



UNIVERSITY OF CALIFORNIA
SANTA CRUZ

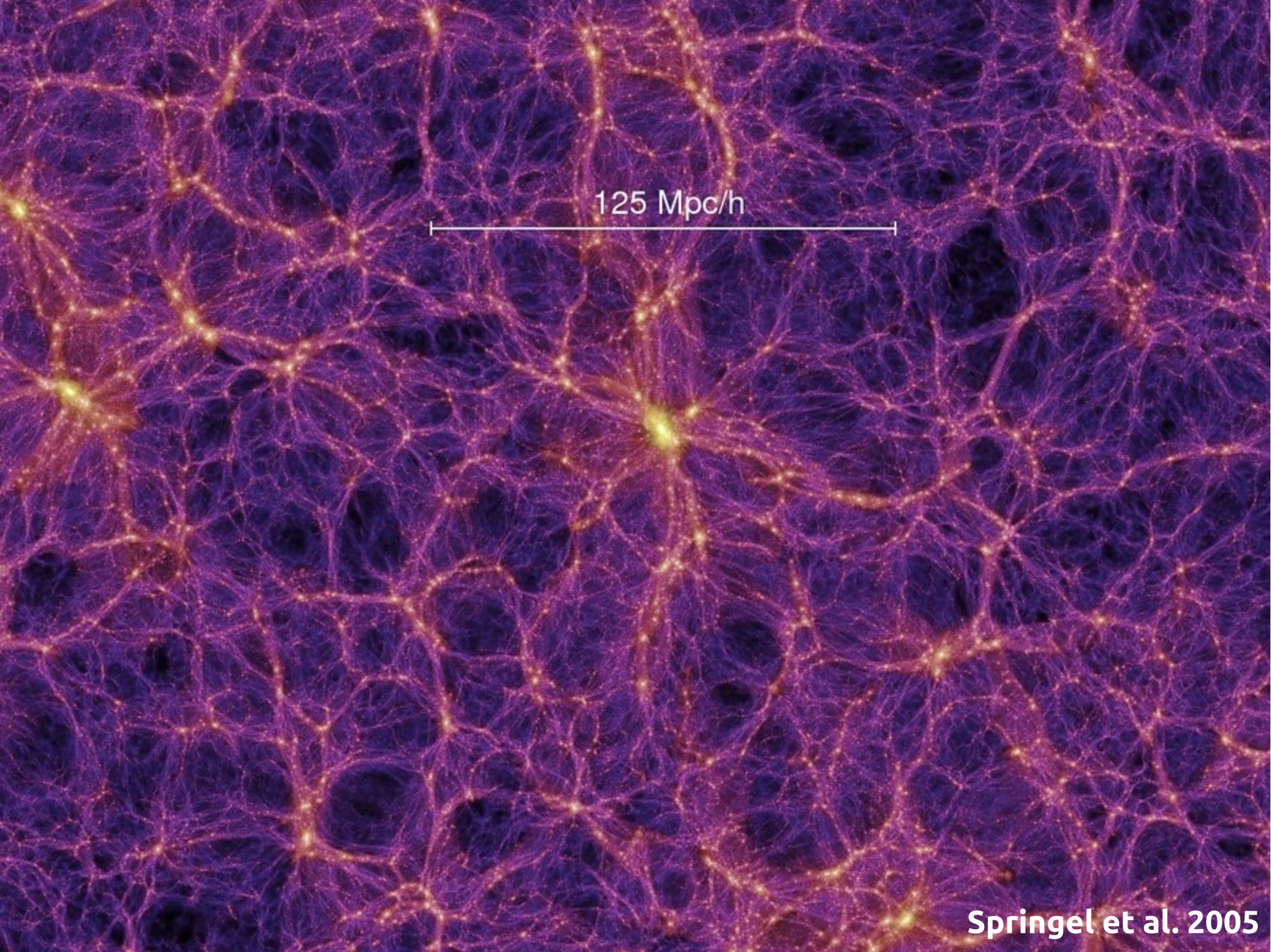


Durham
University

The IGM-galaxy connection

Nicolas Tejos

Simon Morris, Neil Crighton, Charles Finn,
Tom Theuns, et al.



Springel et al. 2005

Outline

- **Part I: The IGM-galaxy cross-correlation at $z < 1$**
(Tejos et al. 2014, MNRAS, 437, 2017)
- **Part II: The IGM within and around galaxy voids at $z < 0.1$**
(Tejos et al. 2012, MNRAS, 425, 245)
- **Conclusions**

Part I:

IGM-galaxy cross-correlation

Cross-correlation

- **Definition:**

$$\xi_{ab}(r) = \frac{\langle n_a(\vec{r} + r) n_b(\vec{r}) \rangle}{\langle n_a \rangle \langle n_b \rangle} - 1 .$$

e.g. Peebles 1980

Cross-correlation

- **Definition:**

$$\xi_{ab}(r) = \frac{\langle n_a(\vec{r} + r) n_b(\vec{r}) \rangle}{\langle n_a \rangle \langle n_b \rangle} - 1 .$$

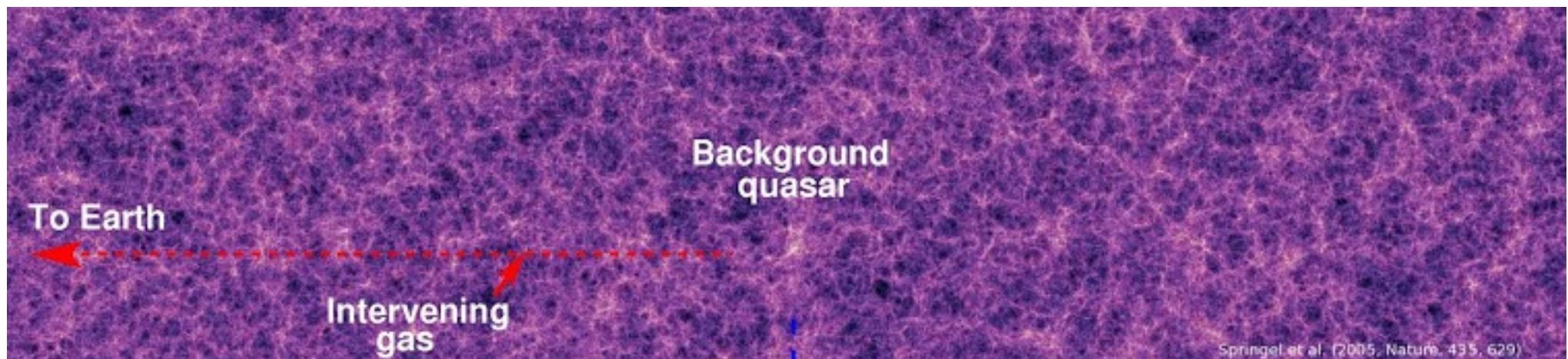
e.g. Peebles 1980

- **Estimator:**

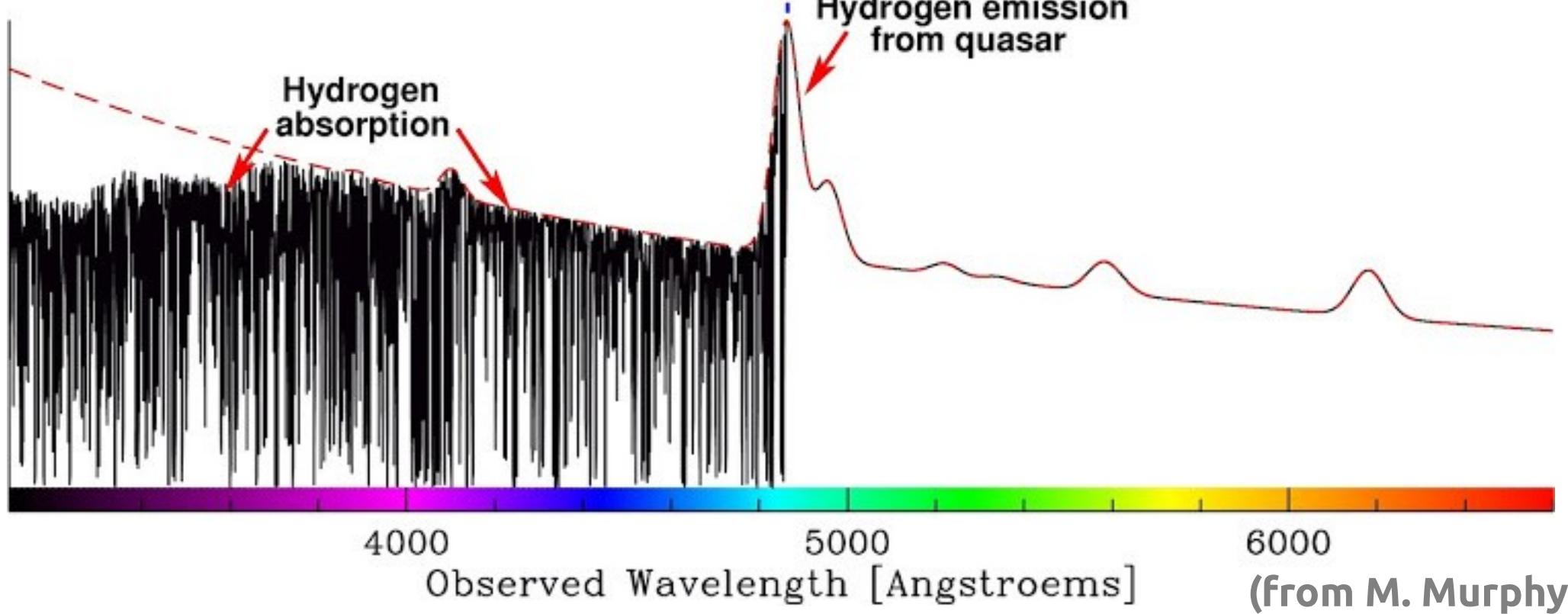
$$\hat{\xi}_{LS} \equiv \frac{D_a D_b - D_a R_b - R_a D_b + R_a R_b}{R_a R_b}$$

Landy & Szalay 1993

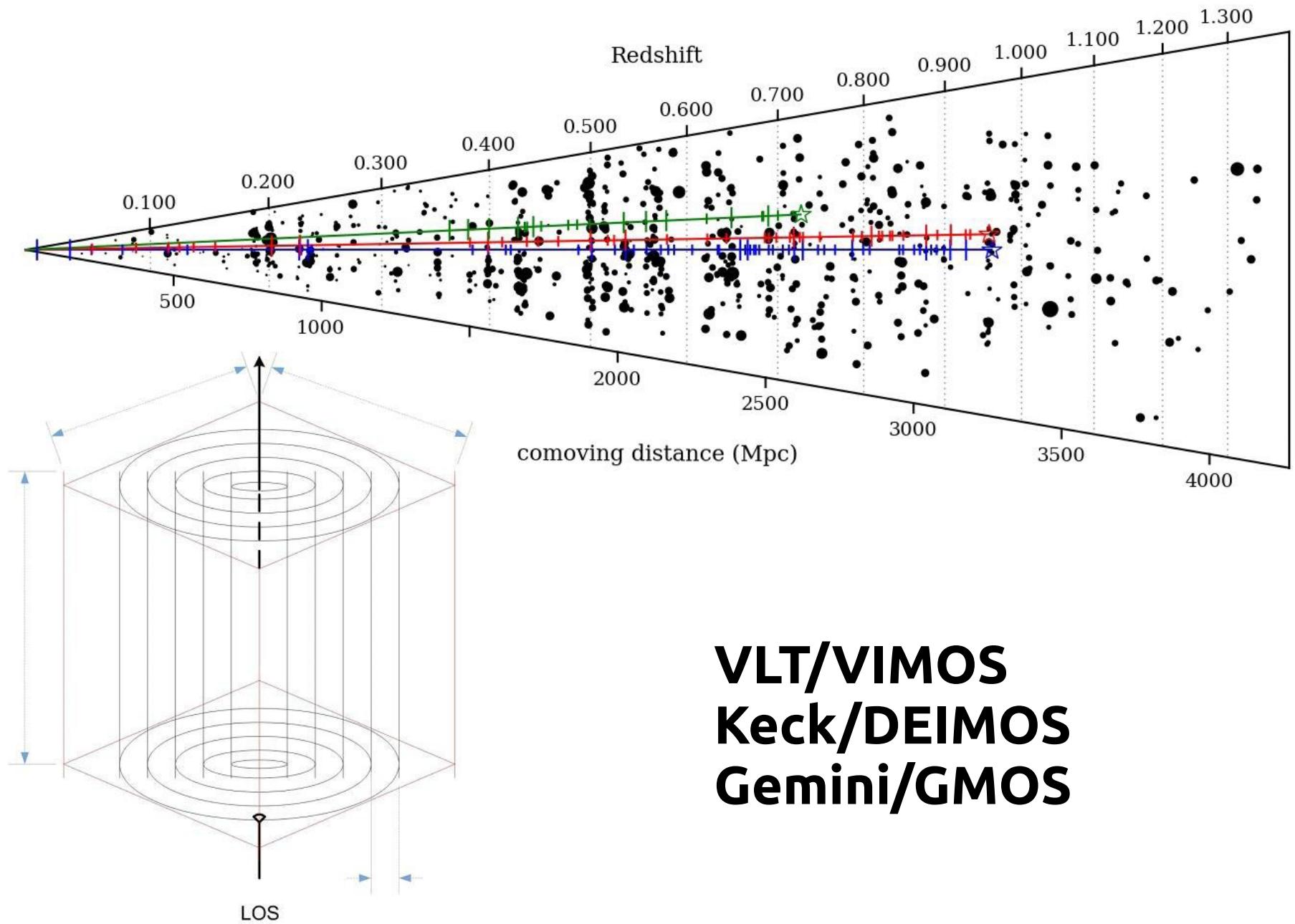
How do we observe the IGM



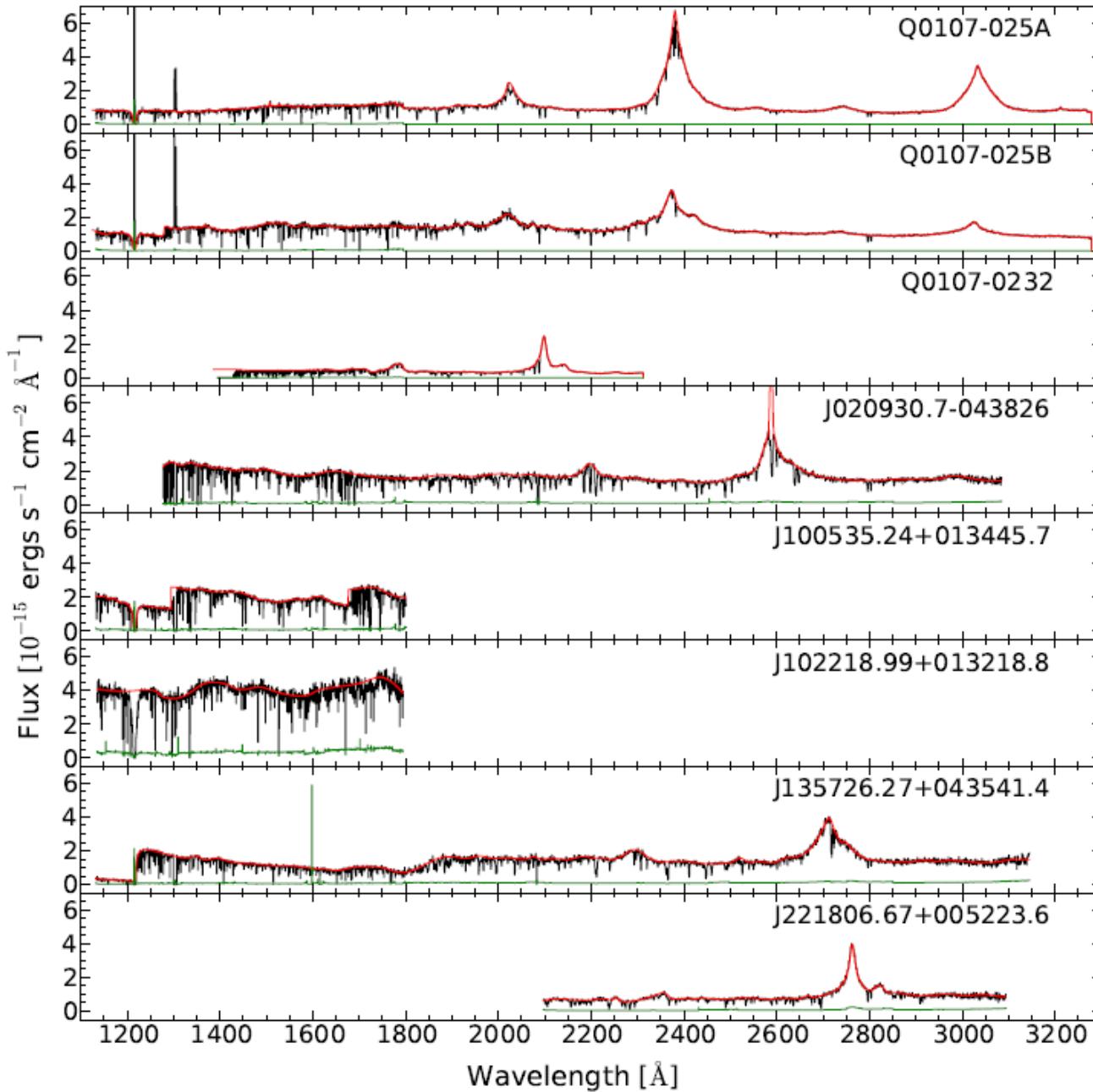
Springel et al. (2005, Nature, 435, 629)



Survey geometry



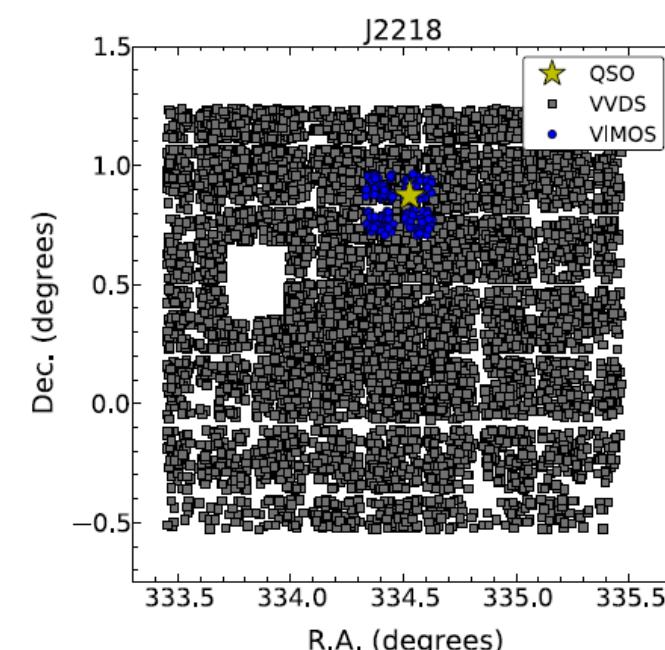
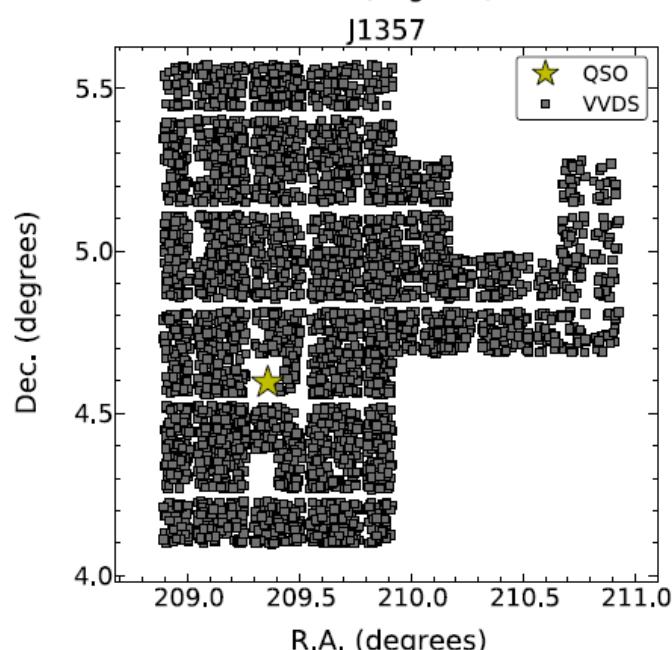
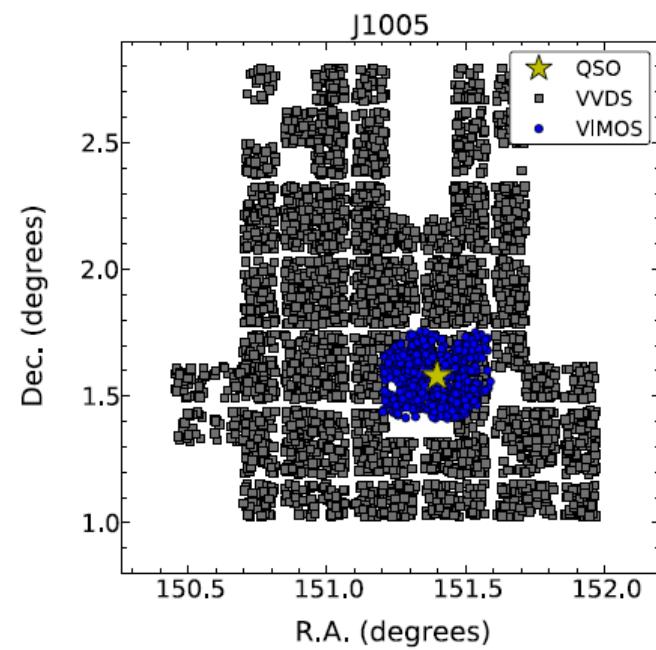
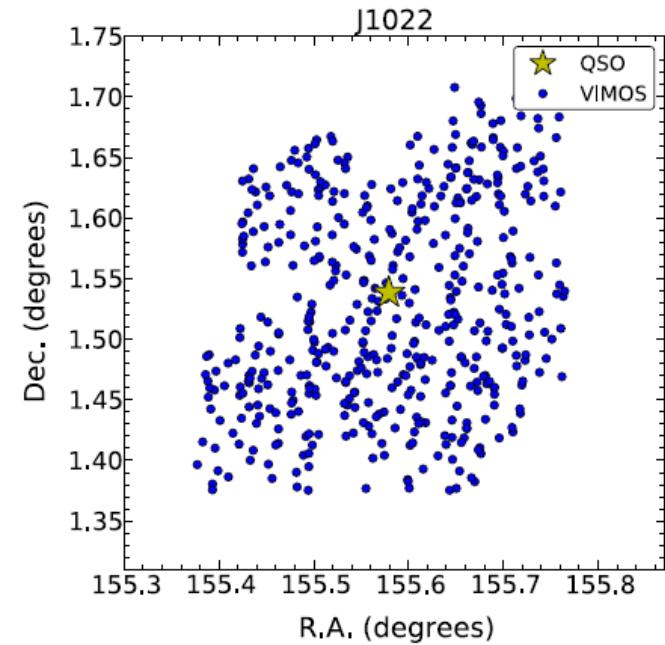
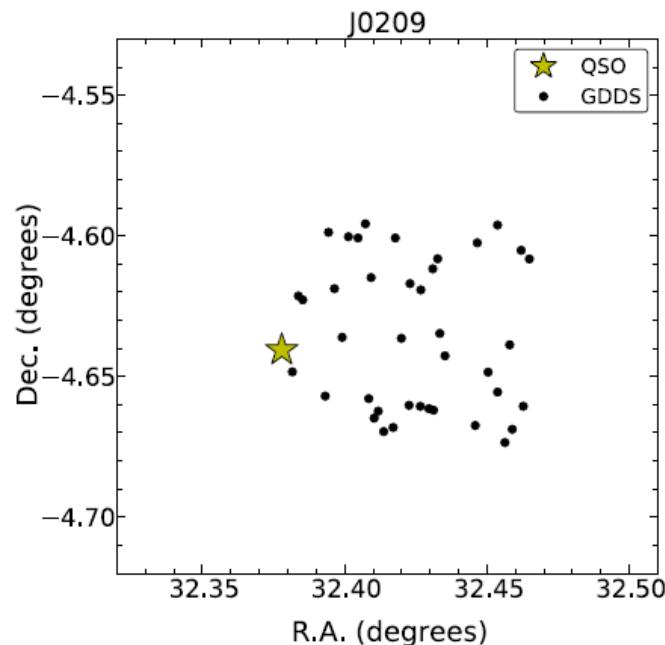
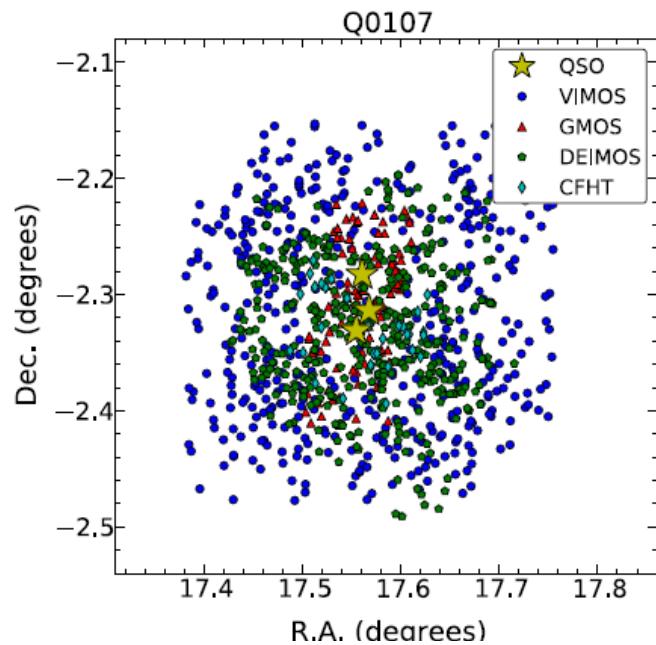
Our sample



**HST/COS
HST/FOS**

(138 orbits excluding J1022)

Our sample



Our sample

Table 6. Summary of the ‘Full Sample’ used for the cross-correlation analysis, as a function of r_{\perp} .

	< 2 Mpc (1)	< 10 Mpc (2)	< 50 Mpc (3)	Total (4)
Galaxies	1354	6871	19509	17509
‘SF’	997	4756	9963	8293
‘non-SF’	193	779	2011	1743
H I	...	...	...	654
‘strong’	...	...	...	165
‘weak’	...	...	...	489

$10^{14} \leq N_{\text{HI}} \lesssim 10^{17} \text{ cm}^{-2}$ (‘strong’)

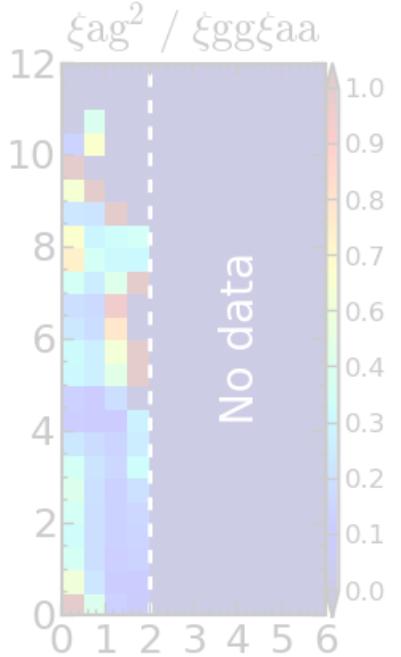
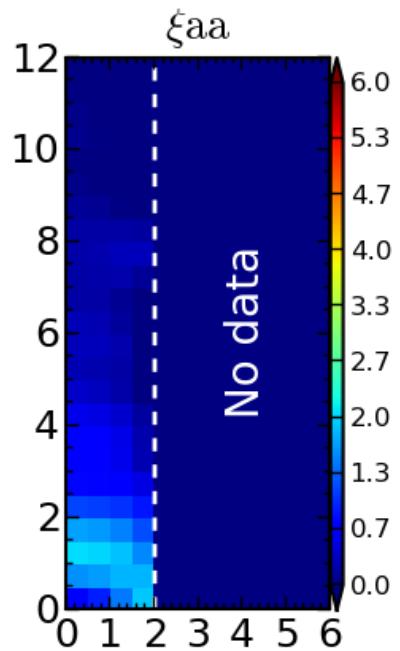
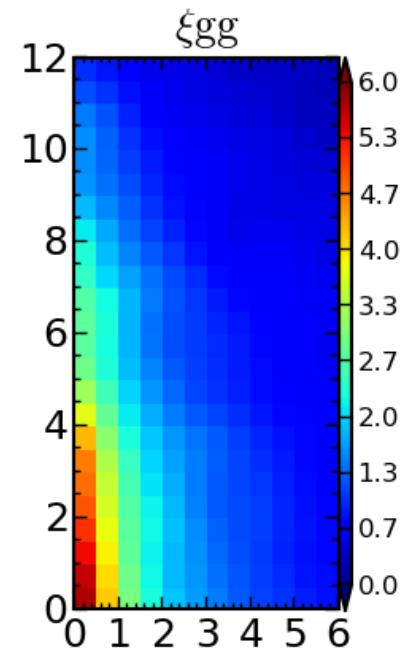
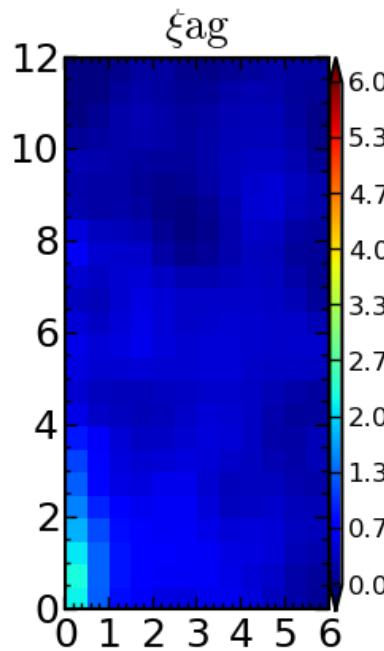
$10^{13} \lesssim N_{\text{HI}} < 10^{14} \text{ cm}^{-2}$ (‘weak’)

Results

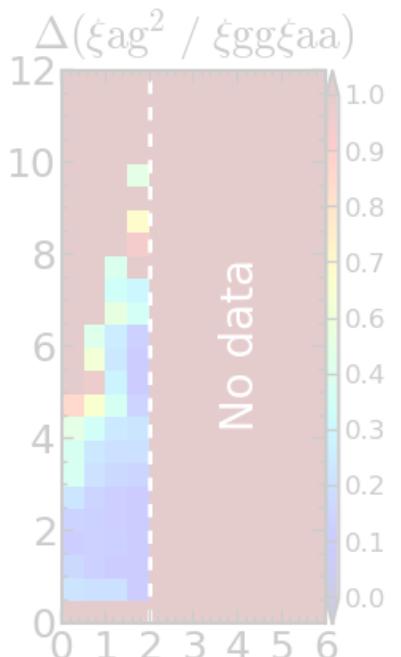
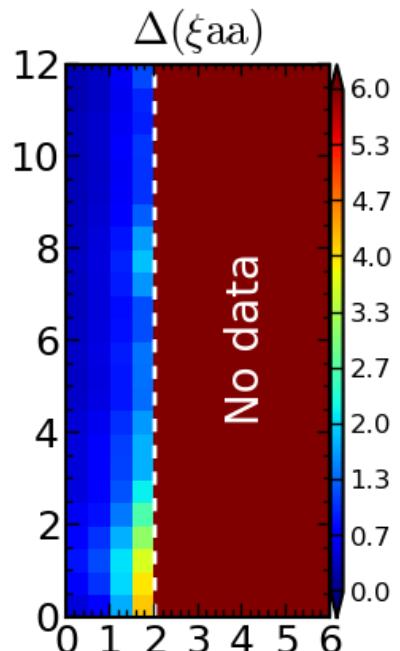
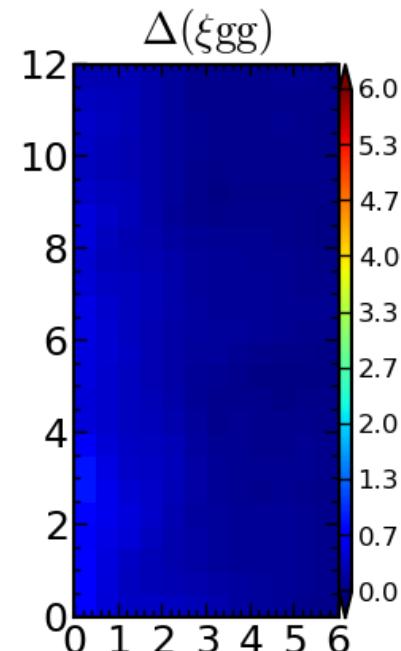
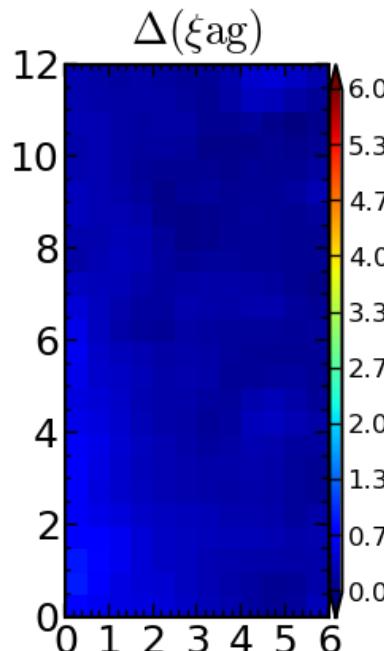
Full Sample

Full Sample

LOS separation, r_{\parallel} [Mpc]

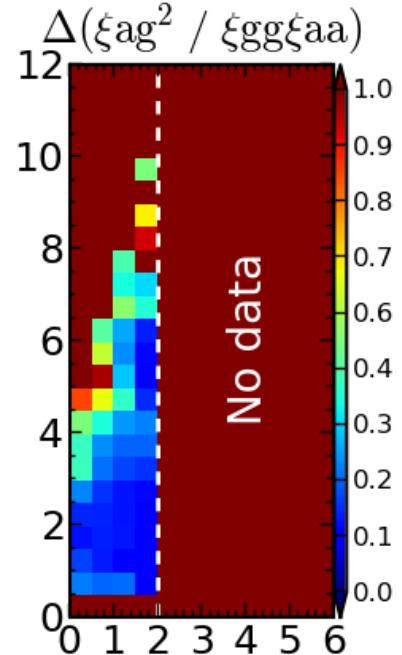
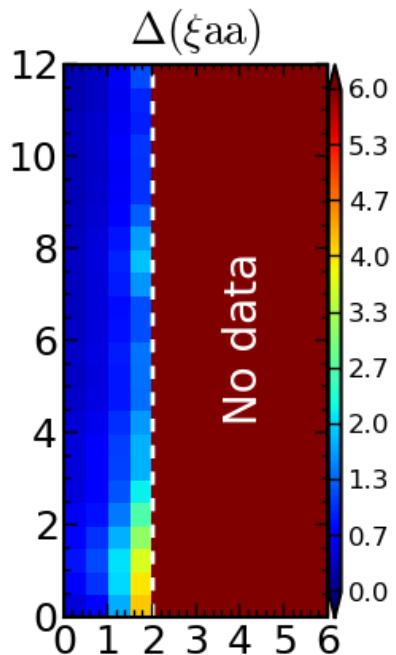
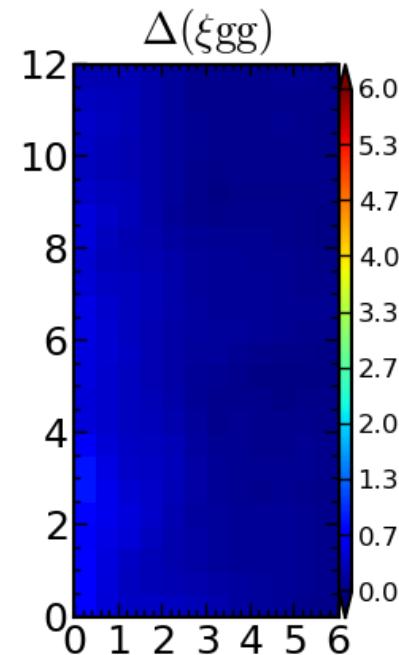
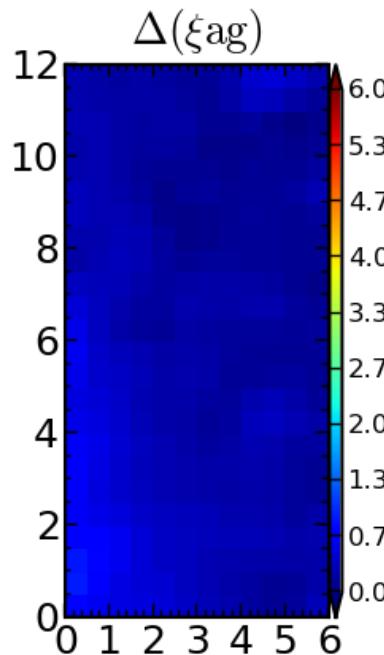
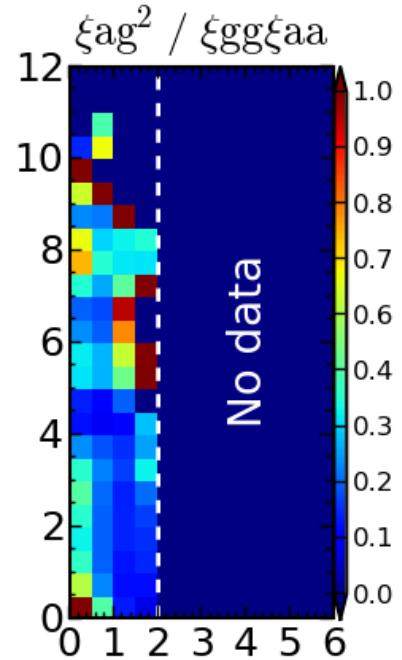
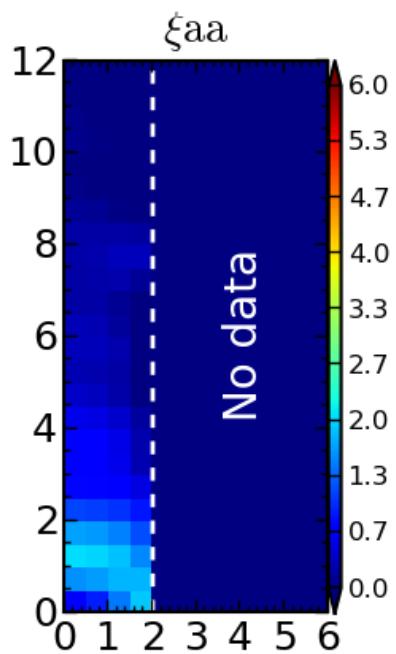
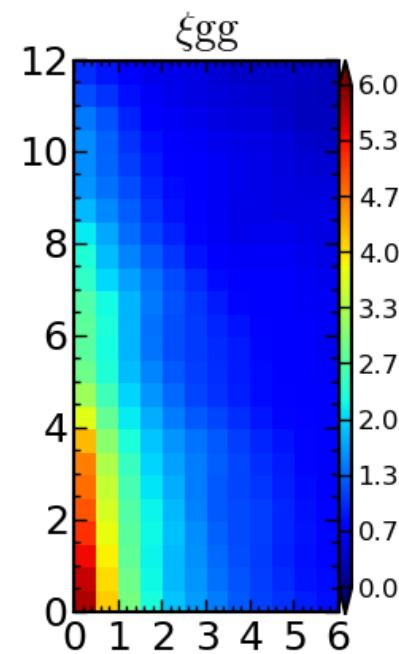
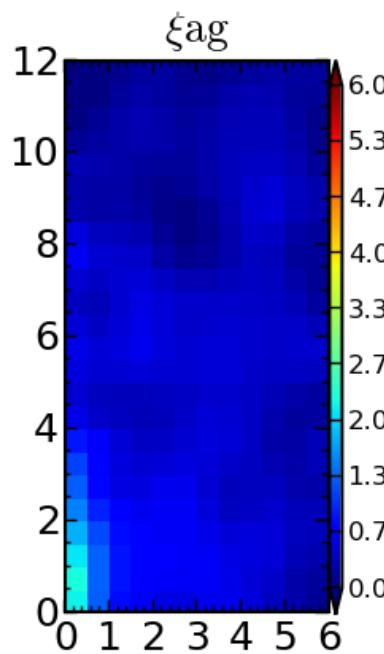


Transverse separation, r_{\perp} [Mpc]



Full Sample

LOS separation, r_{\parallel} [Mpc]



Transverse separation, r_{\perp} [Mpc]

Tejos et al. 2014

Linear dependence

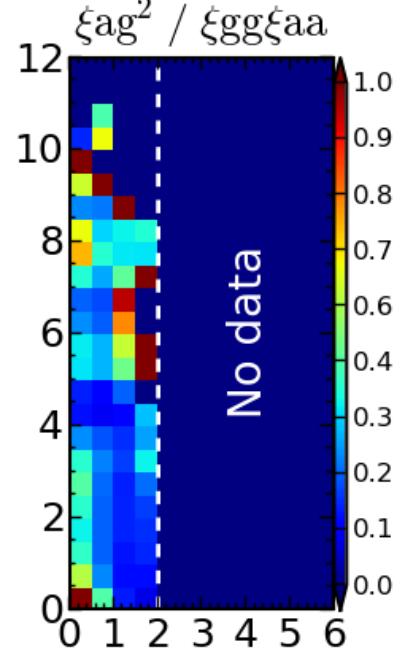
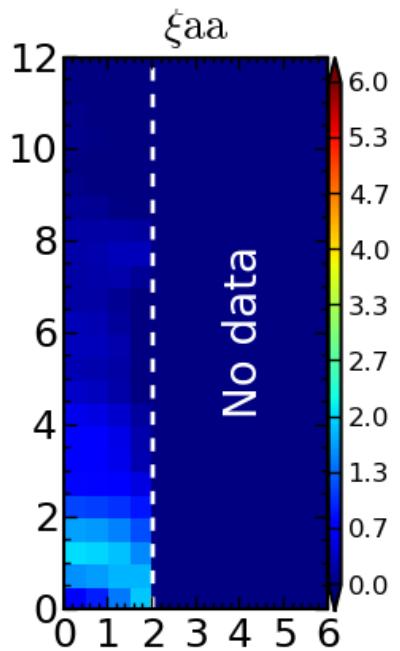
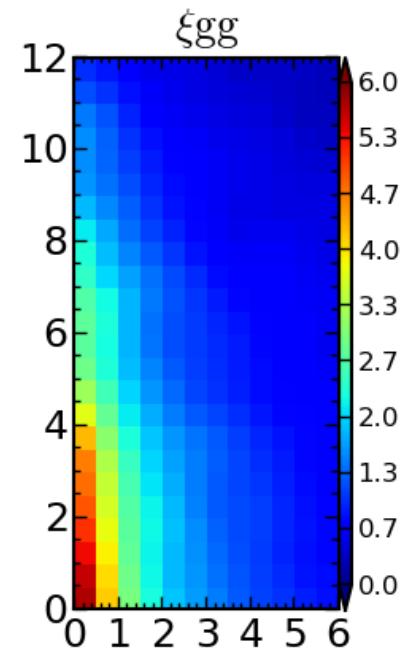
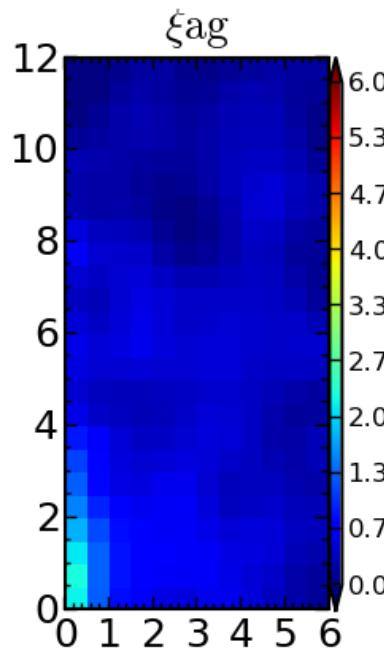
$$\xi_{gg} = b_g^2 \xi_{DM}$$

$$\xi_{aa} = b_a^2 \xi_{DM}$$

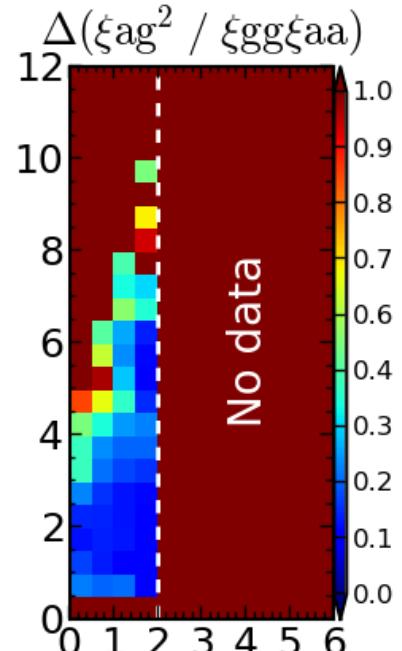
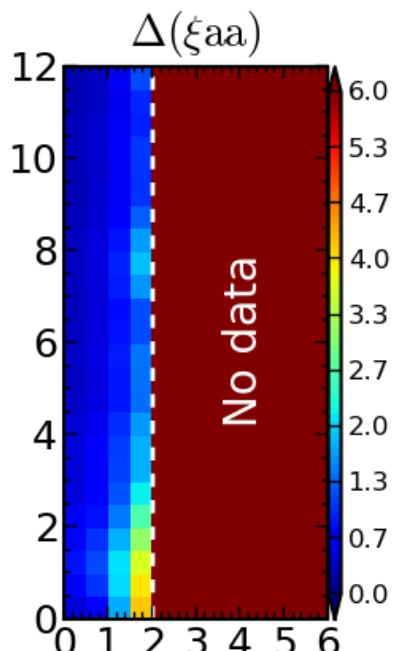
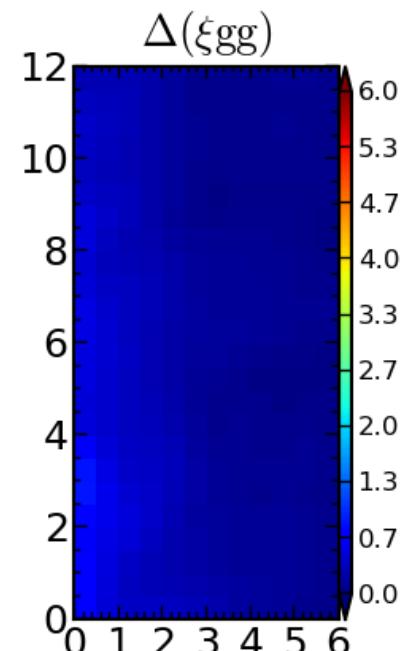
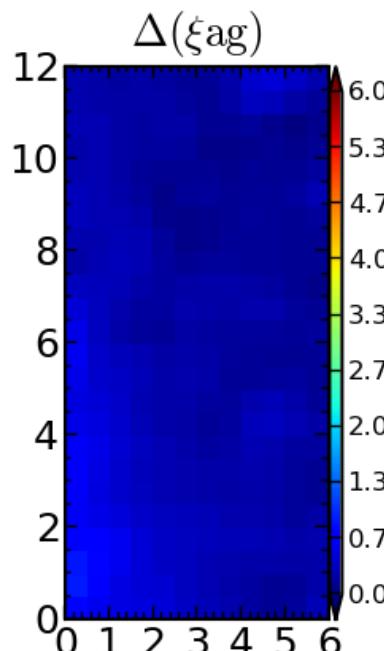
$$\xi_{ag} = b_a b_b \xi_{DM}$$

Full Sample

LOS separation, r_{\parallel} [Mpc]



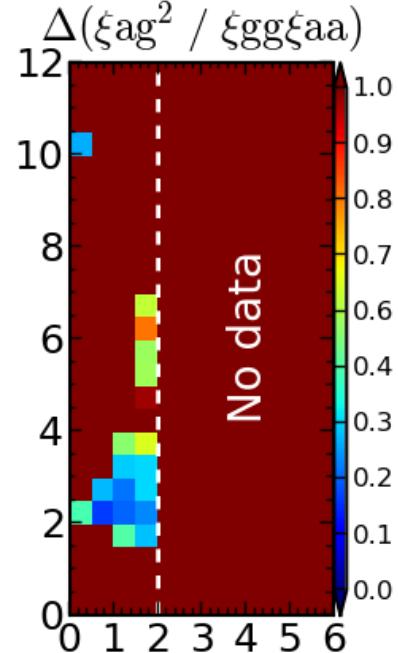
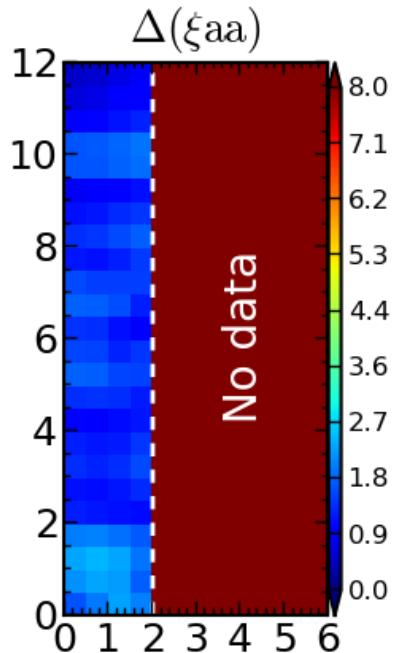
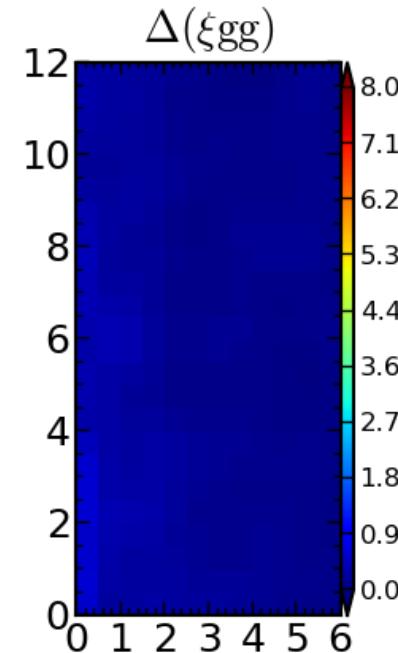
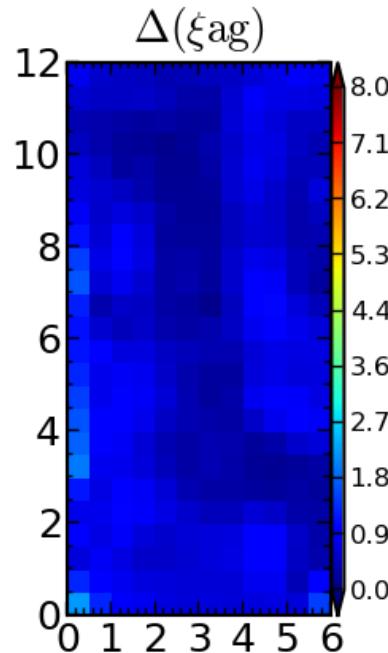
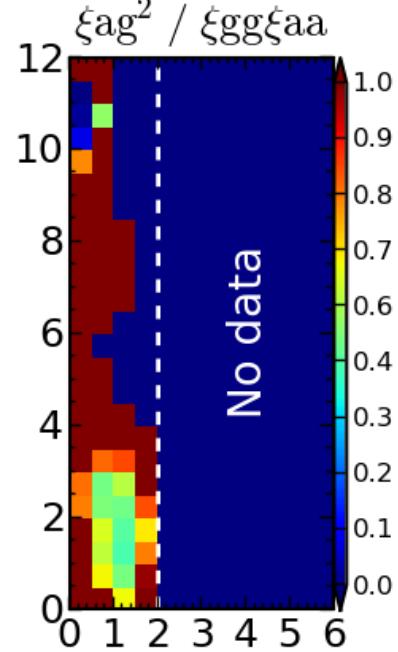
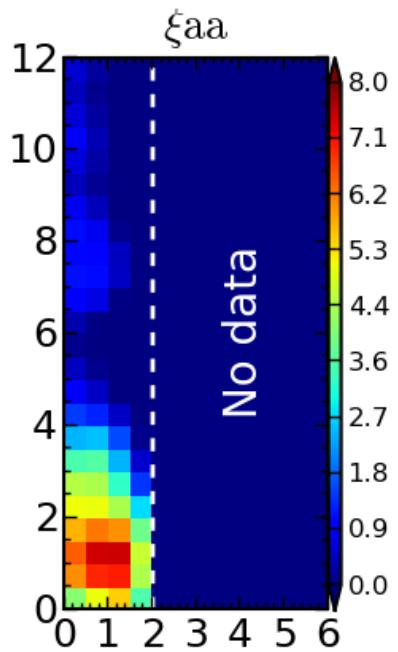
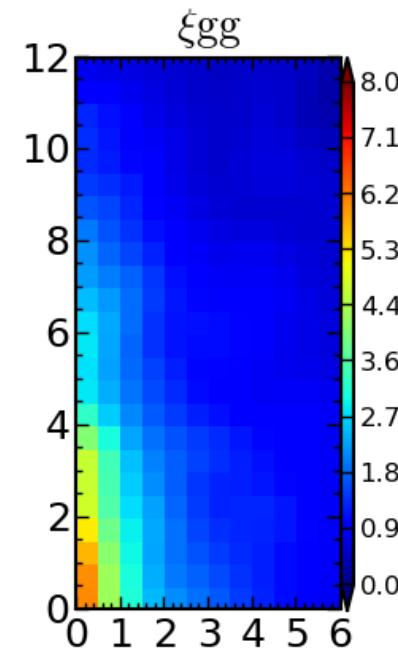
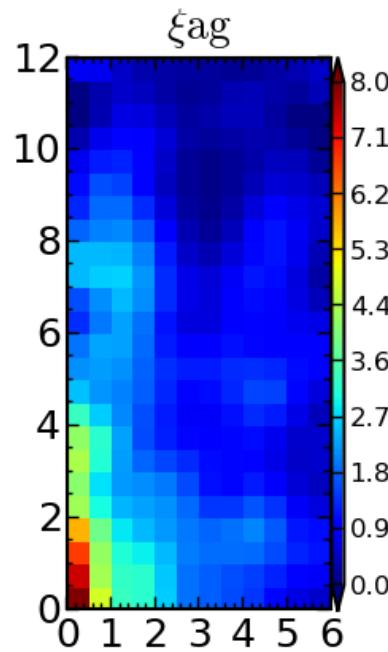
Transverse separation, r_{\perp} [Mpc]



Strong HI + galaxies

*SF, log*N \geq 14.0

LOS separation, r_{\parallel} [Mpc]

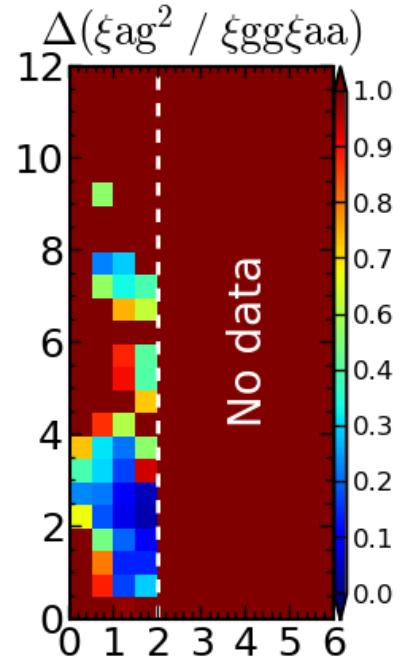
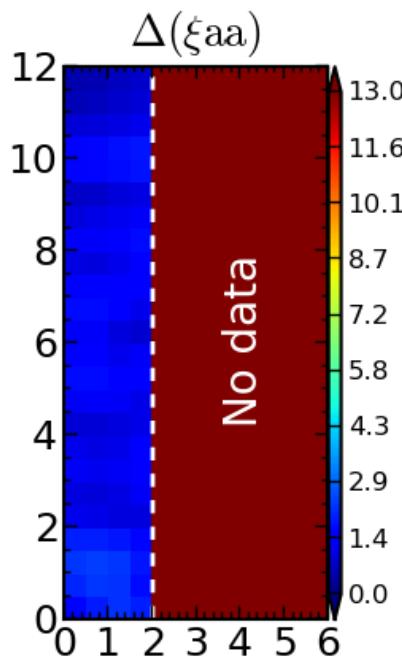
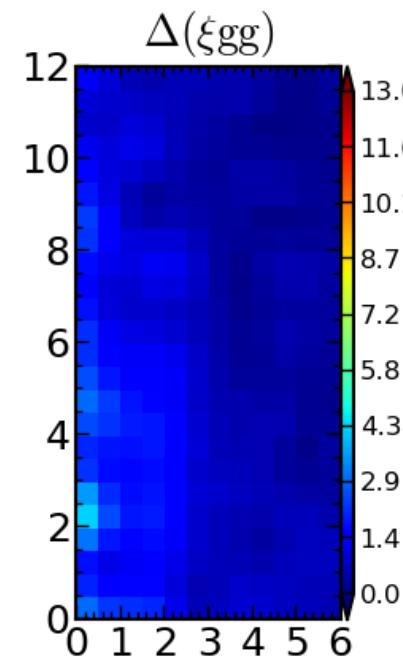
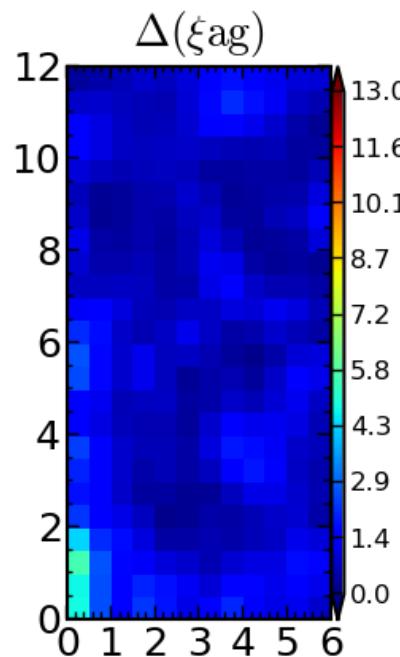
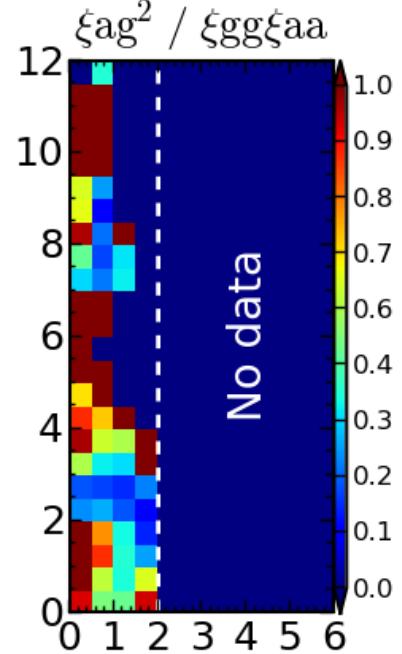
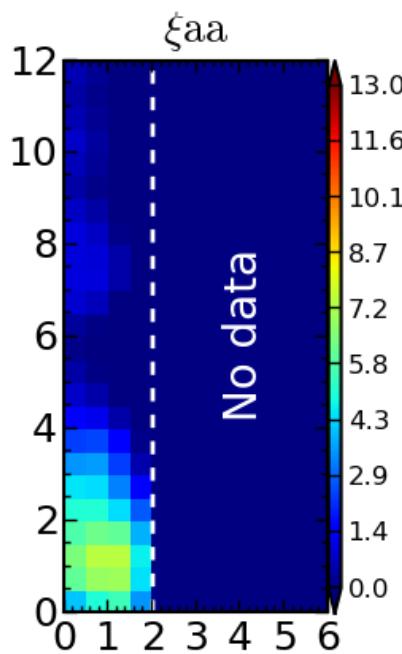
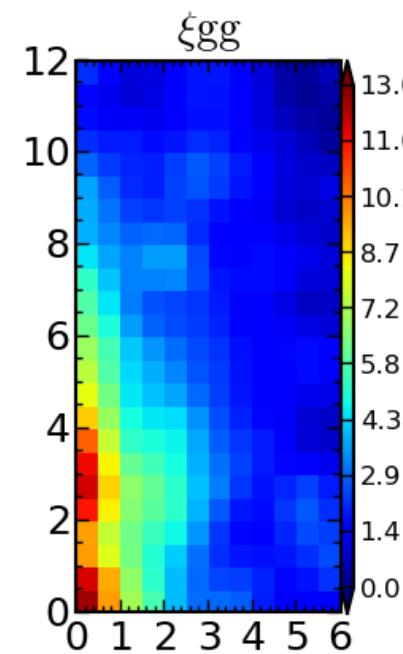
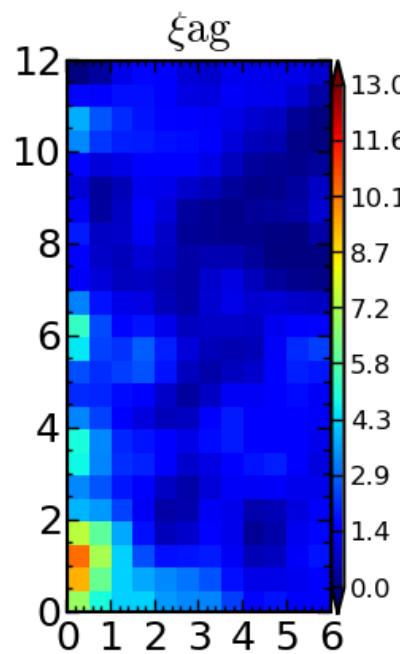


Transverse separation, r_{\perp} [Mpc]

Tejos et al. 2014

non-SF, logN \geq 14.0

LOS separation, r_{\parallel} [Mpc]



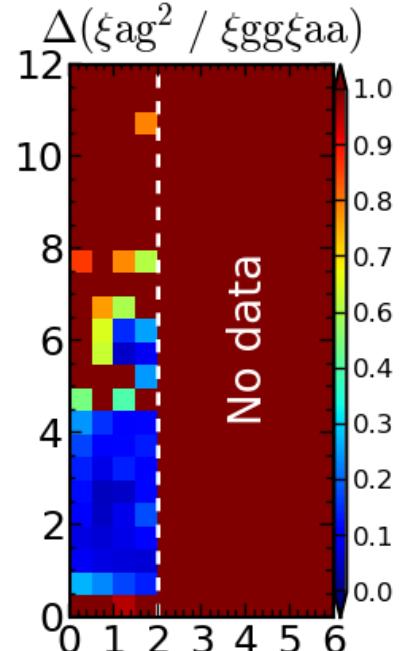
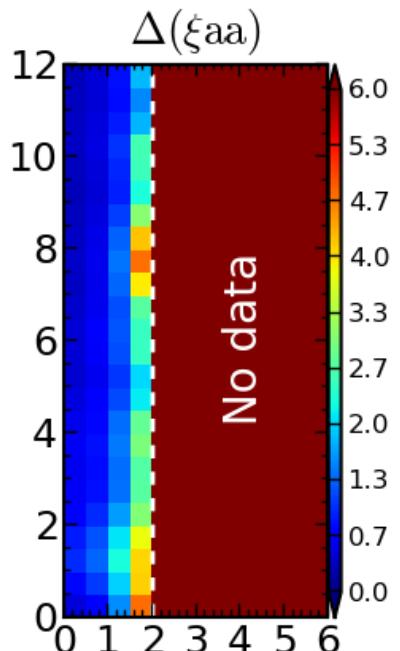
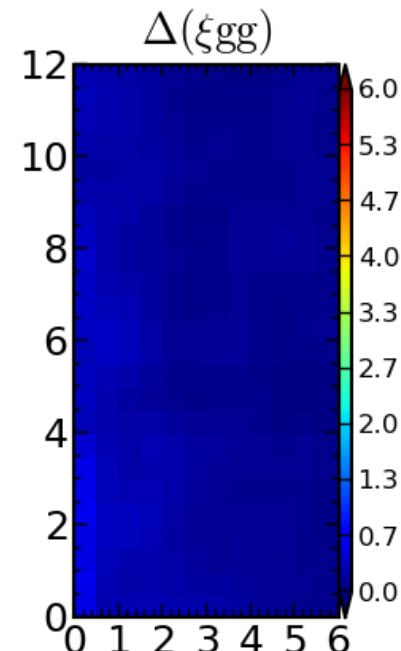
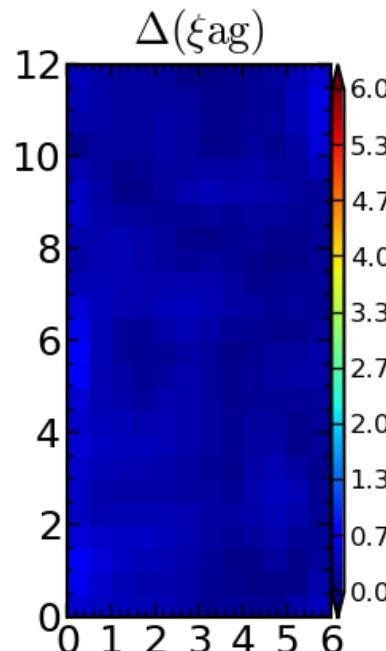
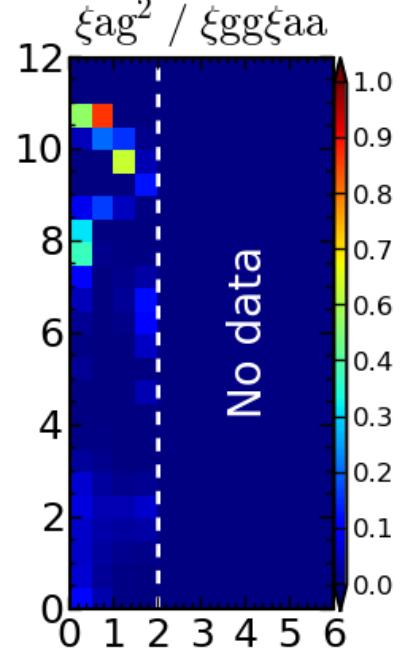
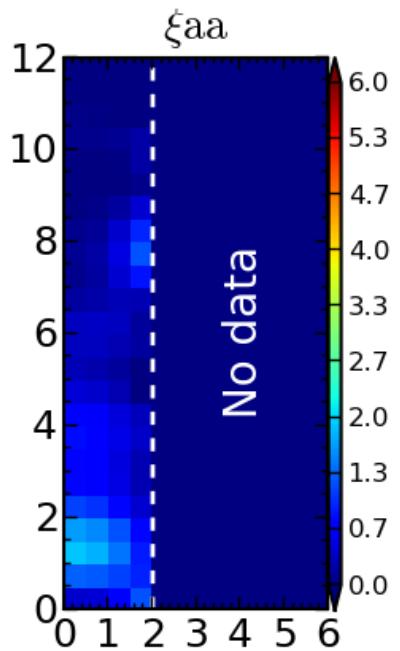
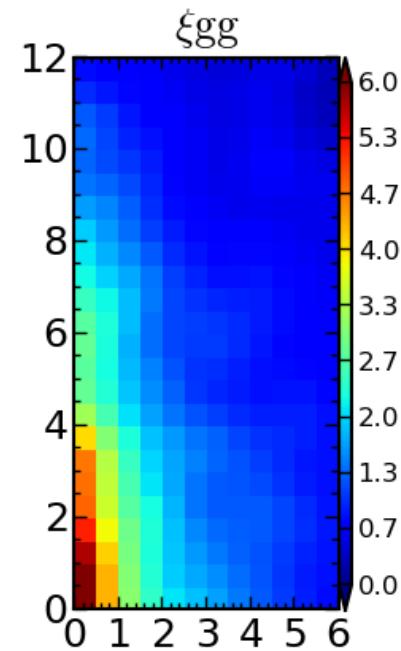
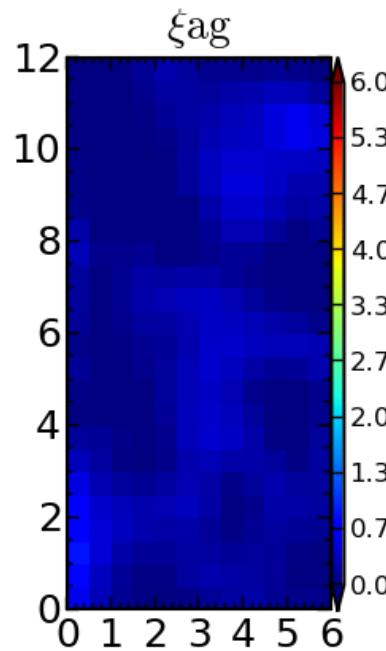
Transverse separation, r_{\perp} [Mpc]

Tejos et al. 2014

Weak HI + galaxies

SF, logN<14.0

LOS separation, r_{\parallel} [Mpc]

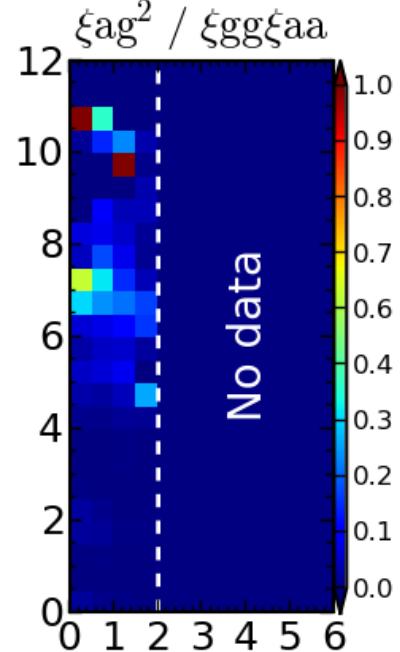
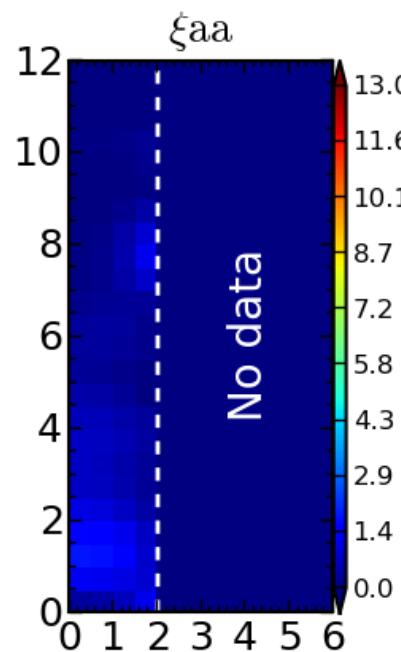
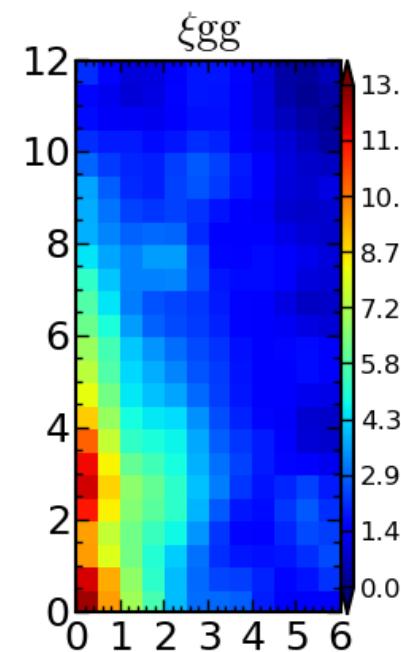
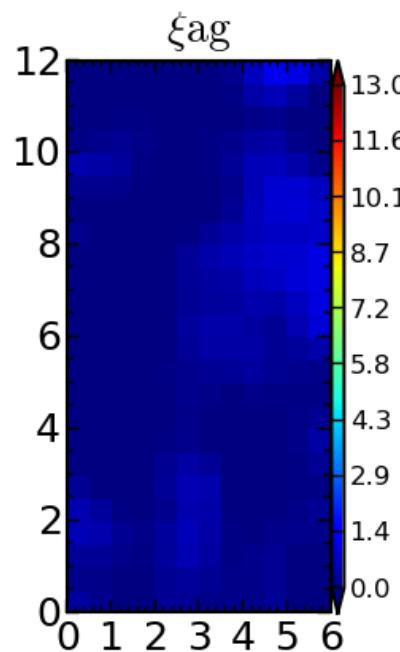


Transverse separation, r_{\perp} [Mpc]

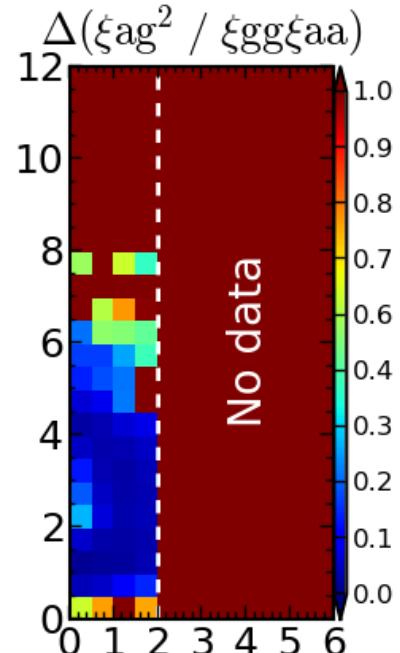
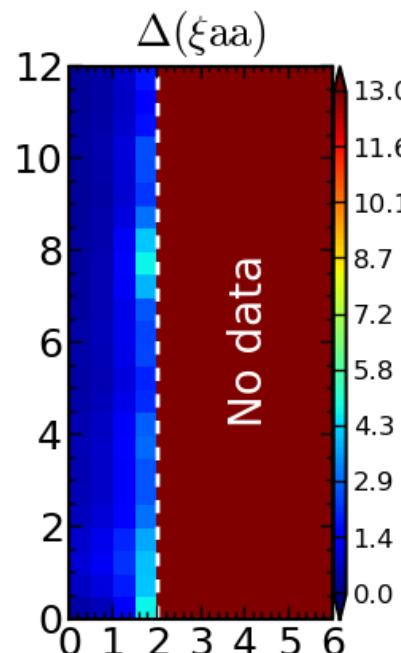
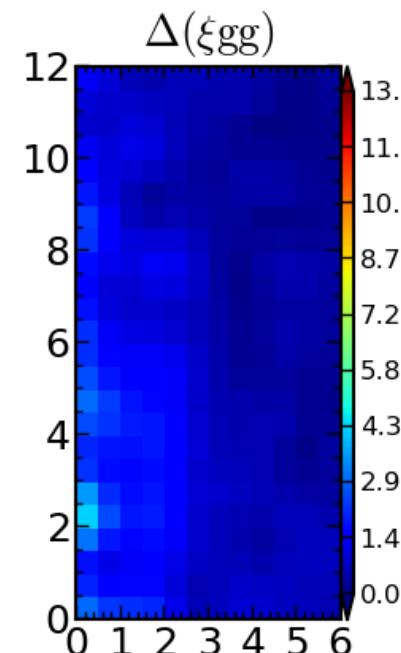
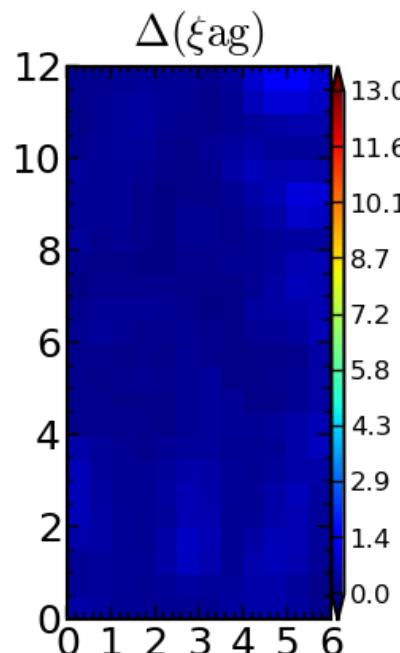
Tejos et al. 2014

non-SF, logN < 14.0

LOS separation, r_{\parallel} [Mpc]



LOS separation, r_{\parallel} [Mpc]



Transverse separation, r_{\perp} [Mpc]

Tejos et al. 2014

Projected along LOS

Results

- **Projected along the LOS:**

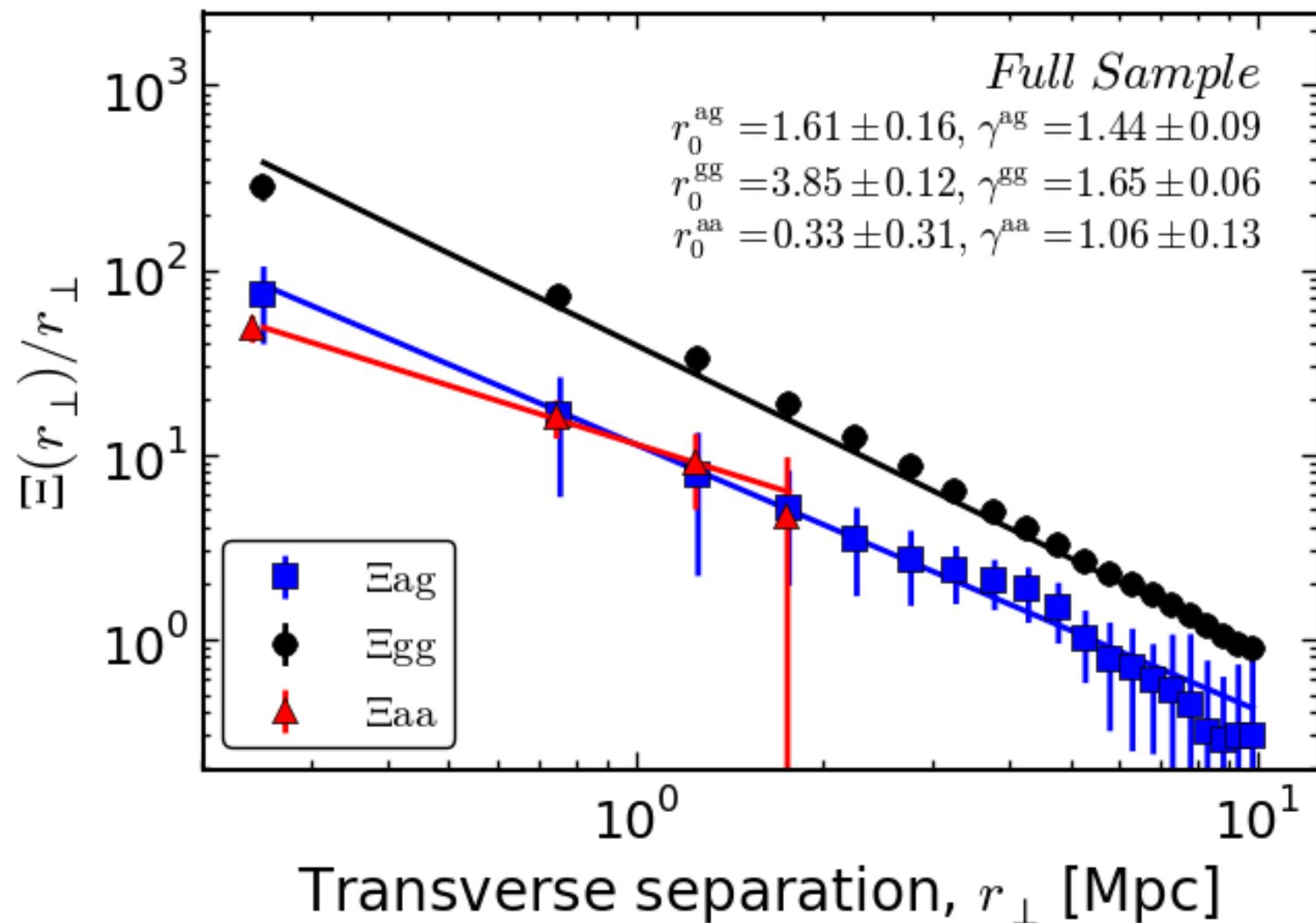
$$\Xi(r_{\perp}) = 2 \int_0^{\infty} \xi(r_{\perp}, r_{\parallel}) dr_{\parallel}$$

- **Real space:**

$$\xi(r) = \left(\frac{r}{r_0} \right)^{-\gamma}$$

e.g. Davis & Peebles 1983

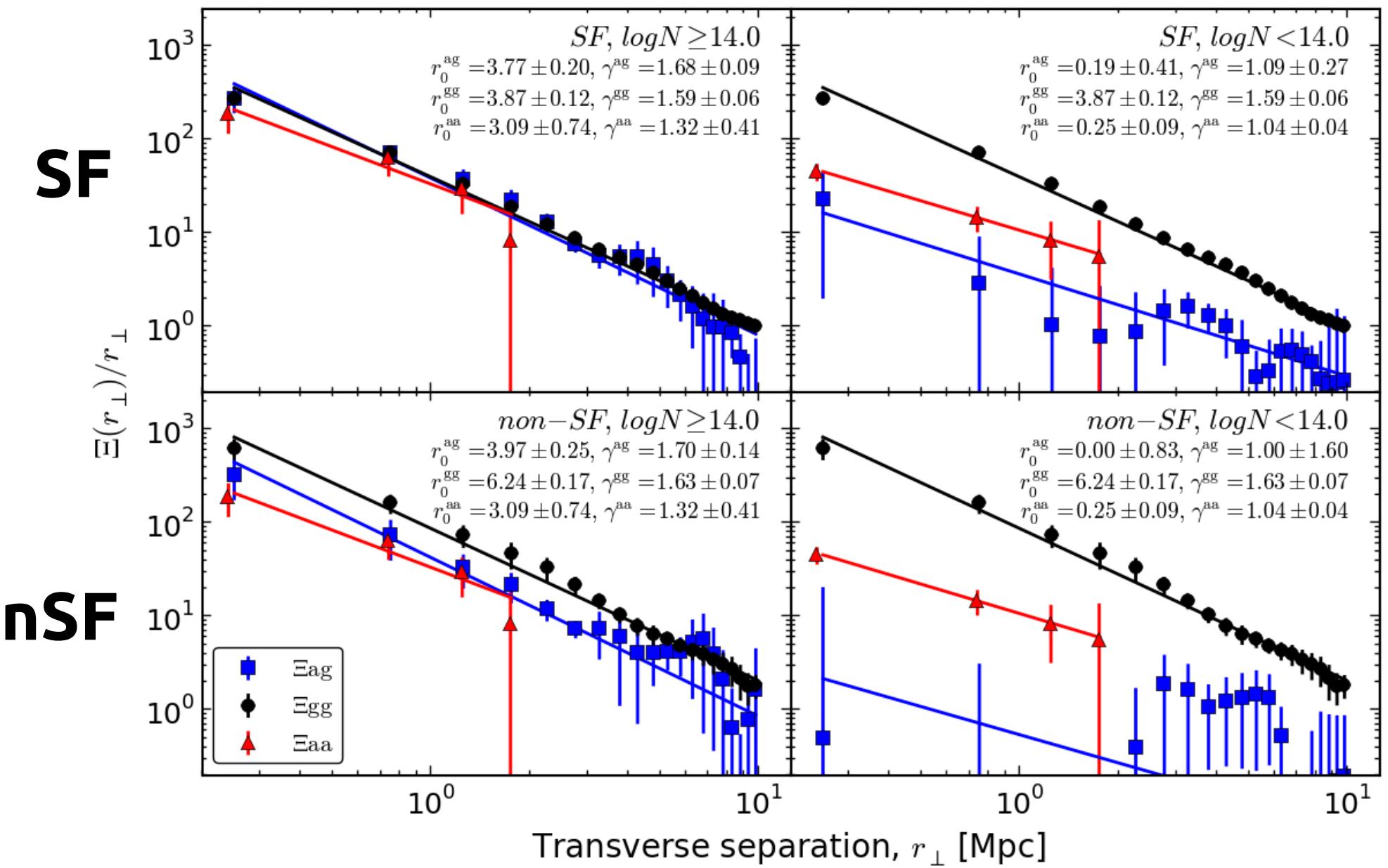
Results



Subsamples

Strong HI

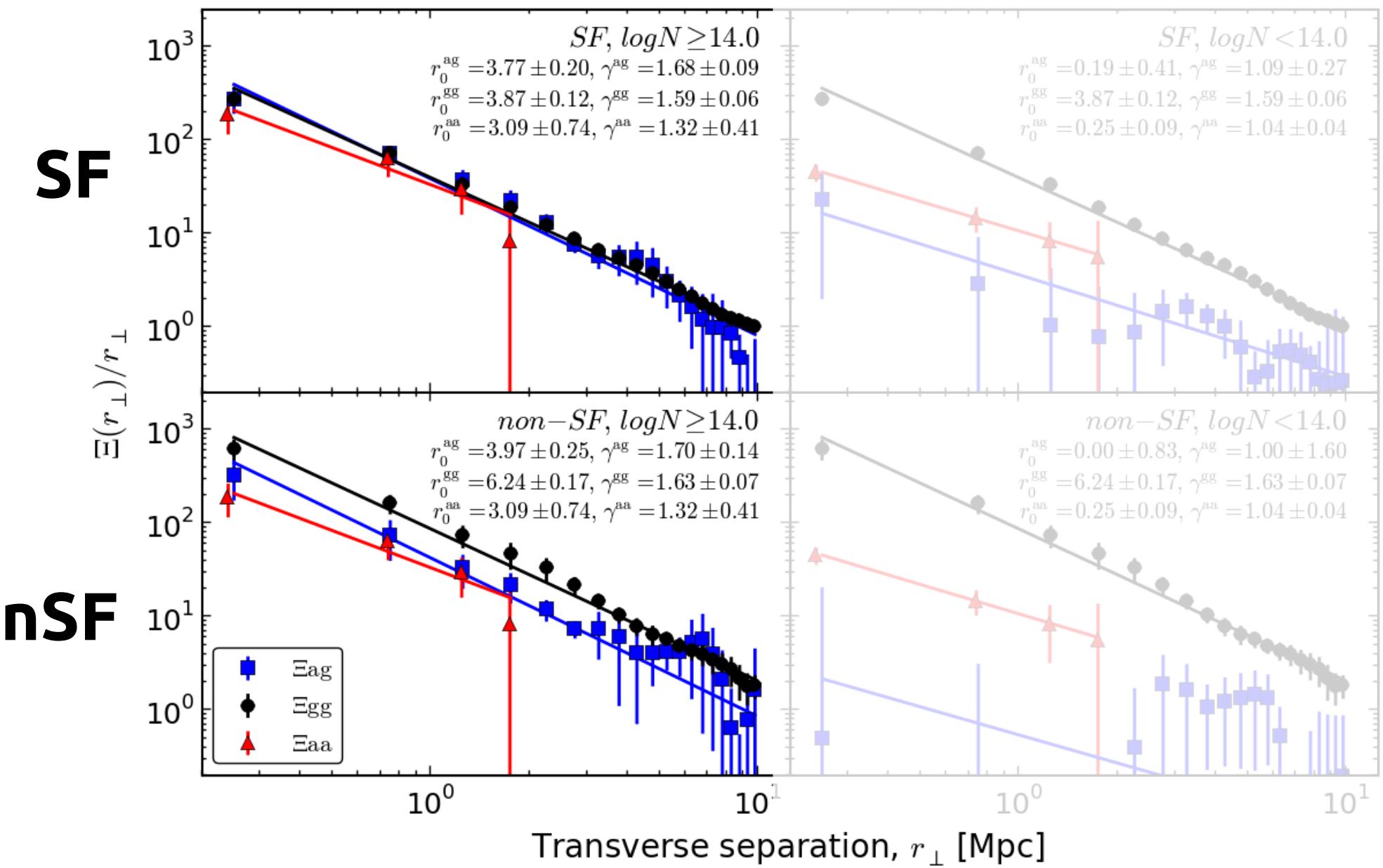
Weak HI



Tejos et al. 2014

Strong HI

Weak HI

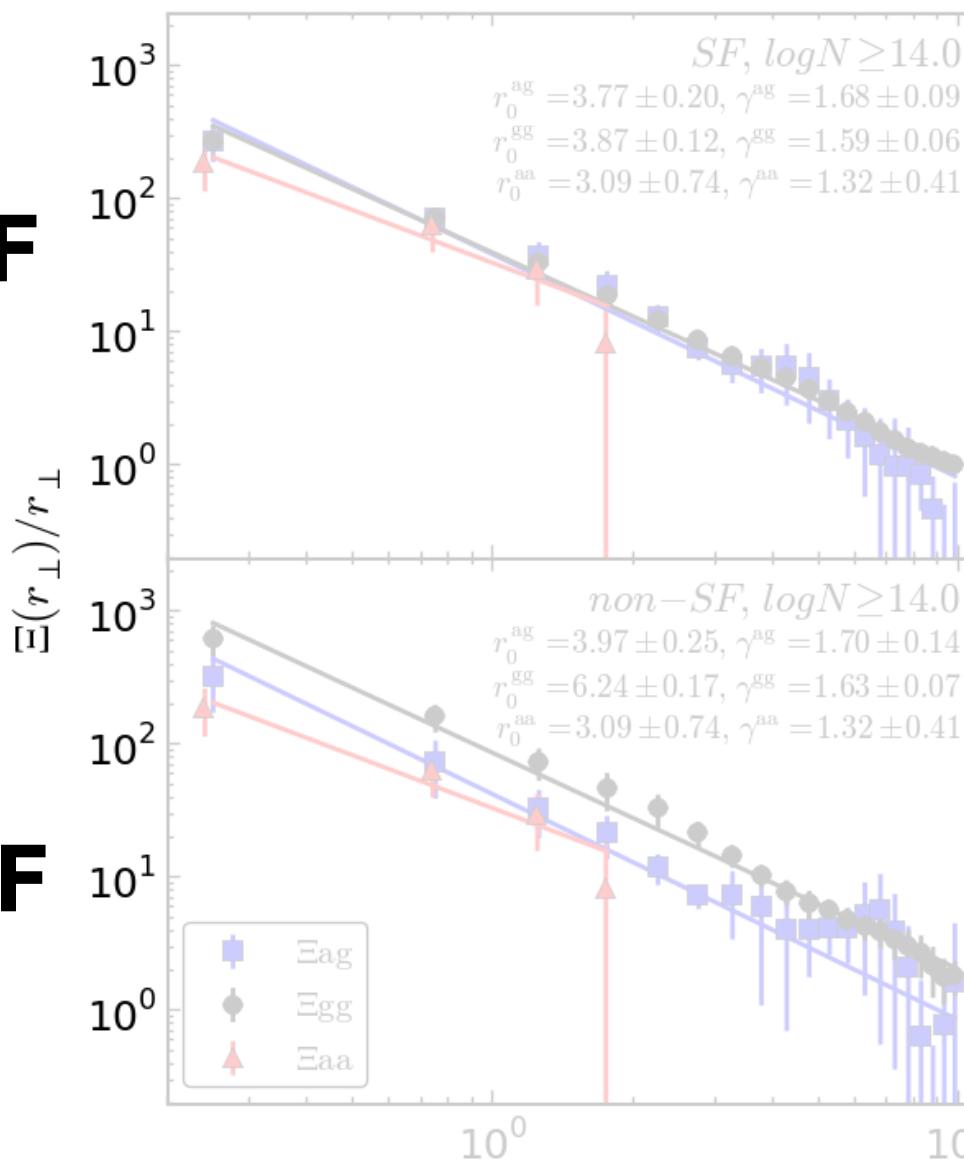


Tejos et al. 2014

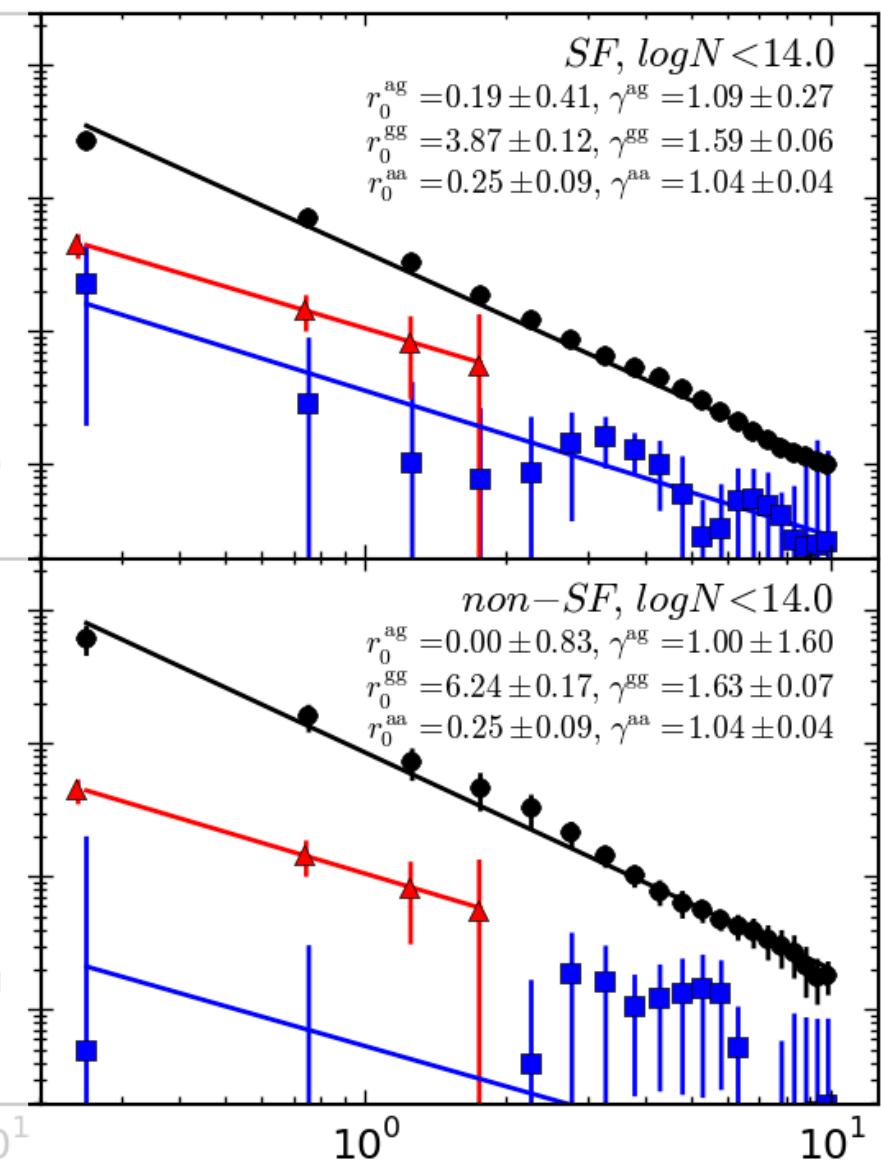
Strong HI

Weak HI

SF



nSF



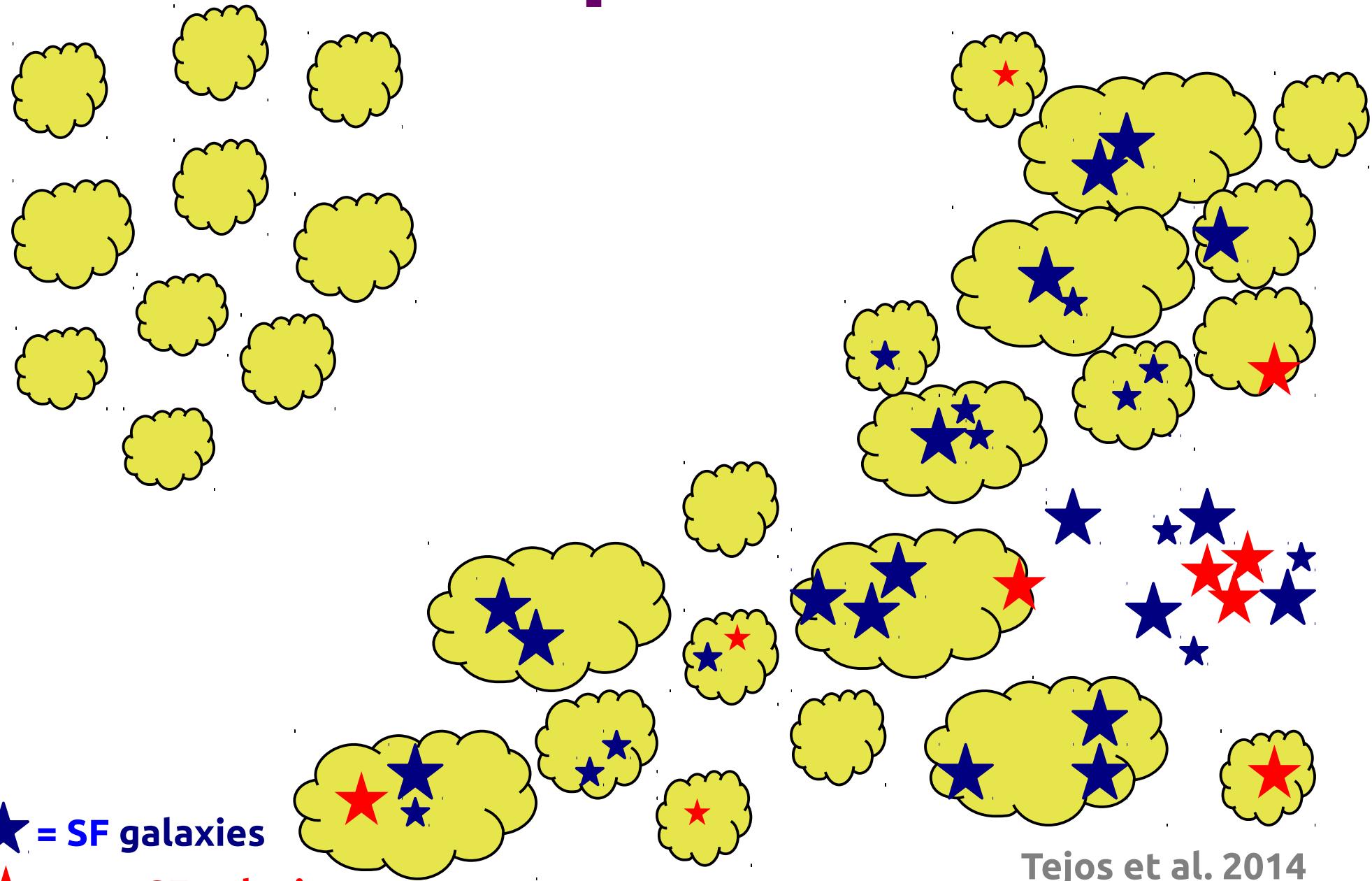
Transverse separation, r_{\perp} [Mpc]

Tejos et al. 2014

Interpretation

Interpretation

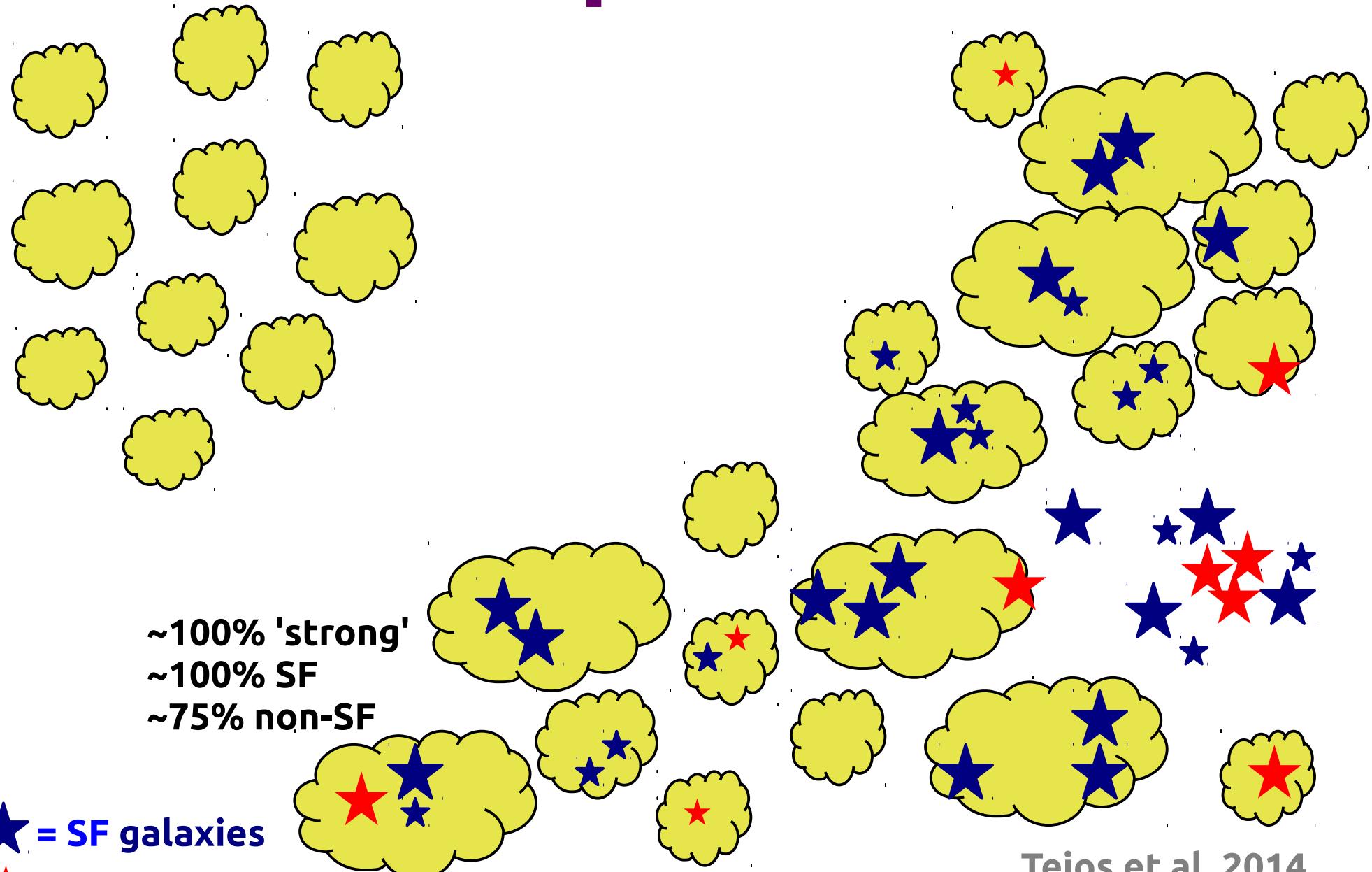
(not to scale)



Tejos et al. 2014

Interpretation

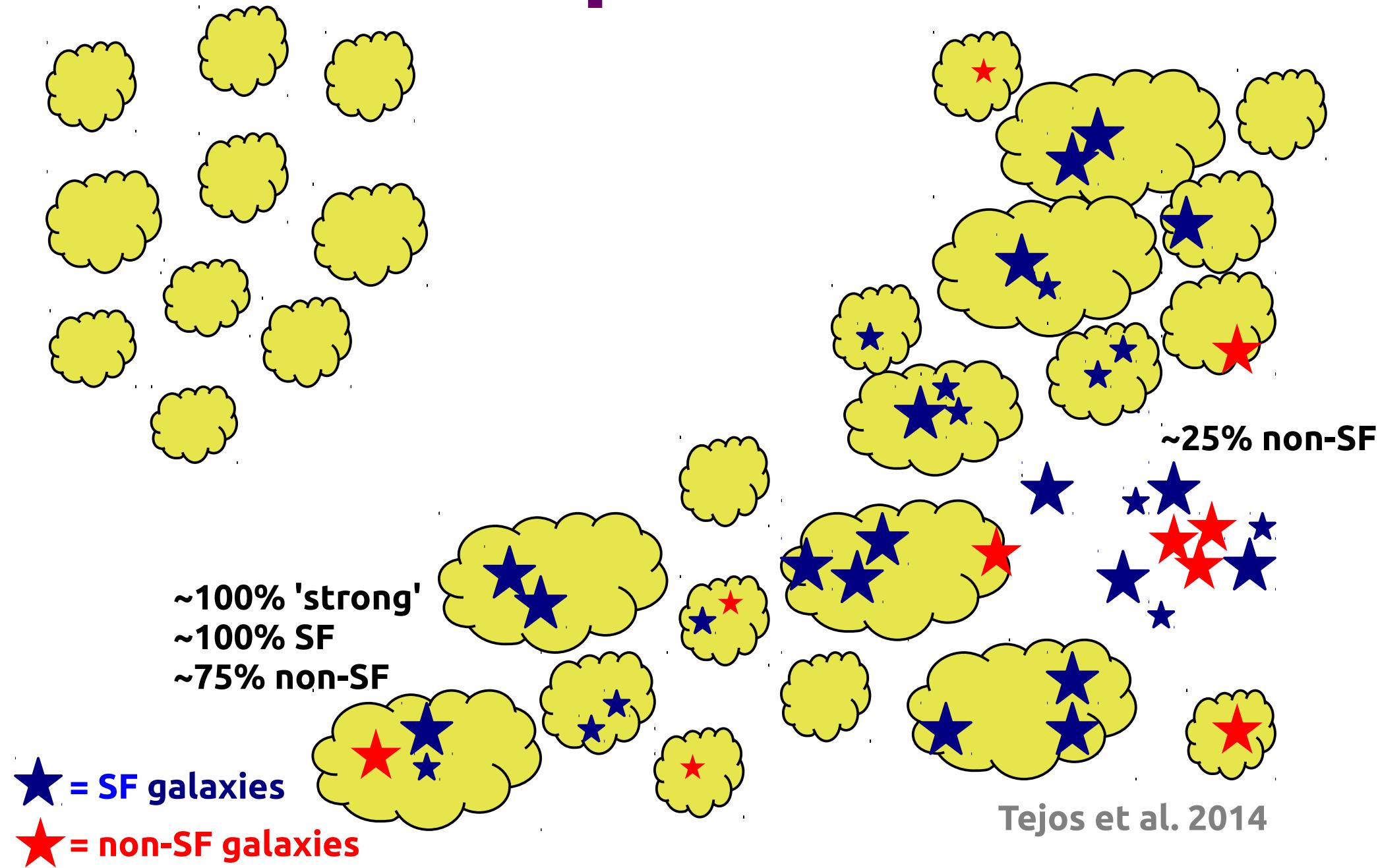
(not to scale)



Tejos et al. 2014

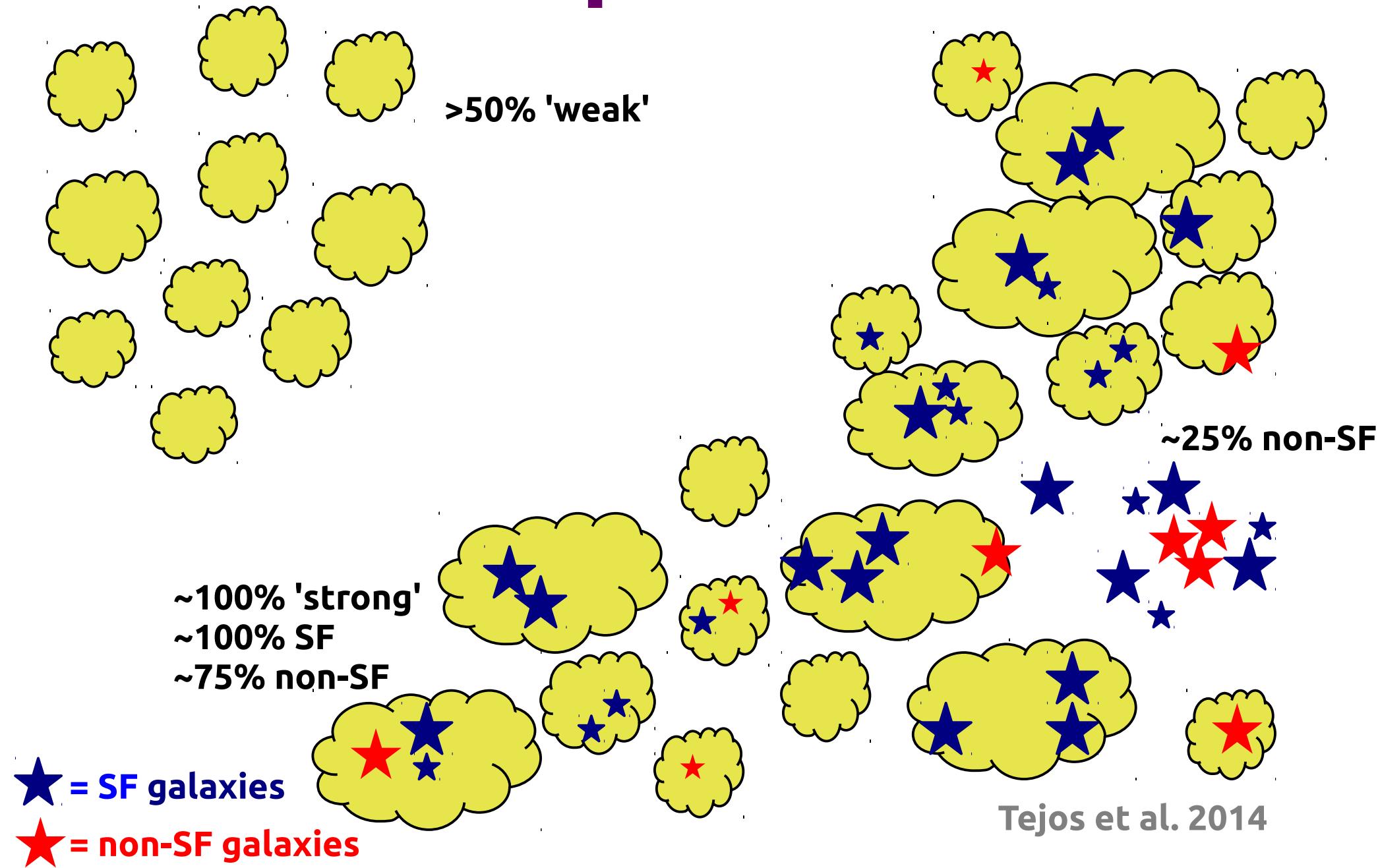
Interpretation

(not to scale)

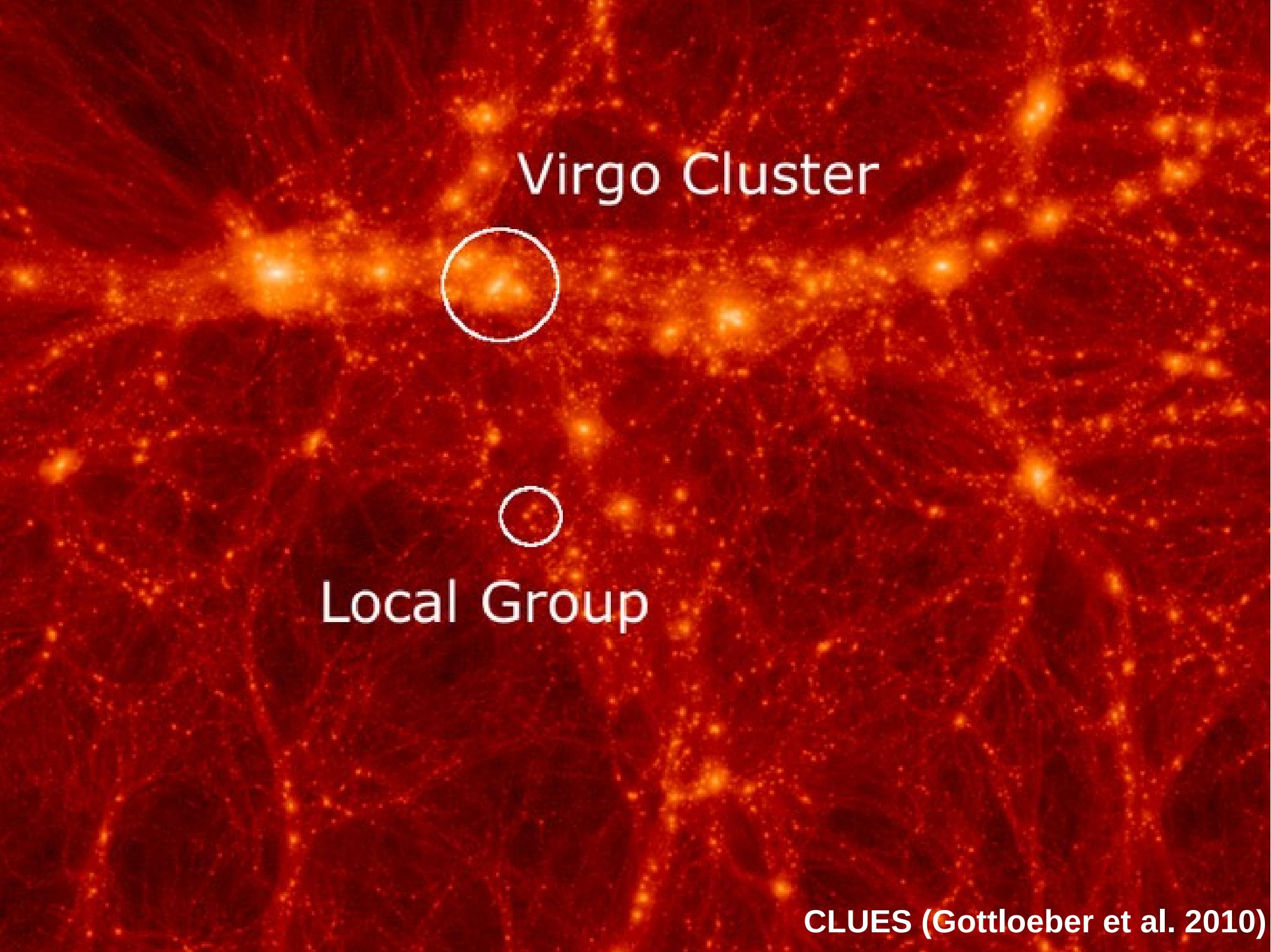


Interpretation

(not to scale)



Part II:
IGM in galaxy voids

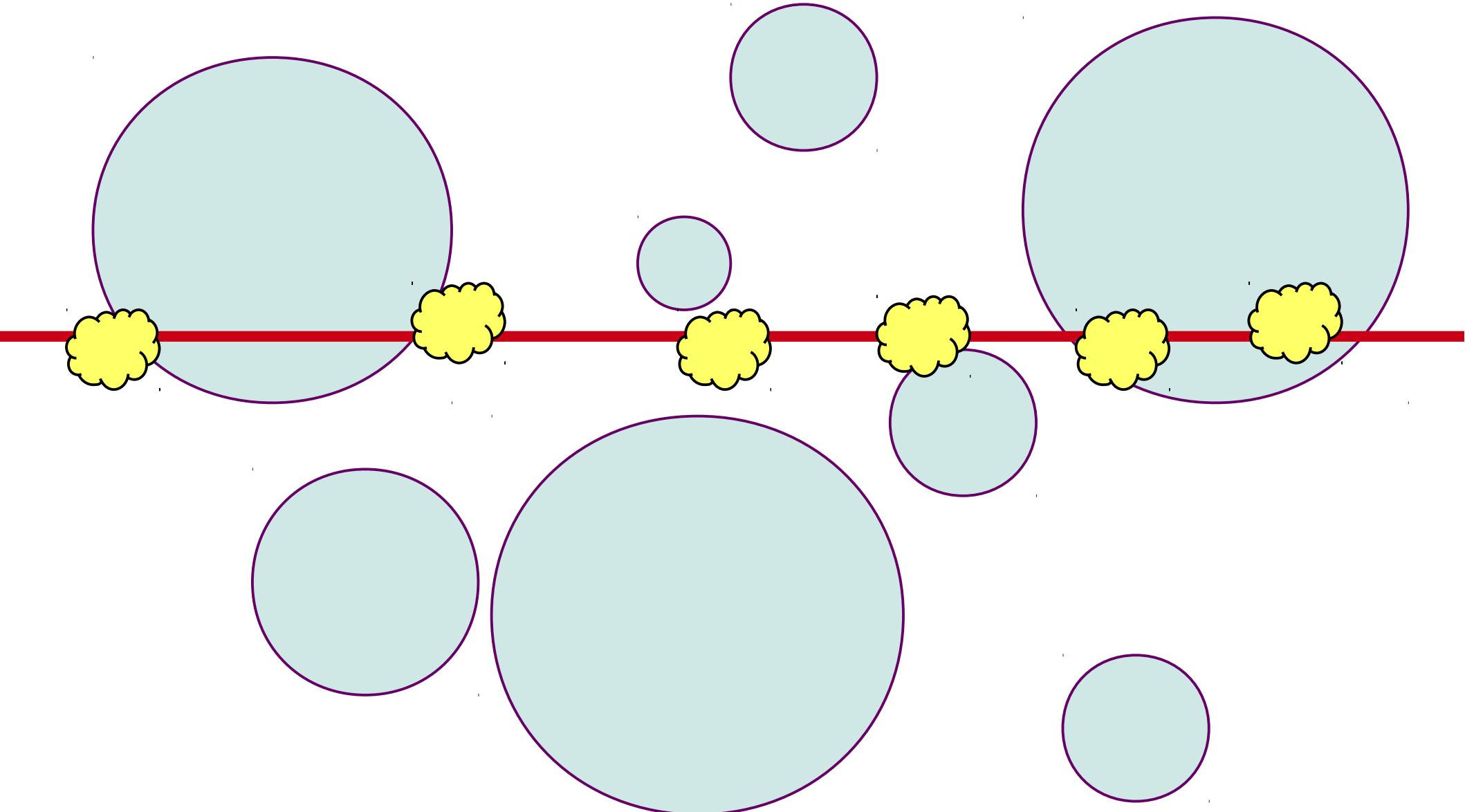


Virgo Cluster

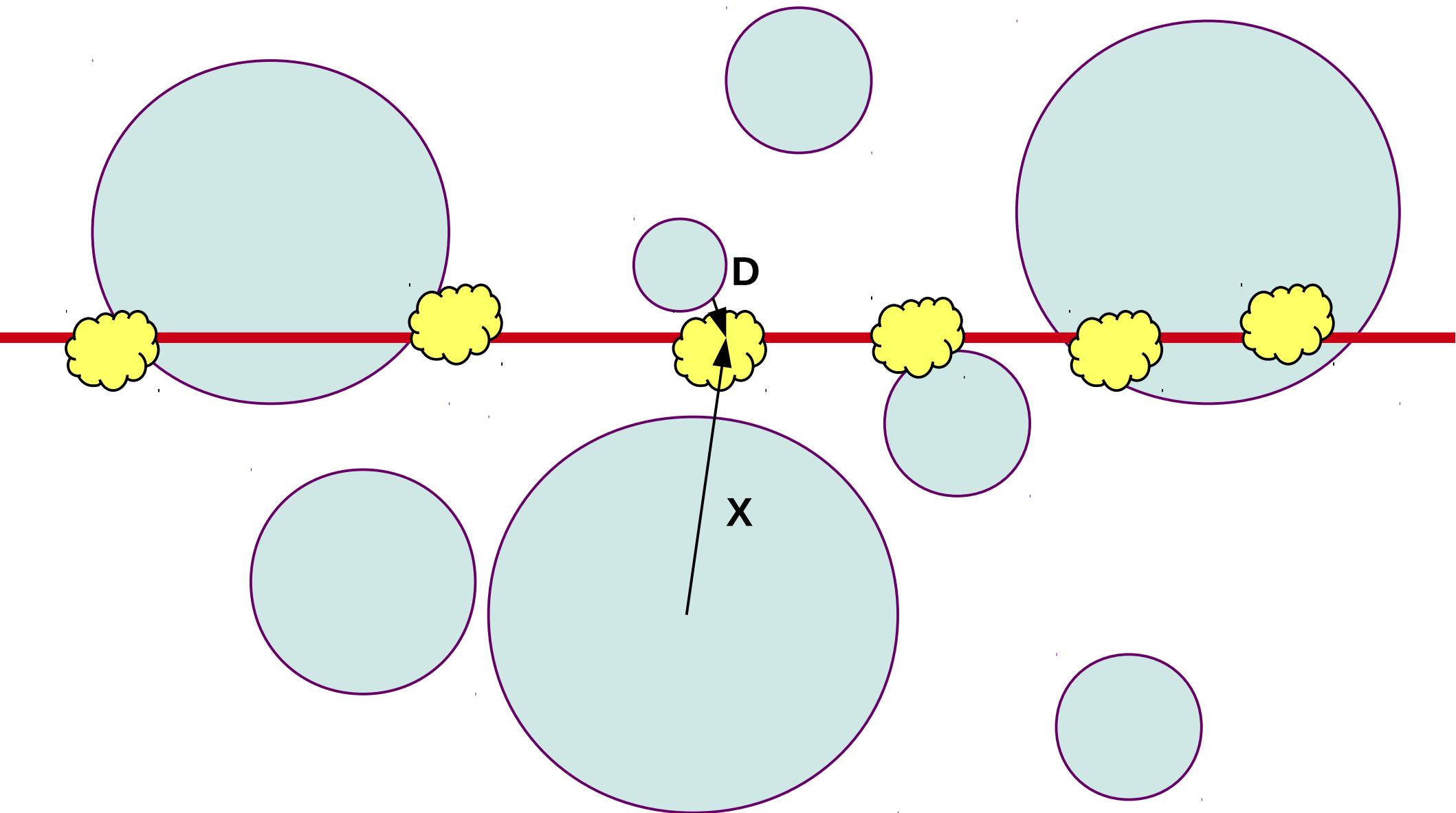


Local Group

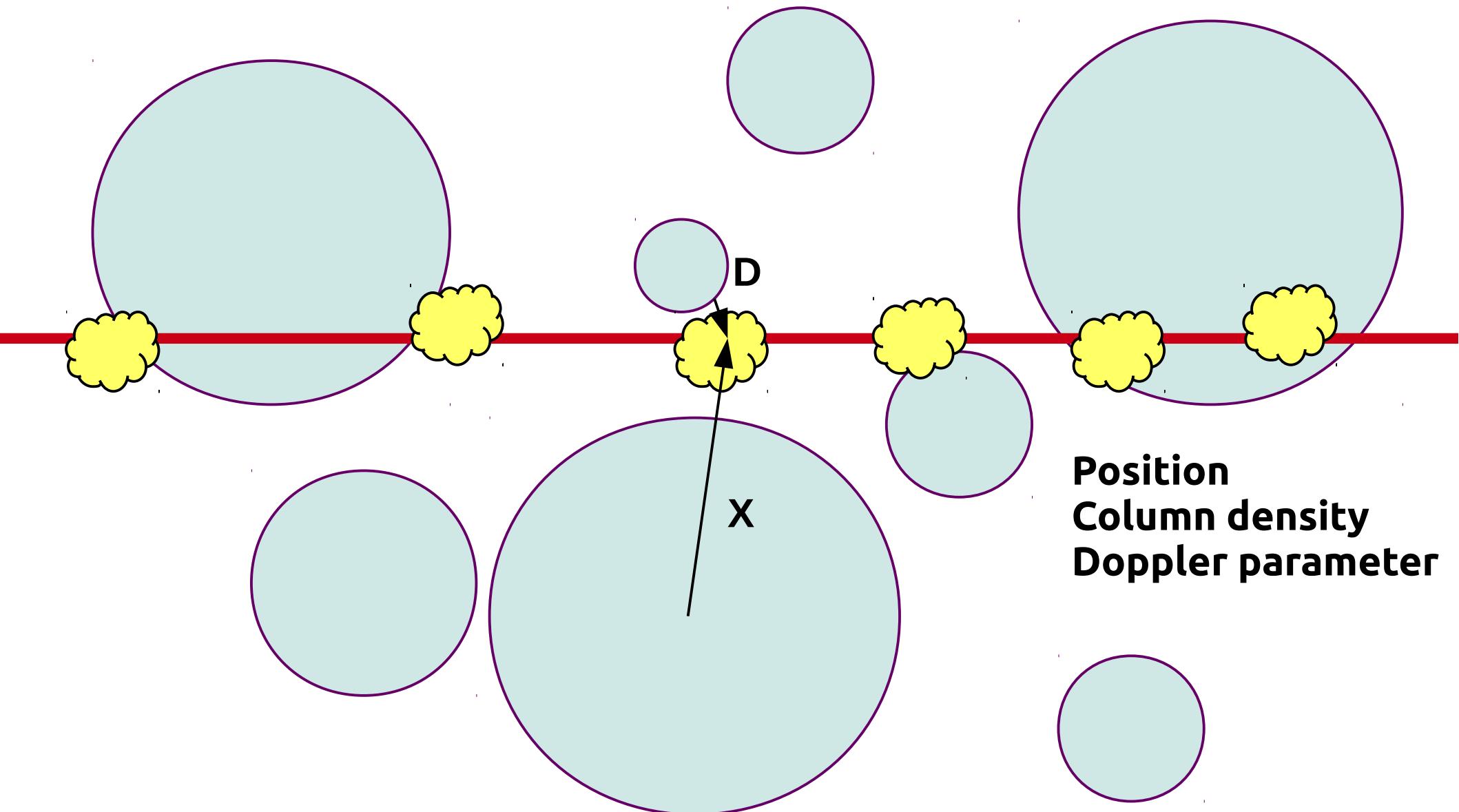
IGM in galaxy voids



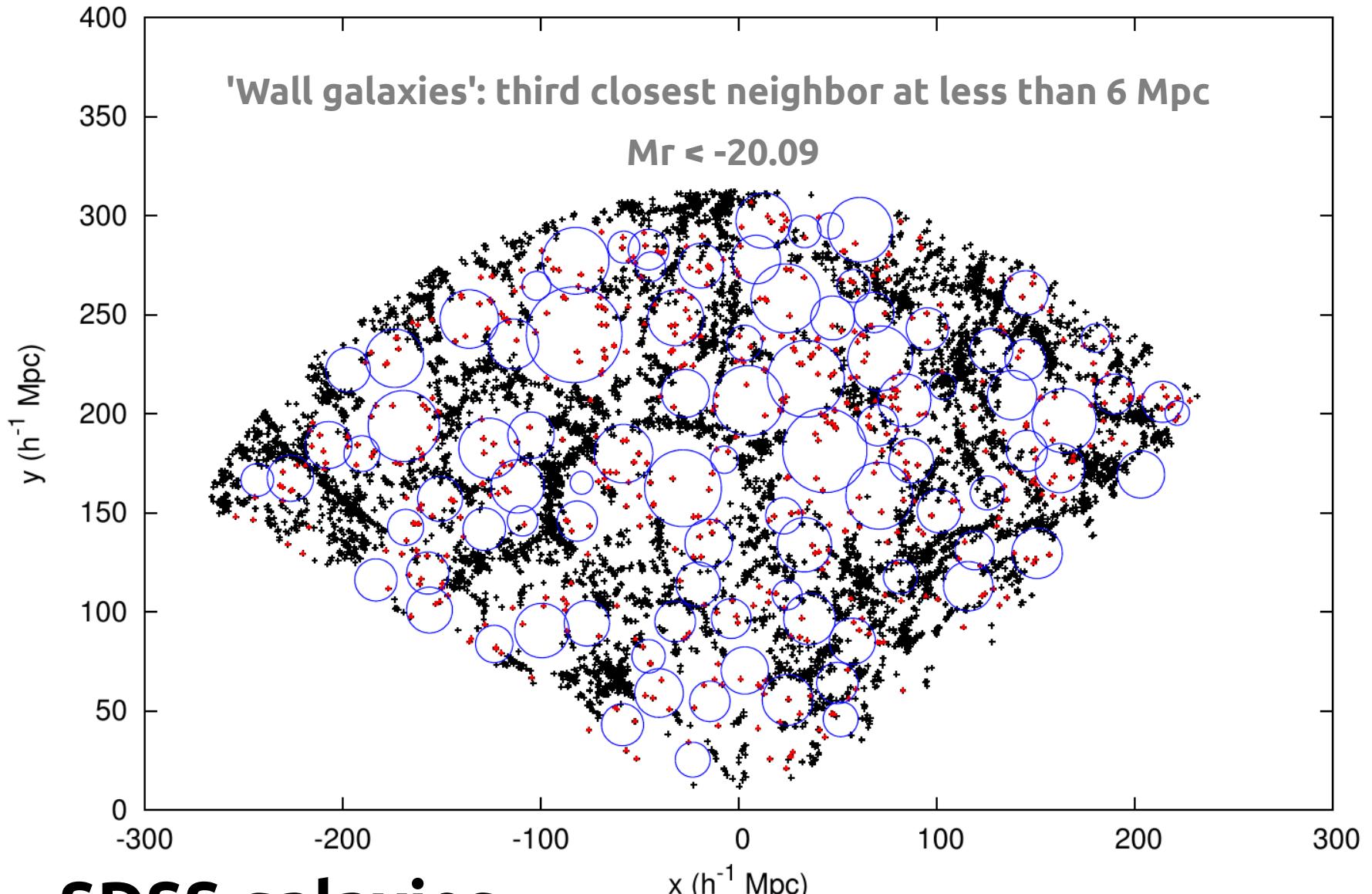
IGM in galaxy voids



IGM in galaxy voids



Galaxy void catalog

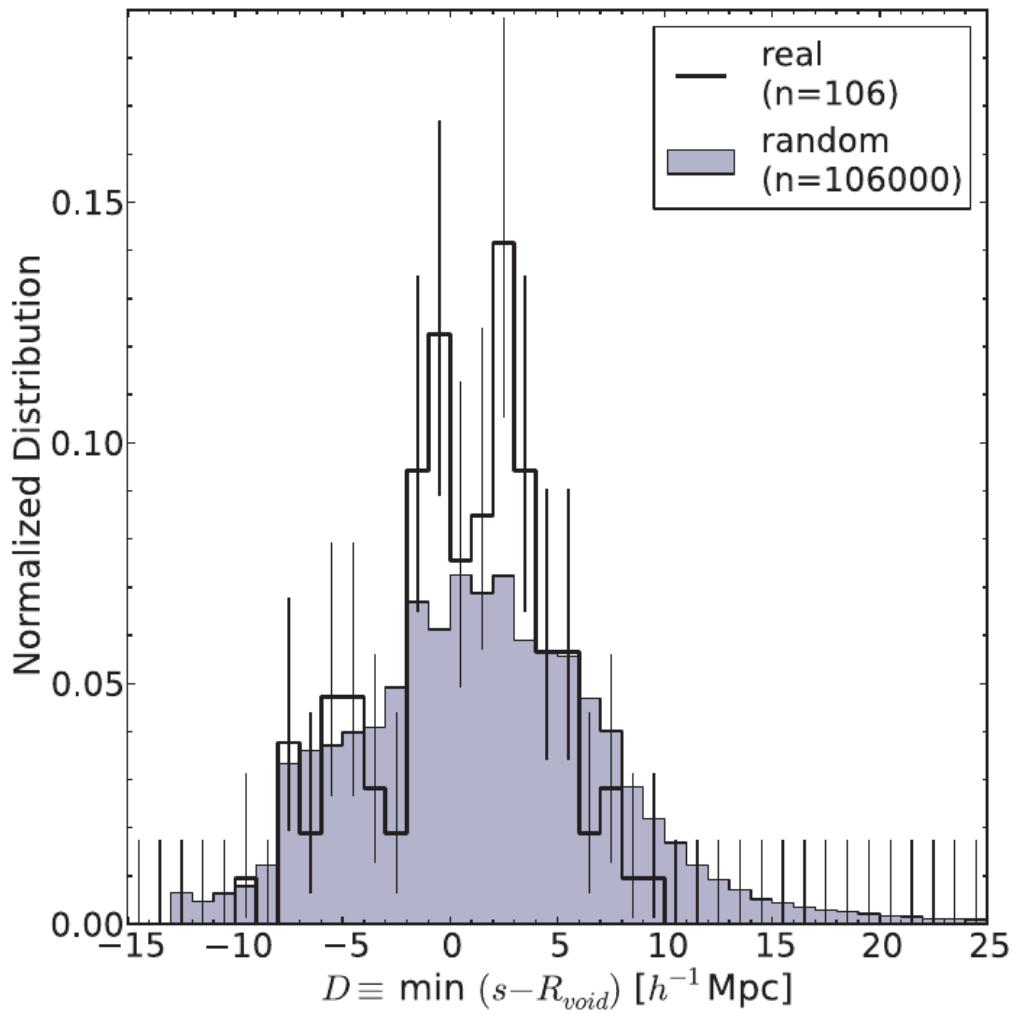
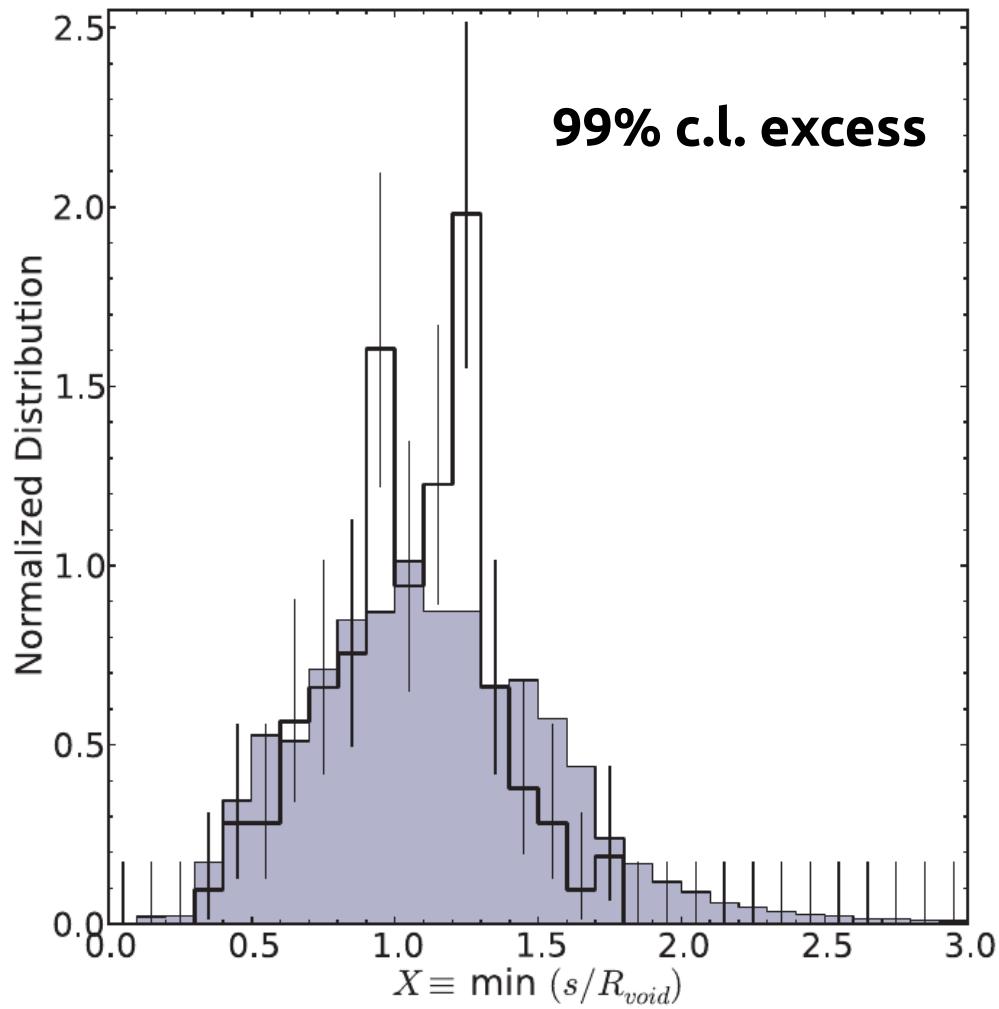


SDSS galaxies

Pan et al. 2012

Results

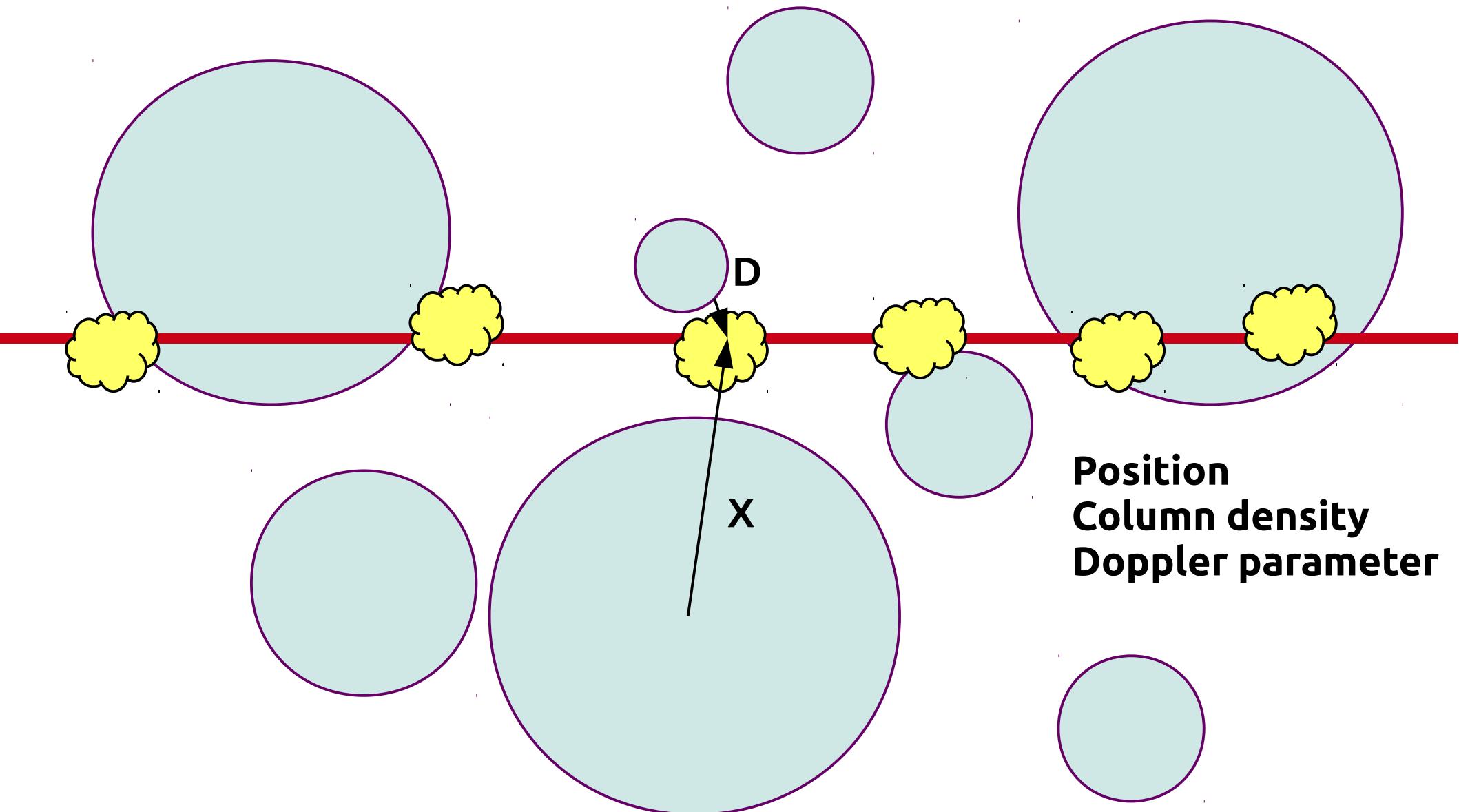
Results



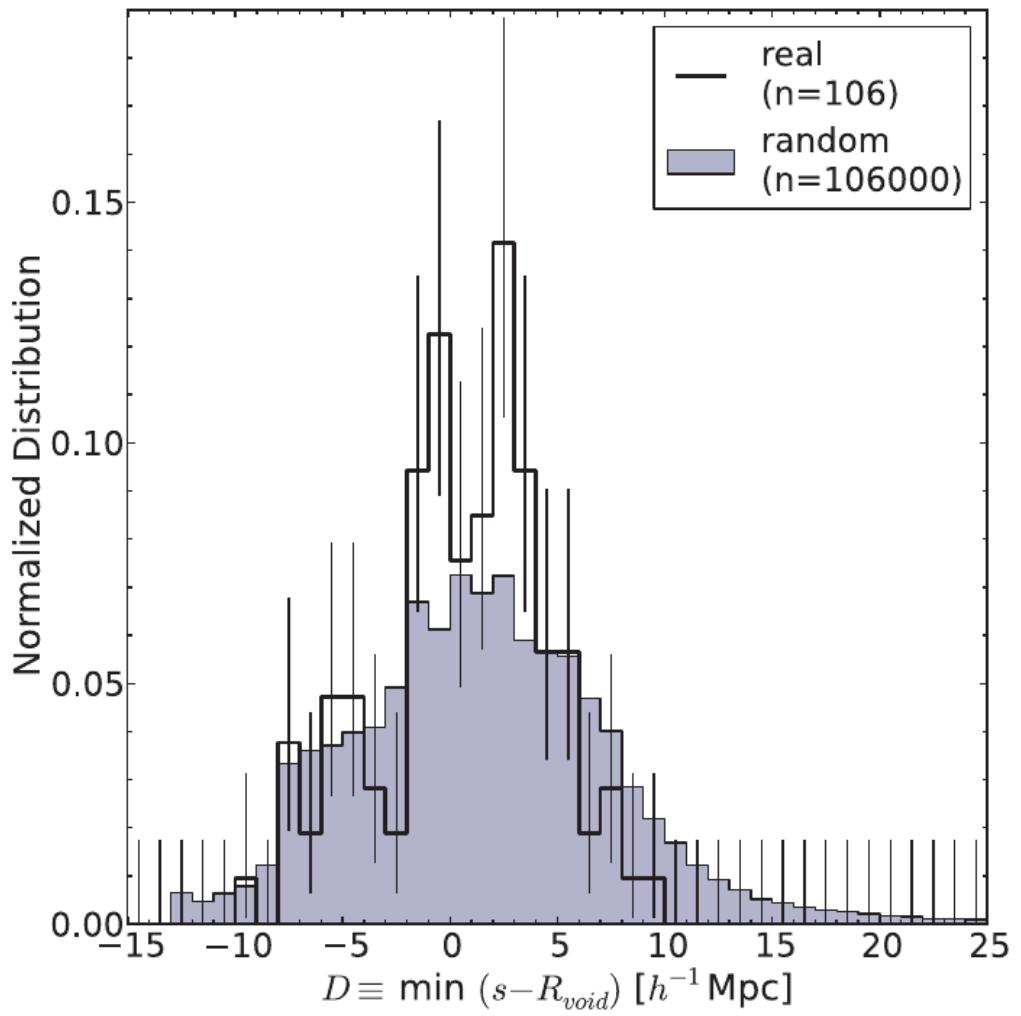
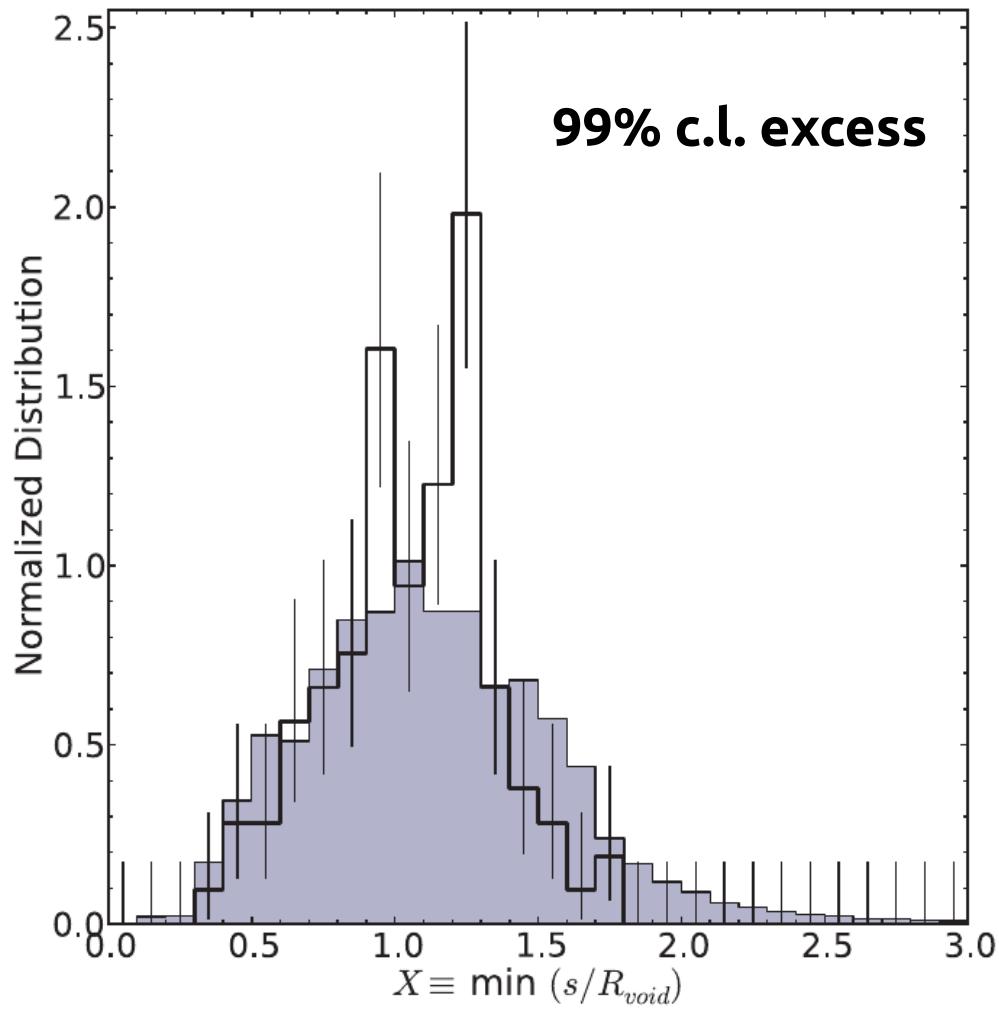
1054 galaxy voids at $z < 0.1$ (Pan et al. 2012)
106 HI absorption systems (Danforth & Shull 2008)

Tejos et al. 2012

IGM in galaxy voids



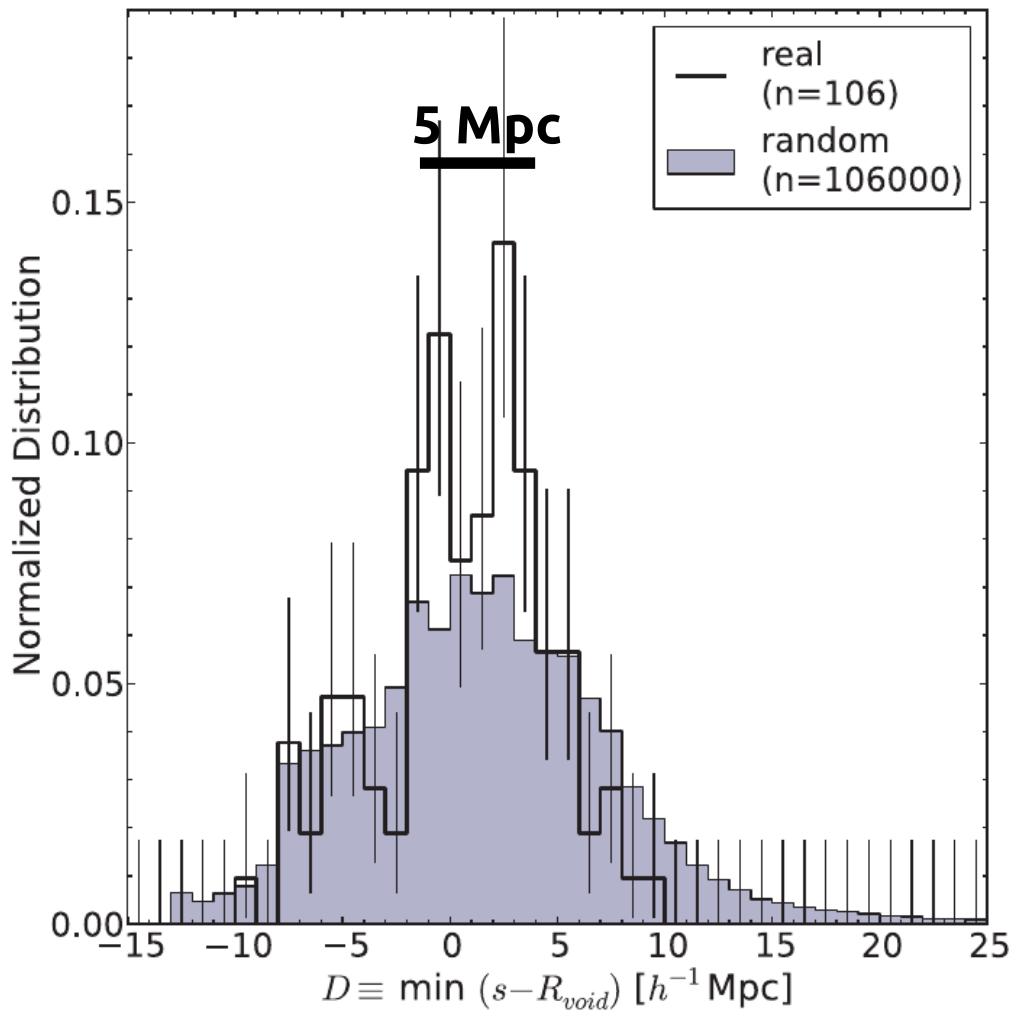
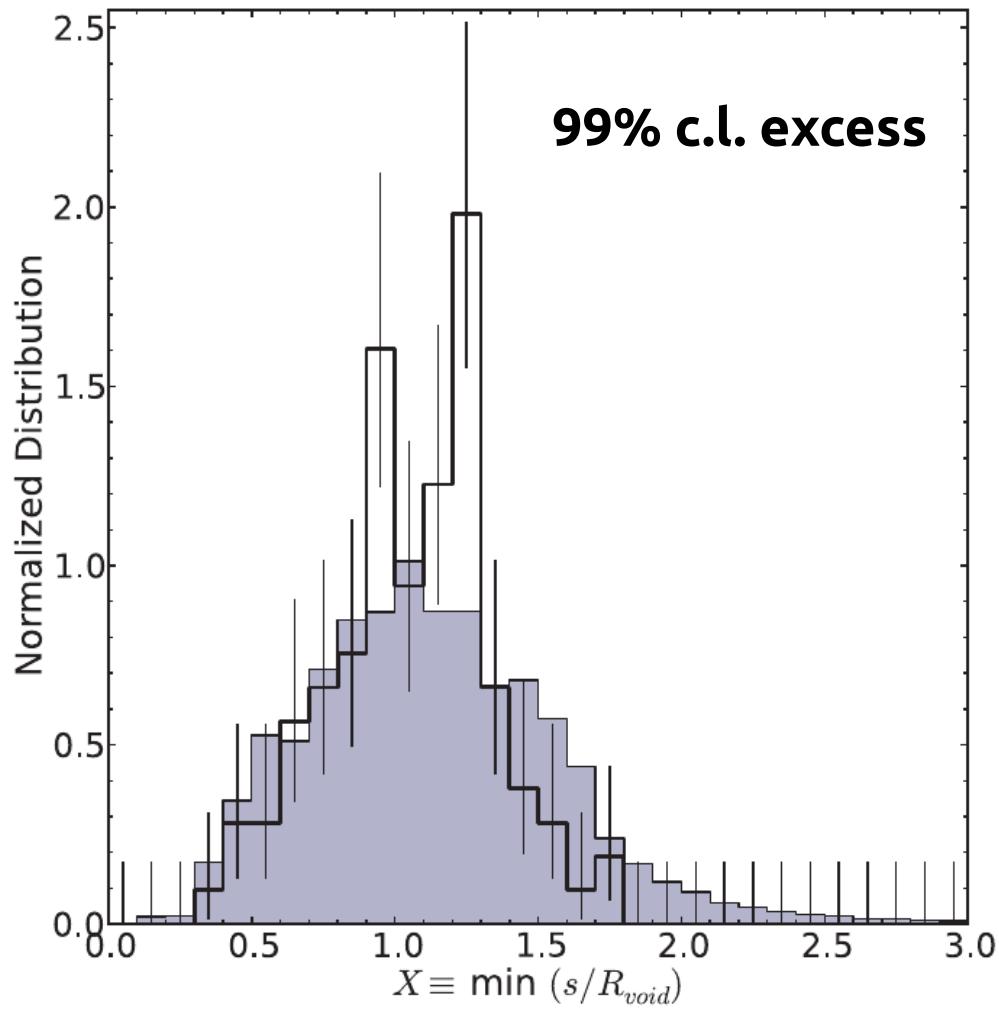
Results



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Tejos et al. 2012

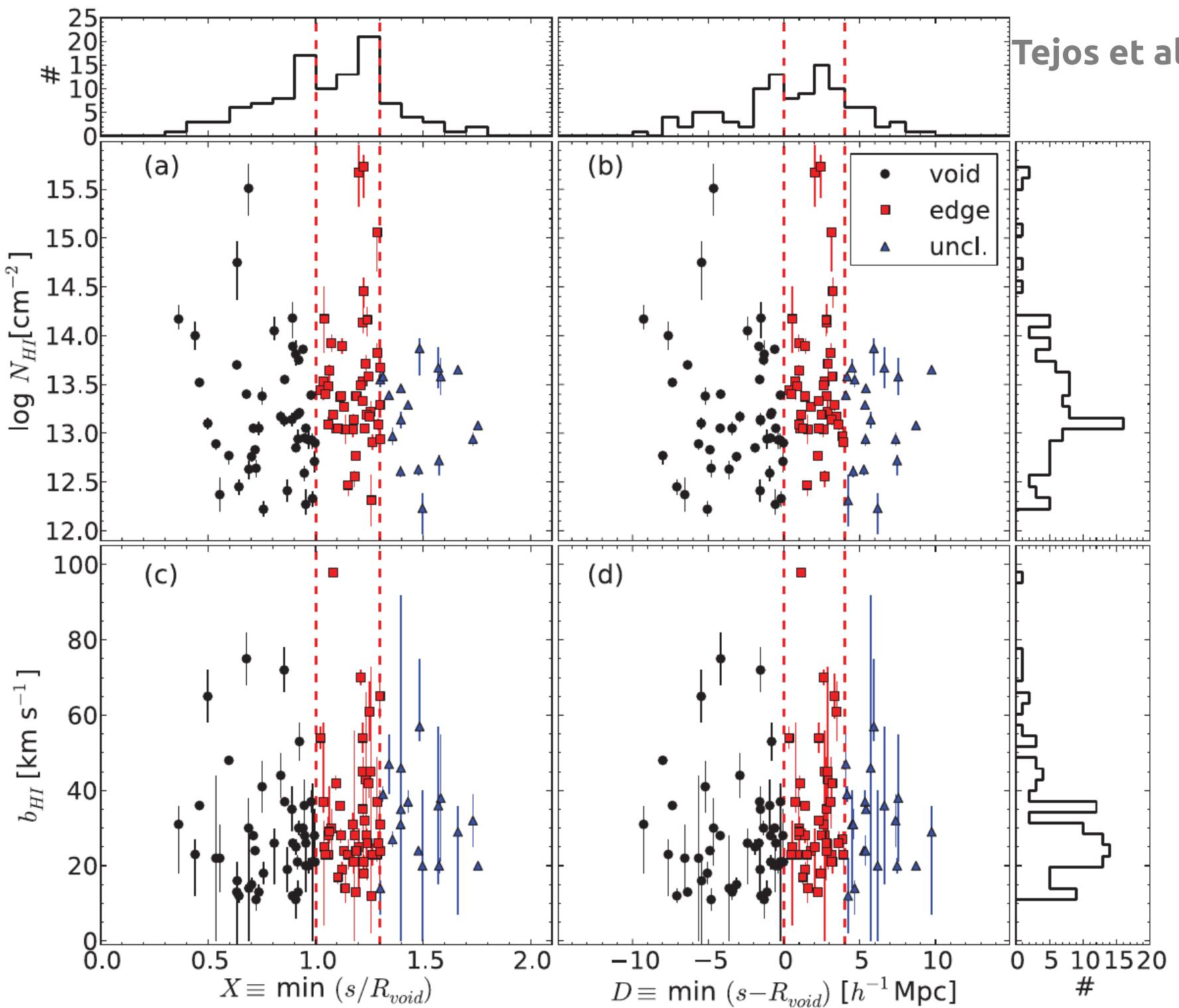
Results

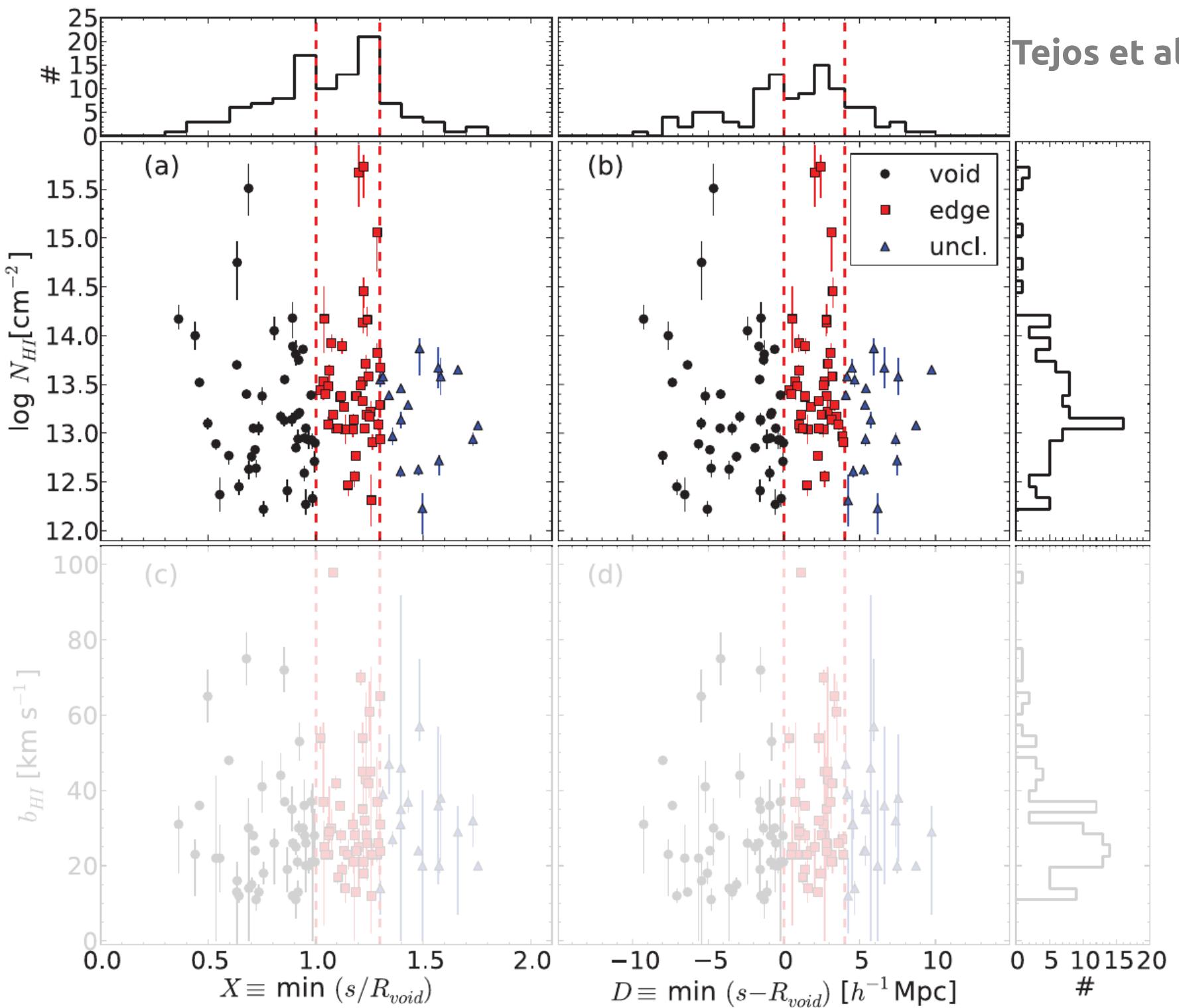


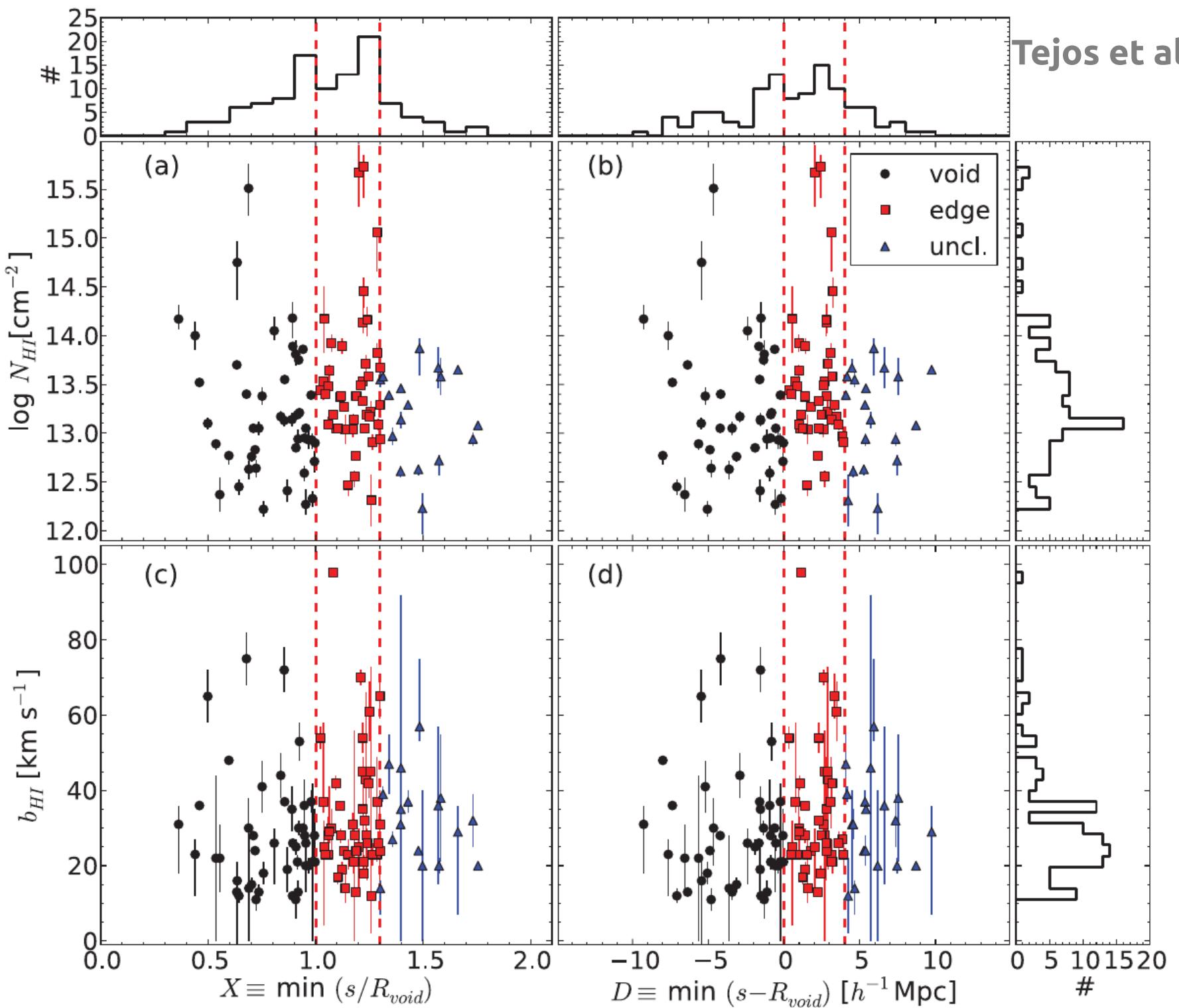
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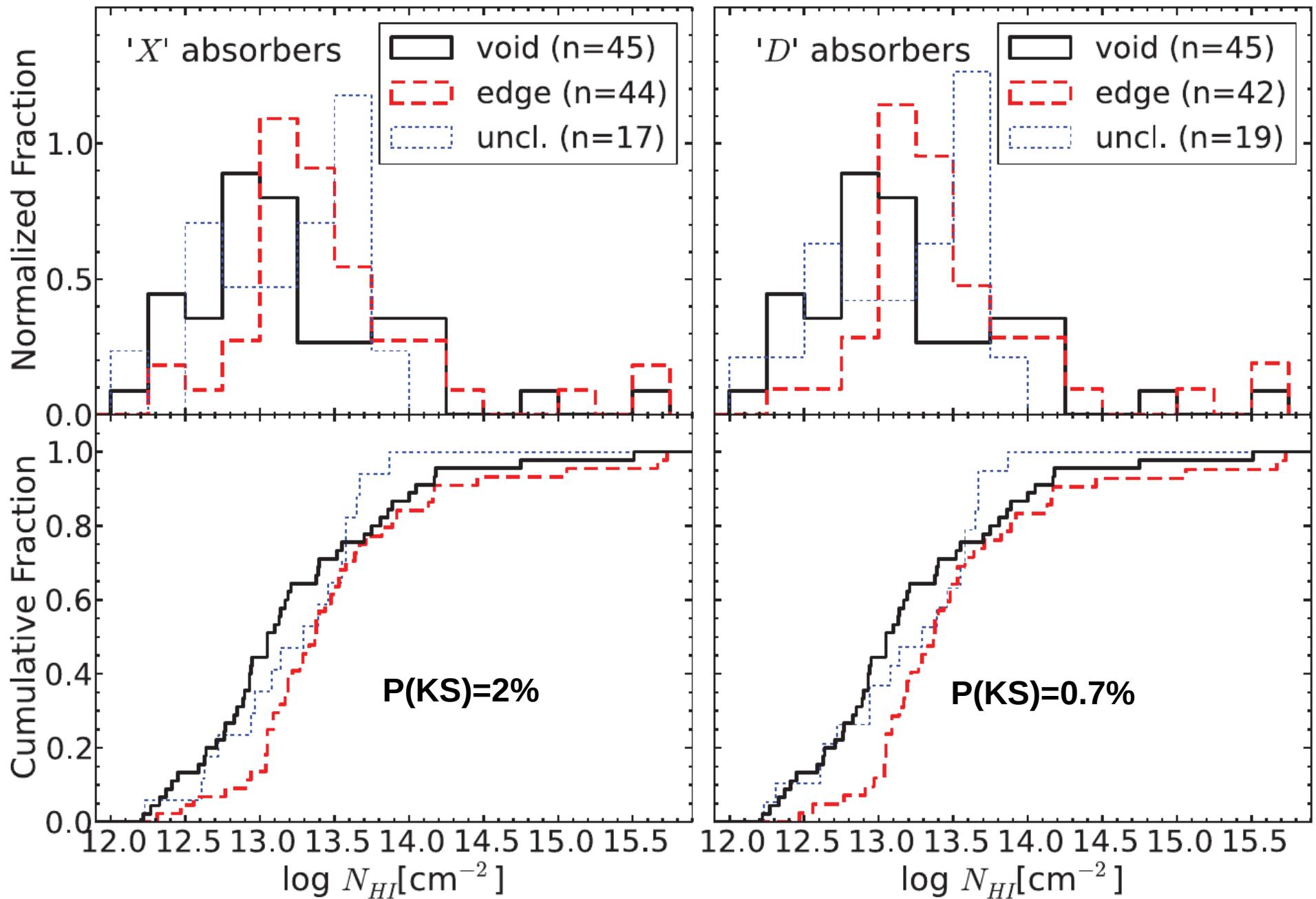
**Are their properties
different?**



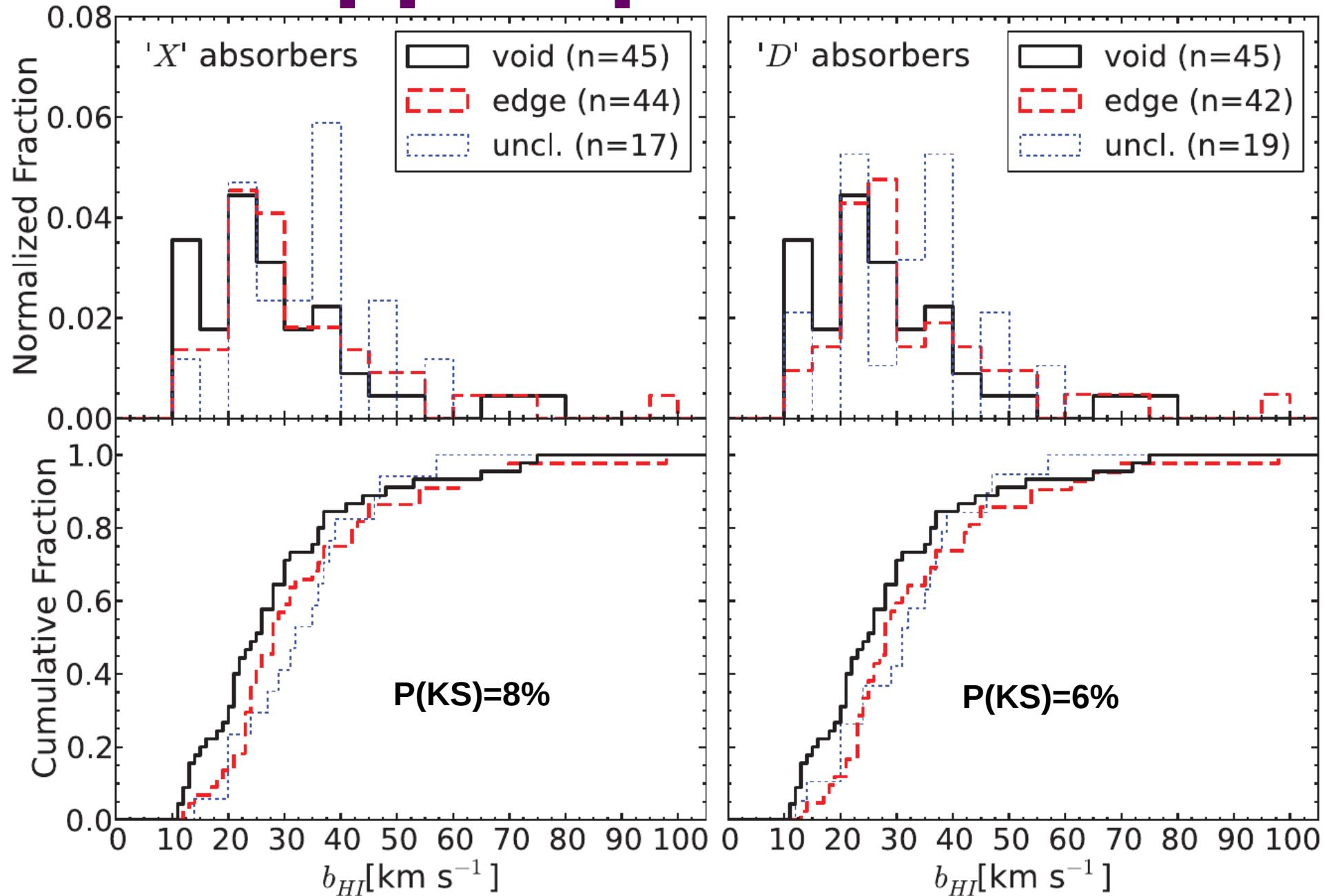




Column densities



Doppler parameters



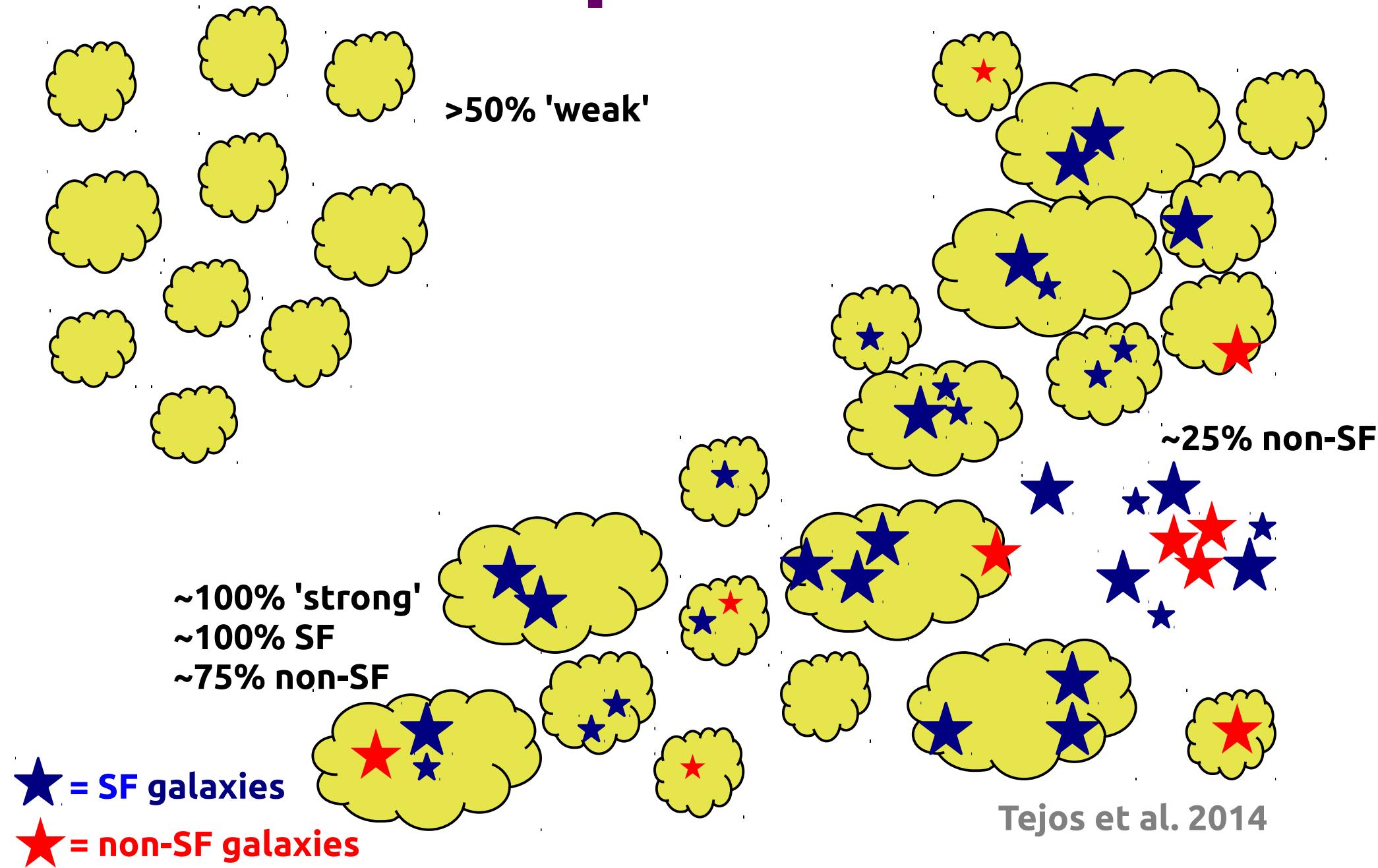
Conclusions

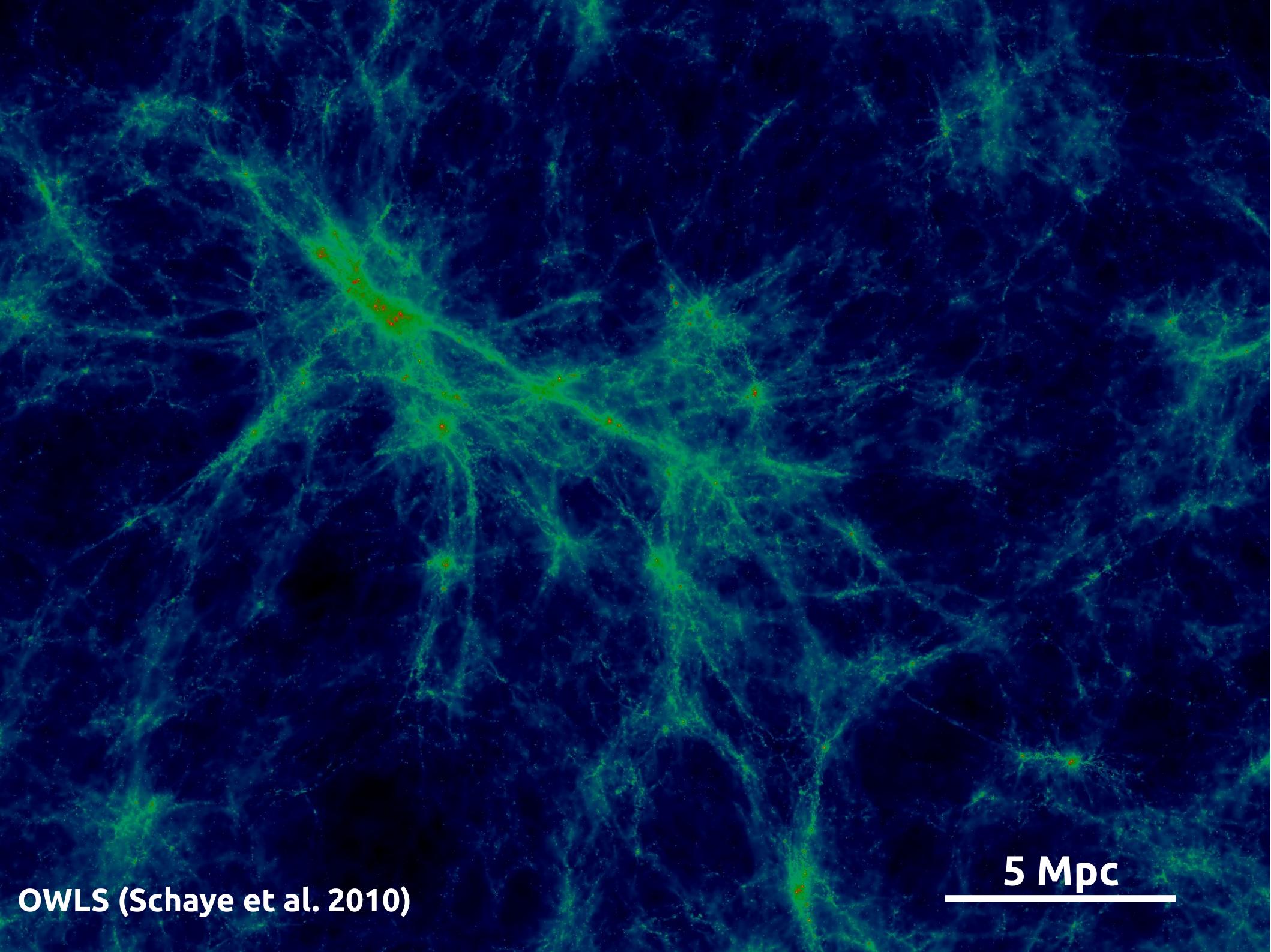
Conclusions

- ~100% 'strong' HI and SF galaxies follow the same underlying dark matter (DM) distribution, in the same volumes. Typical scales of ~5 Mpc.
- ~75% of non-SF galaxies also follow the same underlying DM distribution, in the same volumes. ~25% of non-SF galaxies reside in galaxy clusters and are not correlated with 'strong' HI.
- Galaxy voids are not empty. >50% of 'weak' HI systems reside in regions devoid of galaxies.
- Low-density environments (voids) have smaller values for both N(HI) and b(HI) than higher density ones (edges of voids).
- The bulk of HI around galaxies have little velocity offsets (<120 km/s) w/r to the bulk of galaxies. No strong outflow/inflow signal detected.
- Three types of HI-galaxy relationship:
 - (1) direct one-to-one
 - (2) indirect, because they trace the same DM distribution
 - (3) no-correlation

Interpretation

(not to scale)



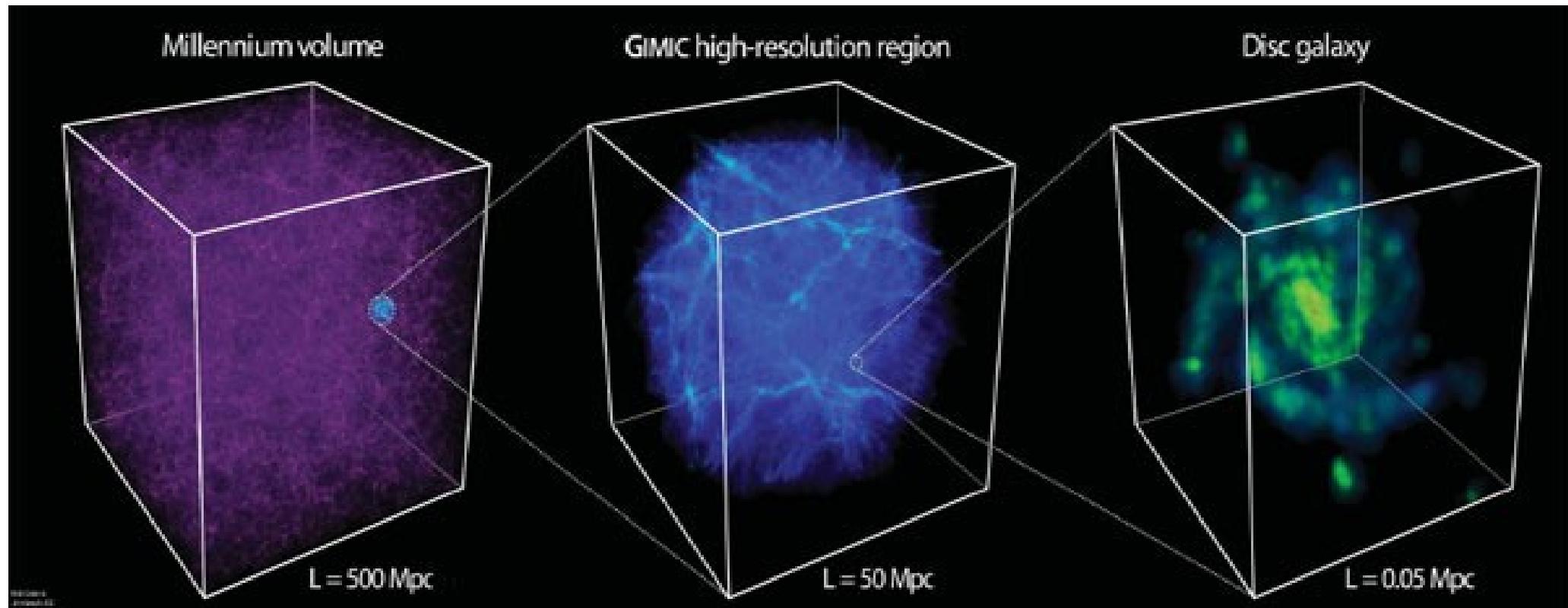


OWLS (Schaye et al. 2010)

5 Mpc

Comparison with simulations

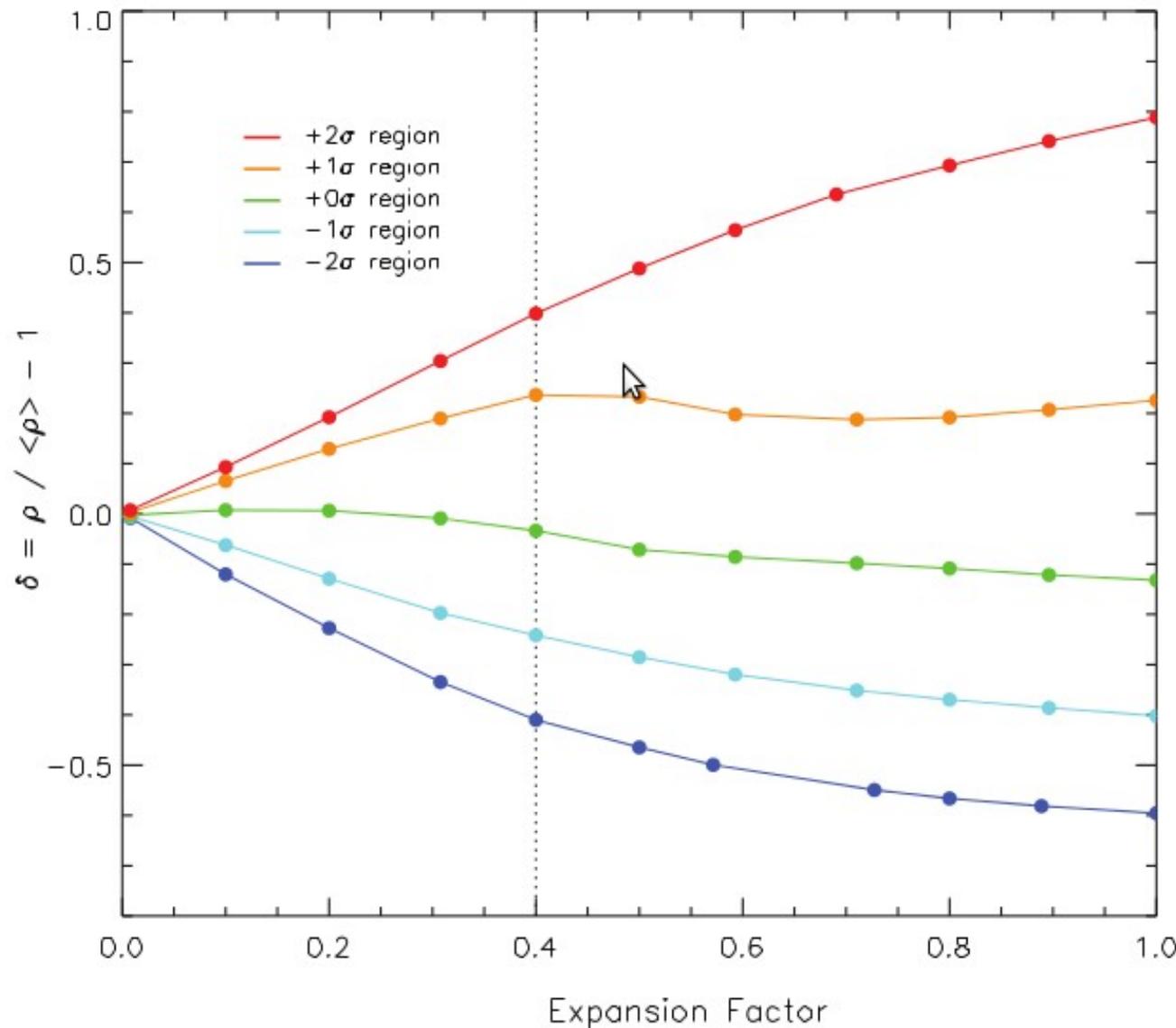
Comparison with GIMIC



**Galaxies Intergalactic-Medium
Interaction Calculation**

Crain et al. 2009

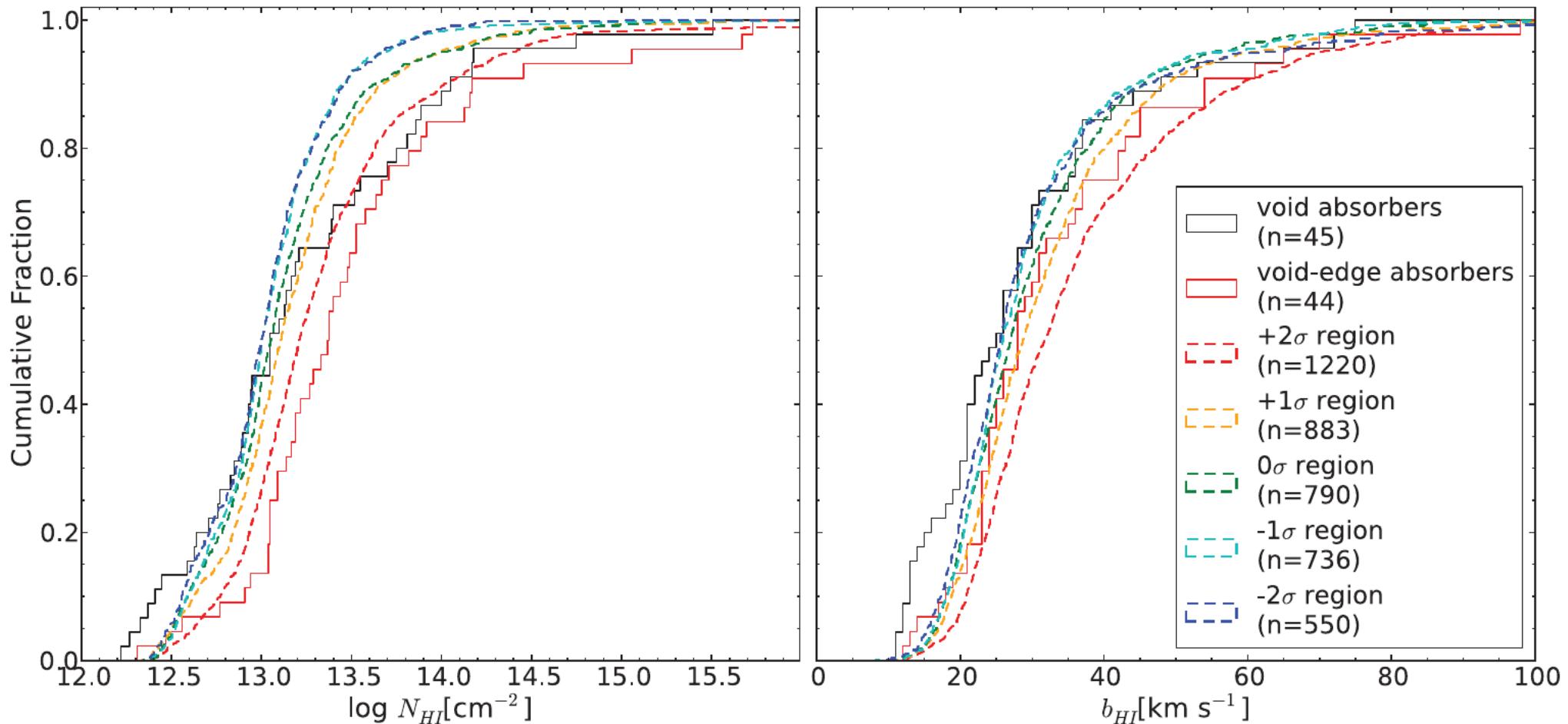
Comparison with GIMIC



5 GIMIC regions

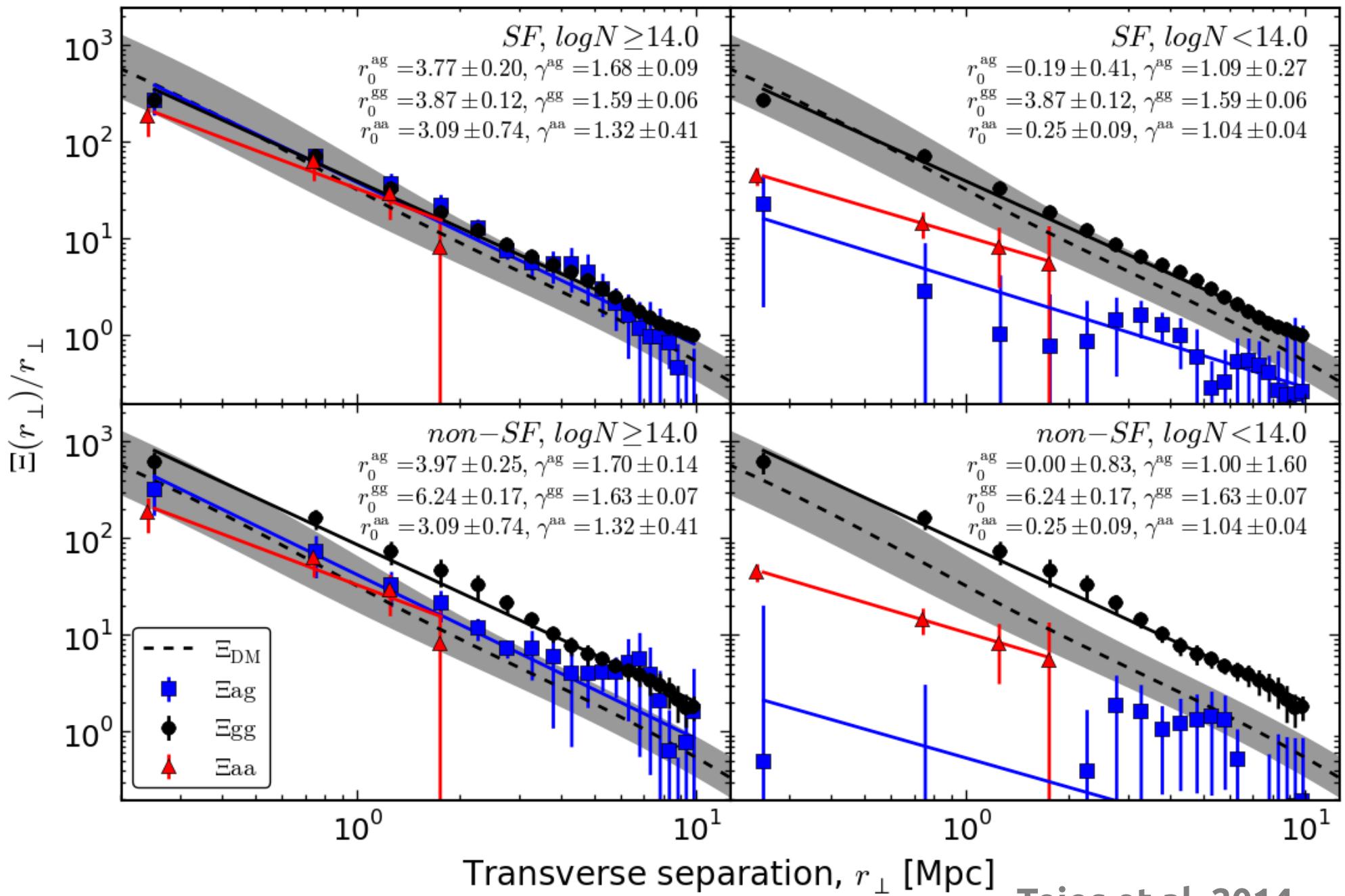
Crain et al. 2009

Comparison with GIMIC



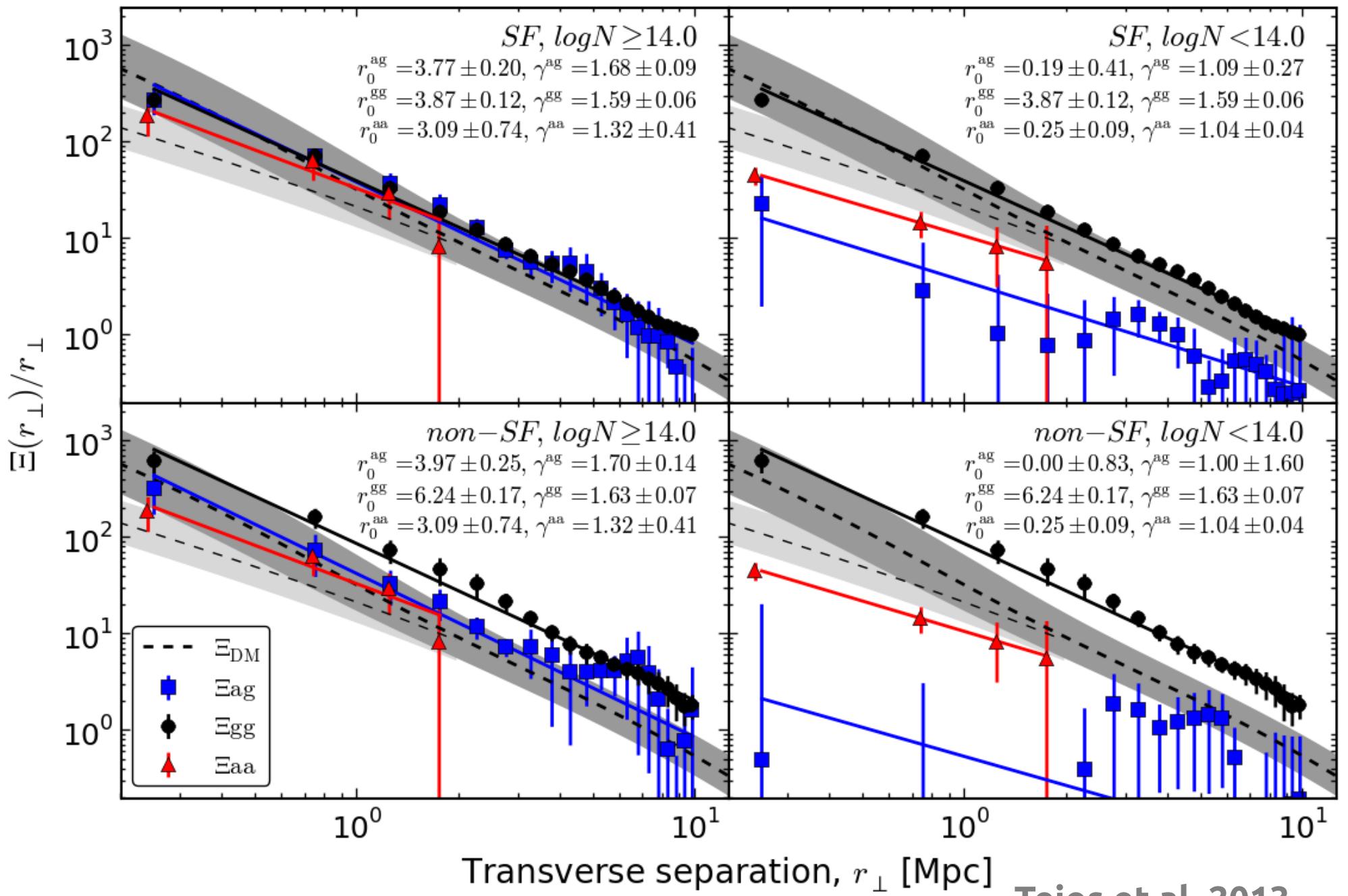
5 GIMIC regions

Tejos et al. 2012



DM clustering: Lewis et al. 2000 + Smith et al. 2003

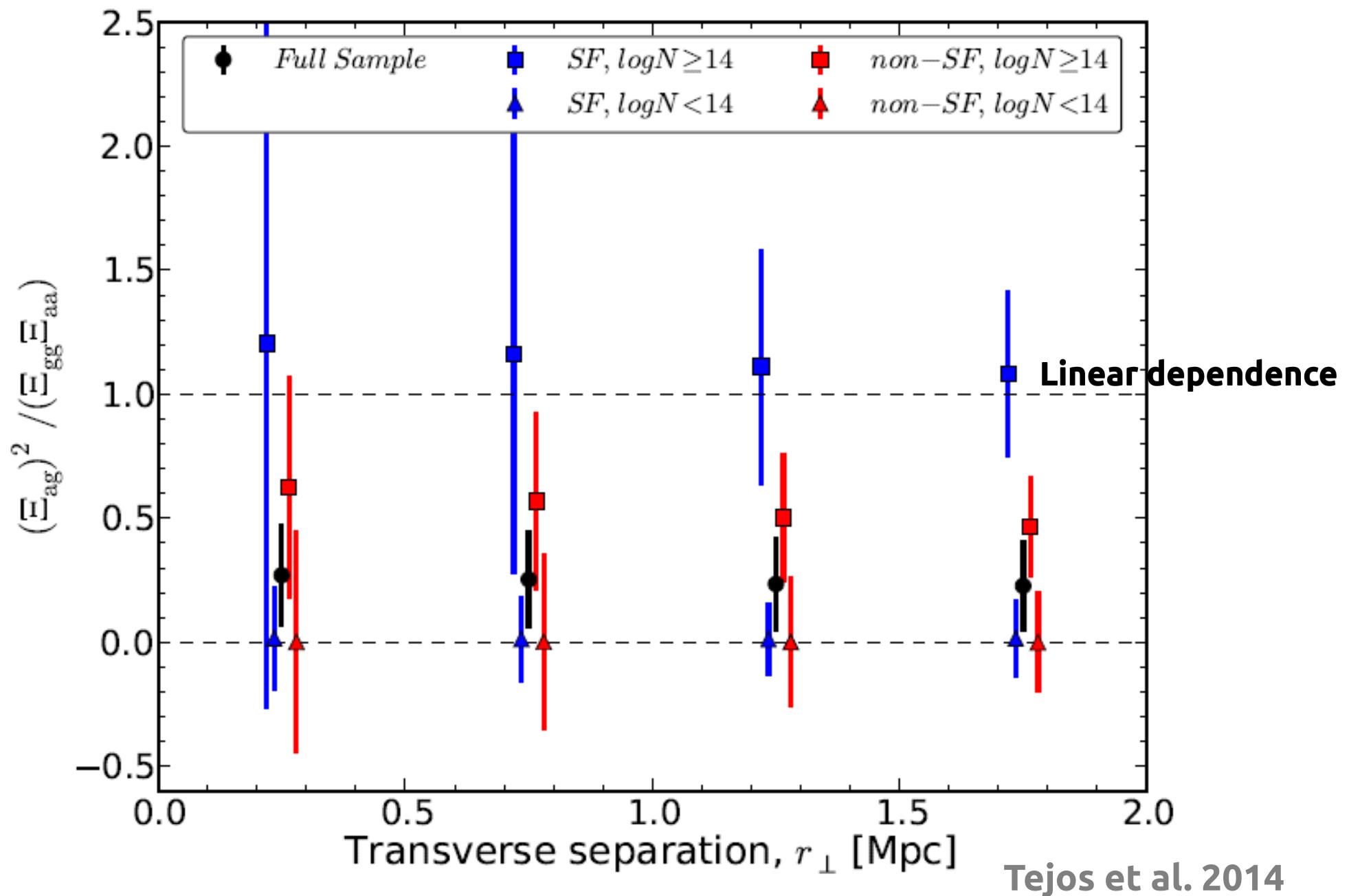
Tejos et al. 2014



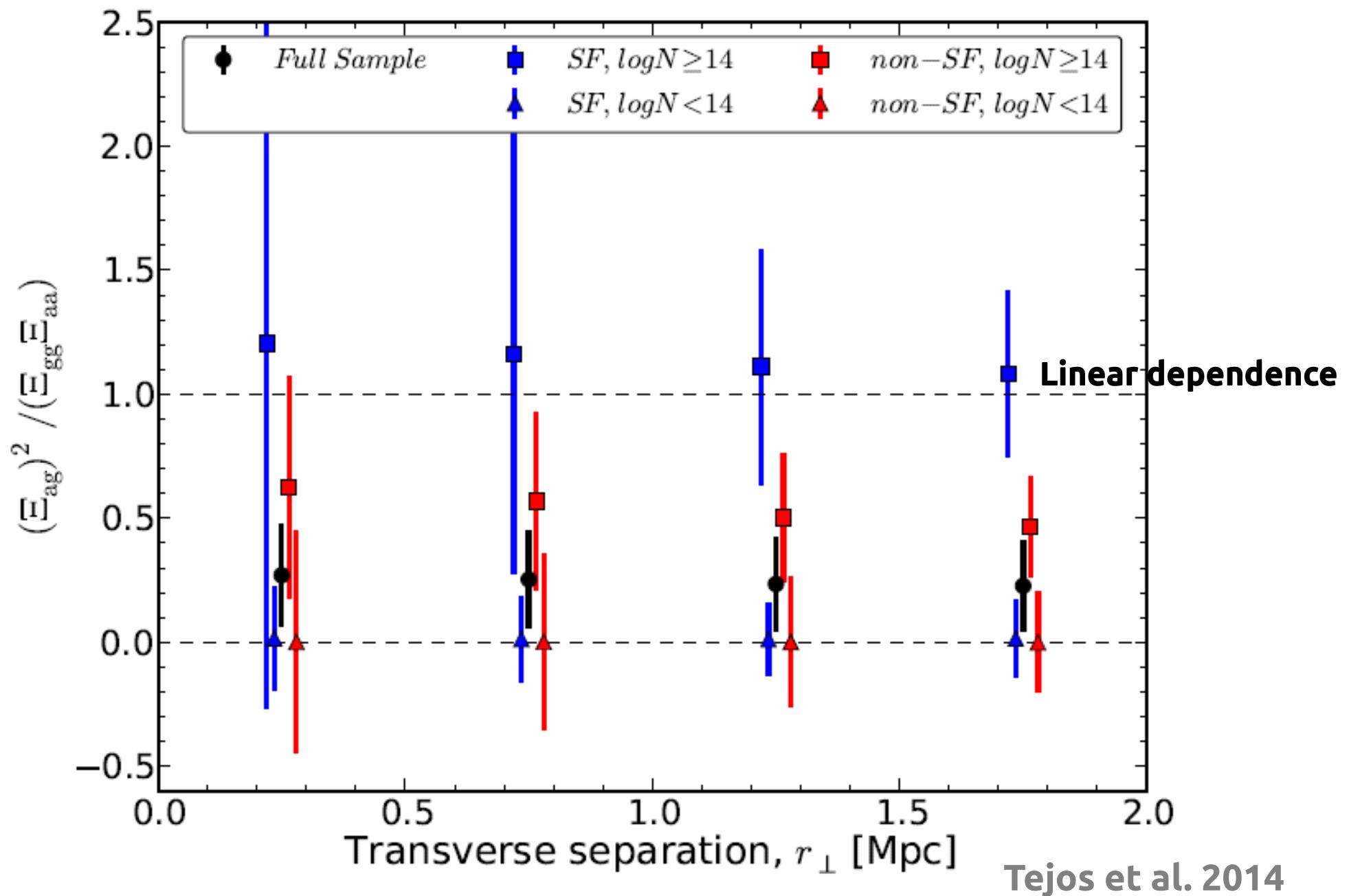
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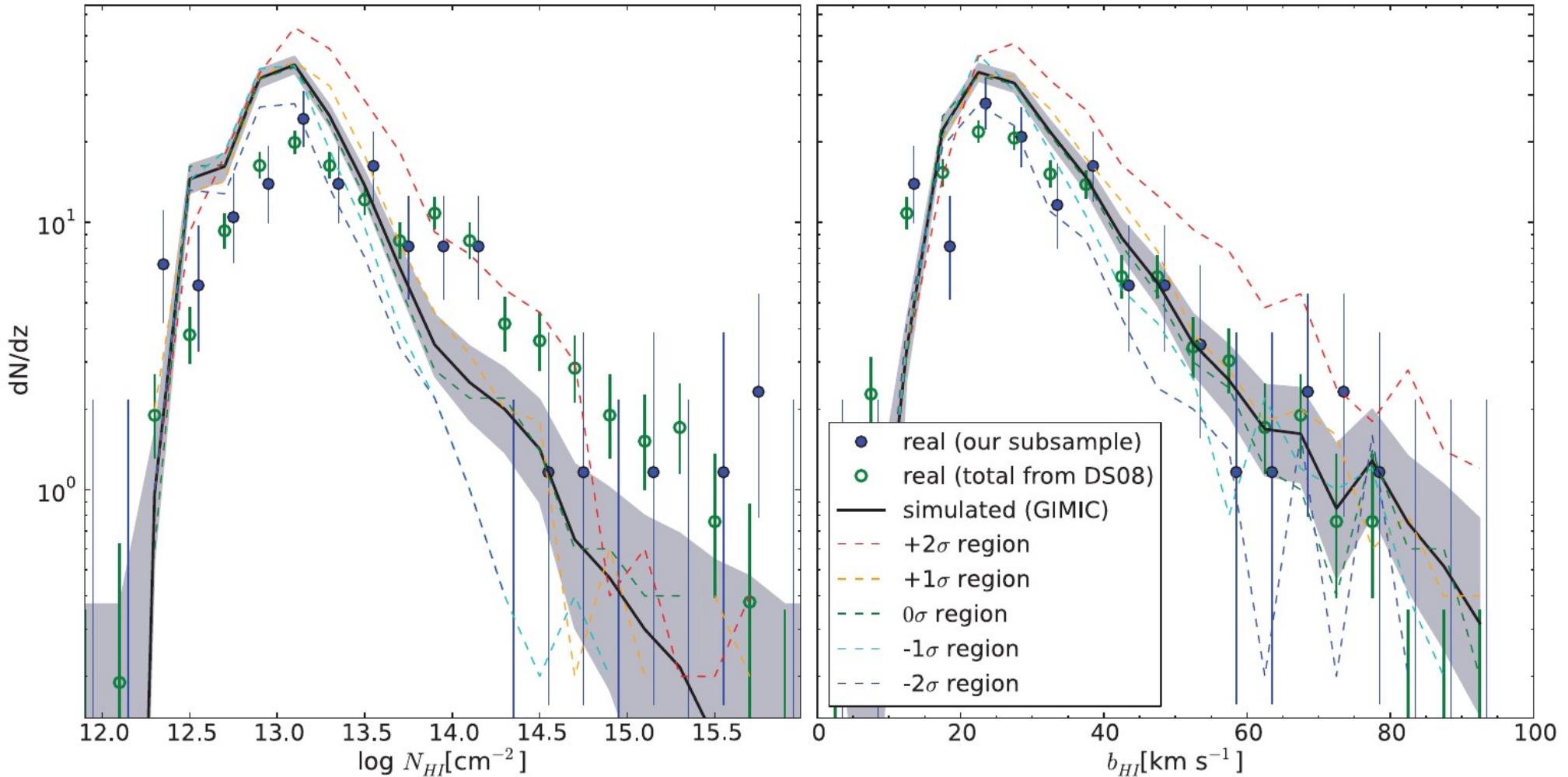
Results



Results



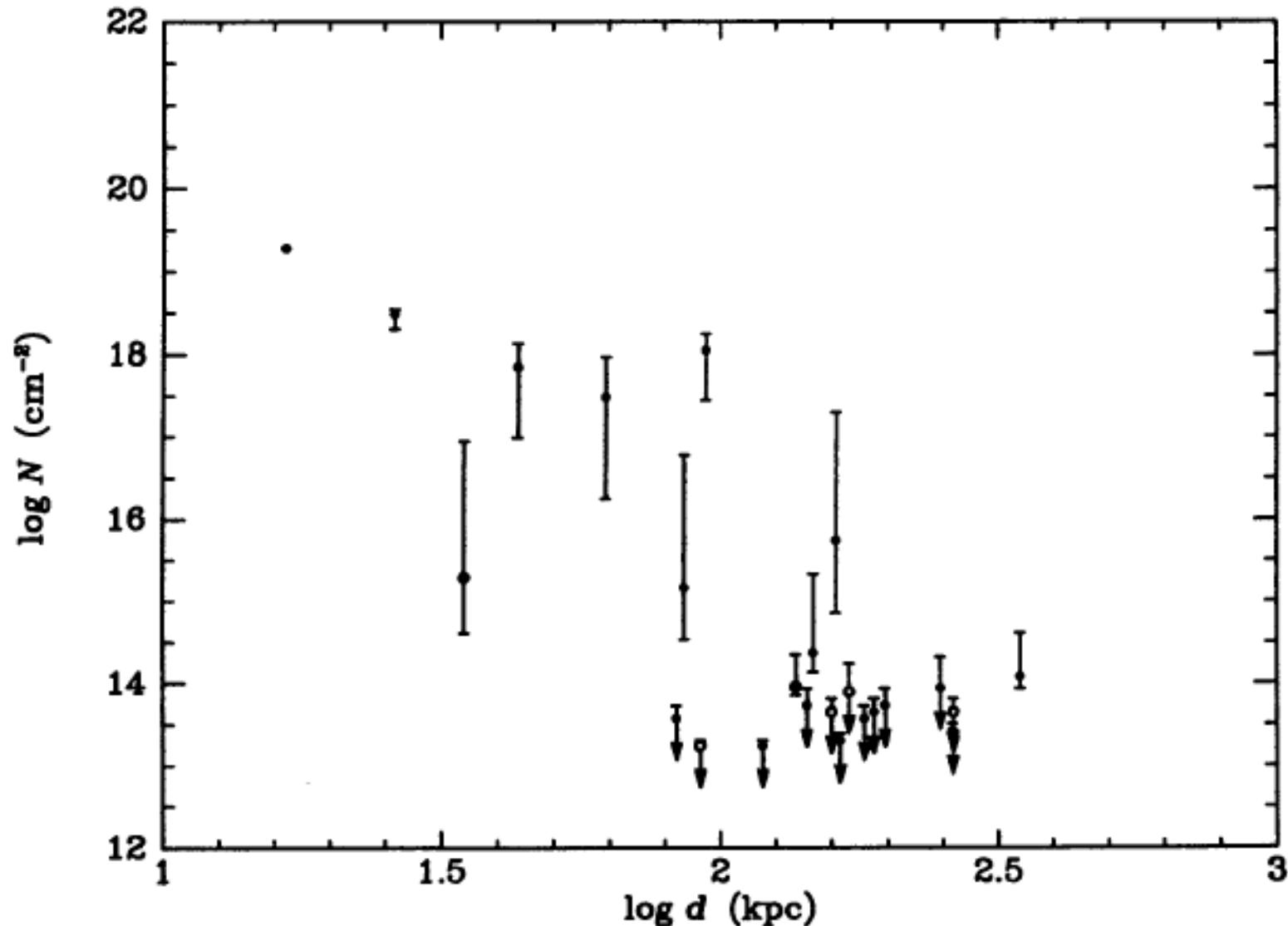
Comparison with simulations



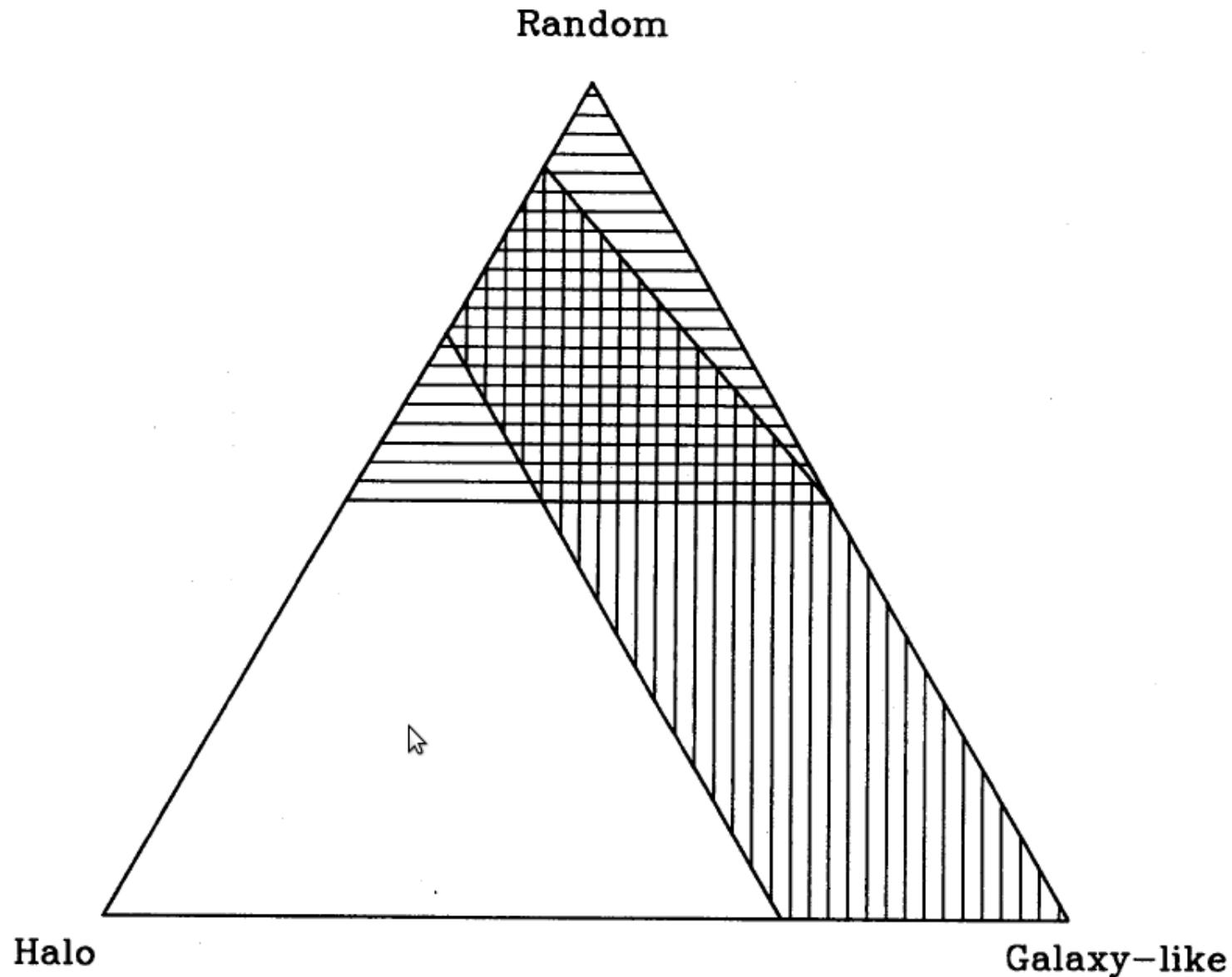
Galaxies Intergalactic-Medium
Interaction Calculation

Tejos et al. 2012

IGM-galaxy connection

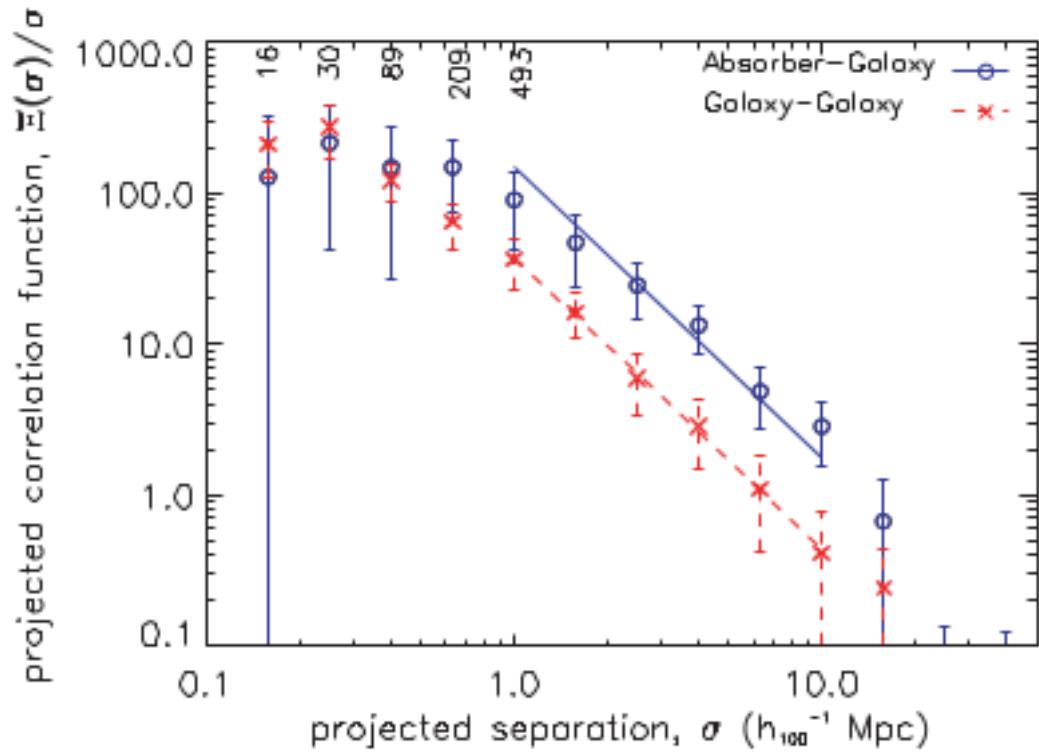
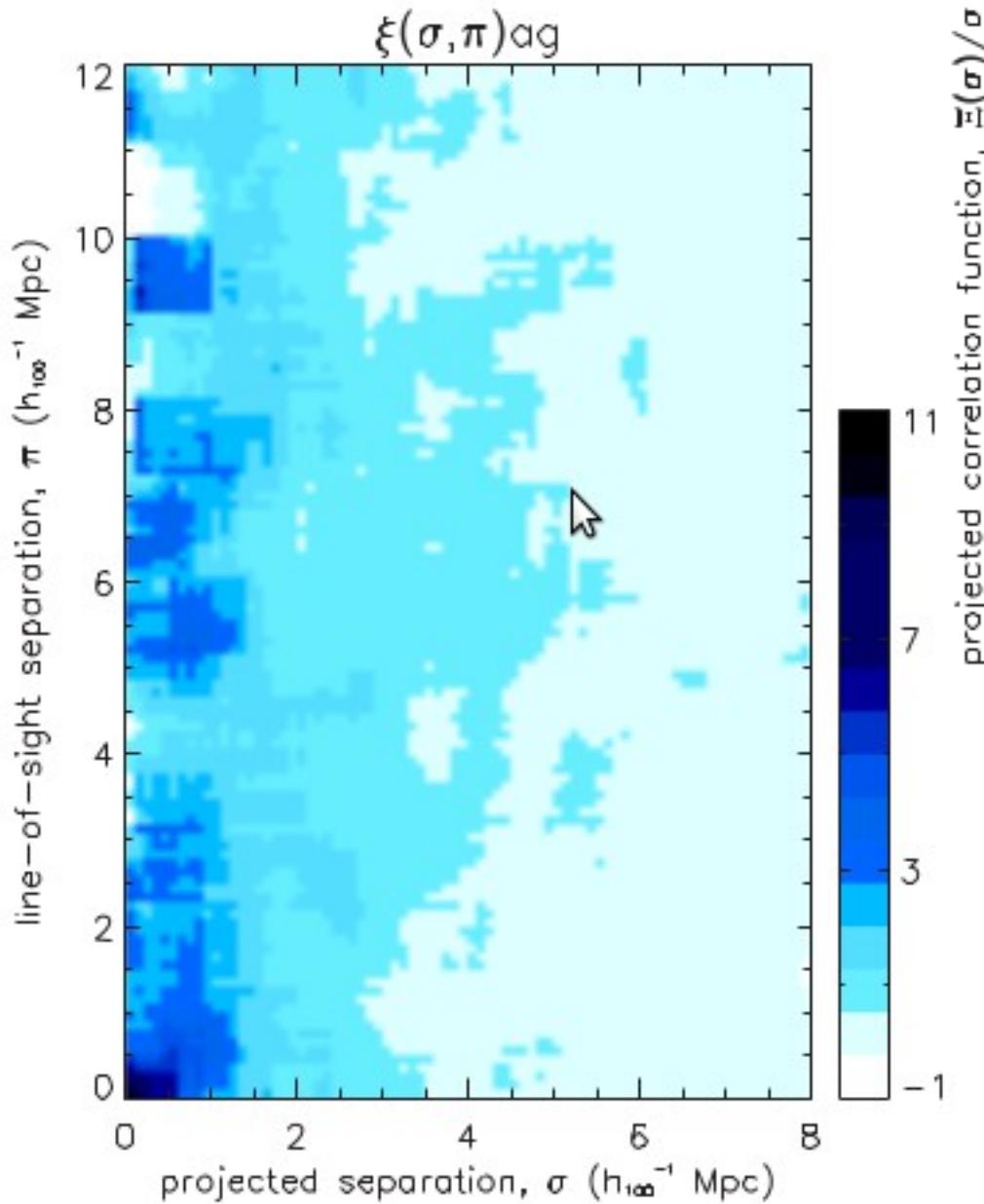


IGM-galaxy connection



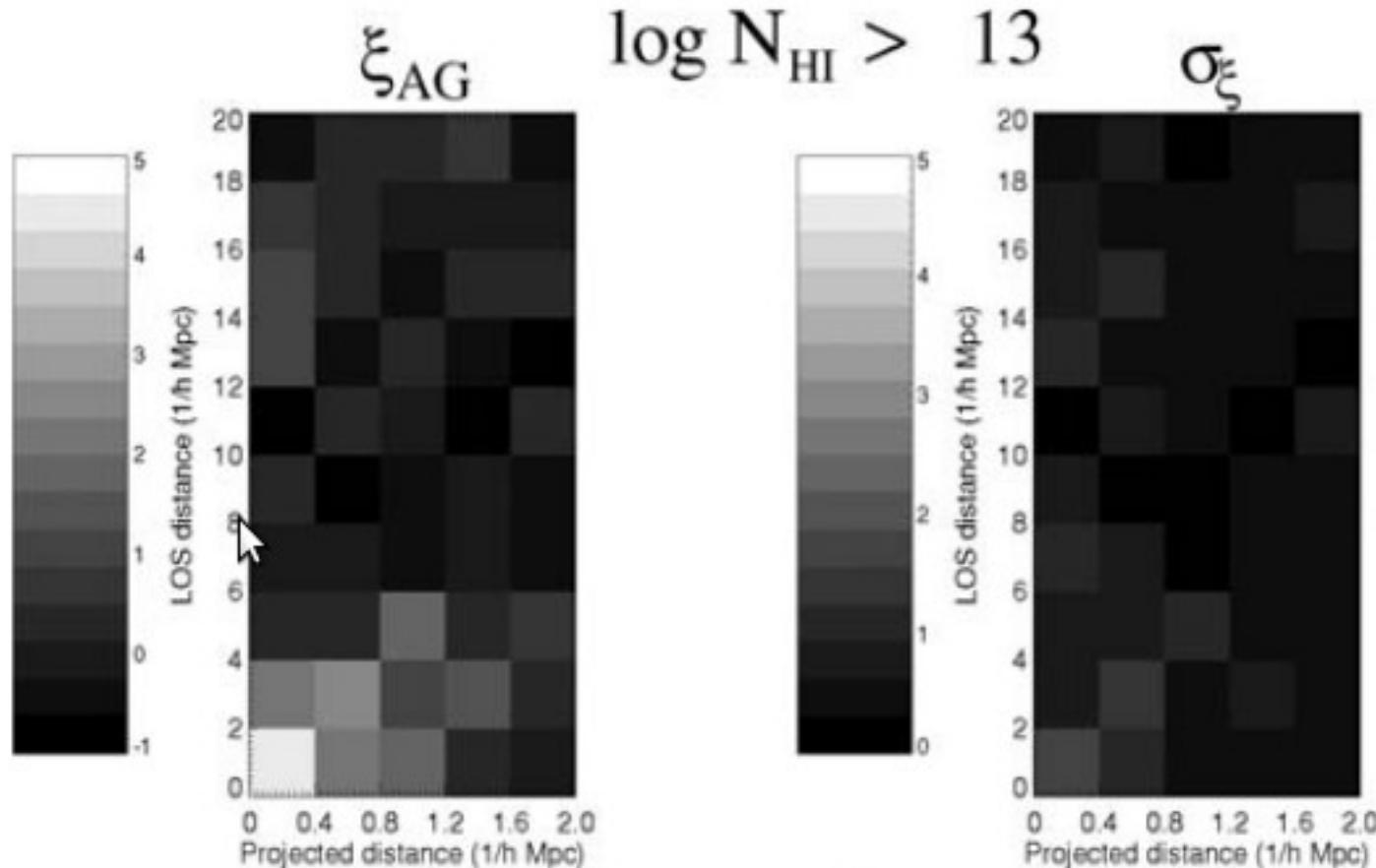
Mo & Morris 1994

Previous results



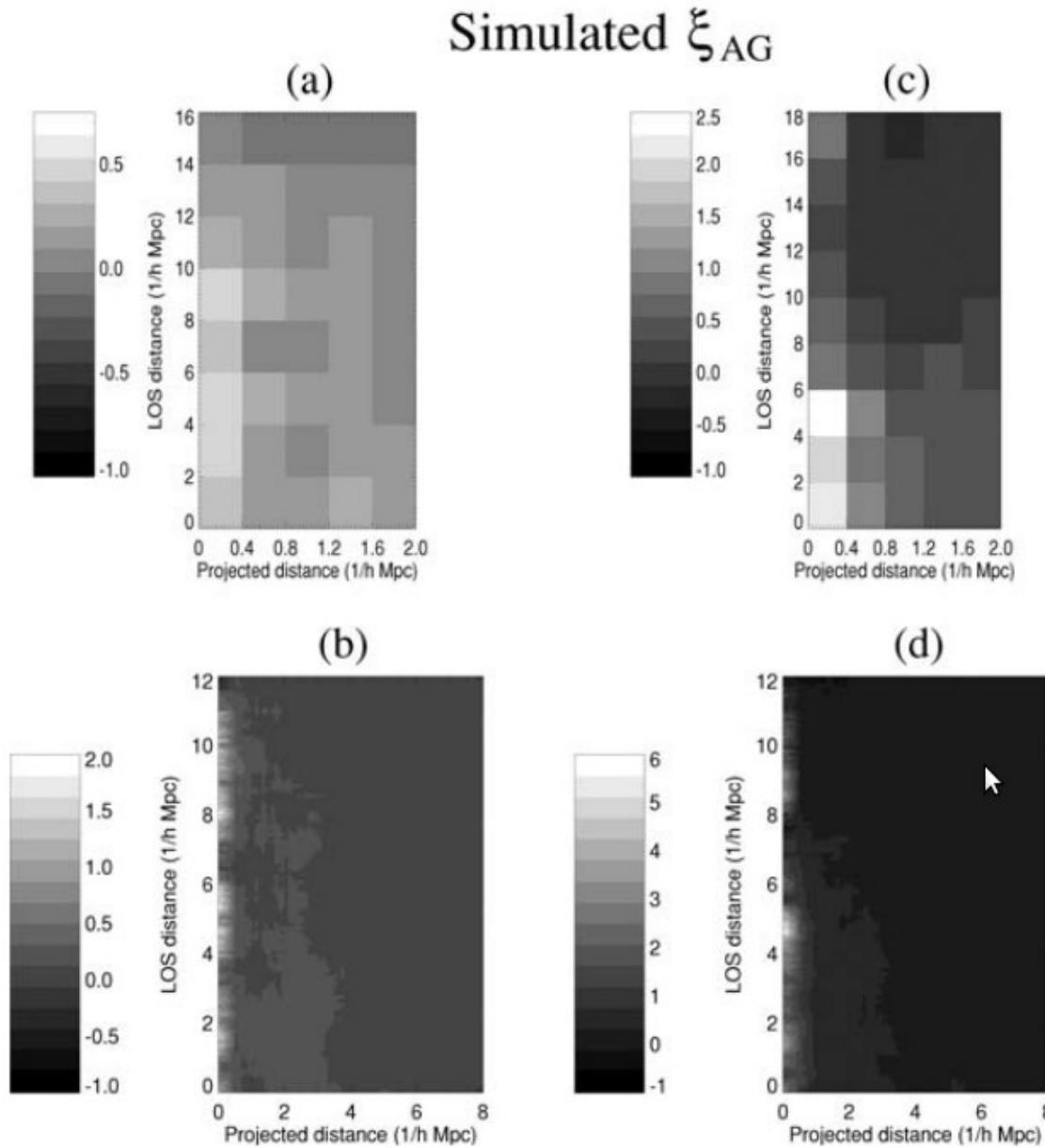
Ryan-Weber 2006

Previous results



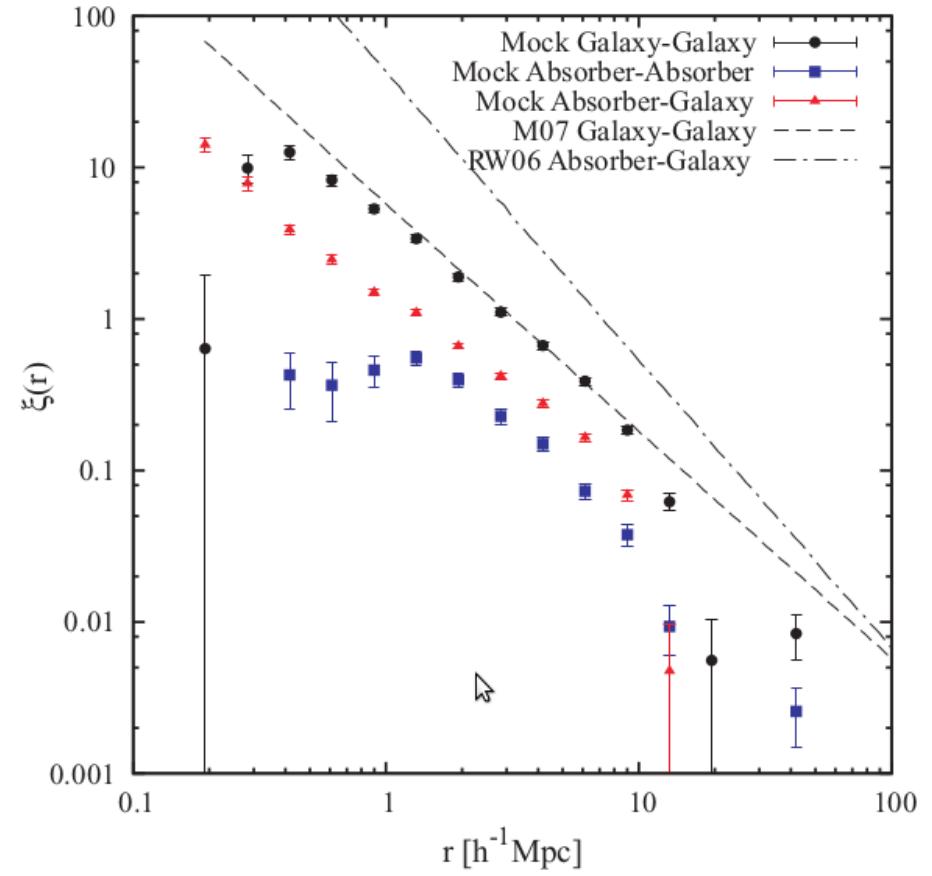
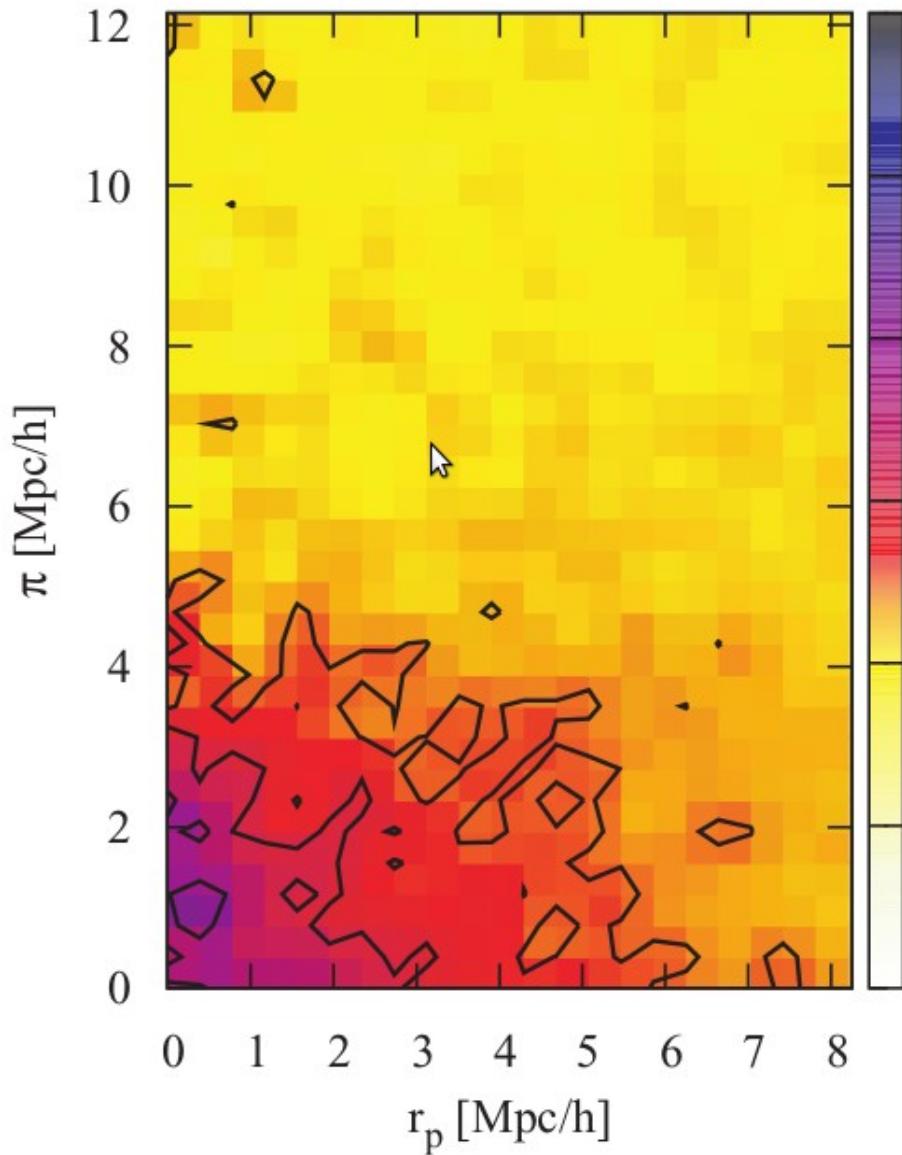
Wilman et al. 2007

Previous results



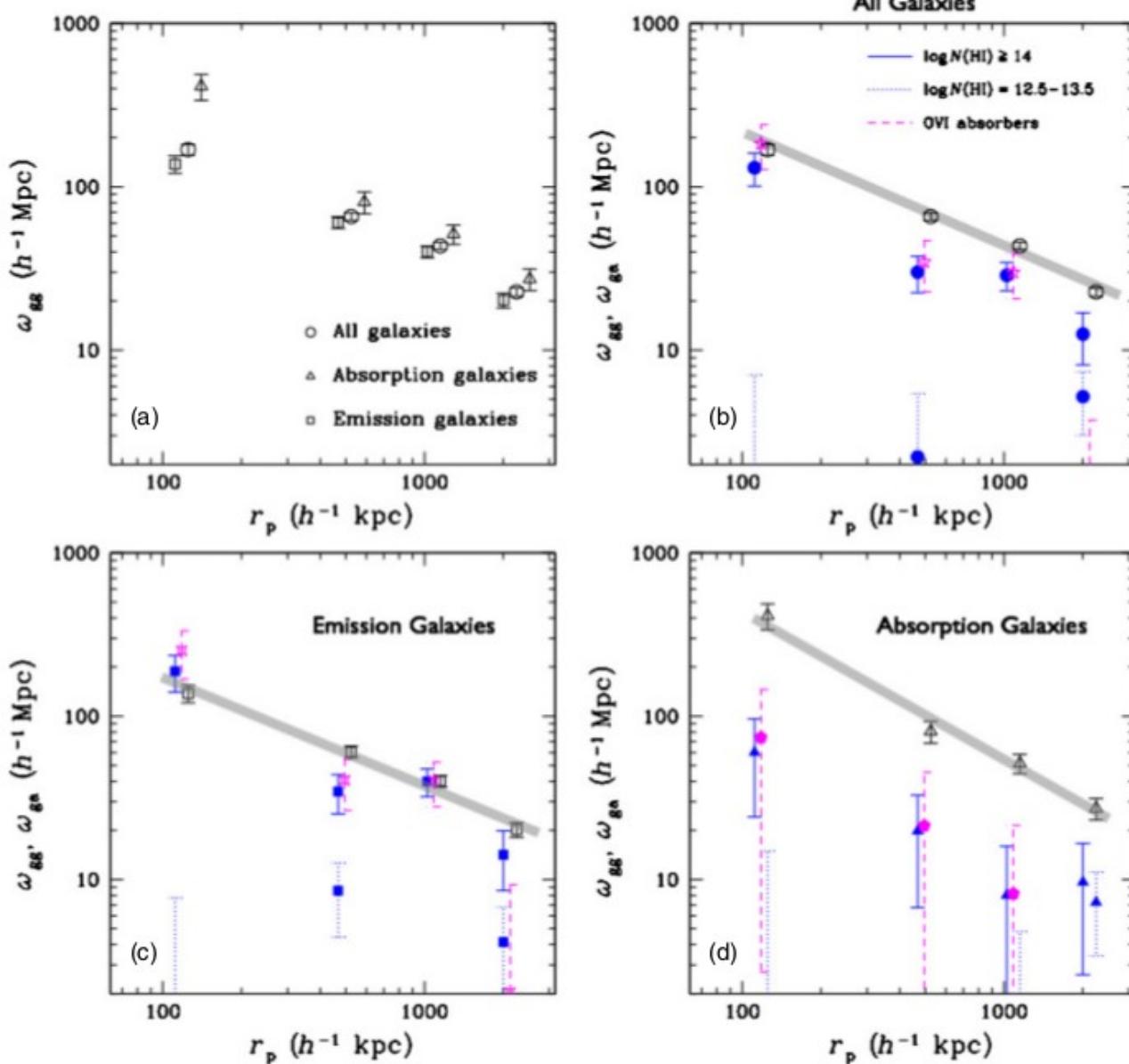
Wilman et al. 2007

Previous results



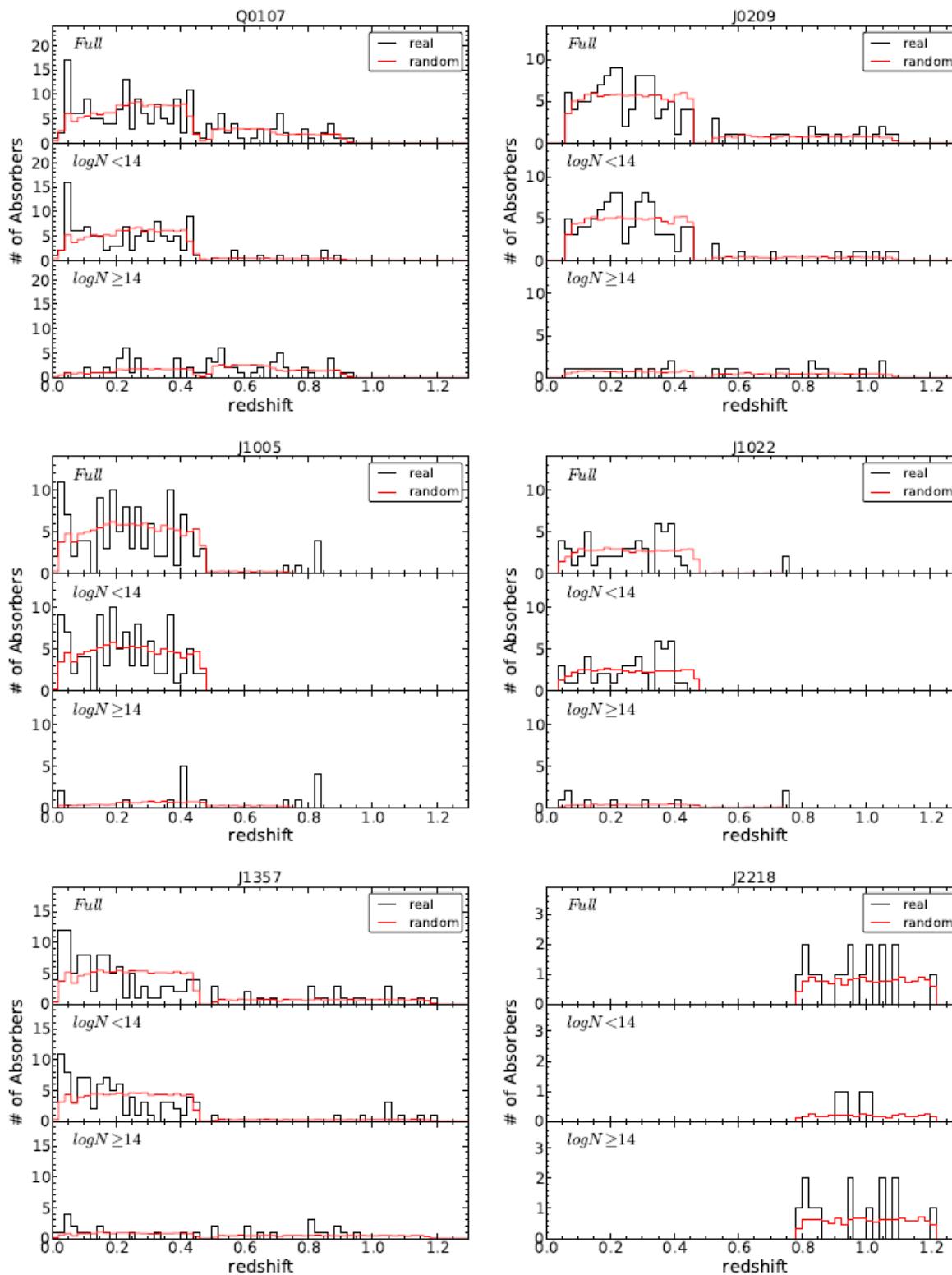
Pierleoni et al. 2008

Previous results



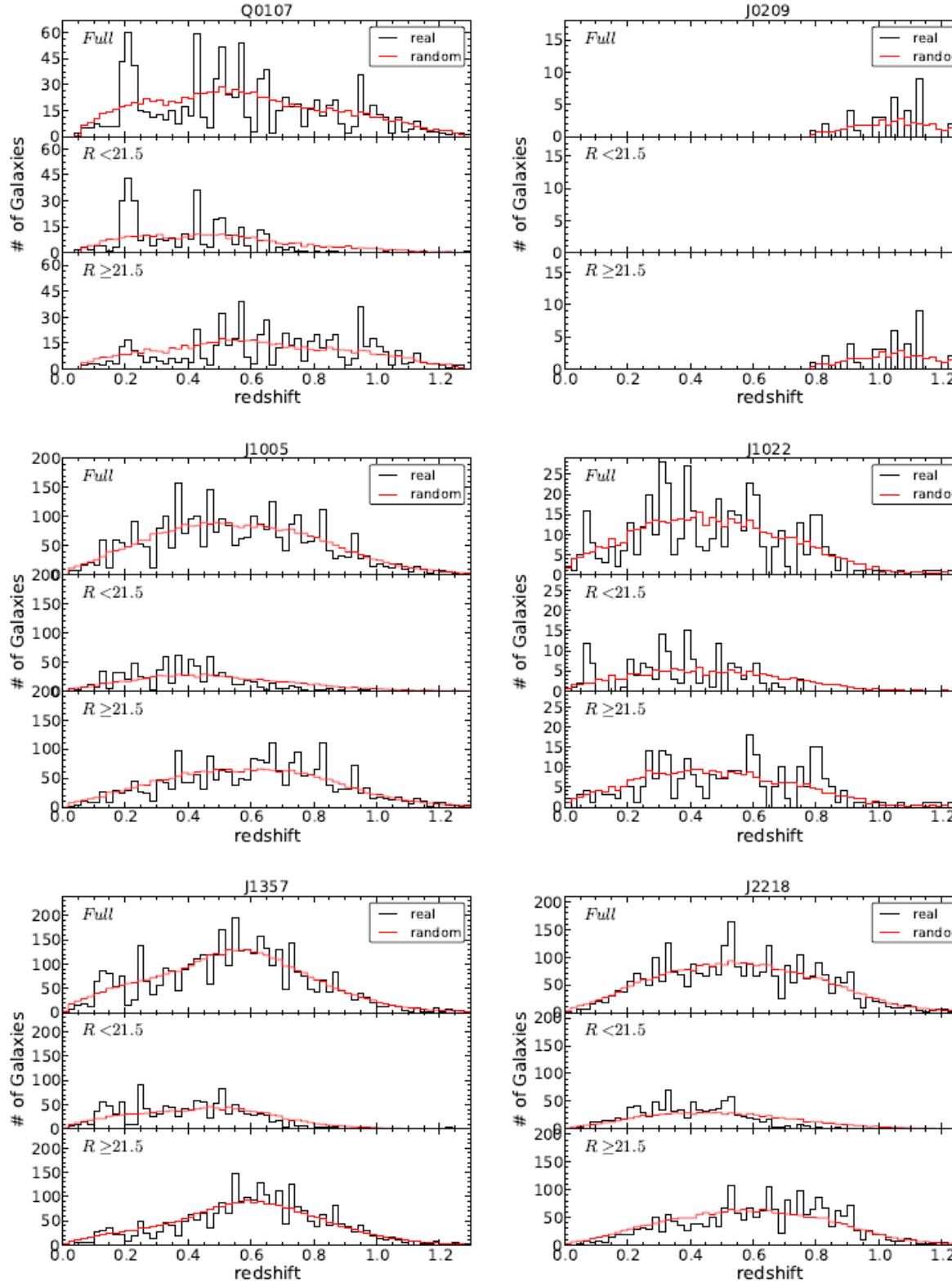
Chen & Mulchaey 2009

Selection functions



Tejos et al. 2014

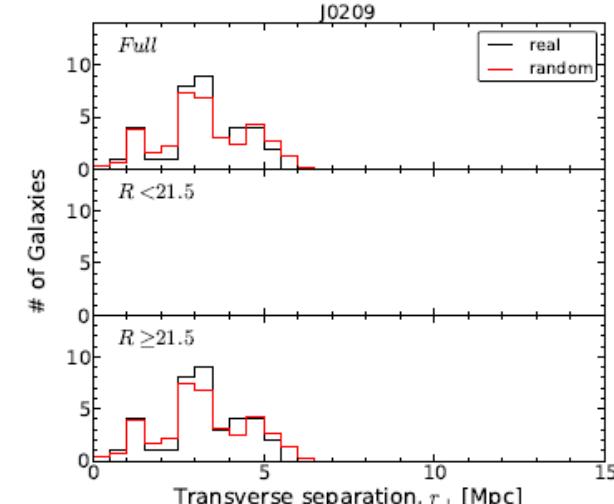
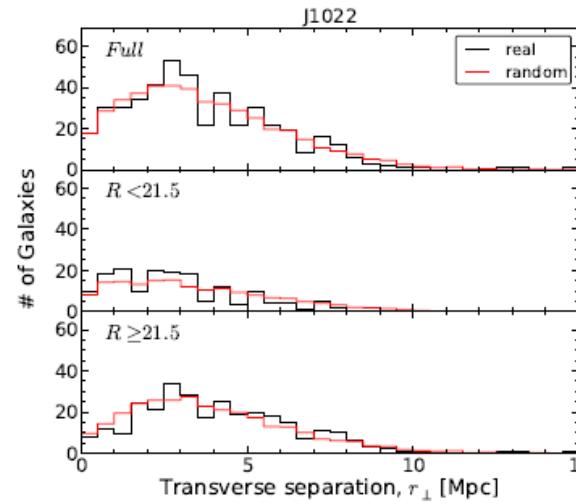
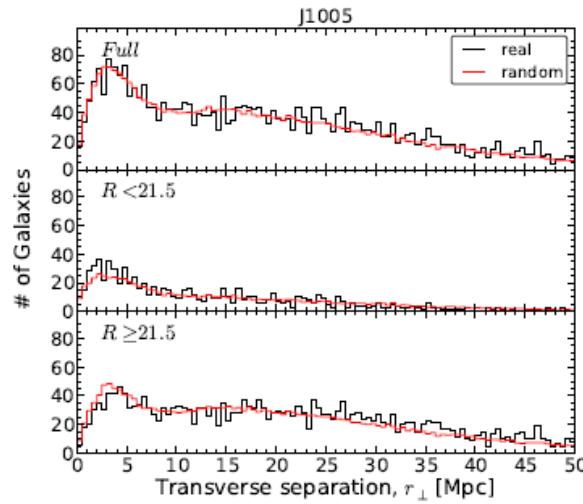
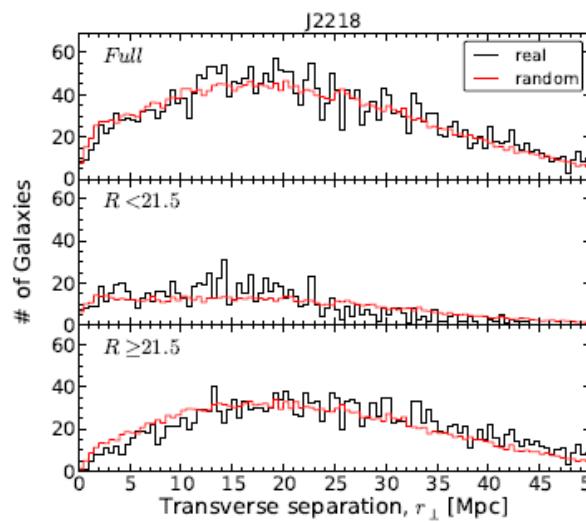
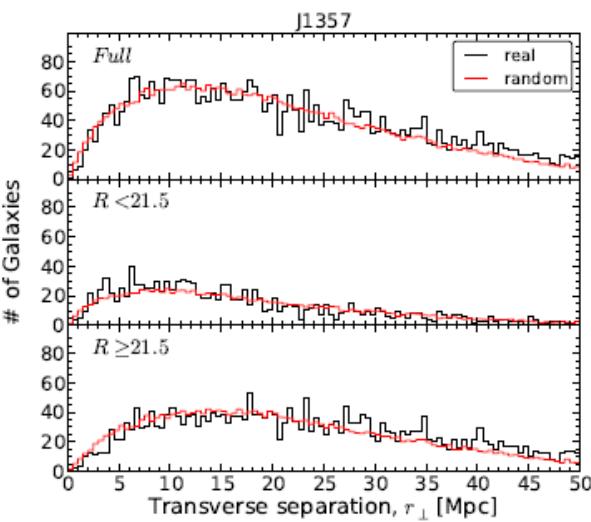
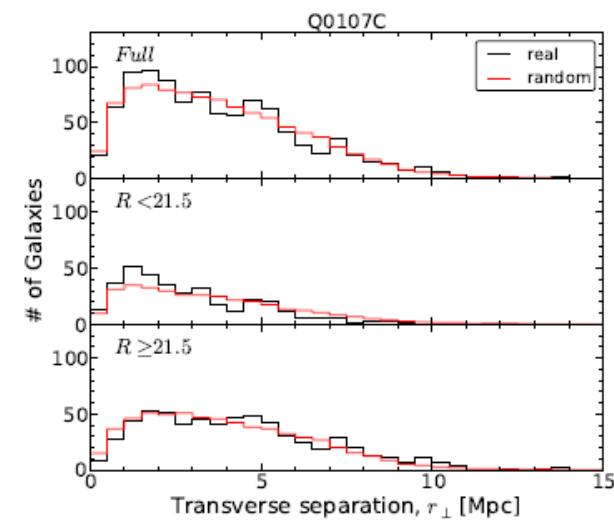
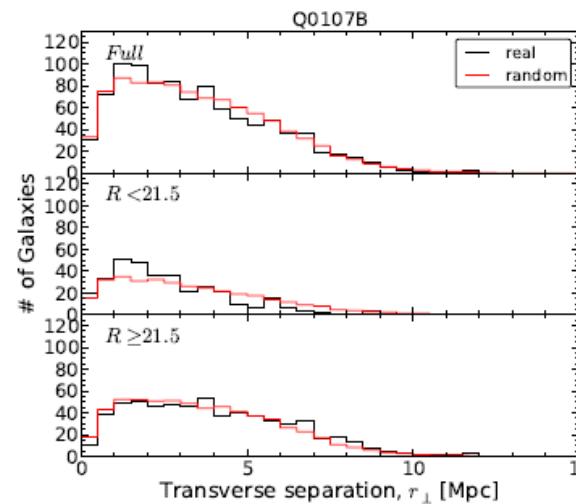
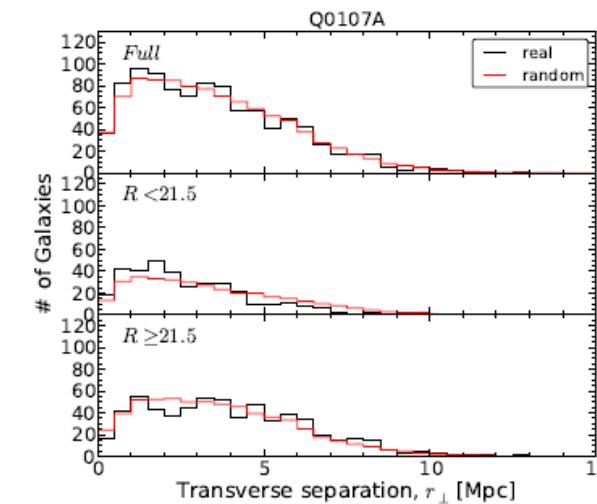
Selection functions



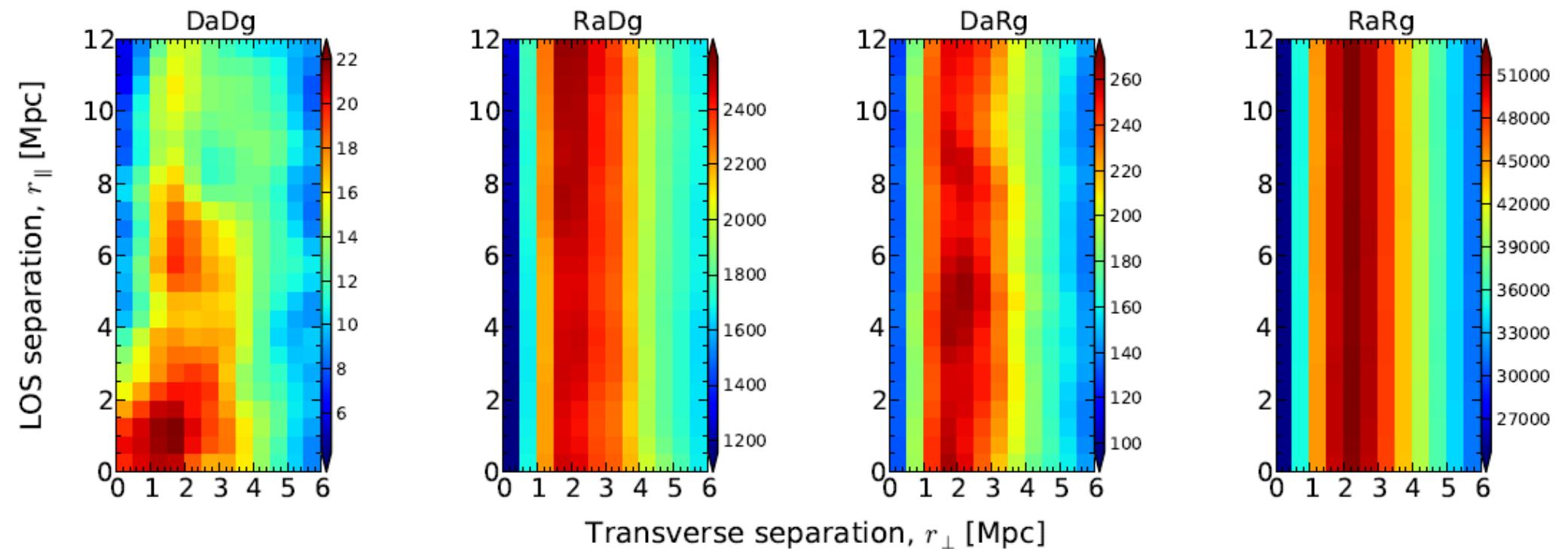
Tejos et al. 2014

Selection functions

Tejos et al. 2014



Cross-counts



Uncertainties

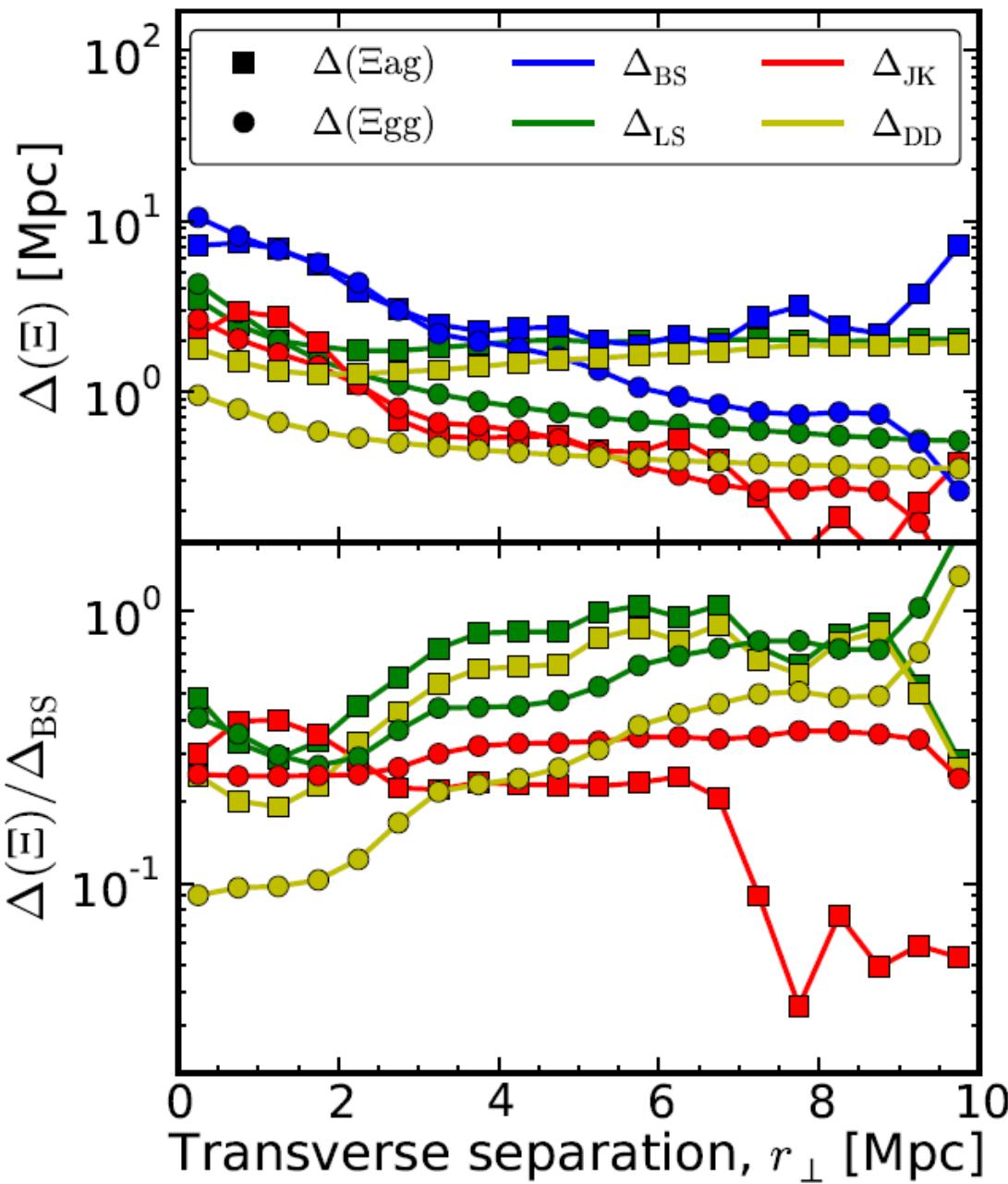
- **Poissonian:**

$$\Delta_{\text{DD}}^2(\xi^{\text{LS}}) = \frac{1 + \xi^{\text{LS}}}{DD}$$

- **Landy & Szalay 1993:**

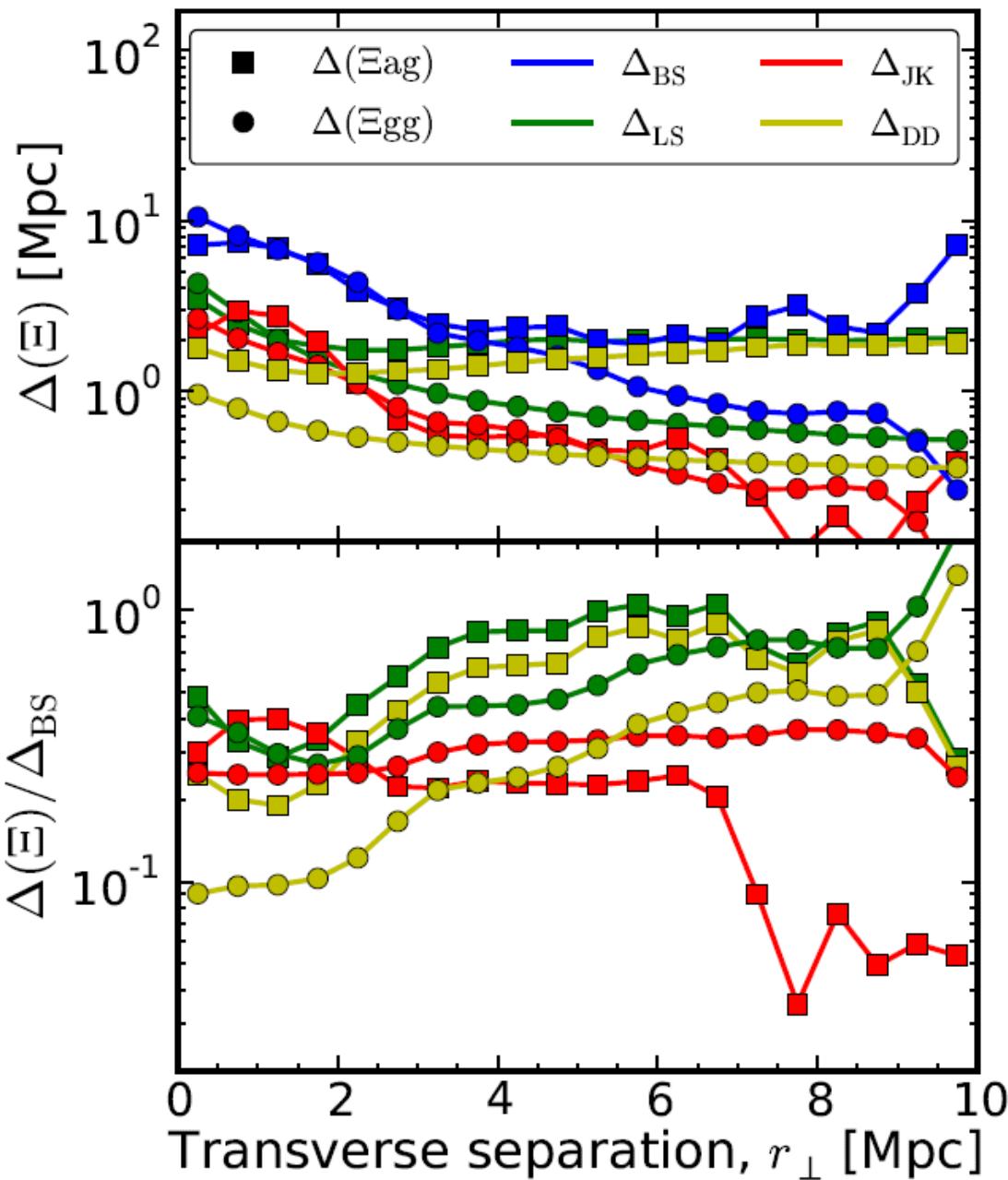
$$\Delta_{\text{LS}}^2(\xi^{\text{LS}}) \approx \frac{(1 + \xi^{\text{LS}})^2}{n_{\text{DD}}(RR/n_{\text{RR}})} \approx \frac{(1 + \xi^{\text{LS}})^3}{DD}$$

Uncertainties



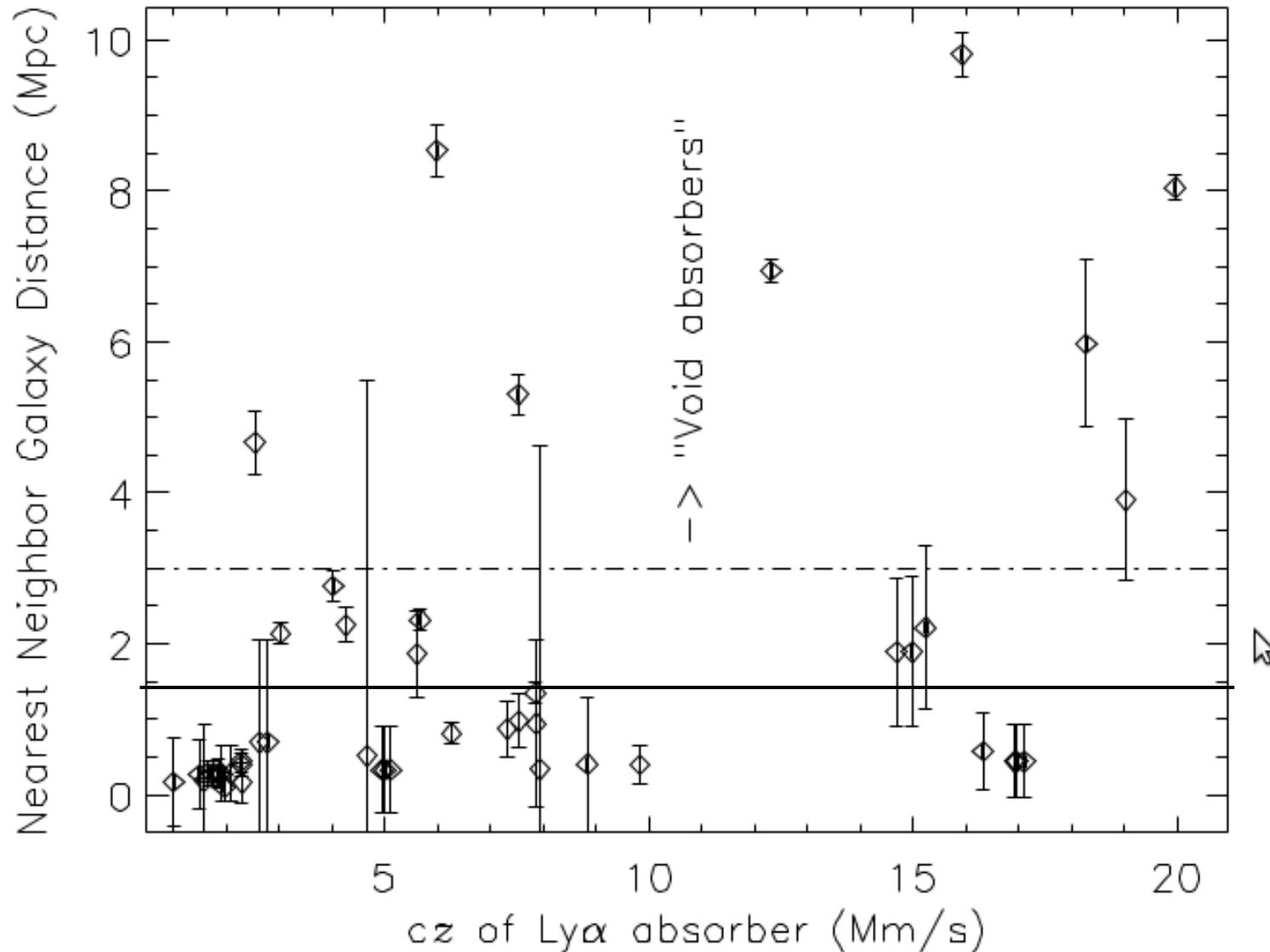
- LS93 preferable over Poissonian.

Uncertainties



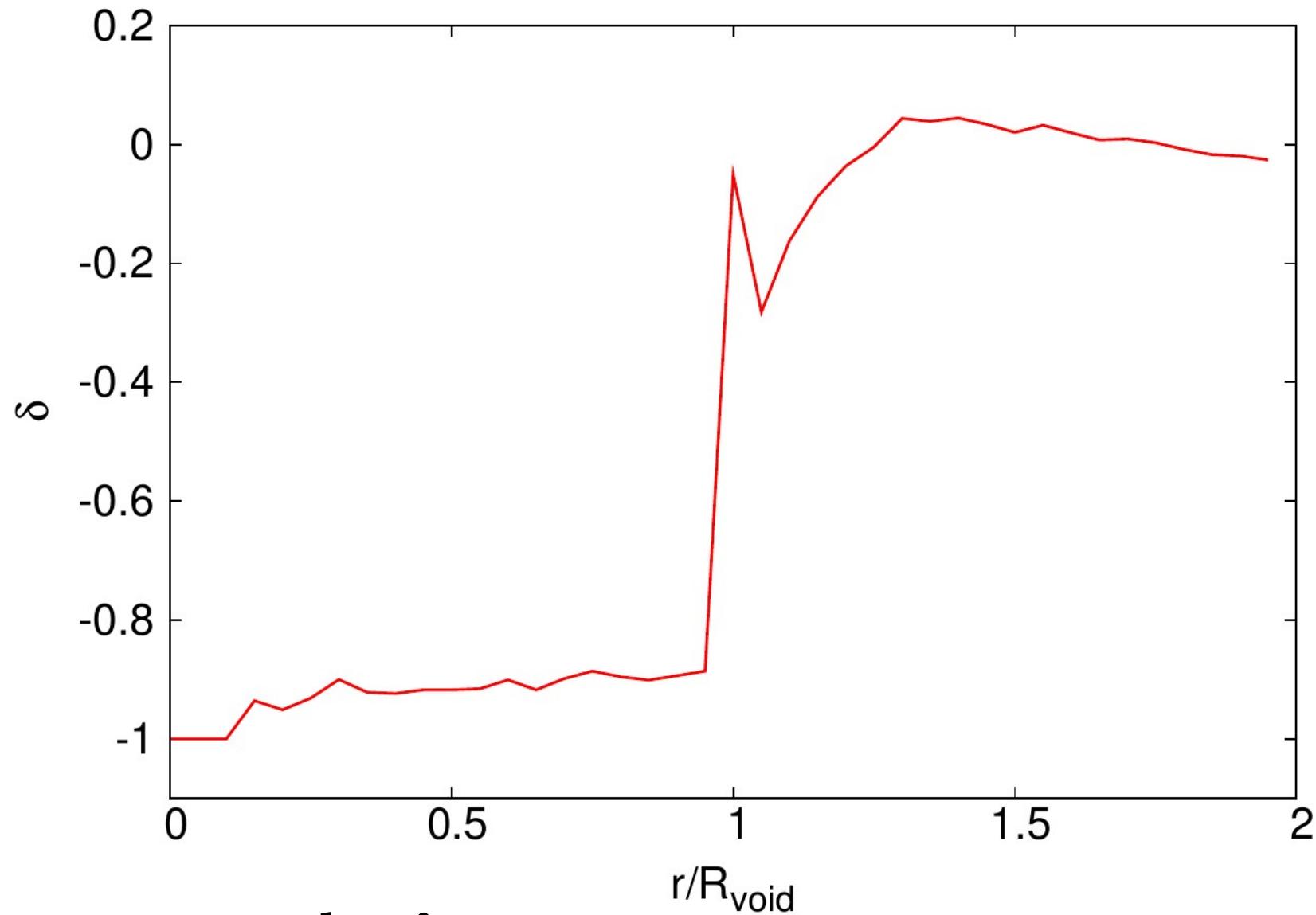
- LS93 preferable over Poissonian.
- We use 'bootstrap' (BS) though.

Previous studies



Penton et al. 2002 (see also Manning 2002, Stocke et al. 2007, Wakker & Savage 2009)

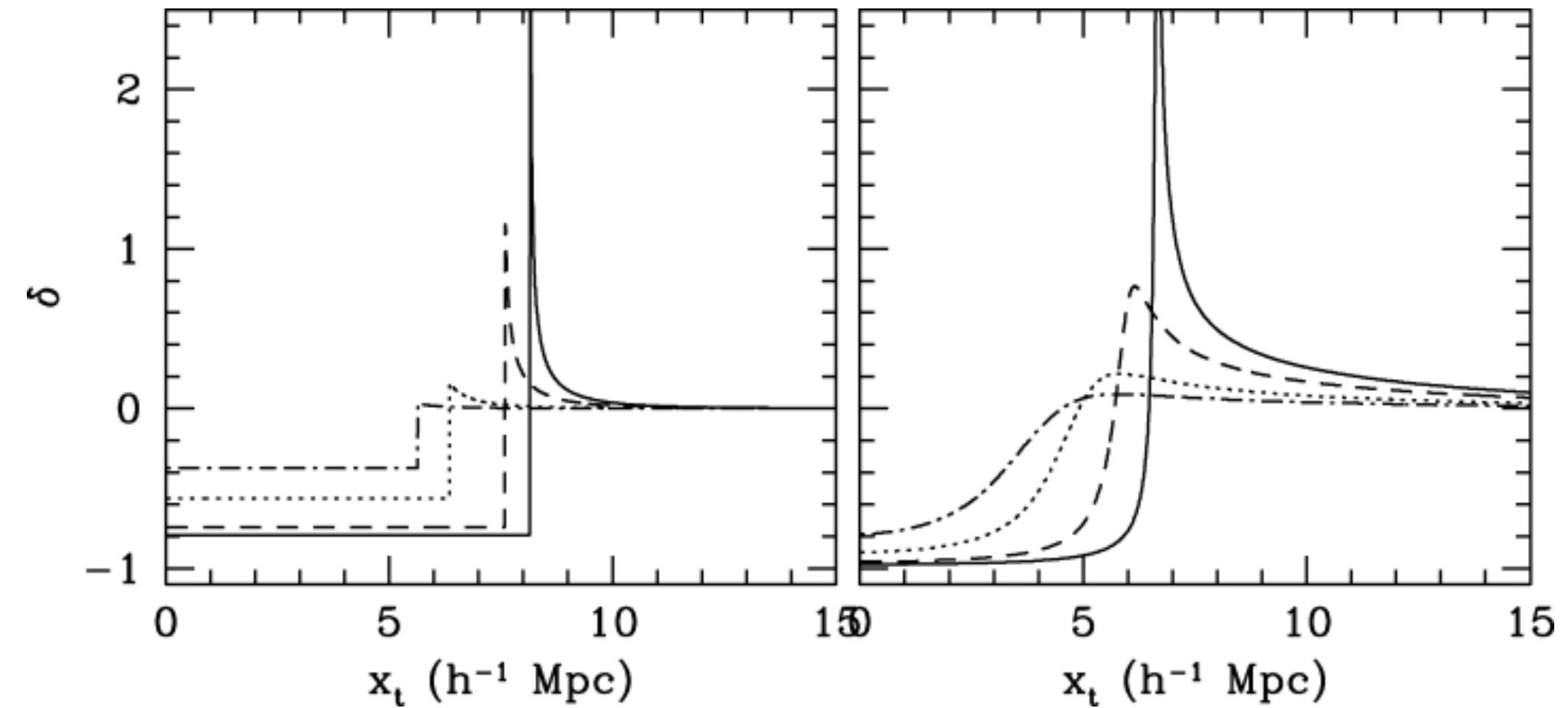
Galaxy void catalog



SDSS galaxies

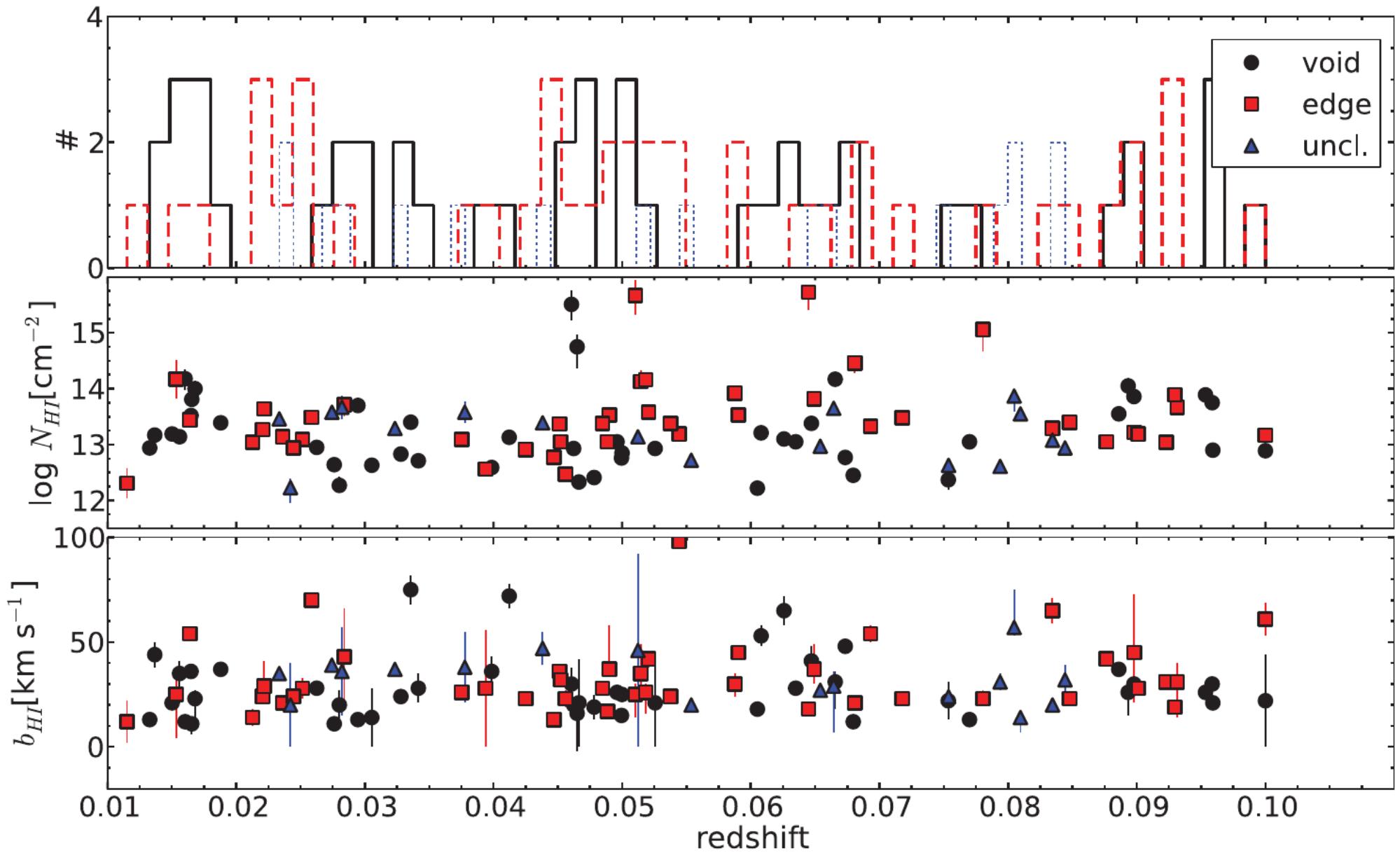
Pan et al. 2012

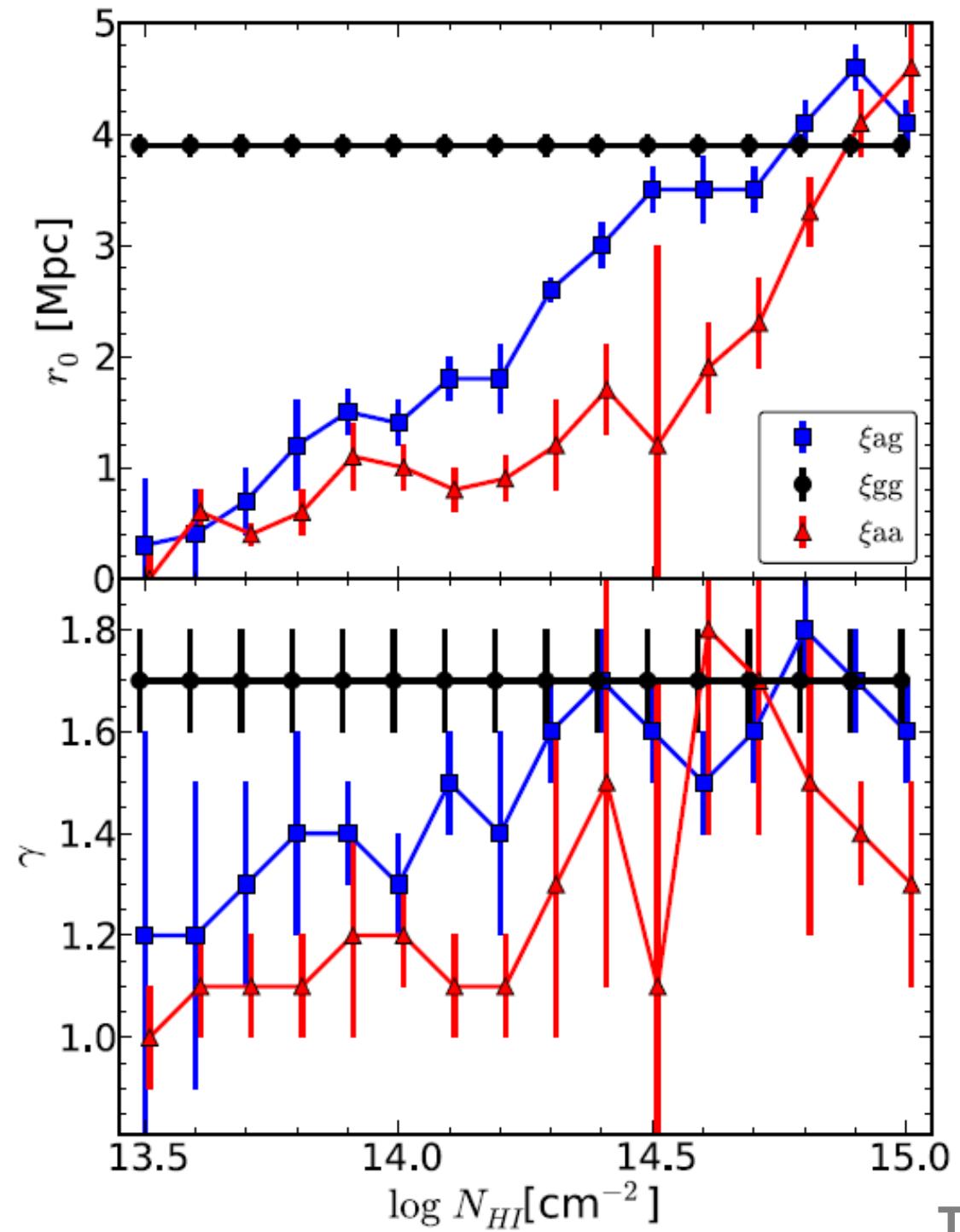
Void density profiles



Sheth & van de Weygaert 2004

Redshift distribution





Tejos et al. 2014