UNIVERSITY OF CALIFORNIA
SANTA CRUZ

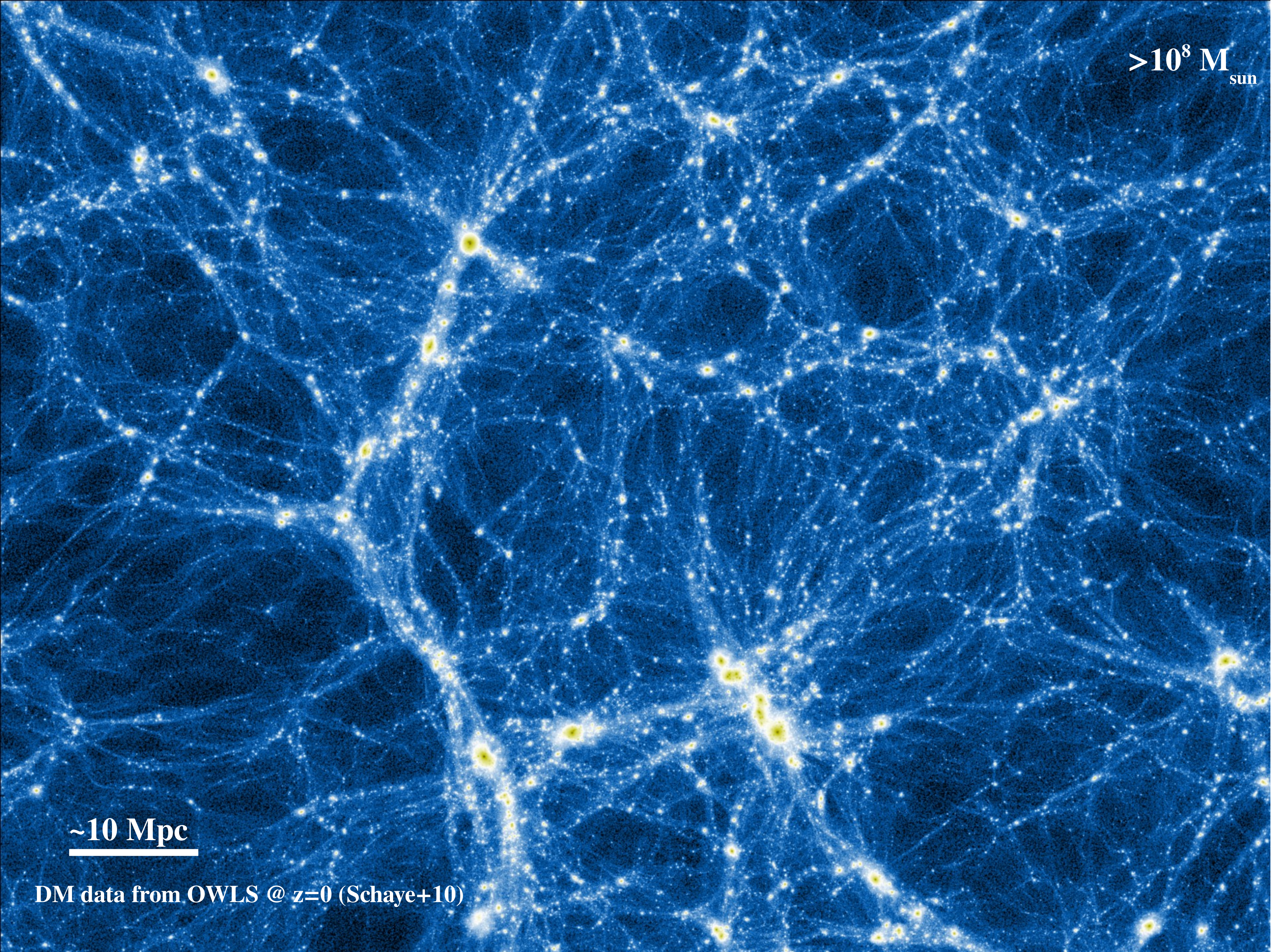
LICK
OBSERVATORY

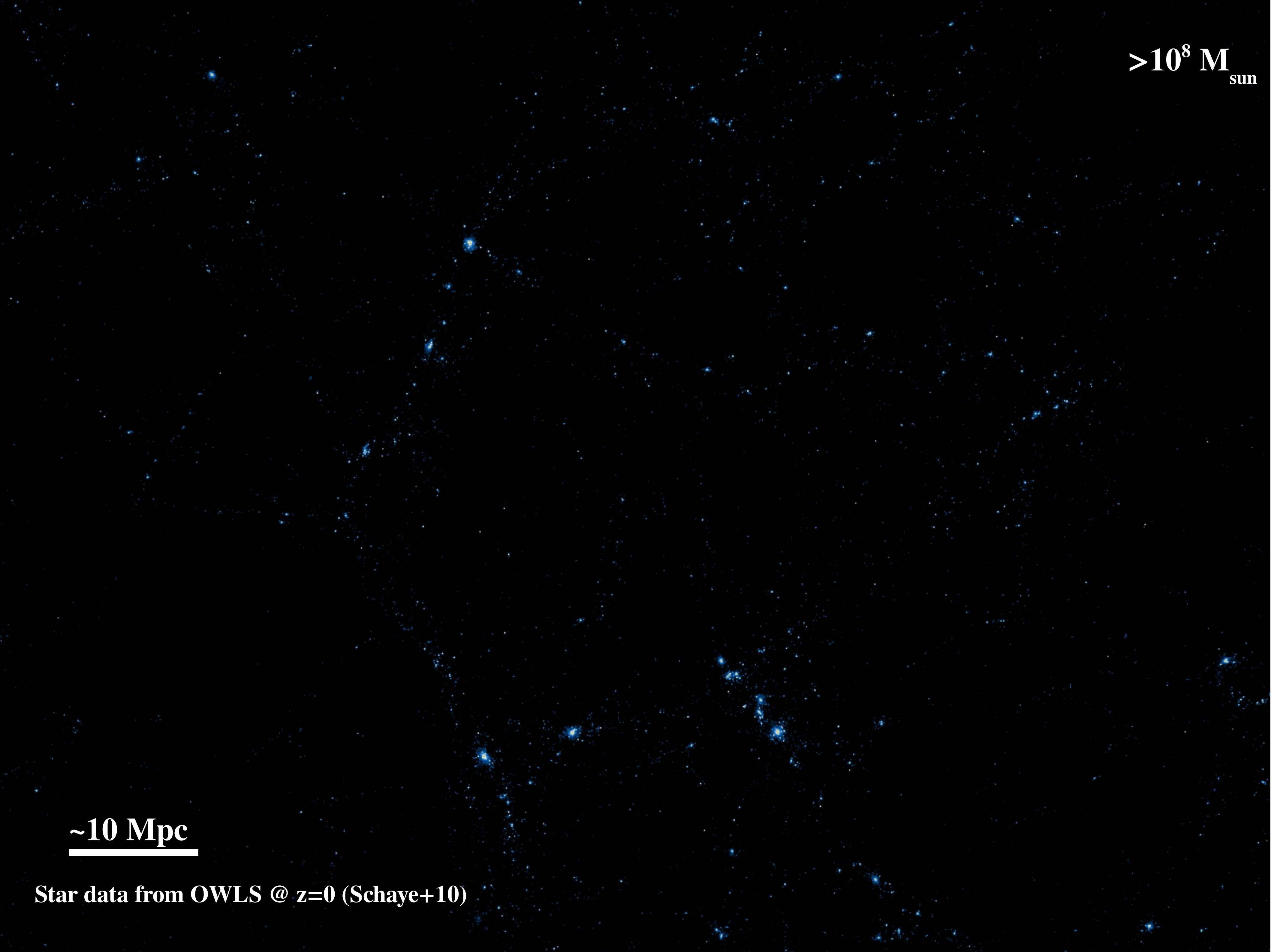
The intergalactic medium in the cosmic web

Nicolas Tejos

(IMPS Fellow, UCO/UCSC)

Xavier Prochaska, Simon Morris, Neil Crighton, Gabriel Altay, Tom Theuns, Charles Finn, et al.


$>10^8$ M_{sun}
~10 Mpc
DM data from OWLS @ z=0 (Schaye+10)


>10^8 M_sun
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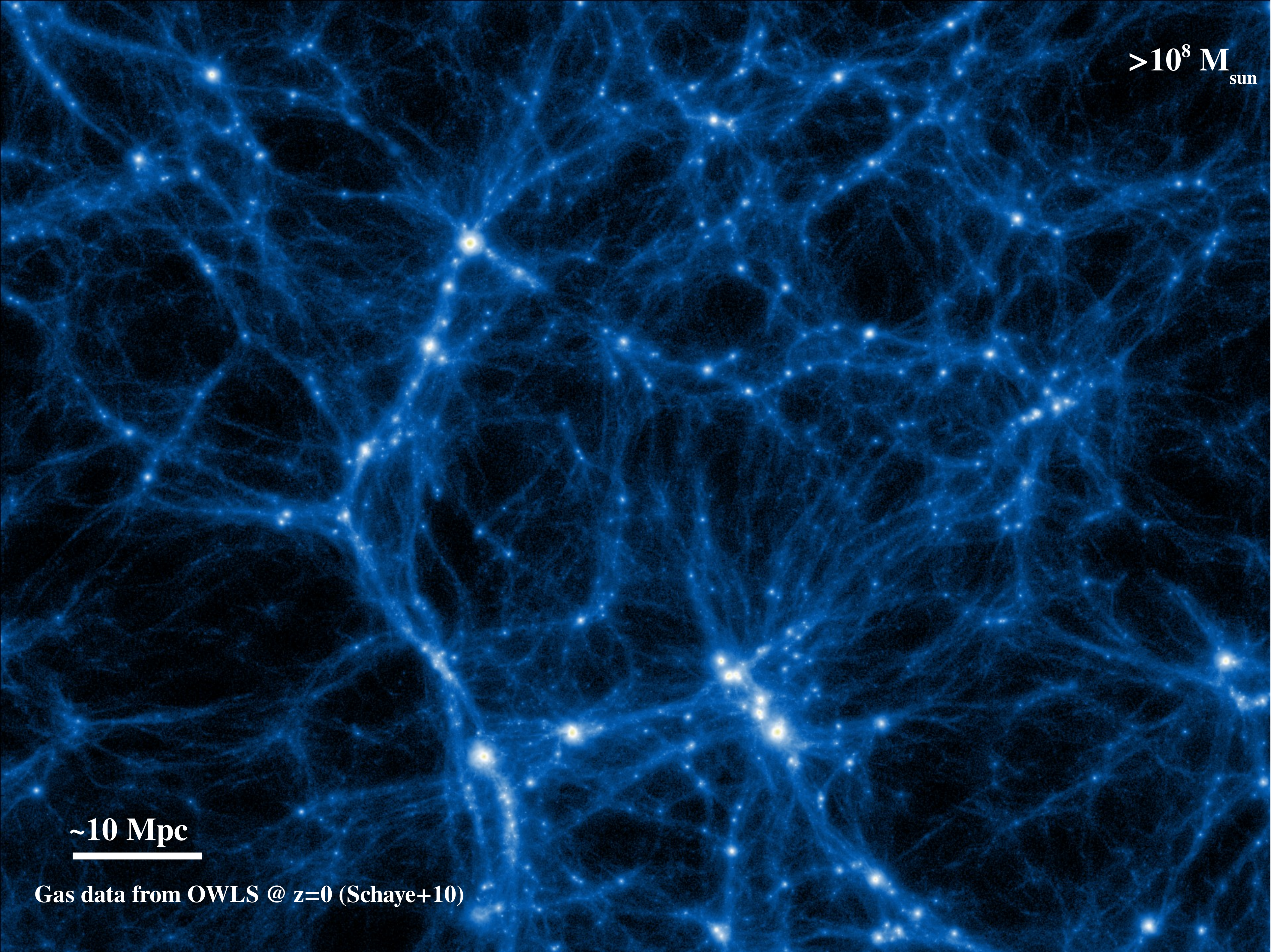
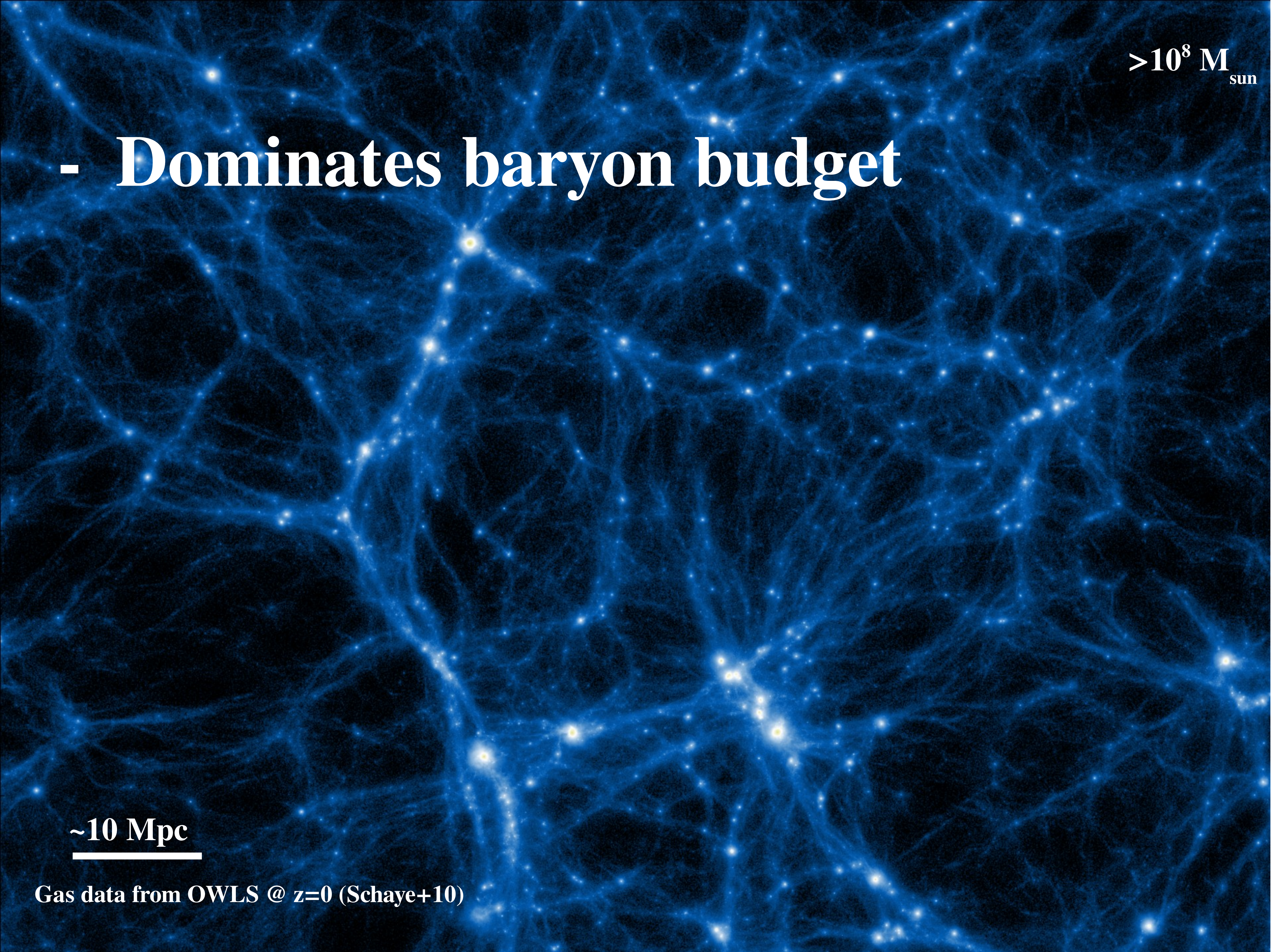
Star data from OWLS @ z=0 (Schaye+10)

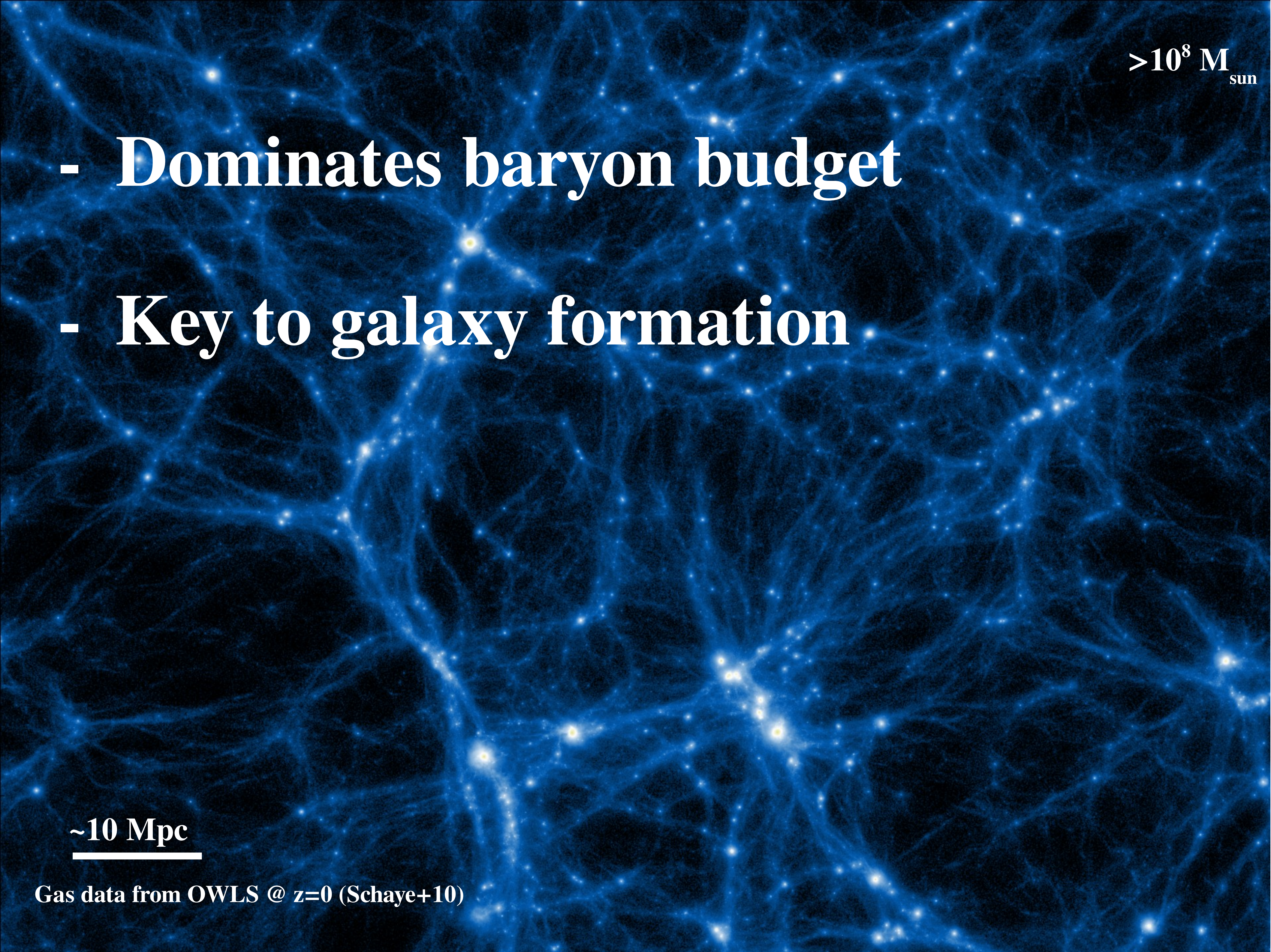


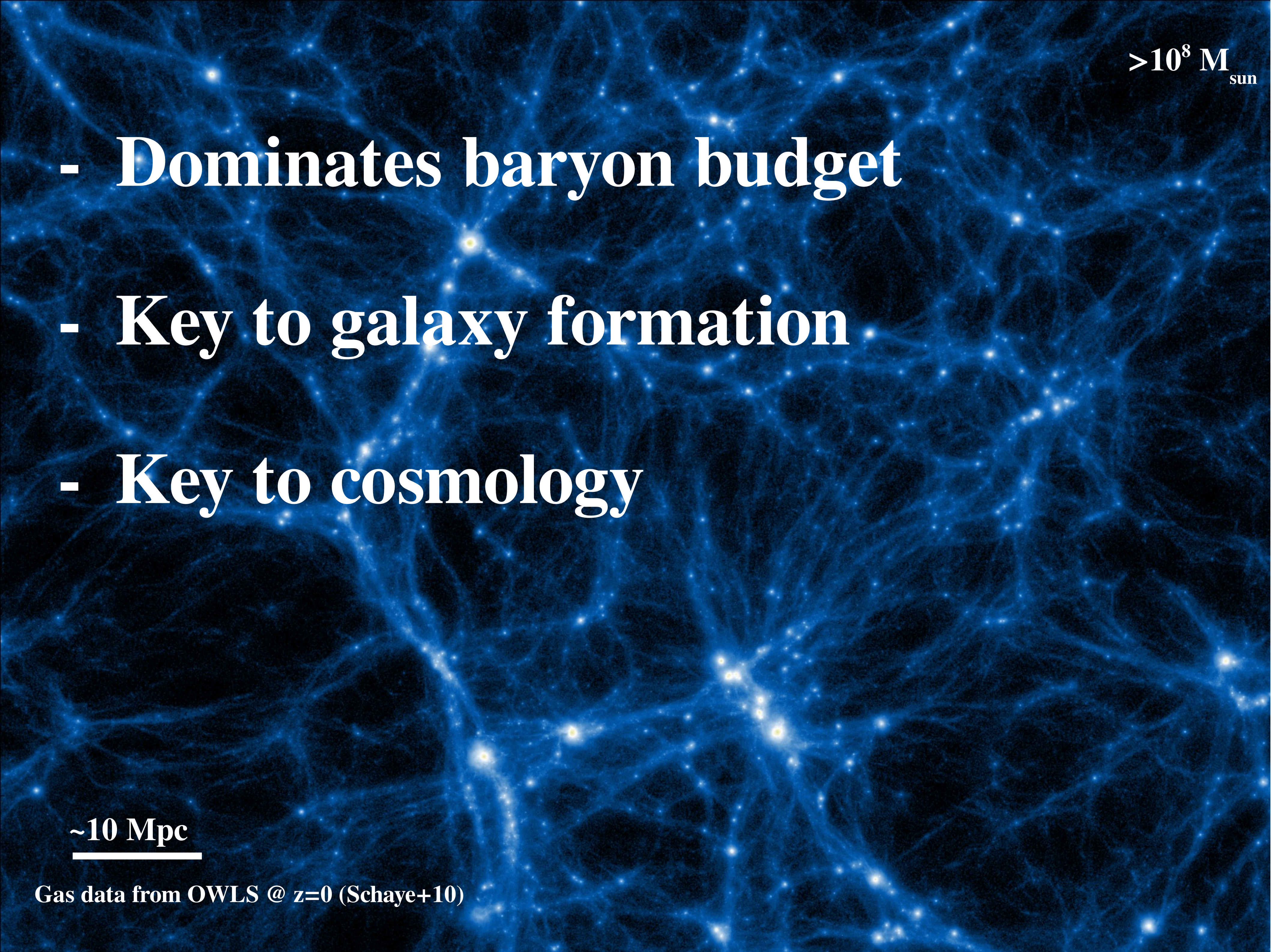
>10^8 M$_{sun}$
~10 Mpc
Gas data from OWLS @ z=0 (Schaye+10)



$>10^8$ M_{sun}
- Dominates baryon budget
~10 Mpc
Gas data from OWLS @ z=0 (Schaye+10)

- Dominates baryon budget
- Key to galaxy formation





- Dominates baryon budget
- Key to galaxy formation
- Key to cosmology

Gas data from OWLS @ z=0 (Schaye+10)

Outline

- **Part I: The IGM-galaxy cross-correlation at z<1**

  (Tejos et al. 2014, MNRAS, 437, 2017)

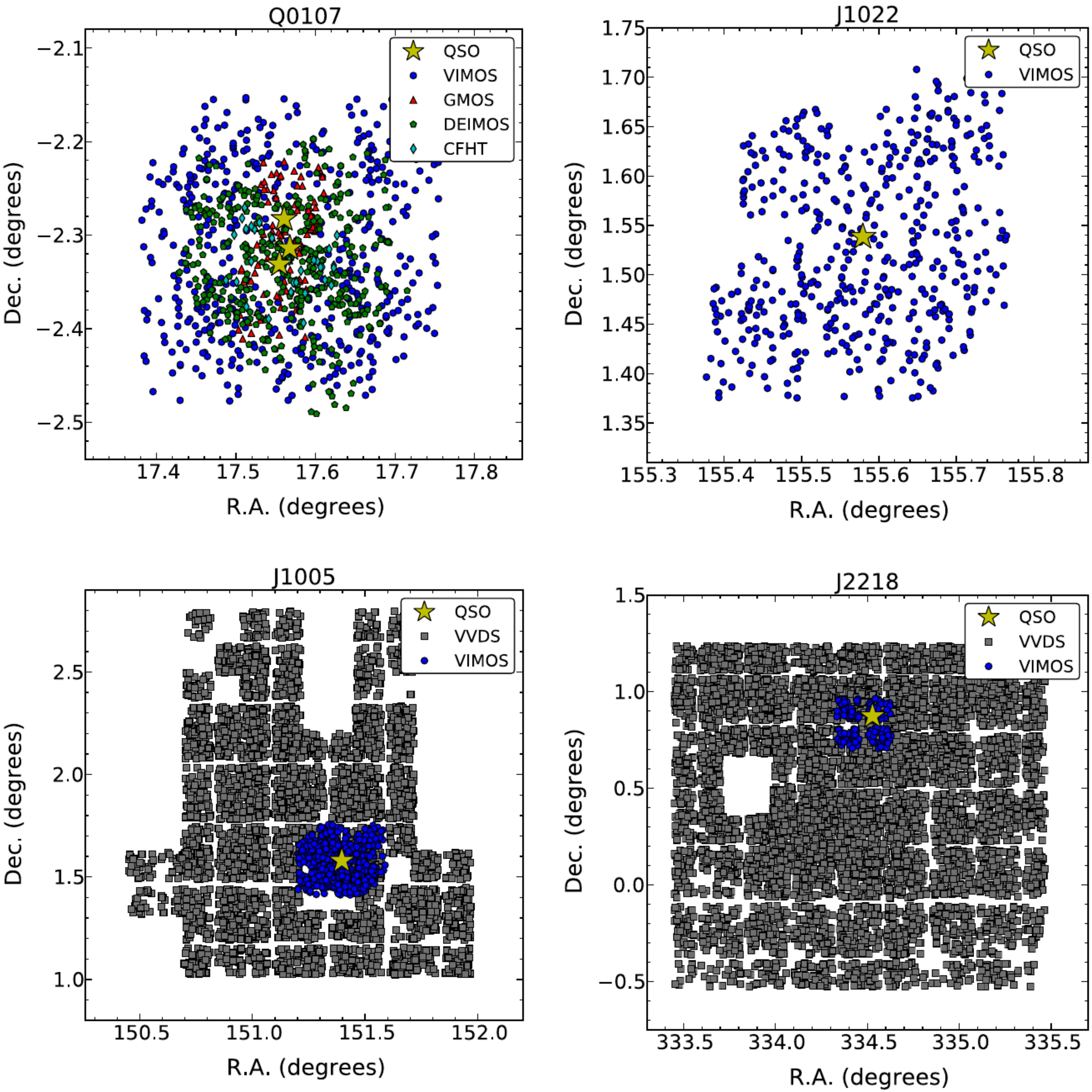
- **Part II: The IGM within and around galaxy voids at z<0.1**
  (Tejos et al. 2012, MNRAS, 425, 245)

- **Part III: The IGM in cosmological filaments at z<0.5**
  (Tejos et al. 2014, in prep.)

- **Summary & Conclusions**

Part I:

The IGM-galaxy cross-correlation at $z<1$



IGM

~700 HI abs. systems

HST/COS

HST/FOS

(138+ orbits)

Galaxies

~17000 galaxies (spec-z)

VLT/VIMOS

Keck/DEIMOS

Gemini/GMOS

+VVDS

(Le Fevre+05,13)

+GDDS

(Abraham+04)

6 fields

Tejos+14

Two-point cross-correlation

- **Definition:**

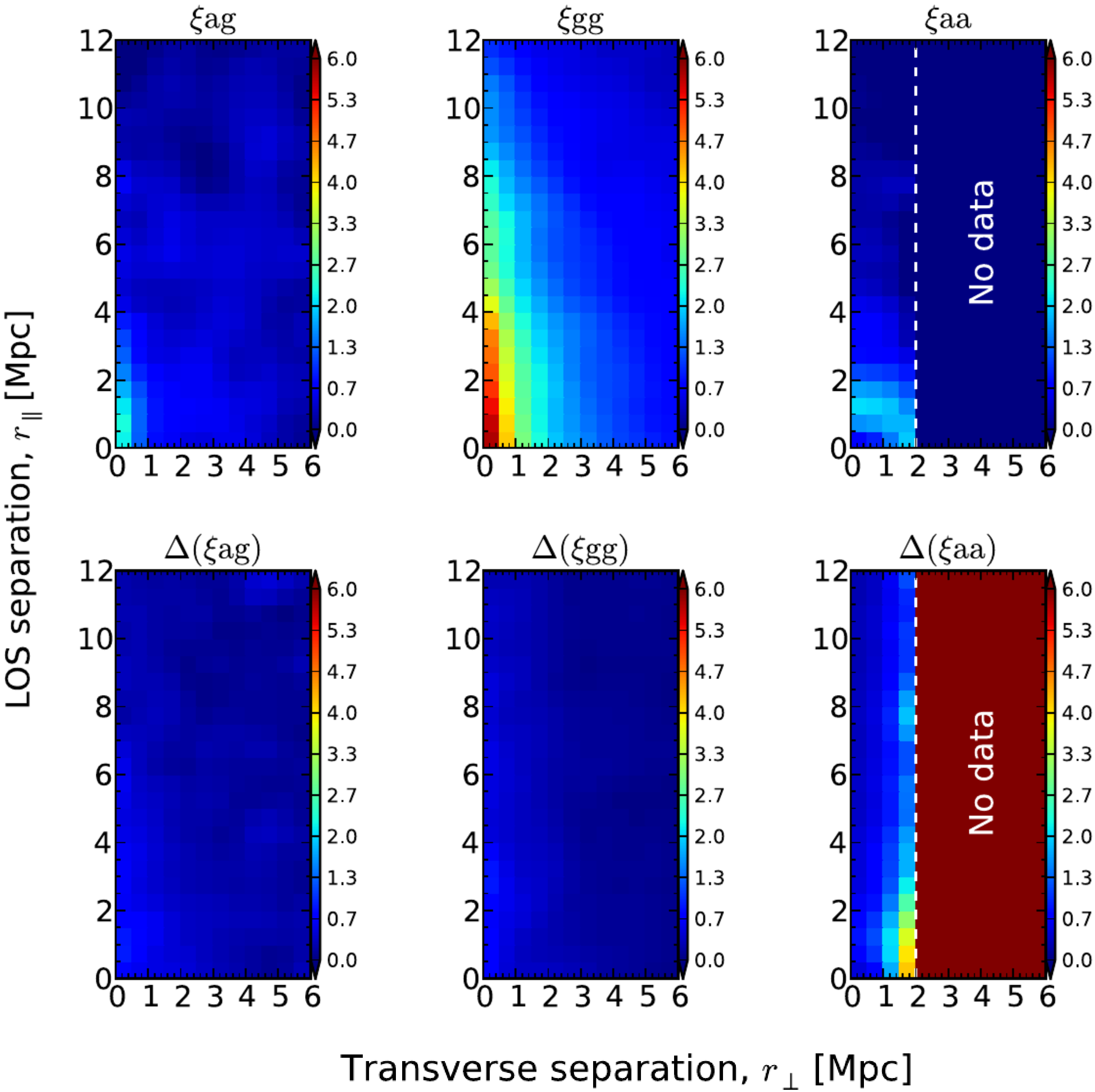
$$\xi_{ab}(r) = \frac{\langle n_a(\vec{r}+r) n_b(\vec{r}) \rangle}{\langle n_a \rangle \langle n_b \rangle} - 1 \ .$$

e.g. Peebles 1980

- **Pairwise 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



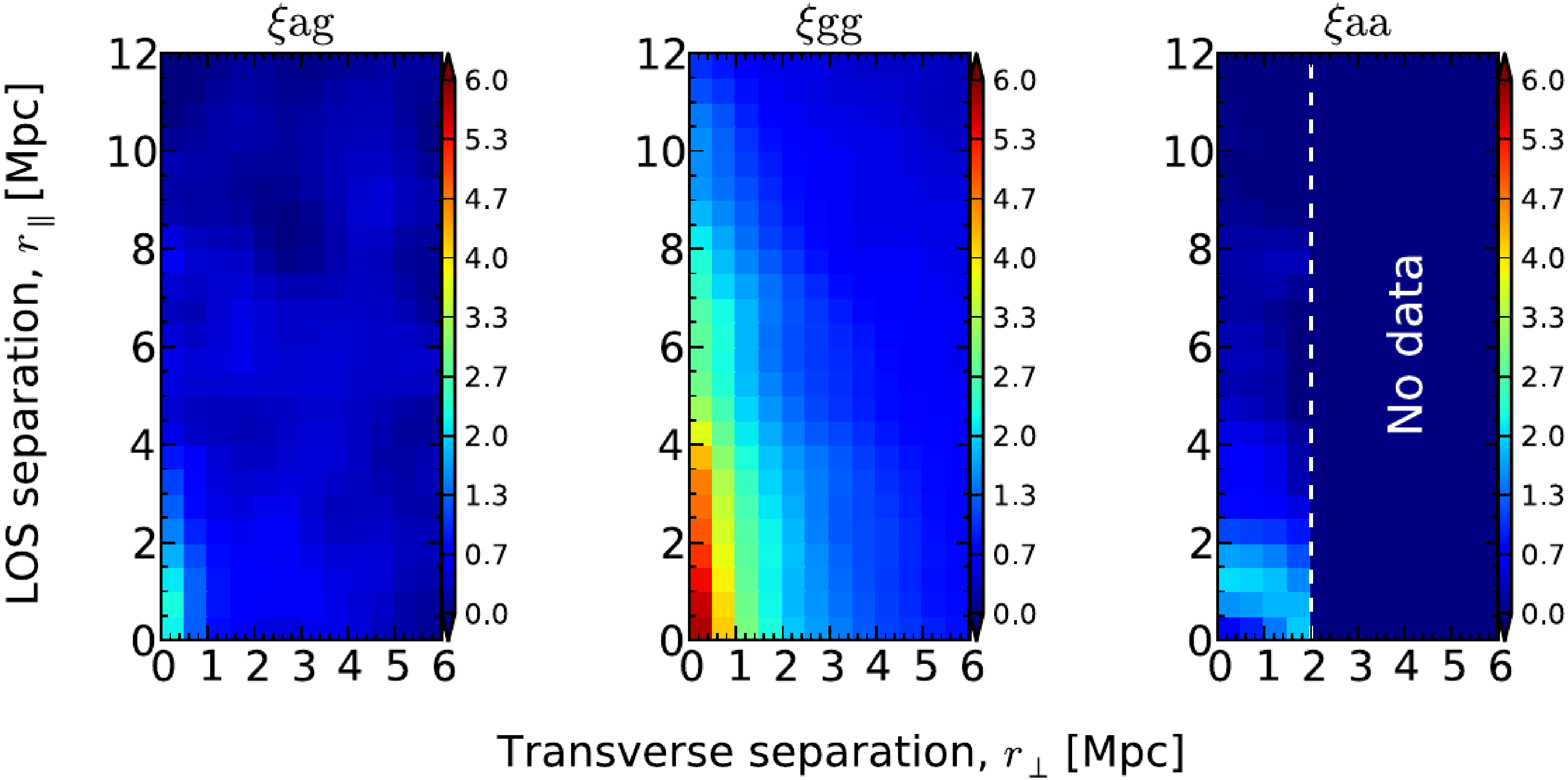
Well constrained measurements
(small uncertainties)

Tejos+14

Part I:

Key results

Test linear dependence



Because we have measured these 3 quantities from the same dataset and independently from each other

Tejos+14

Linear dependence

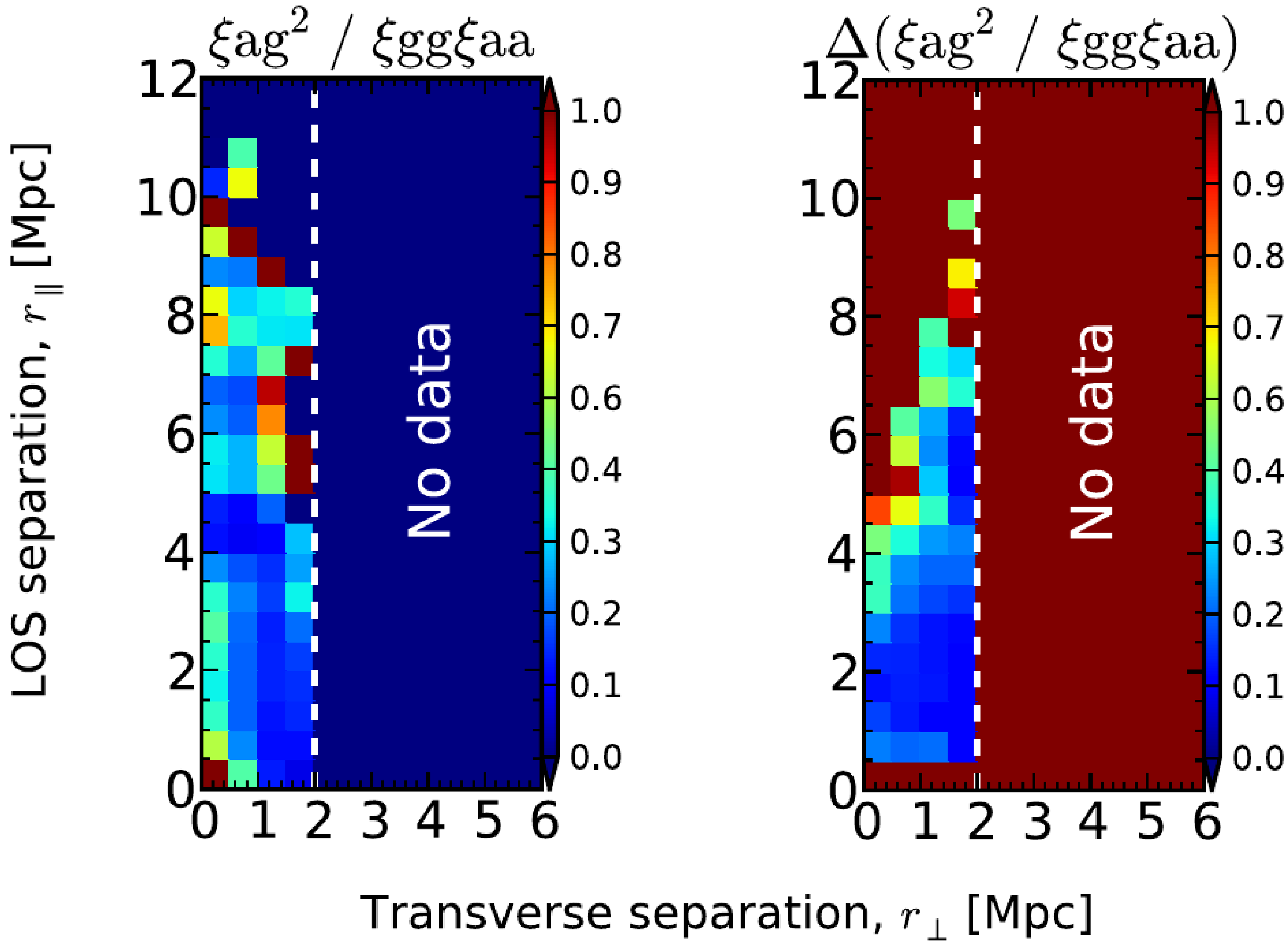
$$\xi_{gg} = b_g^2 \xi_{DM}$$

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

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

$$\Rightarrow \frac{\xi_{ag}^2}{\xi_{gg}\xi_{aa}} = 1$$

HI and galaxies do not trace same structures

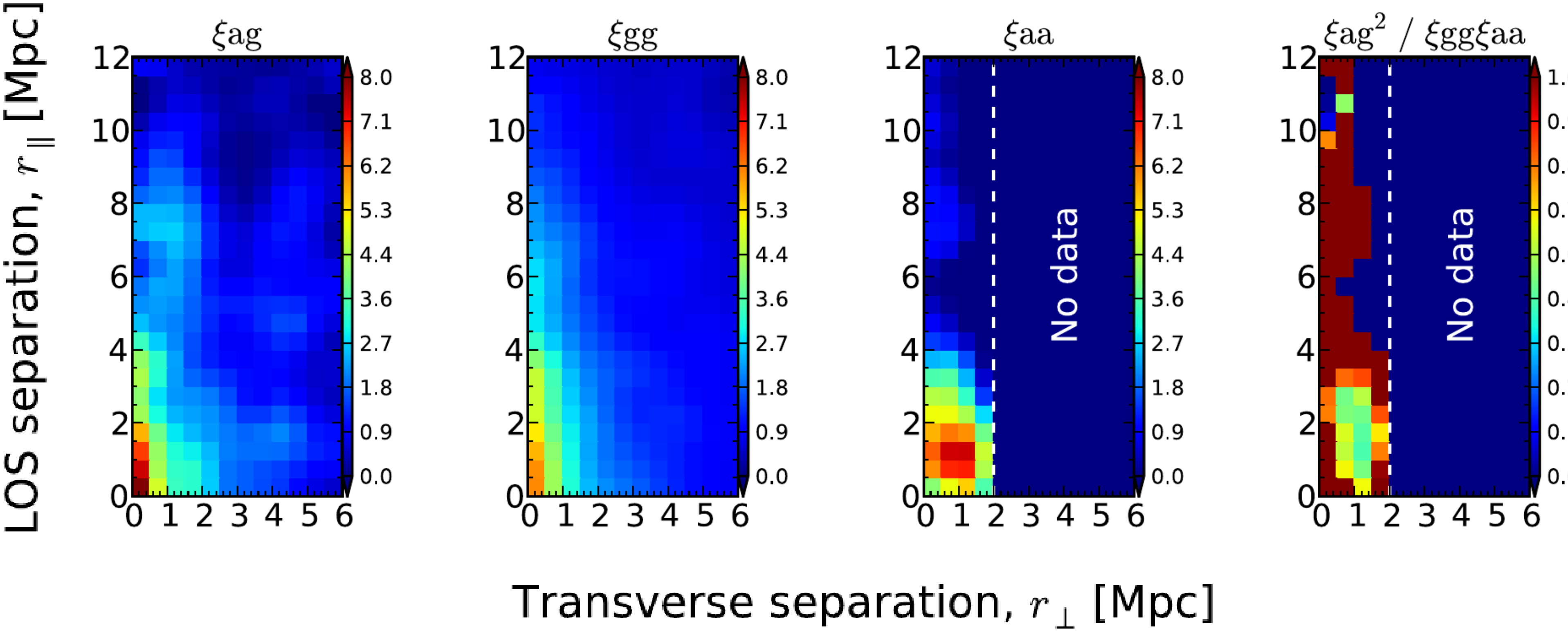


Tejos+14

Part I:

Subsamples

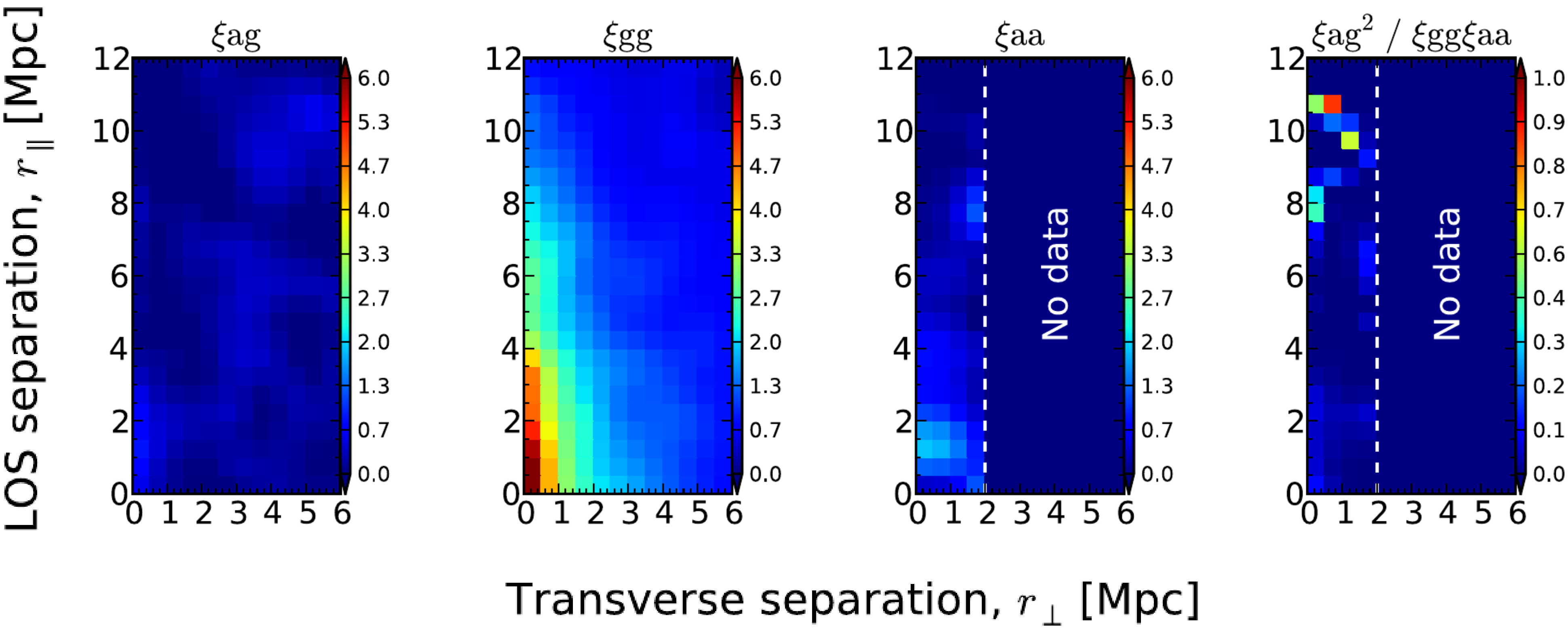
'Strong' HI systems and star-forming galaxies



N_{HI}>10^{14} cm^{-2} HI systems and star-forming galaxies
***do* trace the same structures**

Tejos+14

'Weak' HI systems and star-forming galaxies



N_{HI}<10¹⁴ cm⁻² HI systems and star-forming galaxies

***do not* trace the same structures**

Tejos+14

Part I:

Interpretation

>50% of 'weak' HI systems reside in galaxy voids and hence not correlated with galaxies.

~100% of star-forming galaxies and ~100% of 'strong' HI systems share the same locations in the cosmic web.

(~25% of non-star-forming galaxies reside in galaxy clusters and are not correlated with HI systems; the rest 75% share locations with 'strong' HI and star-forming galaxies.)

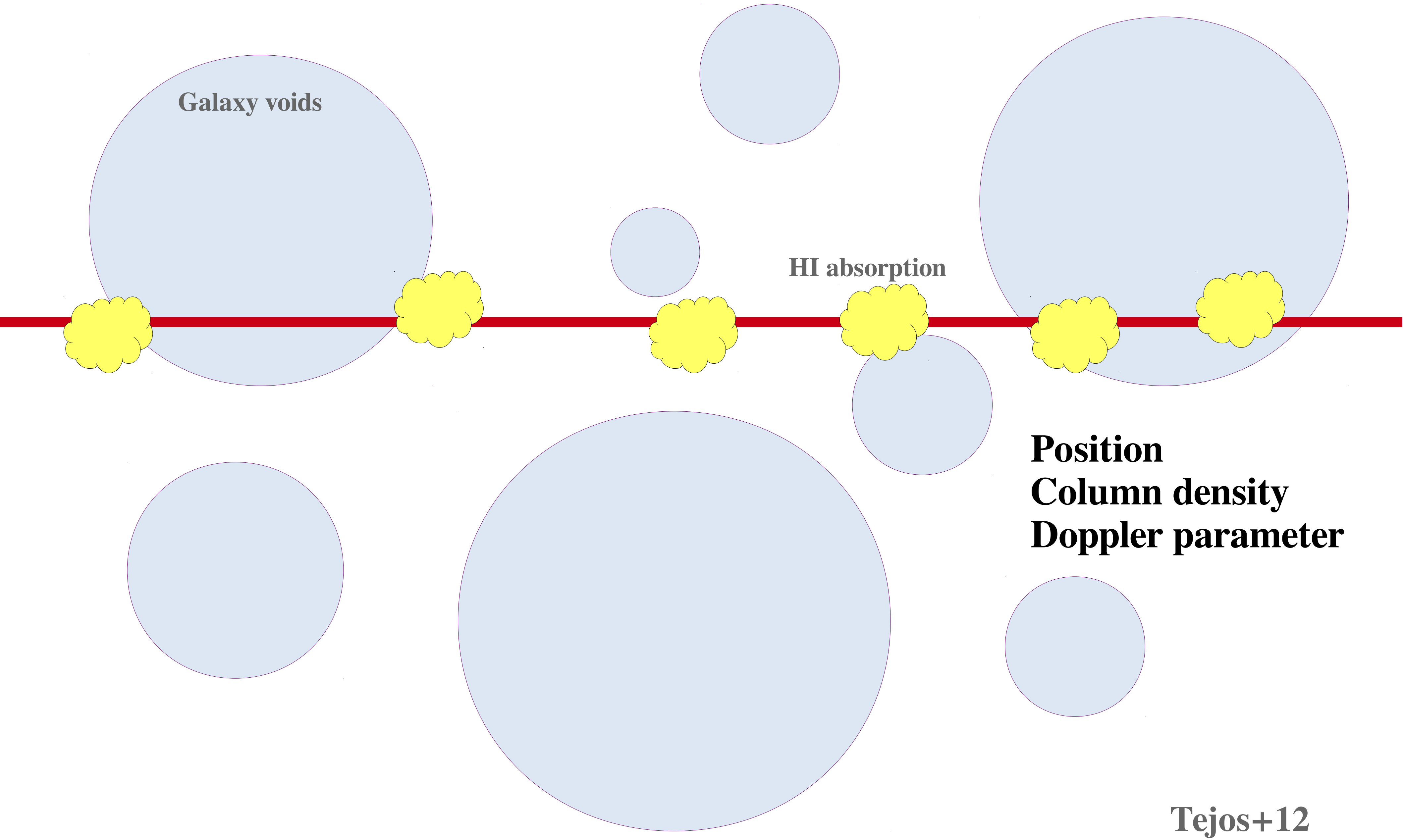
~10 Mpc

Star data from OWLS @ z=0 (Schaye+10)

Part II:

IGM *within* and *around* galaxy voids at z<0.1

Experimental design



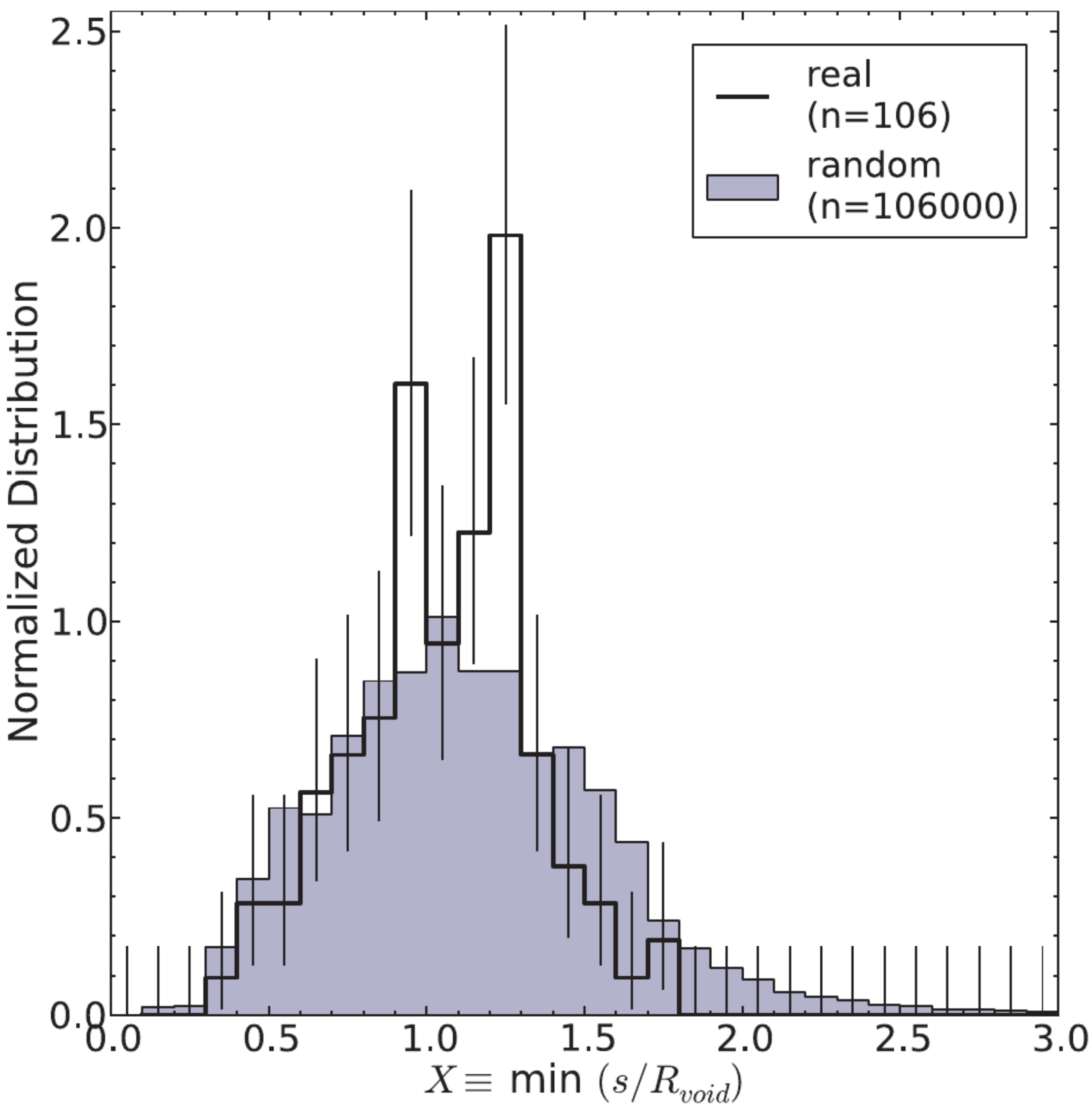
Position
Column density
Doppler parameter

Tejos+12

Part II:

Results

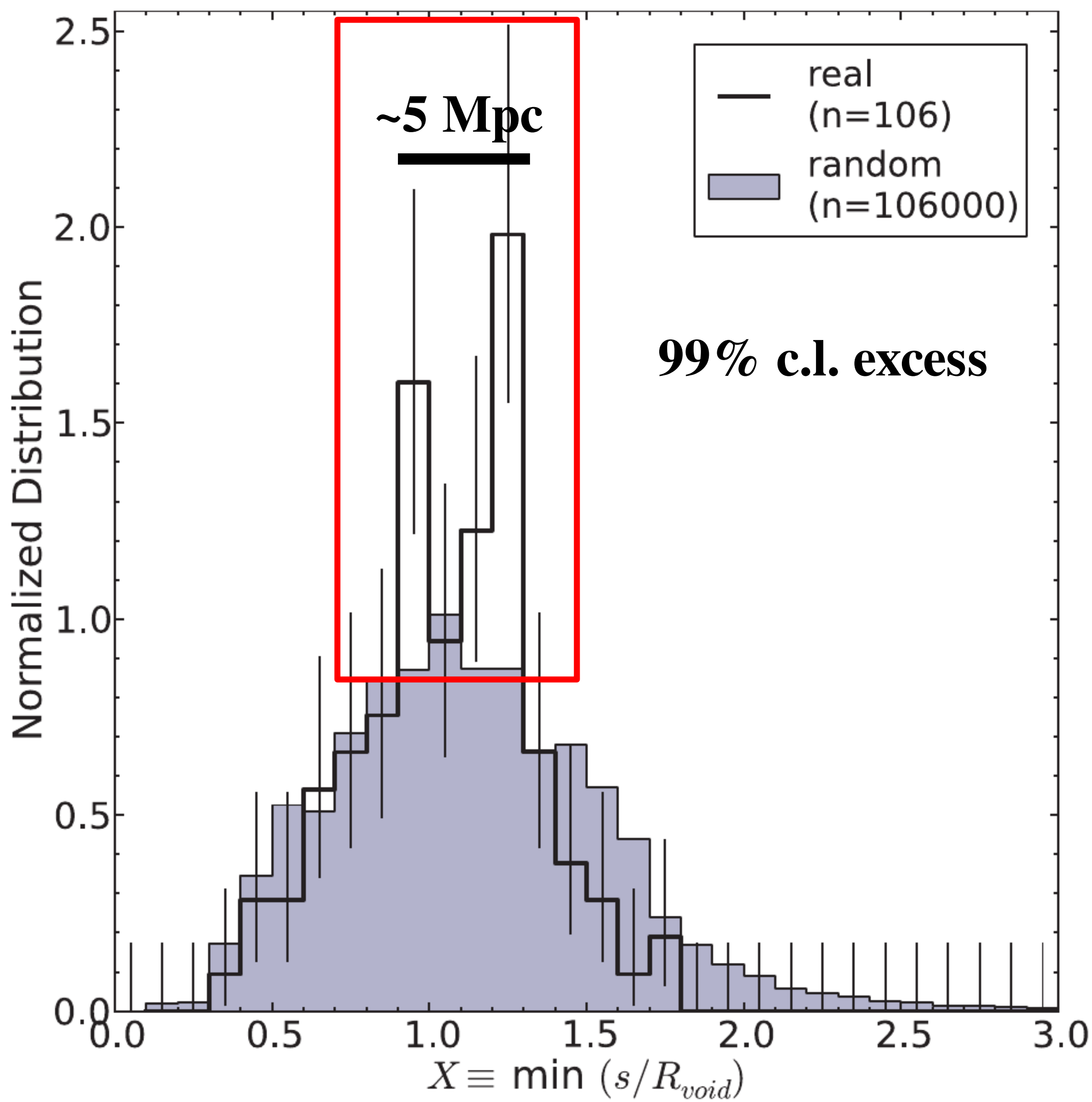
HI distribution w/r 'voids'



1054 galaxy voids at z<0.1 (Pan+12)
106 HI absorption systems (Danforth & Shull 2008)

Tejos+12

HI distribution w/r 'voids'

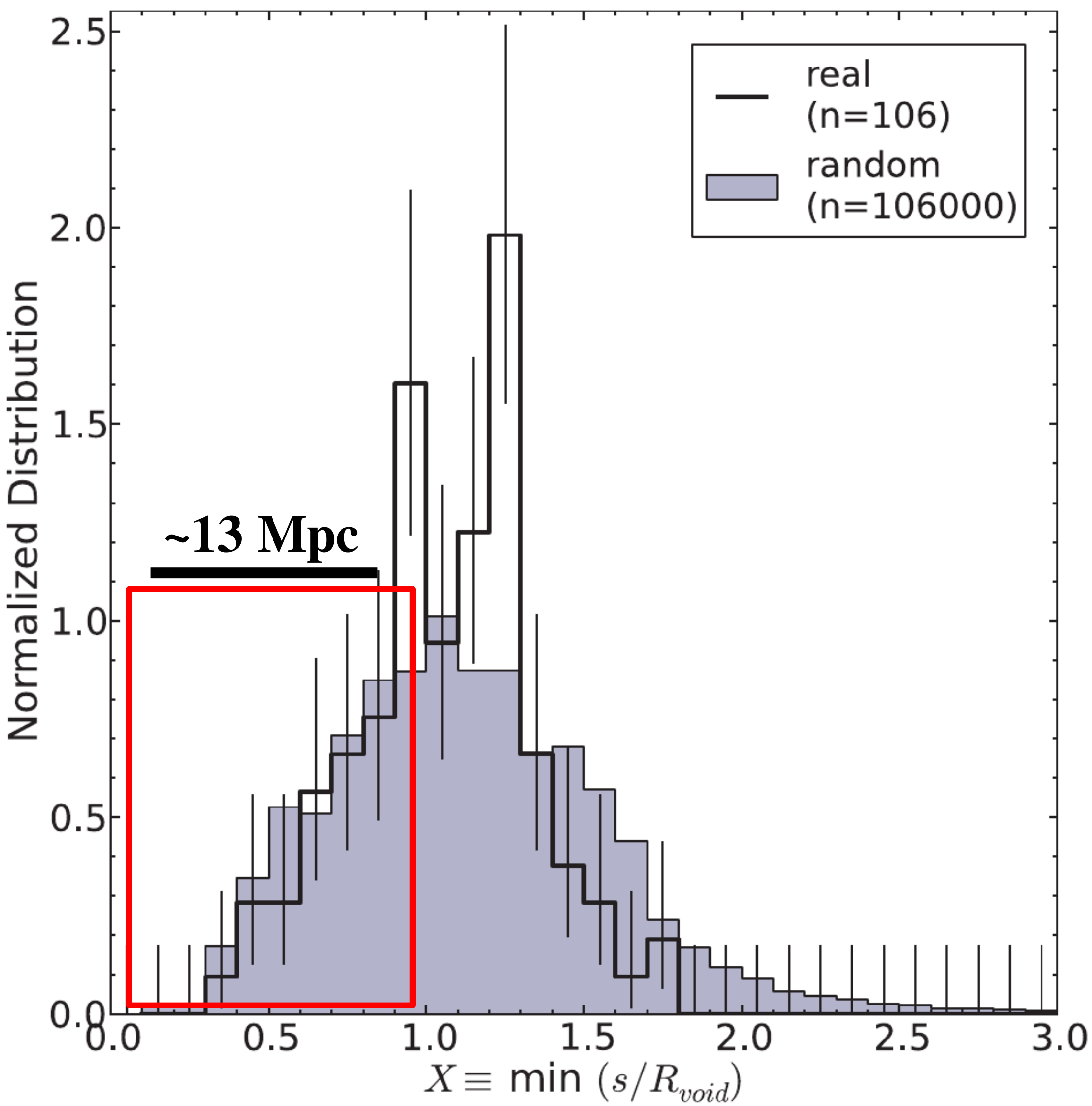


Statistically significant excess of HI at the edges of galaxy voids

1054 galaxy voids at z<0.1 (Pan+12)
106 HI absorption systems (Danforth & Shull 2008)

Tejos+12

HI distribution w/r 'voids'



Statistically significant excess of HI at the edges of galaxy voids

No significant deficit of HI inside galaxy voids!

1054 galaxy voids at z<0.1 (Pan+12)
106 HI absorption systems (Danforth & Shull 2008)

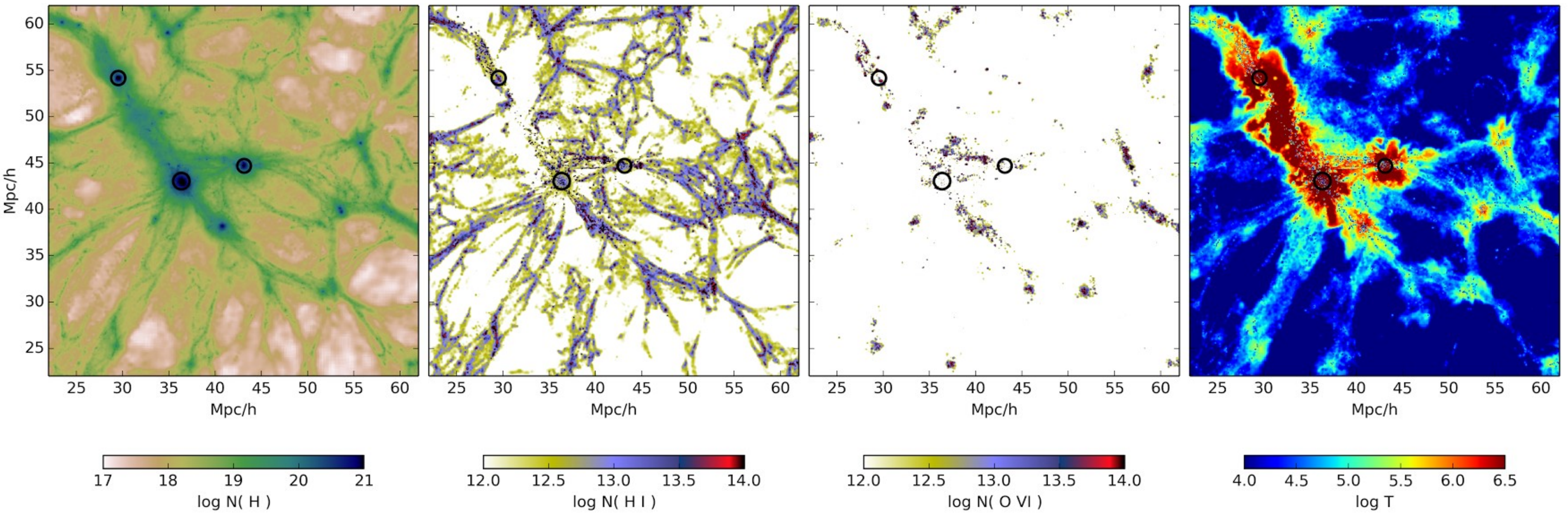
Tejos+12

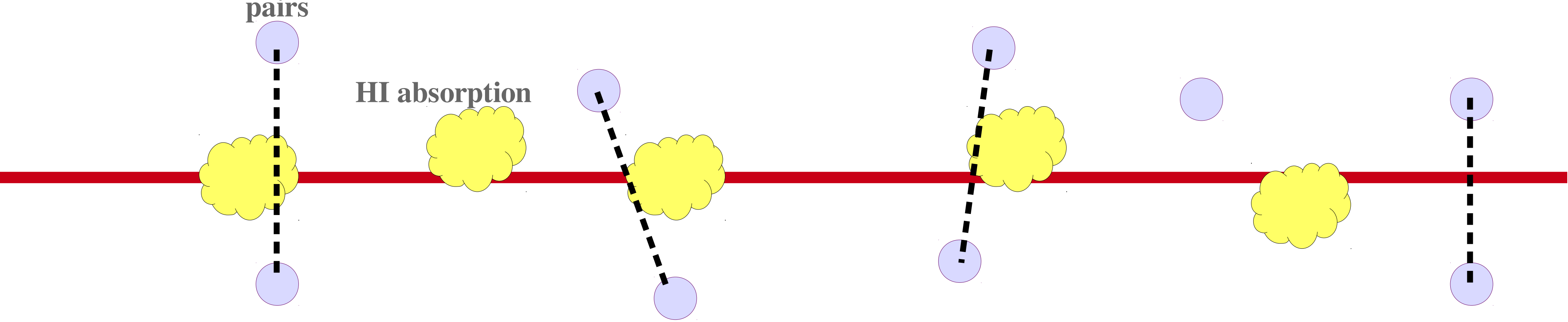
Part III:

The IGM in cosmological filaments at $z<0.5$

Experimental design

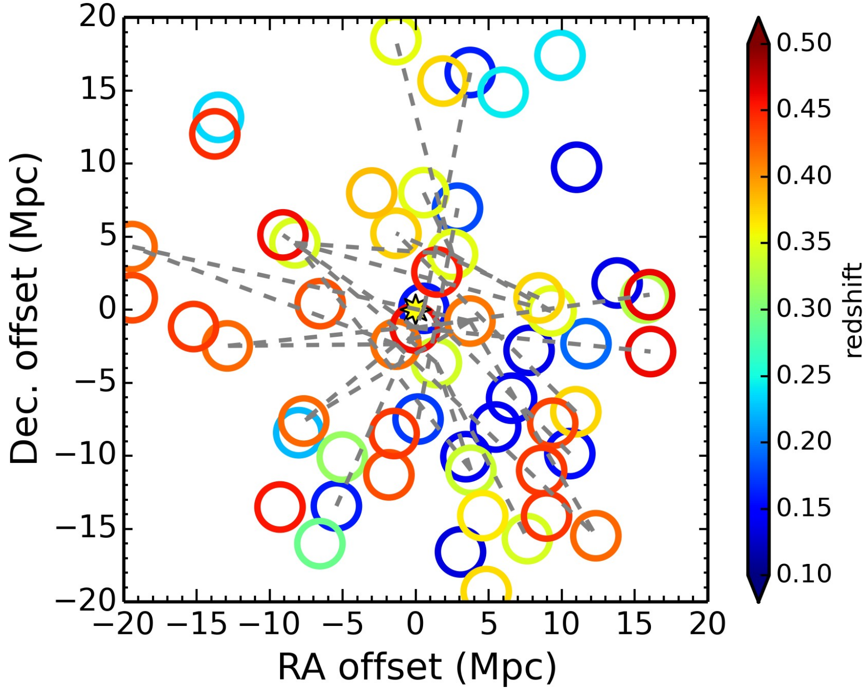
Data from OWLS (Schaye+10)

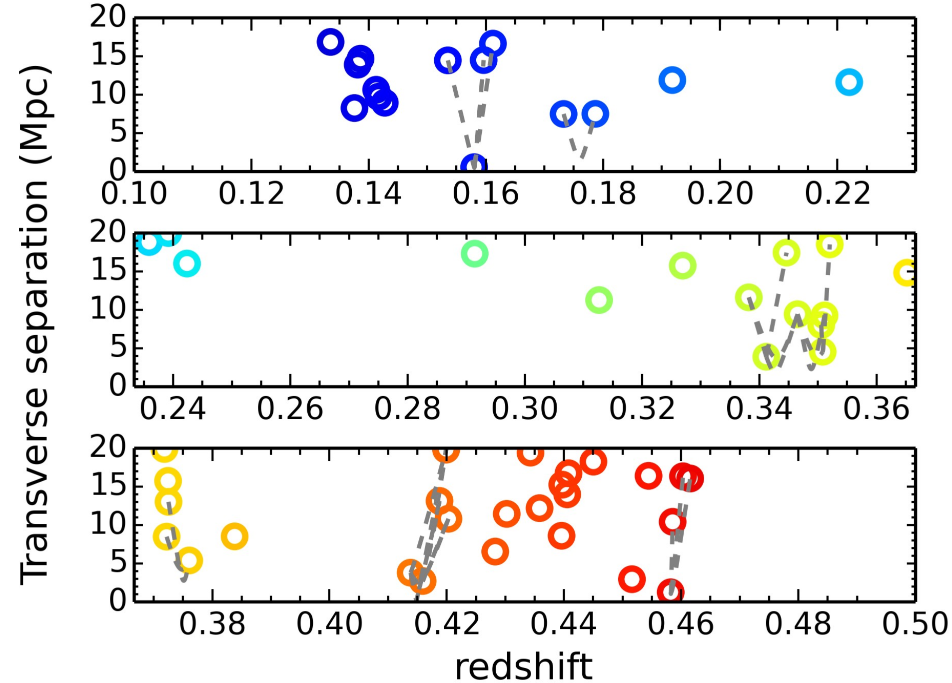




Data

- **HST/COS** (12 orbits)
- 1 QSO whose sightline intersects **7 independent (27 total)** cluster-pairs
- The random expectations are **~1.6 ± 1.5 independent (~3.5 ± 4.2 total)**
- Clusters from redMapper catalog (Rykoff+14)

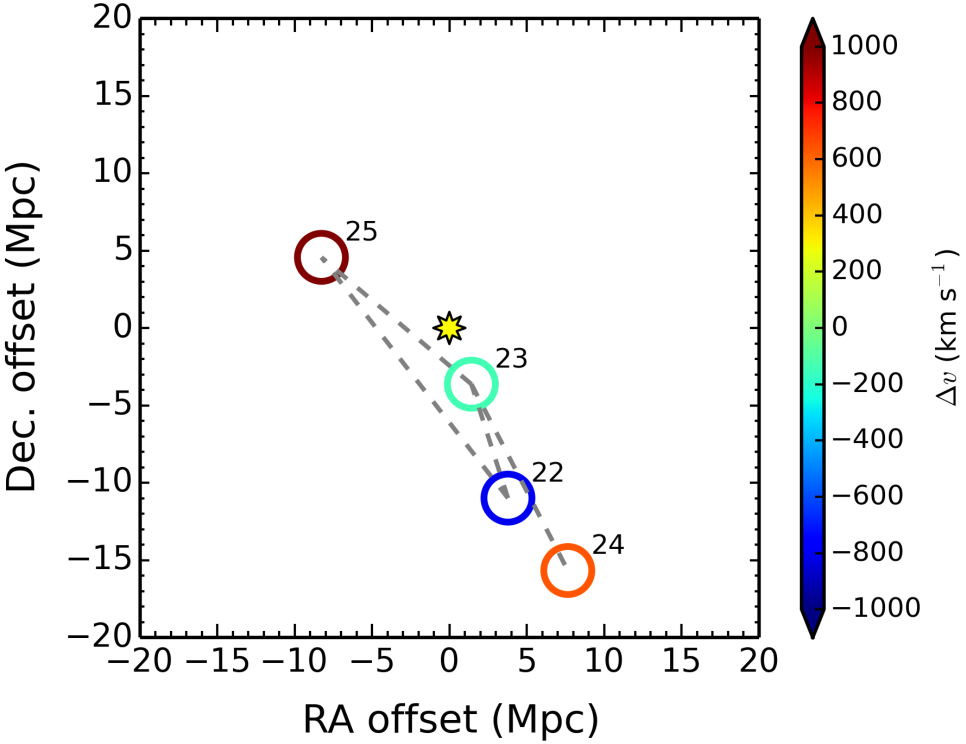


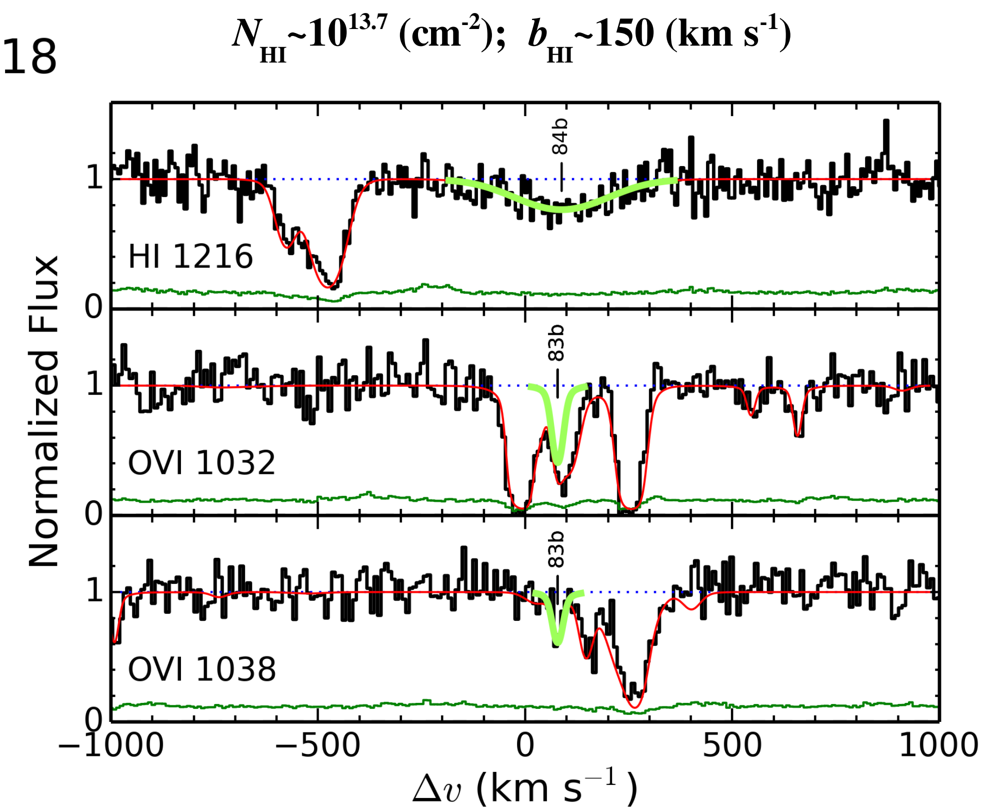


This is a highly exceptional sightline!

Tejos+14b in prep.

Examples



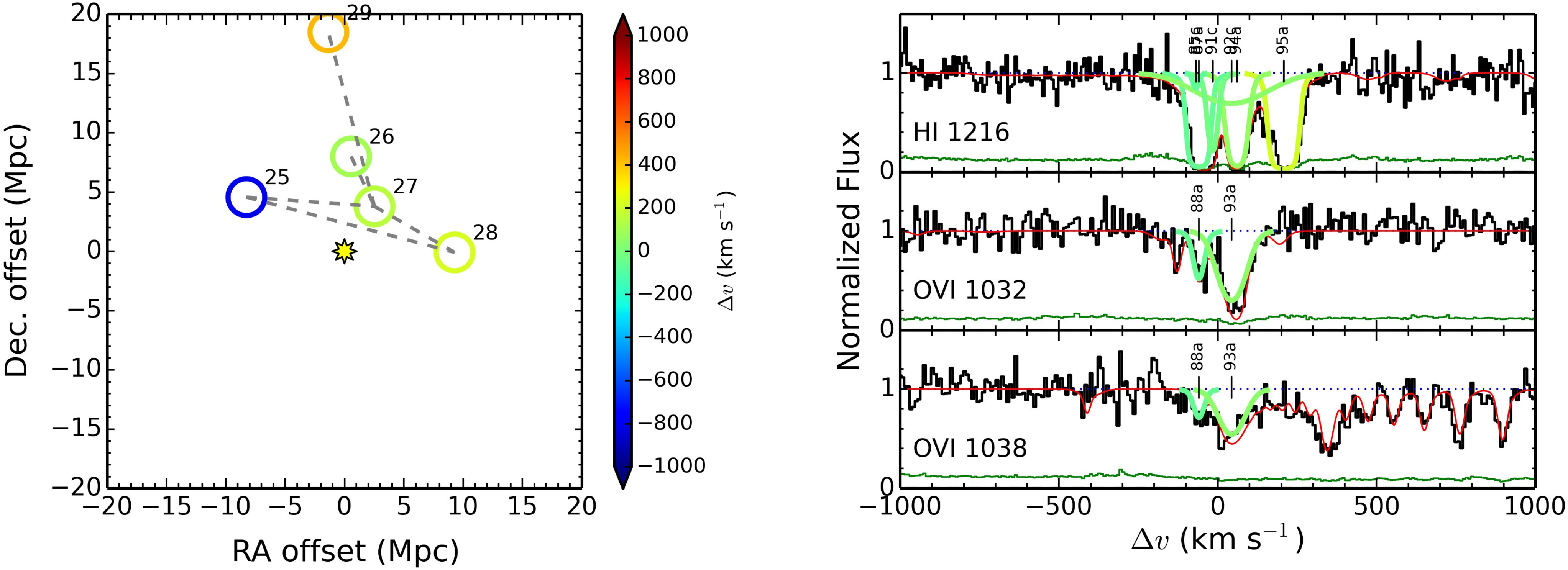


Tejos+14b in prep.

Examples

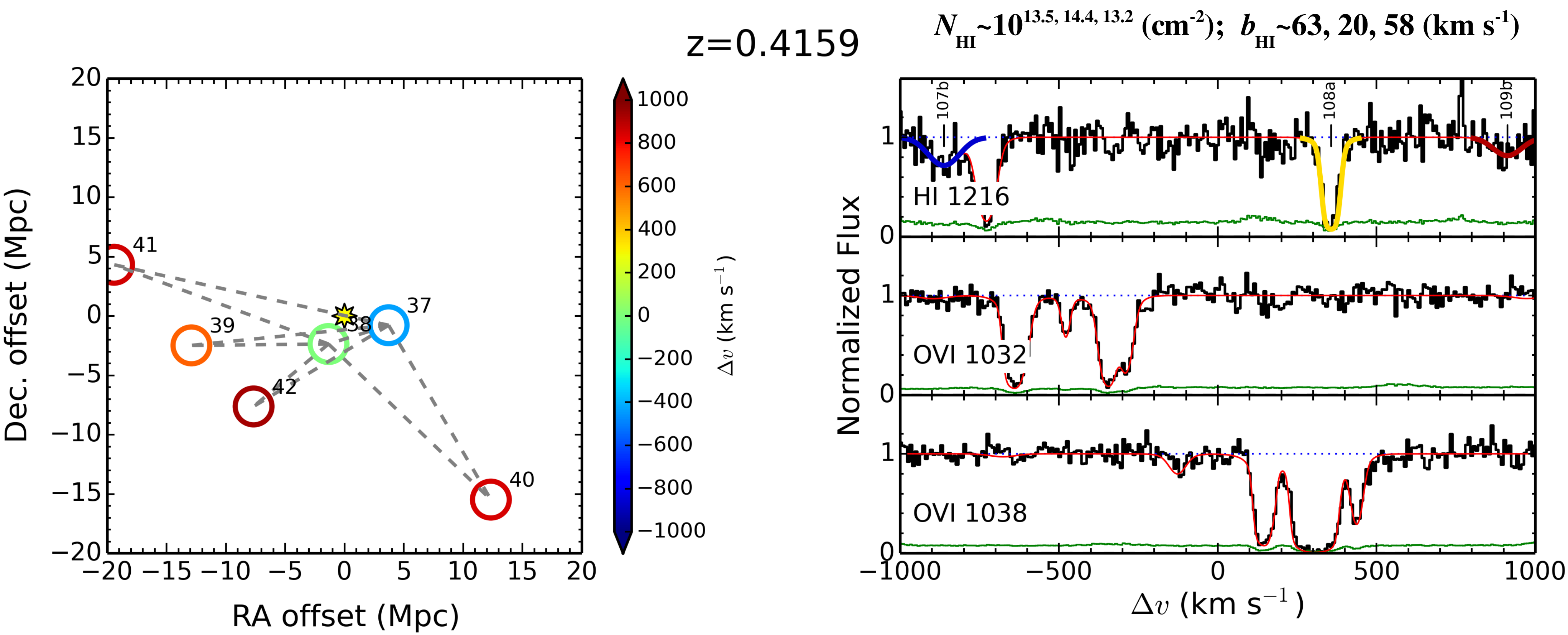
N_{HI}~$10^{15.4}$ (cm^{-2}); b_{HI}~25 (km s^{-1})

z=0.3501



Tejos+14b in prep.

Examples

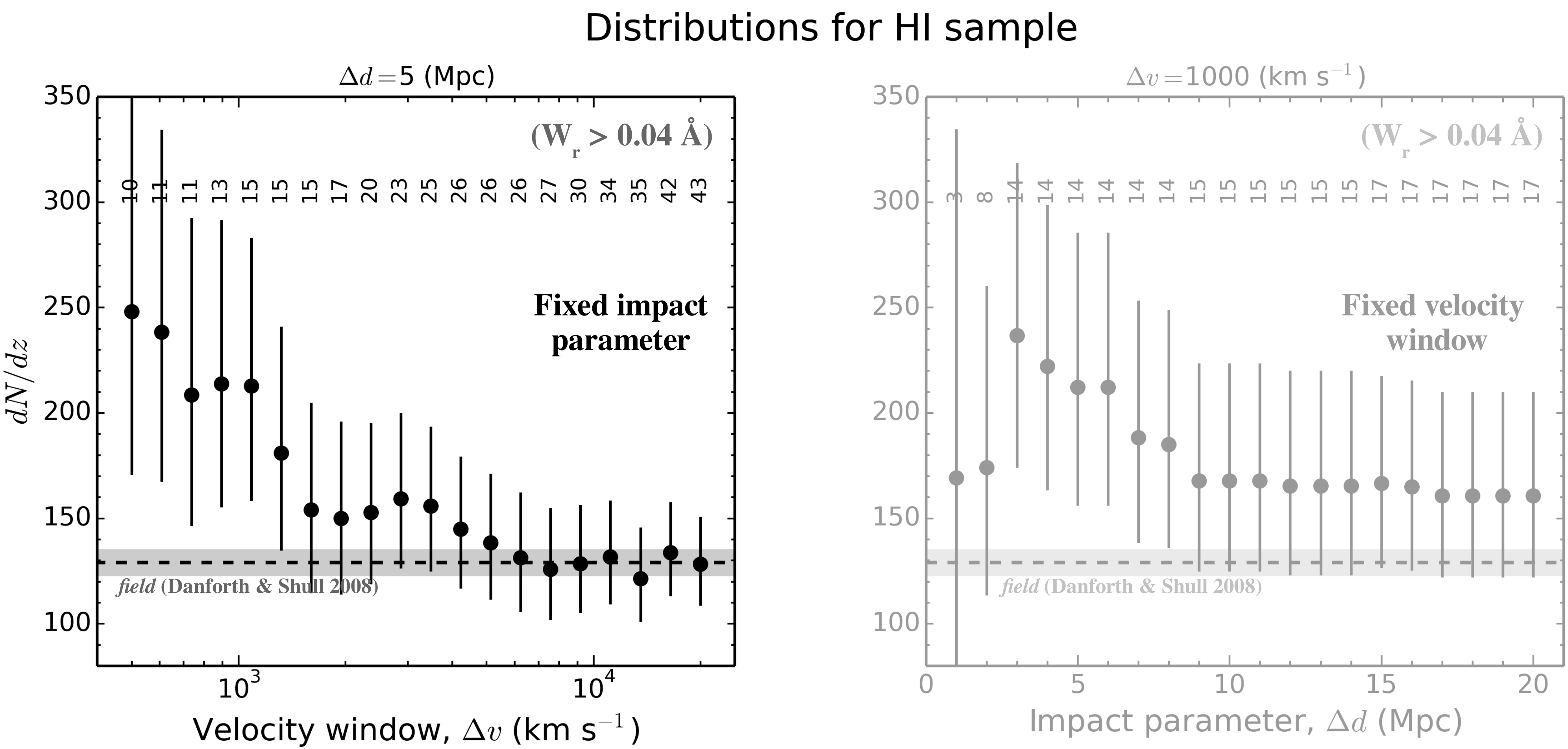


Tejos+14b in prep.

Part III:

Results

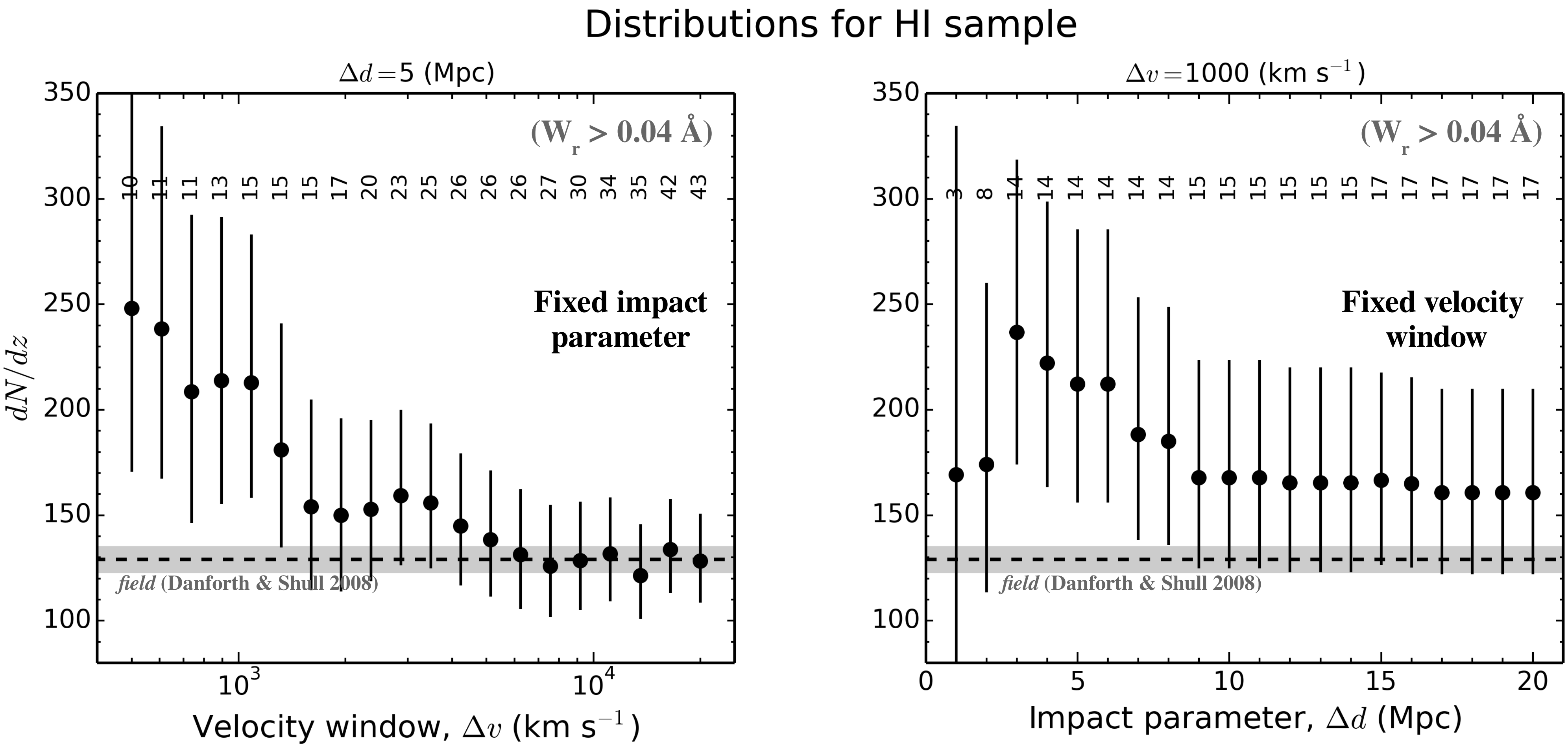
HI in cosmological filaments



A factor of ~2 excess!

Tejos+14b in prep.

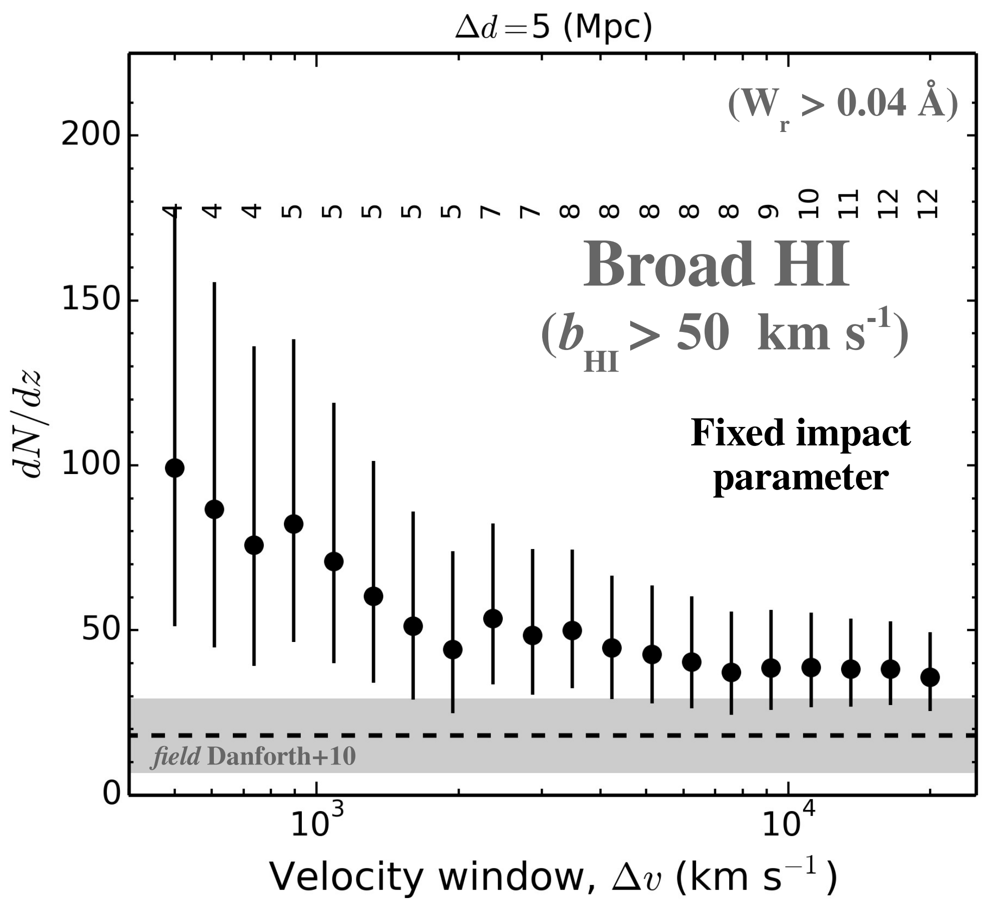
HI in cosmological filaments

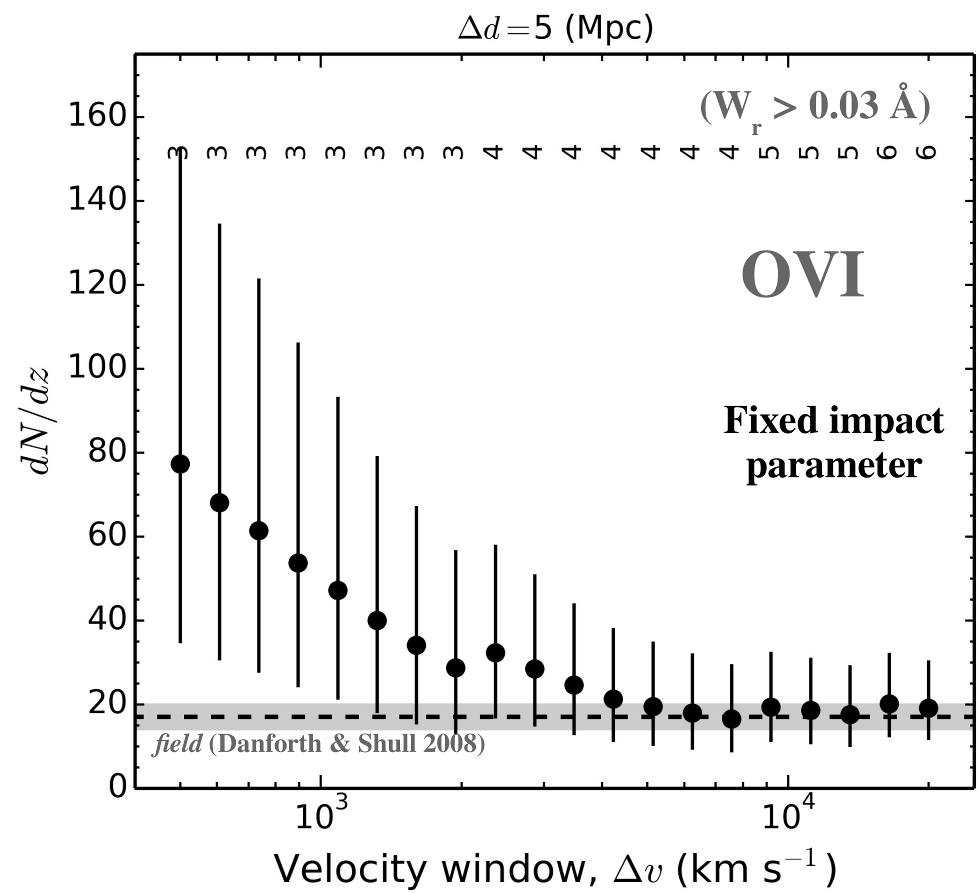


A factor of ~2 excess!

Tejos+14b in prep.

Hot gas in cosmological filaments (WHIM)

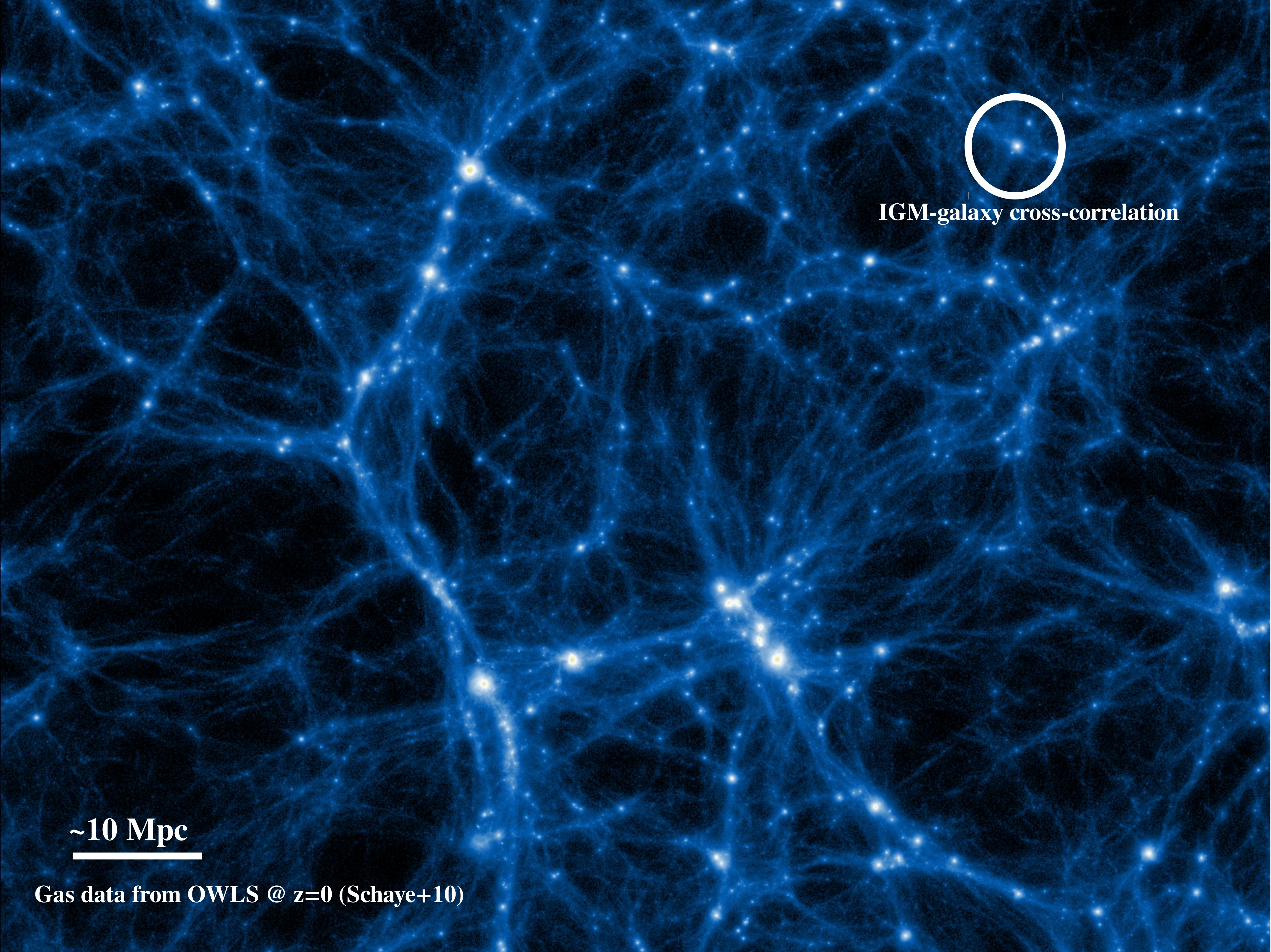


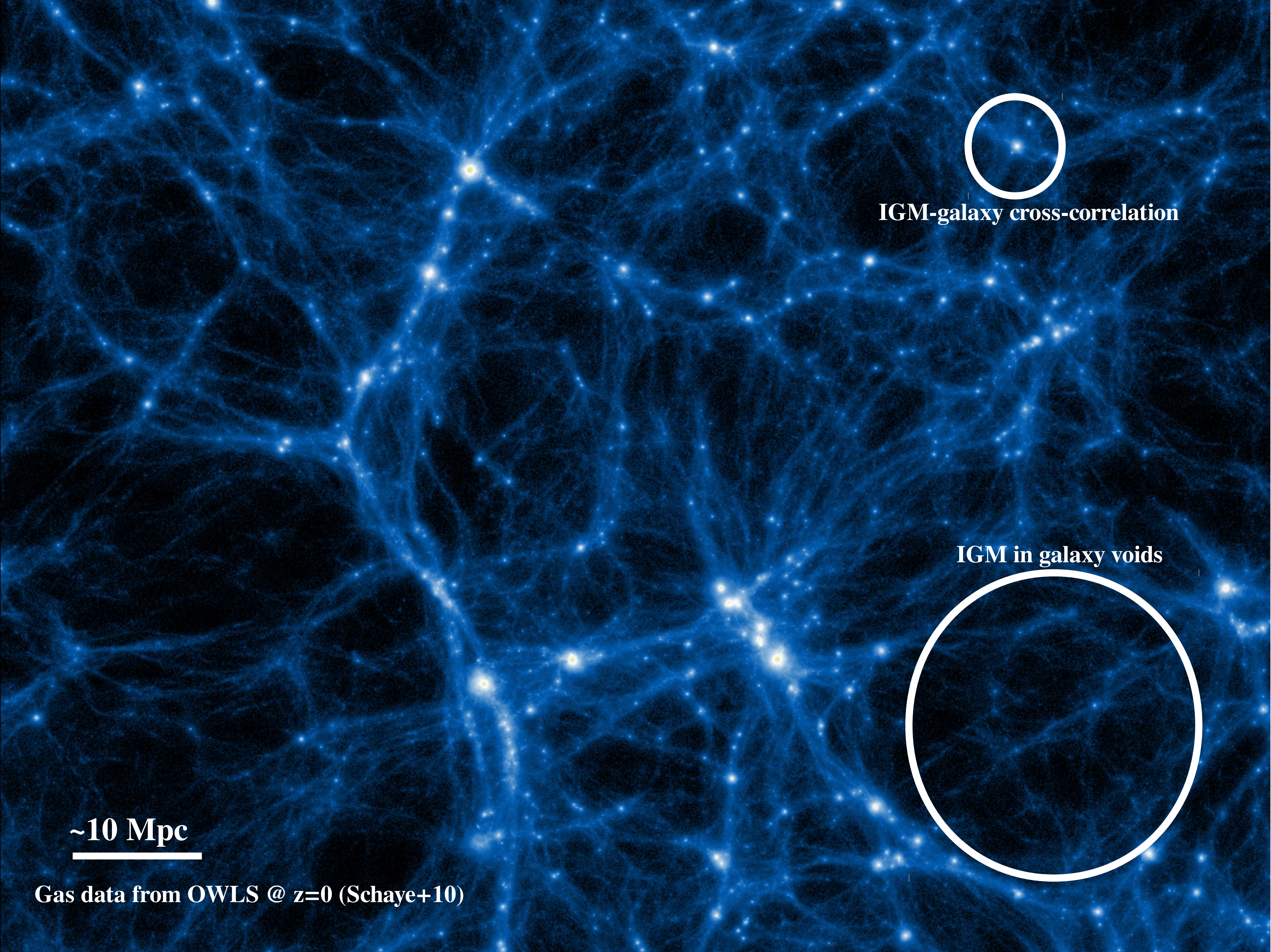


A factor of ~3 excess?

Tejos+14b in prep.

Summary & Conclusions


IGM-galaxy cross-correlation
~10 Mpc
Gas data from OWLS @ z=0 (Schaye+10)


IGM-galaxy cross-correlation
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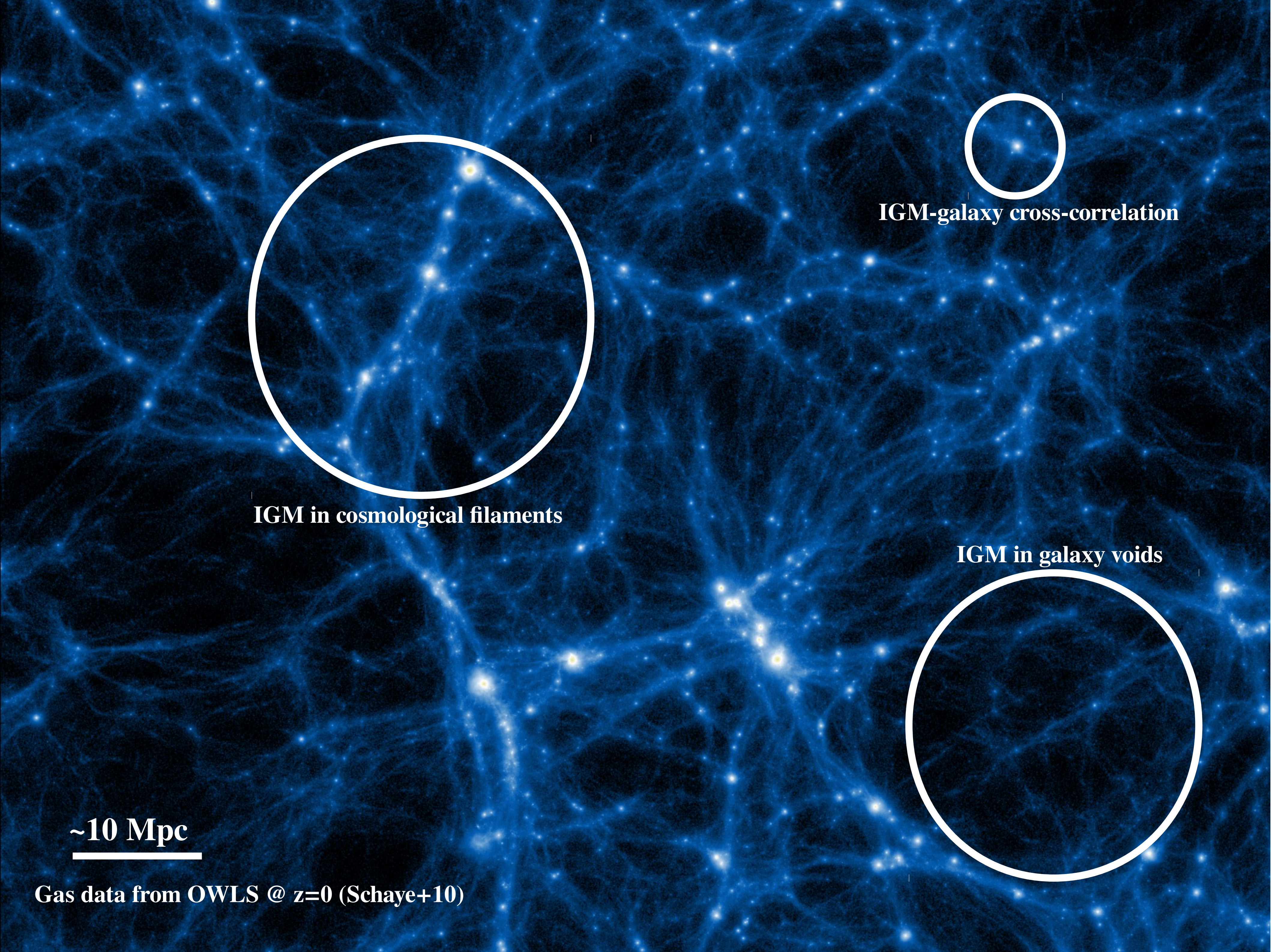
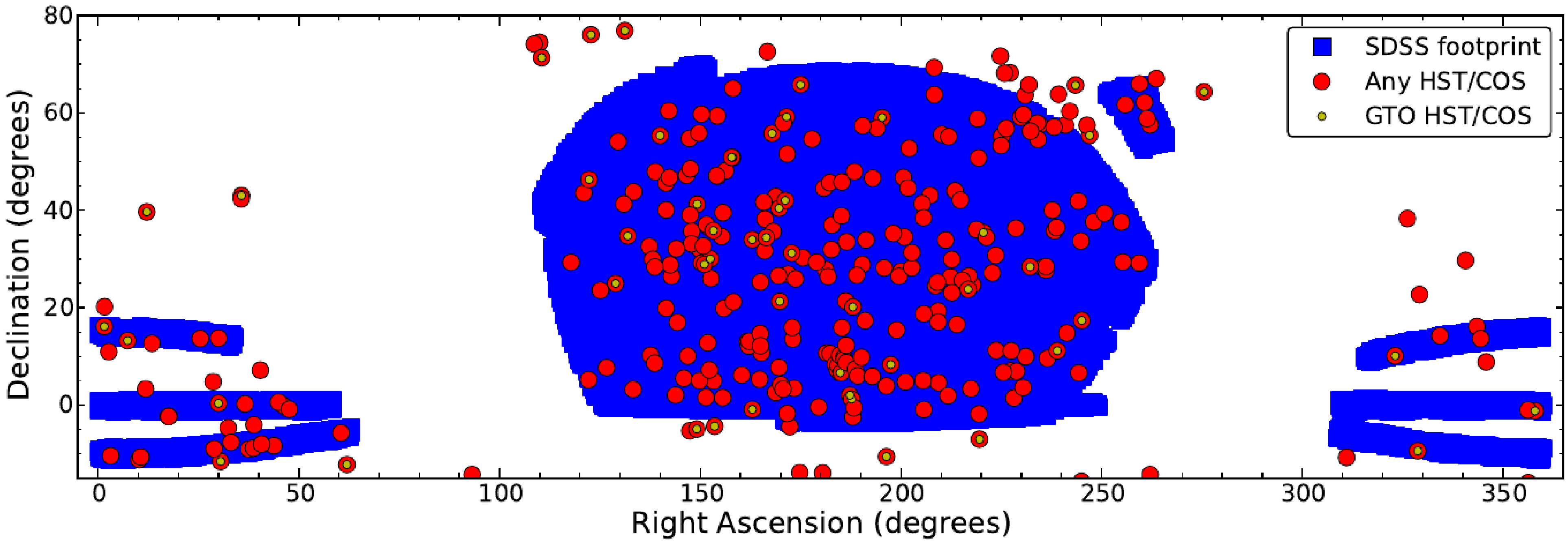

IGM-galaxy cross-correlation
IGM in cosmological filaments
IGM in galaxy voids
~10 Mpc
Gas data from OWLS @ z=0 (Schaye+10)

Summary & Conclusions

- **~100% of both HI systems having $N_{HI}>10^{14}$ cm^{-2} and star-forming galaxies follow the same underlying dark matter distribution, in the same volumes. Typical scales of ~5 Mpc.**
- **(~75% of non-star-forming galaxies also follow the same underlying DM distribution, in the same volumes. ~25% of non-star-forming galaxies reside in galaxy clusters and are not strongly correlated with HI systems having $N_{HI}>10^{14}$ cm^{-2}.)**
- **Galaxy voids are not empty. >50% of HI systems having $N_{HI}<10^{14}$ cm^{-2} 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). These trends are mild but theoretically expected.)**
- **(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 in HI.)**
- **There is an excess of HI (narrow and broad) and OVI systems in cosmological filaments. (Their masses could account for a significant fraction of the 'missing baryons' at low-z.)**

Future work

Future work

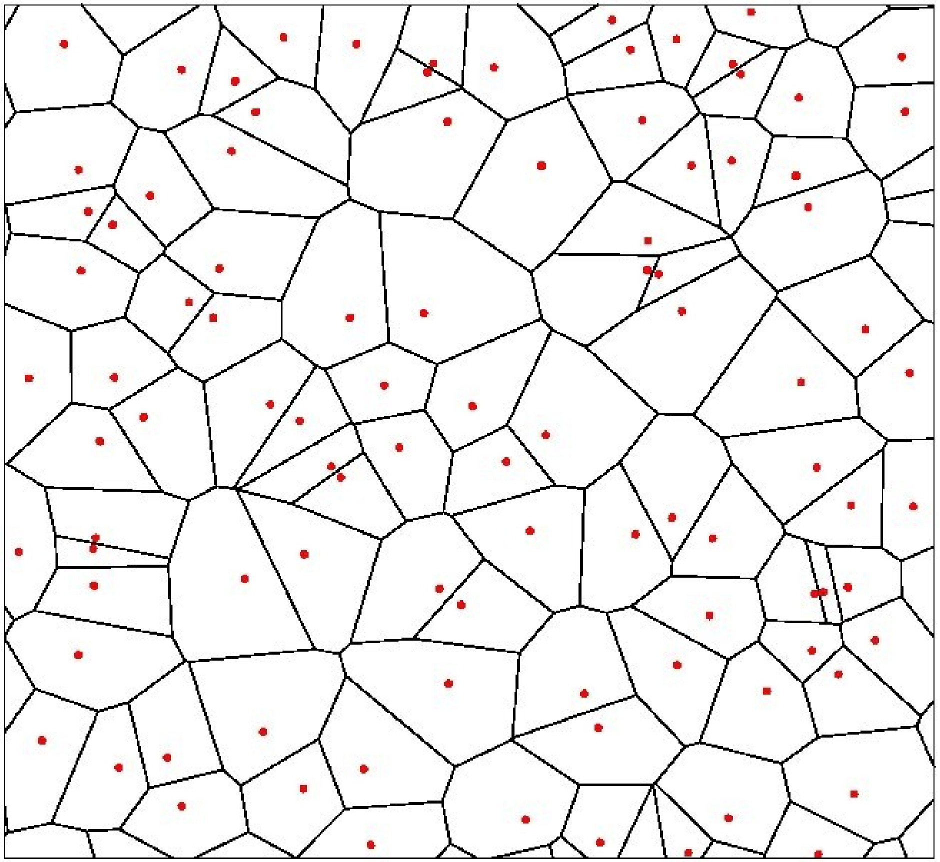


All these projects are currently being further developed with new data.

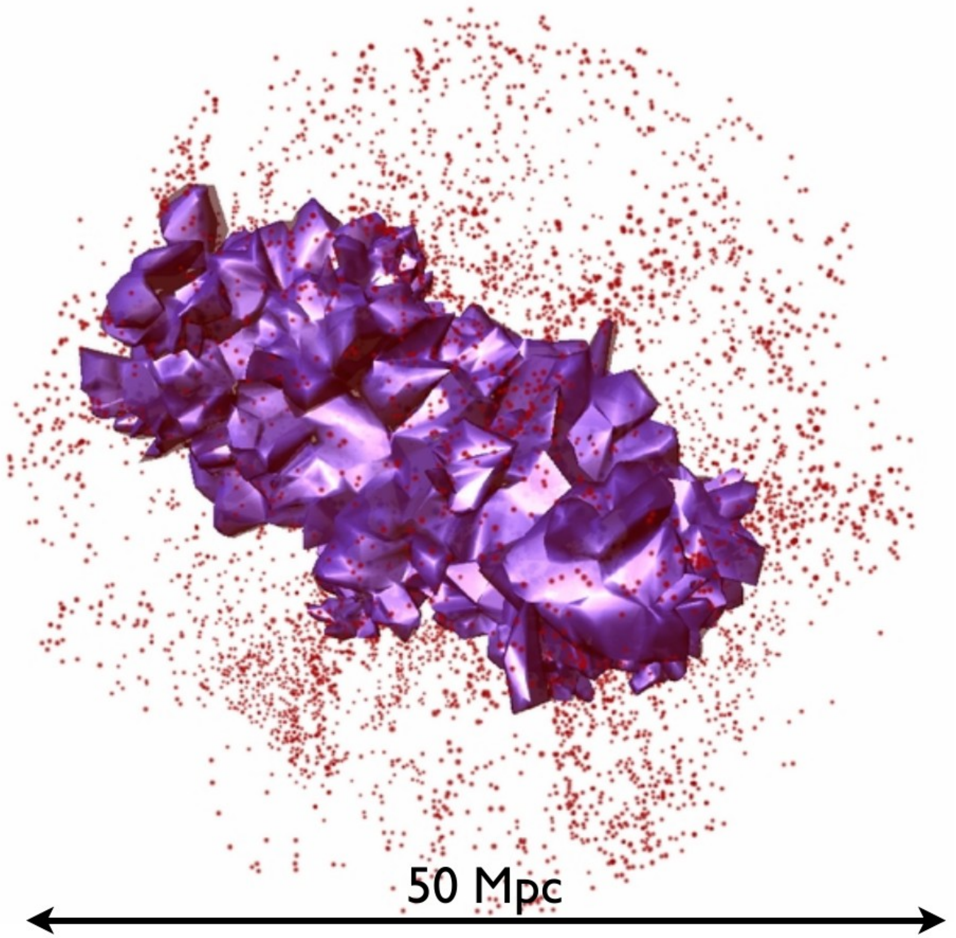
We will reduce statistical uncertainties, and will better constraint systematics.

We are also developing new analyses on the IGM in the cosmic web.

Future work

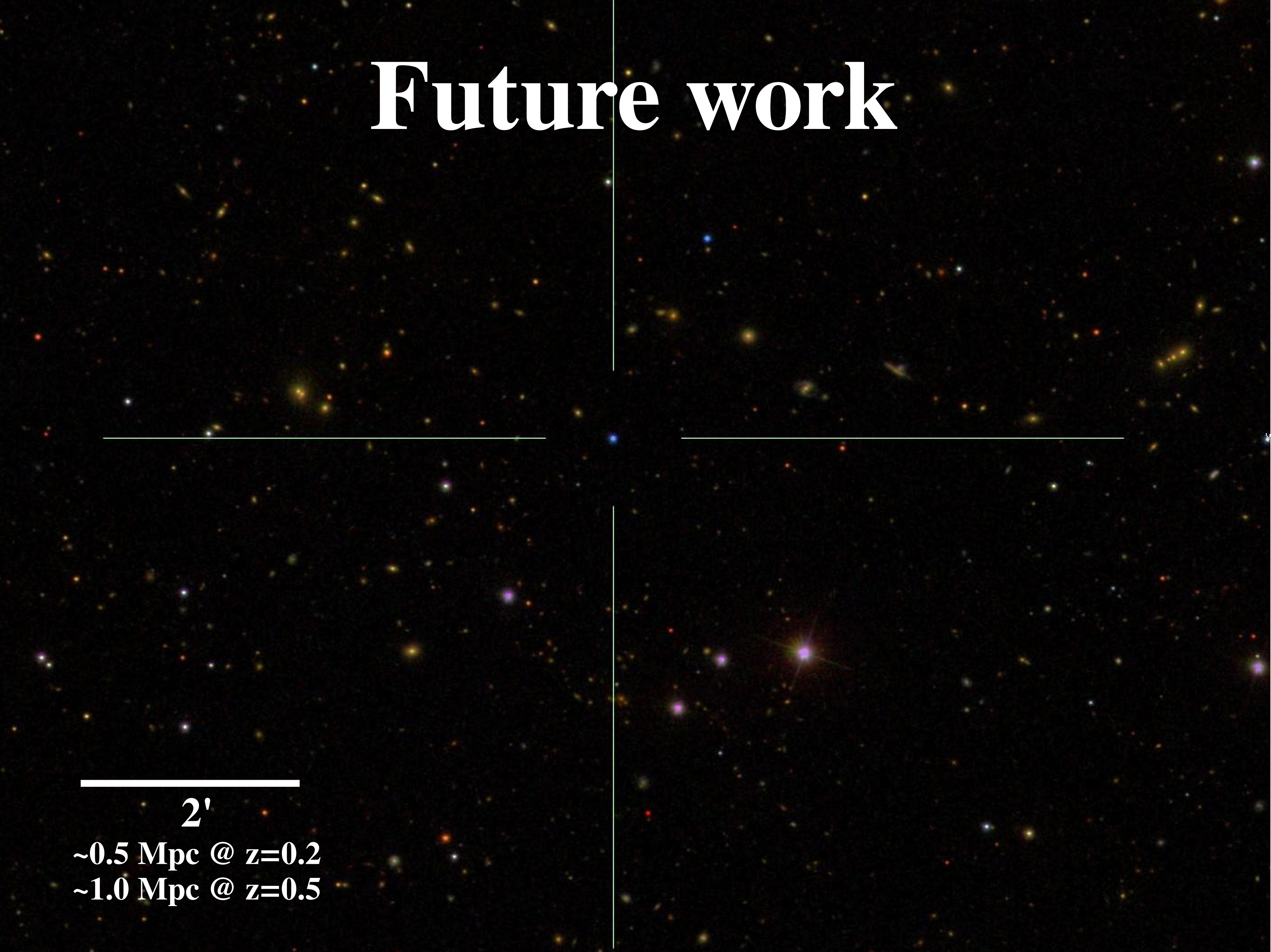


Voronoi tesselation

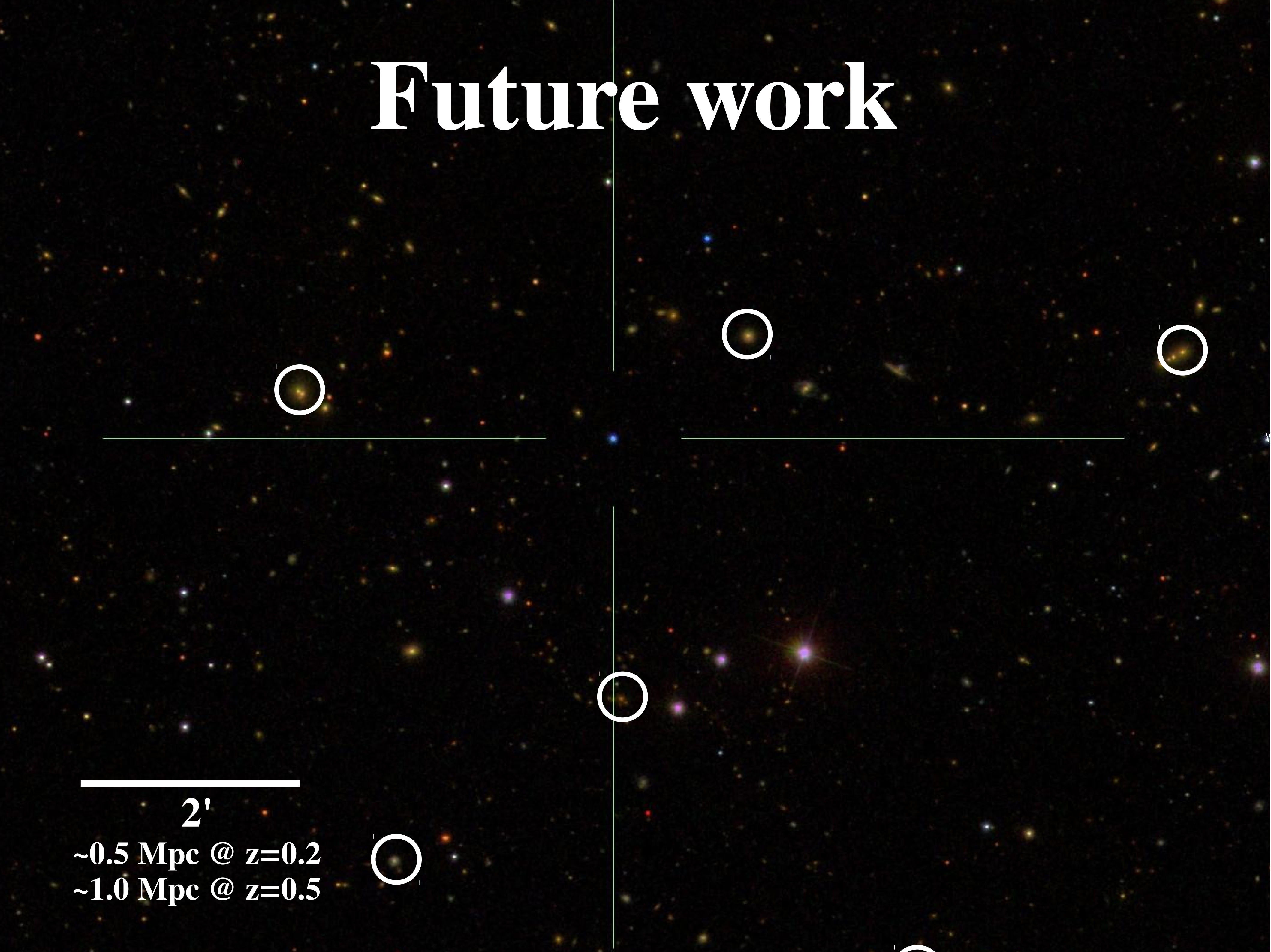


Sutter+12

Future work



Future work



Conclusions

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- (~75% of non-star-forming galaxies also follow the same underlying DM distribution, in the same volumes. ~25% of non-star-forming galaxies reside in galaxy clusters and are not strongly correlated with HI systems having $N_{HI}>10^{14}$ cm^{-2}.)
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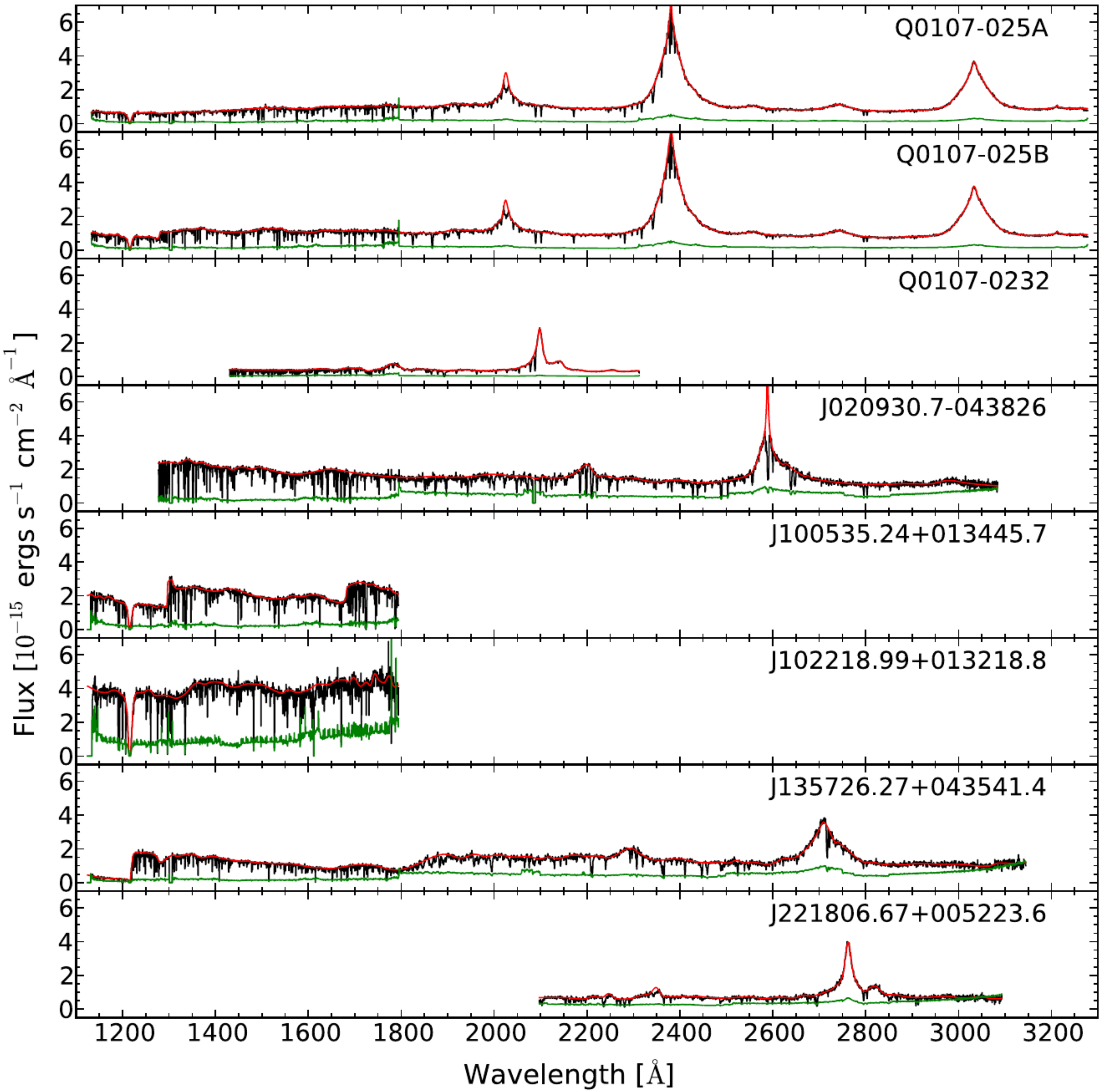

QSO sample

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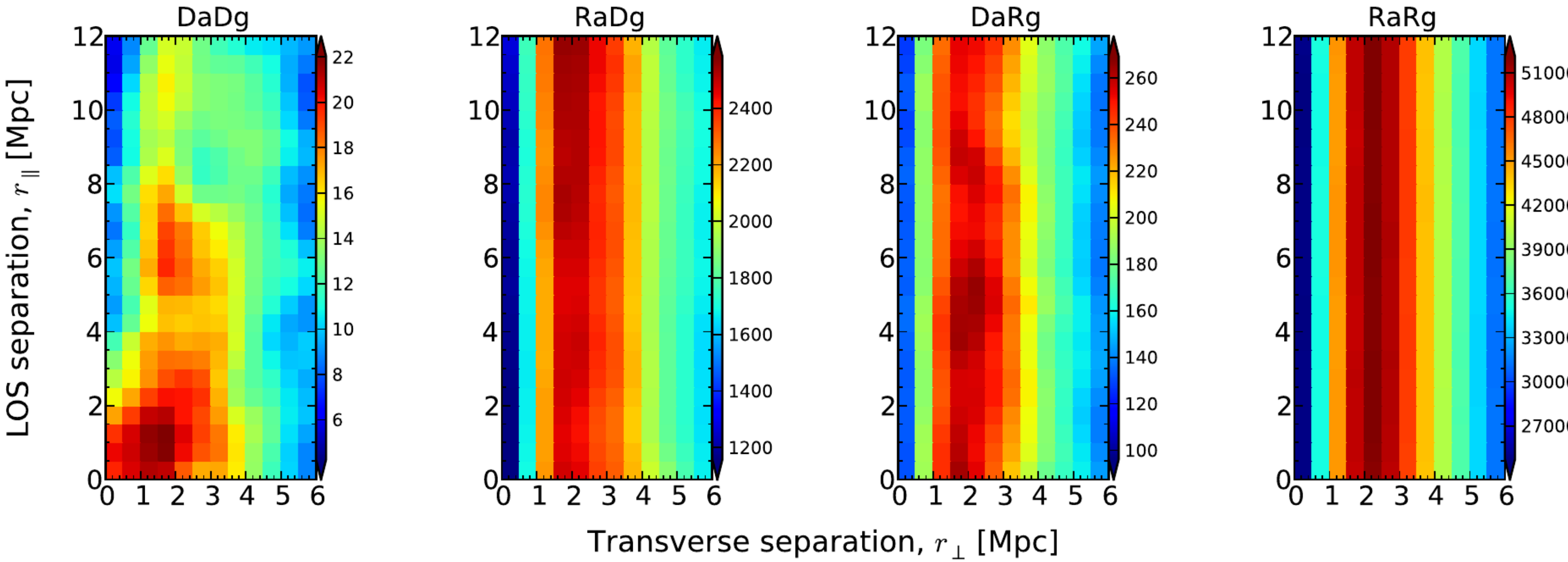
Cross-counts



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

Tejos+14

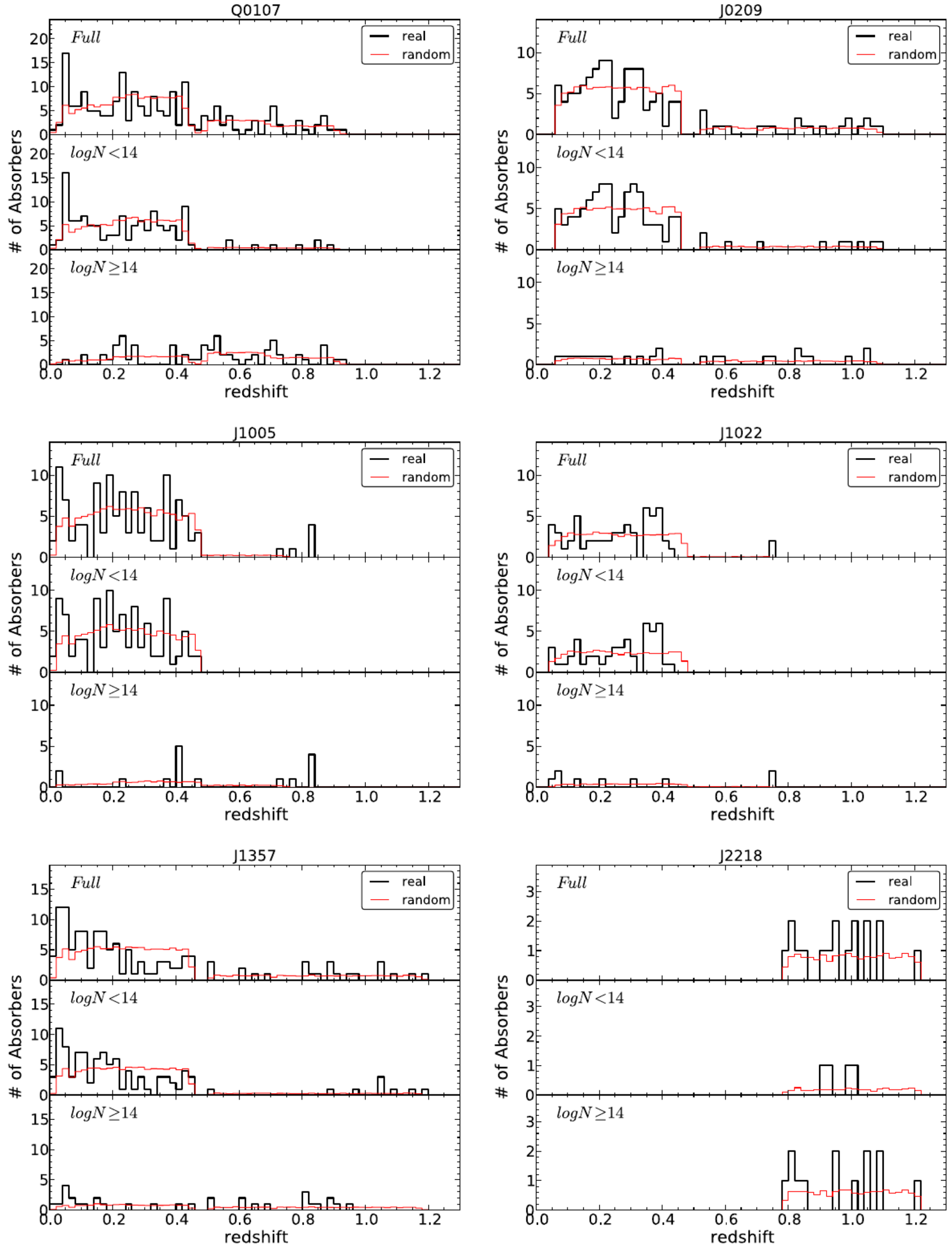
Samples

Table 6. Summary of the 'Full Sample' used for the cross-correlation analysis, as a function of $r_\perp$.

	<0.5 Mpc (1)	<1 Mpc (2)	<2 Mpc (3)	<10 Mpc (4)	<50 Mpc (5)	Total (6)
Galaxies	141	466	1354	6871	19509	17509
'SF'	105	339	997	4756	9963	8293
'non-SF'	24	66	193	779	2011	1743
H I	–	–	–	–	–	654
'strong'	–	–	–	–	–	165
'weak'	–	–	–	–	–	489

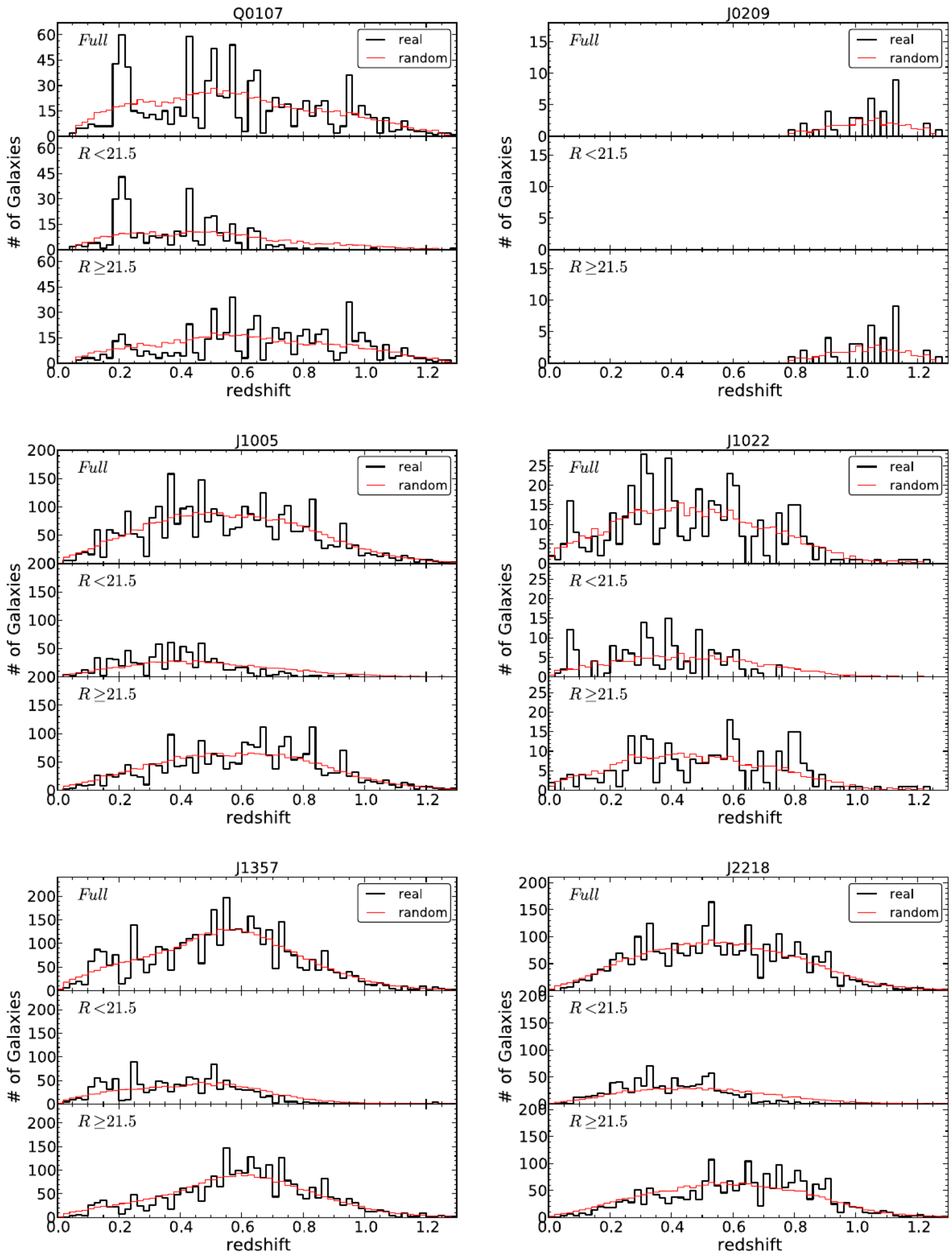
$10^{14} \leqslant N_{\rm HI} \lesssim 10^{17}$ cm^{-2} ('strong')
$10^{13} \lesssim N_{\rm HI} < 10^{14}$ cm^{-2} ('weak')

Tejos+14



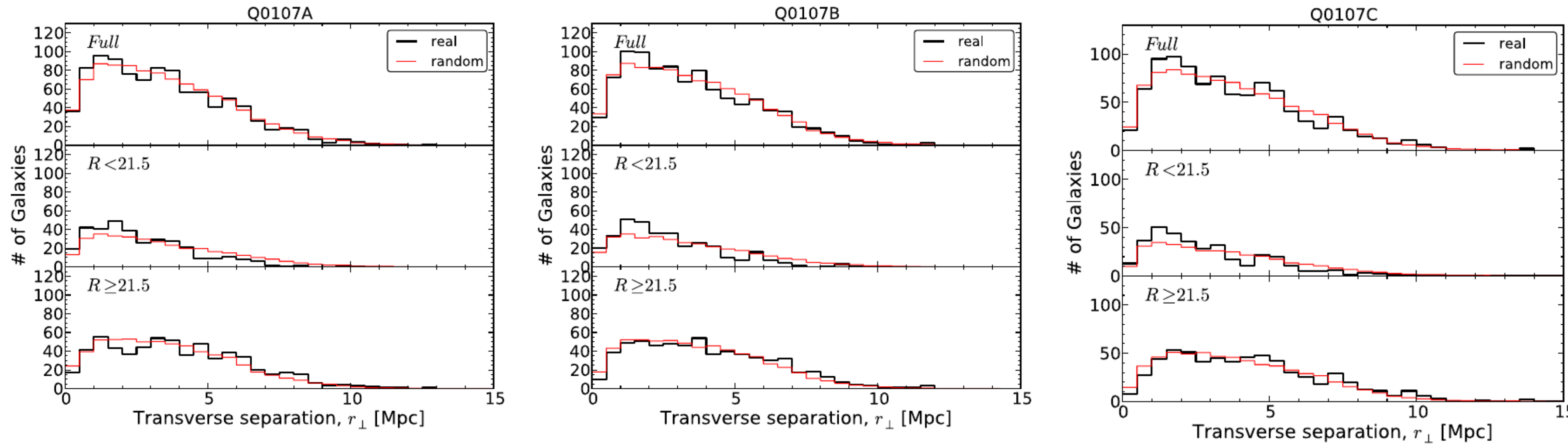
Selection function

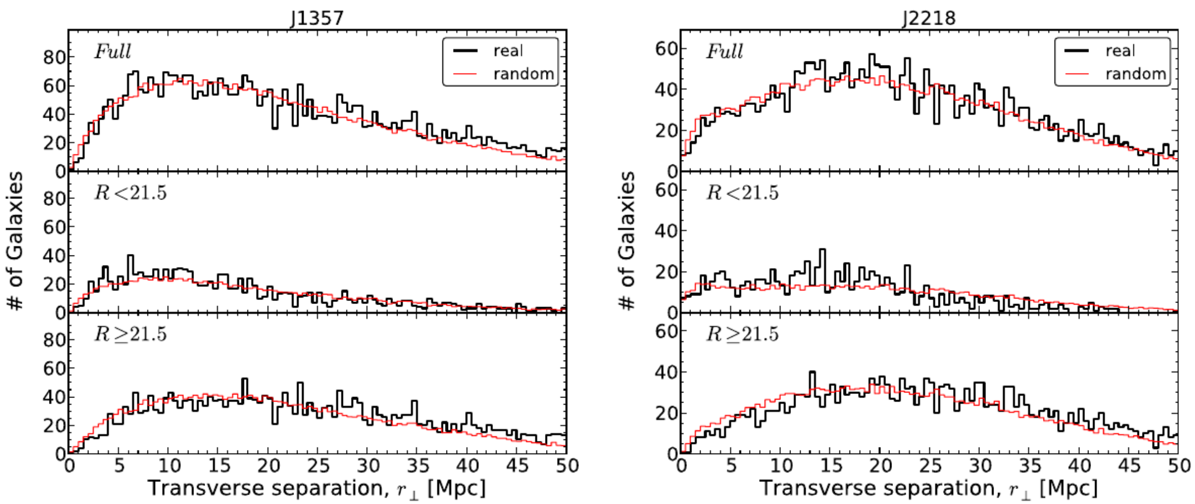
Tejos+14



Selection function

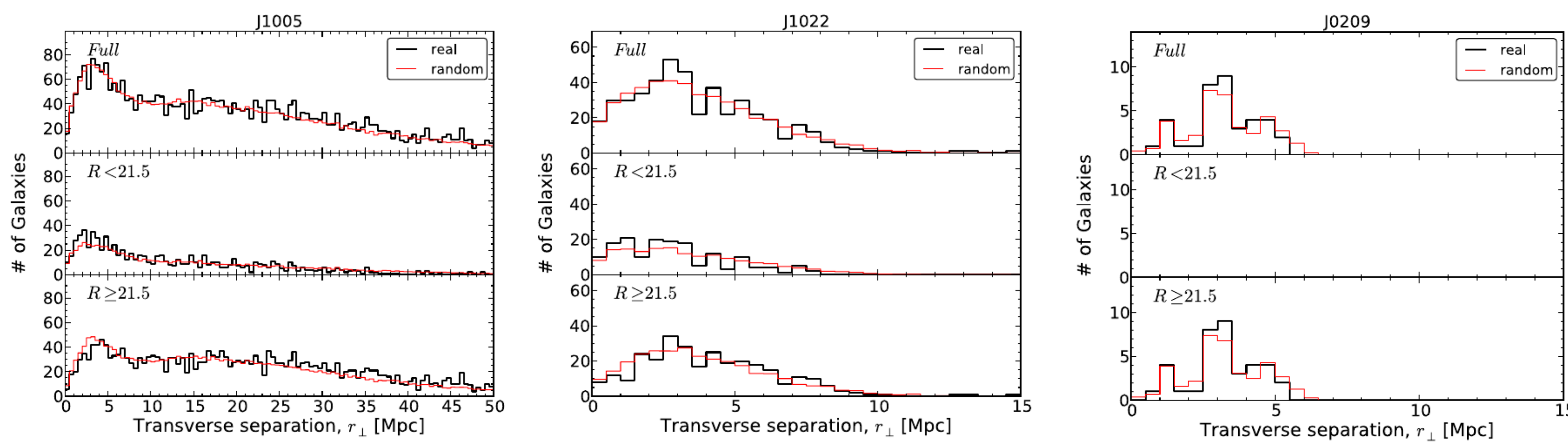
Tejos+14



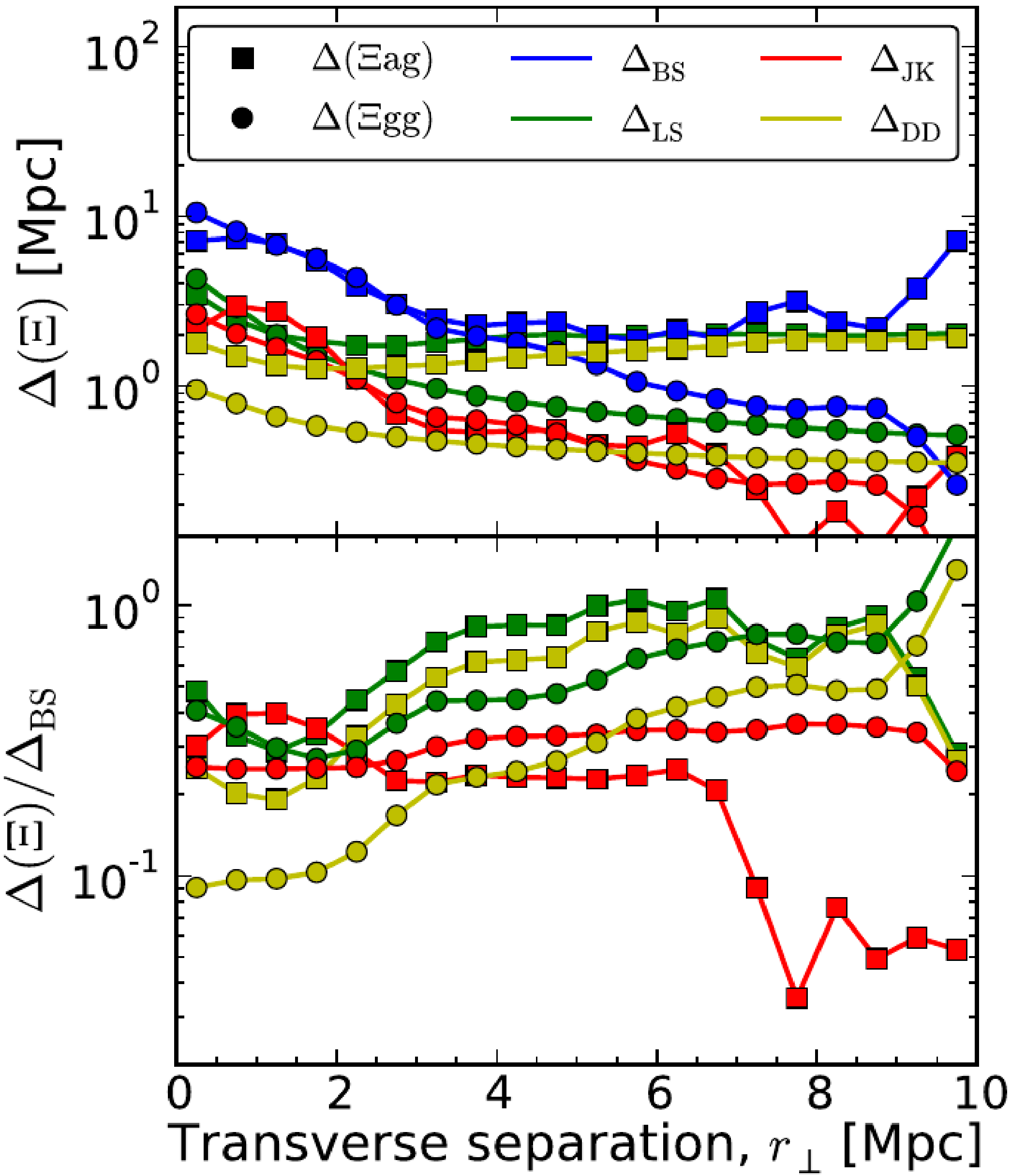


Selection function

Tejos+14

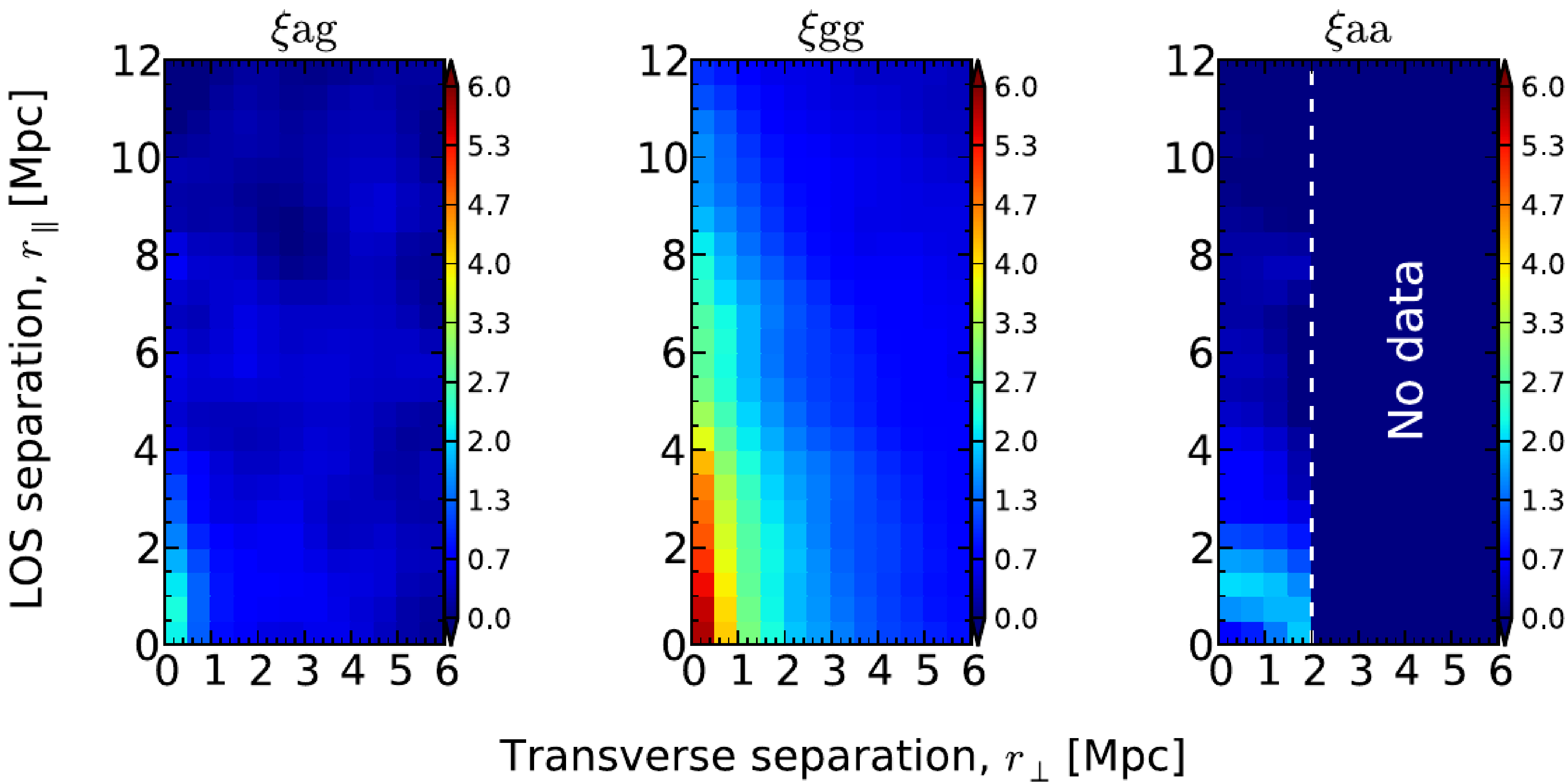


Uncertainties



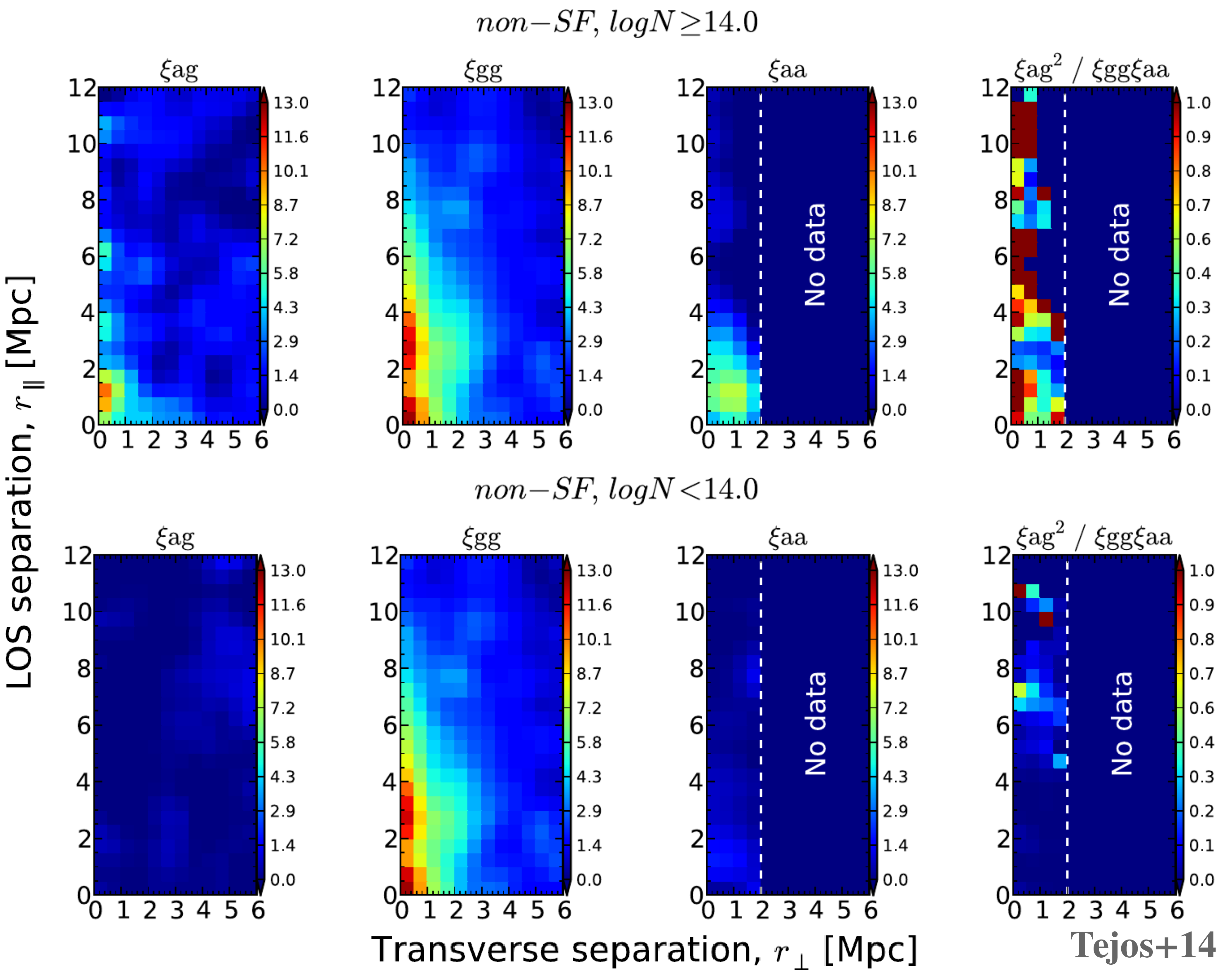
Tejos+14

No strong outflow/inflow

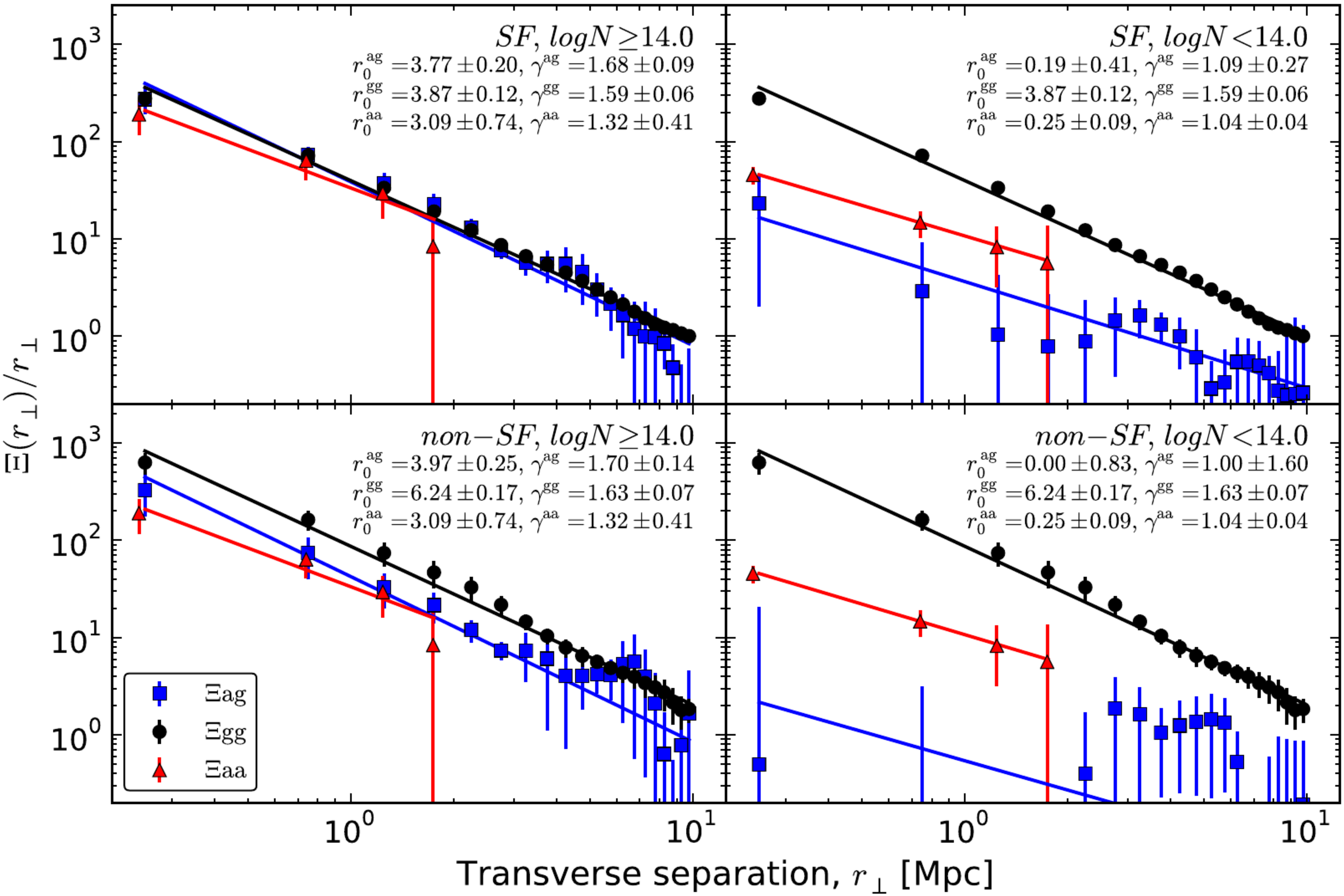


All observed anisotropies are consistent with being due to galaxy redshift uncertainties (~60-120 km/s)

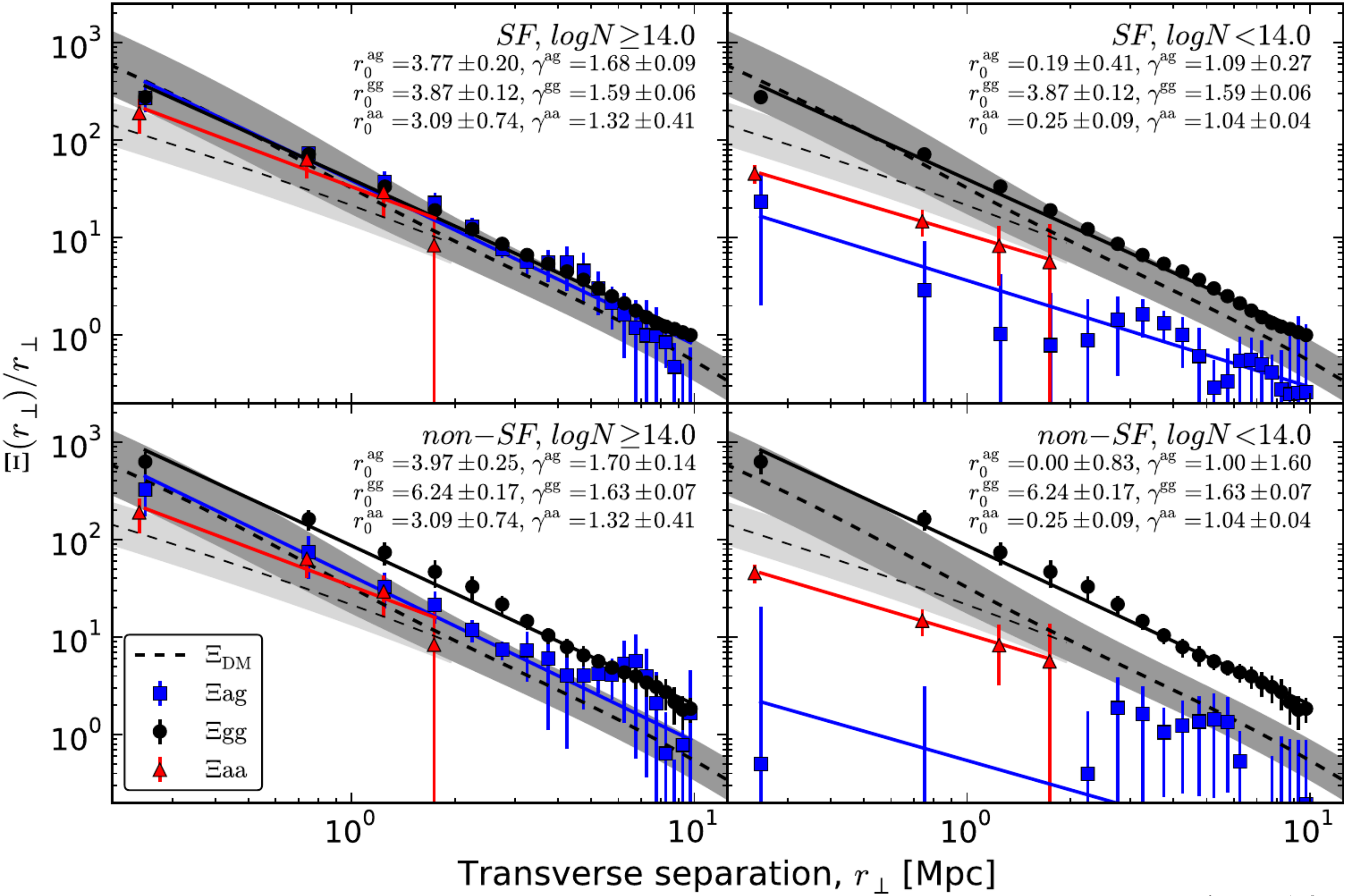
Tejos+14



non−SF, logN ≥14.0
ξag
ξgg
ξaa
ξag² / ξggξaa
No data
No data
non−SF, logN <14.0
ξag
ξgg
ξaa
ξag² / ξggξaa
No data
No data
13.0
11.6
10.1
8.7
7.2
5.8
4.3
2.9
1.4
0.0
1.0
0.9
0.8
0.7
0.6
0.4
0.3
0.2
0.1
0.0
LOS separation, r∥ [Mpc]
Transverse separation, r⊥ [Mpc]
Tejos+14

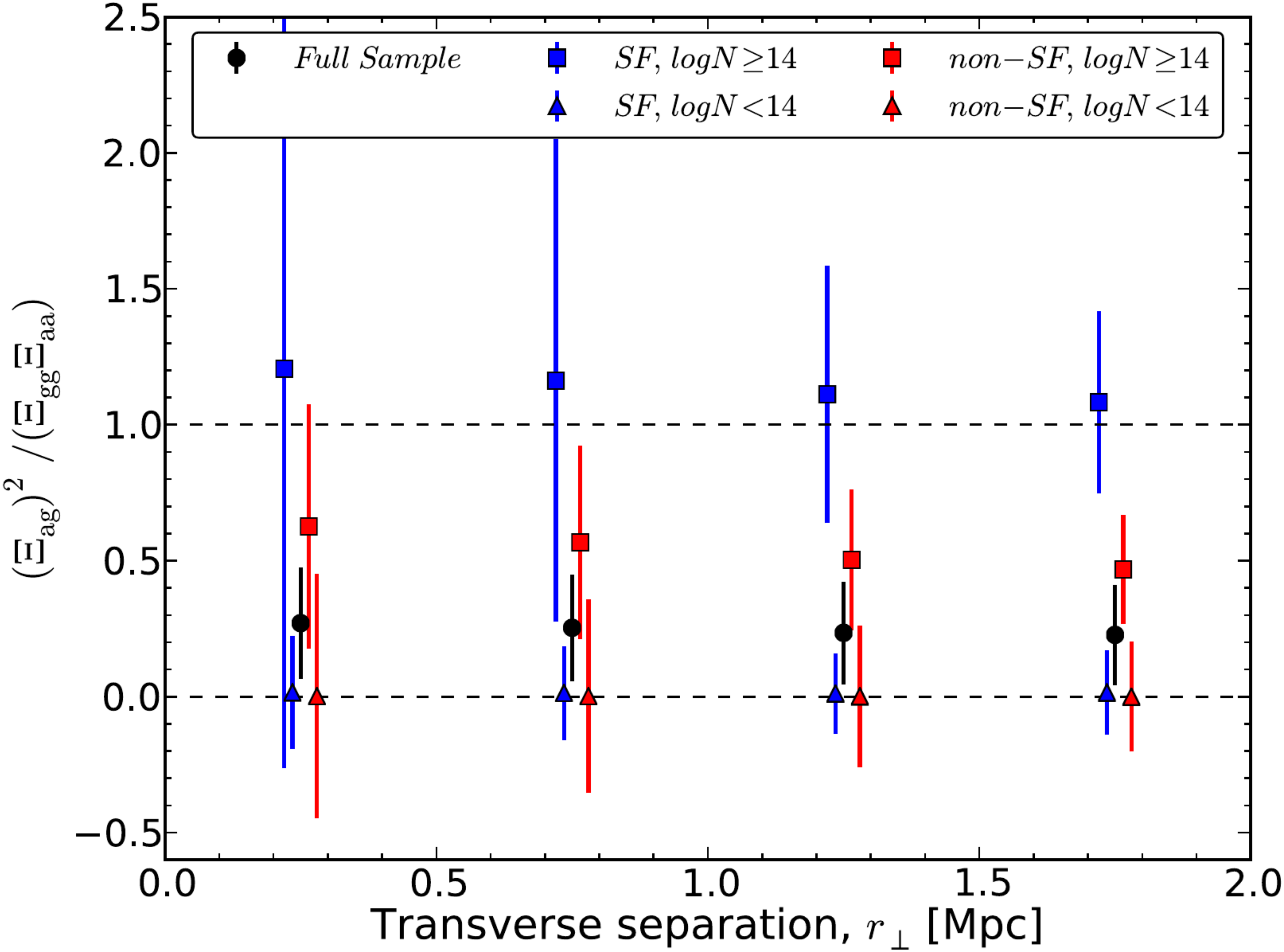

SF, logN ≥14.0
r_0^{ag} =3.77 ±0.20, γ^{ag} =1.68 ±0.09
r_0^{gg} =3.87 ±0.12, γ^{gg} =1.59 ±0.06
r_0^{aa} =3.09 ±0.74, γ^{aa} =1.32 ±0.41
SF, logN <14.0
r_0^{ag} =0.19 ±0.41, γ^{ag} =1.09 ±0.27
r_0^{gg} =3.87 ±0.12, γ^{gg} =1.59 ±0.06
r_0^{aa} =0.25 ±0.09, γ^{aa} =1.04 ±0.04
non−SF, logN ≥14.0
r_0^{ag} =3.97 ±0.25, γ^{ag} =1.70 ±0.14
r_0^{gg} =6.24 ±0.17, γ^{gg} =1.63 ±0.07
r_0^{aa} =3.09 ±0.74, γ^{aa} =1.32 ±0.41
non−SF, logN <14.0
r_0^{ag} =0.00 ±0.83, γ^{ag} =1.00 ±1.60
r_0^{gg} =6.24 ±0.17, γ^{gg} =1.63 ±0.07
r_0^{aa} =0.25 ±0.09, γ^{aa} =1.04 ±0.04
Ξag
Ξgg
Ξaa
$\Xi(r_\perp)/r_\perp$
Transverse separation, $r_\perp$ [Mpc]

Tejos+14

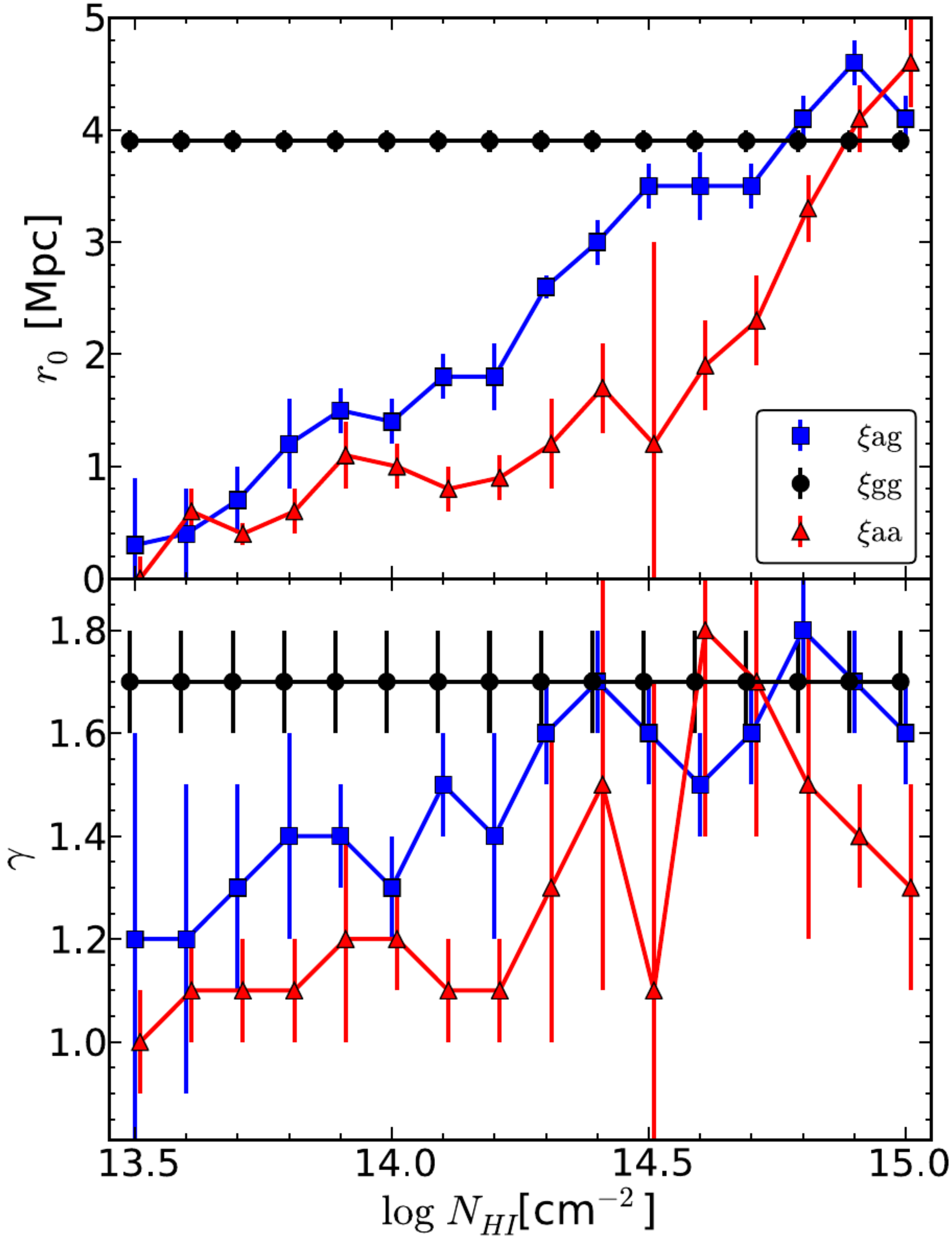


SF, logN≥14.0
r0ag =3.77±0.20, γag =1.68±0.09
r0gg =3.87±0.12, γgg =1.59±0.06
r0aa =3.09±0.74, γaa =1.32±0.41
SF, logN<14.0
r0ag =0.19±0.41, γag =1.09±0.27
r0gg =3.87±0.12, γgg =1.59±0.06
r0aa =0.25±0.09, γaa =1.04±0.04
non−SF, logN≥14.0
r0ag =3.97±0.25, γag =1.70±0.14
r0gg =6.24±0.17, γgg =1.63±0.07
r0aa =3.09±0.74, γaa =1.32±0.41
non−SF, logN<14.0
r0ag =0.00±0.83, γag =1.00±1.60
r0gg =6.24±0.17, γgg =1.63±0.07
r0aa =0.25±0.09, γaa =1.04±0.04
ΞDM
Ξag
Ξgg
Ξaa
Ξ(r⊥)/r⊥
Transverse separation, r⊥ [Mpc]

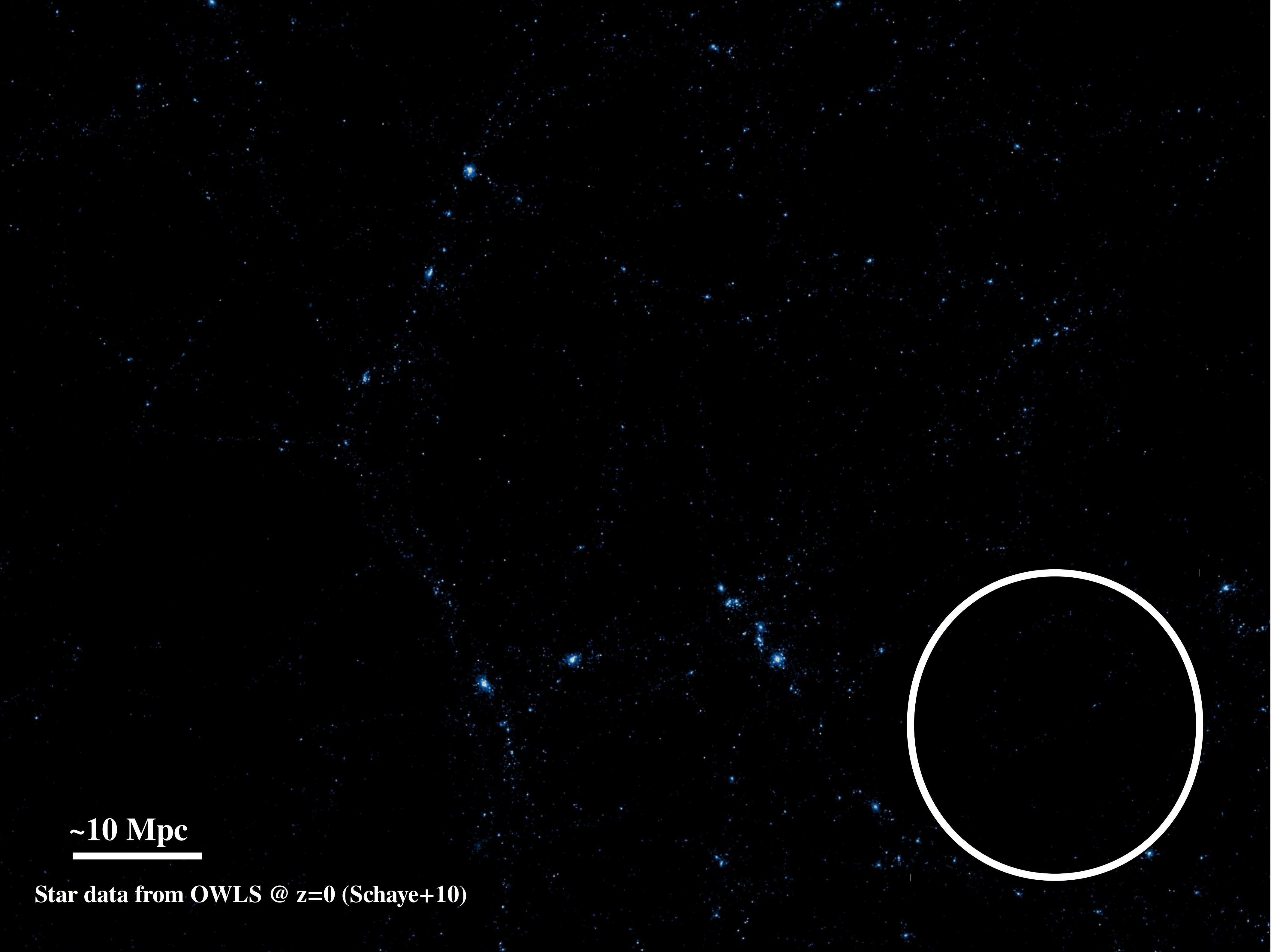
Tejos+14

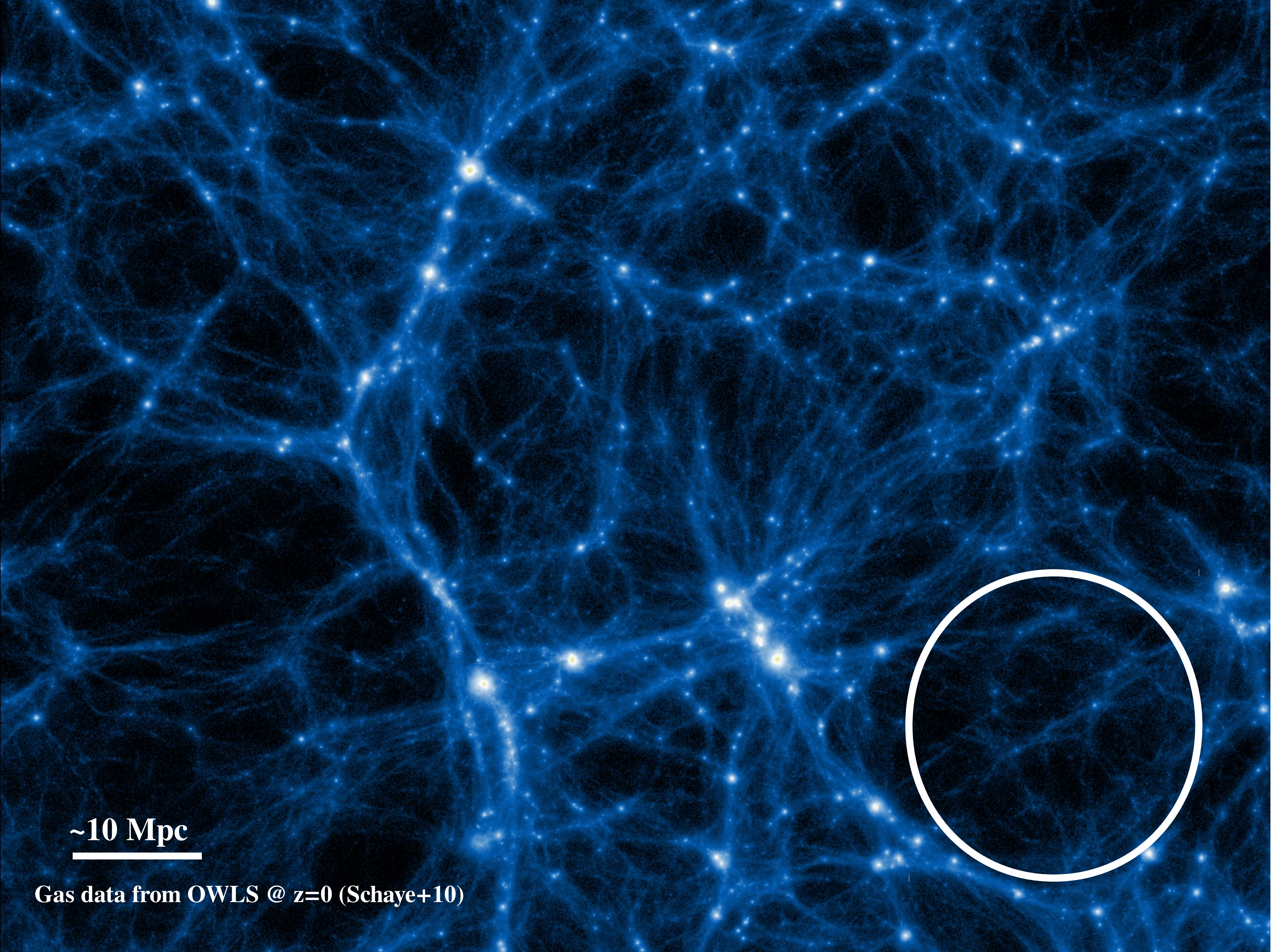

Full Sample
SF, logN≥14
non−SF, logN≥14
SF, logN<14
non−SF, logN<14
(Ξag)² / (Ξgg Ξaa)
Transverse separation, r⊥ [Mpc]
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
0.0
0.5
1.0
1.5
2.0

Tejos+14

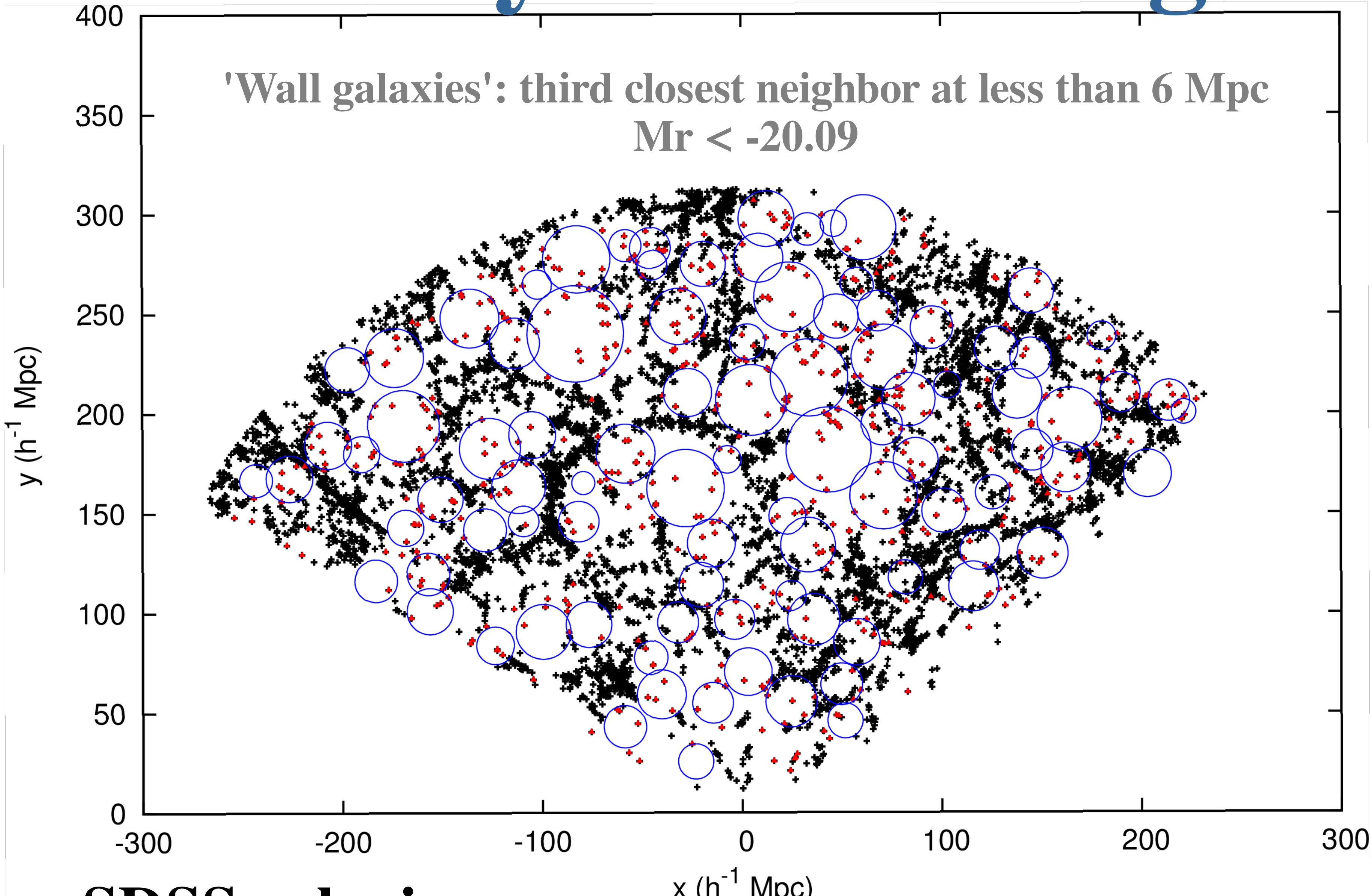


Tejos+14


~10 Mpc
Star data from OWLS @ z=0 (Schaye+10)


~10 Mpc
Gas data from OWLS @ z=0 (Schaye+10)

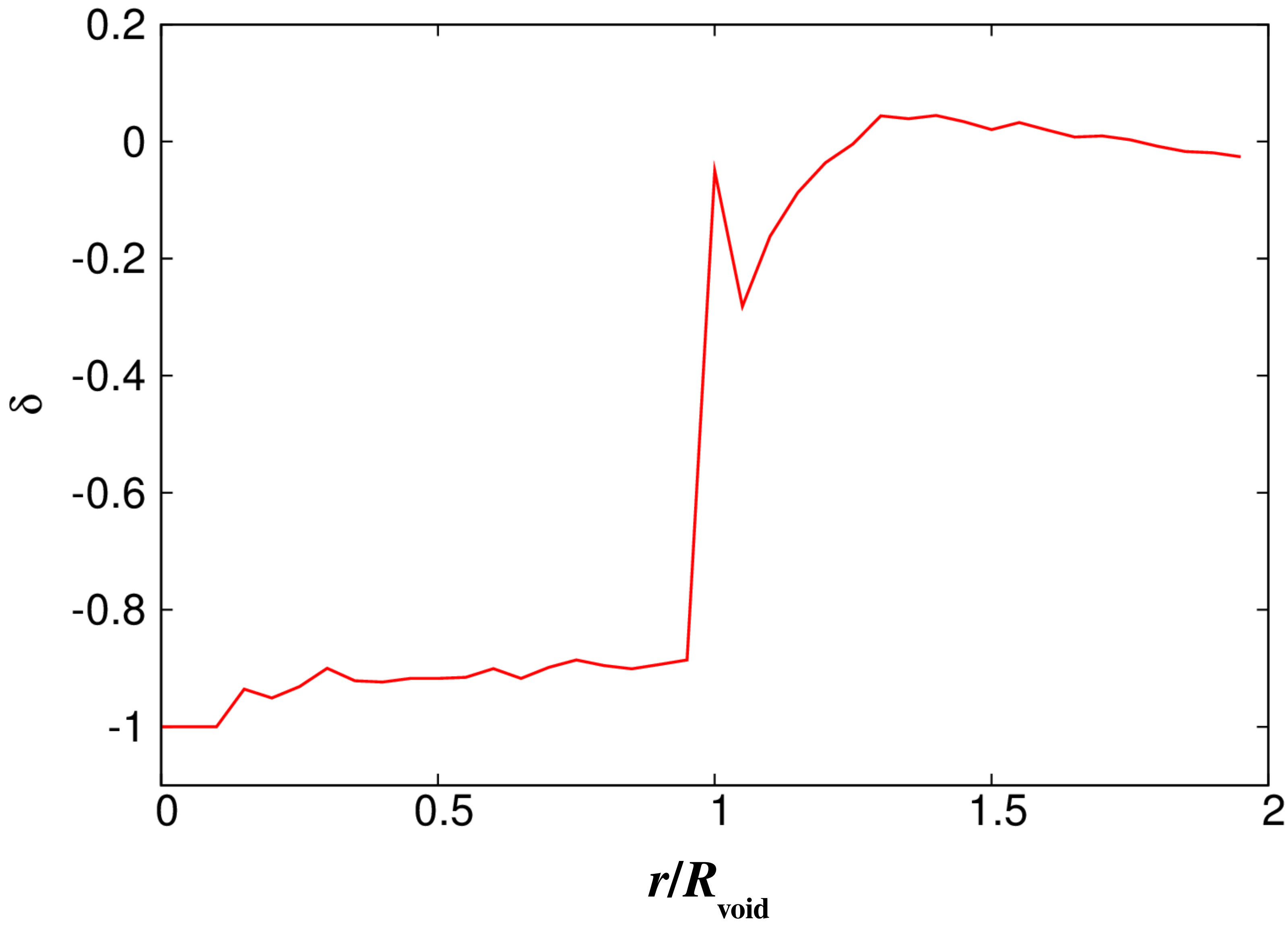
Galaxy void catalog



SDSS galaxies

Pan+12

Galaxy void catalog

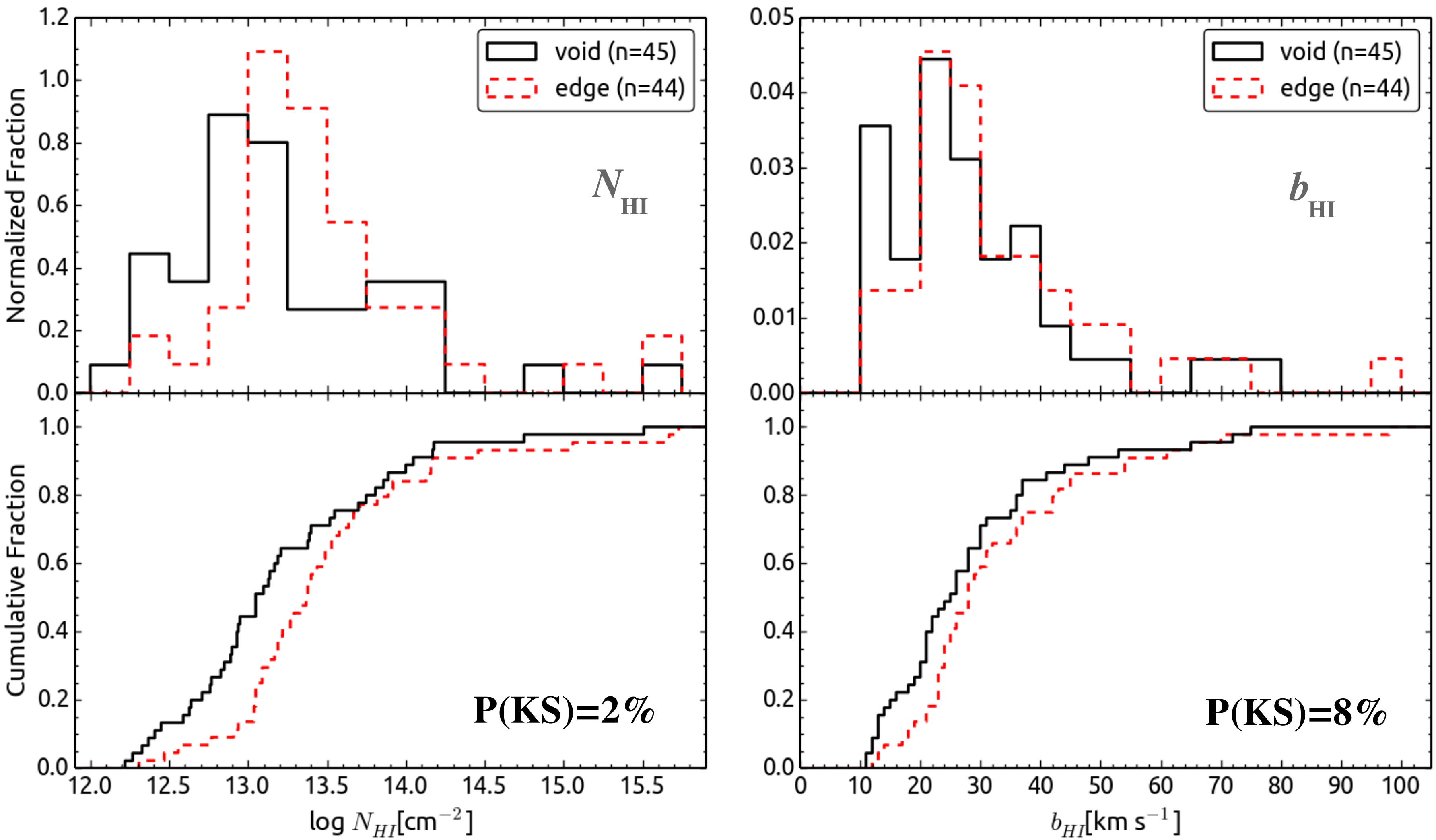


Pan+12

Part II:

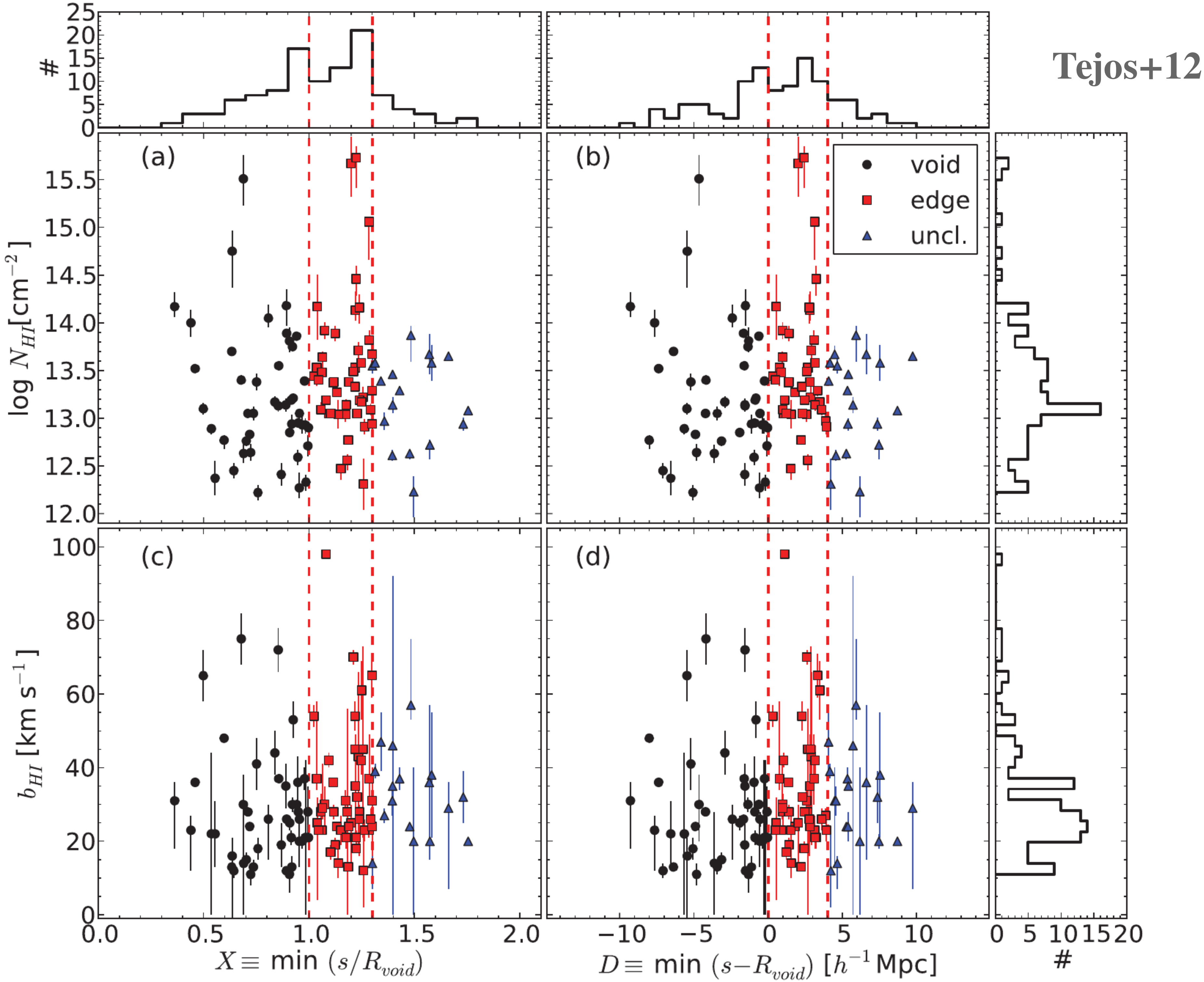
Are their properties different?

Properties of HI w/r 'voids'



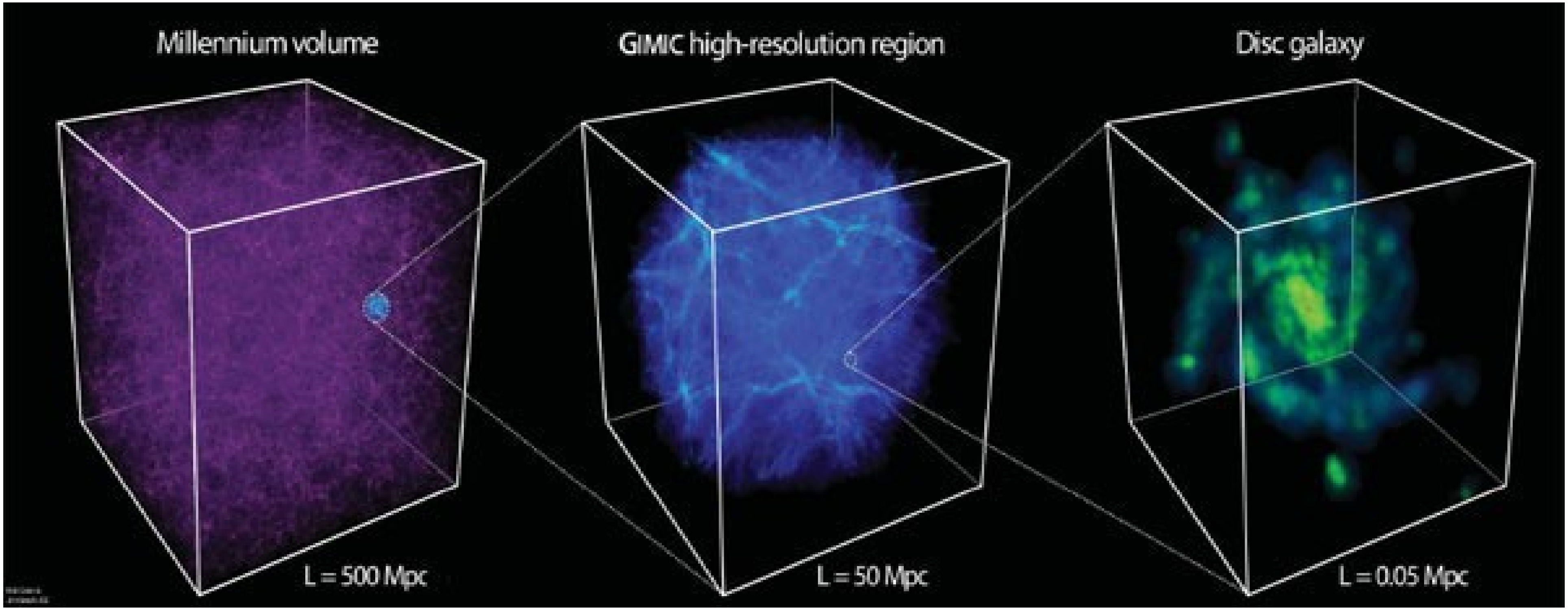
Mild trends present / no sharp transitions
These are theoretically expected

Tejos+12



Tejos+12
(a)
(b)
(c)
(d)
void
edge
uncl.
#
log N_{HI} [cm^{-2}]
b_{HI} [km s^{-1}]
$X \equiv$ min (s/R_{void})
$D \equiv$ min $(s - R_{void})$ [h^{-1} Mpc]

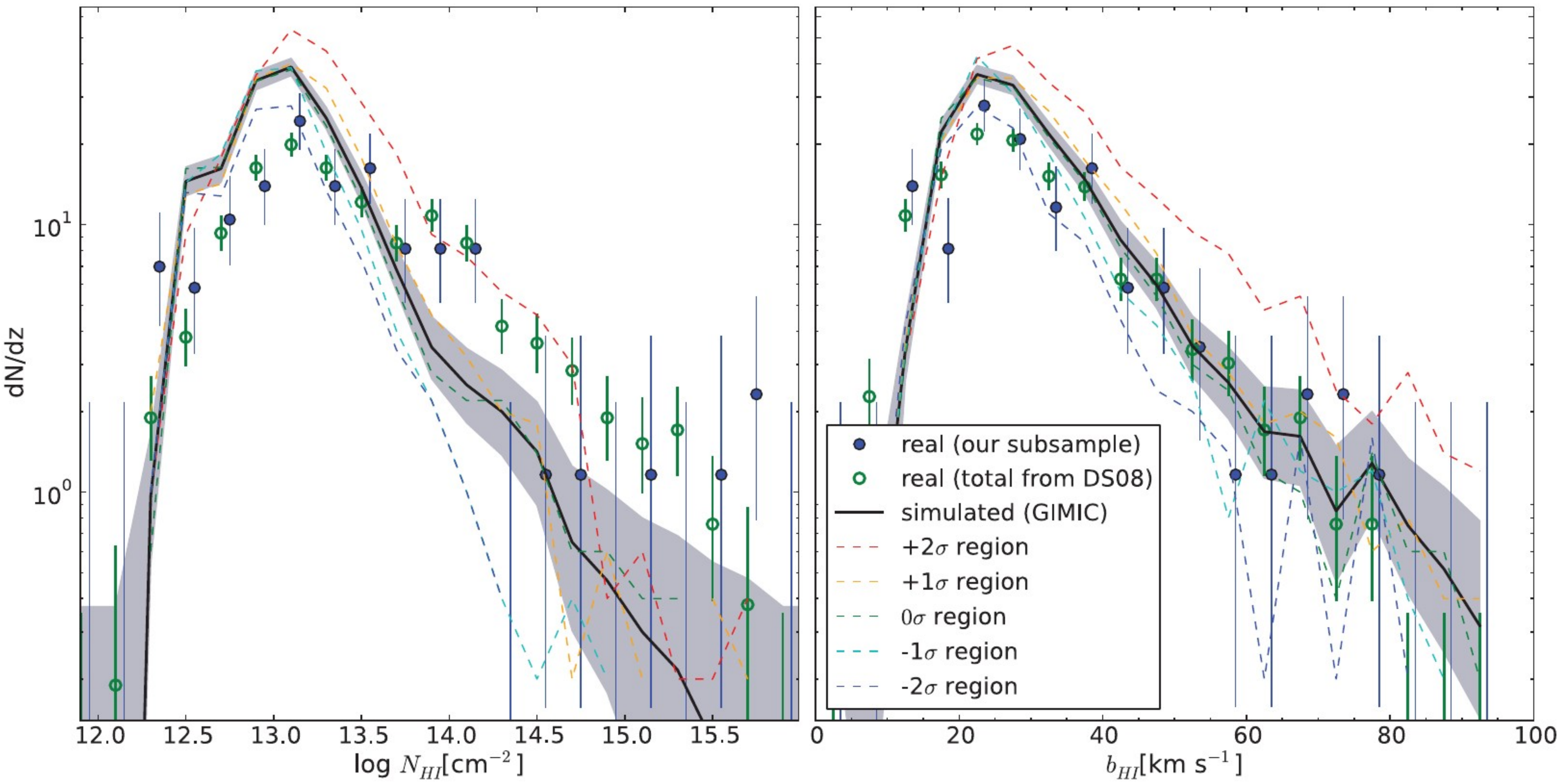
Comparison to simulations



GIMIC simulations **(Crain+09)**

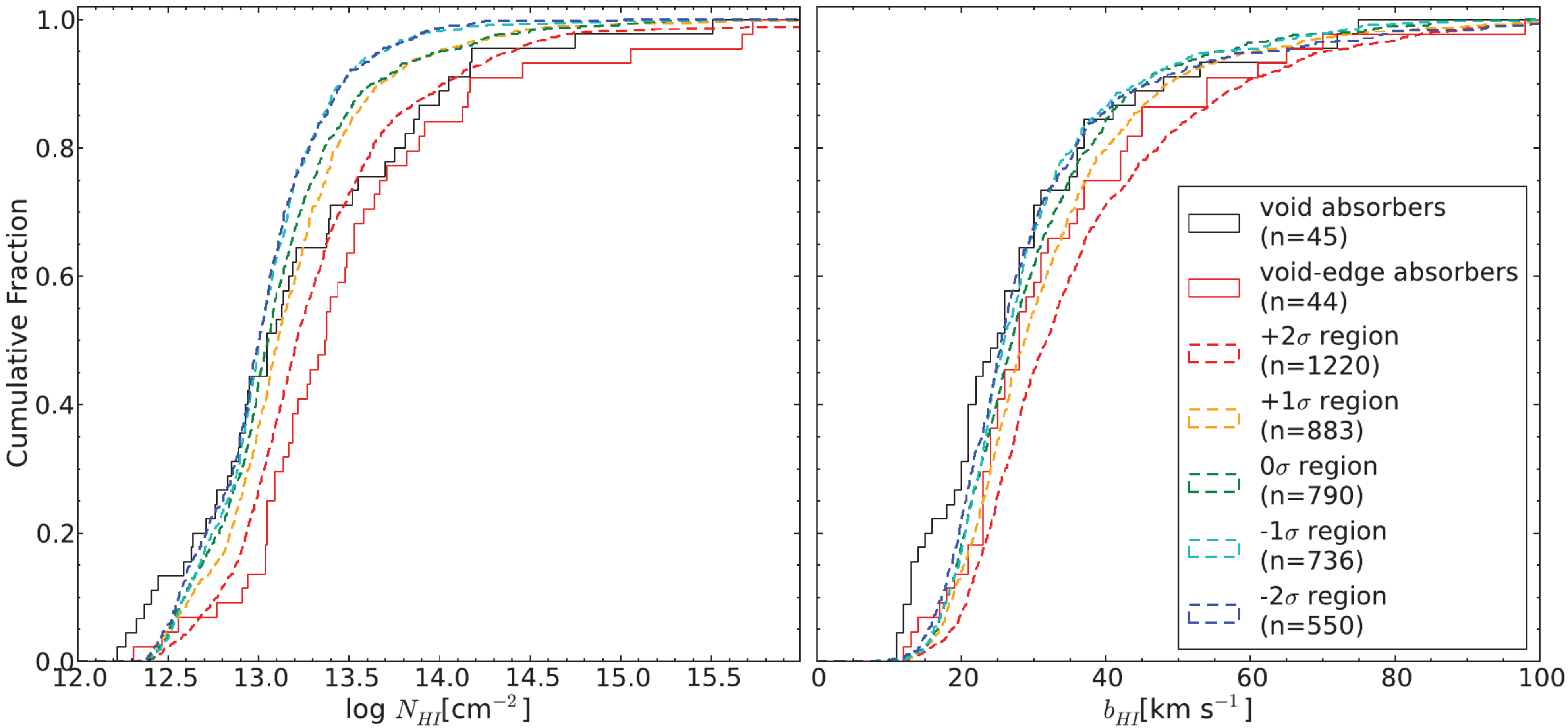
Tejos+12

Comparison to simulations



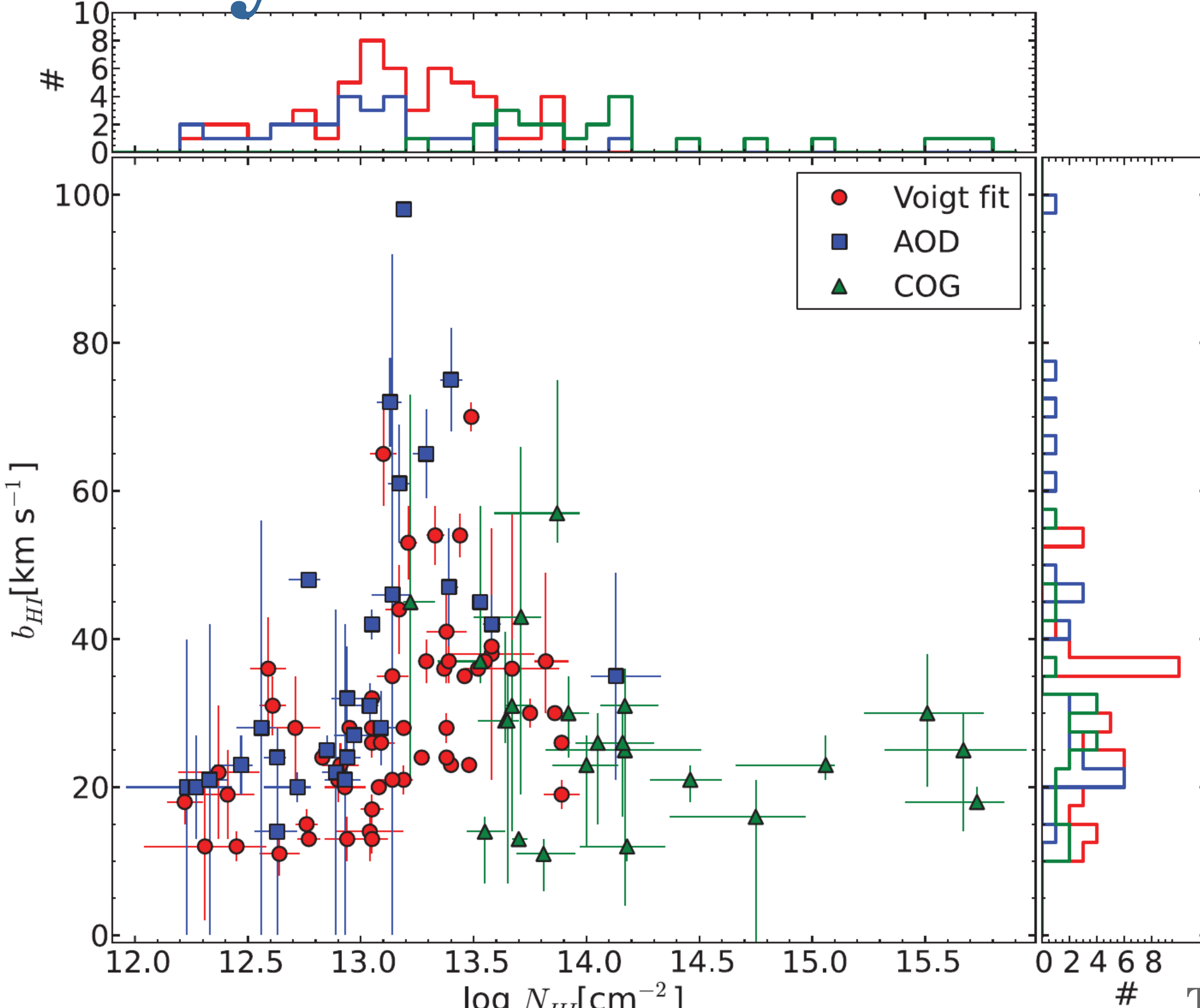
Tejos+12

Comparison to simulations



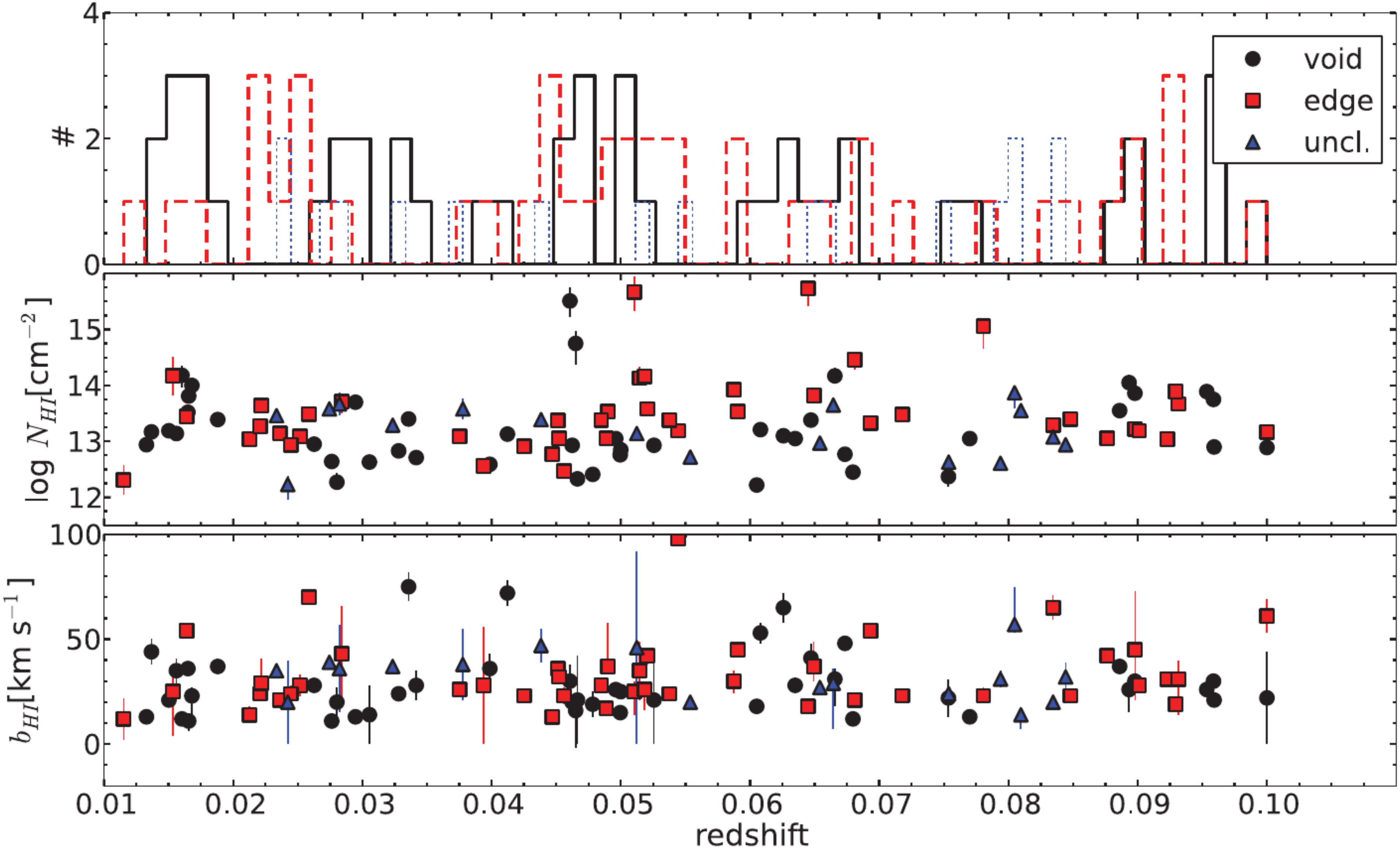
Tejos+12

Systematic effects



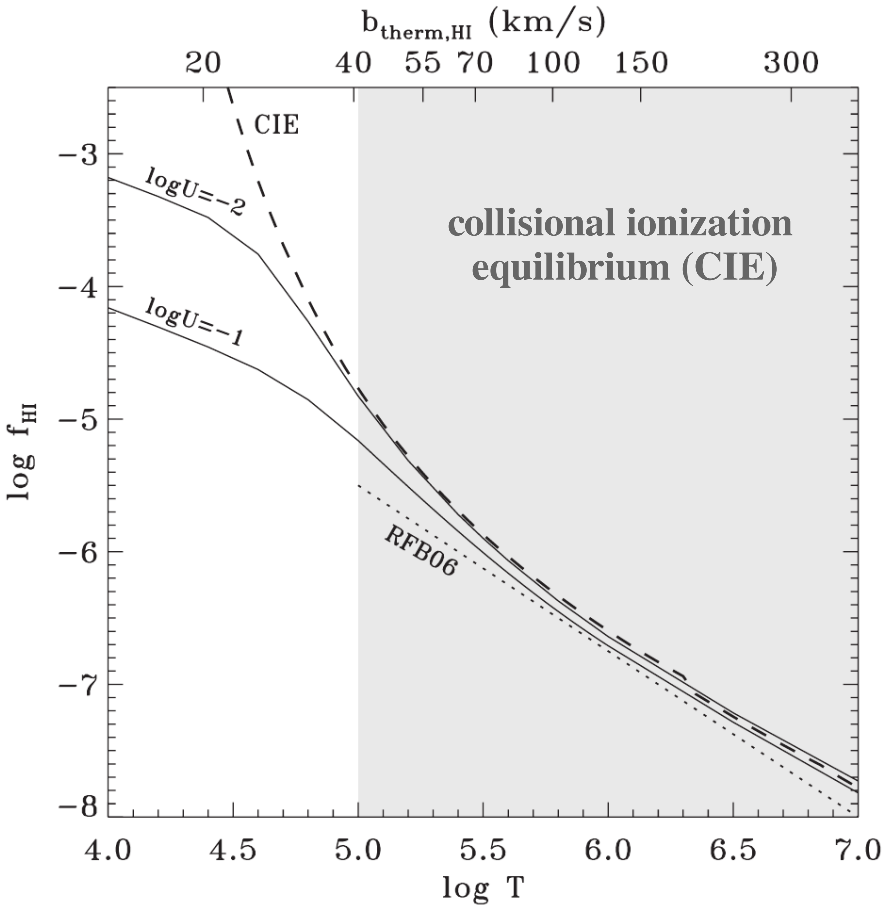
Tejos+12

Systematic effects

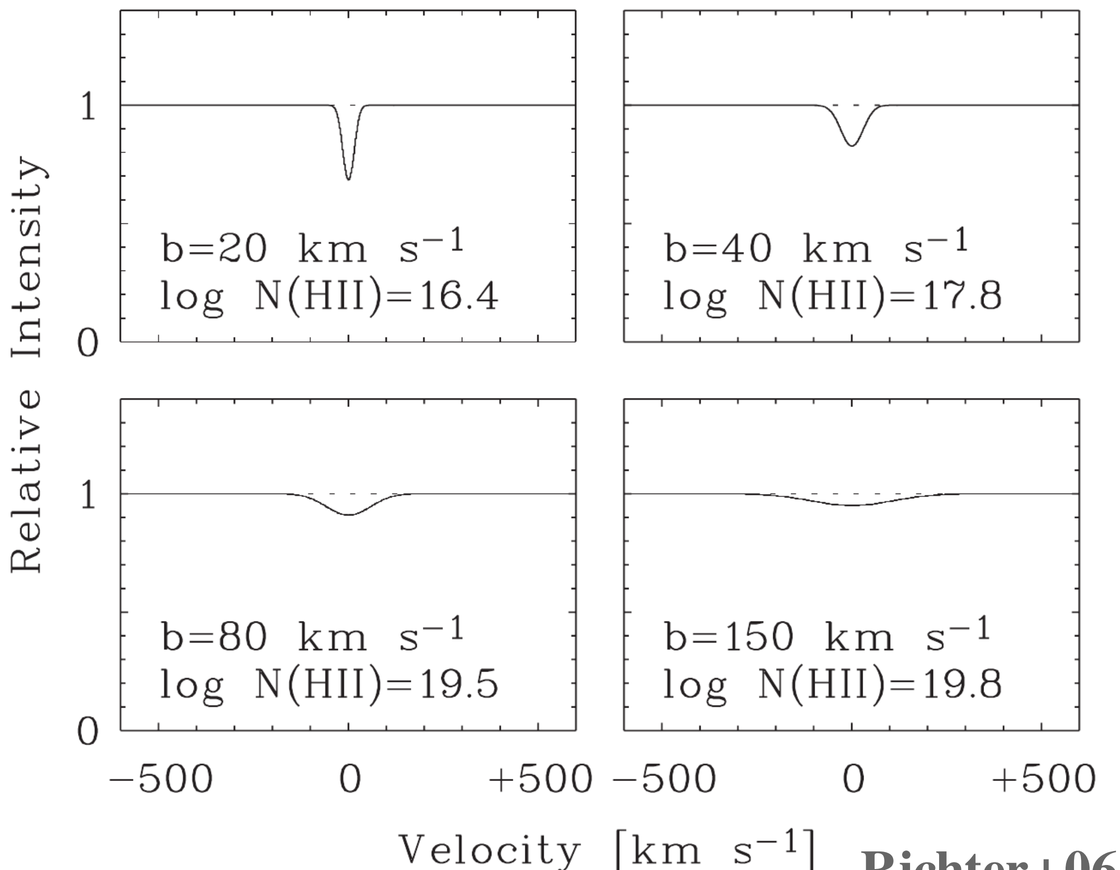


Tejos+12

Experimental challenge



Danforth+10

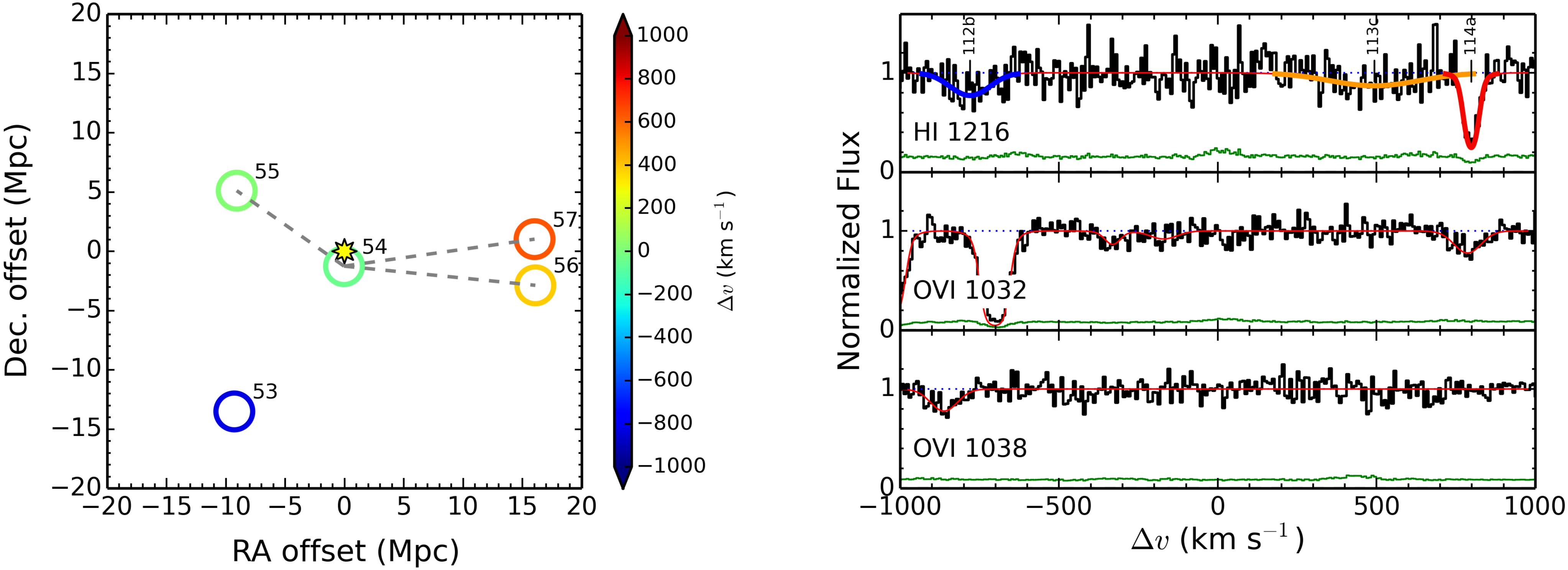


Richter+06

The higher the temperature, the more difficult to detect HI in absorption

Examples

z=0.4584



Tejos+14b in prep.