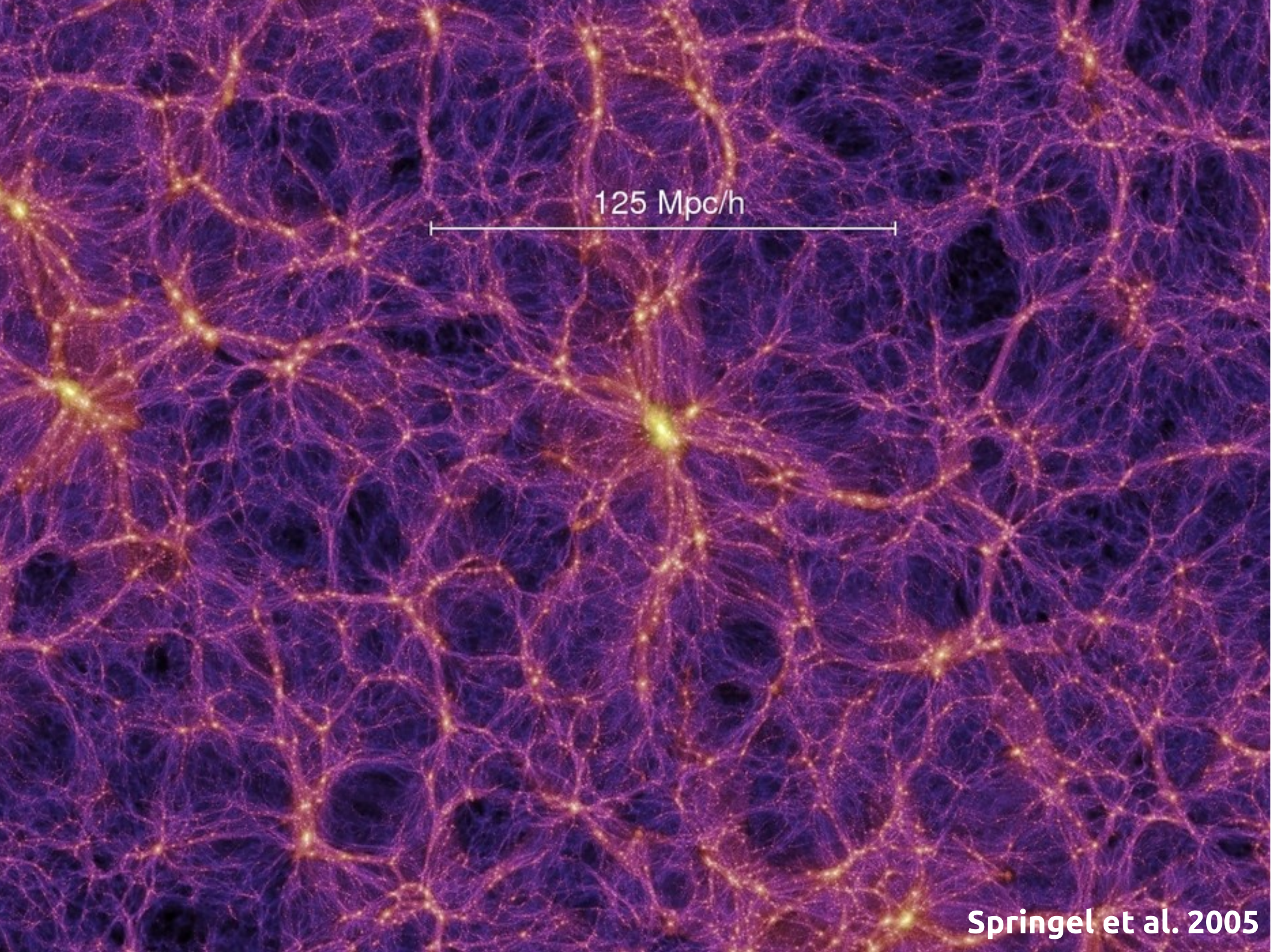


The IGM-galaxy connection

Nicolas Tejos

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



125 Mpc/h

Springel et al. 2005

Outline

- **The IGM-galaxy cross-correlation at $z < 1$**
(Tejos et al. 2013, in prep.)
- **The IGM within and around galaxy voids at $z < 0.1$**
(Tejos et al. 2012, MNRAS, 425, 245)
- **Conclusions**

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:**

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

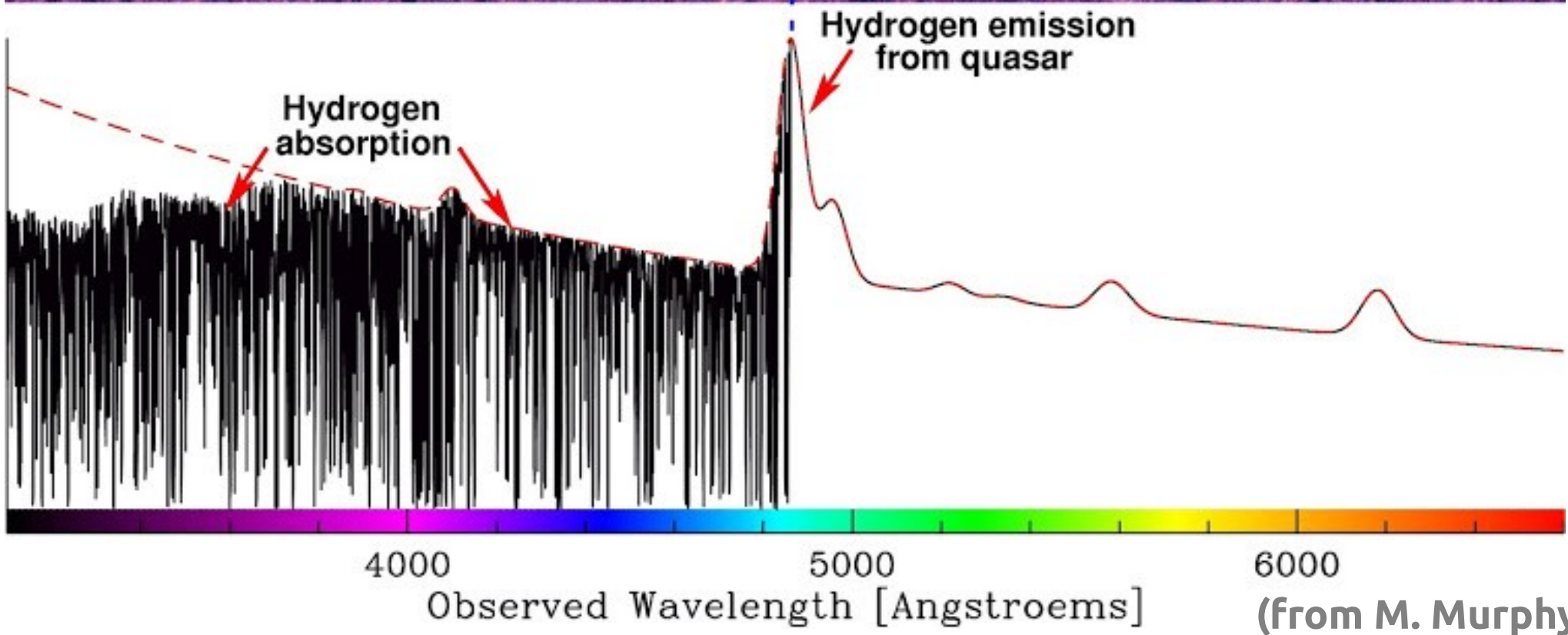
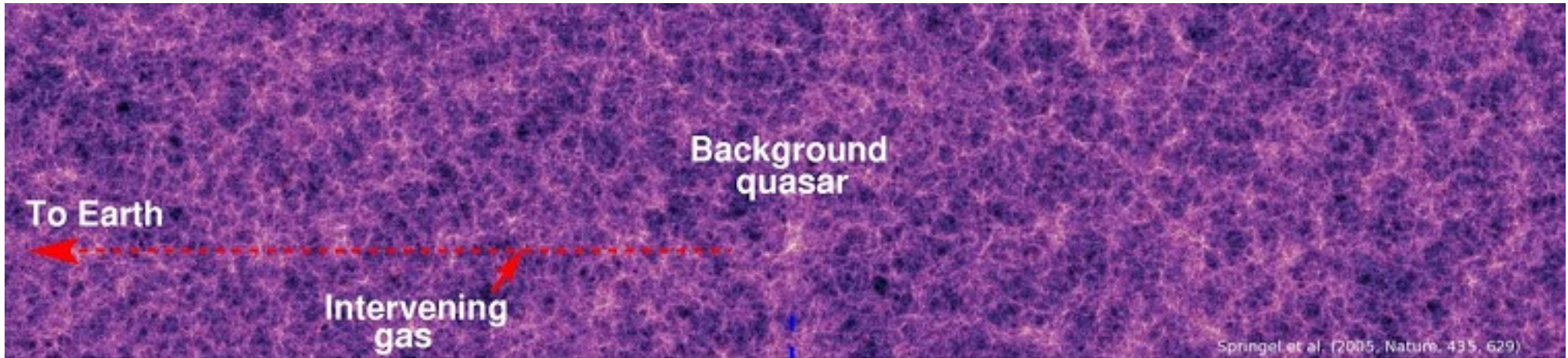
e.g. Peebles 1980

- **Estimator:**

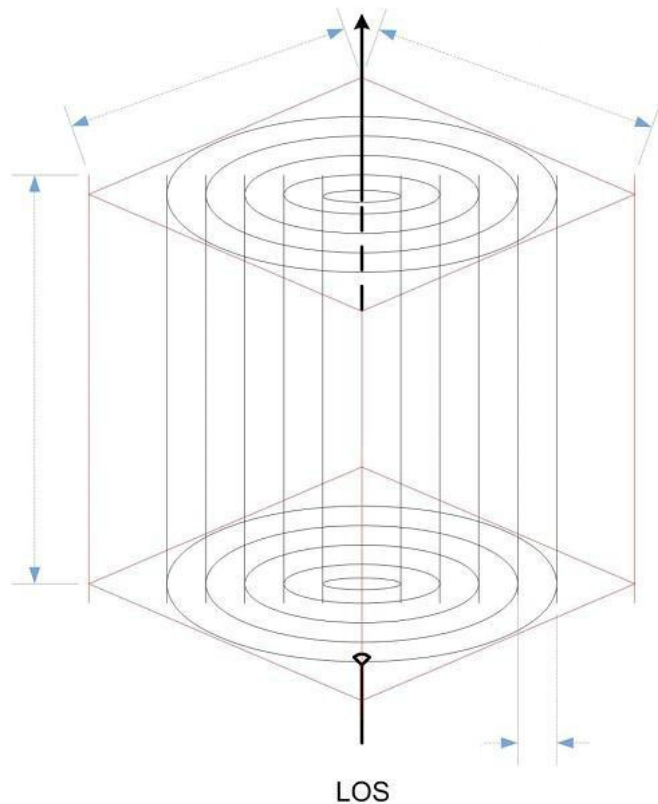
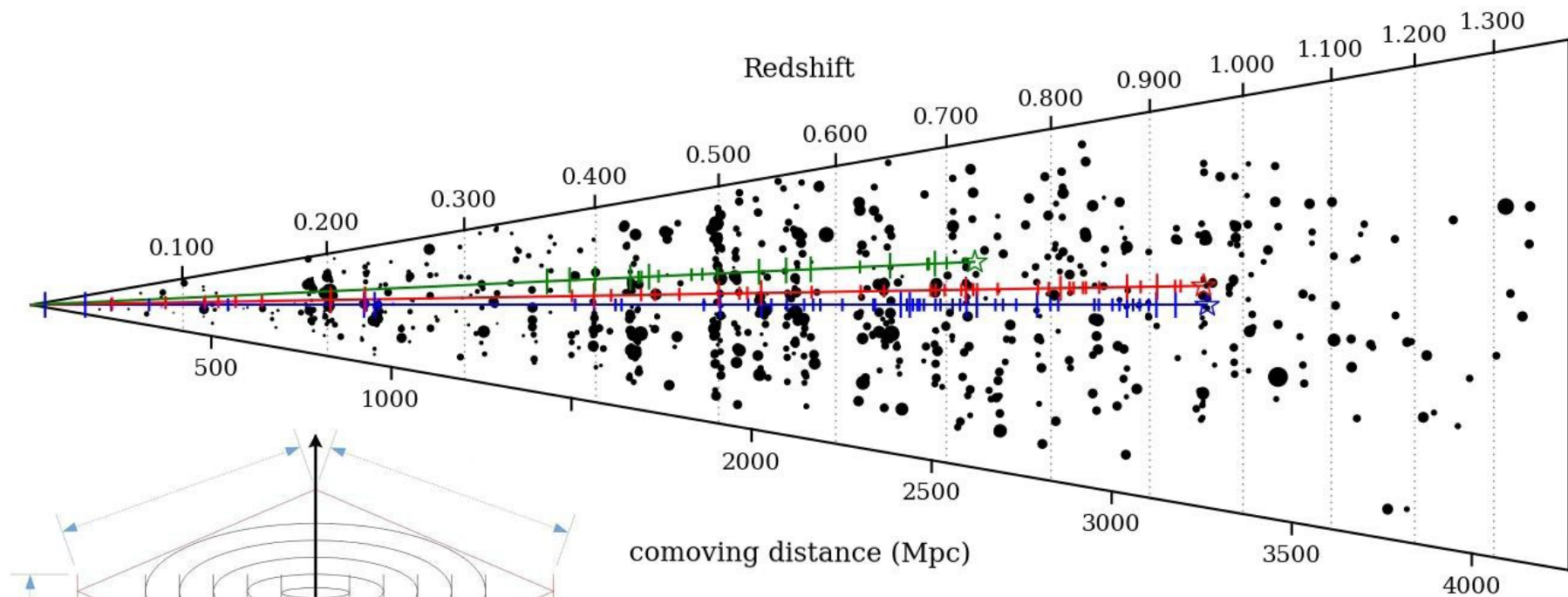
$$\hat{\xi}_{LS} \equiv \frac{D_a D_b - D_a R_b - R_a D_b + R_a R_b}{R_a R_b}$$

Landy & Szalay 1993

How do we observe the IGM

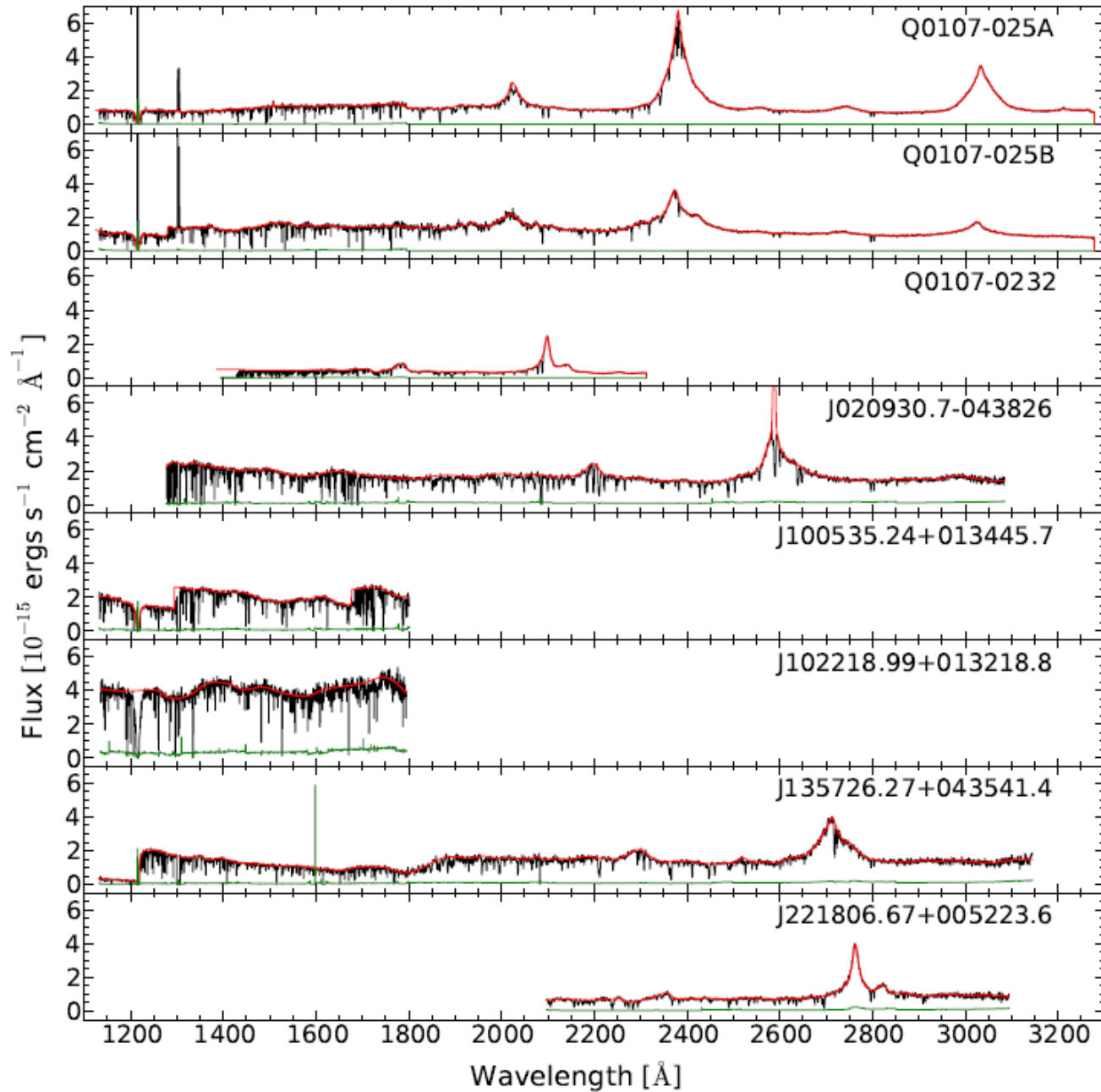


Survey geometry



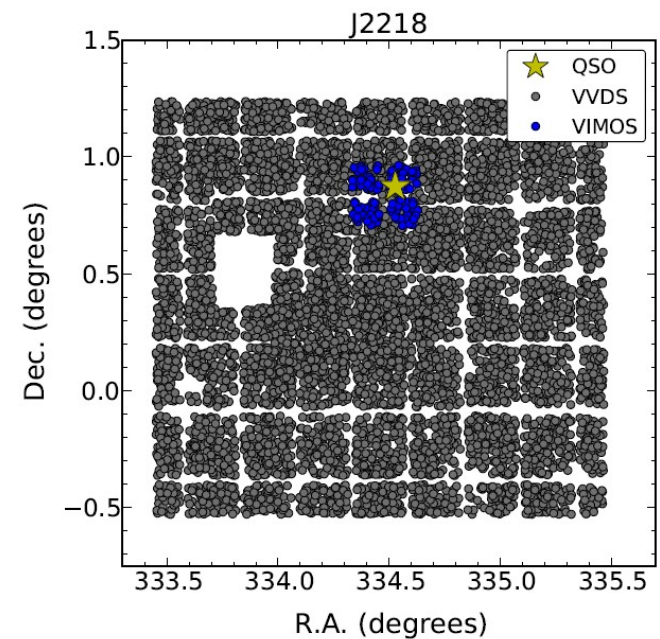
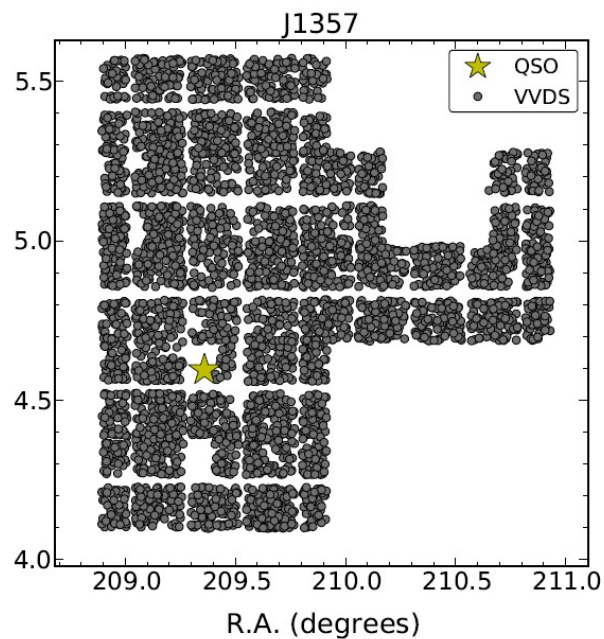
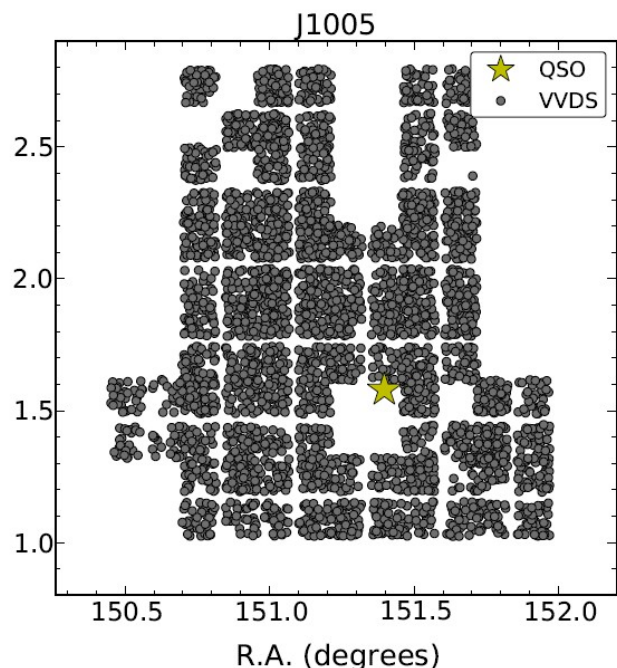
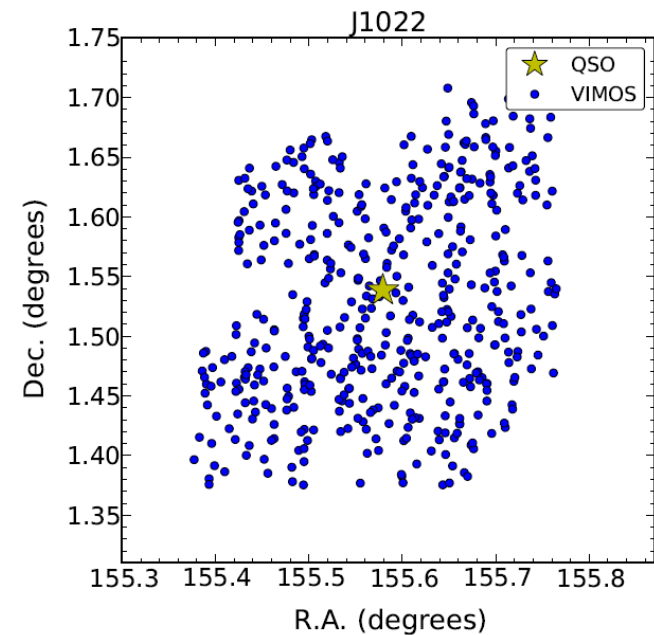
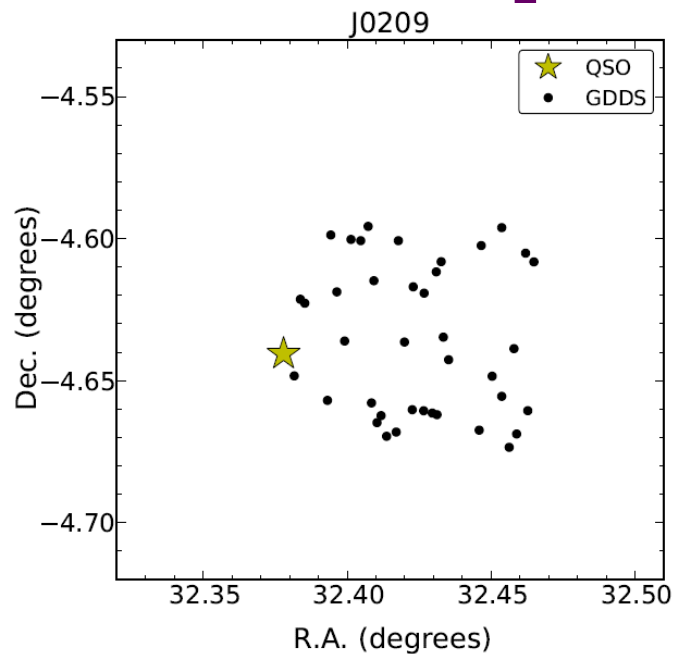
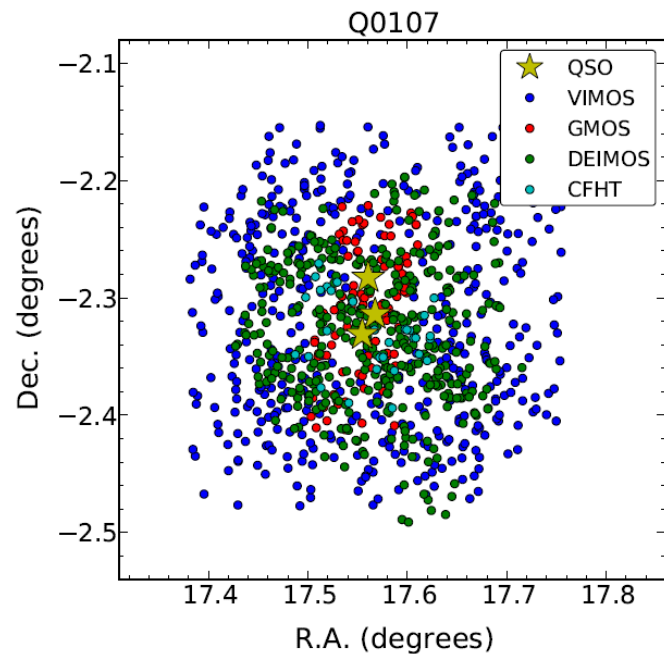
VLT/VIMOS
Keck/DEIMOS
Gemini/GMOS

Our sample



HST/COS
HST/FOS

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

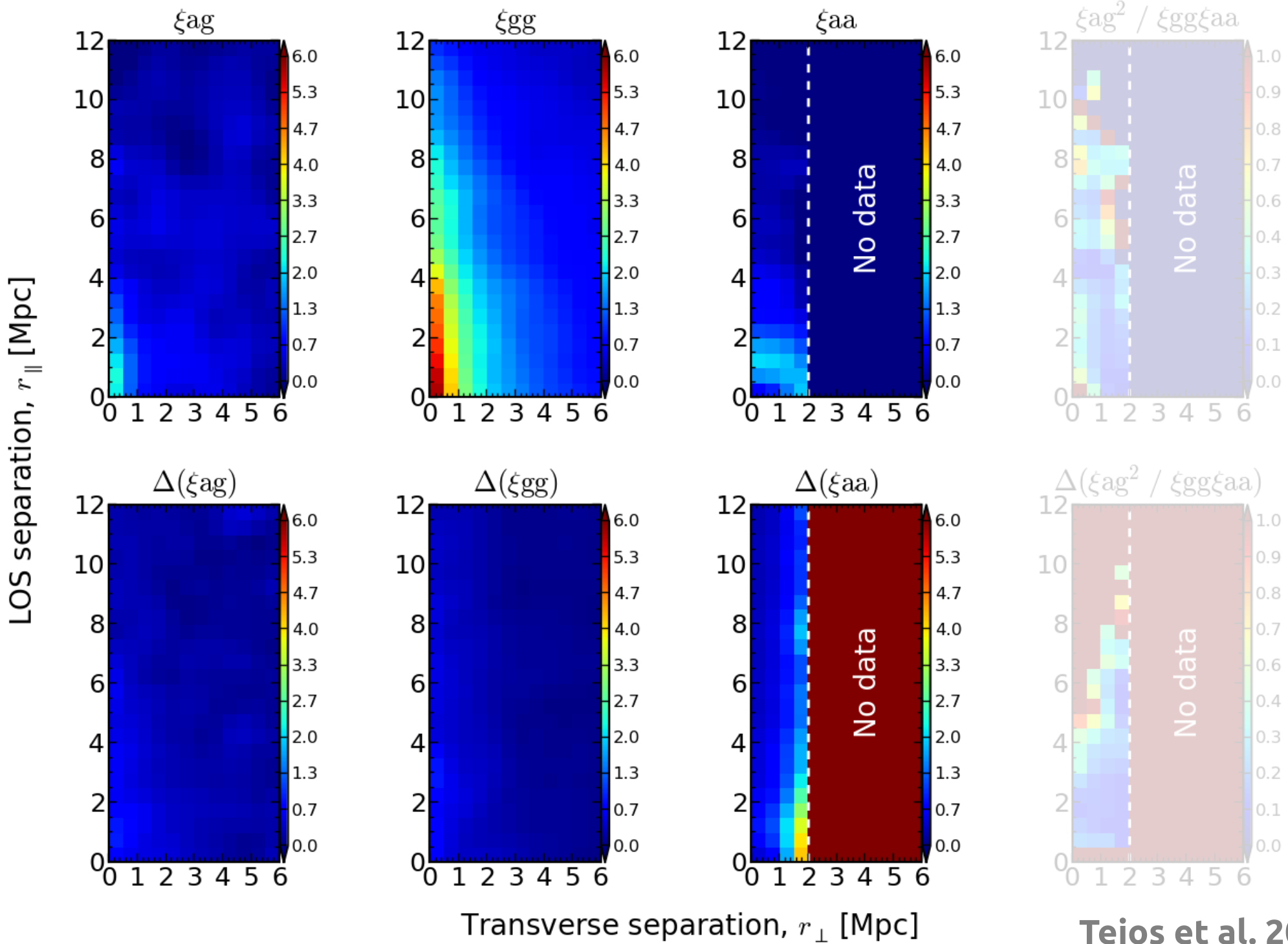
$$10^{14} \leq N_{\text{HI}} \lesssim 10^{17} \text{ cm}^{-2} \text{ (‘strong’)}$$

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

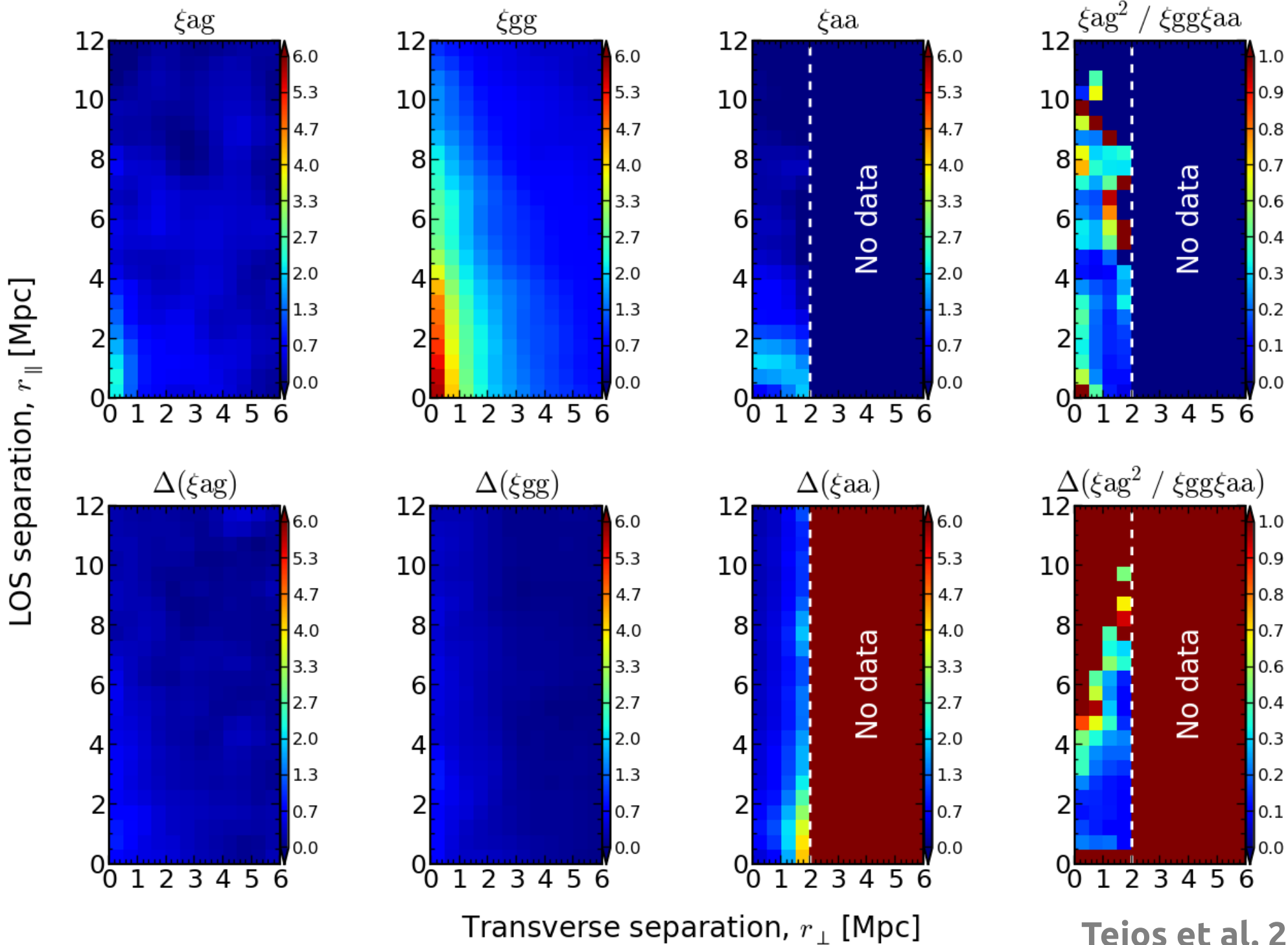
Results

Full Sample

Full Sample



Full Sample



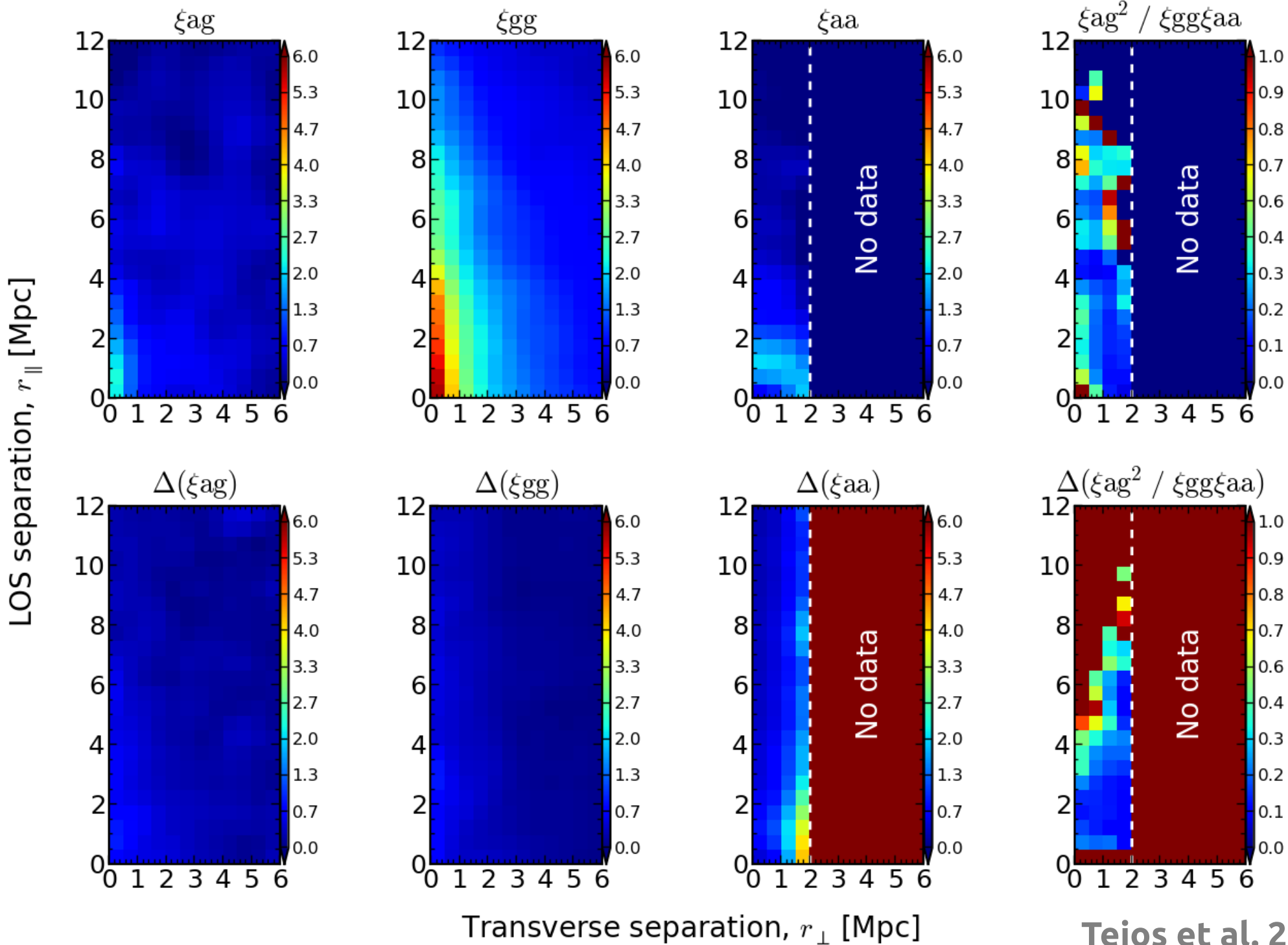
Linear dependence

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

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

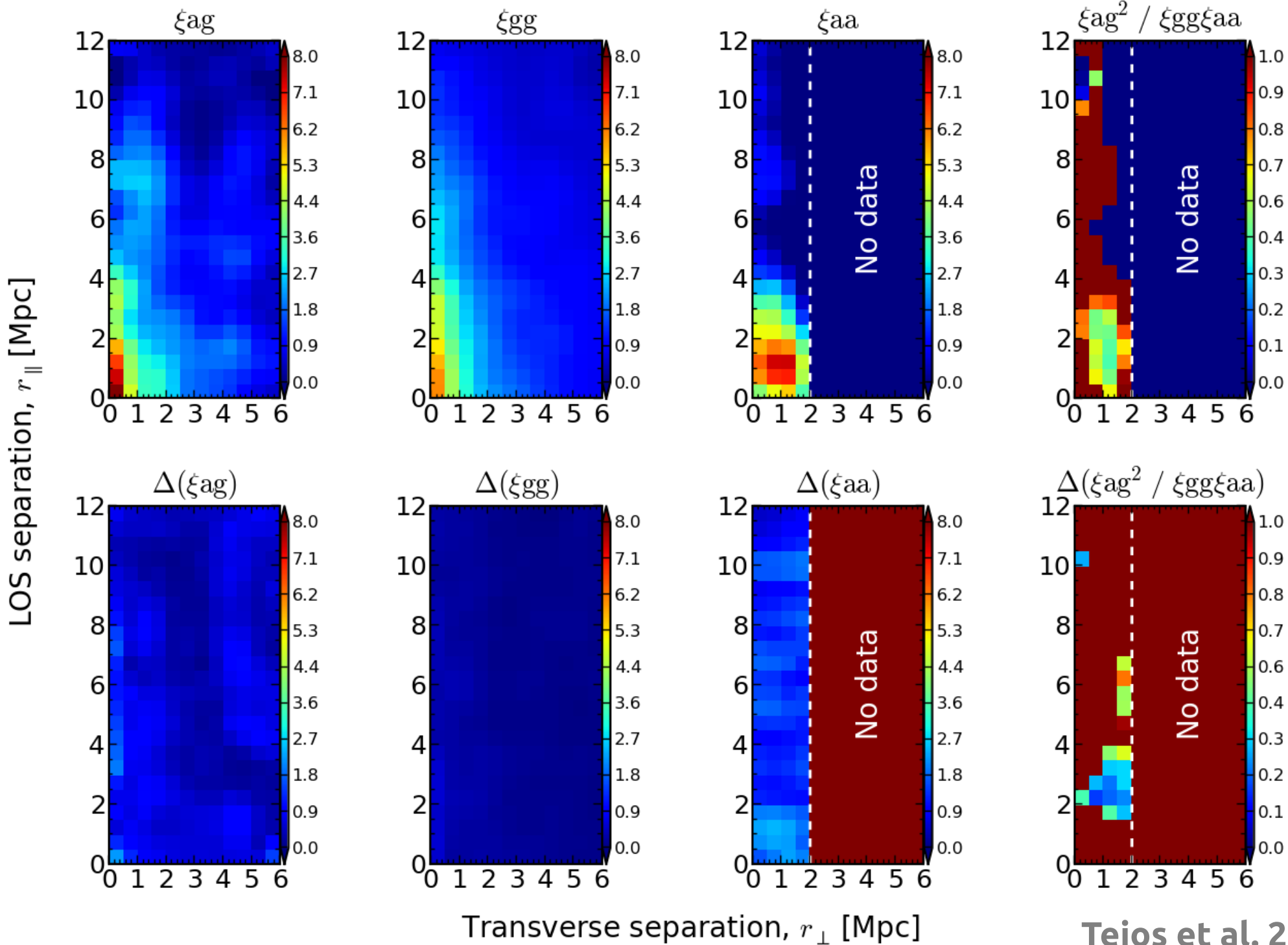
$$\xi_{ag} = b_a b_b \xi_{DM}$$

Full Sample

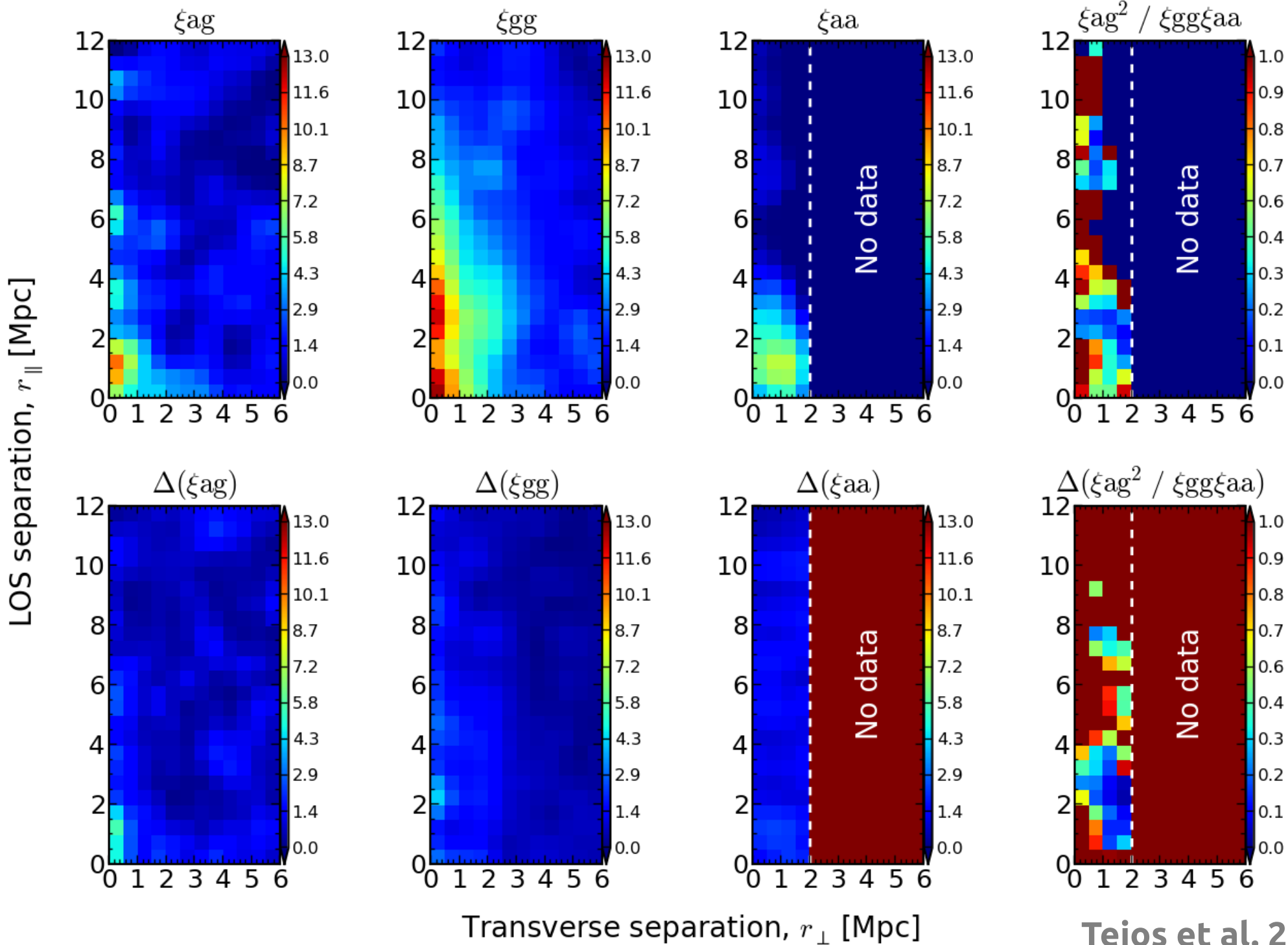


Strong HI + galaxies

$SF, \log N \geq 14.0$

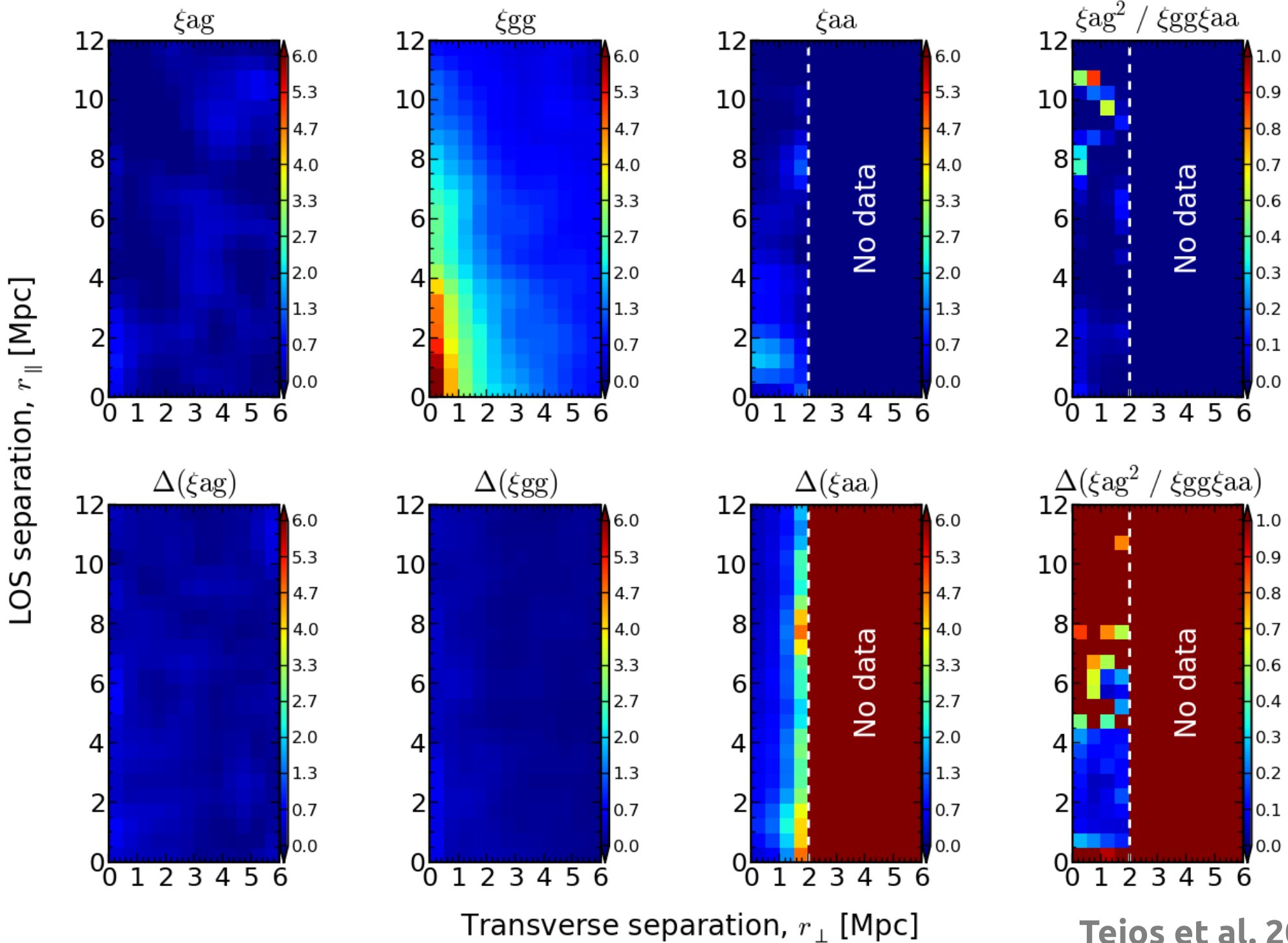


non-SF, logN ≥ 14.0

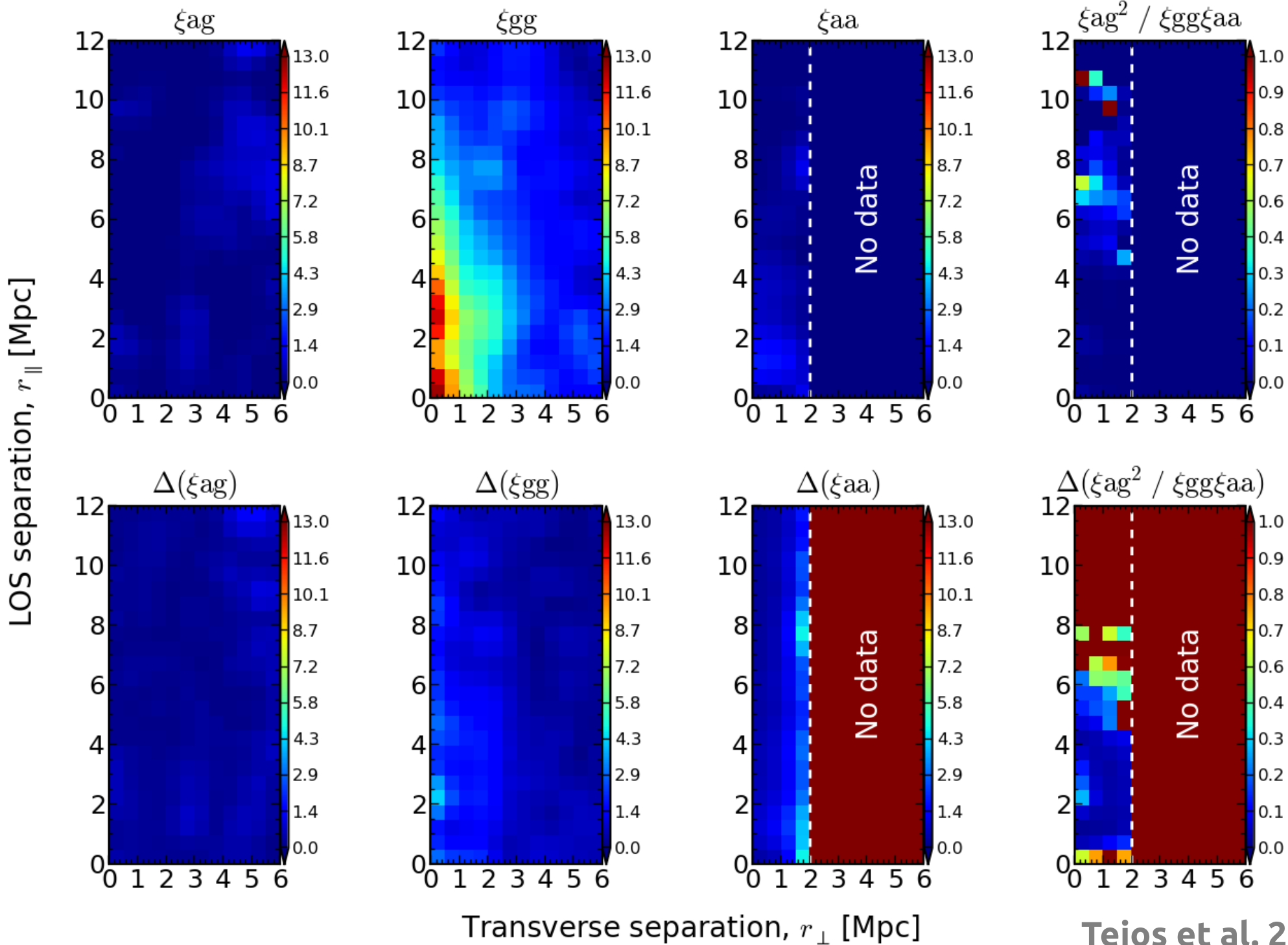


Weak HI + galaxies

$SF, \log N < 14.0$



non-SF, logN < 14.0



Projected along LOS

Results

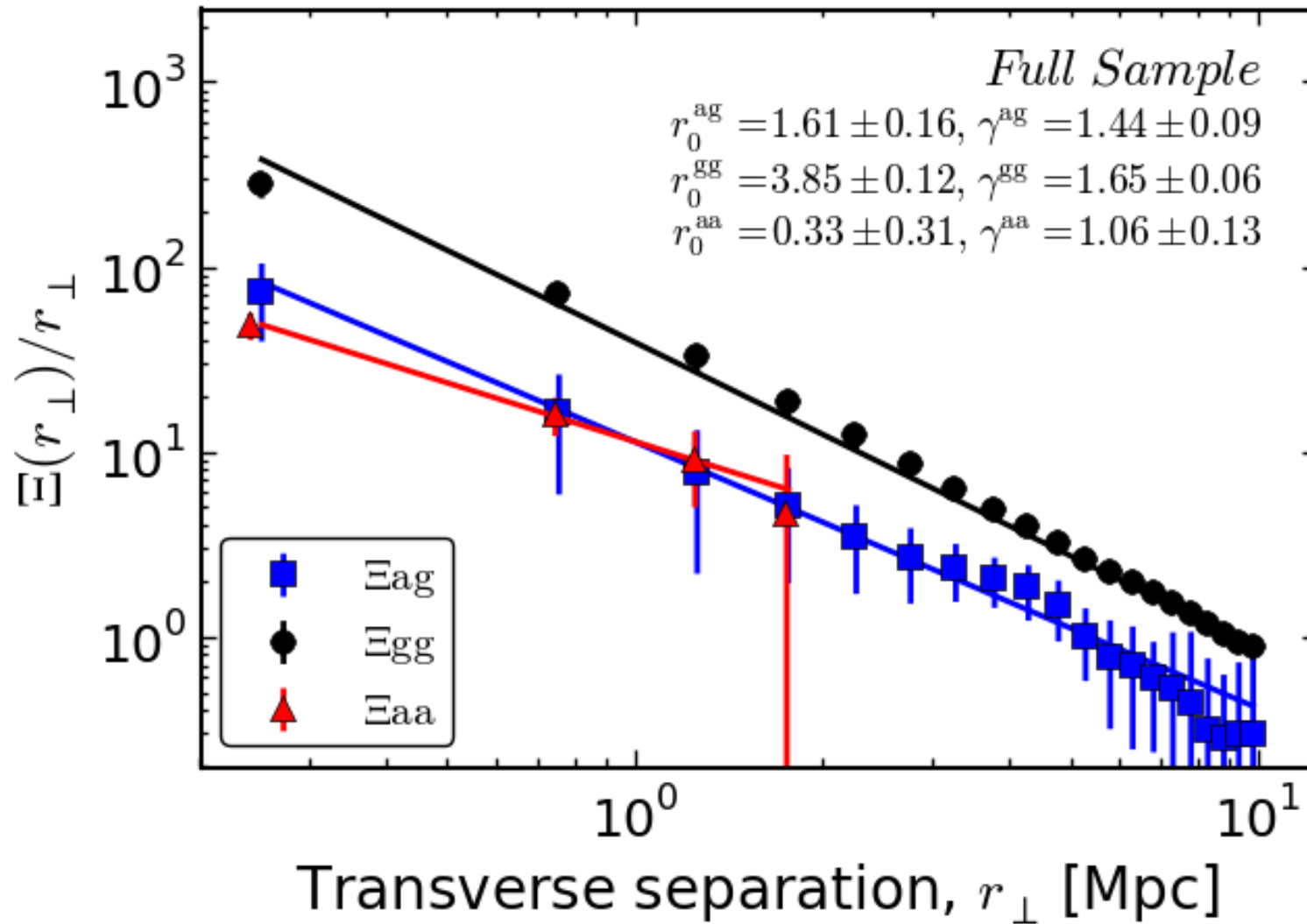
- **Projected along the LOS:**

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

- **Real space:**

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

Results

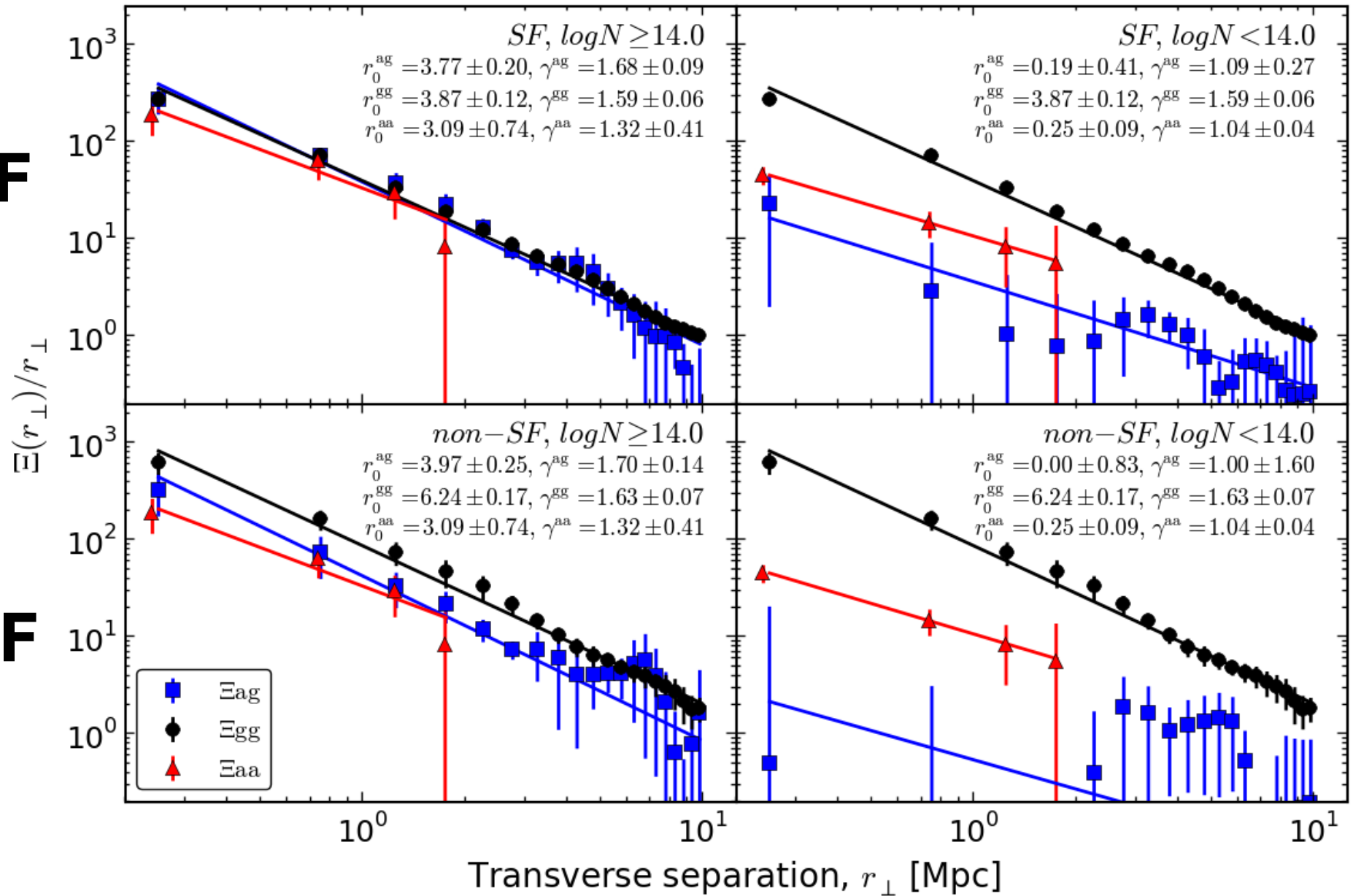


Subsamples

Strong HI

Weak HI

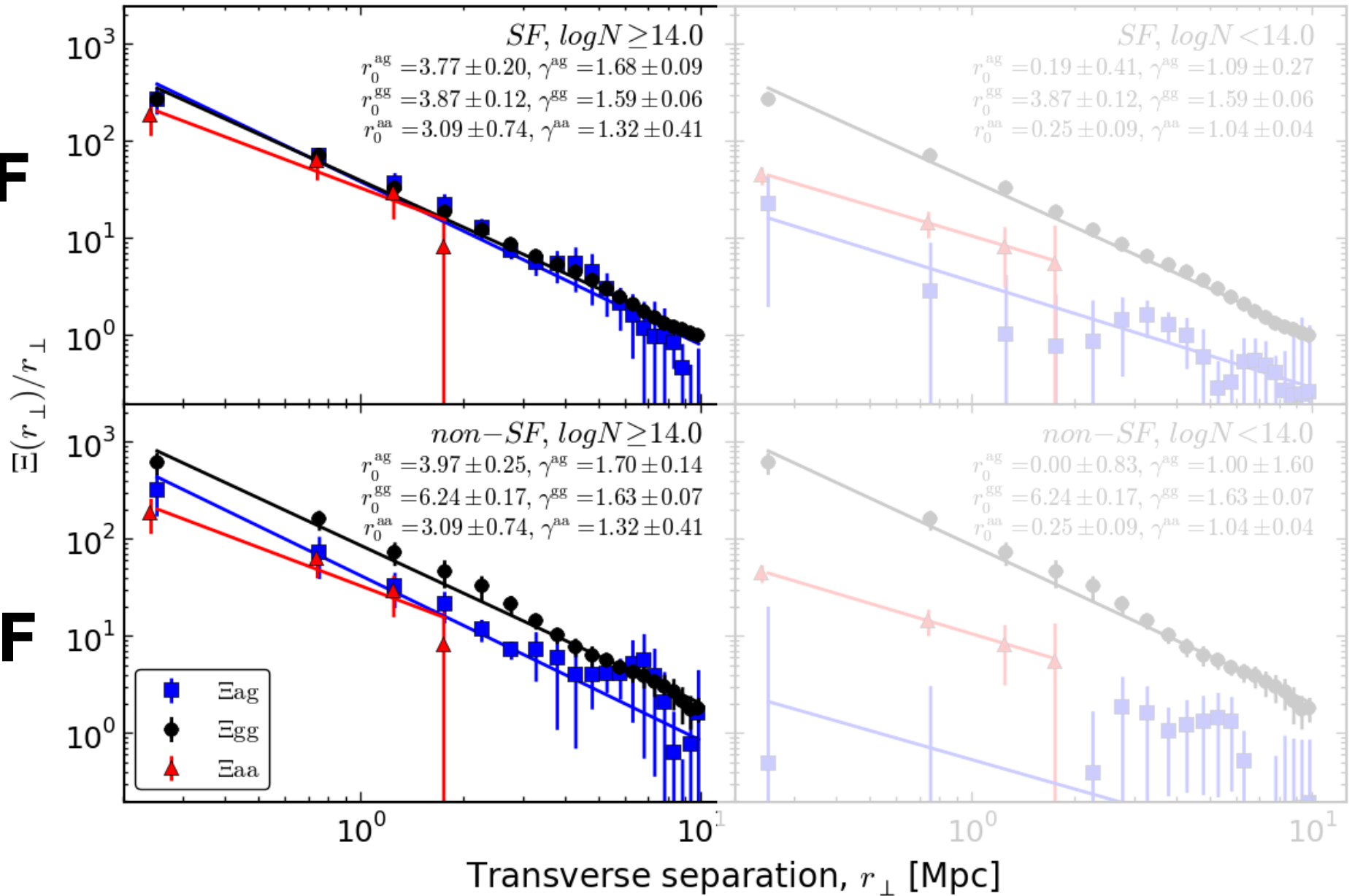
SF



Strong HI

Weak HI

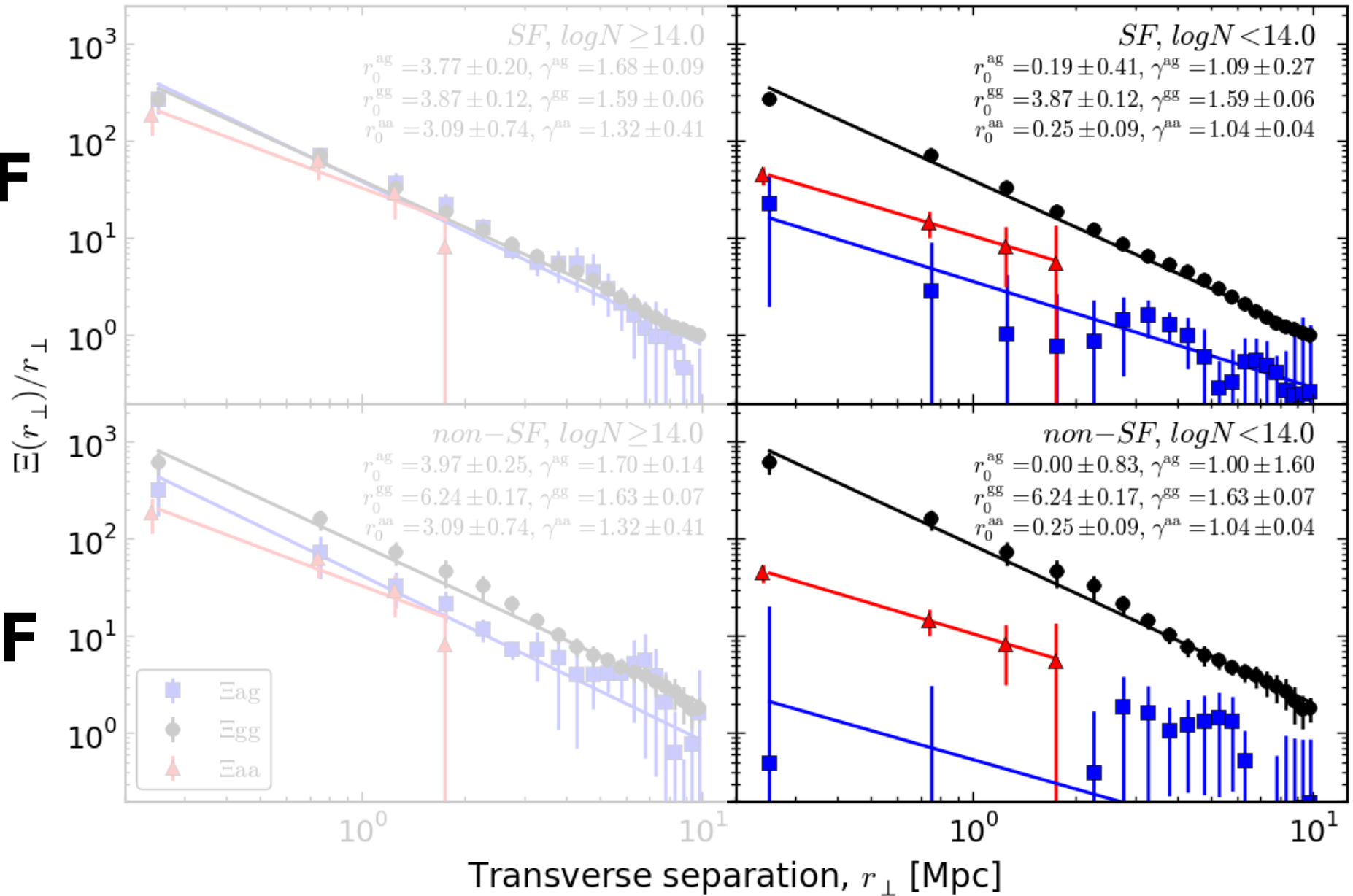
SF



Strong HI

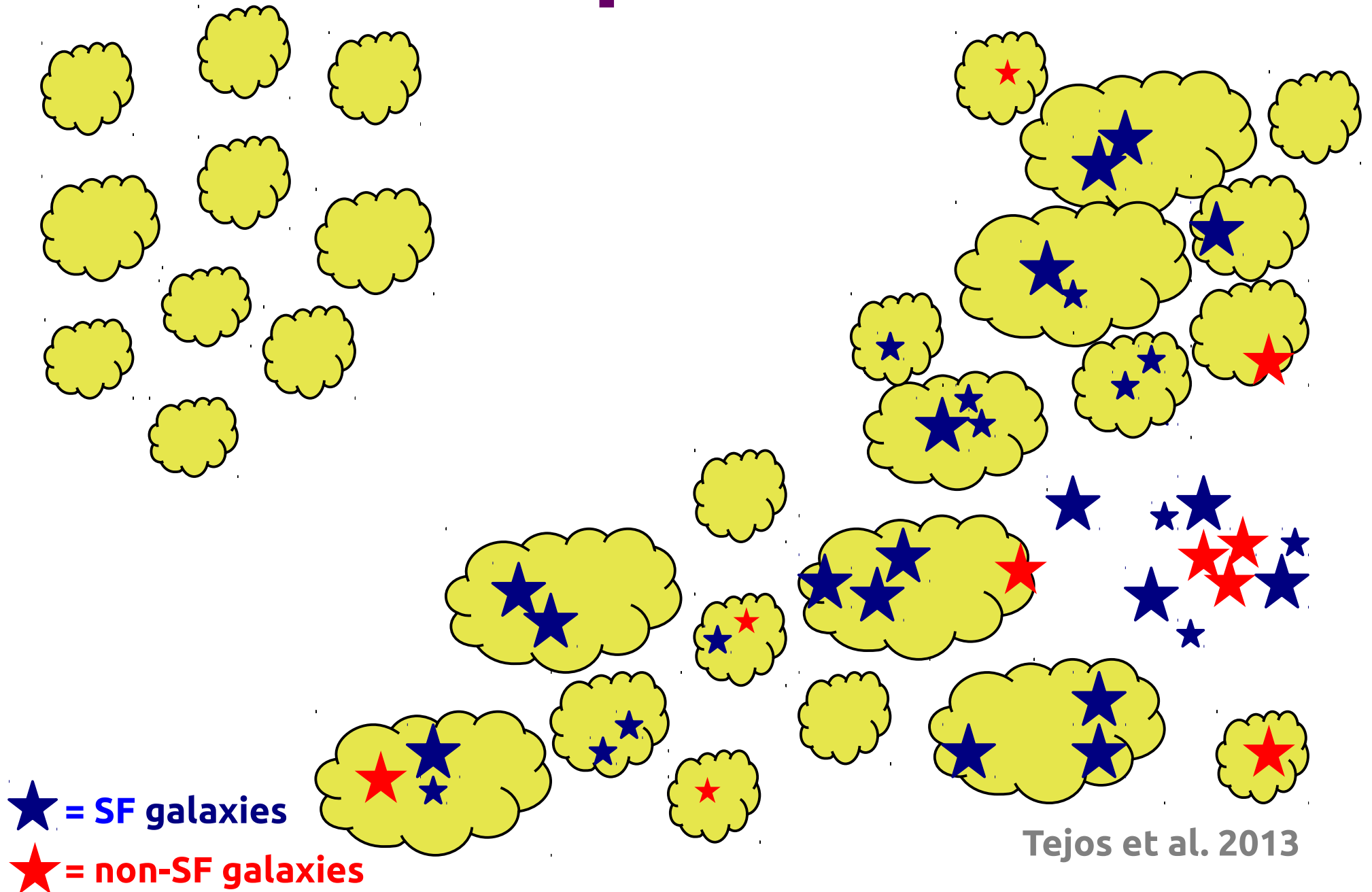
Weak HI

SF

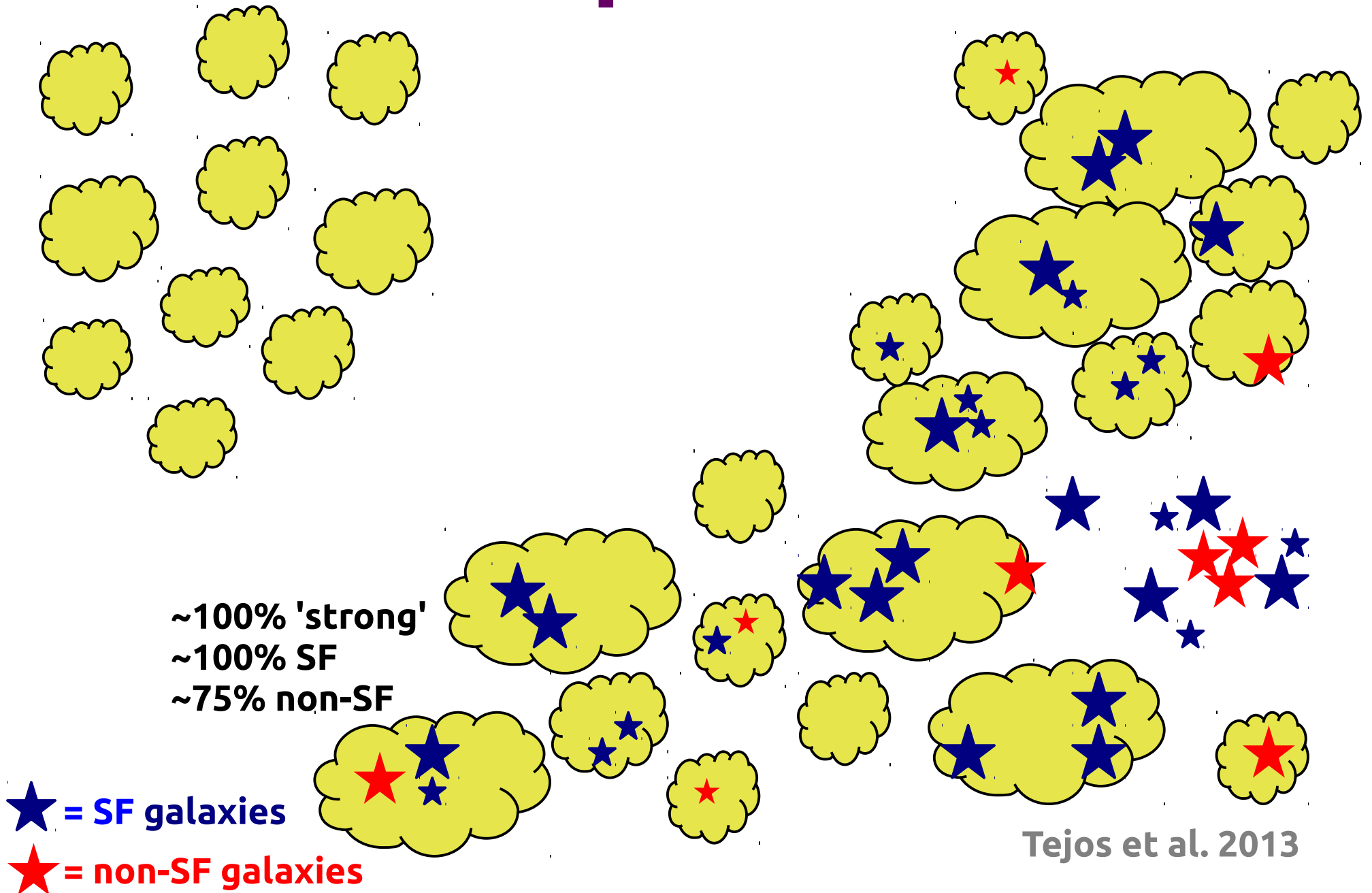


Interpretation

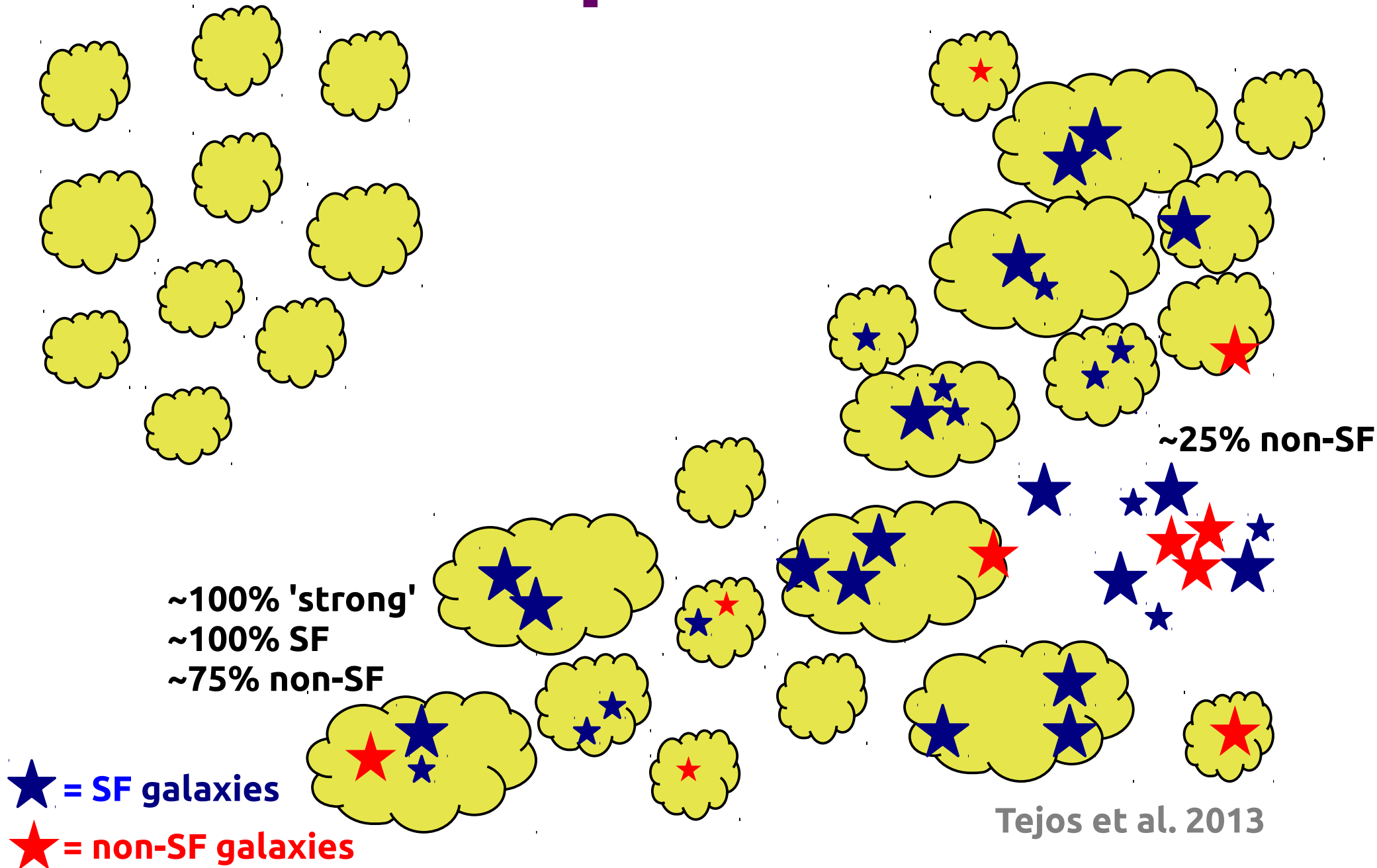
Interpretation (not to scale)



Interpretation (not to scale)

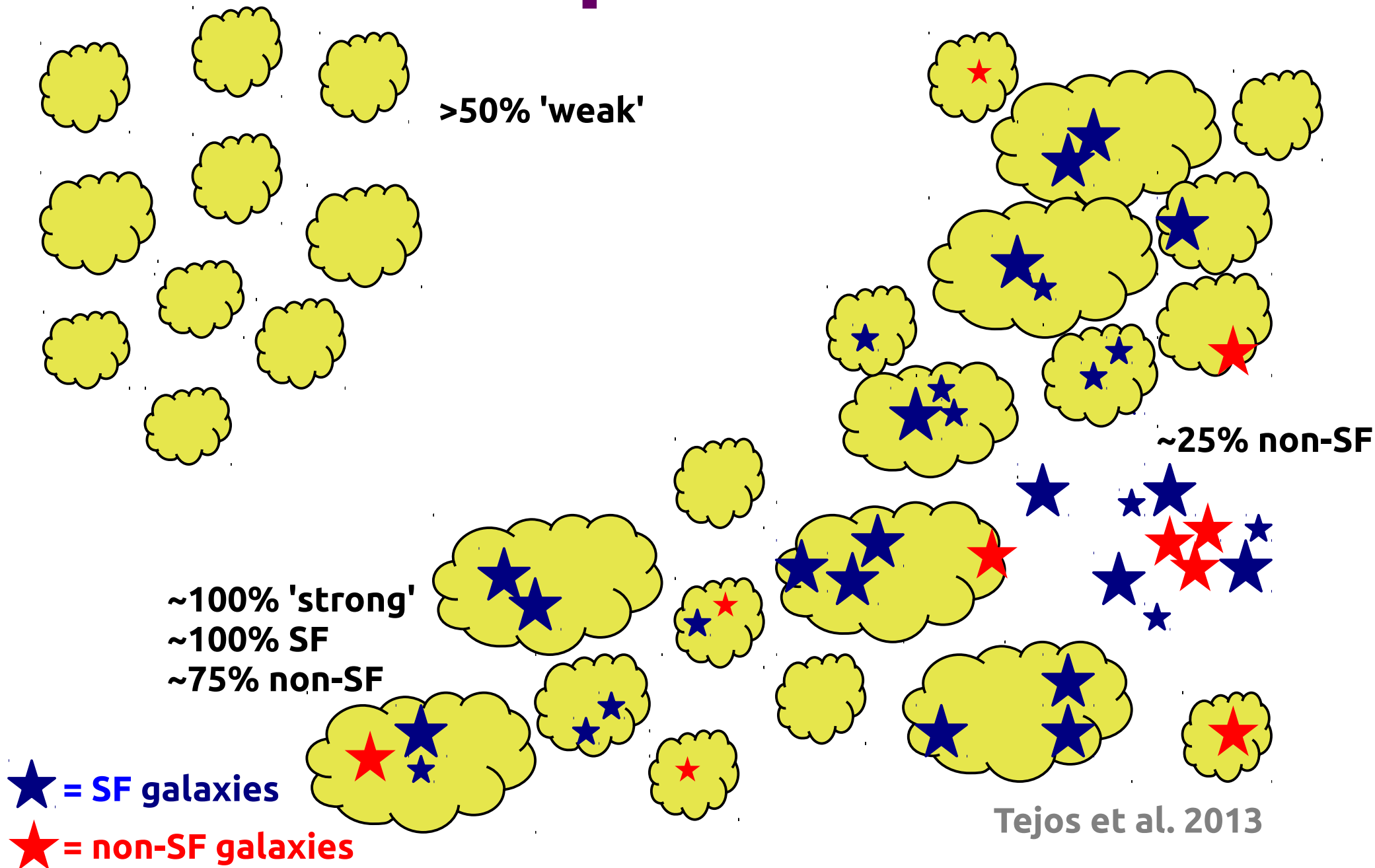


Interpretation (not to scale)



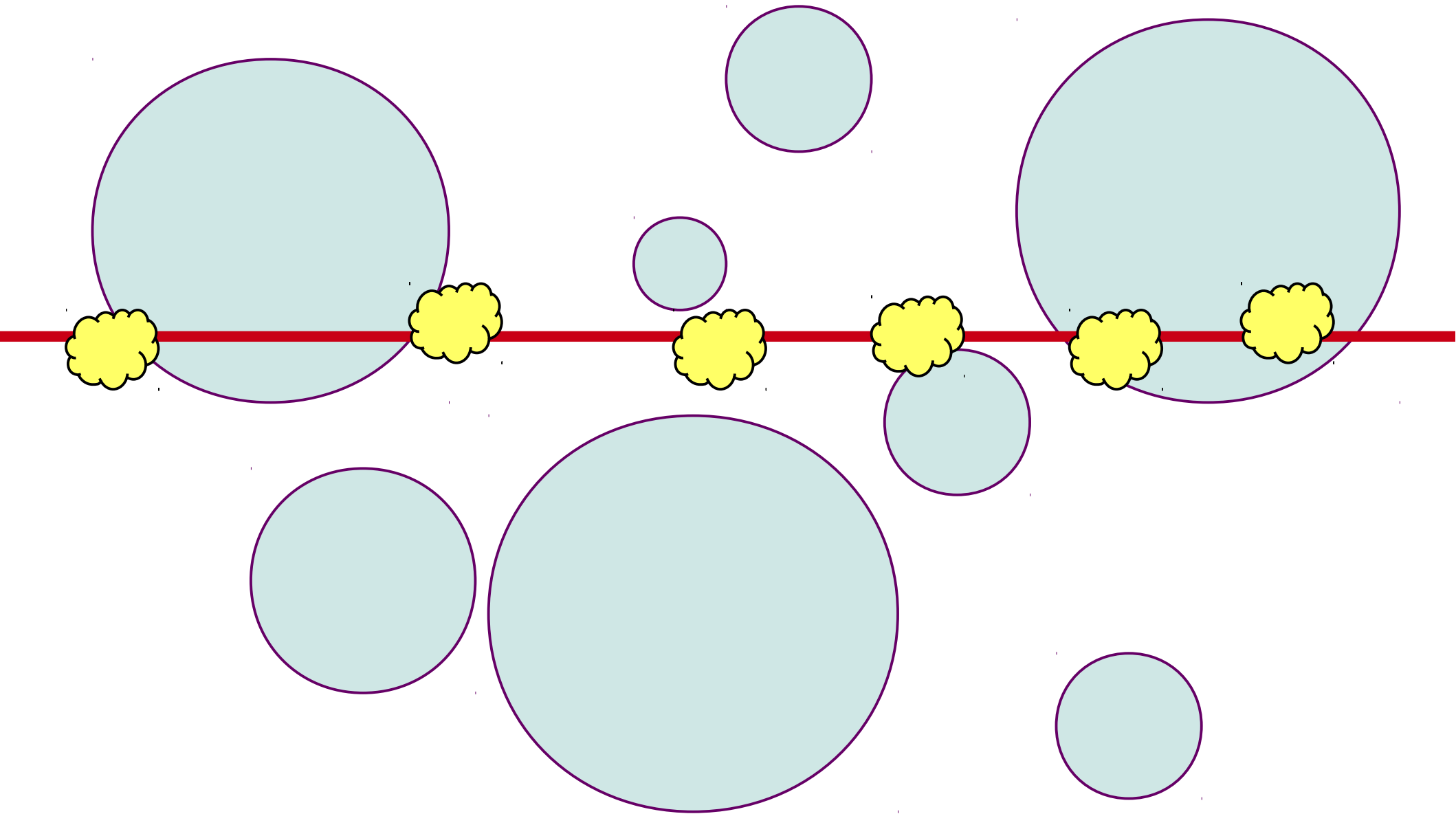
Interpretation

(not to scale)

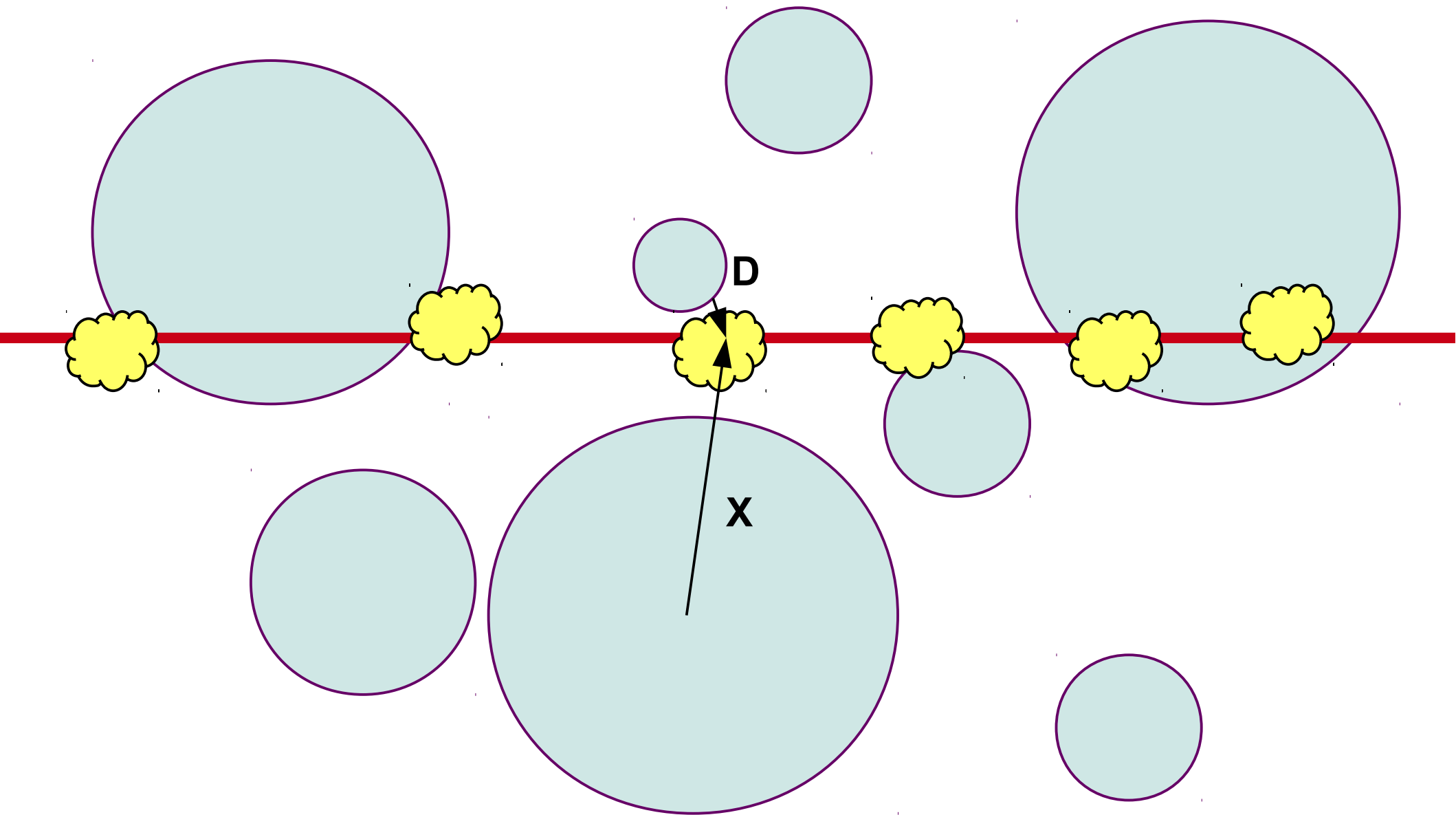


IGM in galaxy voids

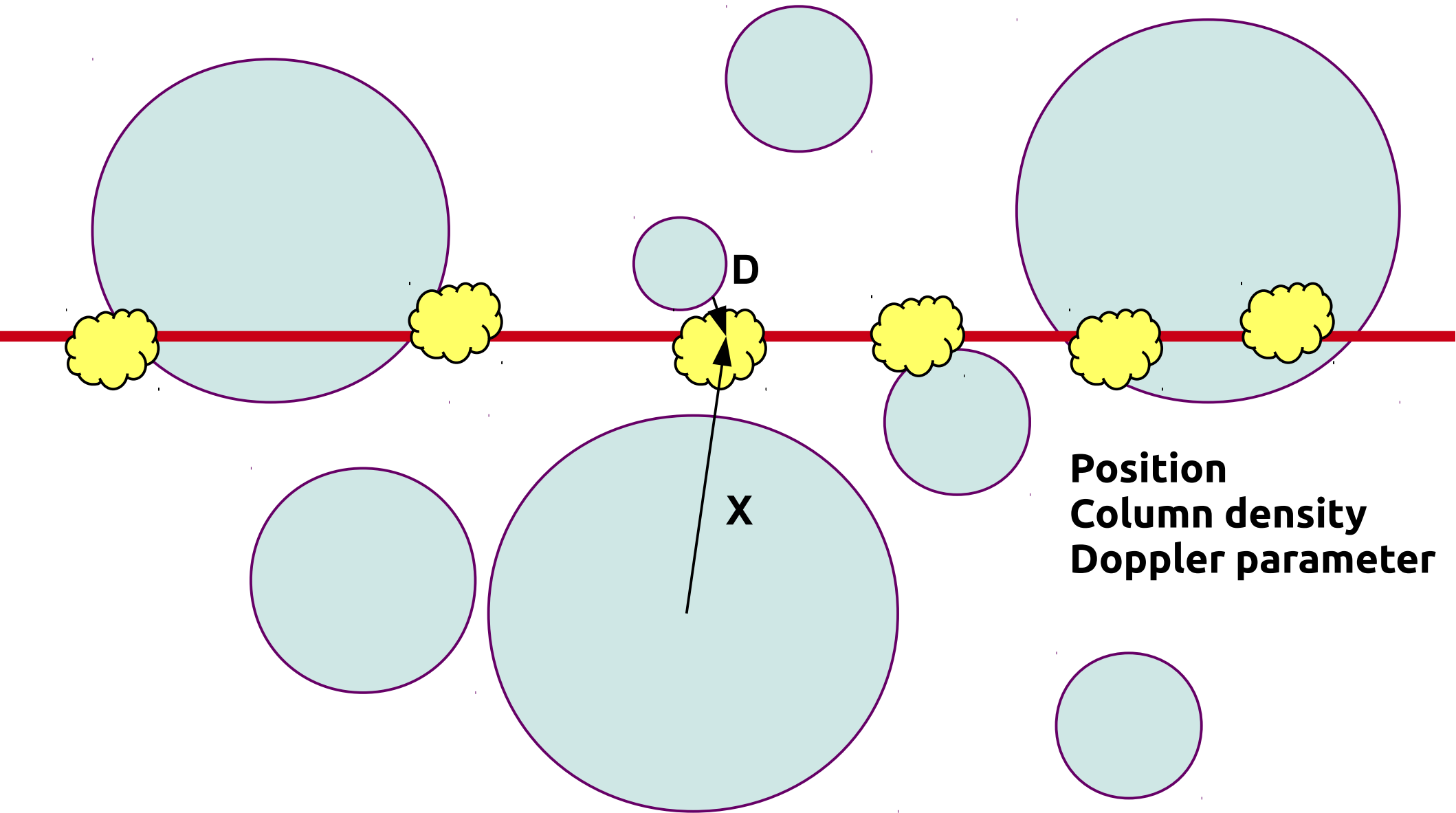
IGM in galaxy voids



IGM in galaxy voids

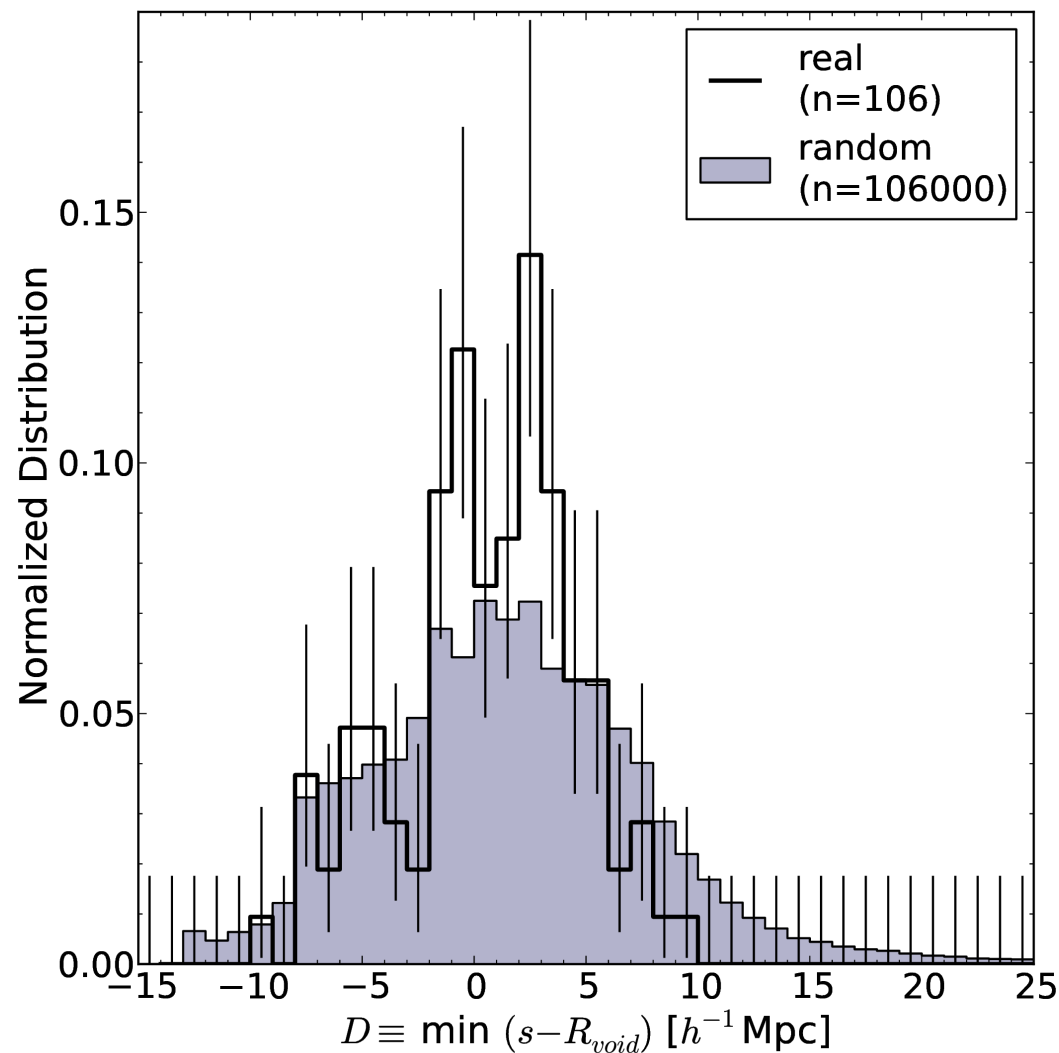
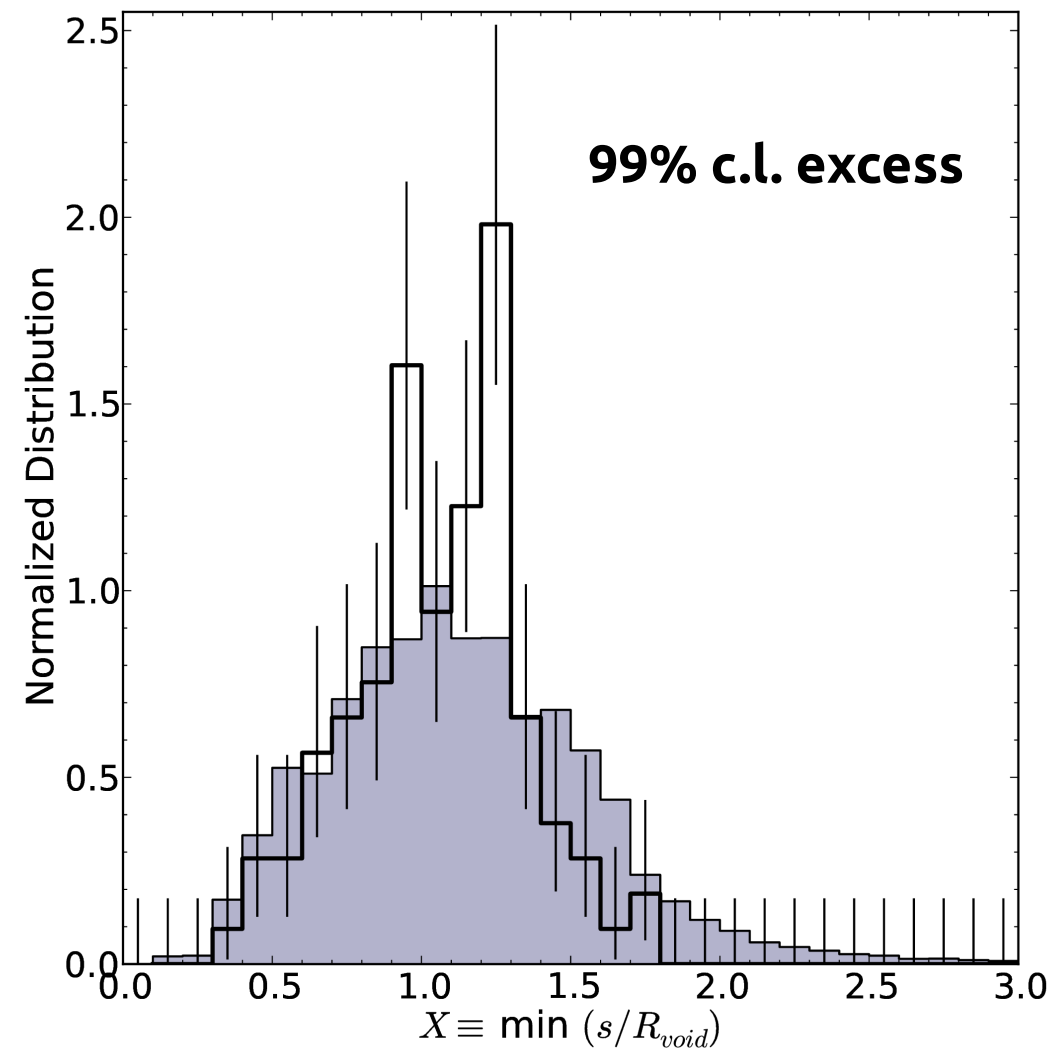


IGM in galaxy voids



Results

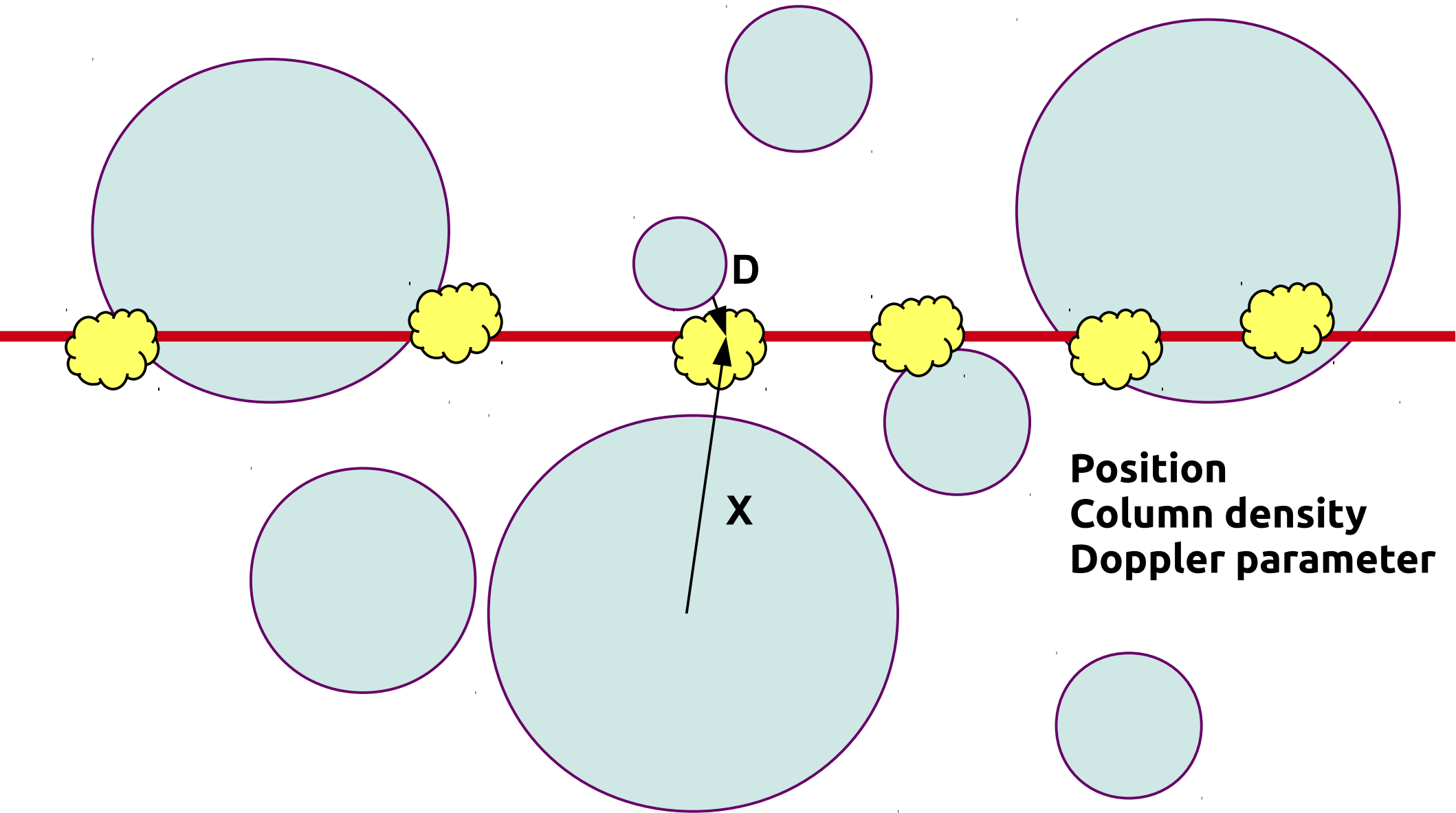
Results



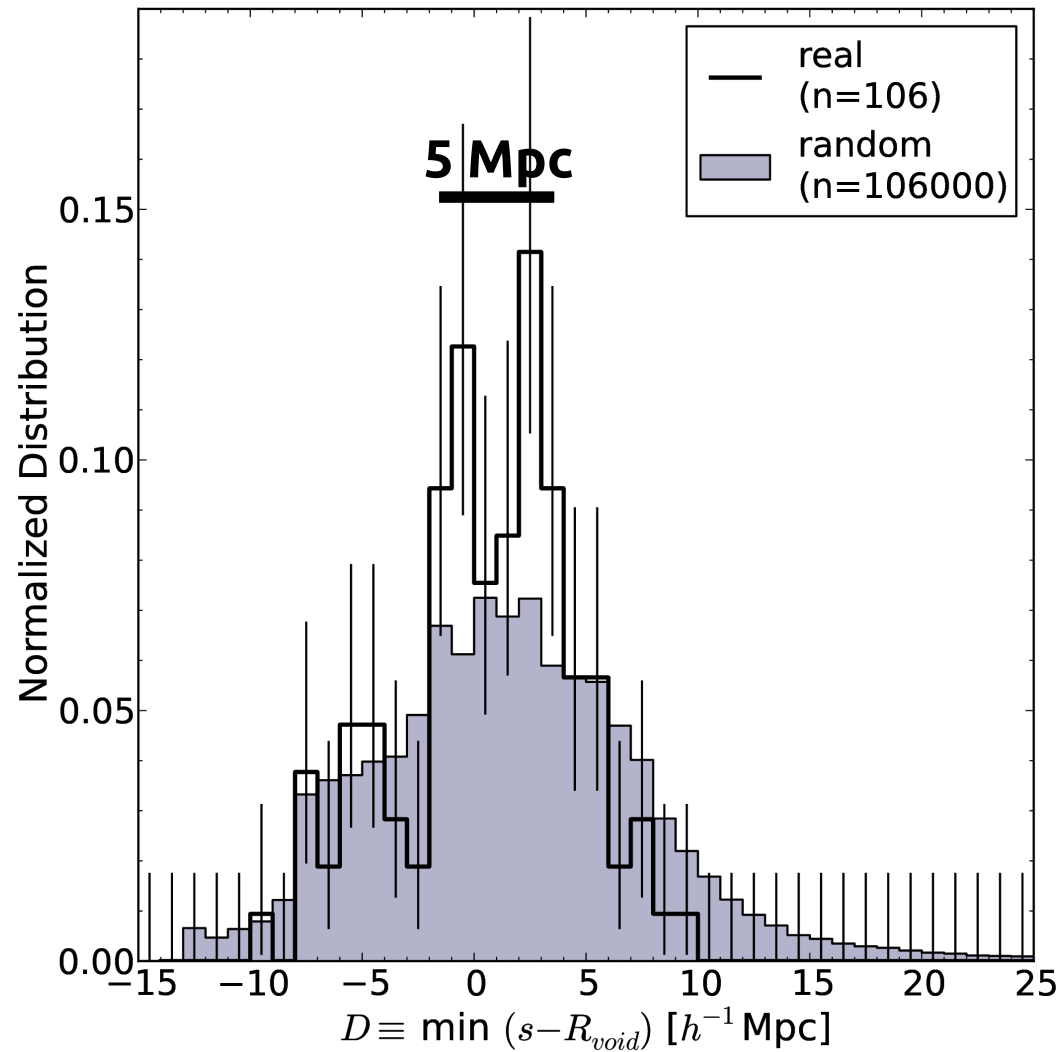
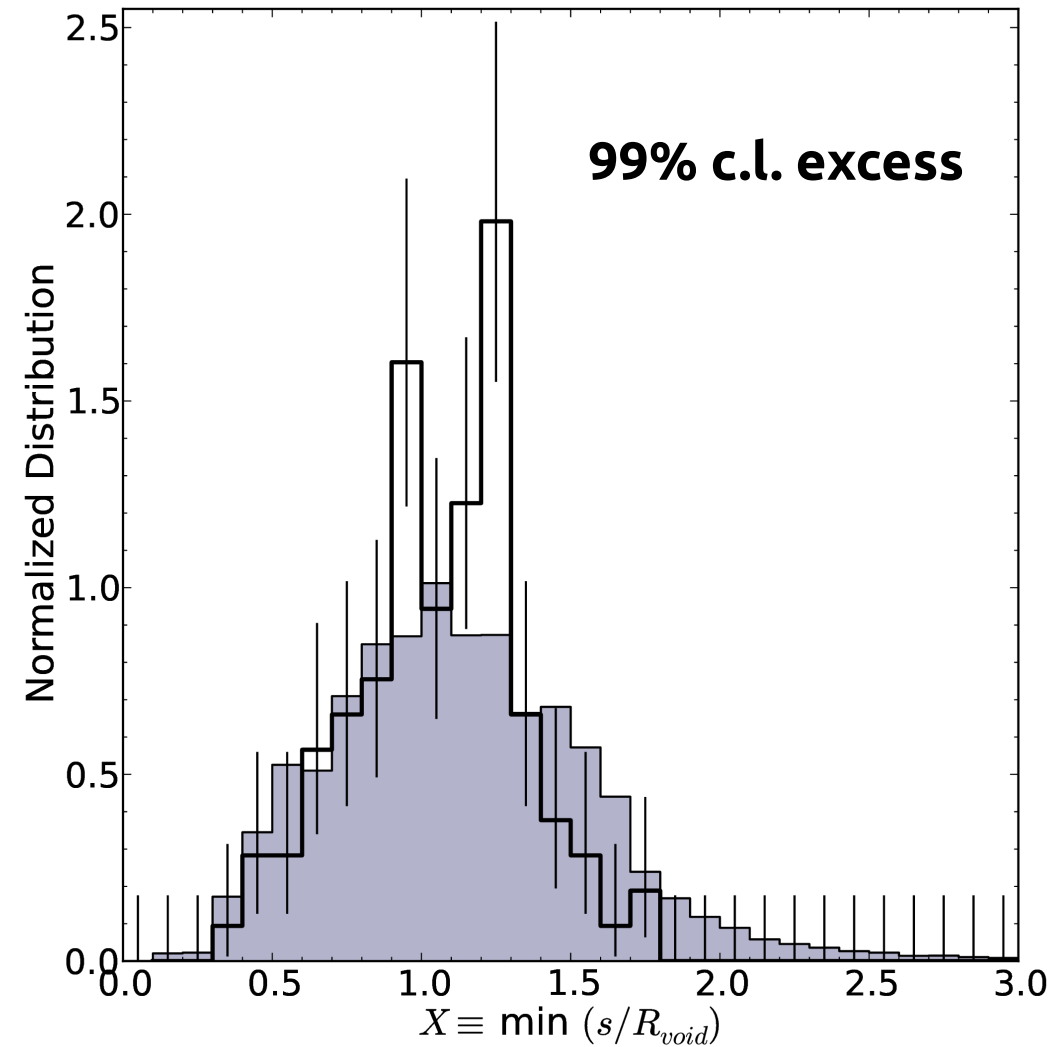
1054 galaxy voids at $z < 0.1$ (Pan et al. 2012)
106 HI absorption systems (Danforth & Shull 2008)

Tejos et al. 2012

IGM in galaxy voids



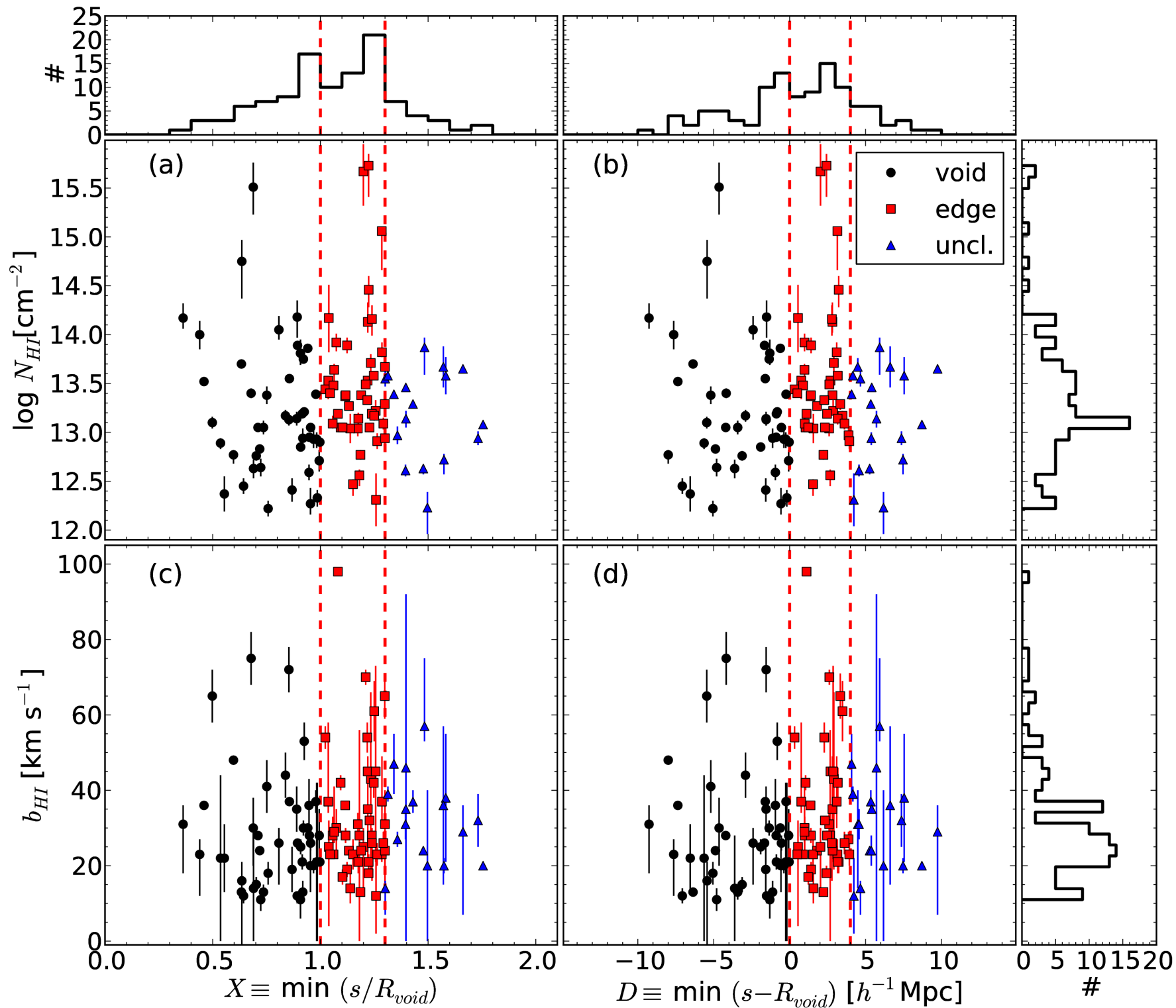
Results

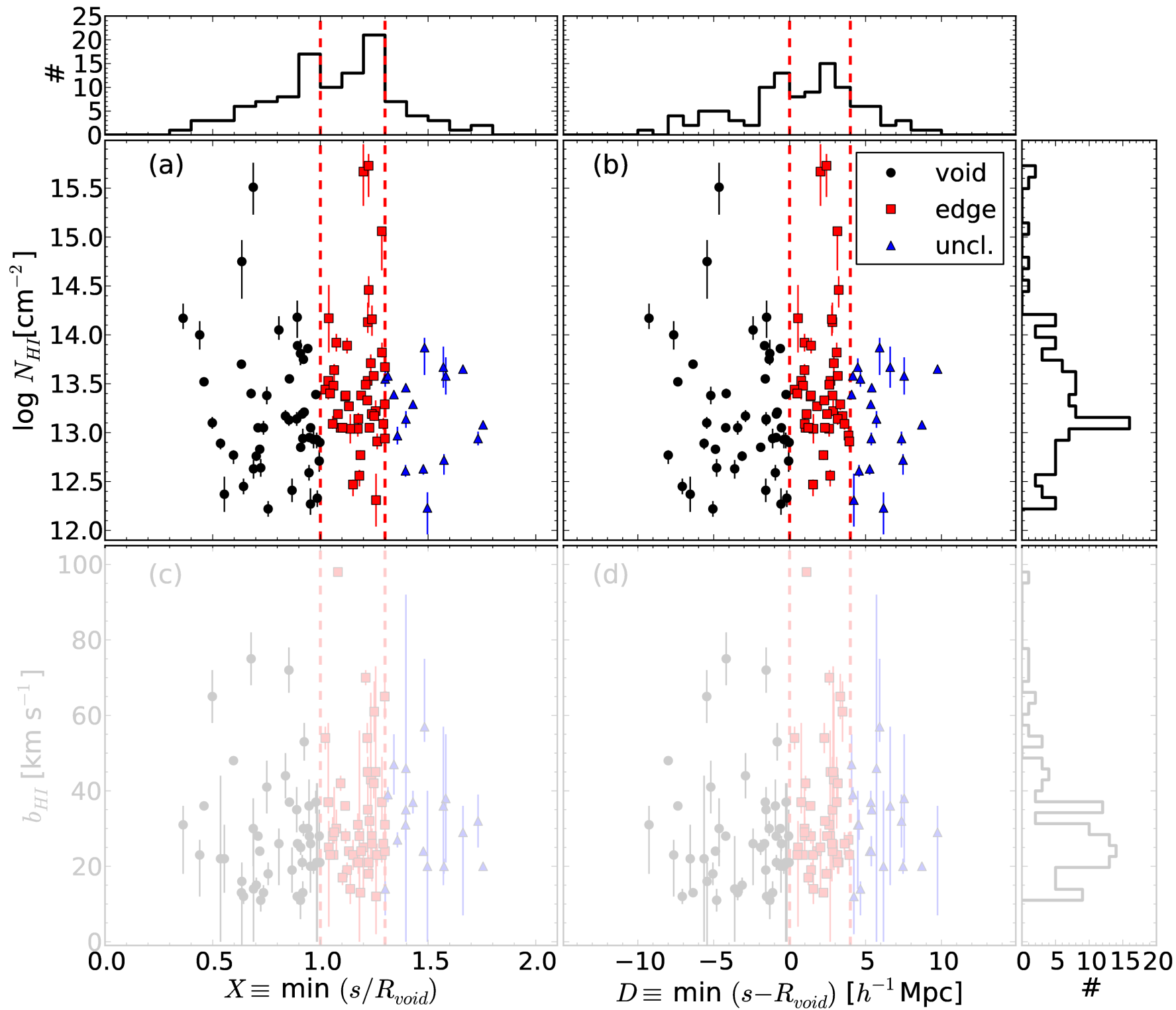


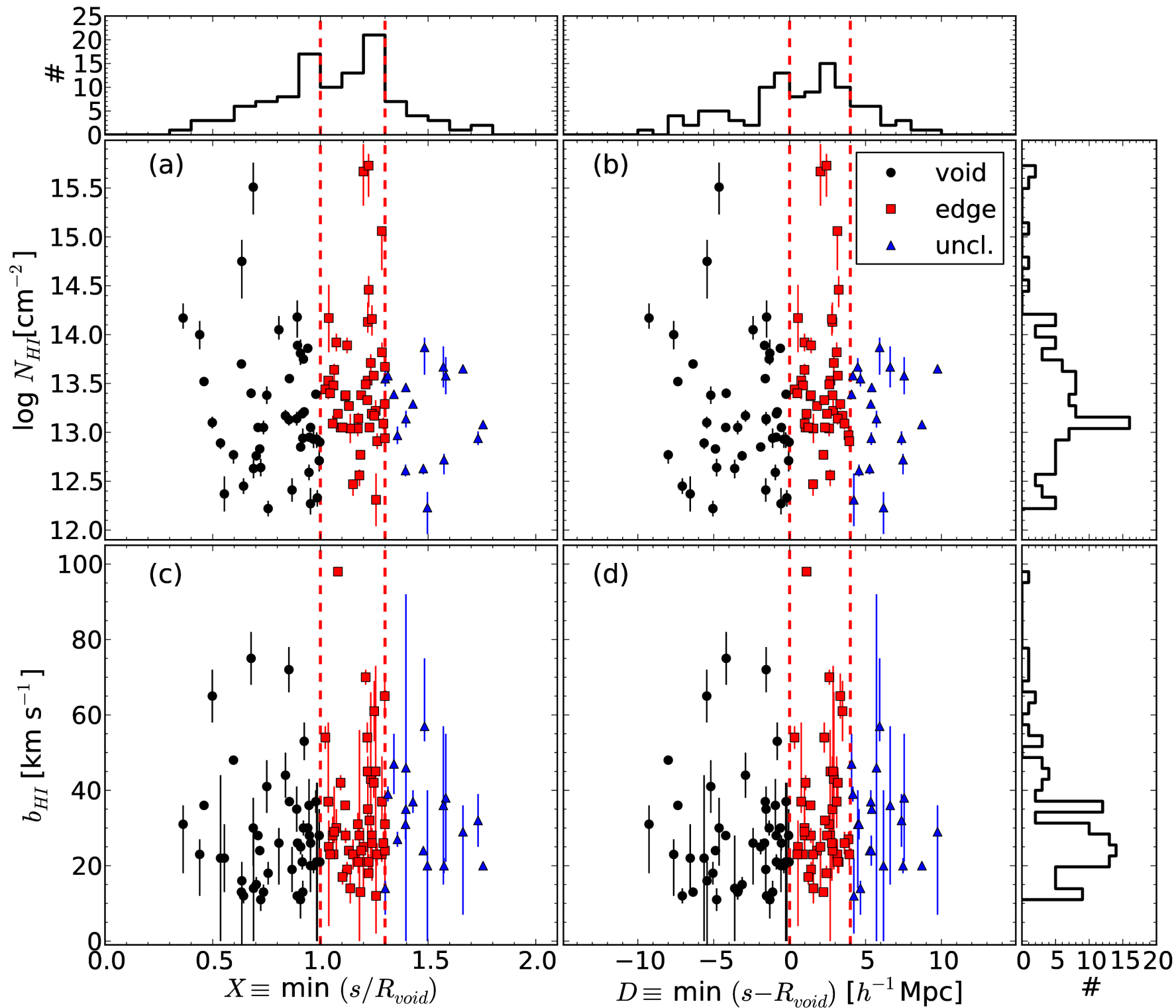
1054 galaxy voids at $z < 0.1$ (Pan et al. 2012)
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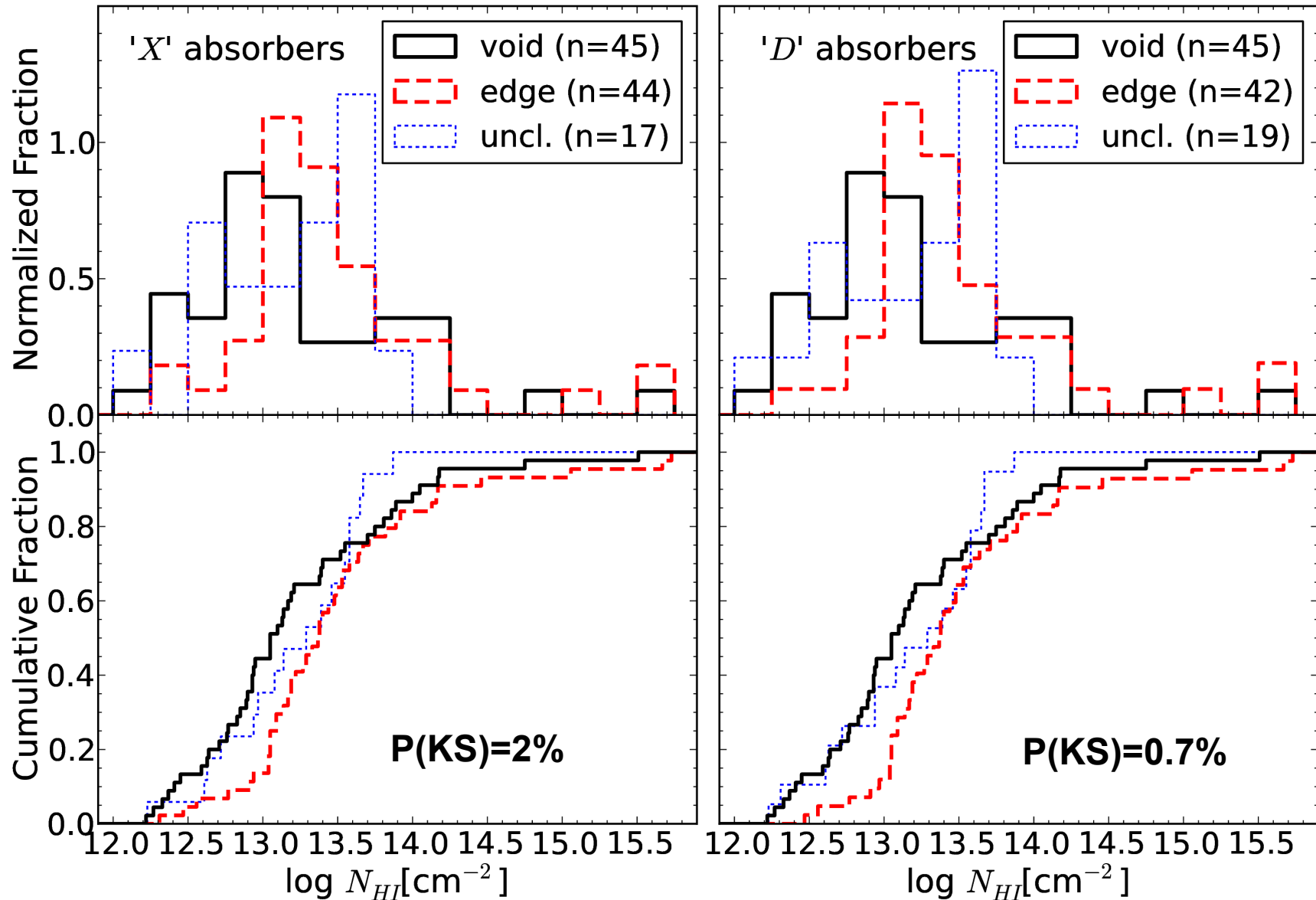
**Are their properties
different?**



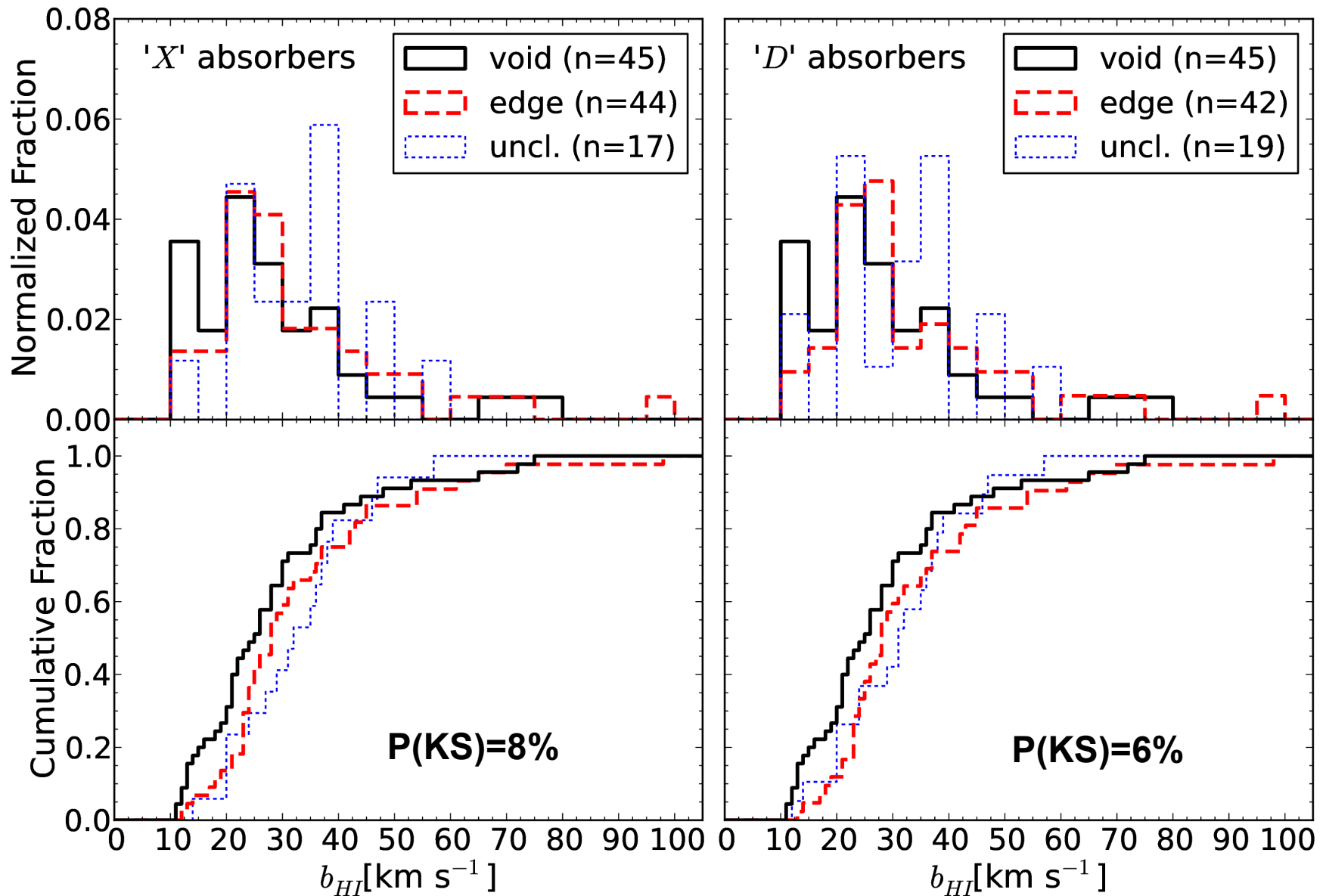




Column densities



Doppler parameters



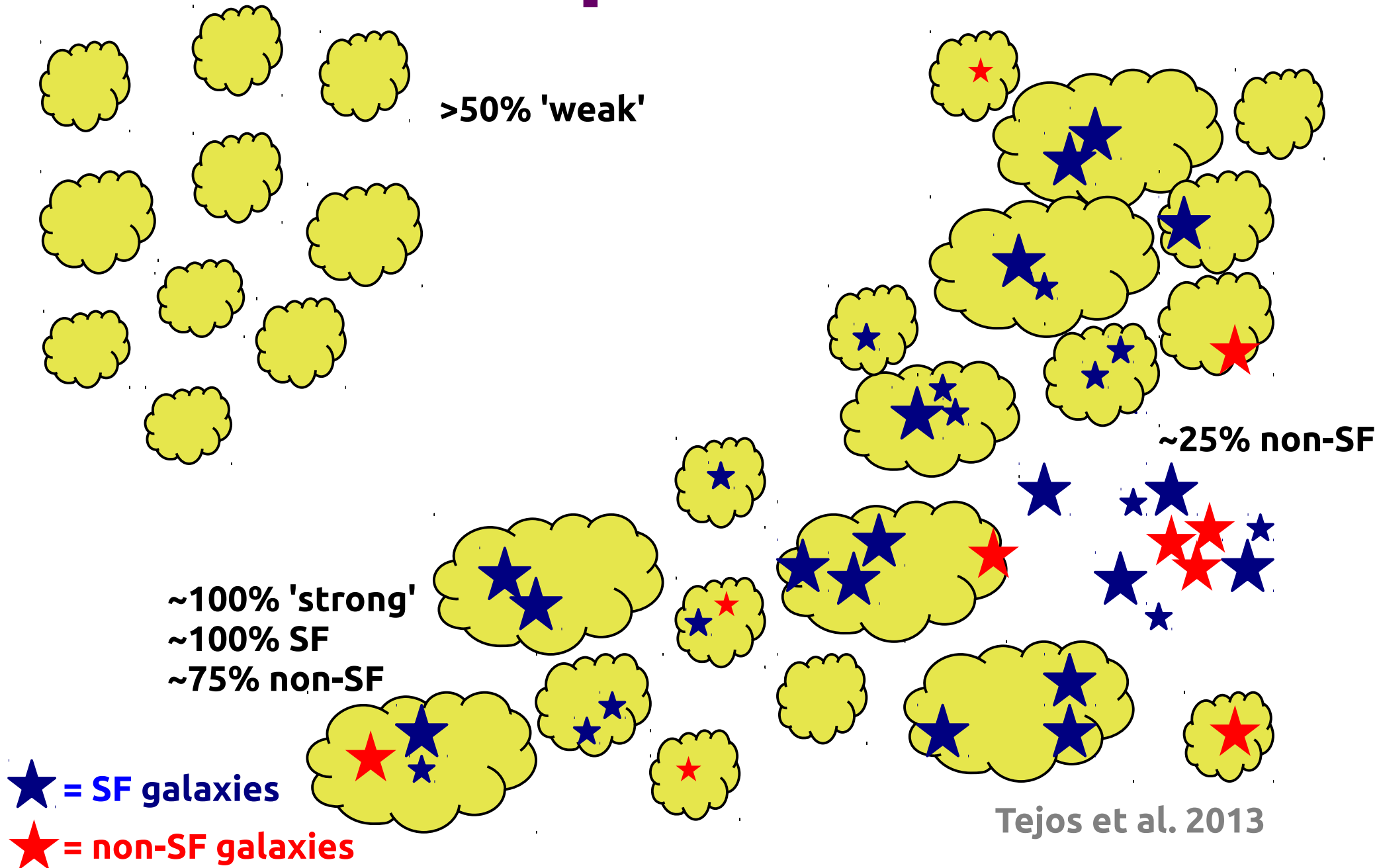
Conclusions

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 $N(\text{HI})$ and $b(\text{HI})$ 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.**
- **(The absolute biases of 'weak' HI systems might be $b < 1$).**
- **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)





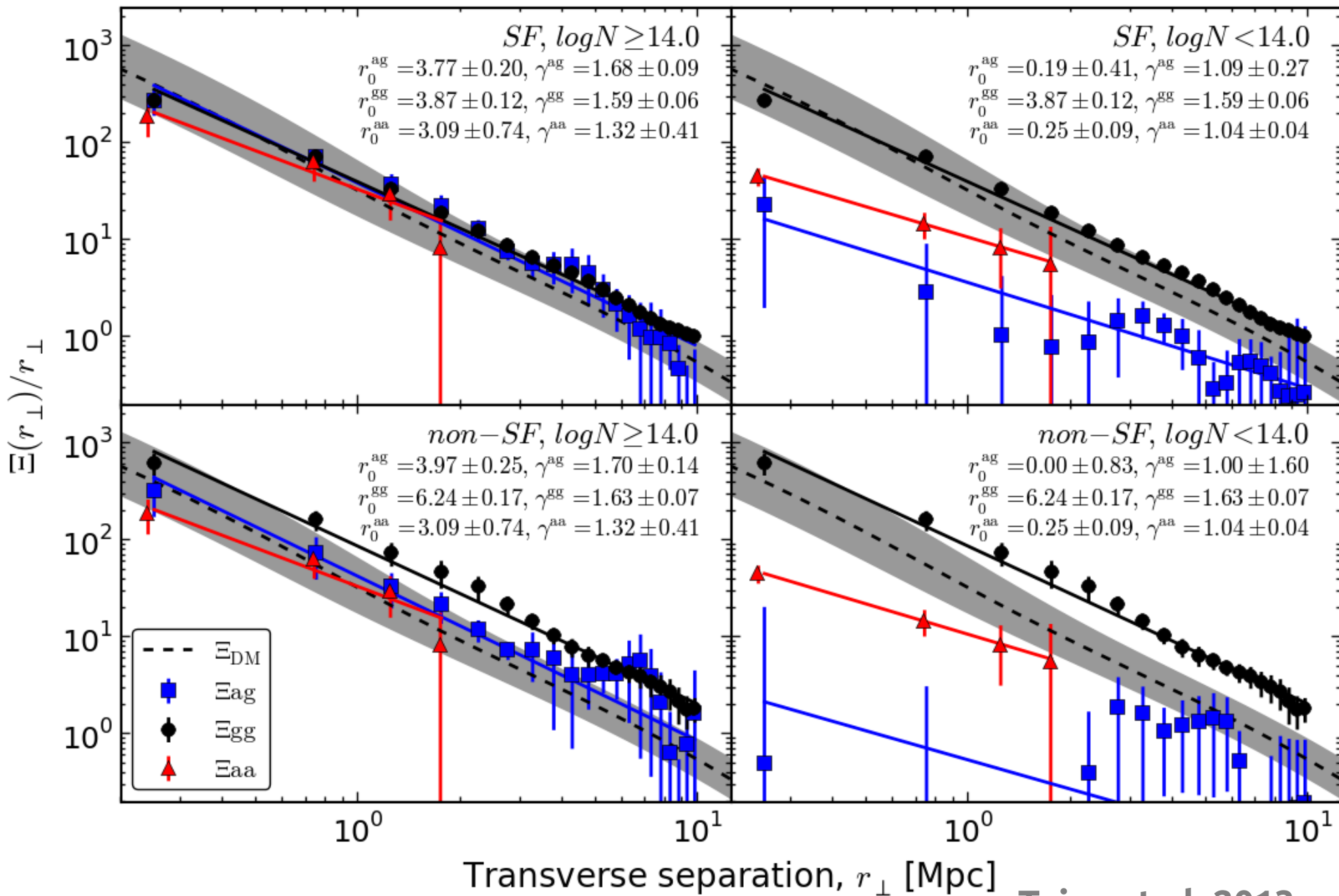
No discrete clouds

No sharp transitions

Feedback processes

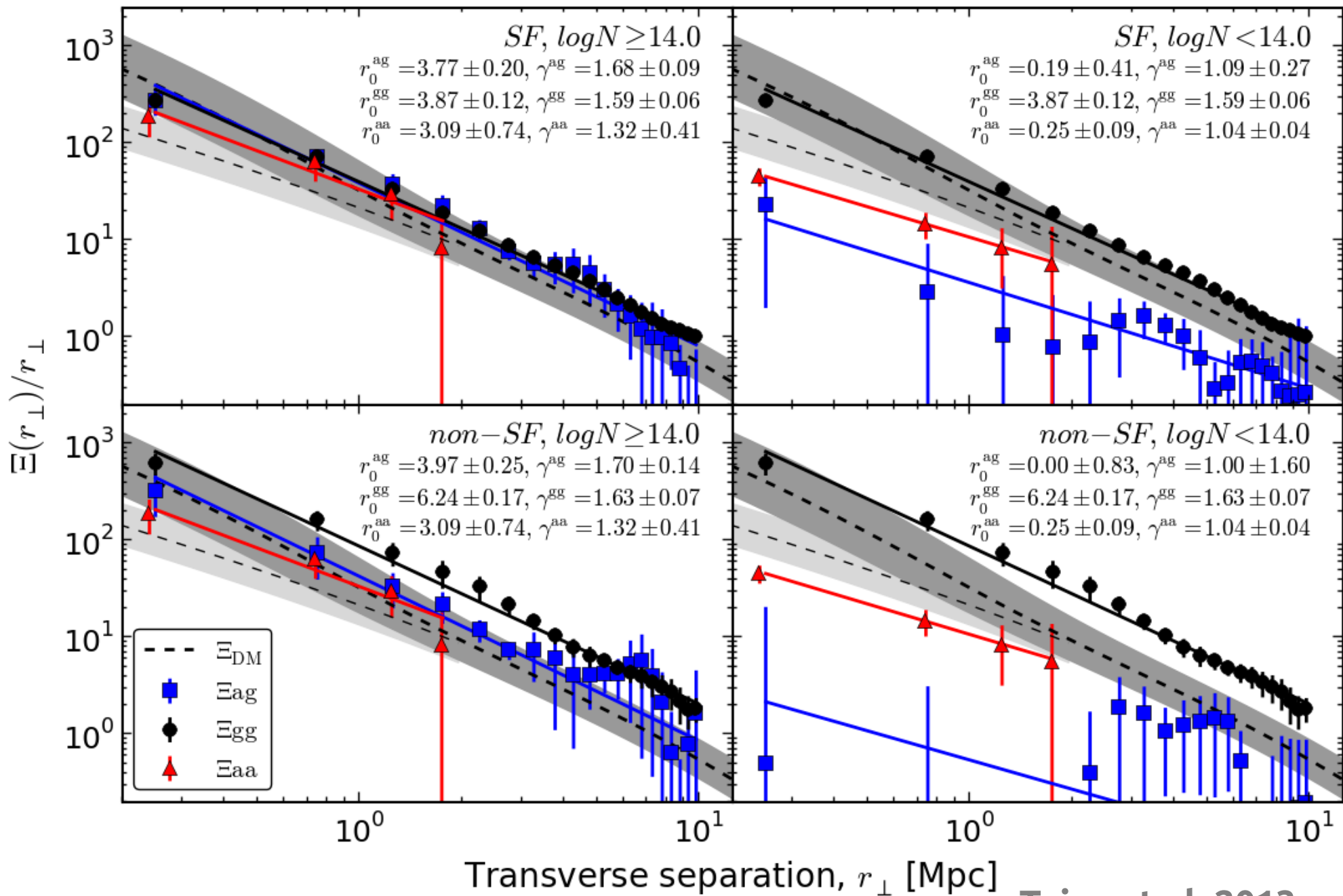
5 Mpc

OWLS (Schaye et al. 2010)



Tejos et al. 2013

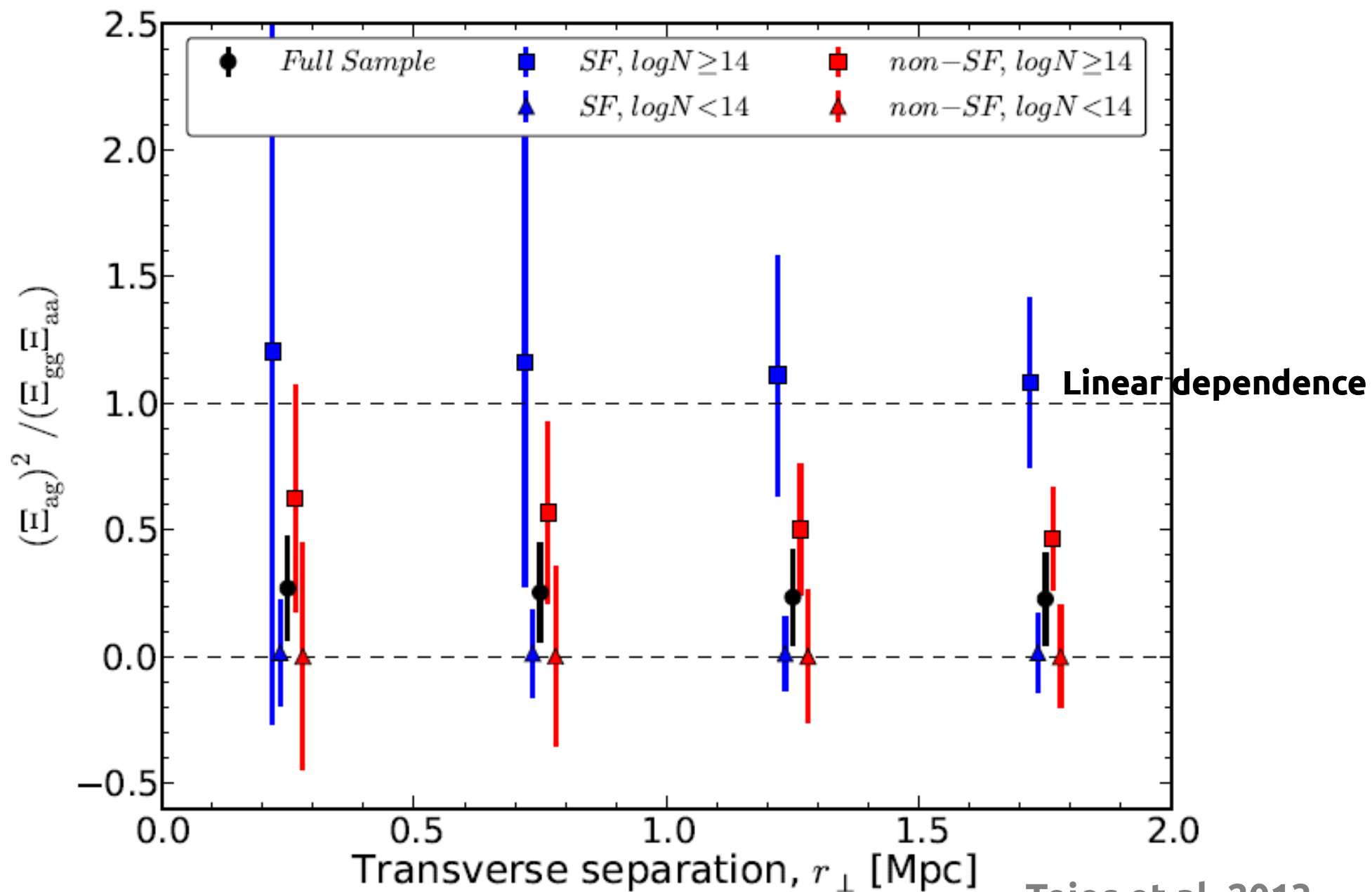
DM clustering: Lewis et al. 2000 + Smith et al. 2003



Tejos et al. 2013

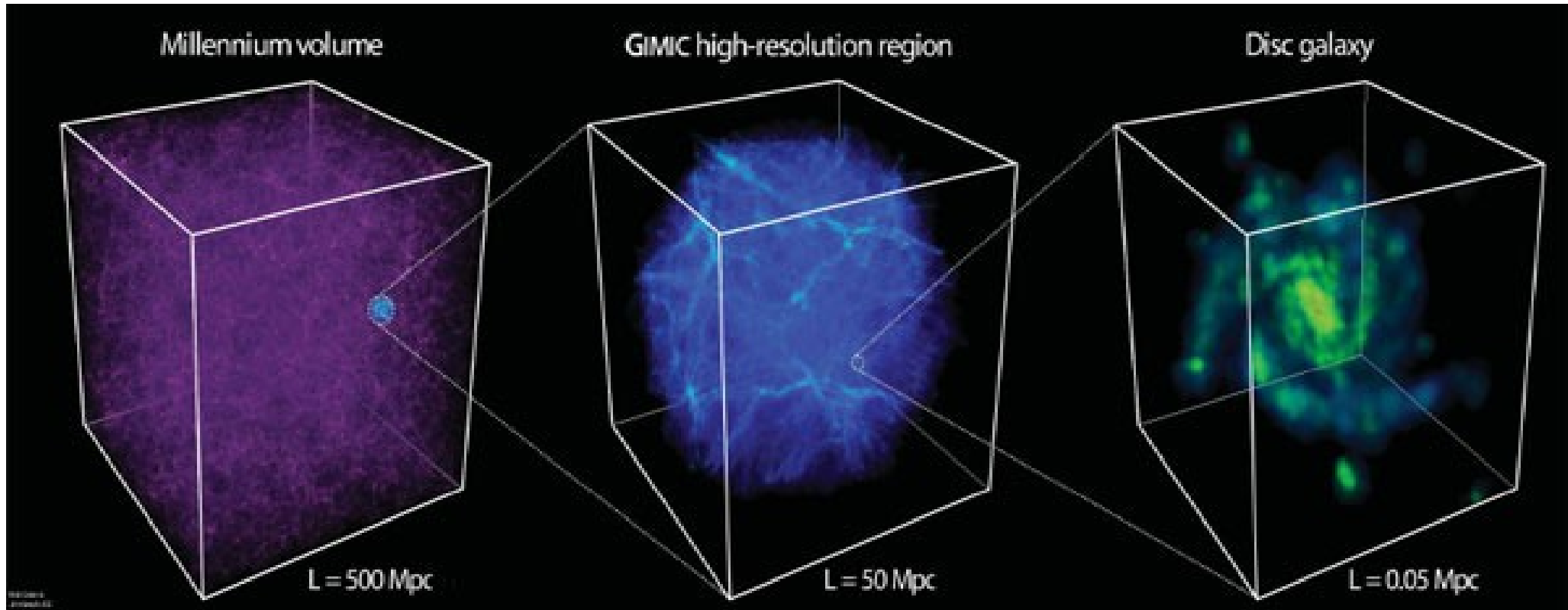
DM clustering: Lewis et al. 2000 + Smith et al. 2003

Results



Comparison with simulations

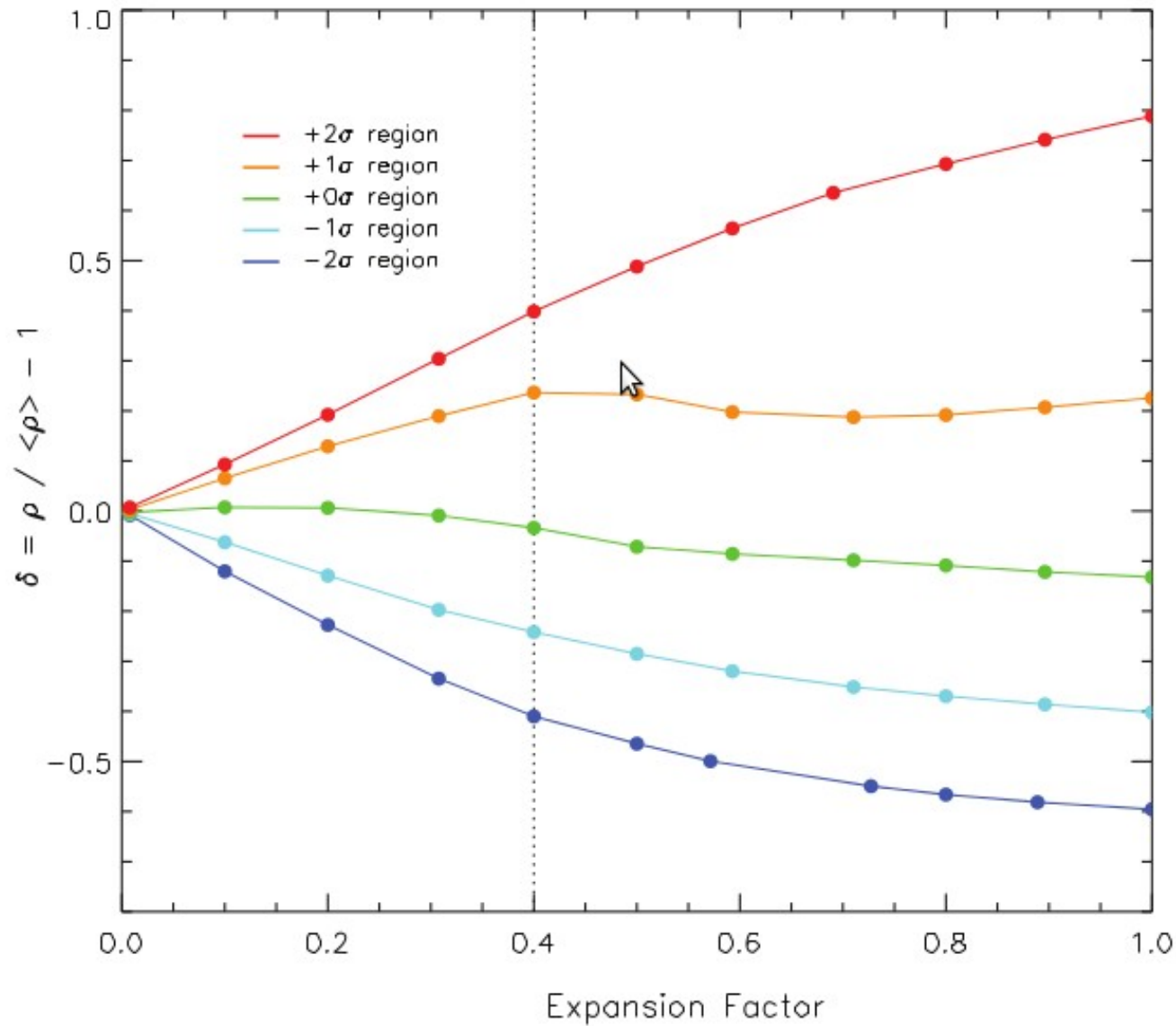
Comparison with GIMIC



**Galaxies Intergalactic-Medium
Interaction Calculation**

Crain et al. 2009

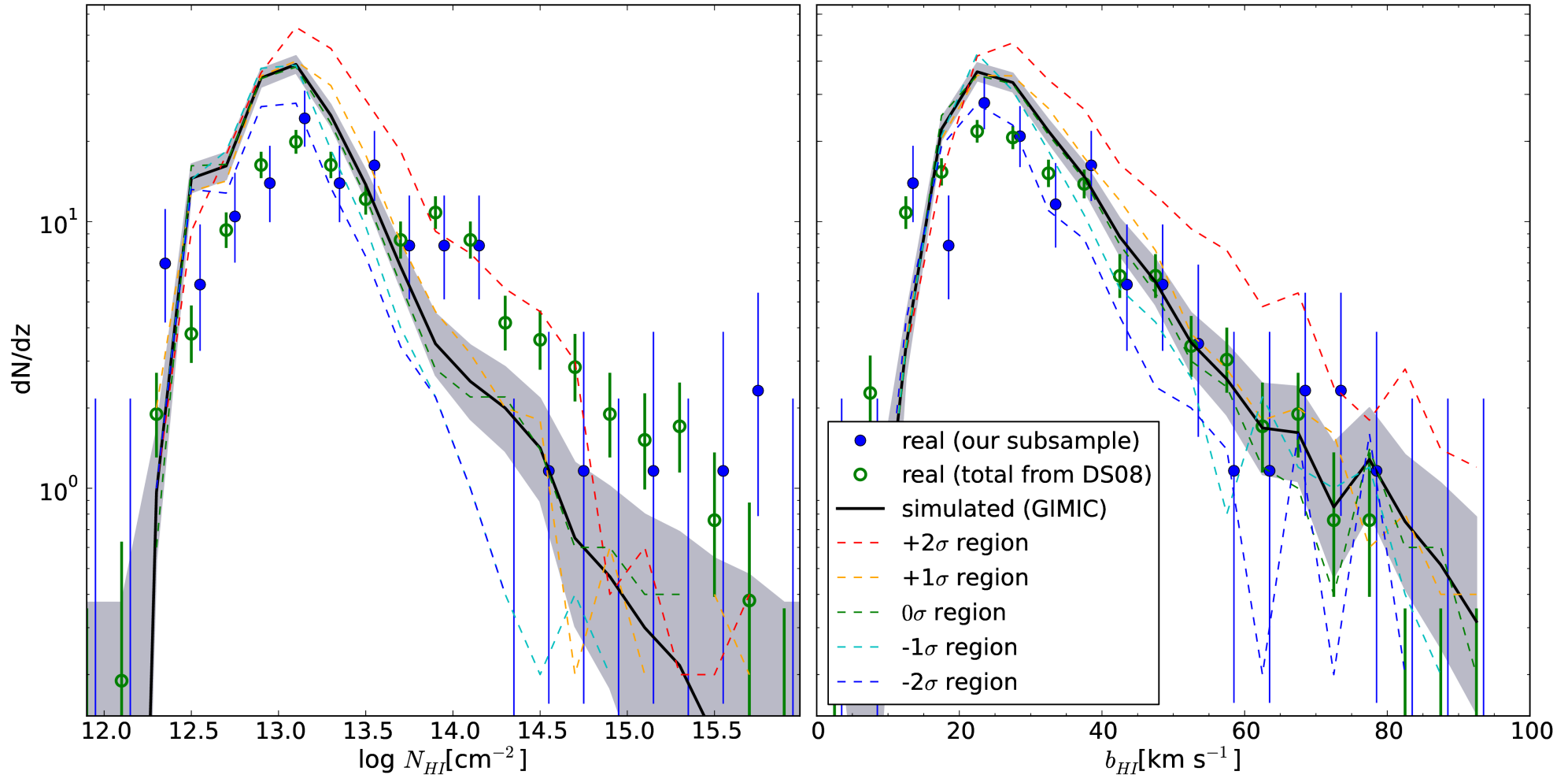
Comparison with GIMIC



5 GIMIC regions

Crain et al. 2009

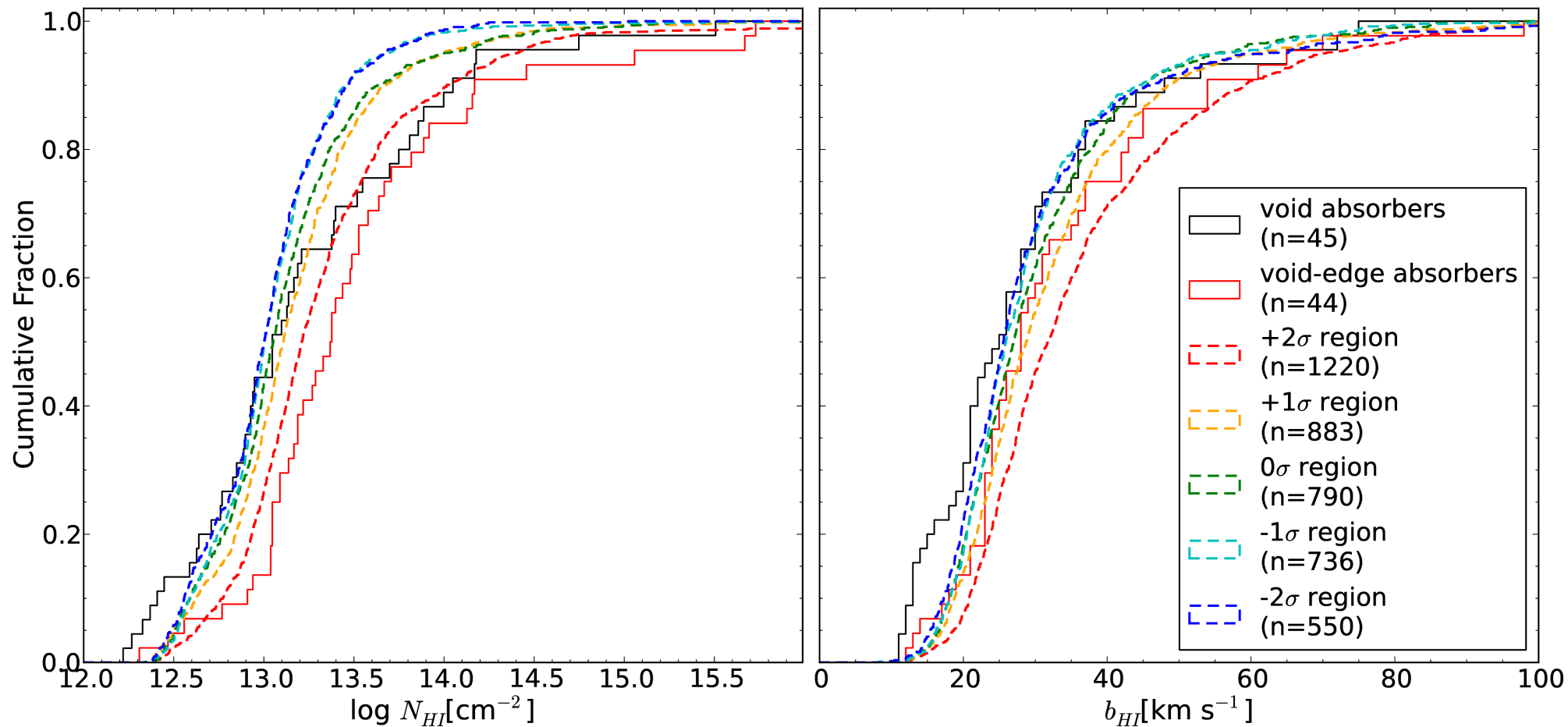
Comparison with simulations



**Galaxies Intergalactic-Medium
Interaction Calculation**

Tejos et al. 2012

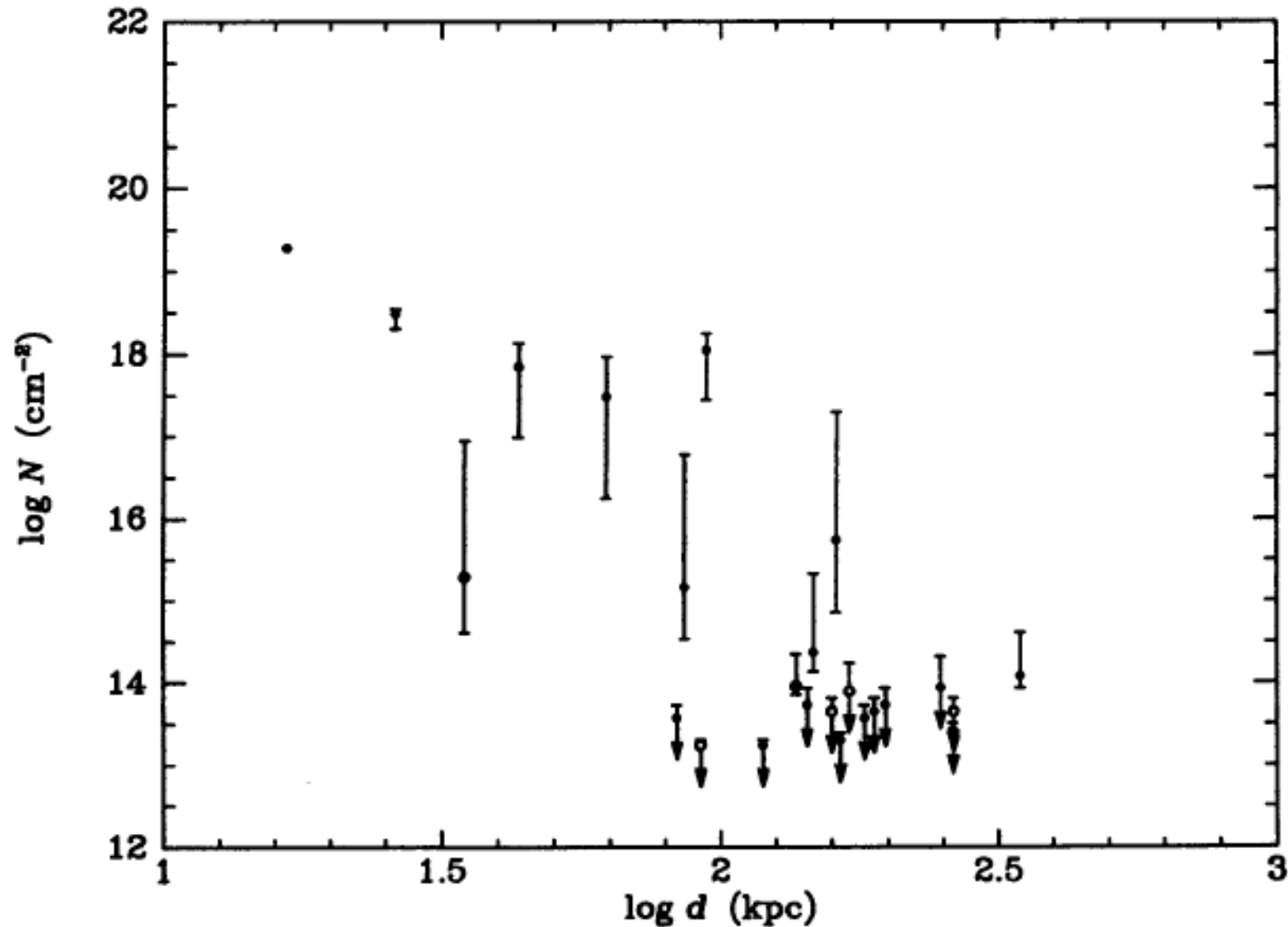
Comparison with GIMIC



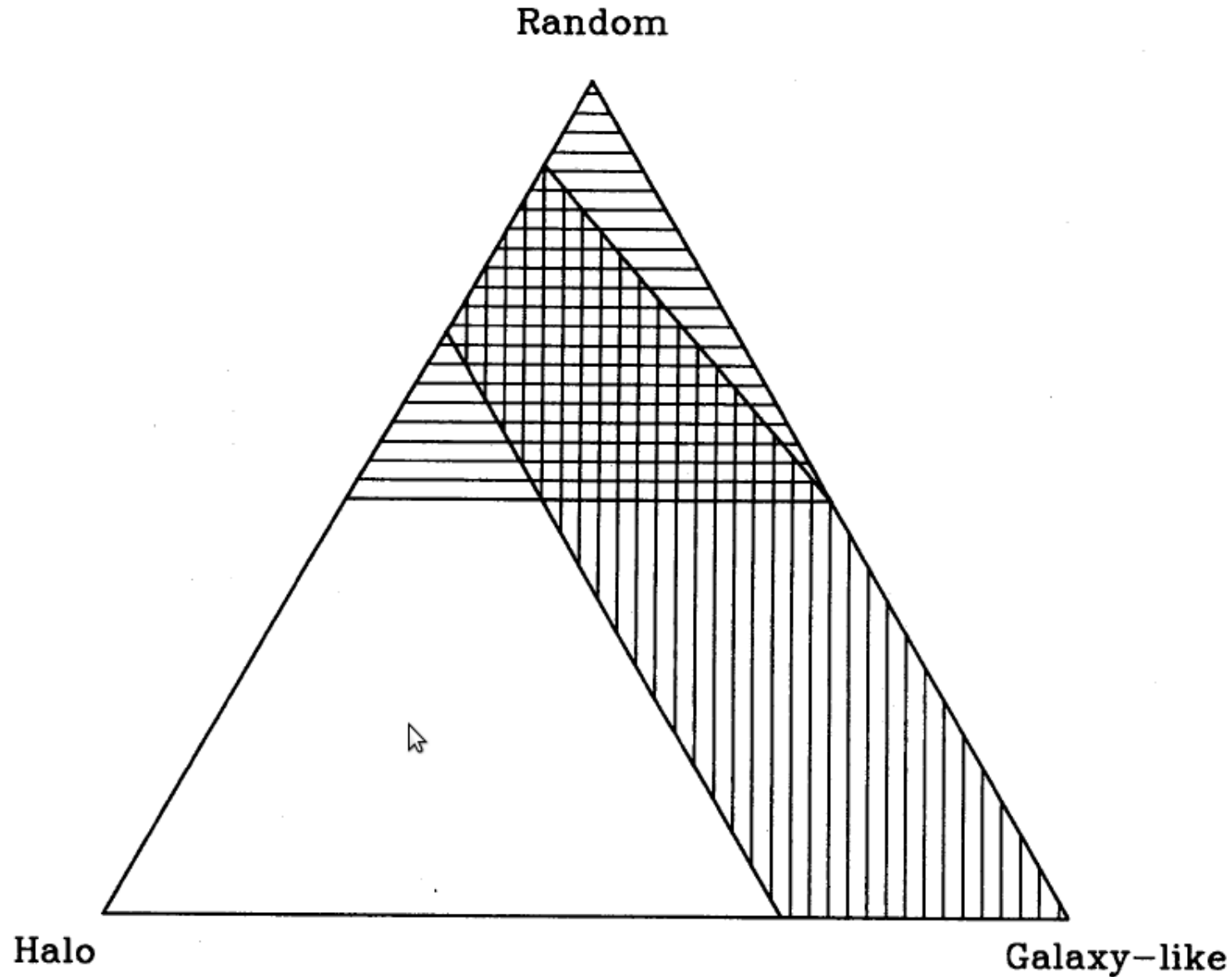
5 GIMIC regions

Tejos et al. 2012

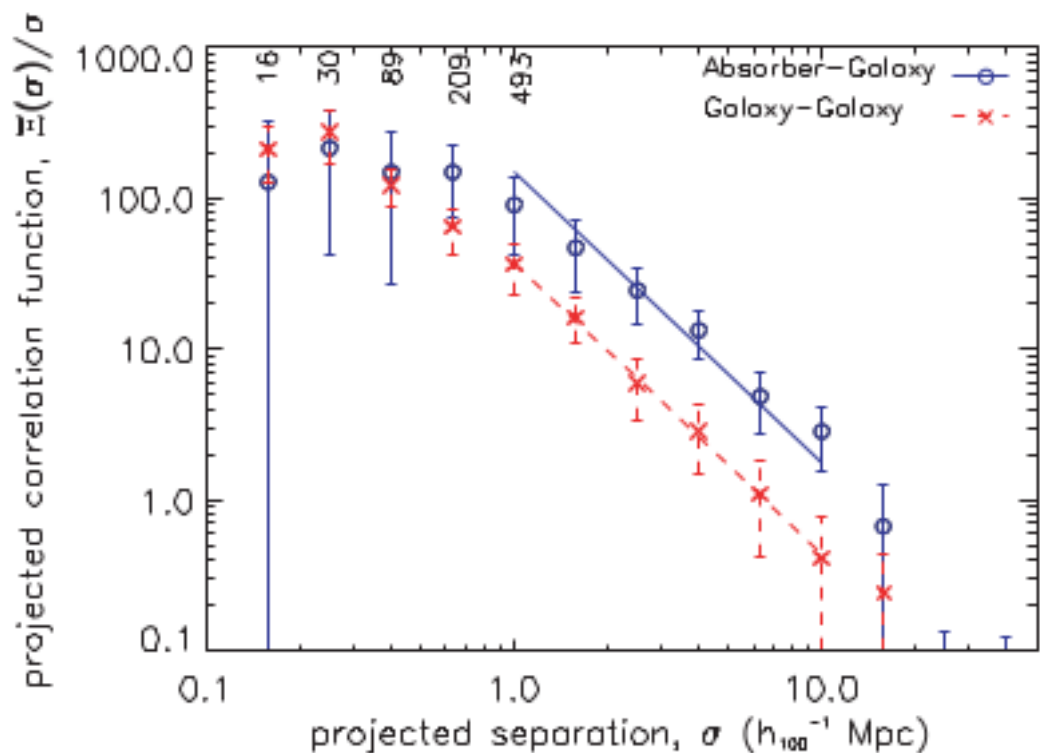
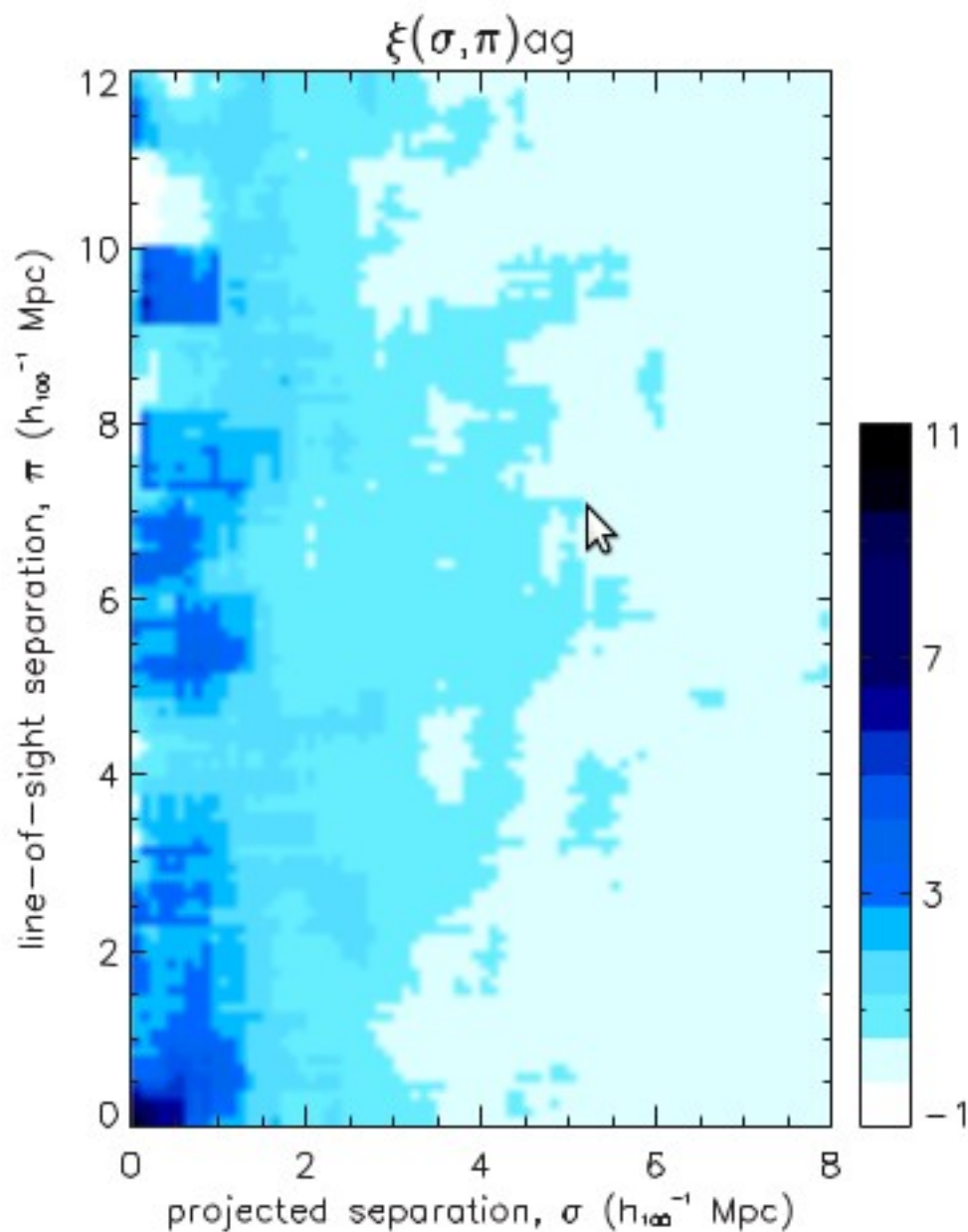
IGM-galaxy connection



IGM-galaxy connection

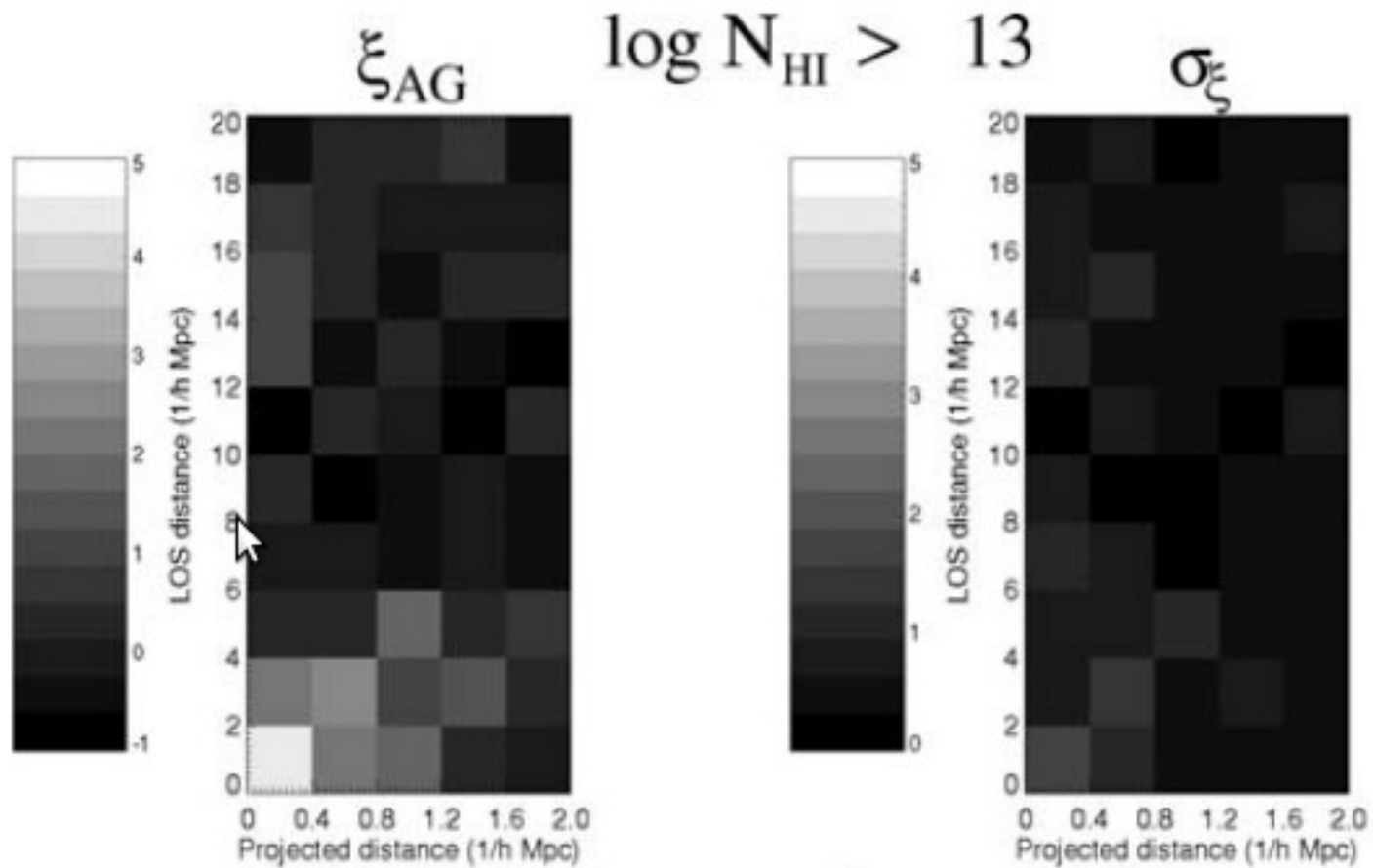


Previous results



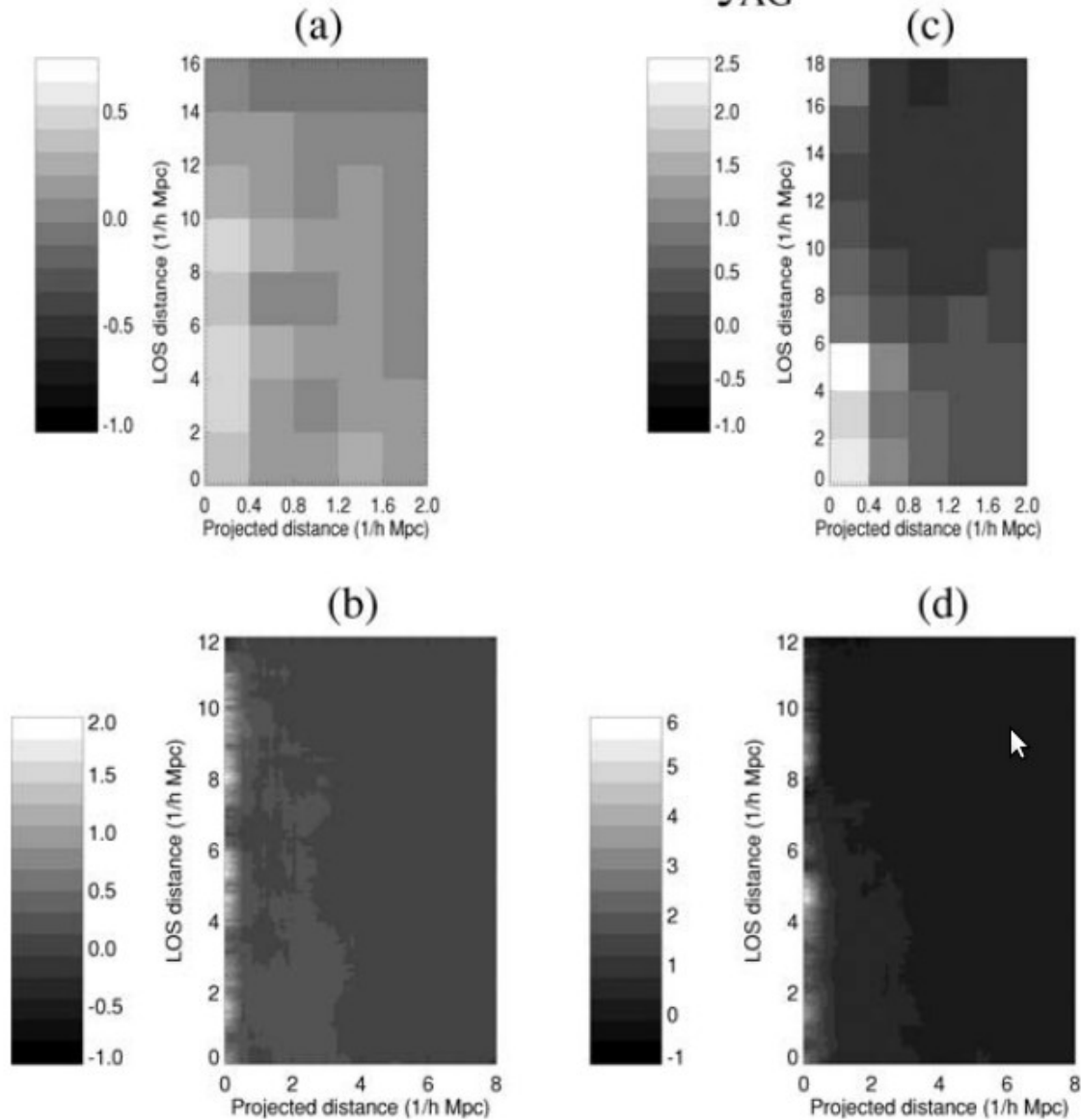
Ryan-Weber 2006

Previous results



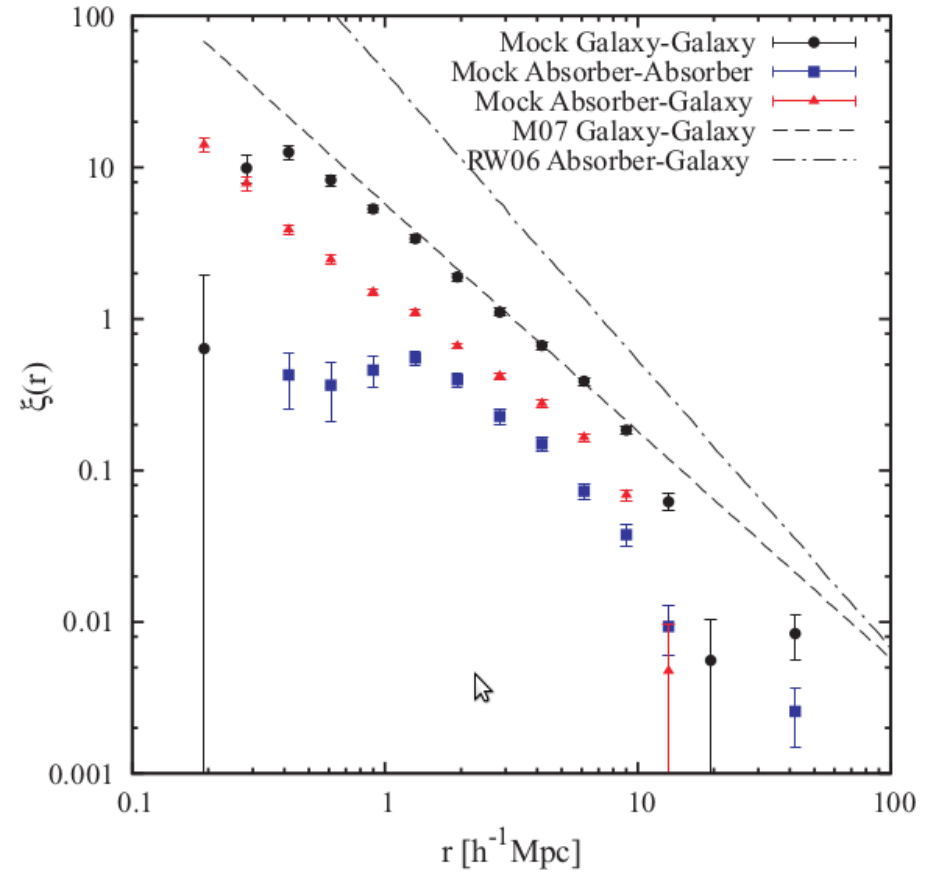
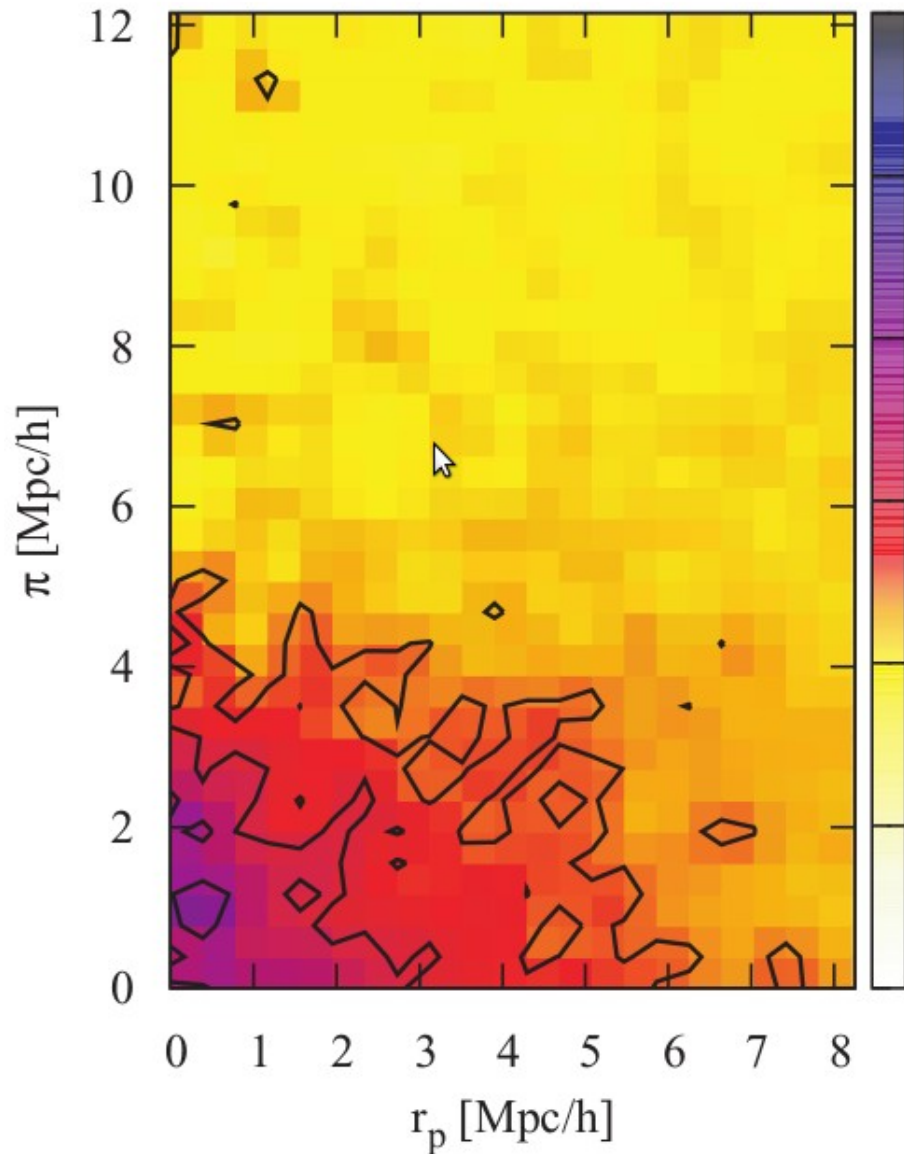
Previous results

Simulated ξ_{AG}



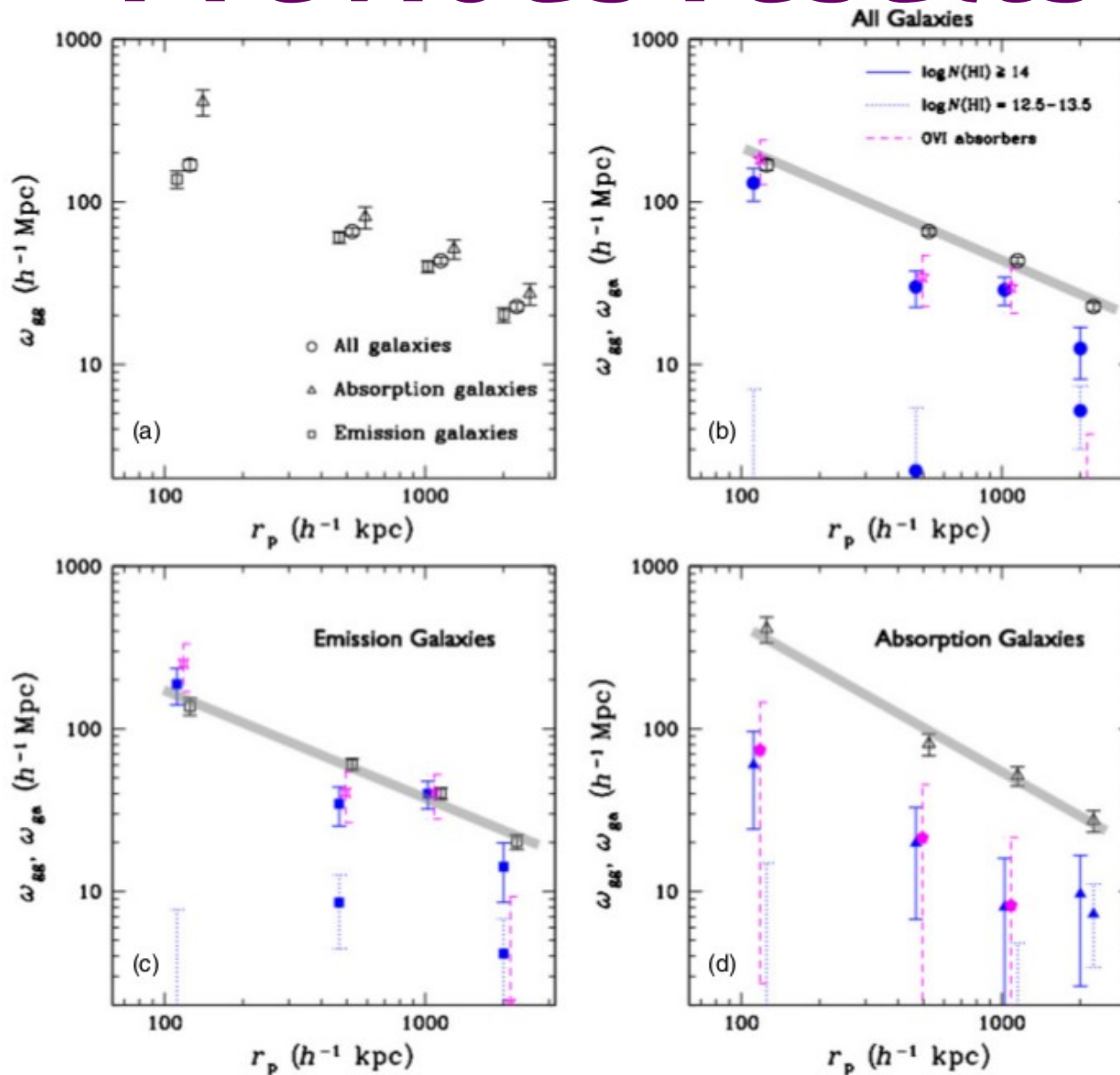
Wilman et al. 2007

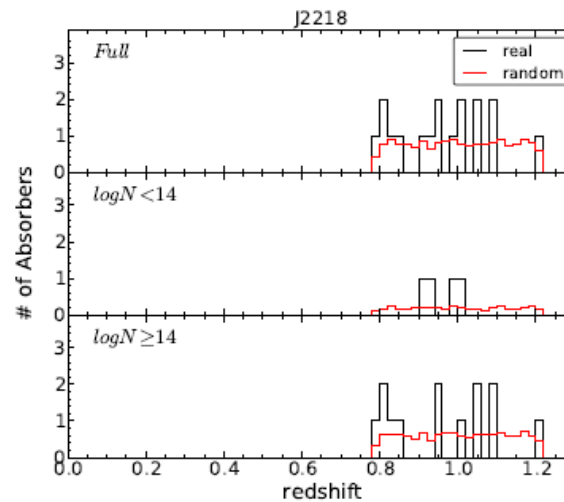
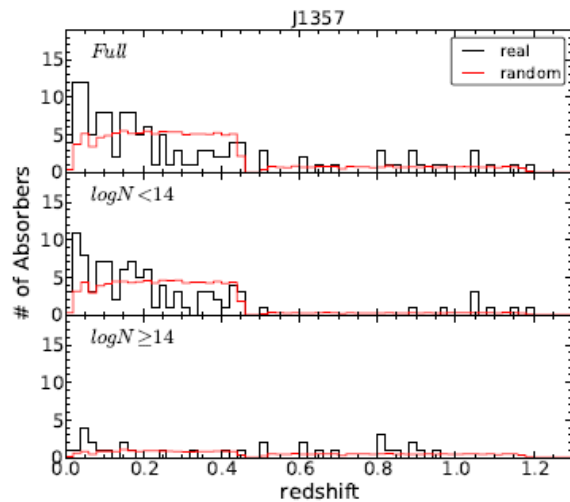
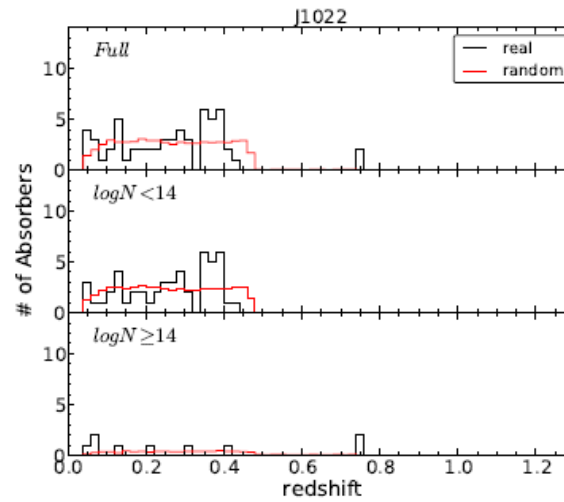
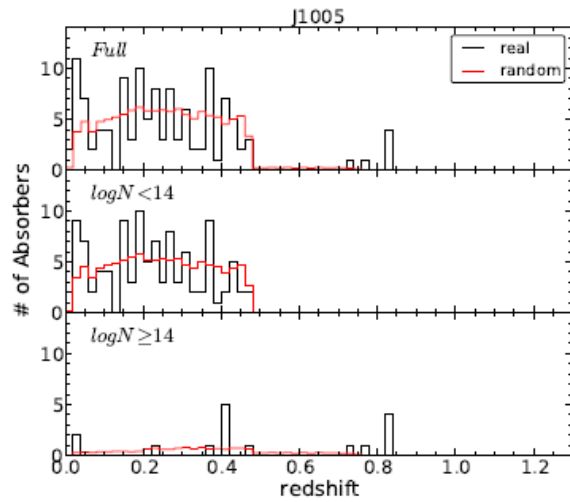
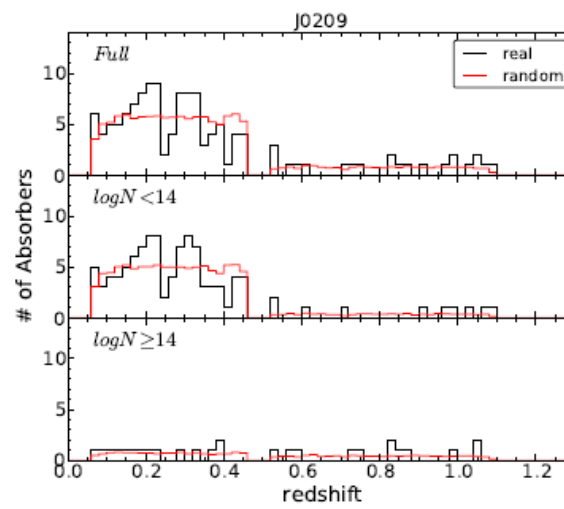
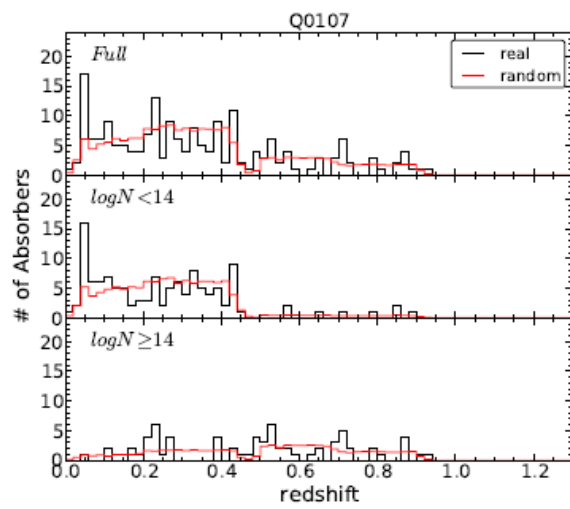
Previous results



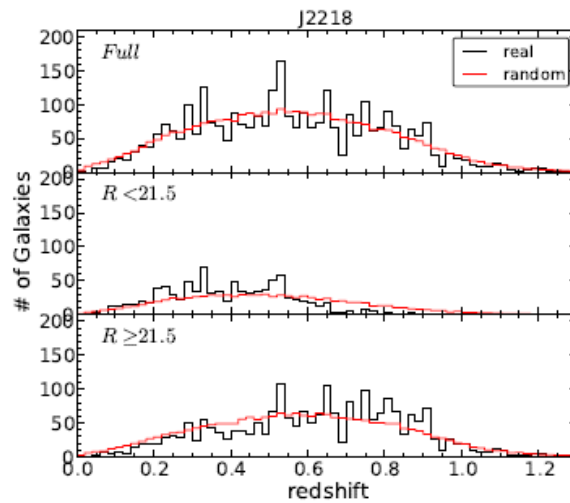
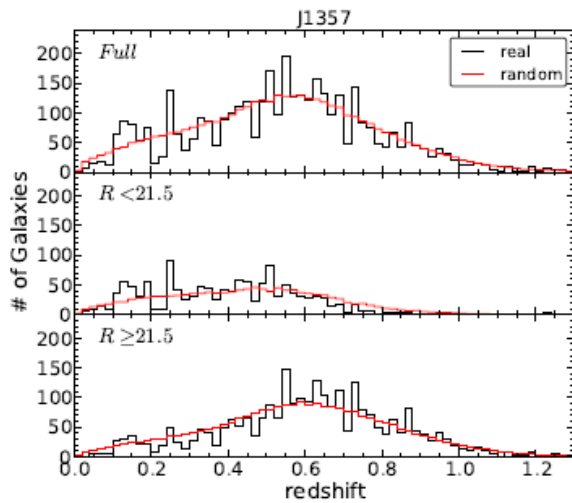
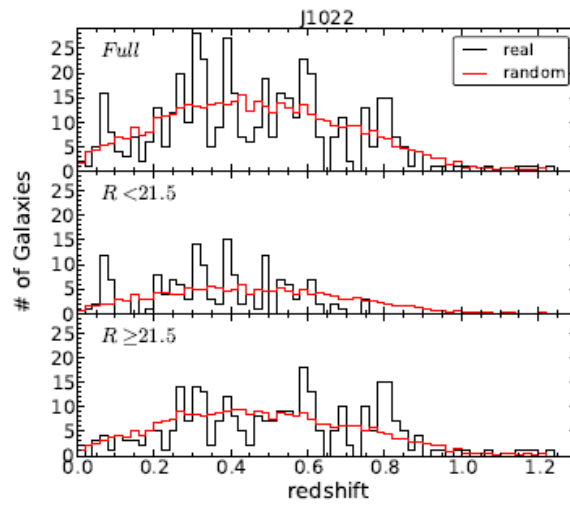
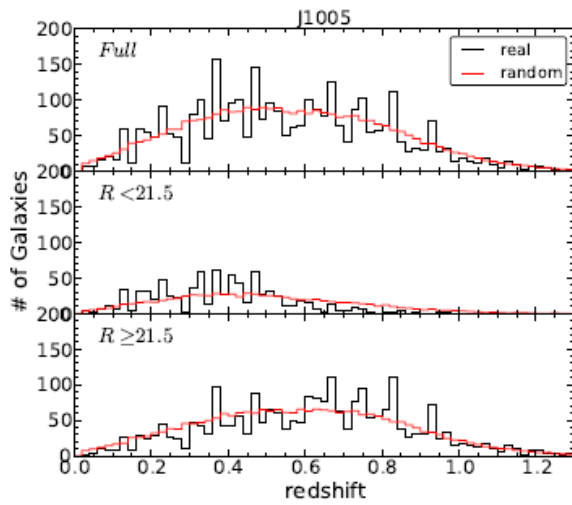
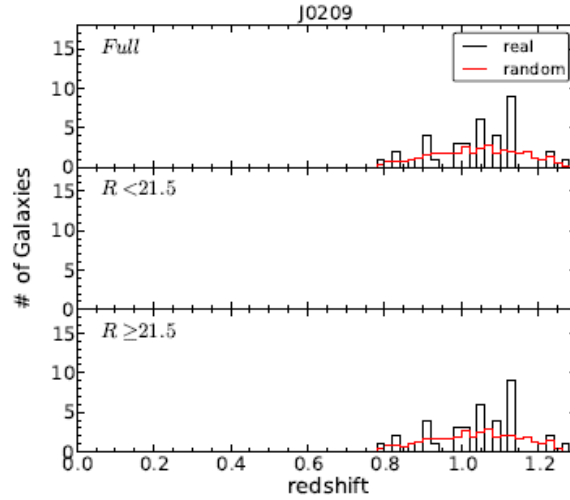
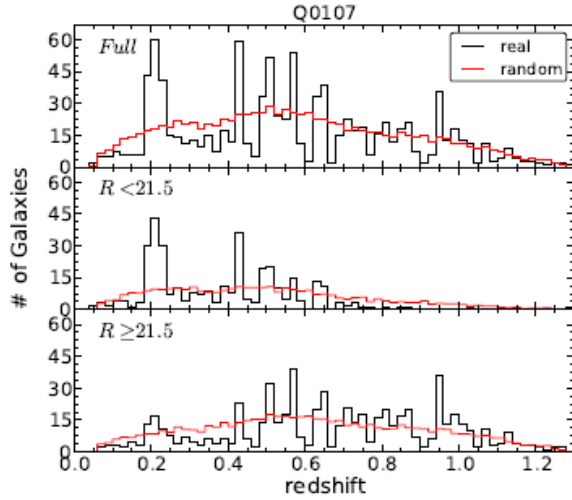
Pierleoni et al. 2008

Previous results

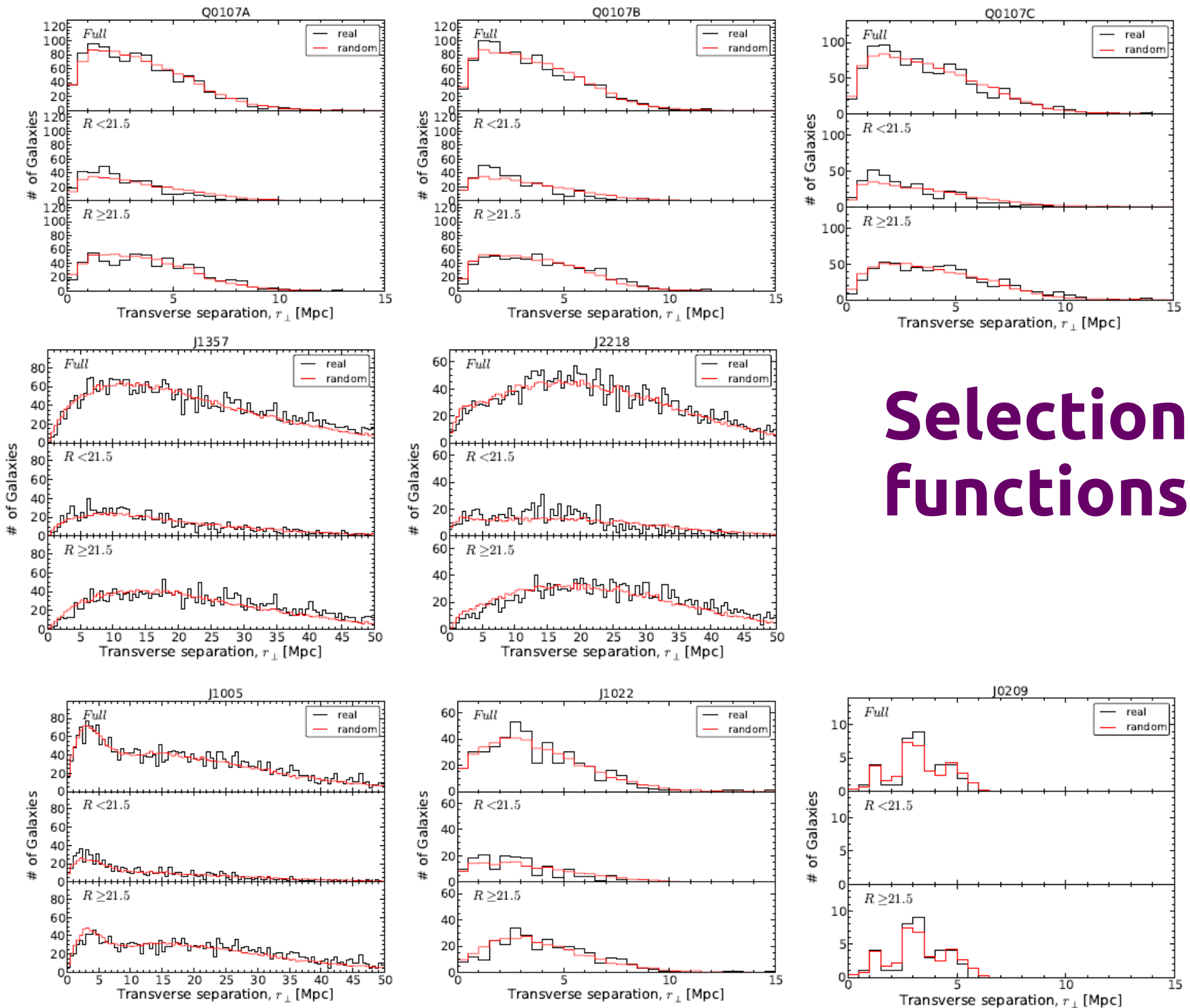




Selection functions

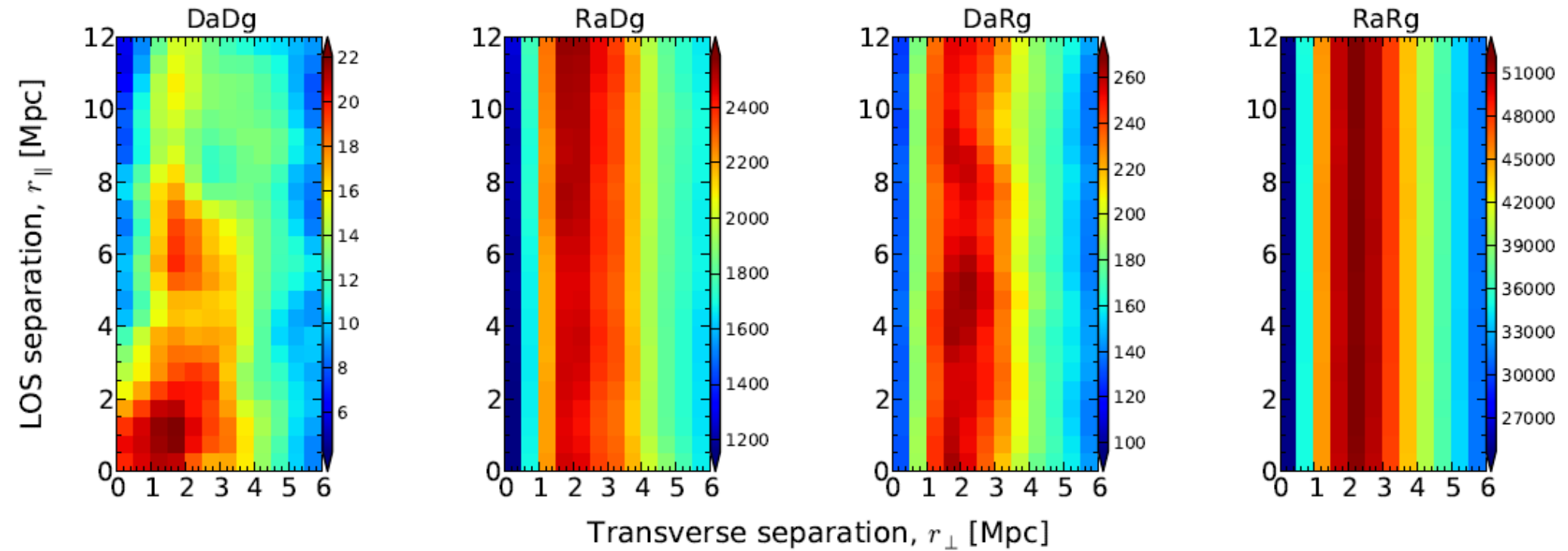


Selection functions



Selection functions

Cross-counts



Uncertainties

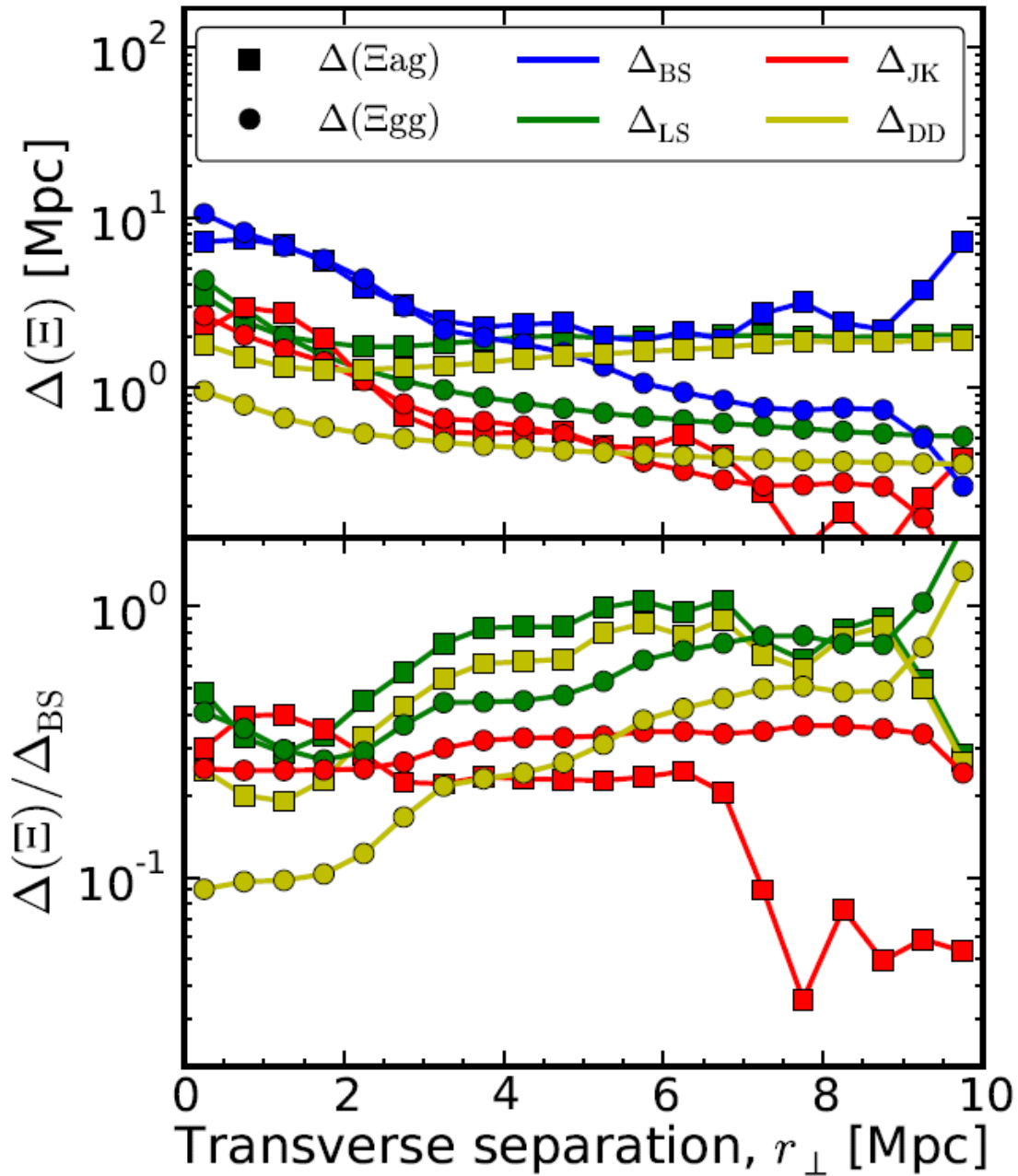
- **Poissonian:**

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

- **Landy & Szalay 1993:**

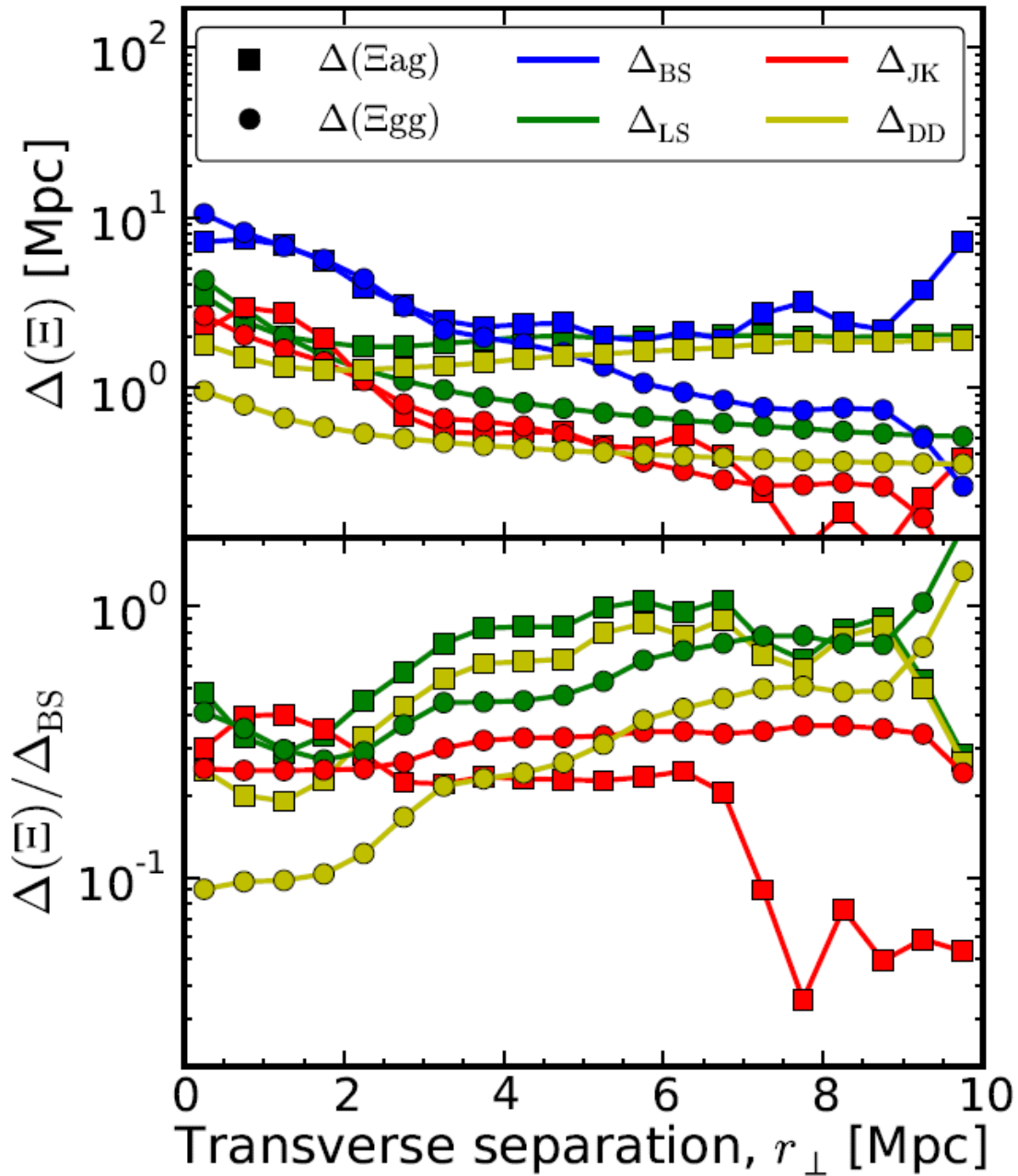
$$\Delta_{LS}^2(\xi^{LS}) \approx \frac{(1 + \xi^{LS})^2}{n_{DD}(RR/n_{RR})} \approx \frac{(1 + \xi^{LS})^3}{DD}$$

Uncertainties



- **LS93 preferable over Poissonian.**

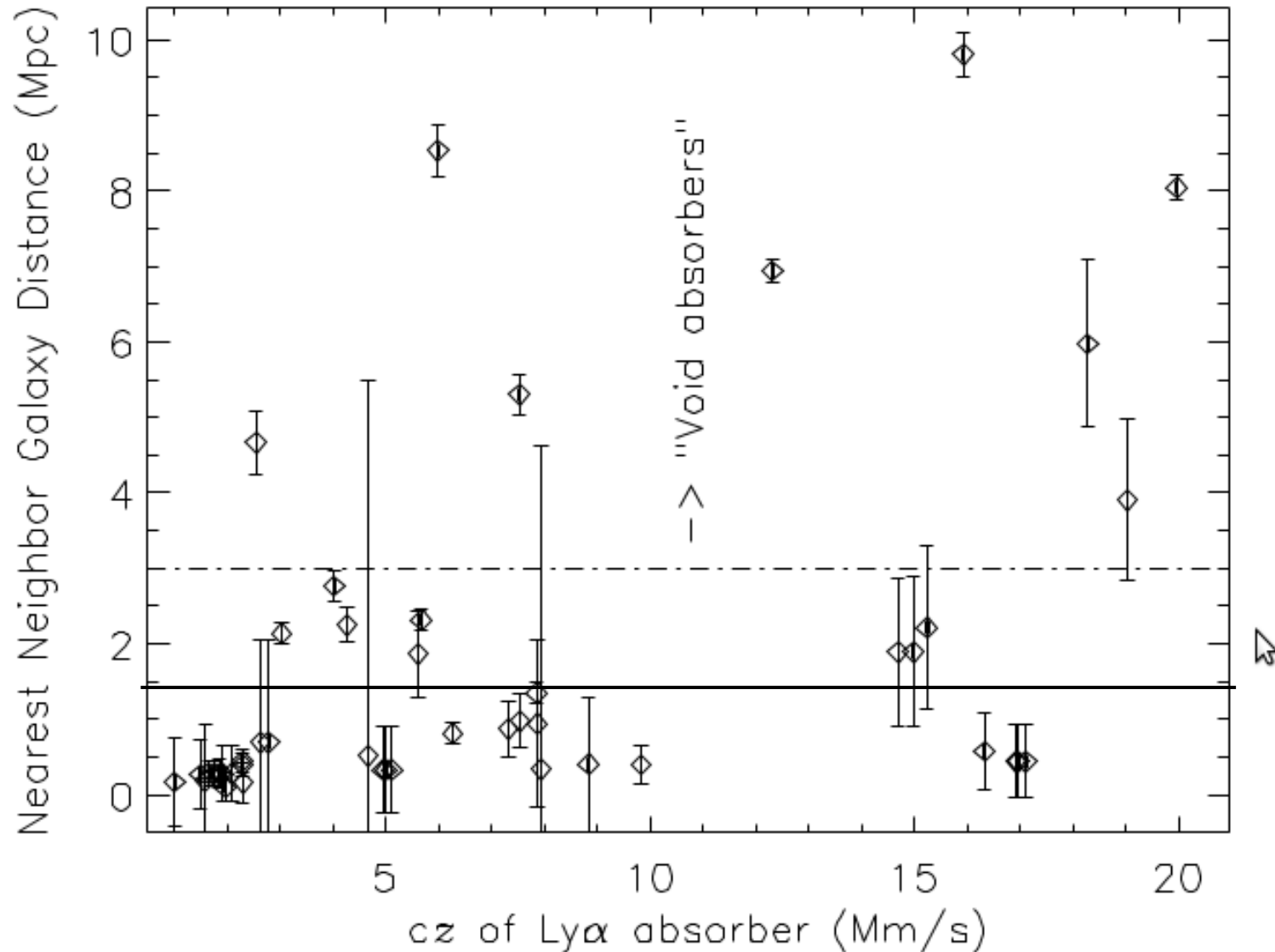
Uncertainties



- **LS93 preferable over Poissonian.**

- **We use 'bootstrap' (BS) though.**

Previous studies



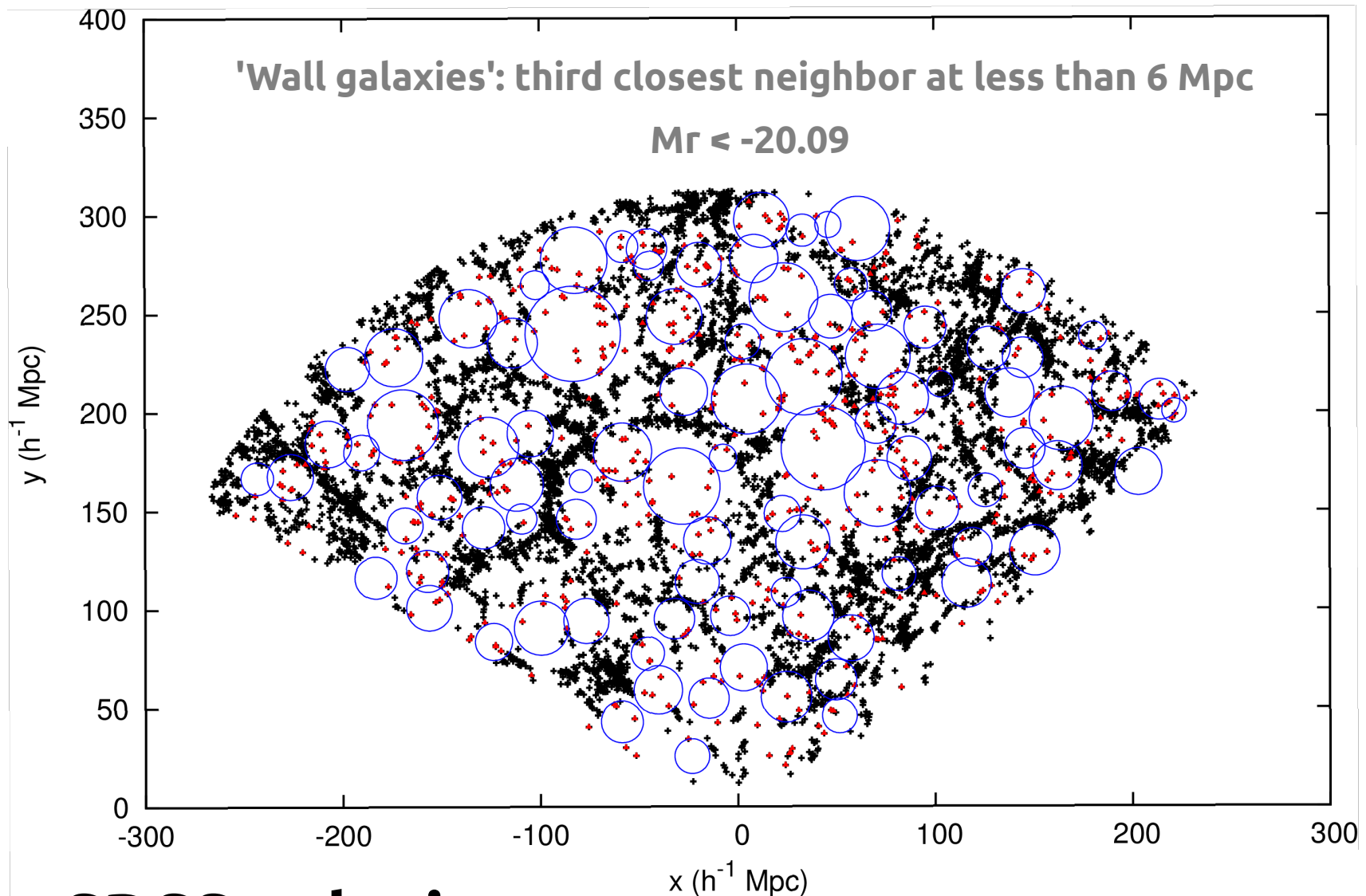
Penton et al. 2002 (see also Manning 2002, Stocke et al. 2007, Wakker & Savage 2009)

A visualization of the cosmic web, showing a dense network of orange and red filaments and nodes. Two specific regions are highlighted with white circles: a larger one at the top labeled 'Virgo Cluster' and a smaller one below it labeled 'Local Group'. The background is a complex, interconnected web of matter.

Virgo Cluster

Local Group

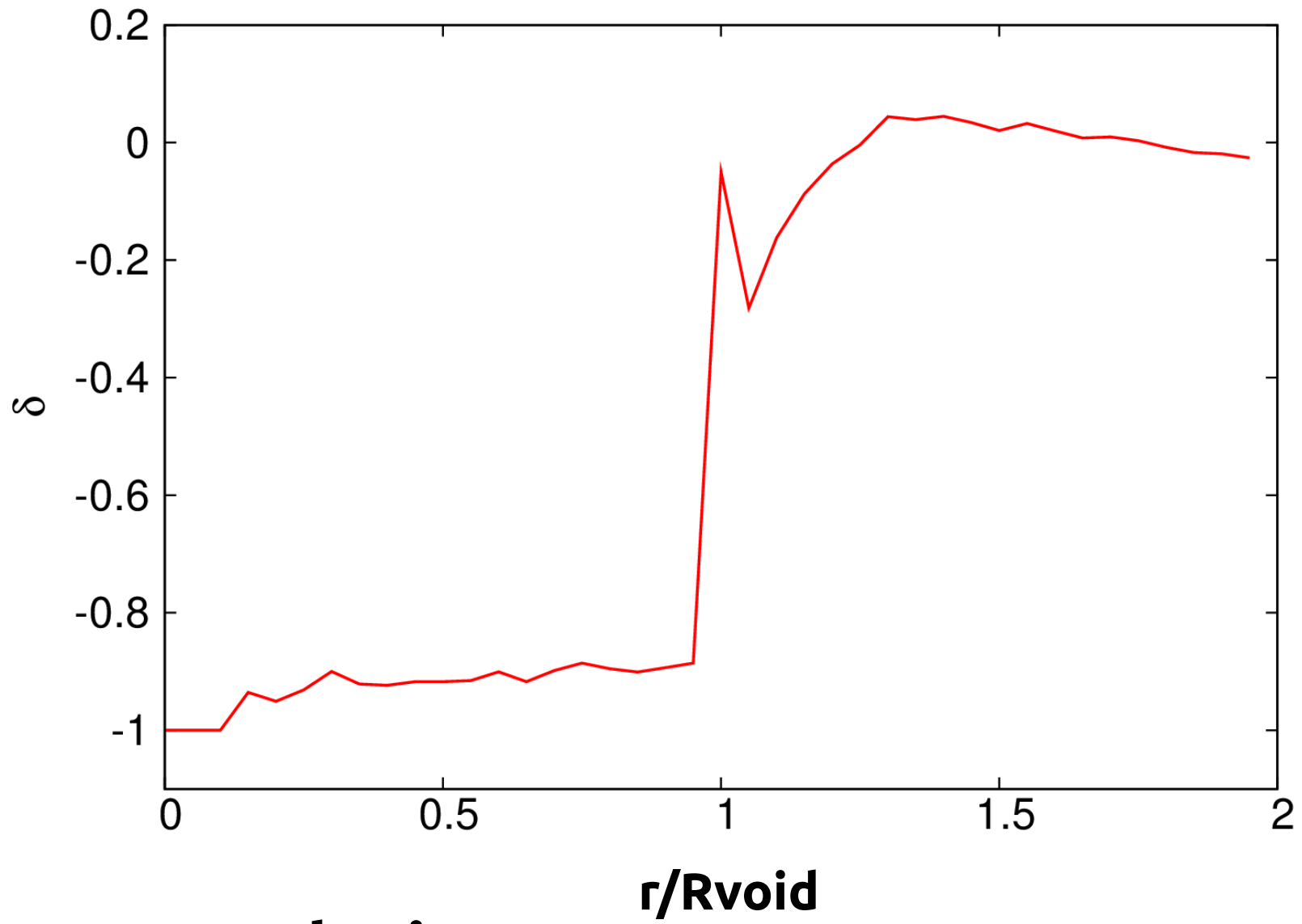
Galaxy void catalog



SDSS galaxies

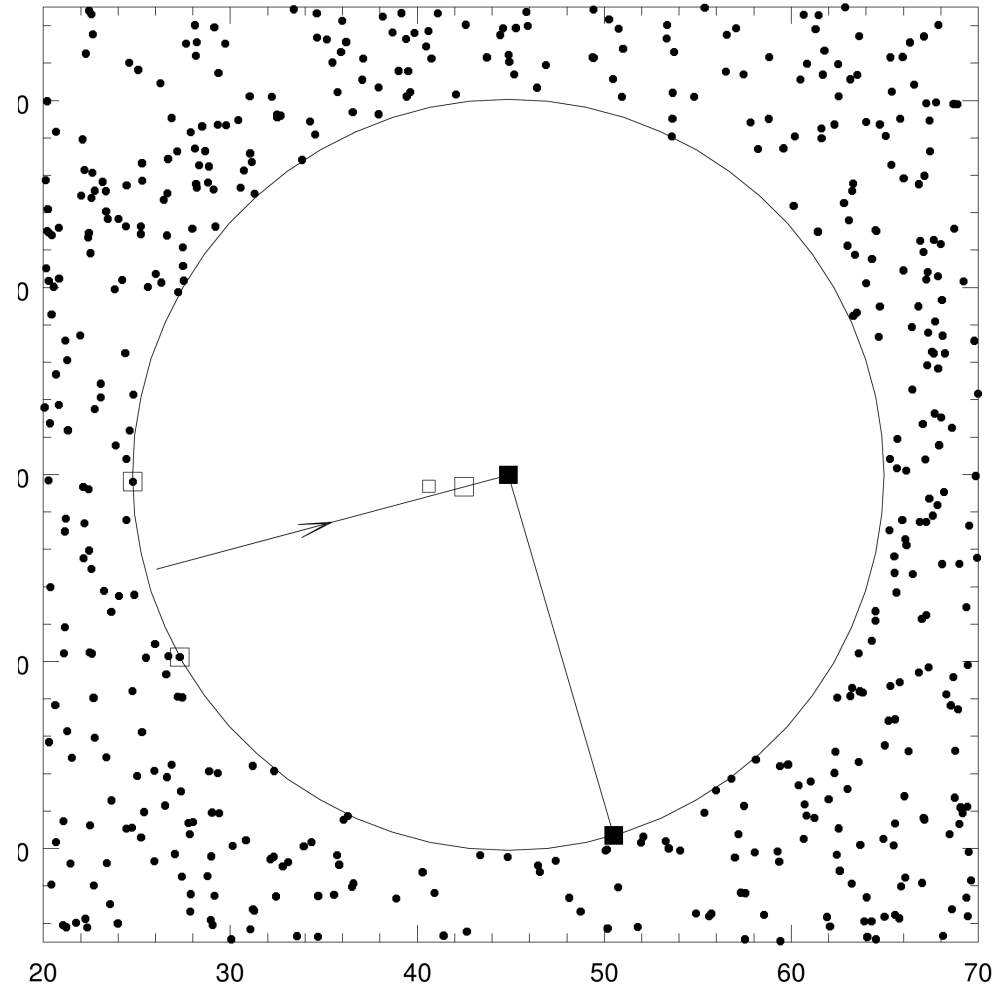
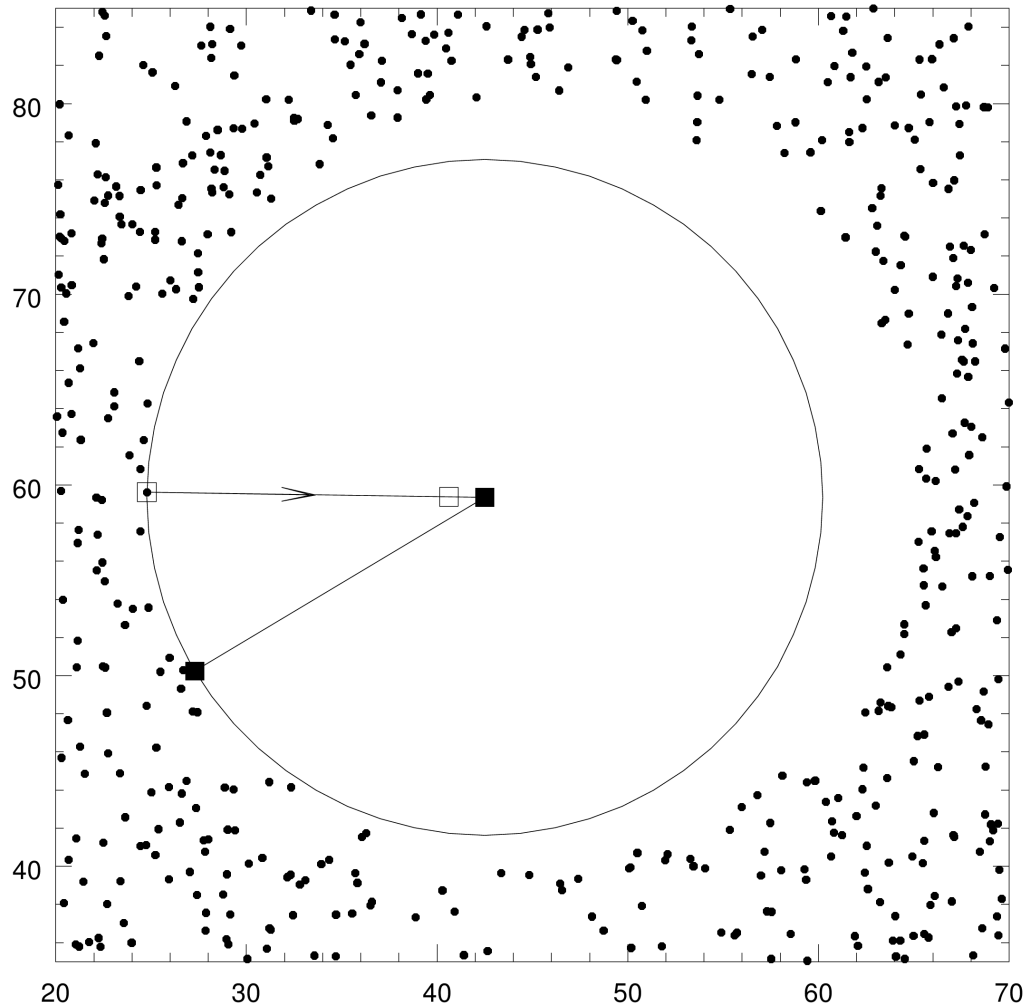
Pan et al. 2012

Galaxy void catalog

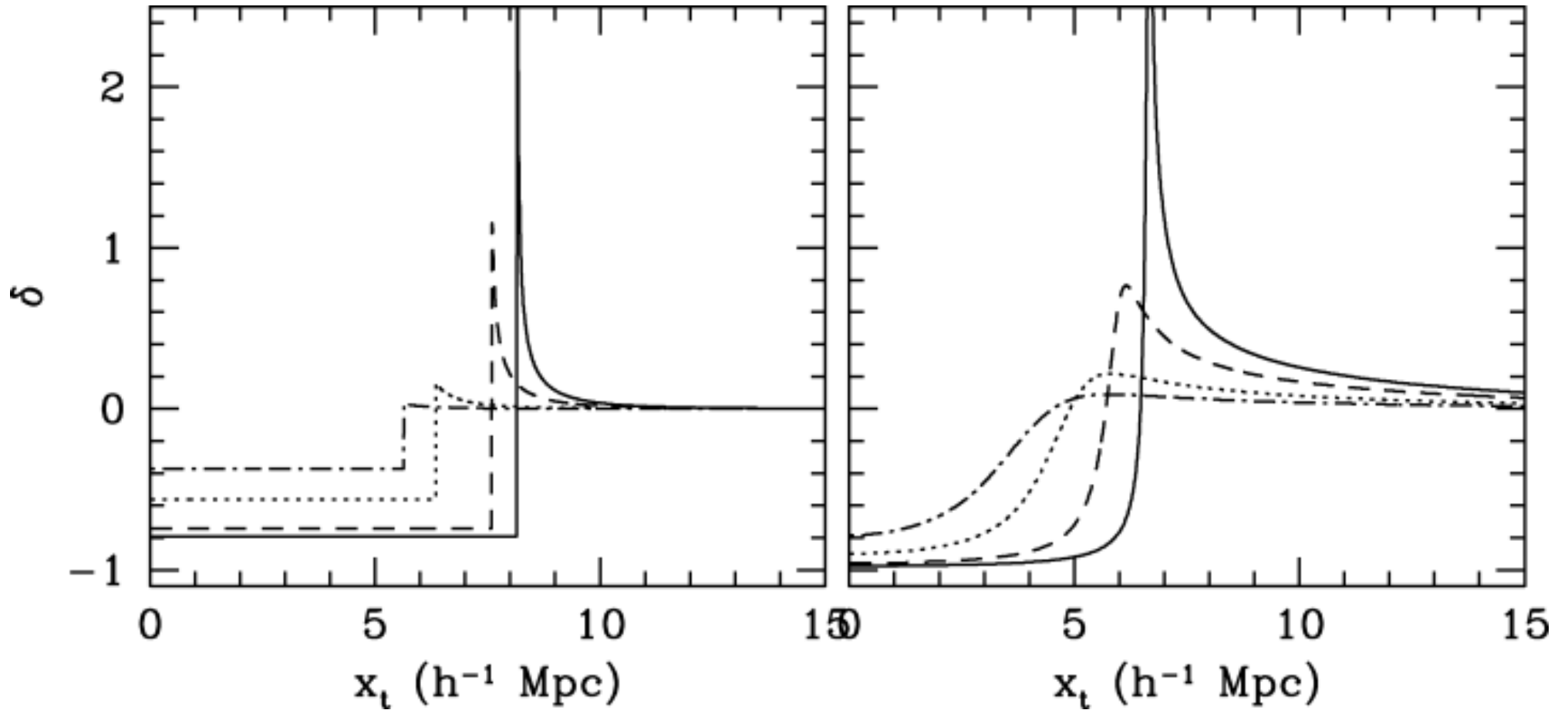


SDSS galaxies

Void Finder Algorithm



Void density profiles



Redshift distribution

