The connection between HI and QSO absorbers

Understanding the Flow of Hydrogen Between
Galaxies and the Cosmic Web

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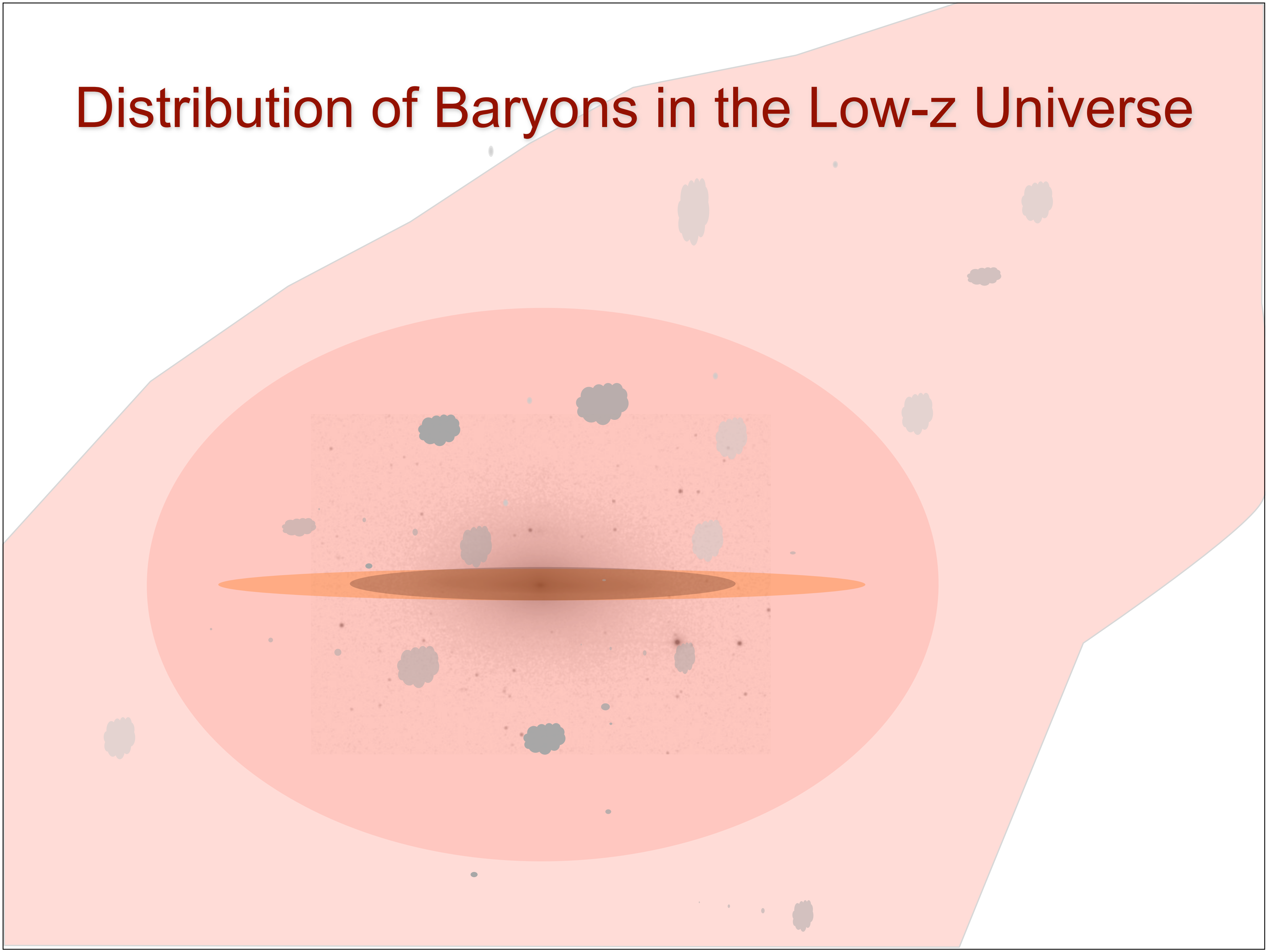
Donald York (Univ. of Chicago)

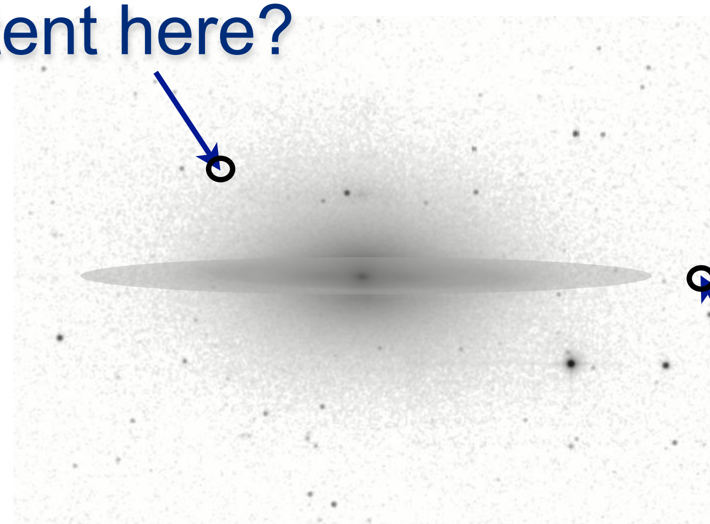
Distribution of Baryons in the Low-z Universe



Distribution of Baryons in the Low-z Universe

Given: The basic properties of a galaxy

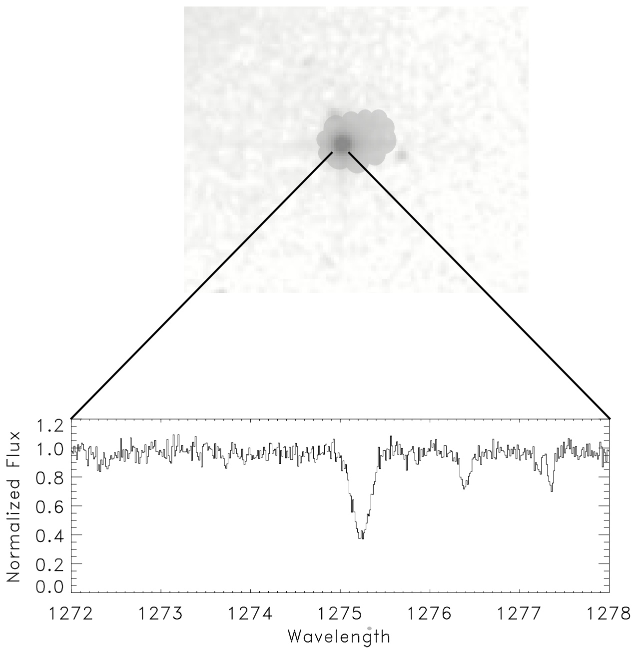
Aim:
Can we predict what's the baryonic content here?



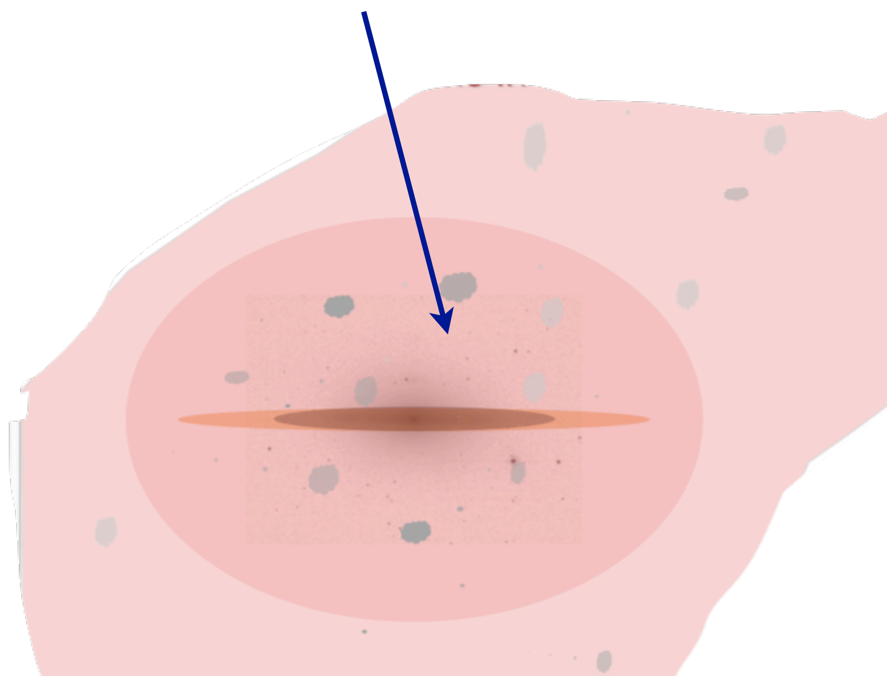
or there?

Distribution of Baryons in the Low-z Universe

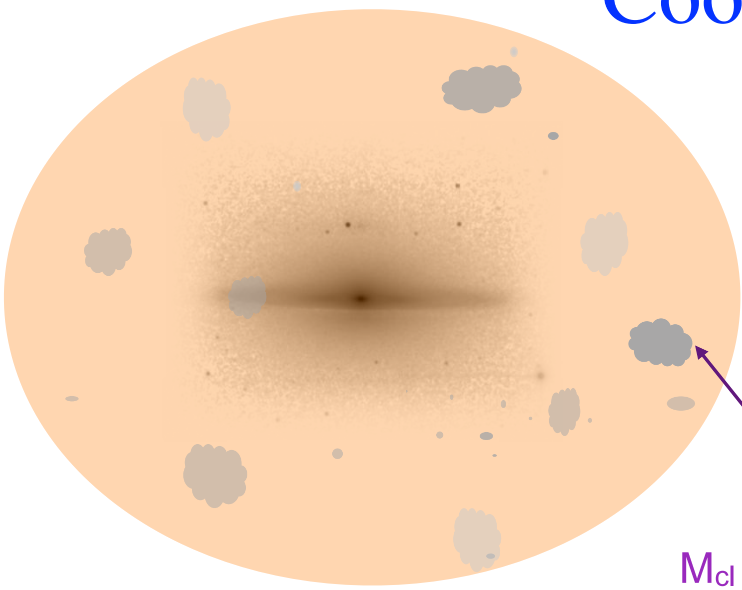
Given: The basic properties of an absorber



Can we tell if this gas associated with galaxy halo, extended disk or IGM ?



Cool Gas In and Around Galaxies



Condensation of halo Gas

Hot halo gas condenses through multi-phase cooling into clouds of $\sim 10^4$ K.

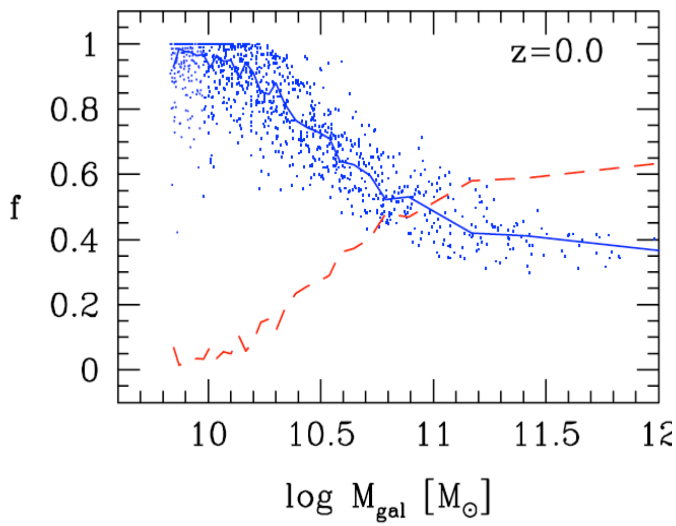
Maller & Bullock (2004)

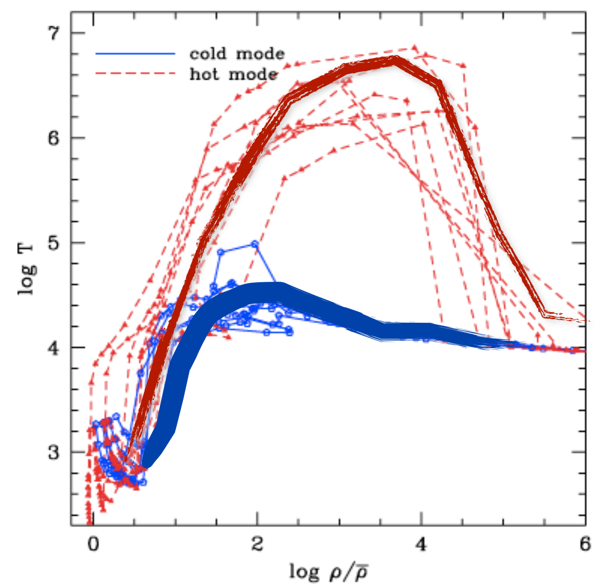
$M_{cl} \sim 5 \times 10^6 M_\odot$
Size ~ 1 kpc

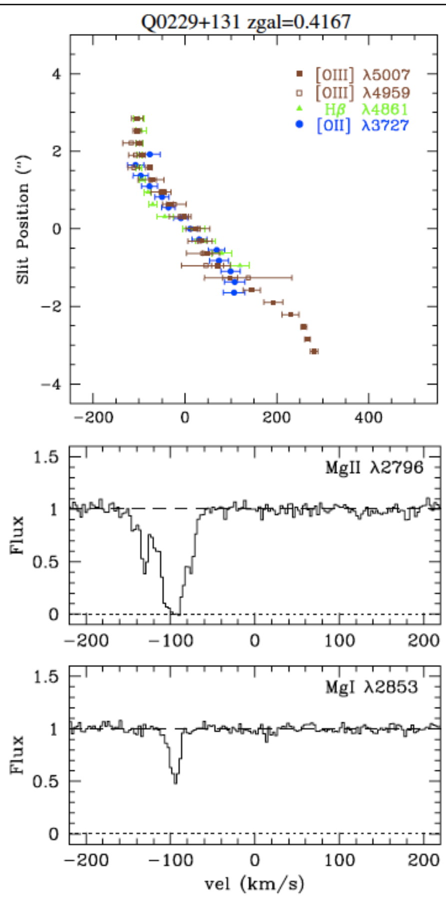
Cold-mode accretion

Galaxies with baryonic mass smaller than **10.3(dex) $M_\odot$** accrete through the "cold-mode"

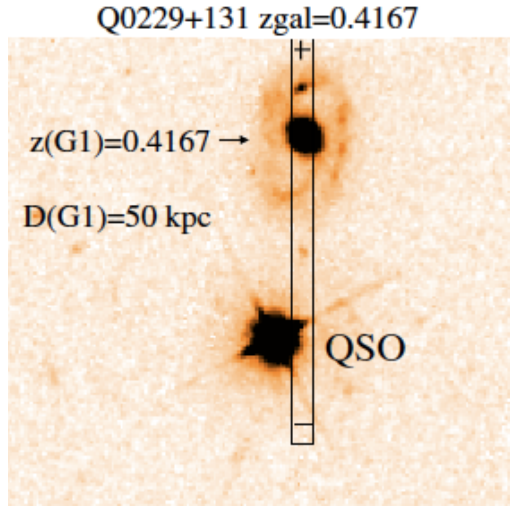
Keres et al. (2005)







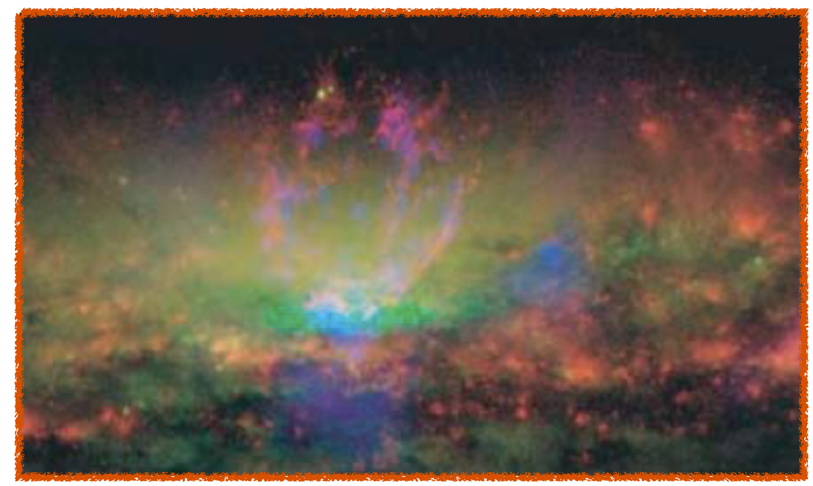
Cool Gas In and Around Galaxies



Kacprzak et al. (2010)

Extended Disks

Various studies (e.g. Bowen et al. 1995, Charlton & Churchill 1996, Steidel et al. 2002) found extended disks traced by cool low-ionization gas in absorption.



Close-up of the wind-swept, circumnuclear region of NGC 3079. Colors indicate - Hα + [N II], I-band, and X-rays. Veilleux (ARAA, 2005)

Galactic Outflows

Detected in low-ionization metal absorption transitions Na I and Mg II.

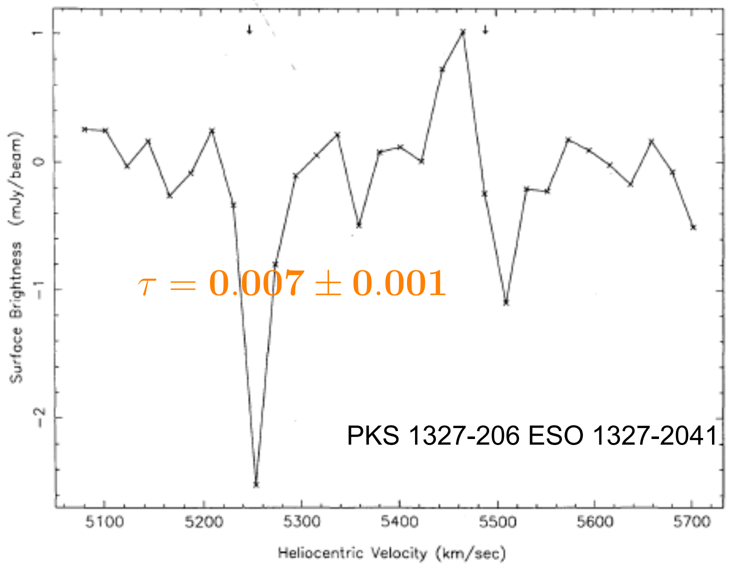
Only 5%–10% of the neutral gas in starburst-driven winds escape into the IGM. (Rupke et al. 2005)

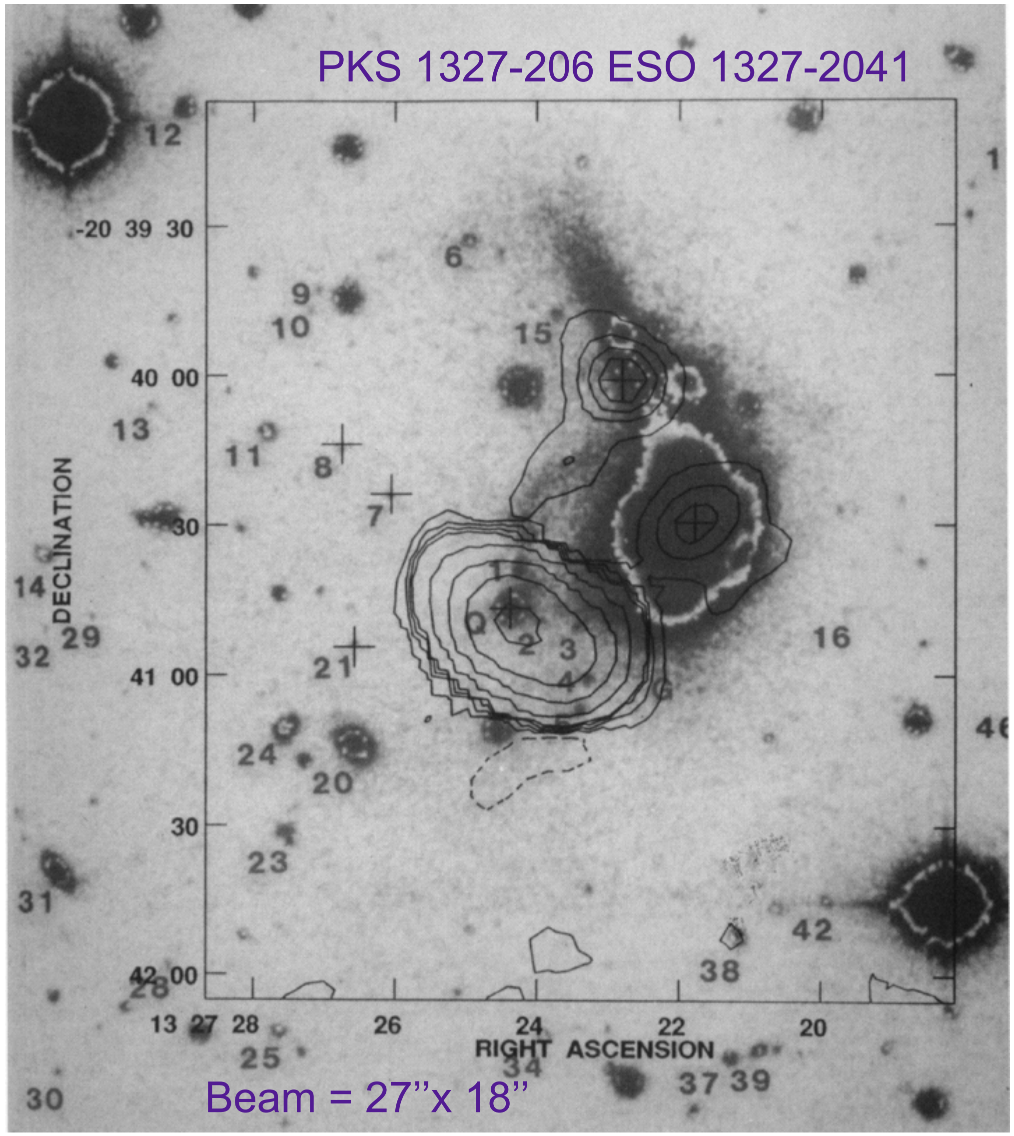
Baryonic material deposited by the winds can eventually cool down and rain back into the galaxies - The Galactic Fountain Model (Shapiro & Field 1976)

Detecting Cold Gas Through Absorption

Corbelli & Schneider (1990) detected 21cm absorber in NGC 4651

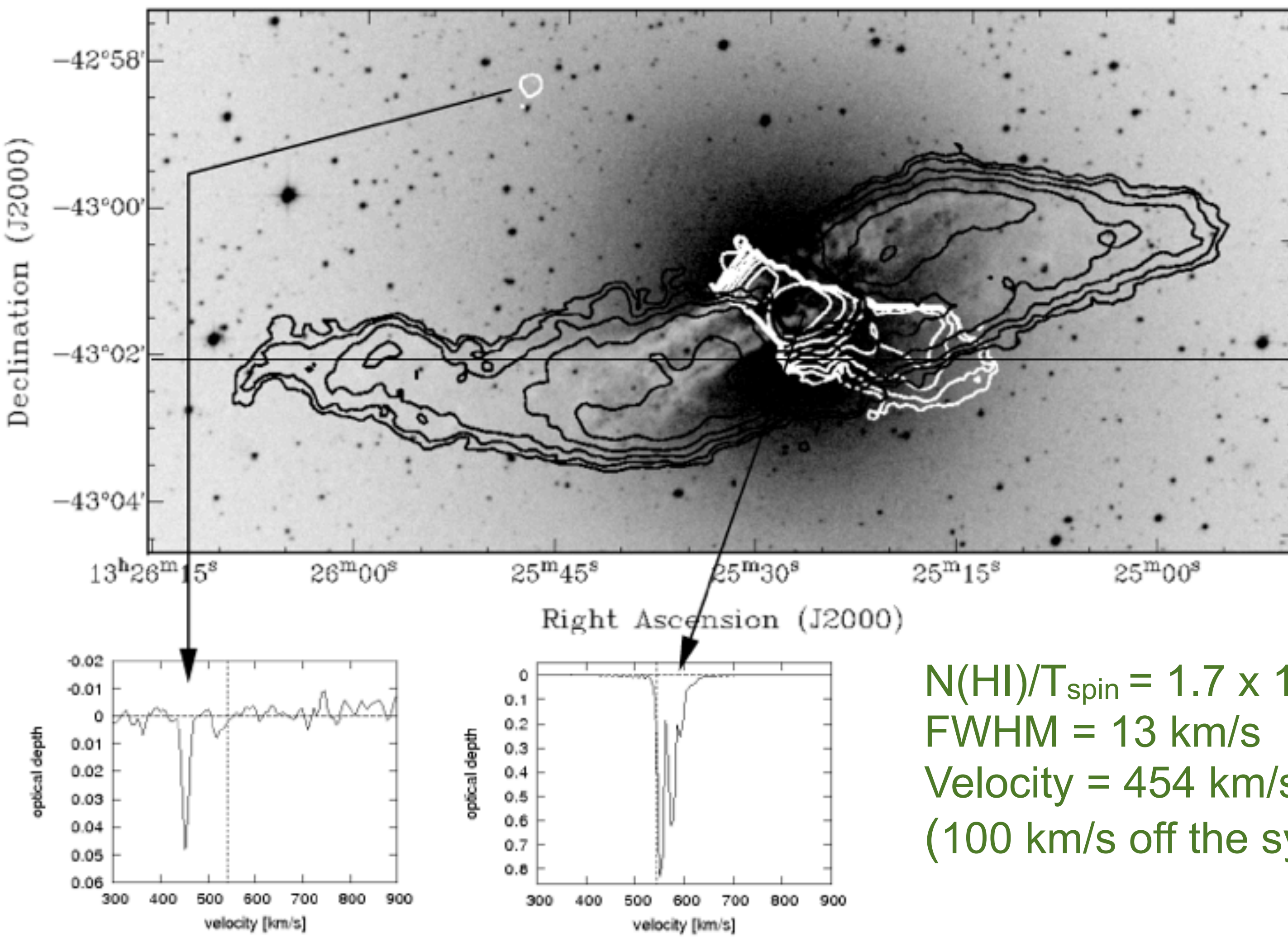
Out of a sample of 4 galaxy-QSO pairs selected due to the presence of Ca II or Na I absorption, Carilli & van Gorkom (1992) detected 21cm HI absorbers in 3 of them.





Carilli & van Gorkom (1992)

Cold Gas (HI) Outside the Stellar disk : Cen A



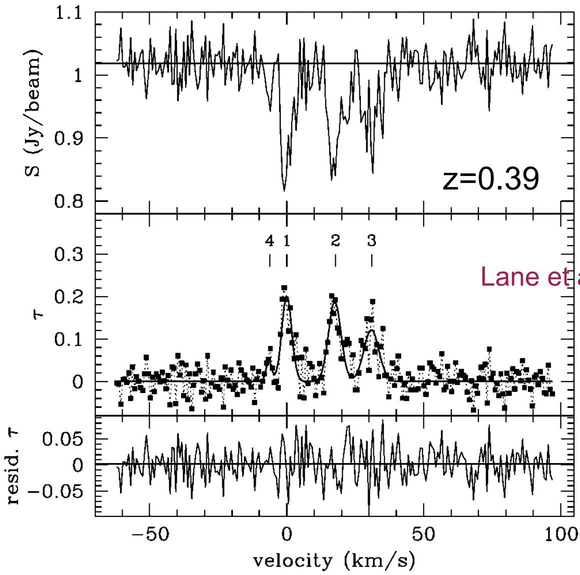
Absorption against the northeast radio lobe of the radio galaxy.

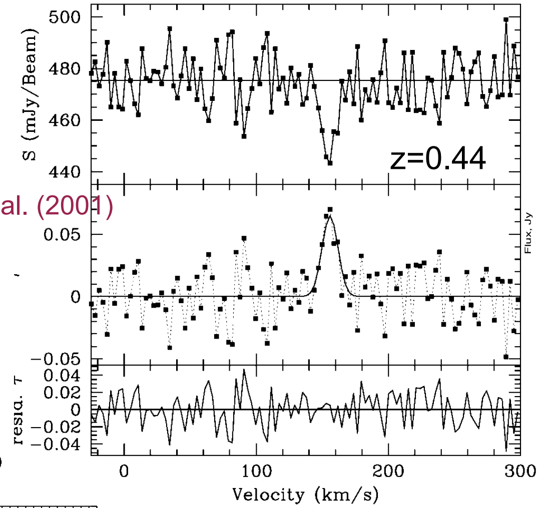
Struve et al. (2010)

$N(HI)/T_{spin}$ = 1.7 x 10^{18} cm^{-2} K^{-1}
FWHM = 13 km/s
Velocity = 454 km/s
(100 km/s off the systemic velocity)

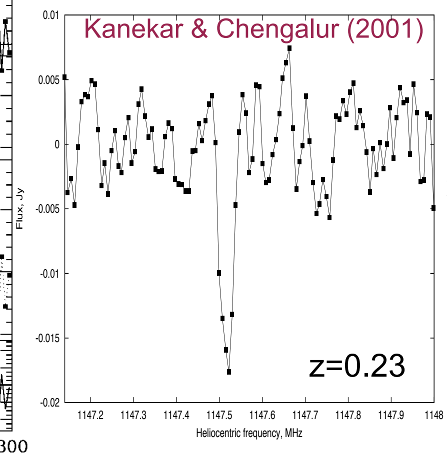
Low Z HI 21cm Absorbers

Lane et al. (2001)

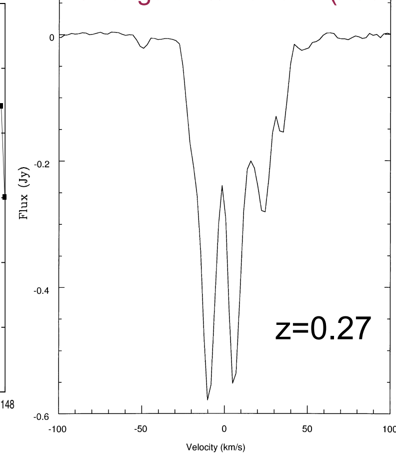




Kanekar & Chengalur (2001)



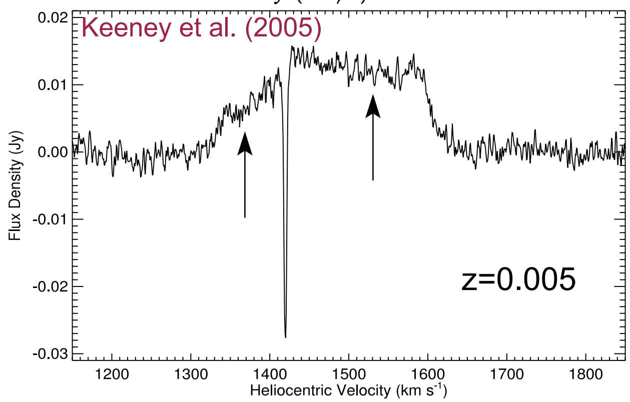
Chengalur & Kanekar(2000)

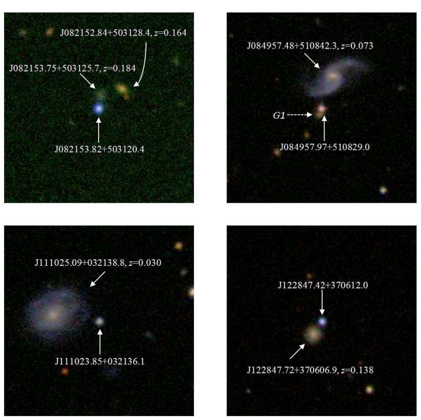


Chengalur & Kanekar(2000)

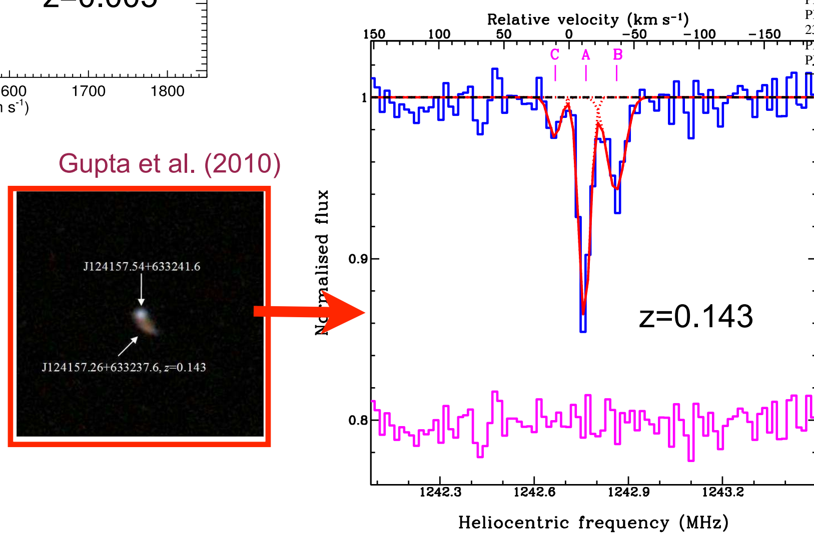
Name	z_{abs}	N_{HI} (cm^{-2})	No. of components	ΔV_{21}[a] ($km\,s^{-1}$)	T_s[b] (K)	Absorber ID	Ref.
0738+313 (A)	0.09123	1.5e21	3	25	825	Dwarf ?	1,2
0738+313 (B)	0.2212	7.9e20	1	16	1120	Dwarf ?	1–3
PKS 1413+135	0.24671	2.0e22	1	39	150	Spiral	4
PKS 1451–375[c]	0.2761	1.3e20	–	–	>1400	–	5,6
PKS 1127–145	0.3127	5.1e21	7	120	910	Group	3,6
PKS 1229–021	0.39498	5.6e20	2	180	170	Spiral ?	7–10
3C196	0.4366	6.3e20	3	250	–	Barred Spiral	11–13
3C446[c]	0.4842	6.3e20	–	–	> 1600	–	5,6
A0 0235+164	0.524	5.0e21	5	125	170	Spiral	14–17
3C286	0.69215	2.0e21	1	18	1200	LSB	9,18–20
PKS 0454+039	0.8596	5.0e20	–	–	>870	Galaxy	9,21,22
MC3 1331+170	1.77636	7.6e21	1	25	770	–	23–25
PKS 1157+014	1.944	6.3e21	1	60	470	Group	26–28
PKS 0458–02	2.03945	8.0e21	2	30	594	–	29,30
PKS 0528–2505	2.8110	2.2e21	–	–	> 730	Group	31–33
2342+342	2.9084	2.0e21	–	–	> 1800	–	31,34
PKS 0336–017	3.0619	1.5e21	–	–	> 2500	–	31,35
PKS 0201+113	3.3875	2.5e21	–	–	> 5600	–	34,36–38

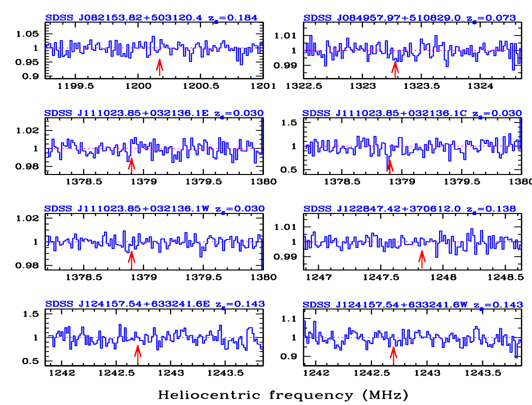
Keeney et al. (2005)





Gupta et al. (2010)

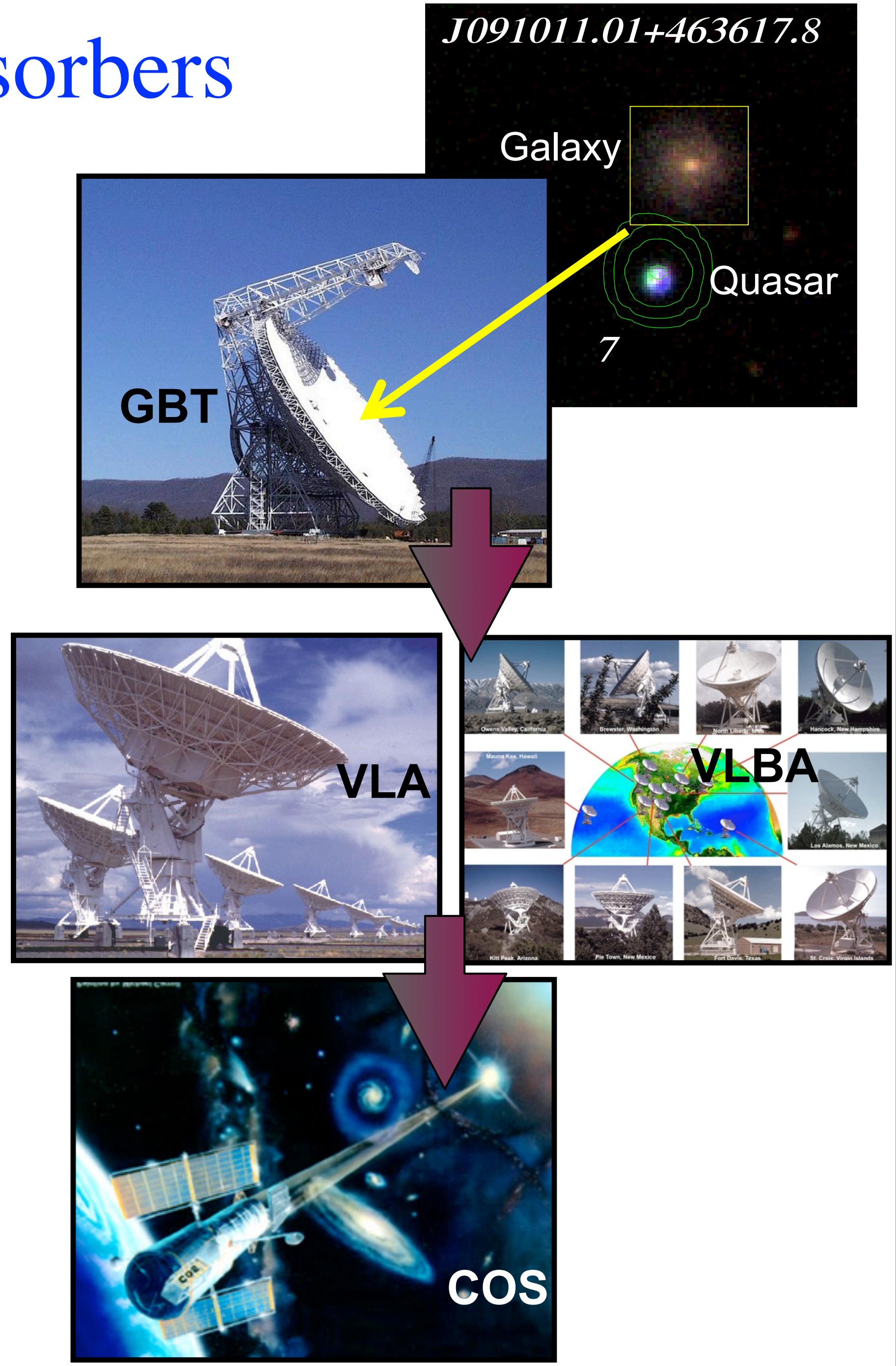




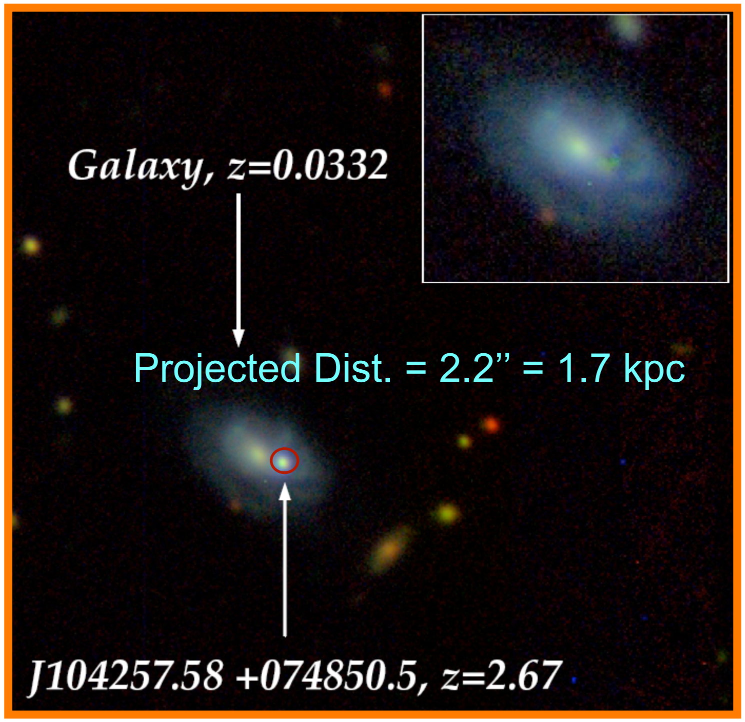
Our Approach: 21cm Absorbers

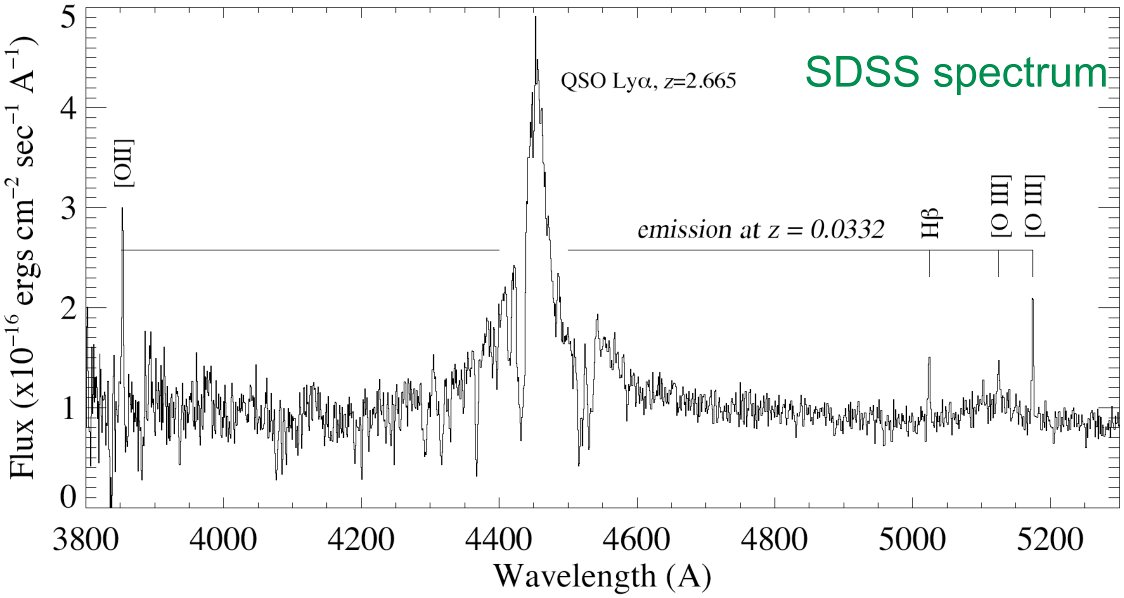
- QSO-foreground galaxy pairs from SDSS
- Observe radio bright QSOs to look for 21cm HI absorbers associated with the foreground galaxies using the GBT
- Follow-up with VLBA/VLA to map the small-scale structure of the ISM/halo clouds of in these galaxies
- Follow-up UV spectroscopy with COS for sub-sample of QSOs, which are bright in UV
  - Possible low-redshift Damped Lyman α absorbers (DLA) or sub-DLAs

Borthakur et al. (2010)



Case I: Probing Cold Gas in the Stellar Disks of Galaxies: J104258+074850 & GQ1042



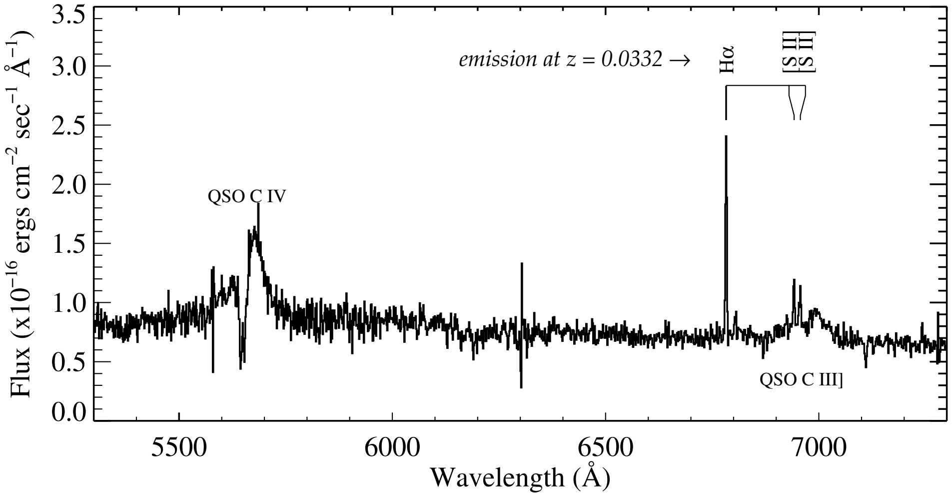


$$SFR(H\alpha) = 7.9 \times 10^{-42} \times L(H\alpha, ergs\ s^{-1})\ M_\odot\ yr^{-1}$$

$$SFRSD(H\alpha) = 4.1 \times 10^{-3}\ M_\odot\ yr^{-1}\ kpc^{-2}$$

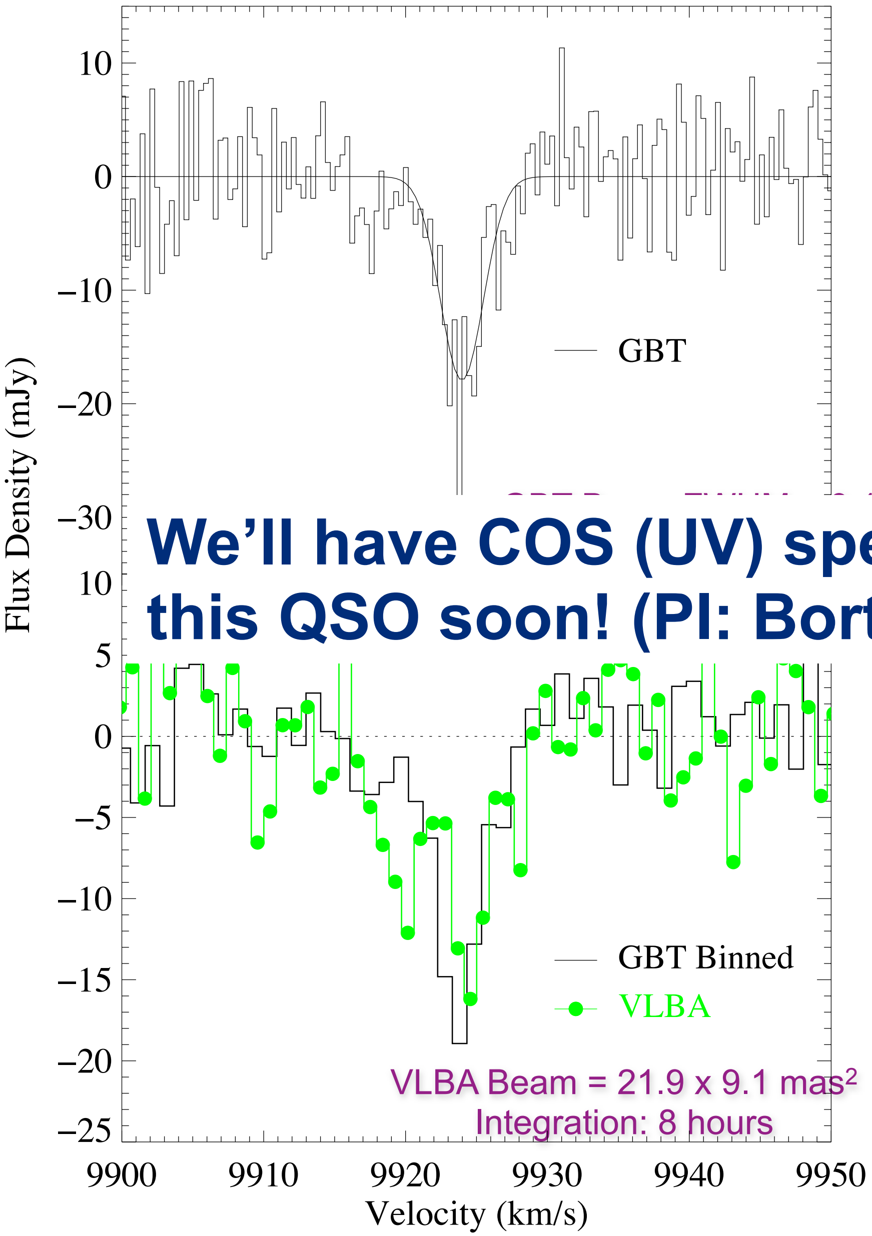
$$SFR(O[II]) = 6.58 \times 10^{-42} \times L(O[II], ergs\ s^{-1})\ M_\odot\ yr^{-1}$$

$$SFRSD(O[II]) = 2.8 \times 10^{-3}\ M_\odot\ yr^{-1}\ kpc^{-2}$$



Borthakur et al. (2010b)

Cold Gas in the Disk of GQ1042



We'll have COS (UV) spectrum of this QSO soon! (PI: Borthakur)

Gaussian of FWHM = 3.6 km/s
Kinetic Temperature ≤ 283 K

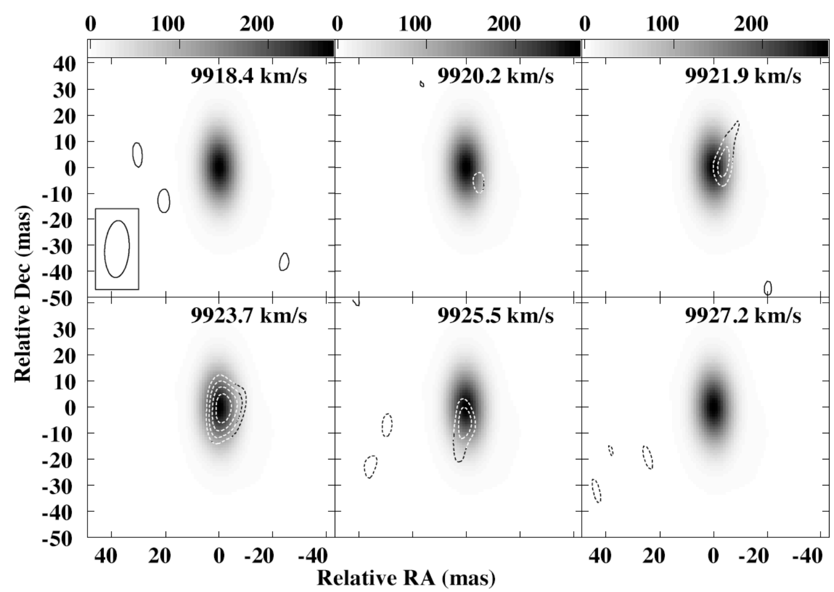
$$N(\mathrm{H\ I}) = 1.823 \times 10^{18}\frac{T_s}{f}\int \tau_{21}(v)dv$$

Assuming f=1 and

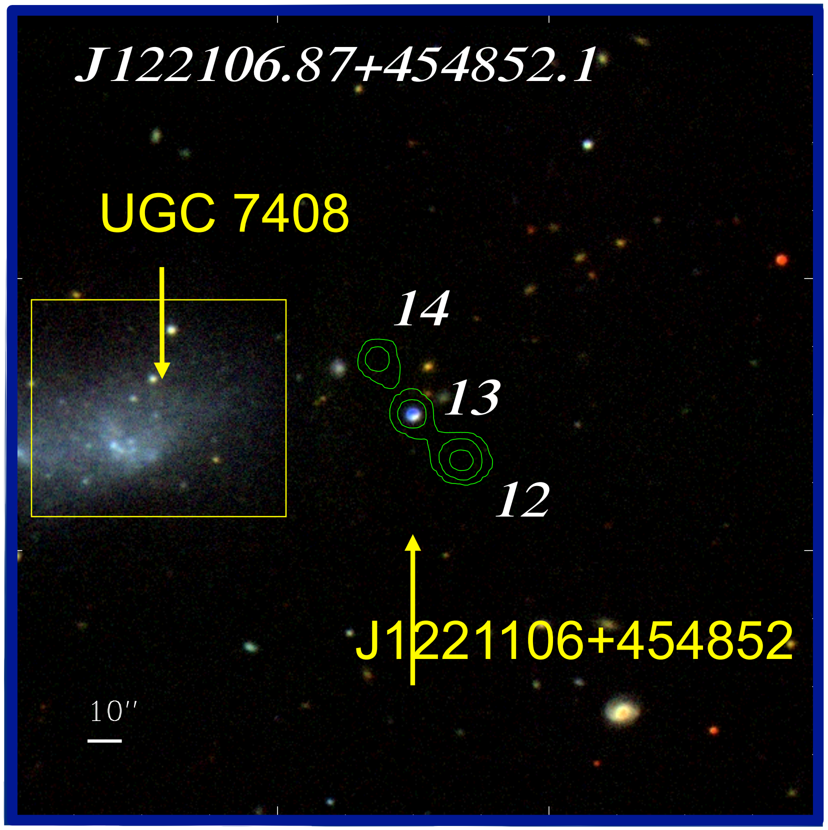
T_s = 283K => N(HI) = 9.6 x 10^{19} cm^{-2}

T_s ≥ 100K => N(HI) ≥ 3.4 x 10^{19} cm^{-2}

Size = 41 x 21 mas² or 26.7 x 13.7 pc²
If T_s = 283 K => Mass = 356 $M_\odot$

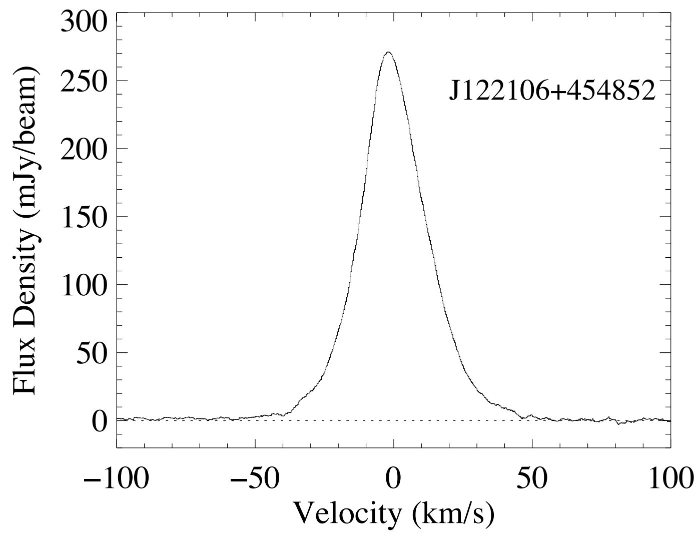


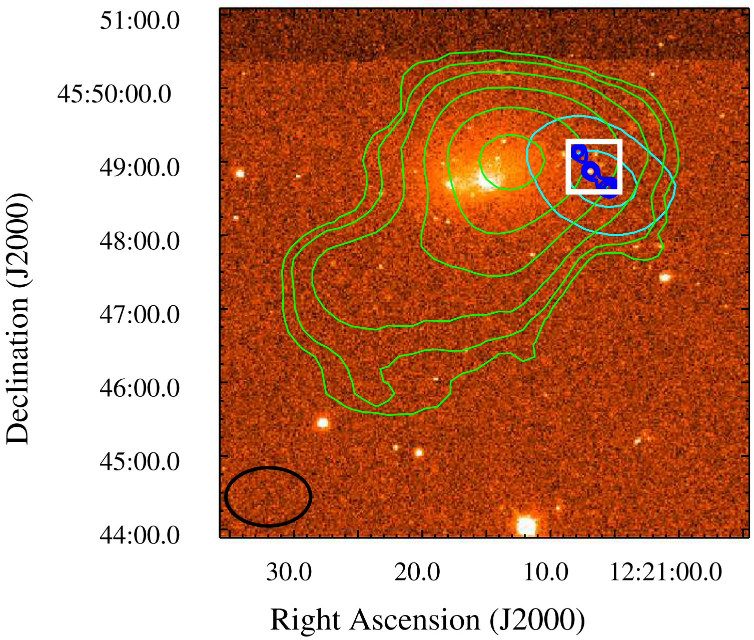
Case II: Probing Cold Gas in Extended Disks: J122106+454852 & UGC 7408



ρ=2.6, 2.8, & 3.3 kpc

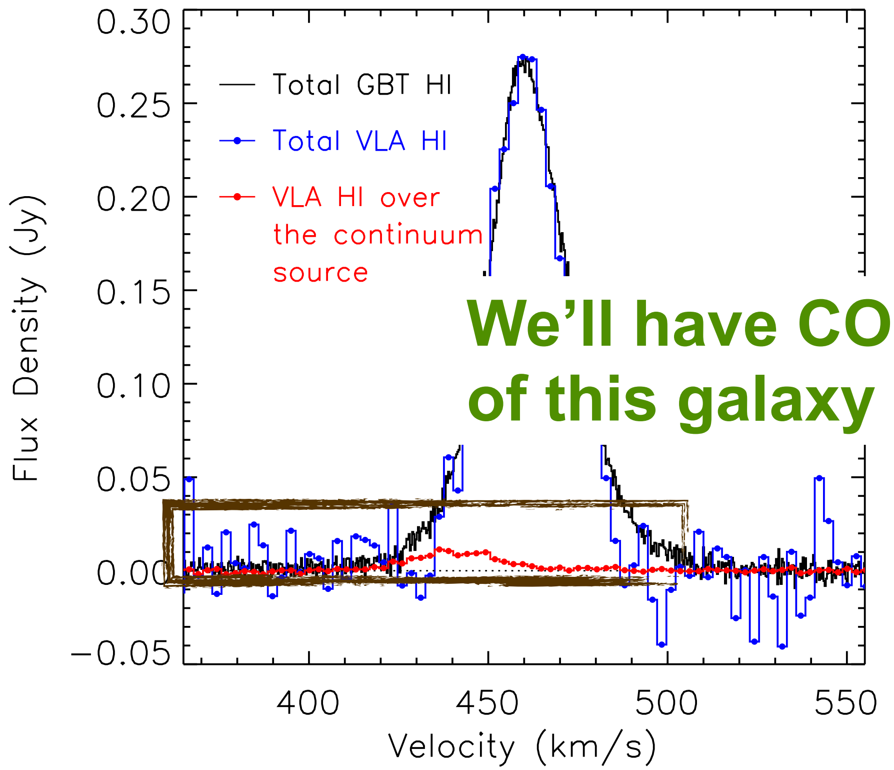
N(HI) = 1.8, 3.6, 7.2, 14.4, 28.8, & 57.6 x 10^{19} cm^{-3}

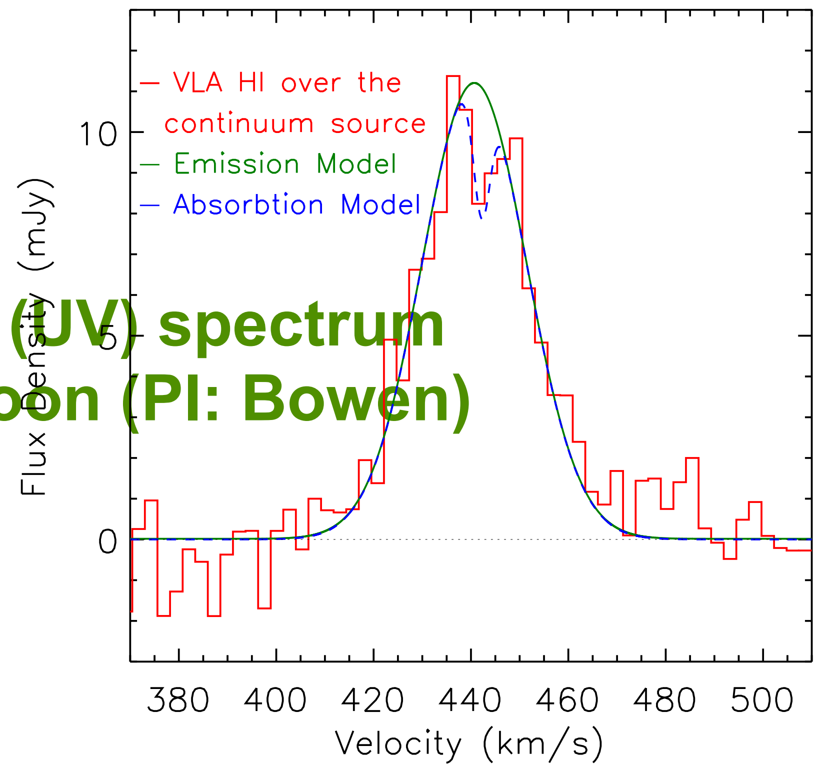




Case HI Emission Versus HI Absorption:

Need For High Spatial Resolution





We'll have COS (UV) spectrum of this galaxy soon (PI: Bowen)

The measured line temperature,

$$T_L = (f_{cl}\ T_s - f_0\ f_C\ T_C)(1 - e^{-\tau})$$

where f_{cl} and f_C are beam filling factors of the H I cloud and continuum source, respectively, and f_0 is the fraction of the continuum source covered by the H I cloud.

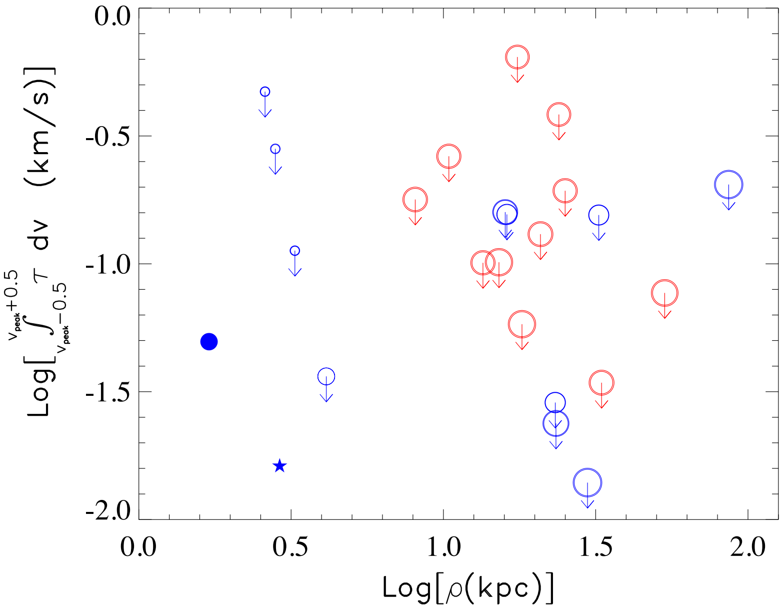
FWHM= 4.75 km/s ⇒ $T_{kinetic} \leq 483$ K

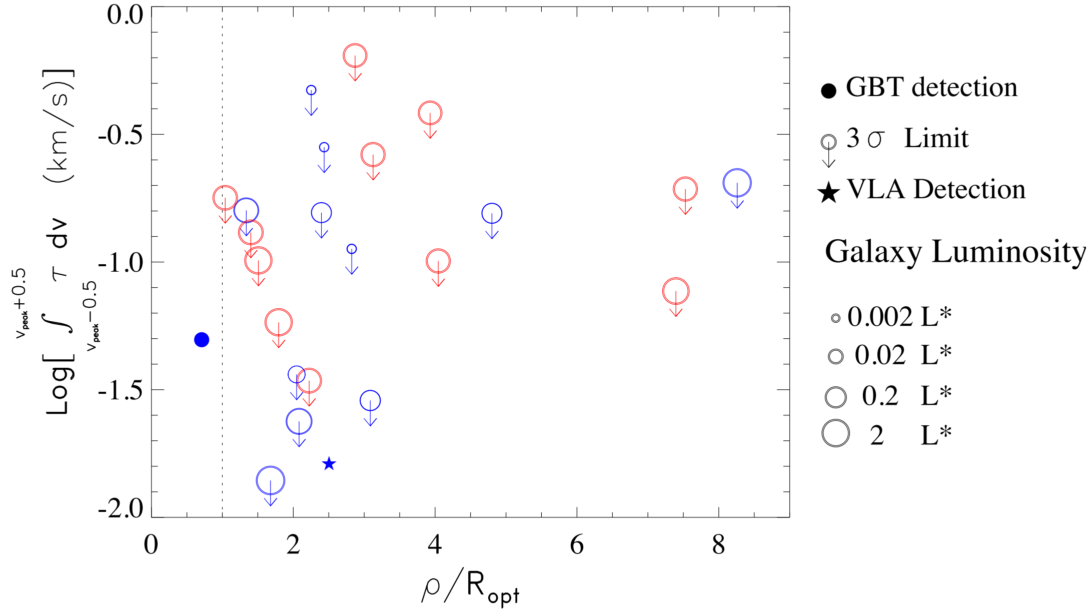
N(HI) ≤ 1.86 x 10^{20} cm^{-3}

If $f_{cl} = 1$ and f_0=1; f_C=0.3

$\Rightarrow T_L = (T_s - 0.3\ T_C)(1 - e^{-\tau})$

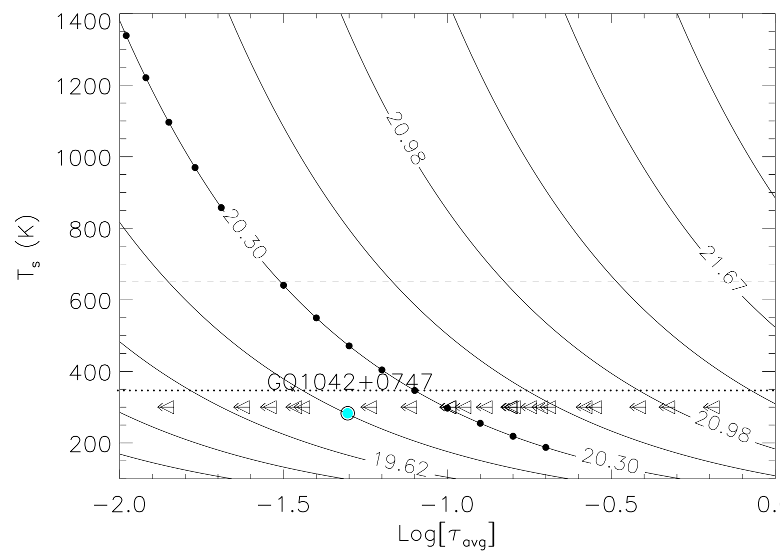
Low Column Density or High Spin Temperature



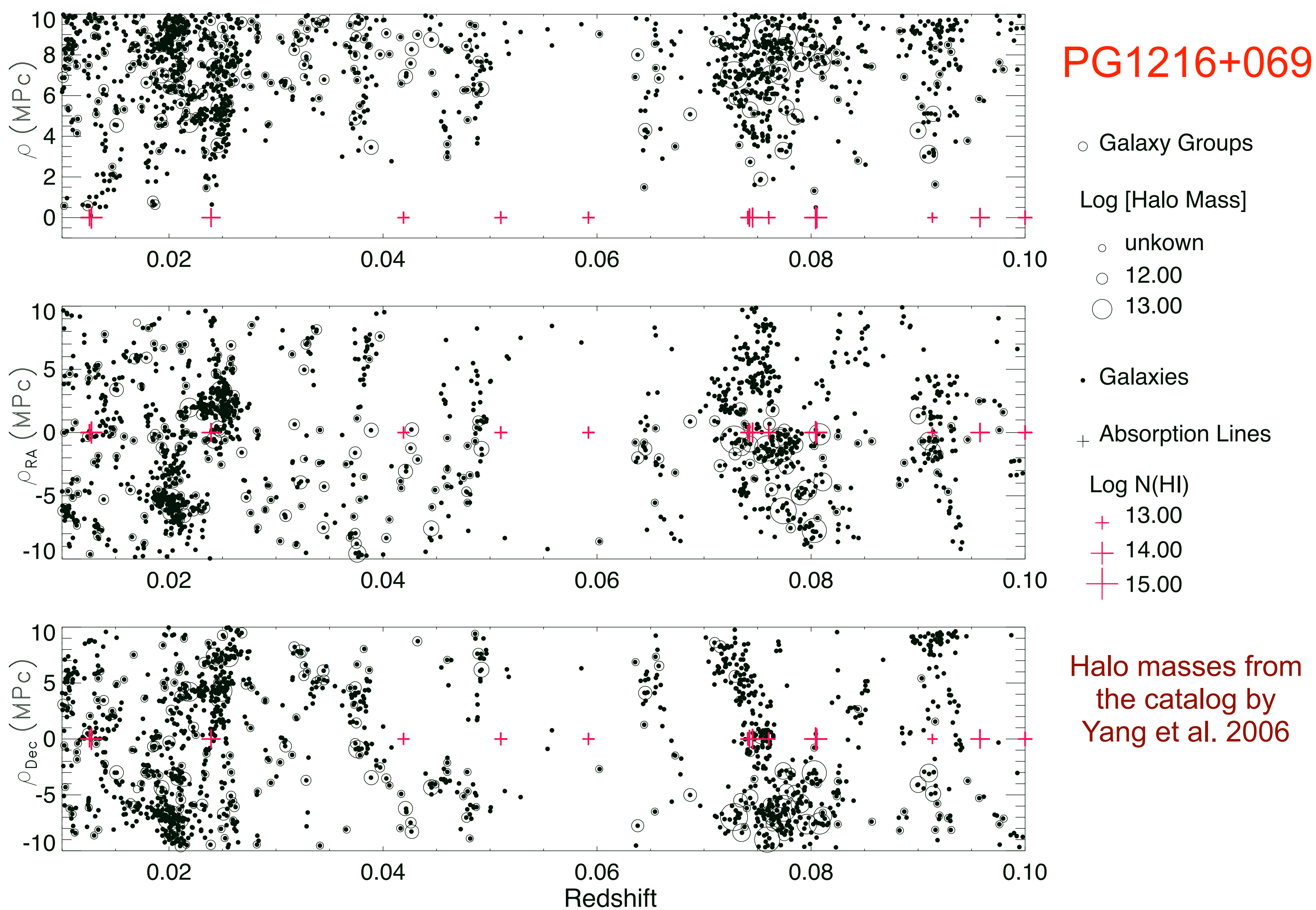


$$N(\text{H I}) = 1.823 \times 10^{18} \frac{T_s}{f} \int \tau_{21}(v) dv$$

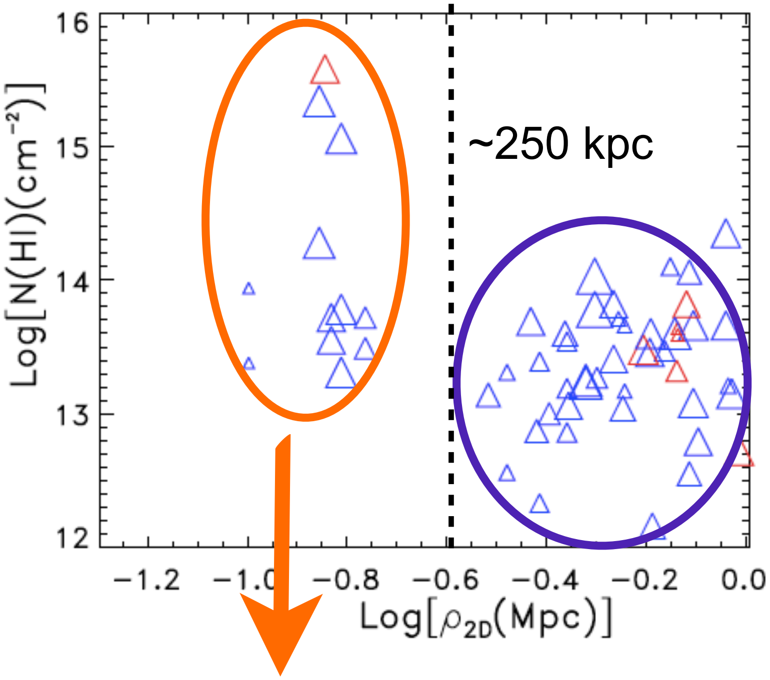
$$N(\text{H I}) \frac{f}{T_s} = 1.823 \times 10^{18} \int \tau_{21}(v) dv$$

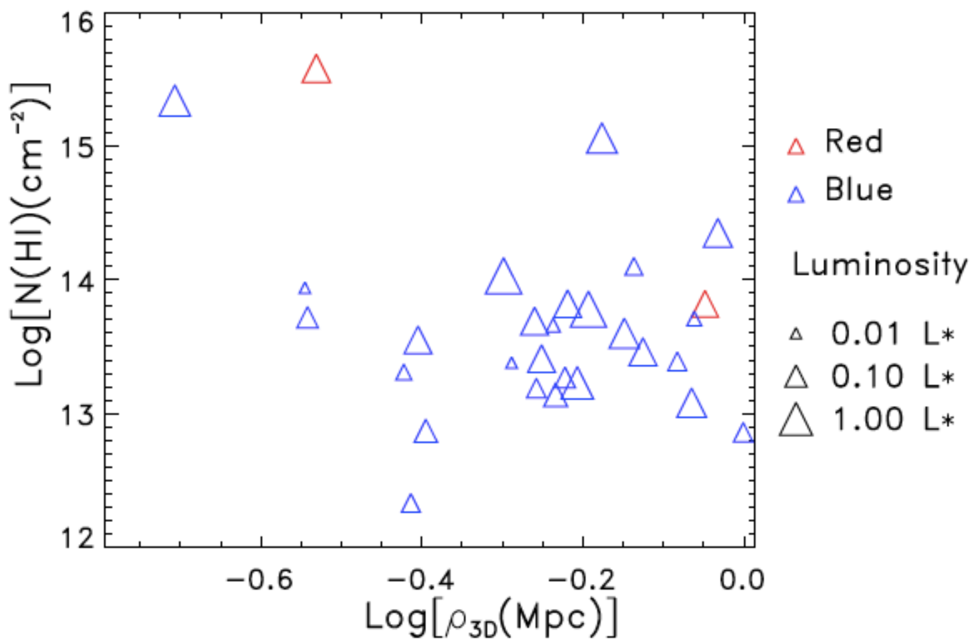


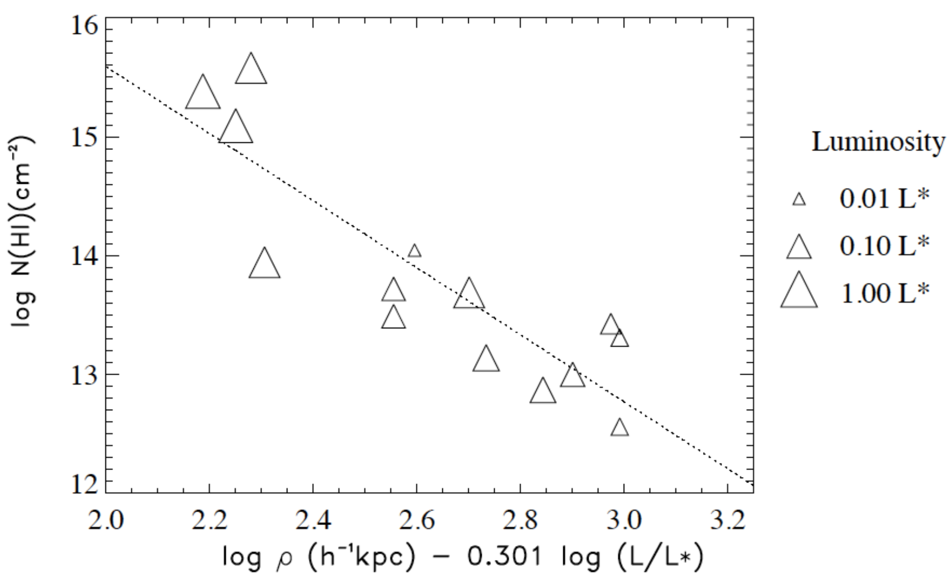
Connection Between Lyman-α Absorbers and Galaxies



Correlation between Impact Parameter & Column Density







Luminosity Corrected Projected Distance:

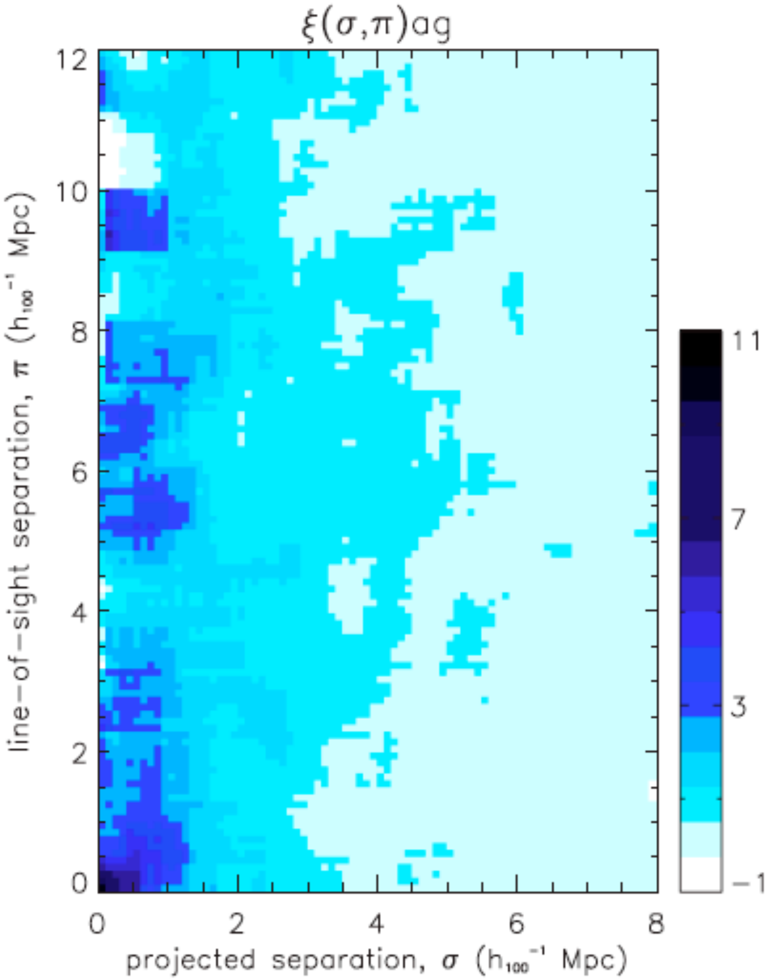
$N(HI) = \alpha \log(\rho) + \beta \log(L) + \text{constant}$

$\alpha = -2.82 \pm 0.66; \beta = 0.85 \pm 0.25$

$N(HI) \propto -(\log(\rho) - 0.301 \log(L))$

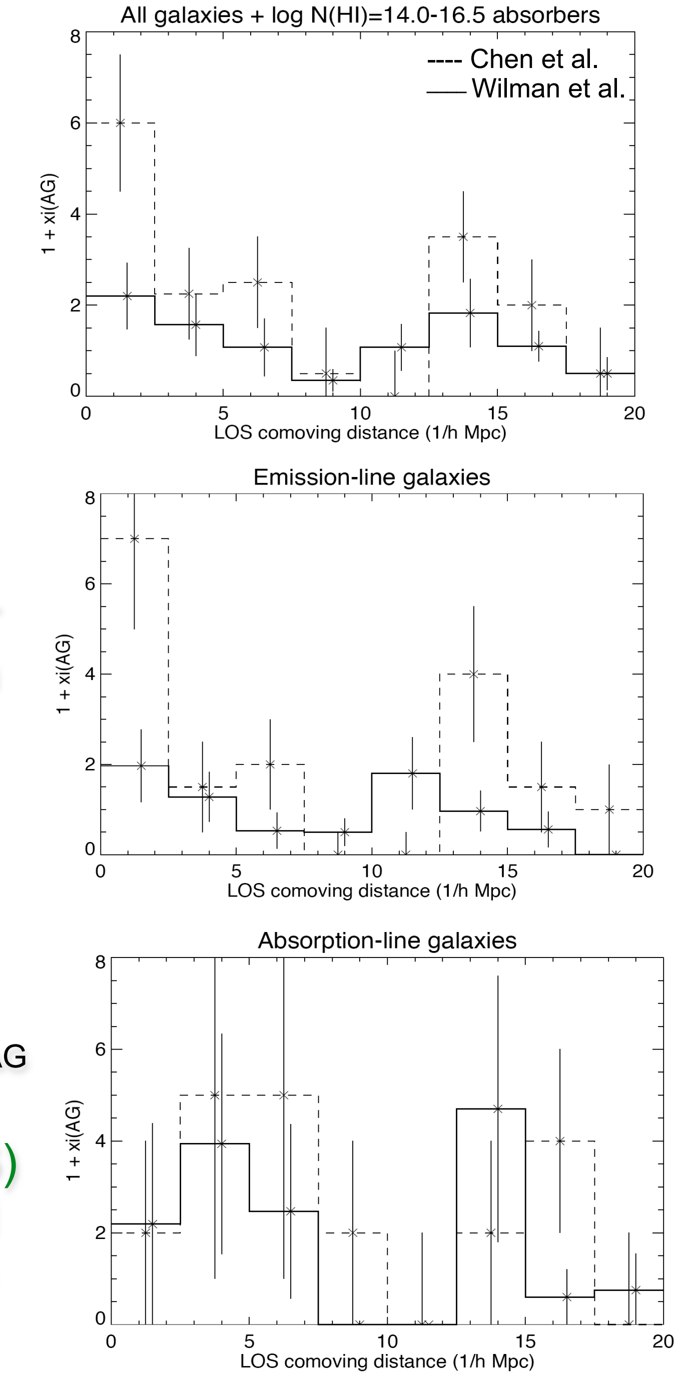
Lyman-alpha Absorbers and its connection to galaxies

Cross-correlation is a measure of the association between any two populations



LEFT::
Galaxy-absorber cross-correlation function (ξ_{AG})
(Ryan-Weber 05)

RIGHT::
Comparison of ξ_{AG} measured by
Wilman et al. (06) (solid lines) and
Chen et al. (06) (dashed lines)



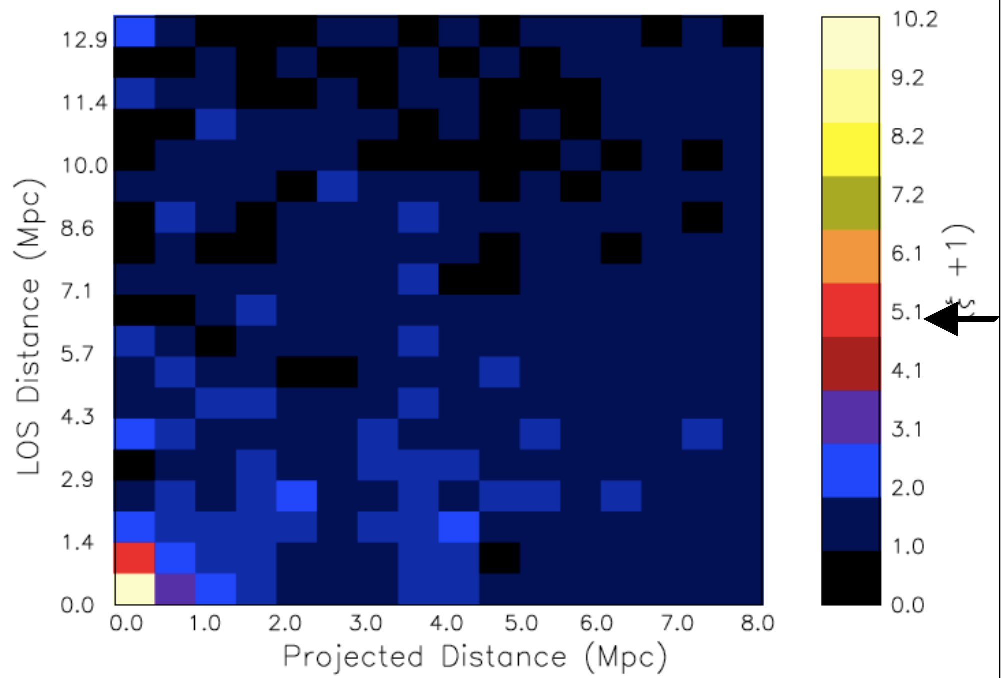
Wilman et al. (2006)

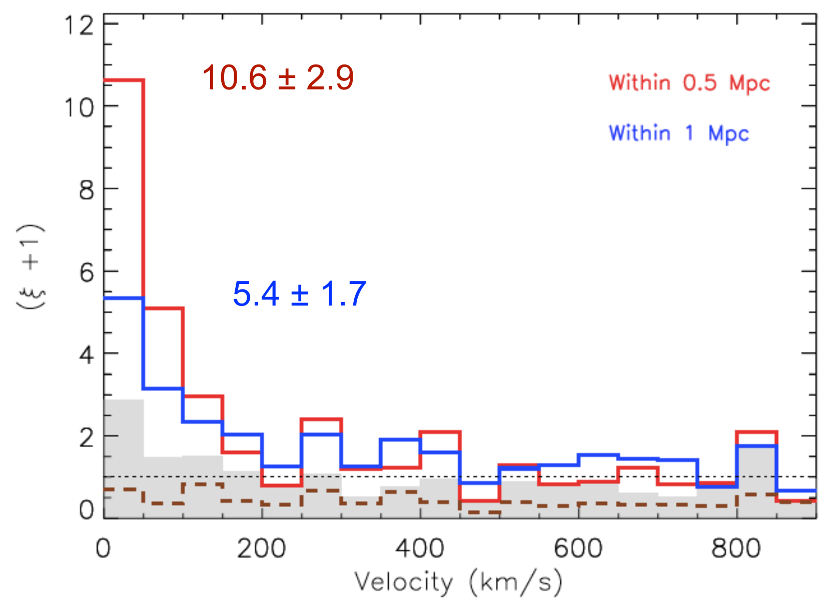
Galaxy-Absorber Cross-correlation Function

$$\xi_{AG}(\sigma, \pi) = \frac{AG(\sigma, \pi) n_{RG}}{RG(\sigma, \pi) n_{AG}} - 1$$

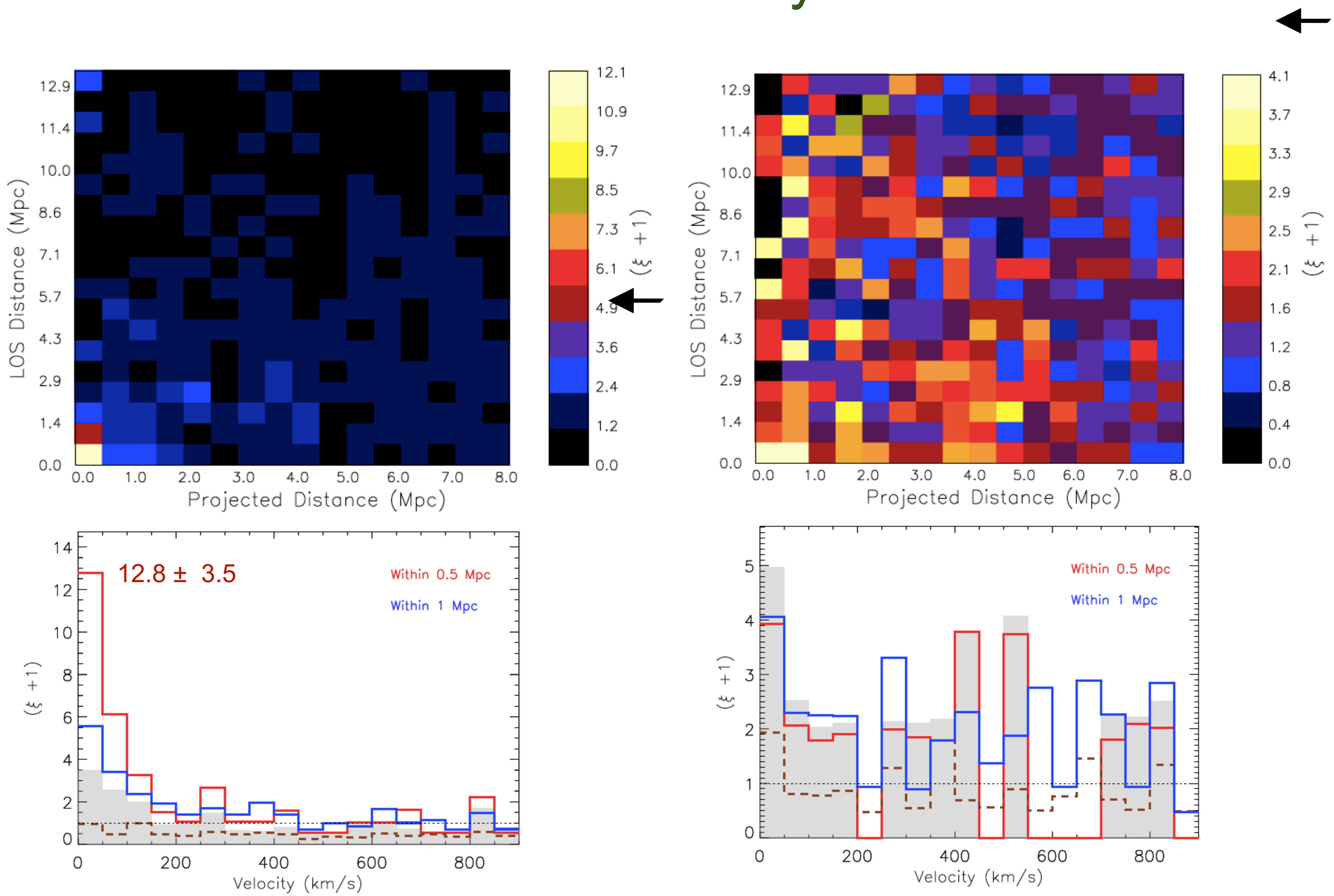
AG(σ,π) and RG(σ,π) are the numbers of true pairs and random pairs as functions of projected distance and line of sight (LOS) distance.

- Our sample = 10 sightlines
  - $0.01 \leq z \leq 0.1$
  - 1000 iterations
  - Window function
- Variation in cross-correlation function between
  - Blue & Red galaxies
  - Low mass & high-mass galaxies
- Jackknife error estimator

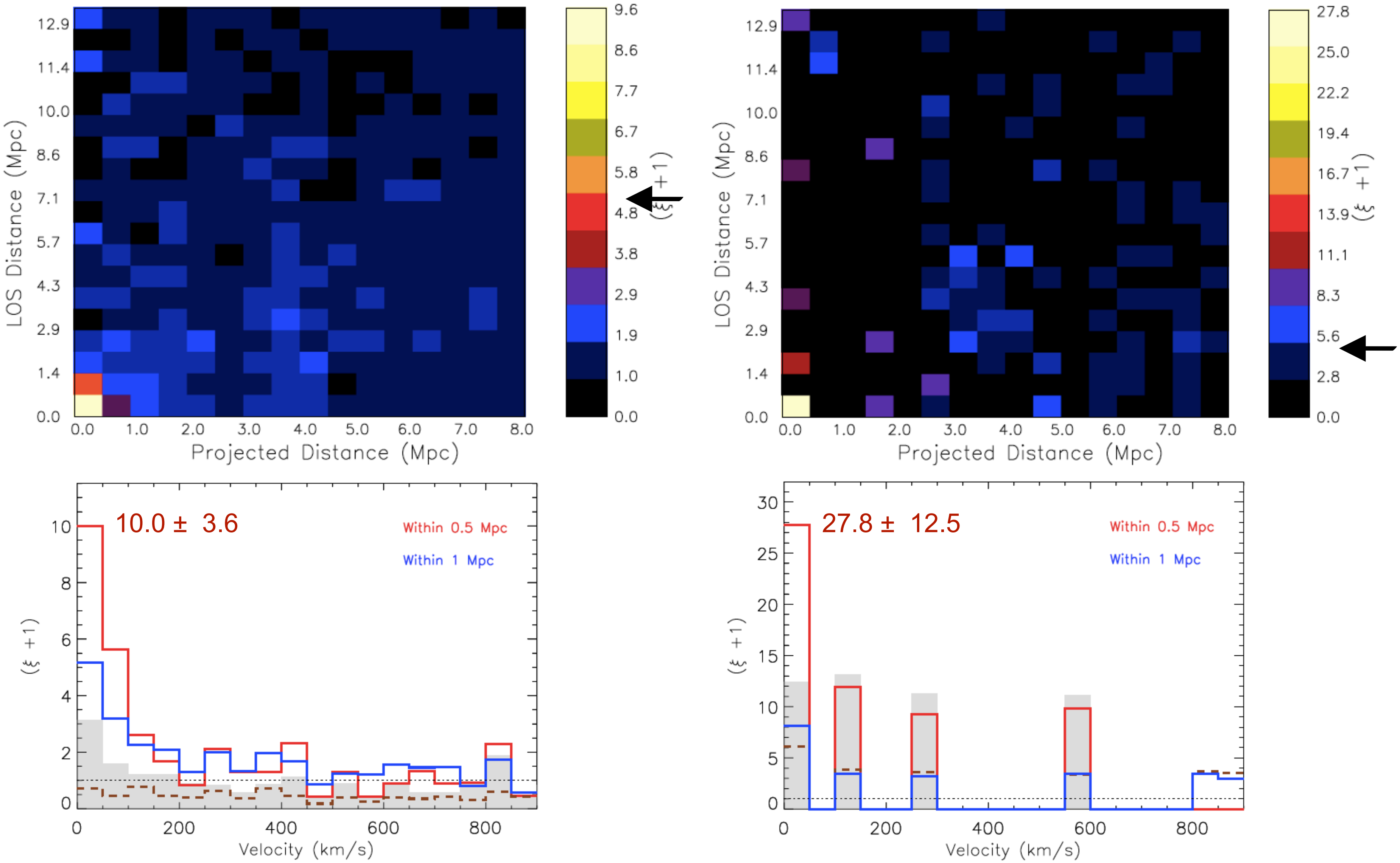




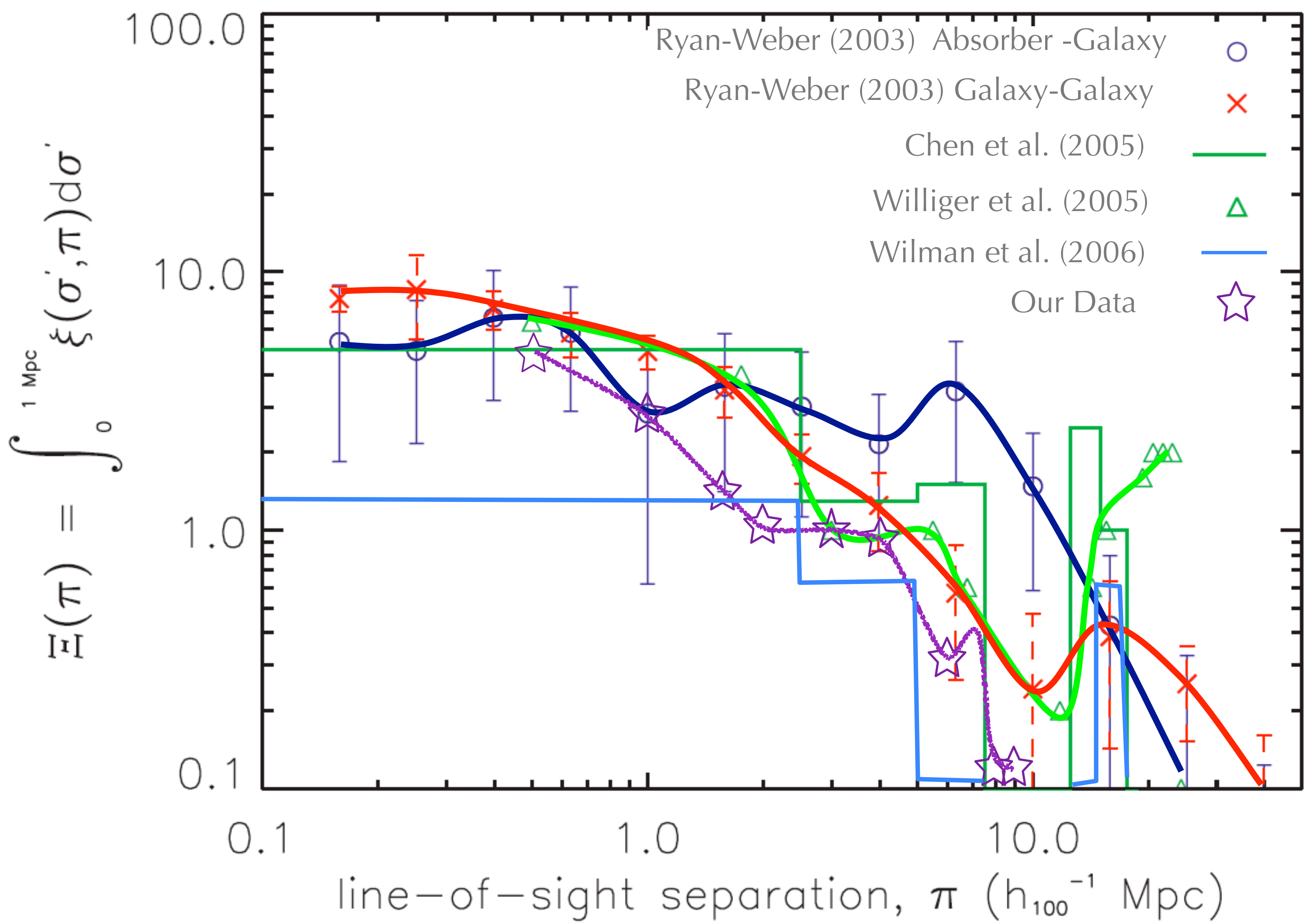
Blue & Red Galaxies with Lyman α Absorbers



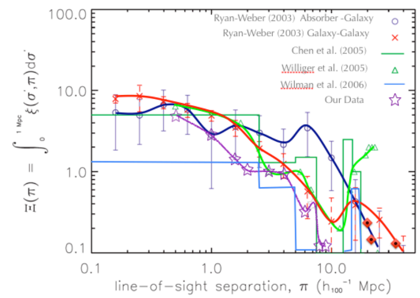
Low & High-mass Galaxies with Lyman α Absorbers



Comparison With Other Studies



Why Do We Have So Many Different Results?



Chen et al. 2005 & Williger et al. 2005: single sightline

Ryan-Weber et al. 2006: HI bright galaxies => no ellipticals

Geometric mean of HIPASS galaxies is log (M/ $\mathbf{M_\odot}$) = 8.8 h^{-1}

=> Halo mass ~ log (M/ $\mathbf{M_\odot}$) = 11 h^{-1}

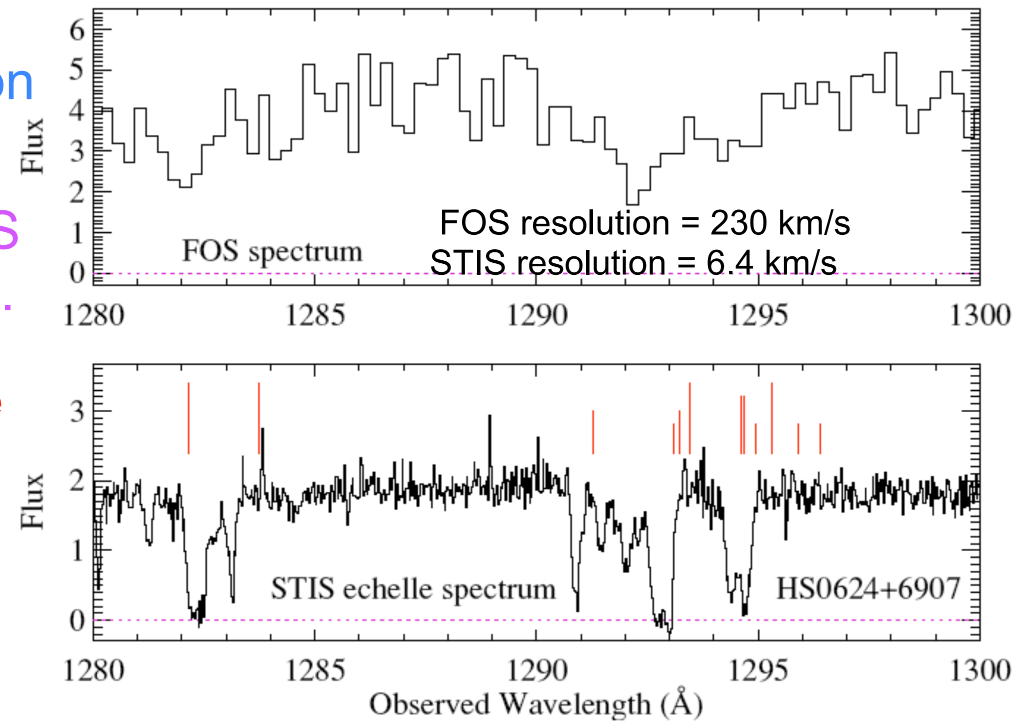
Optical catalog of -22 < MB < -18

=> Halo mass ~ log (M/ $\mathbf{M_\odot}$) = 12-13 h^{-1}

Critical halo mass log (M)= 11.4 $\mathbf{M_\odot}$ or baryonic mass, log (M)= 10.3 $\mathbf{M_\odot}$

Wilman et al. 2006: Low resolution UV data

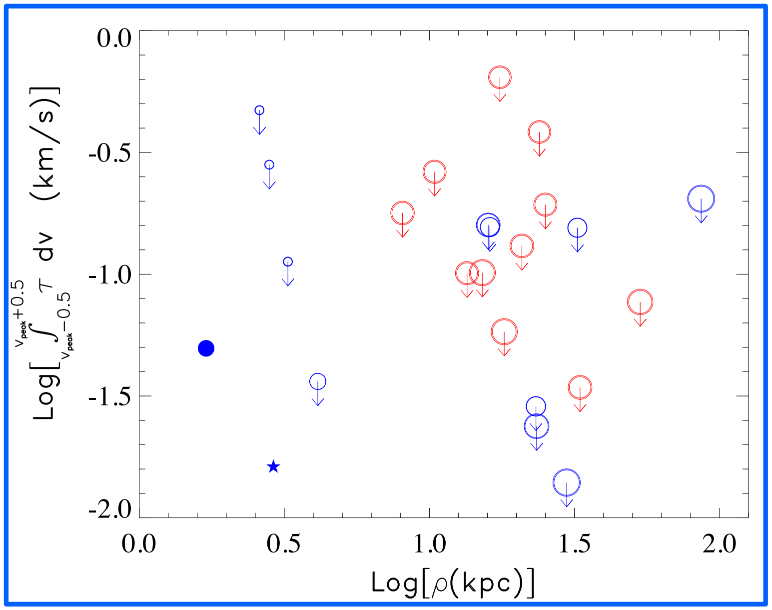
Our Study: Galaxy catalog (SDSS spec. catalog) is not deep enough.



What do we need to get more reliable results?

- A complete galaxy catalog (difficult)
- Weaker absorption features
- Unblended absorption line systems

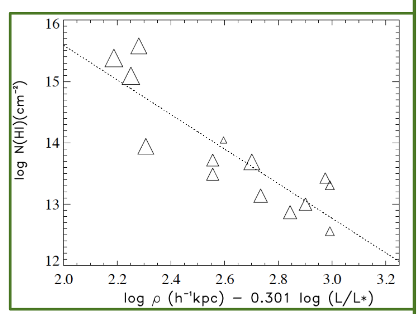
Conclusions

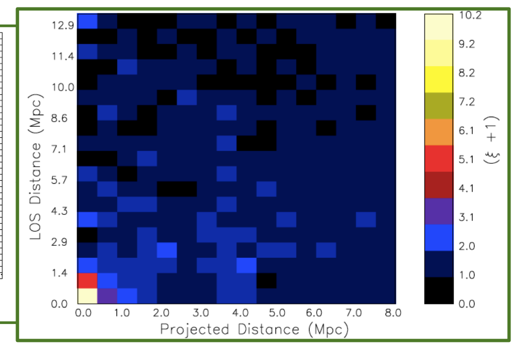


No cold HI found ρ ≥ 10 kpc.
Baryons at these distances are likely to exist in warmer states (i.e traced Lyman α and/or metal transitions).

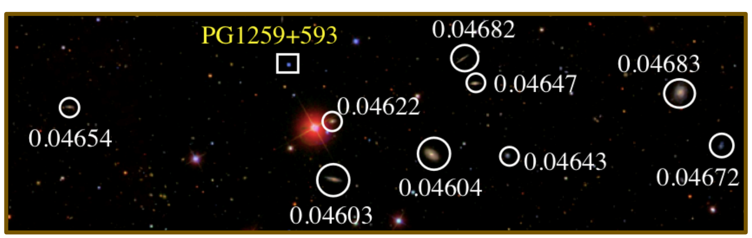
- Issues with a larger beam
- Possible absorbers in UGC~7408 and in two other galaxies

ρ, N(Ly α) tightly correlated when corrected for galaxy luminosity for ρ < 200 kpc





ξ stronger within 0.5 Mpc; Blue and low mass galaxies correlate with absorbers



Some Lyman α absorbers may be associated with the intra-group medium