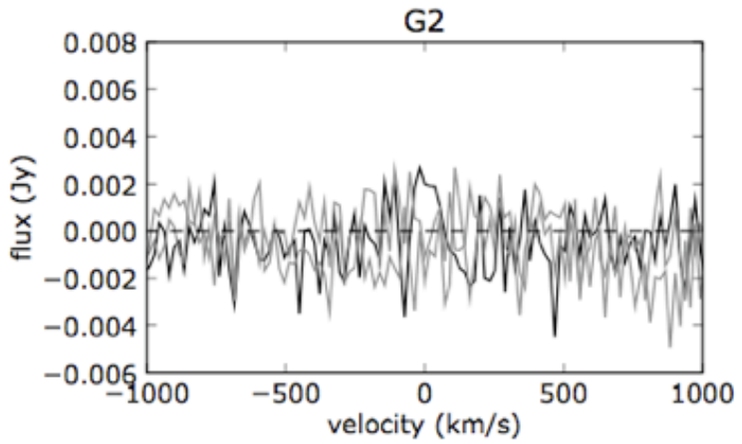

C9 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

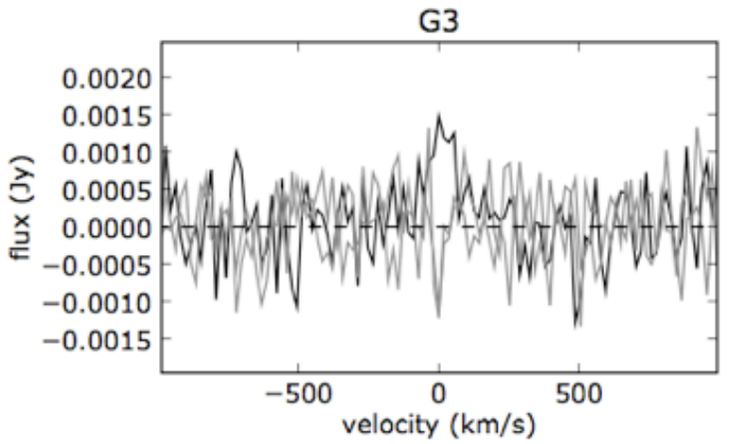

C10 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

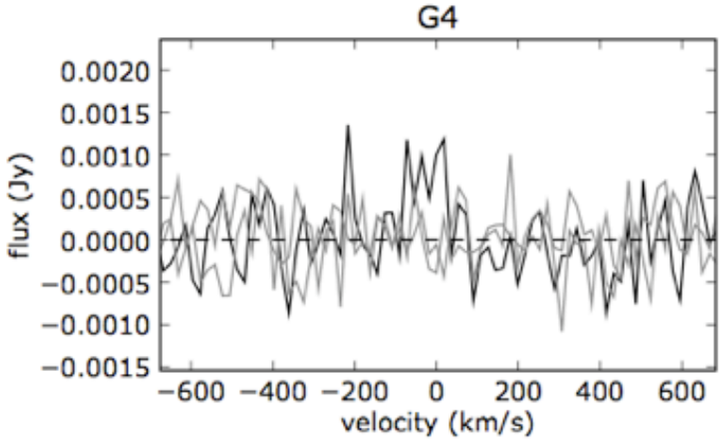

C11 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

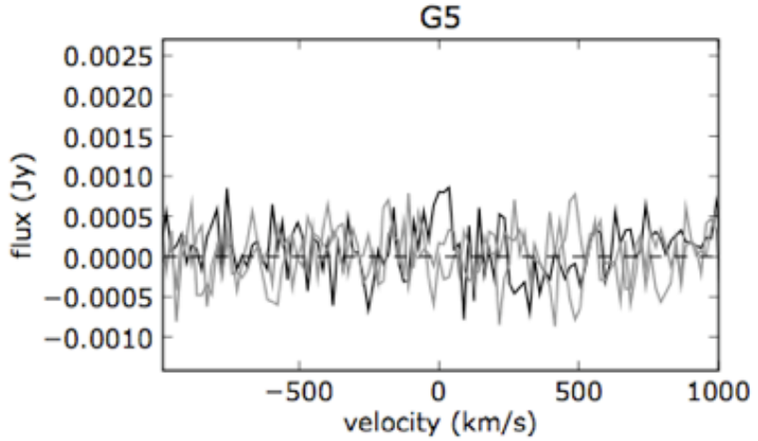

C12 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

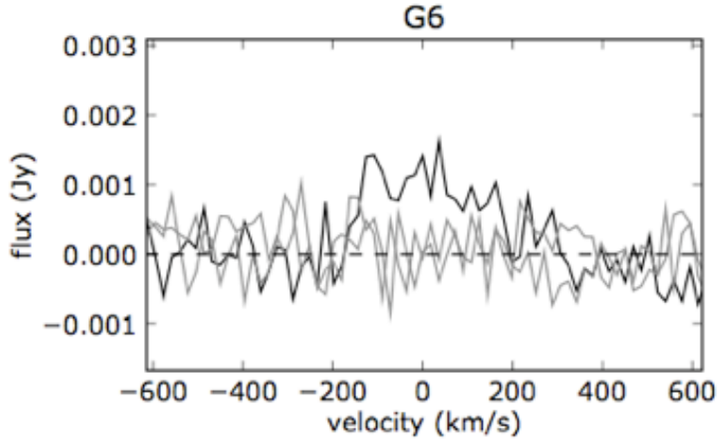

G1
flux (Jy)
velocity (km/s)

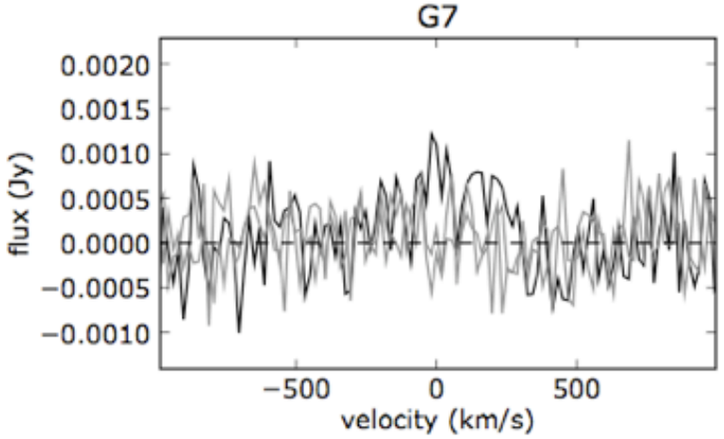

G2
flux (Jy)
velocity (km/s)

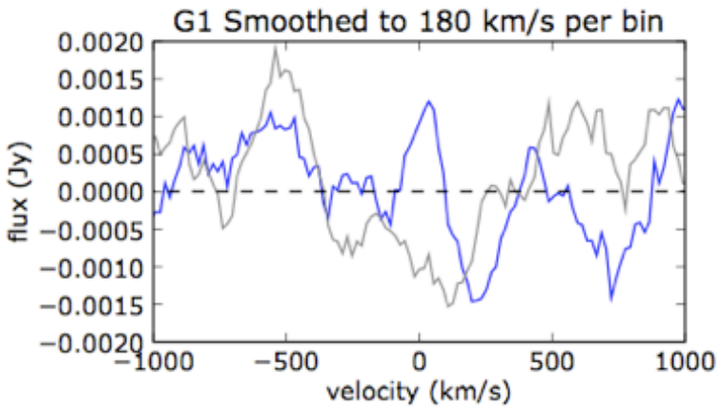

G3
flux (Jy)
velocity (km/s)

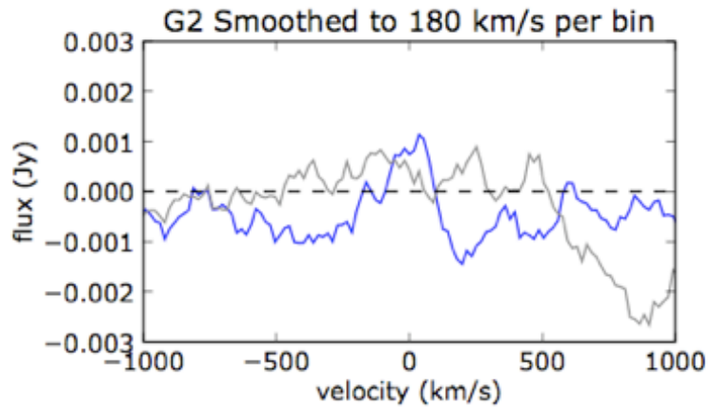

G4
flux (Jy)
velocity (km/s)

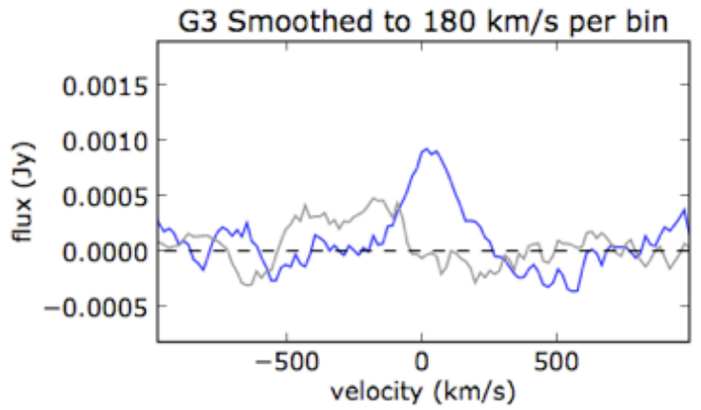

G5
flux (Jy)
velocity (km/s)

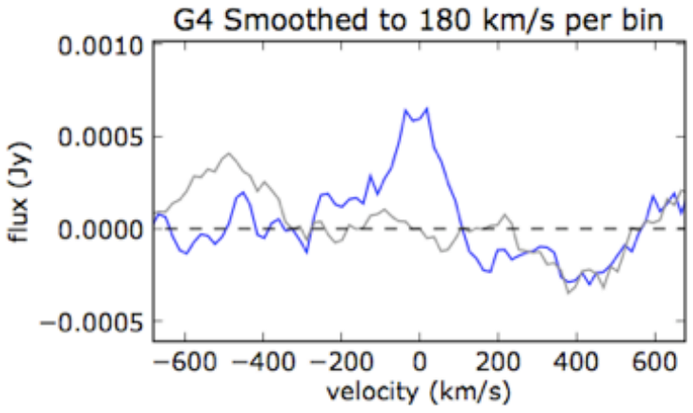

G6
flux (Jy)
velocity (km/s)

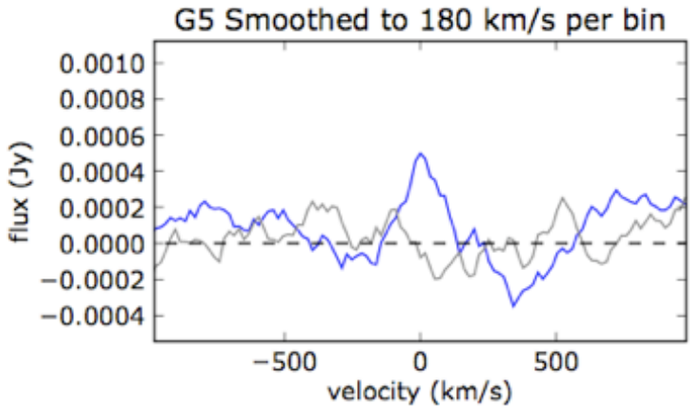

G7
flux (Jy)
velocity (km/s)

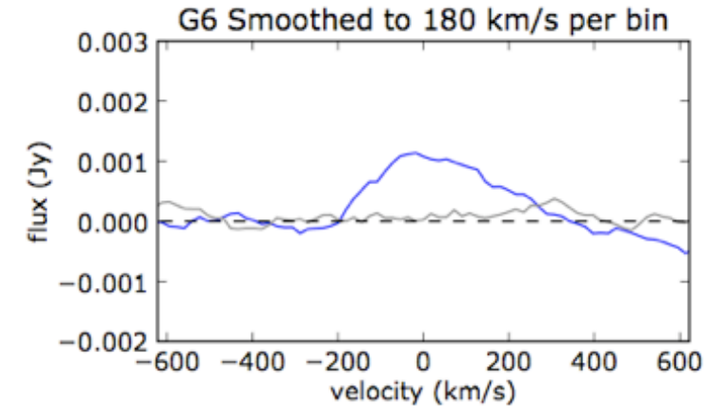

G1 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

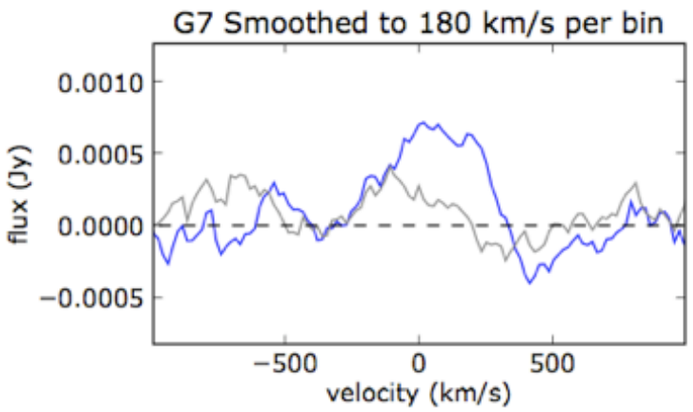

G2 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

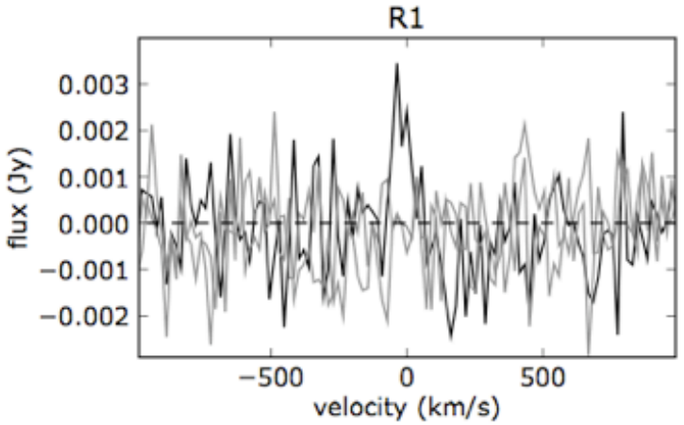

G3 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

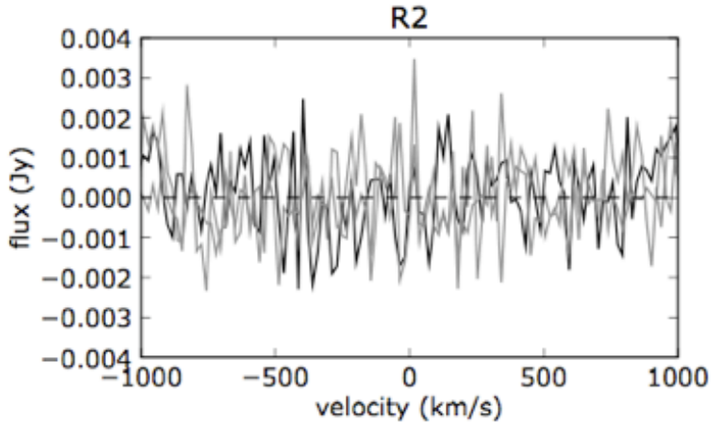

G4 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

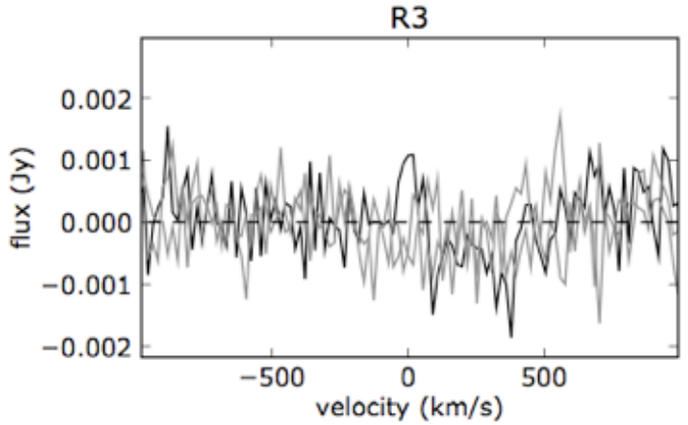

G5 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

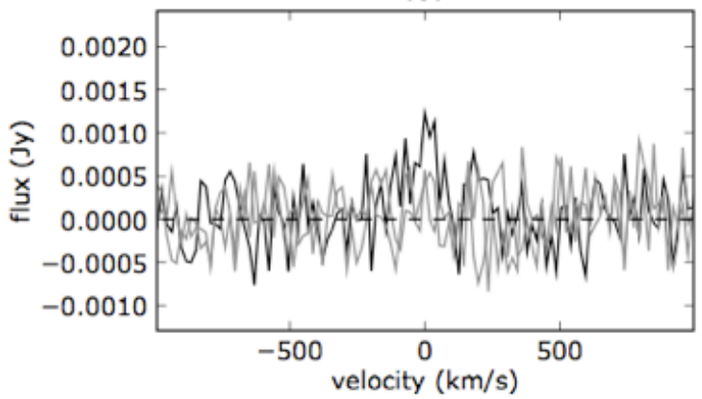

G6 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

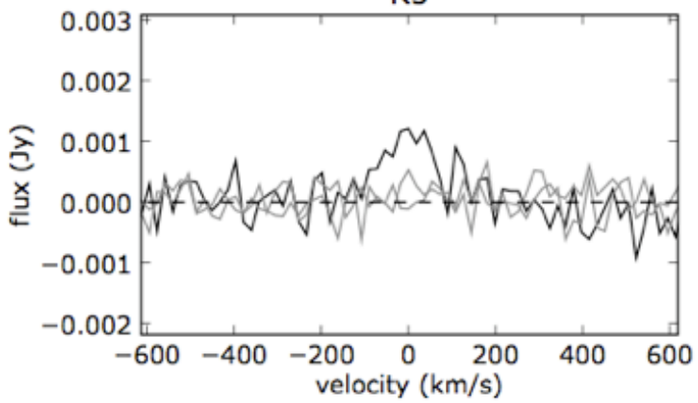

G7 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

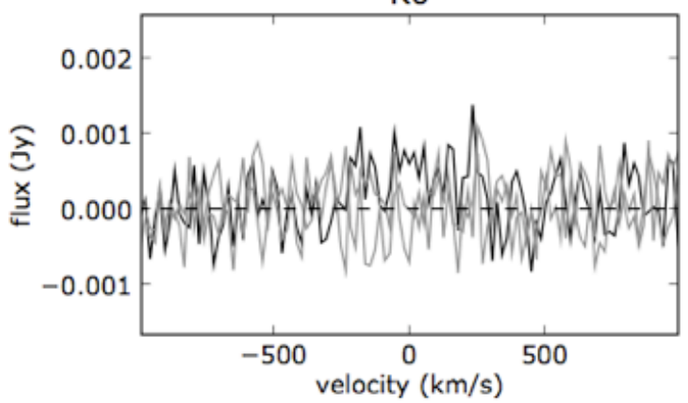

R1
flux (Jy)
0.003
0.002
0.001
0.000
−0.001
−0.002
−500
0
500
velocity (km/s)

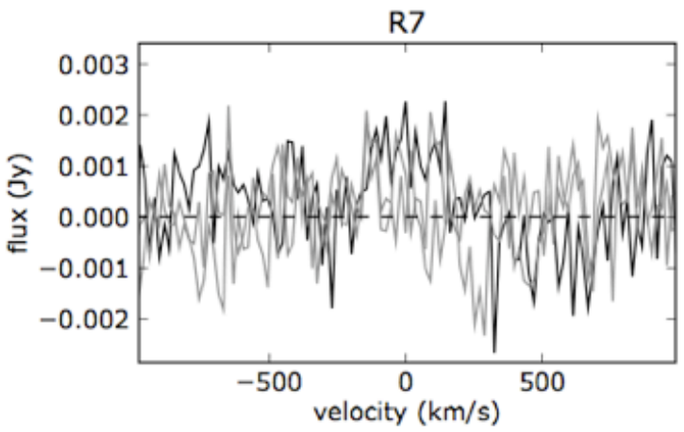

R2
flux (Jy)
0.004
0.003
0.002
0.001
0.000
−0.001
−0.002
−0.003
−0.004
−1000
−500
0
500
1000
velocity (km/s)

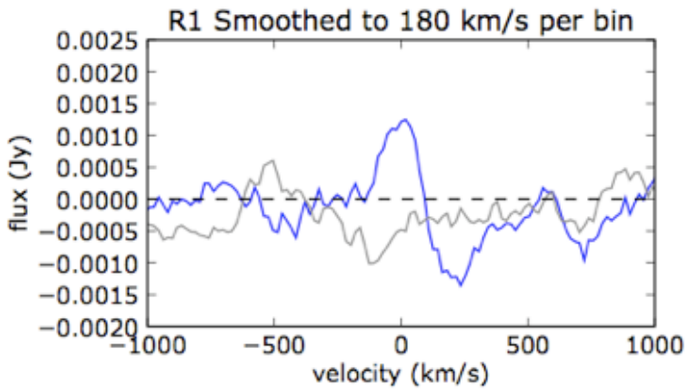

R3
flux (Jy)
0.002
0.001
0.000
−0.001
−0.002
−500
0
500
velocity (km/s)

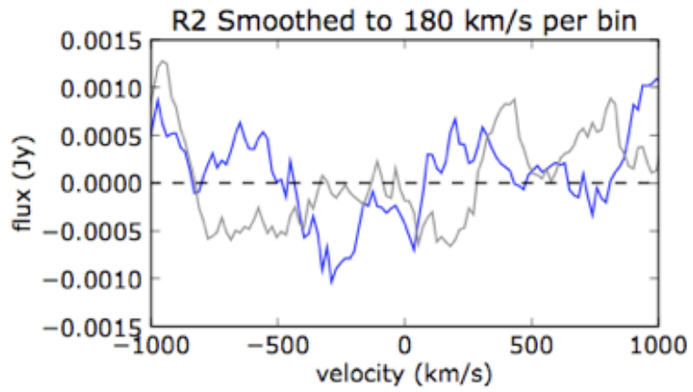

R4
flux (Jy)
0.0020
0.0015
0.0010
0.0005
0.0000
−0.0005
−0.0010
−500
0
500
velocity (km/s)

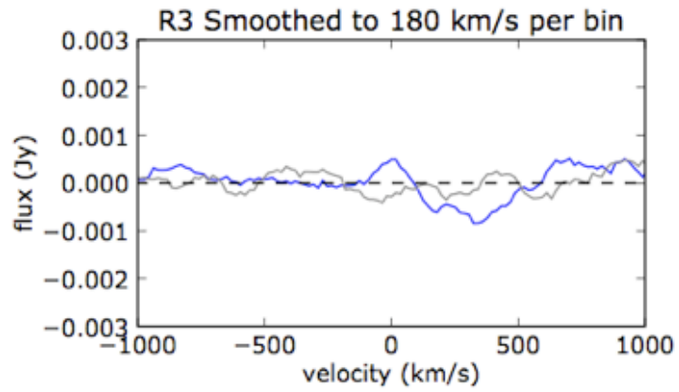

R5
flux (Jy)
0.003
0.002
0.001
0.000
−0.001
−0.002
−600
−400
−200
0
200
400
600
velocity (km/s)

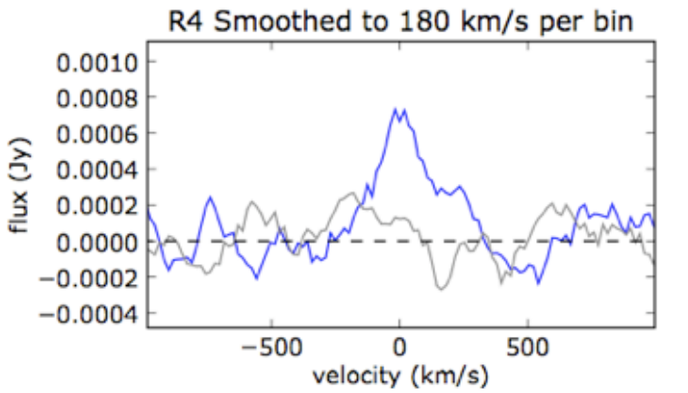

R6
flux (Jy)
0.002
0.001
0.000
−0.001
−500
0
500
velocity (km/s)

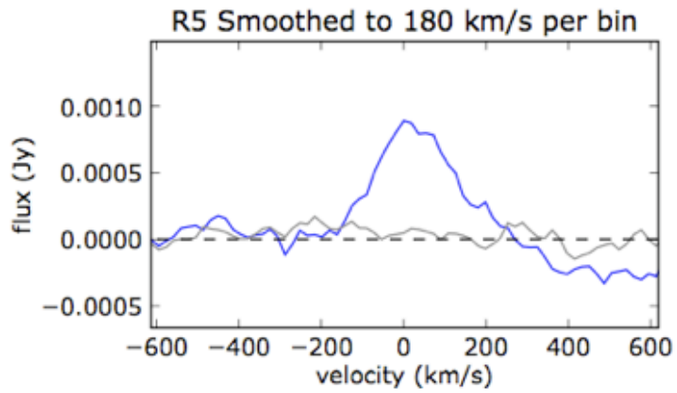

R7
flux (Jy)
0.003
0.002
0.001
0.000
−0.001
−0.002
−500
0
500
velocity (km/s)

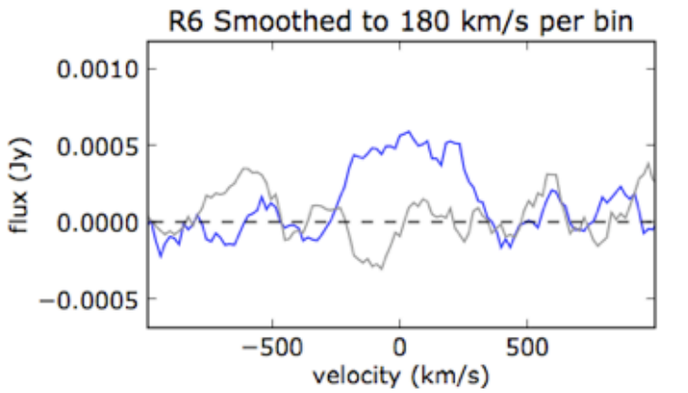

R1 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

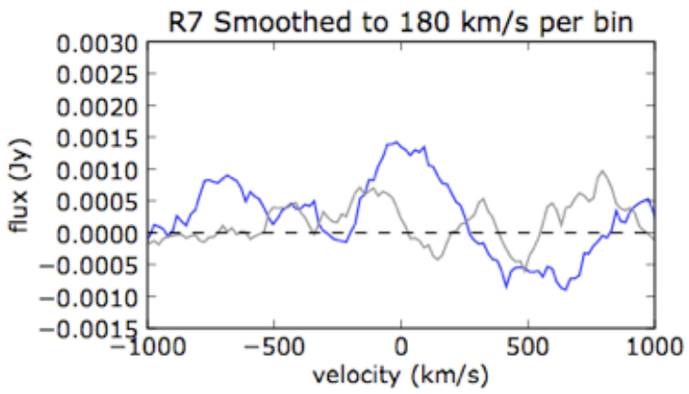

R2 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)


R3 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

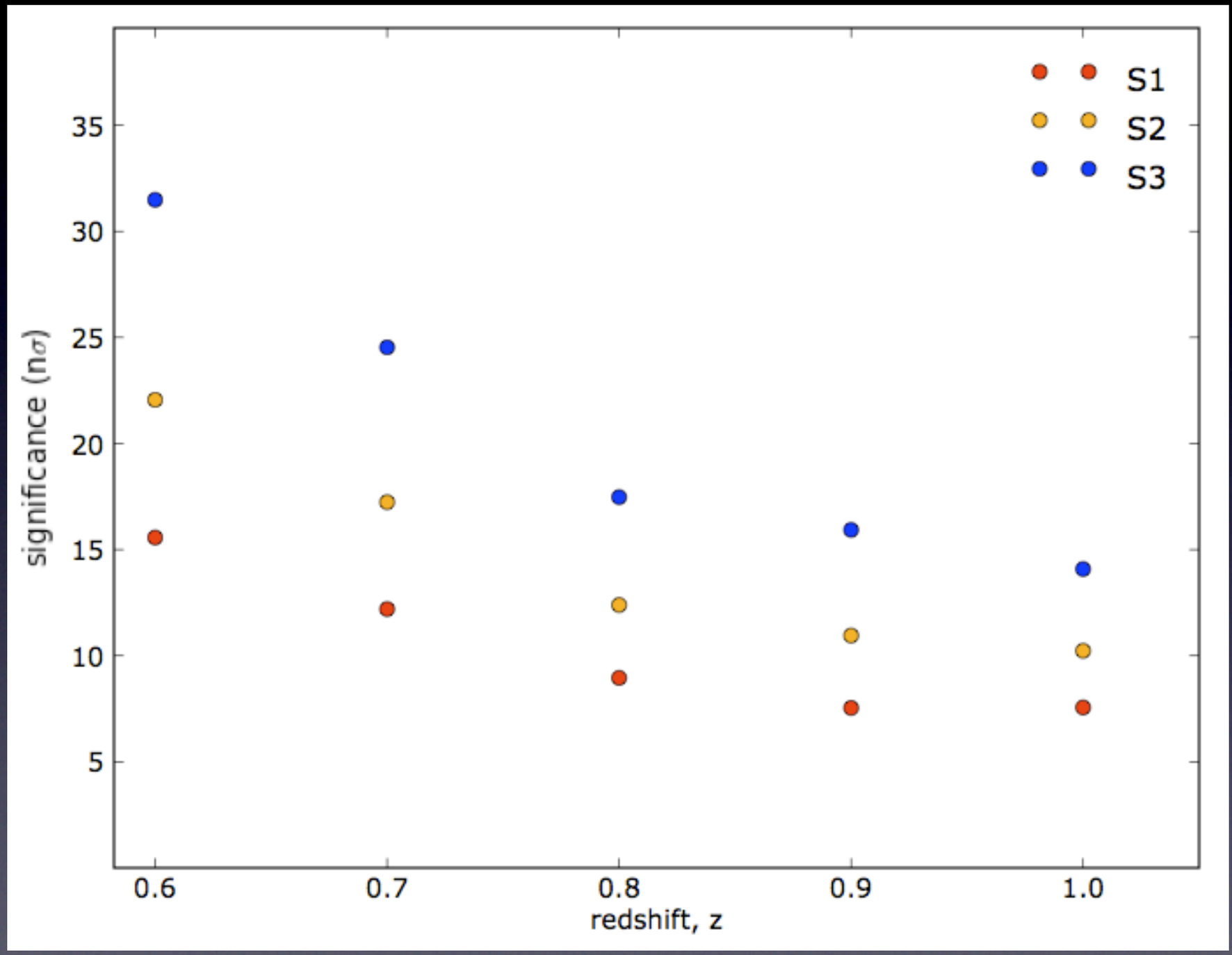

R4 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)


R5 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

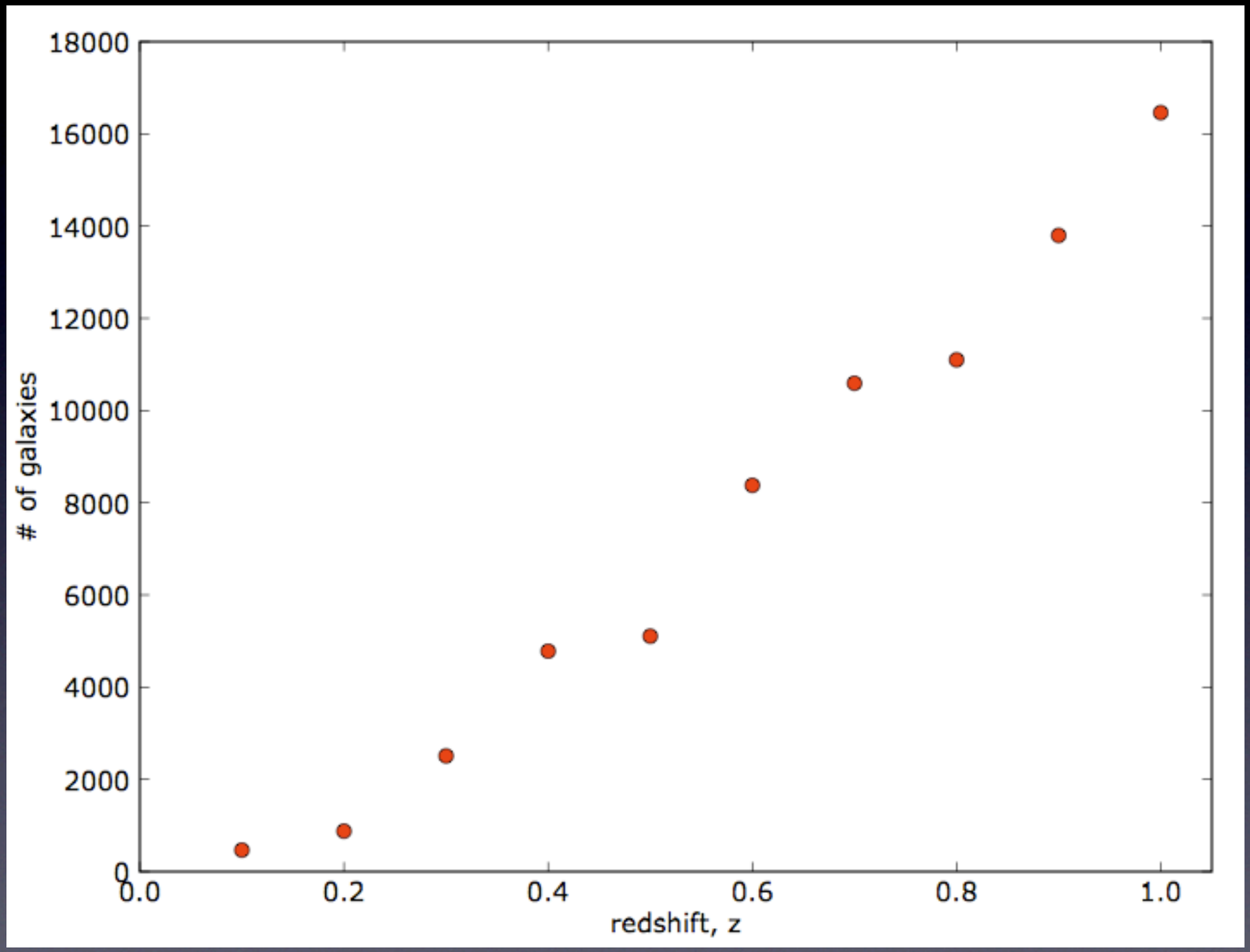

R6 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)


R7 Smoothed to 180 km/s per bin
flux (Jy)
velocity (km/s)

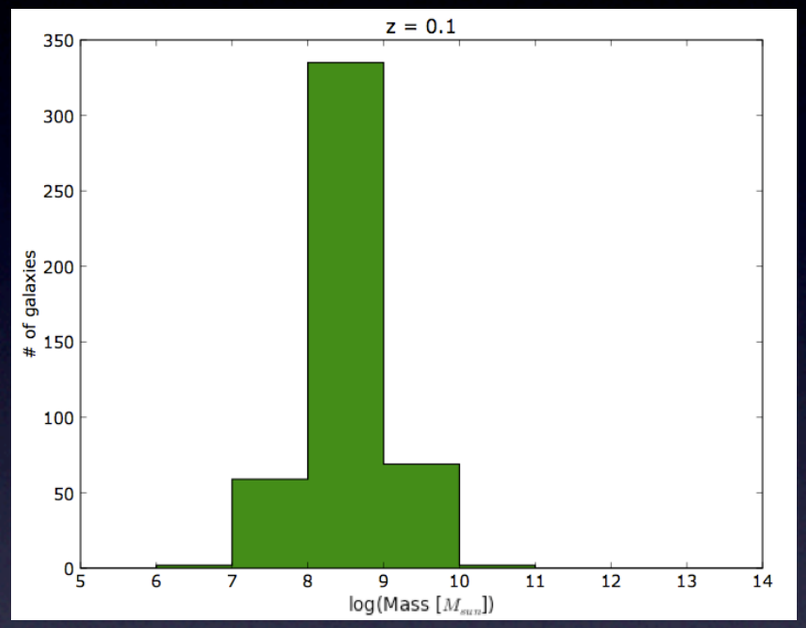
Significance of simulations

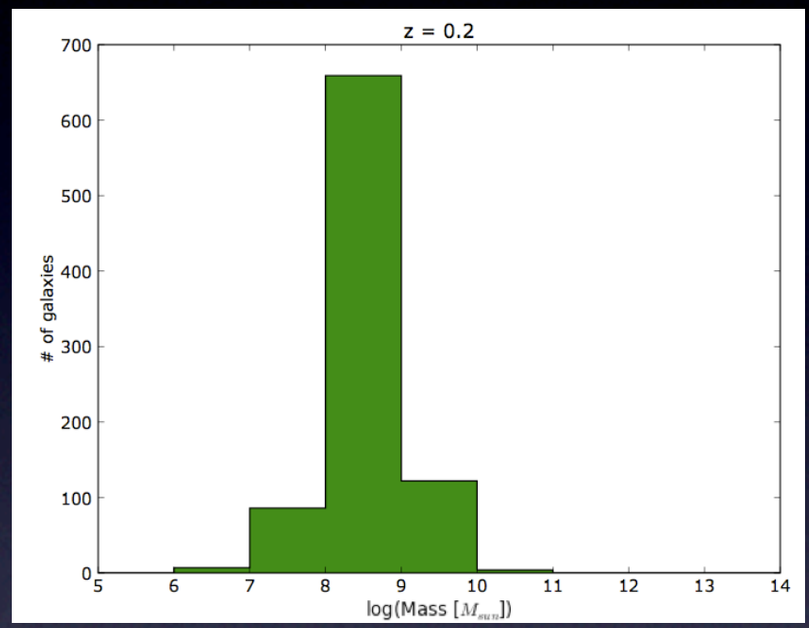


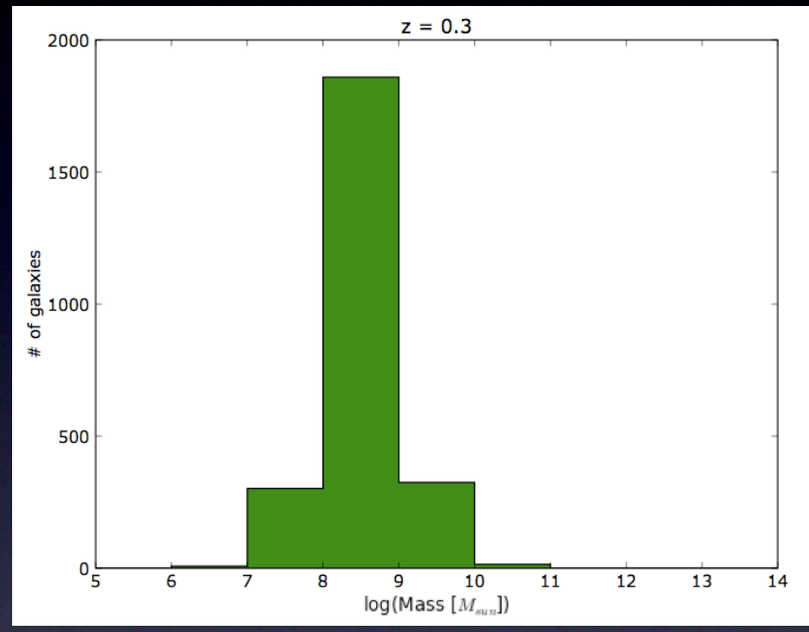
Number dist. for simulations



Input Mass dist. vs. z







Input Mass dist. vs. z