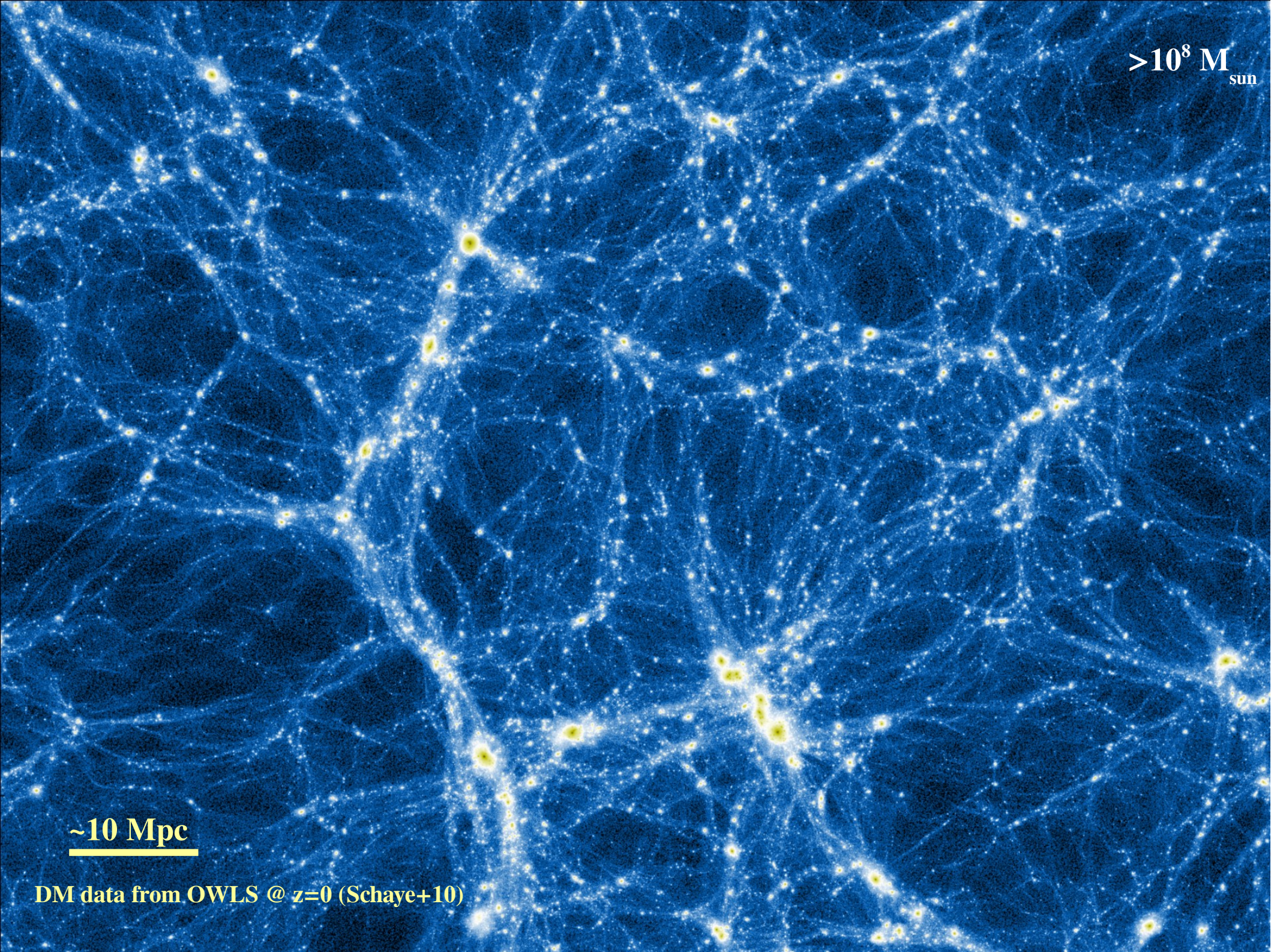
UNIVERSITY OF CALIFORNIA
SANTA CRUZ

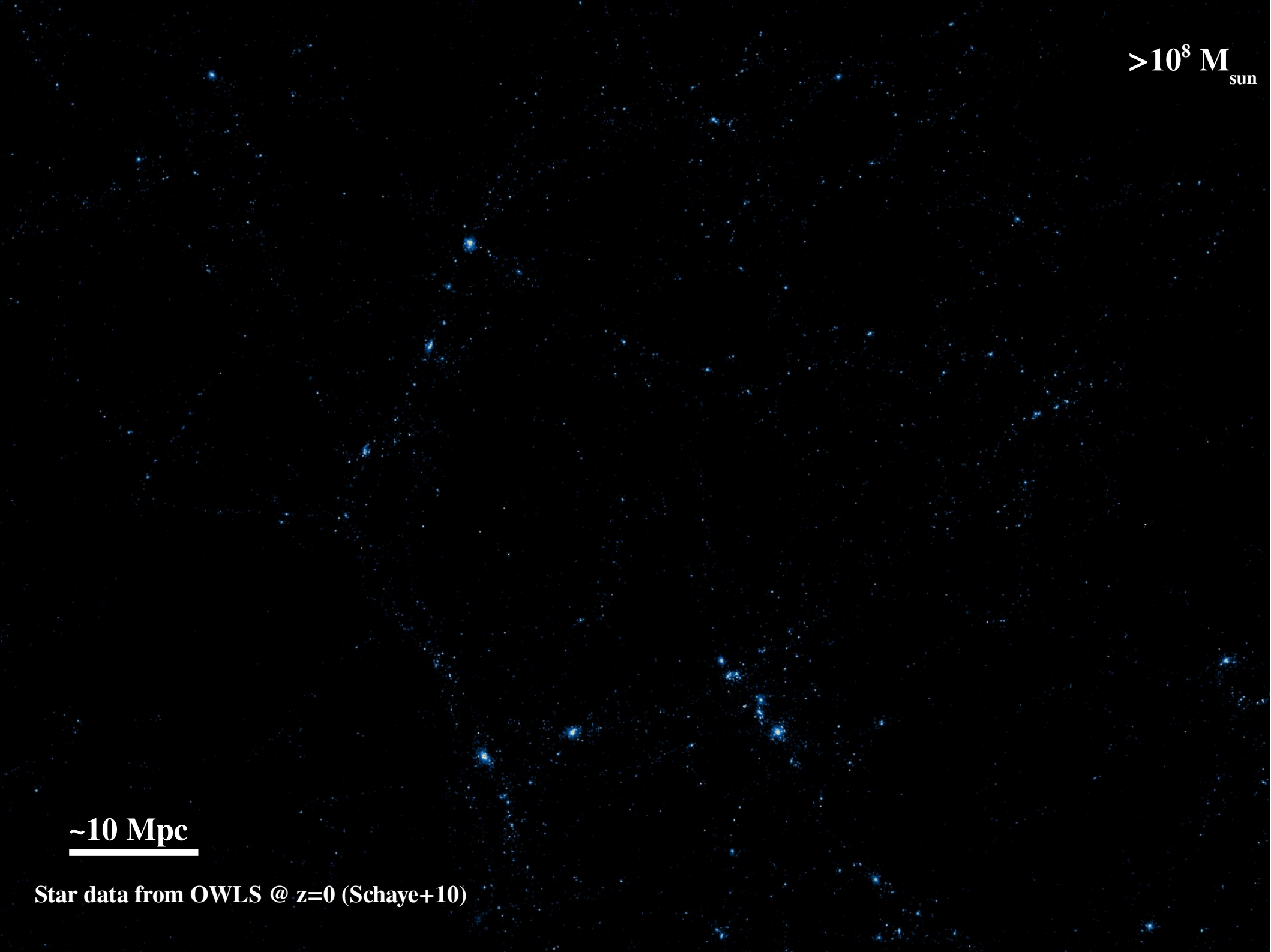
The intergalactic medium in the cosmic web

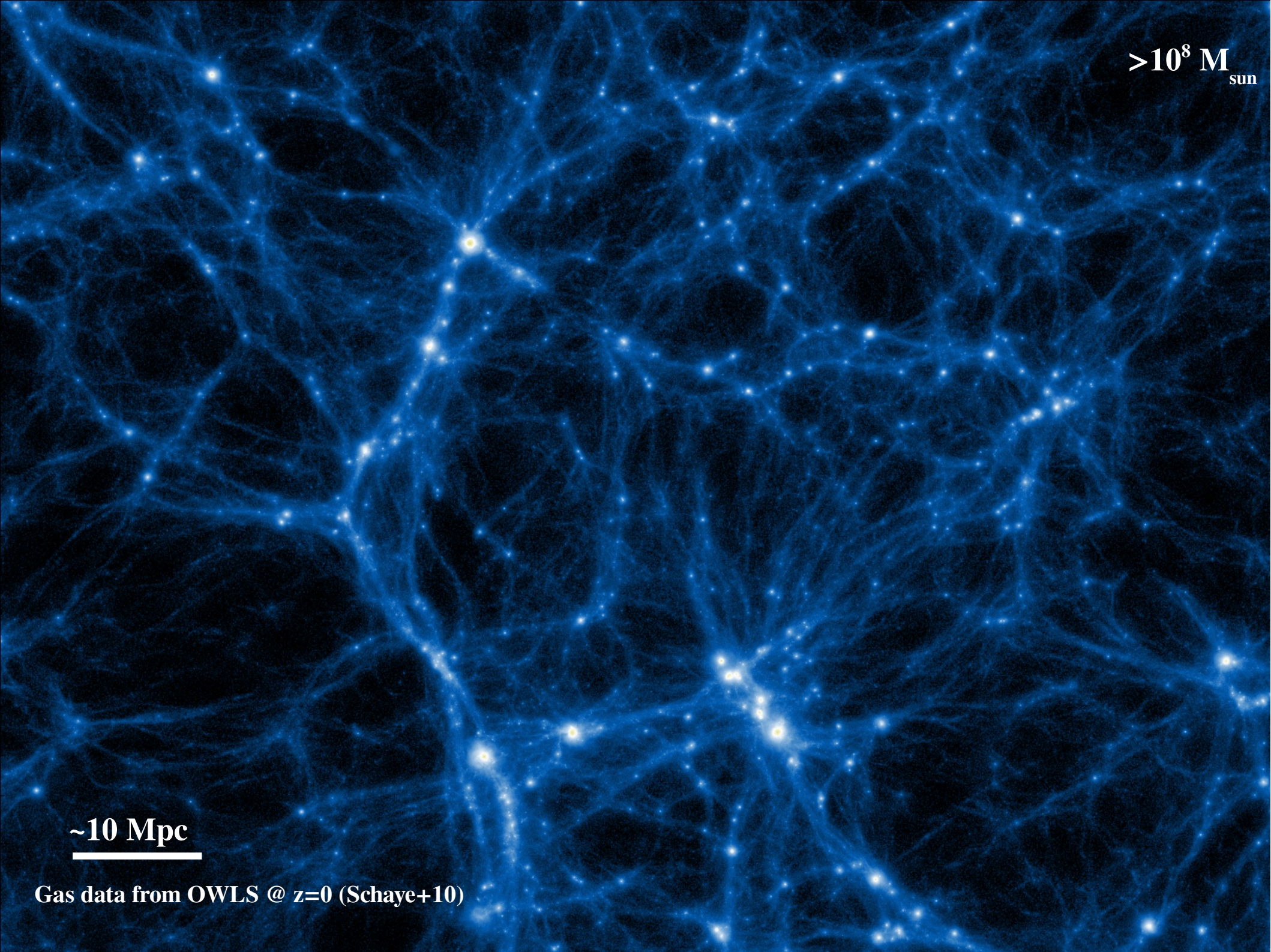
Nicolas Tejos

(IMPS Fellow, UCO/UC Santa Cruz)

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


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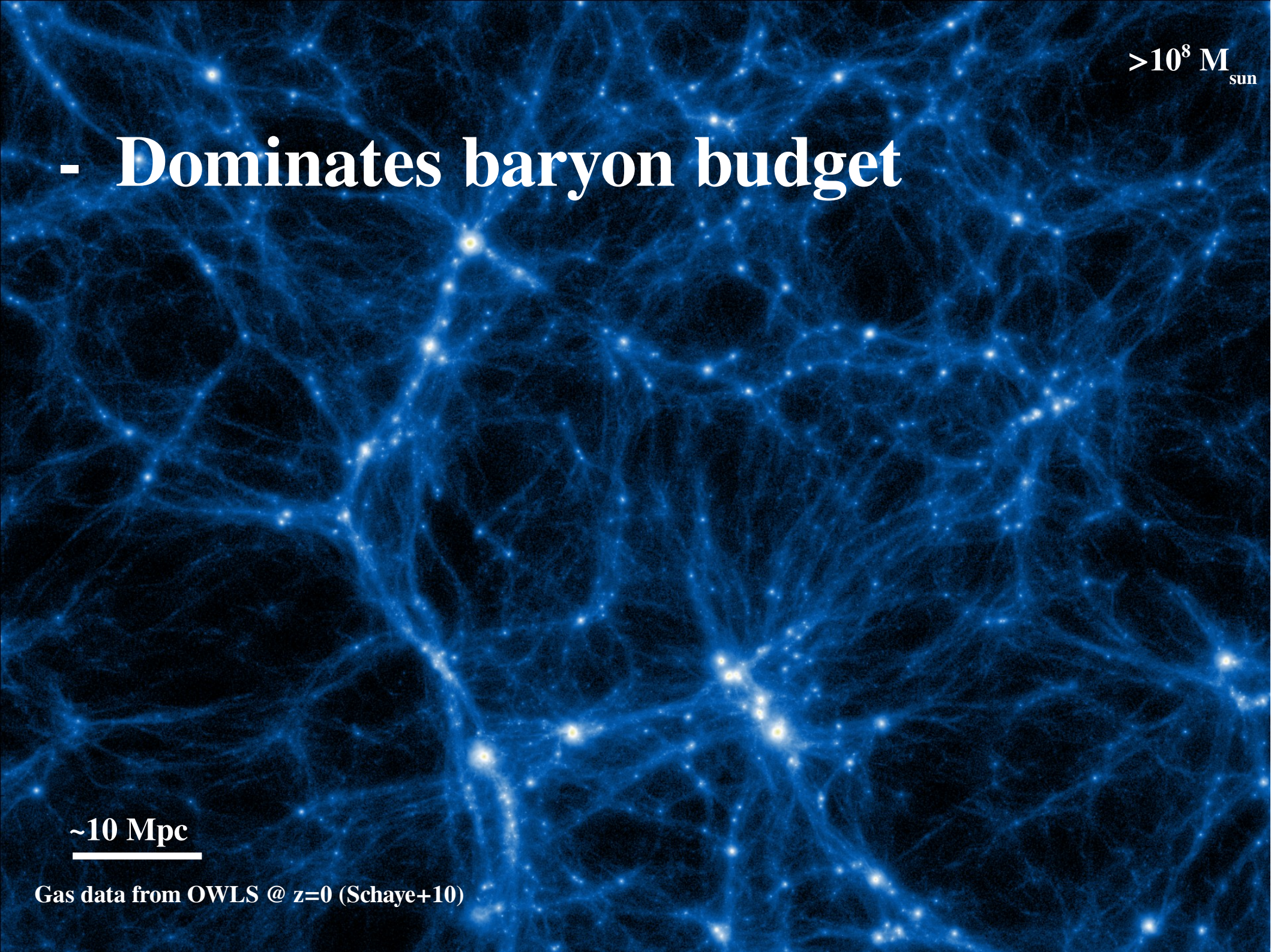
Gas data from OWLS @ z=0 (Schaye+10)


>10^8 M_sun
- Dominates baryon budget
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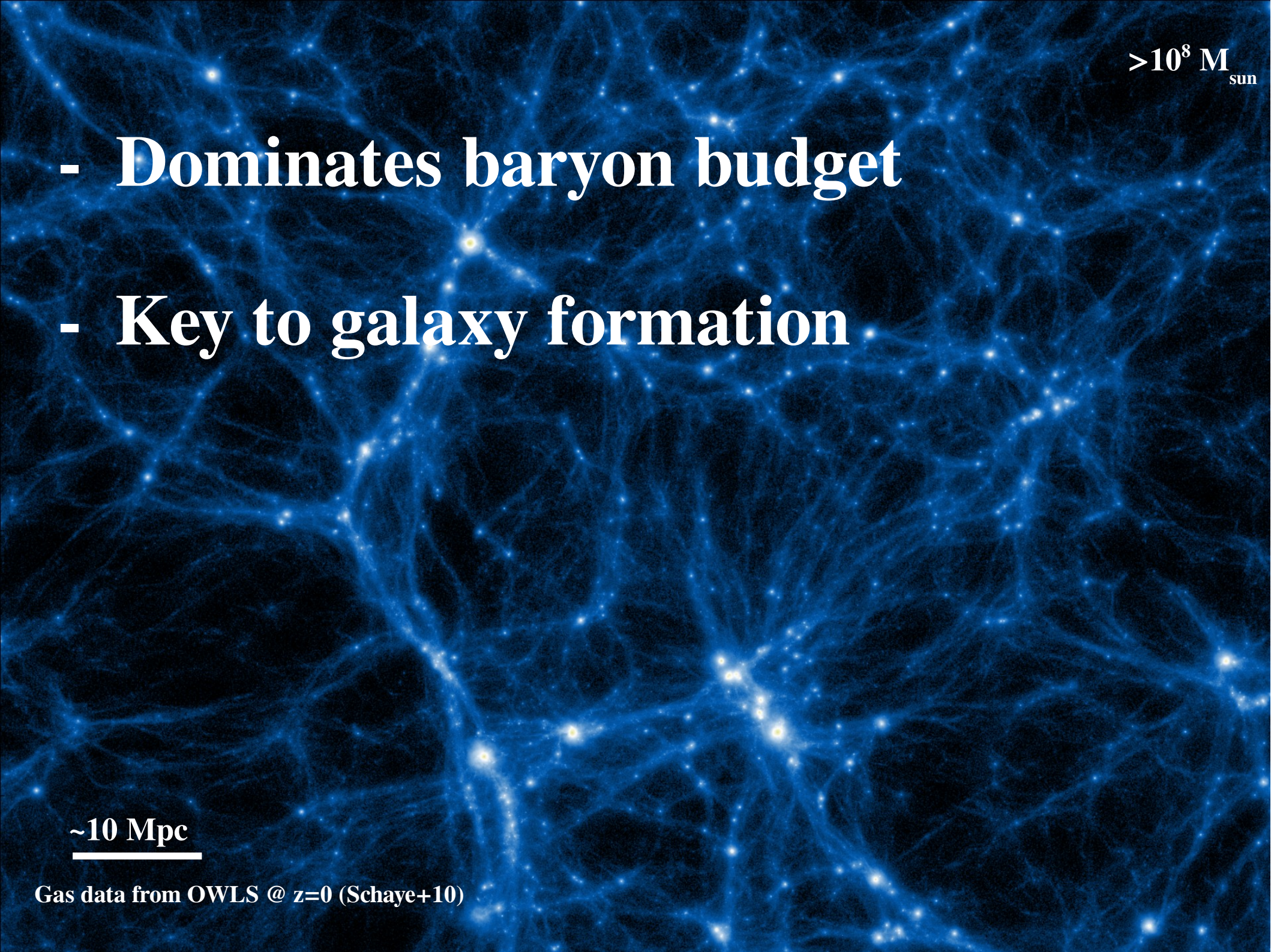
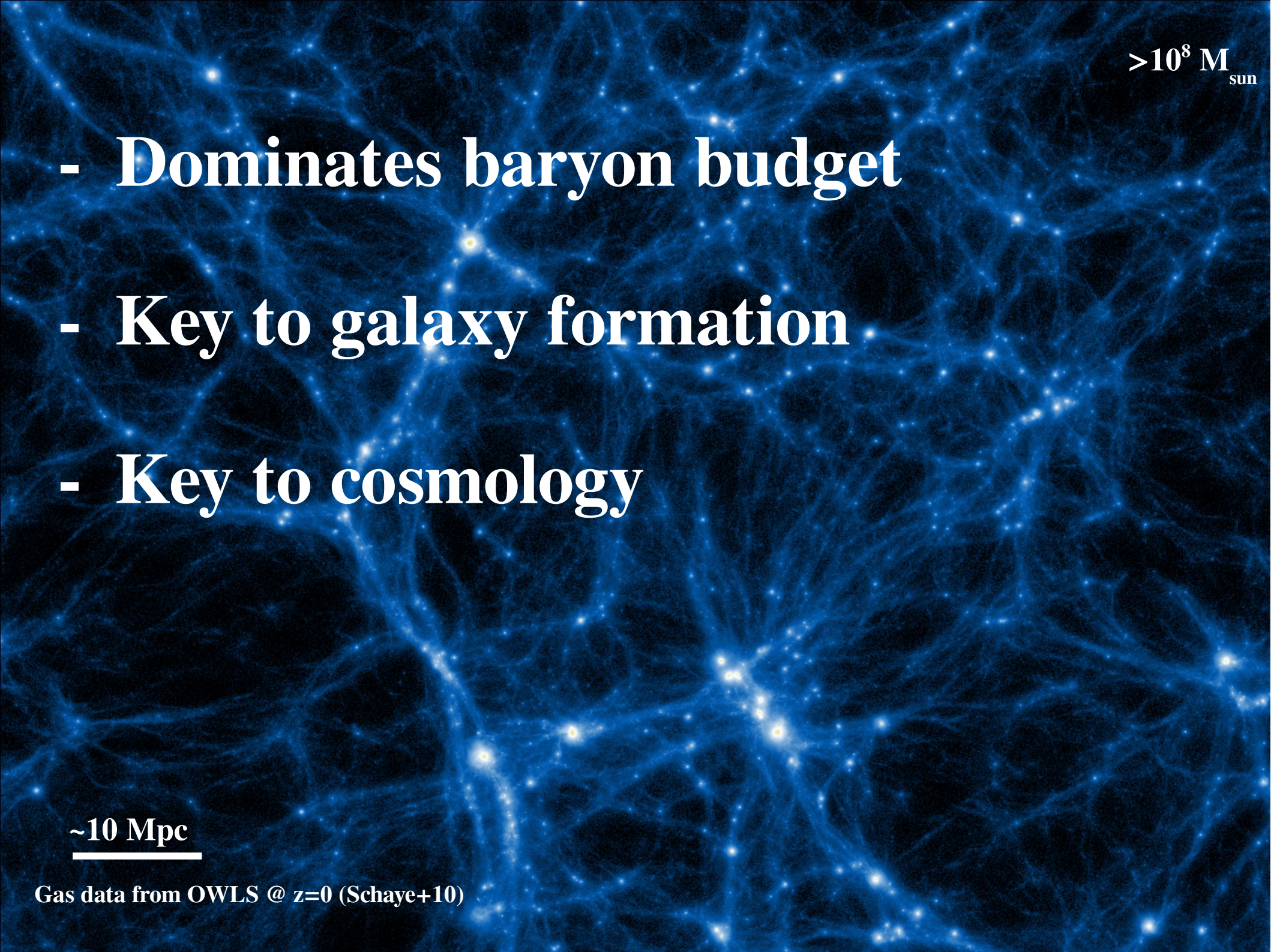
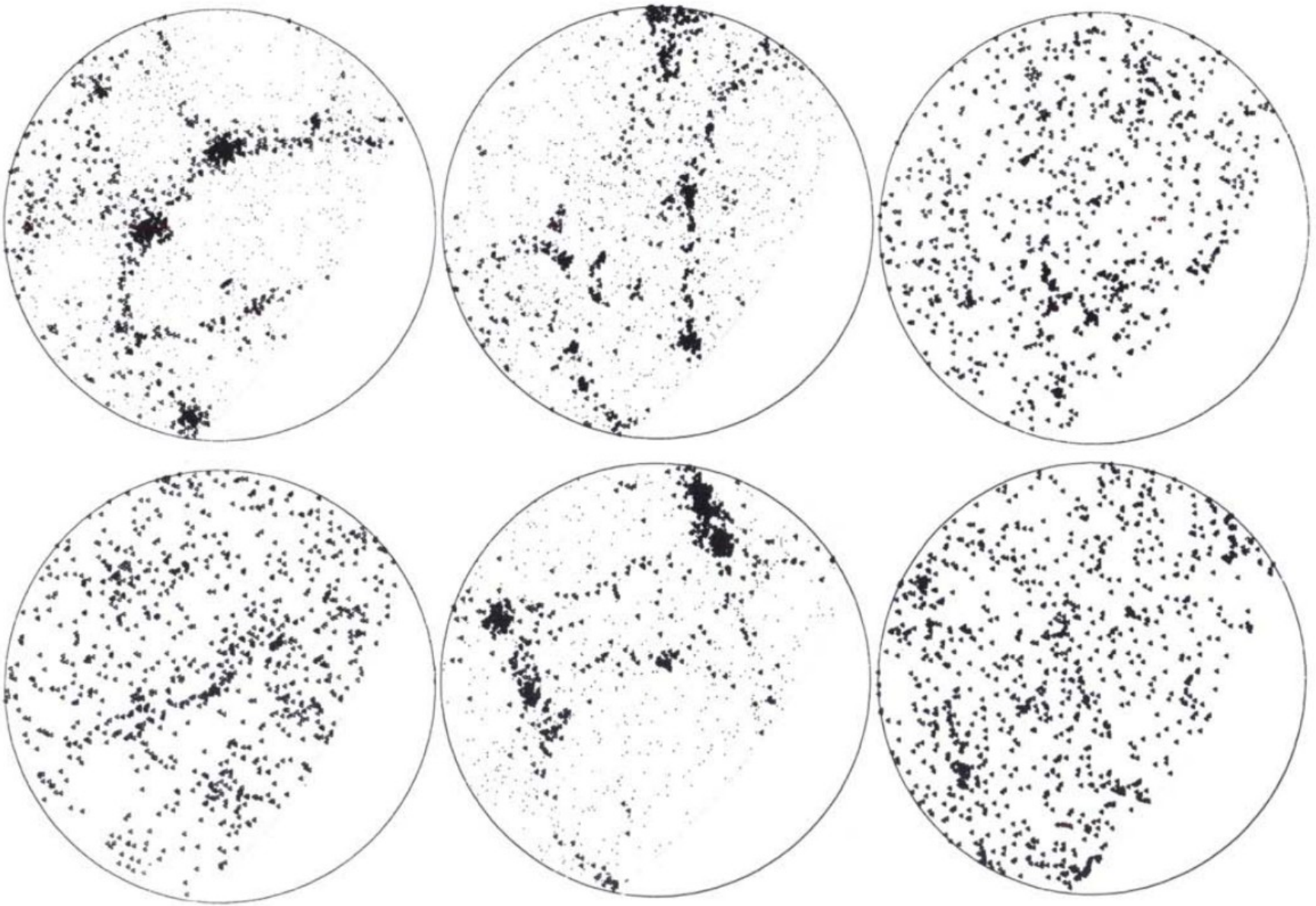
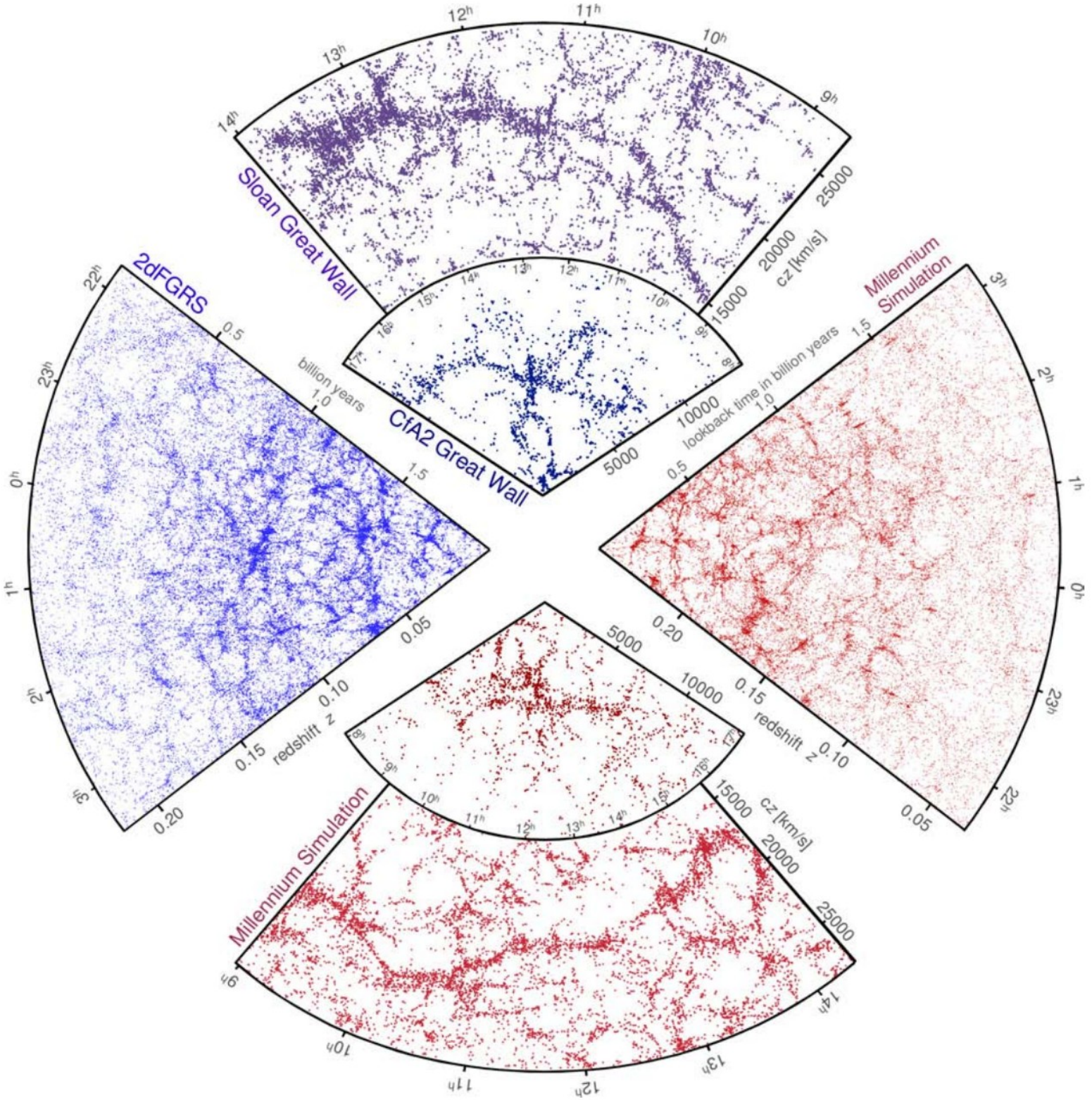
Gas data from OWLS @ z=0 (Schaye+10)


>10^8 M_sun
- Dominates baryon budget
- Key to galaxy formation
~10 Mpc
Gas data from OWLS @ z=0 (Schaye+10)


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




Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
Millennium Simulation
billion years
lookback time in billion years
redshift z
cz [km/s]

Springel+06

Outline

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

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

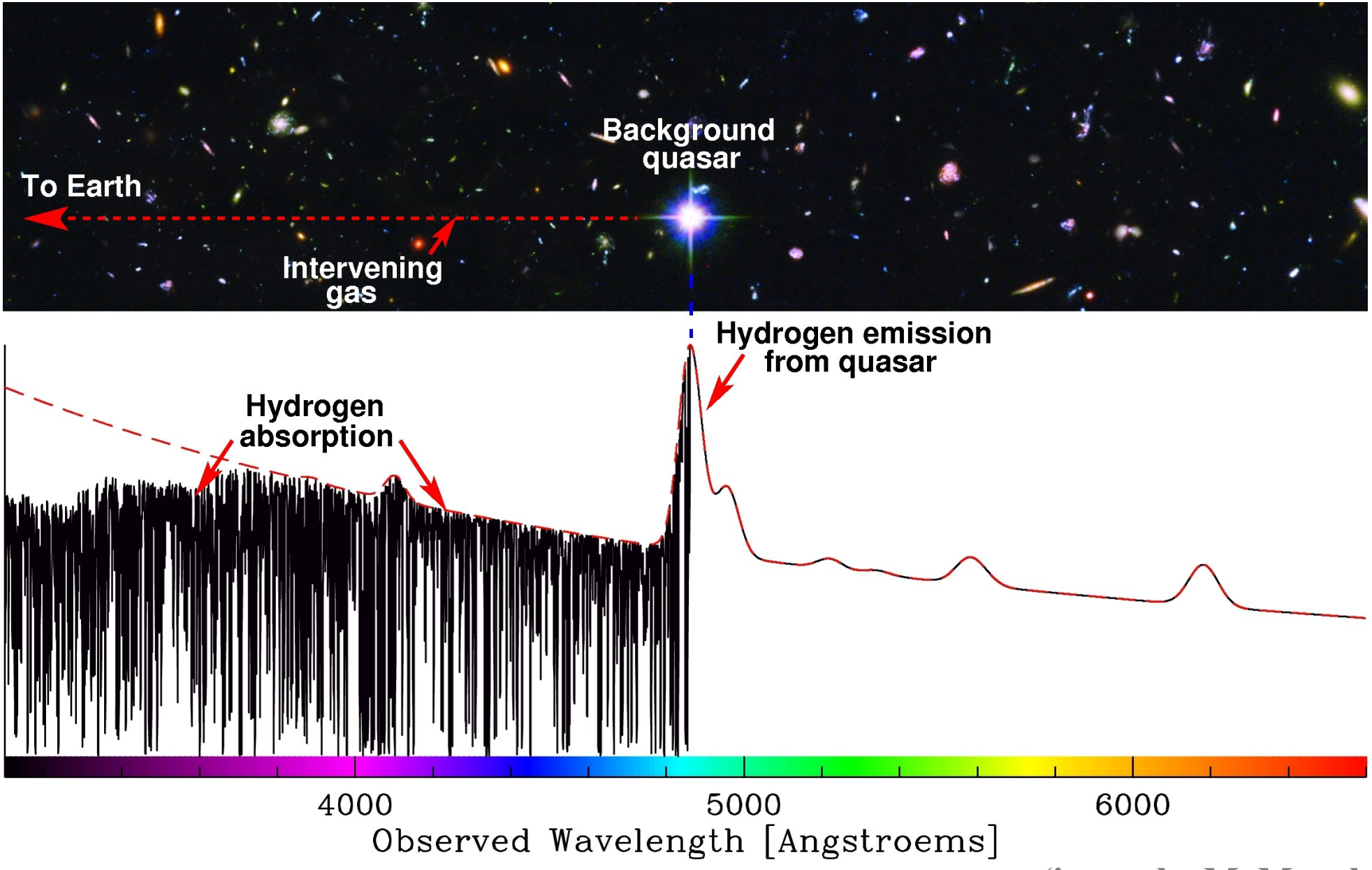
- **Part II: The IGM within and around galaxy voids at z<0.1**
  (Tejos et al. 2012, MNRAS, 425, 245)

- **Part III: The IGM in intercluster filaments at z<0.5**
  (Tejos et al. 2015, in prep.)

- **Summary & Conclusions**

- **(Future work)**

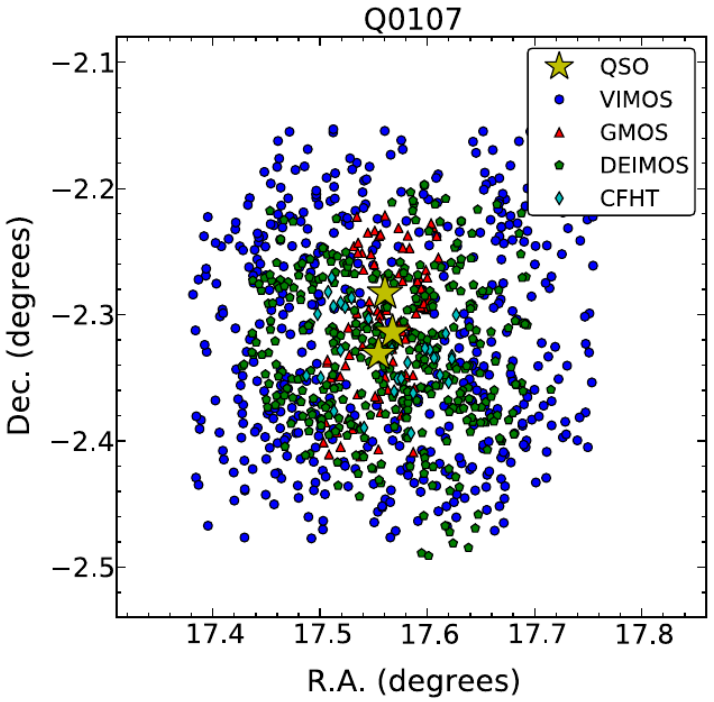
How do we observe the IGM

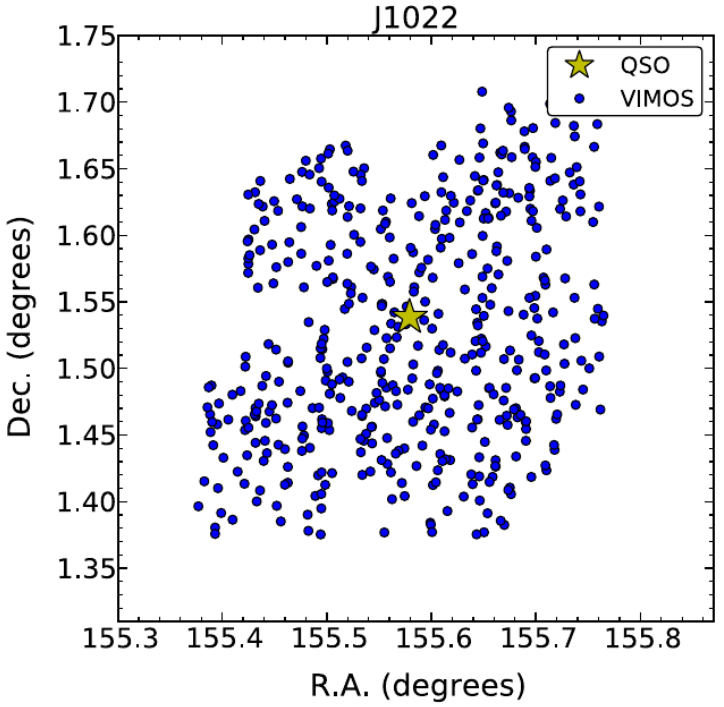


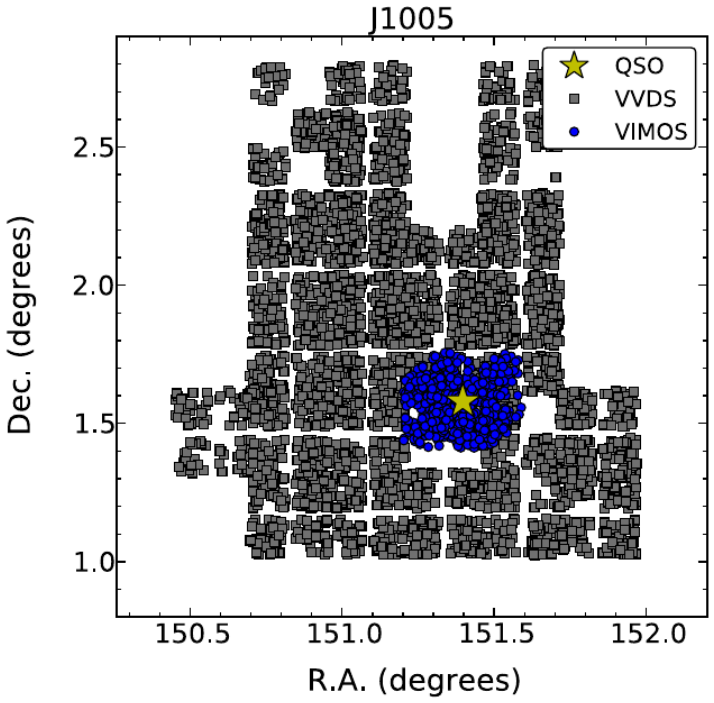
(image by M. Murphy)

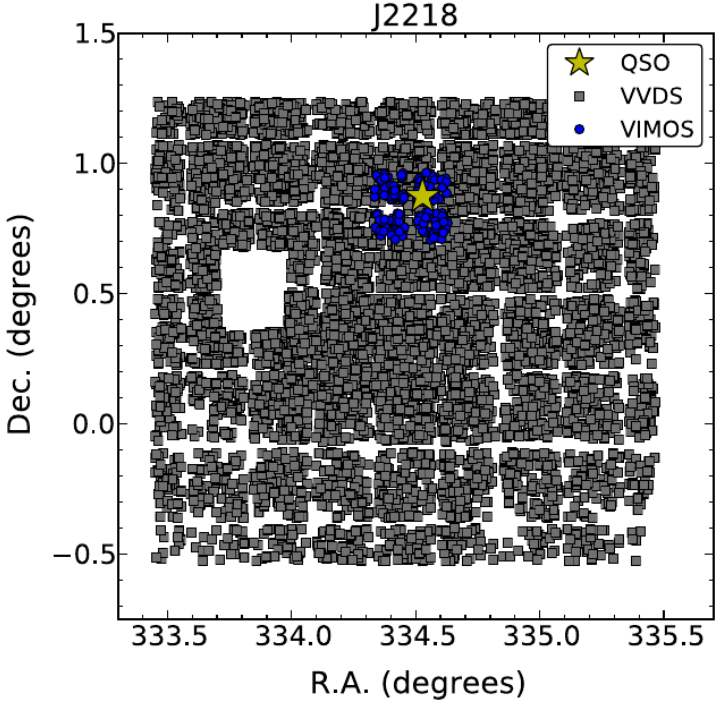
Part I:

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

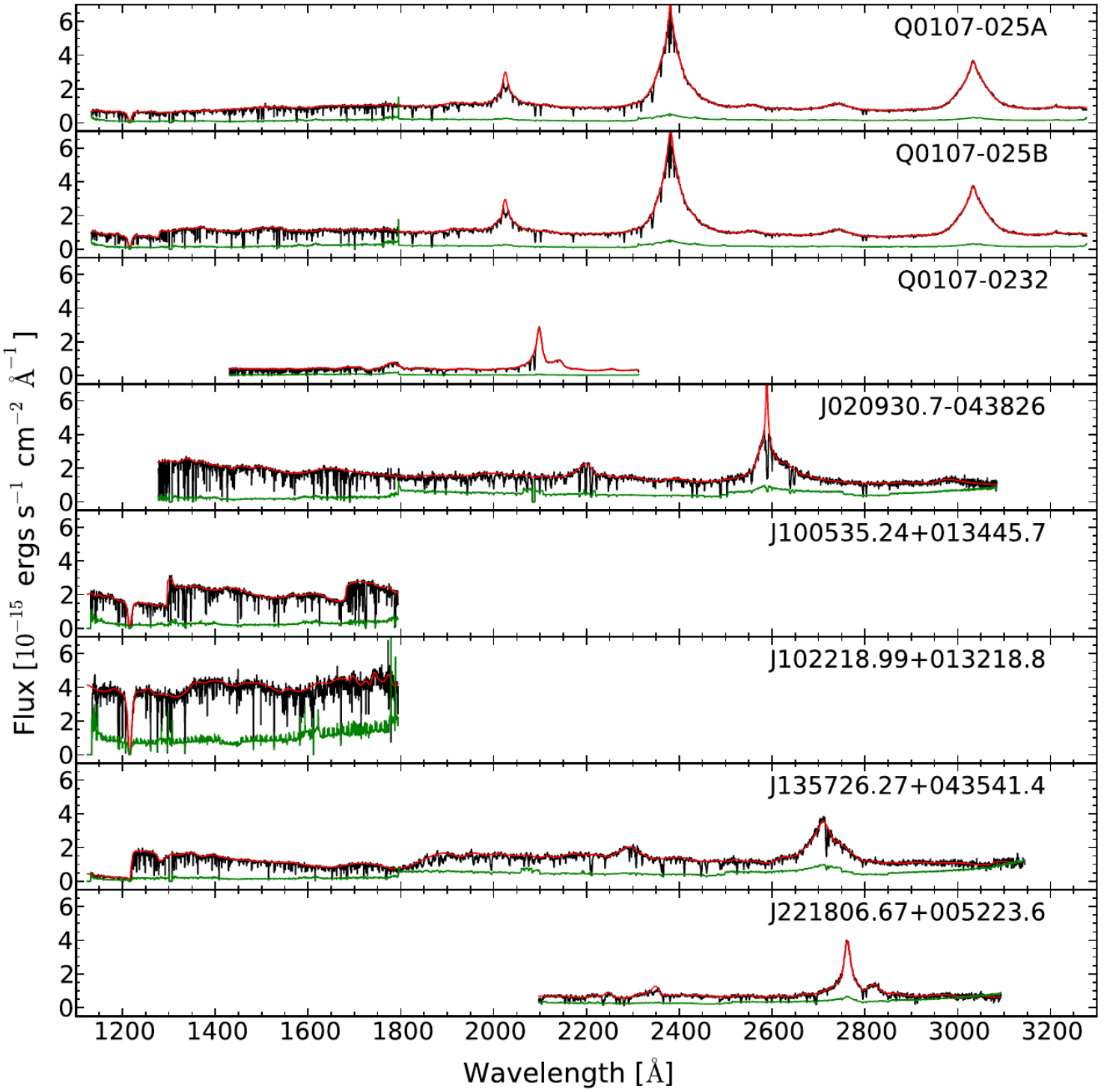
(Le Fevre+05,13)

+GDDS

(Abraham+04)

6 fields

Tejos+14



QSO sample

IGM

~700 HI abs. systems

HST/COS

HST/FOS

(138+ orbits)

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:**

$$\hat{\xi}_{LS} \equiv \frac{D_aD_b - D_aR_b - R_aD_b + R_aR_b}{R_aR_b}$$

Landy & Szalay 1993

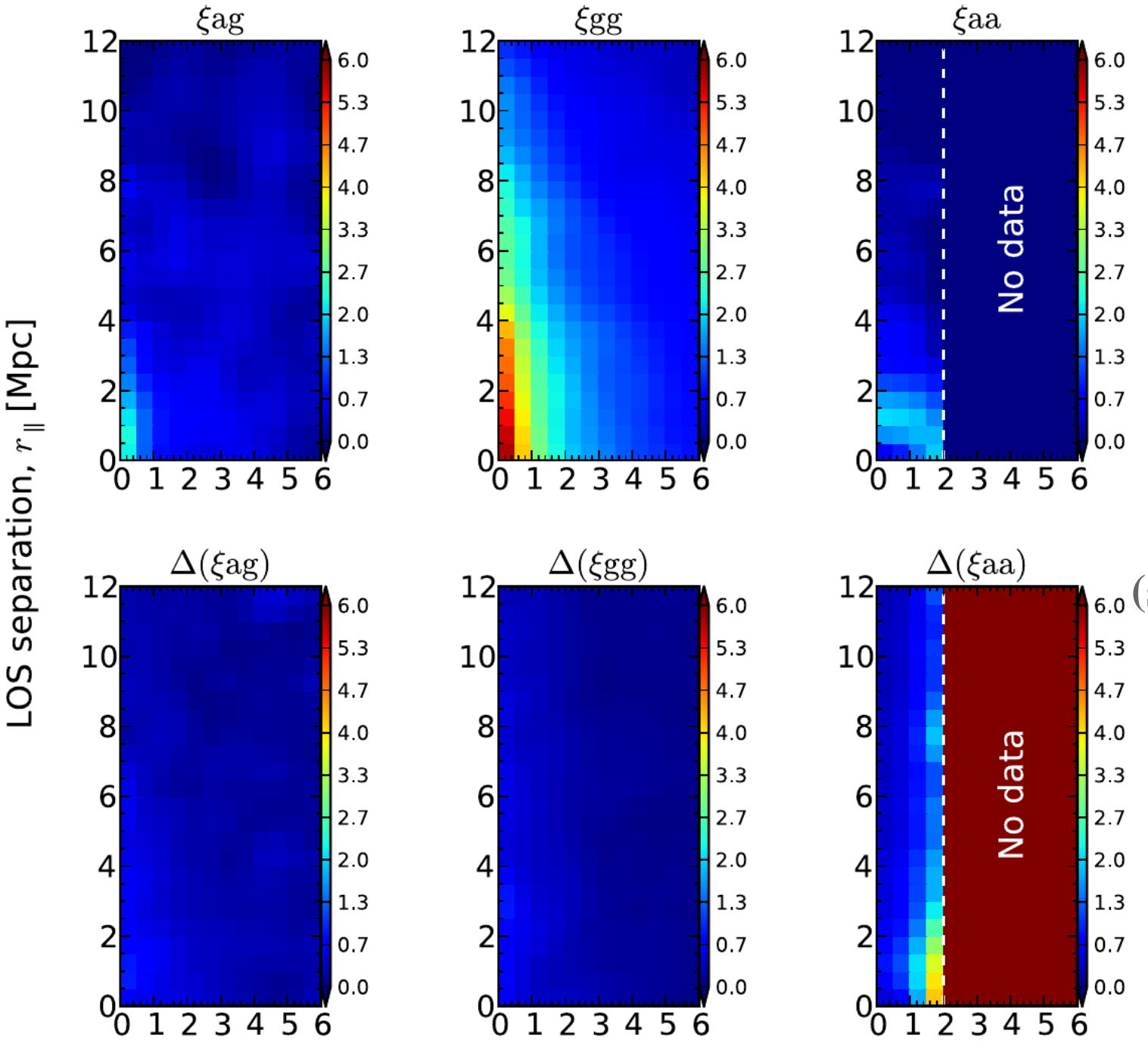
Samples

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



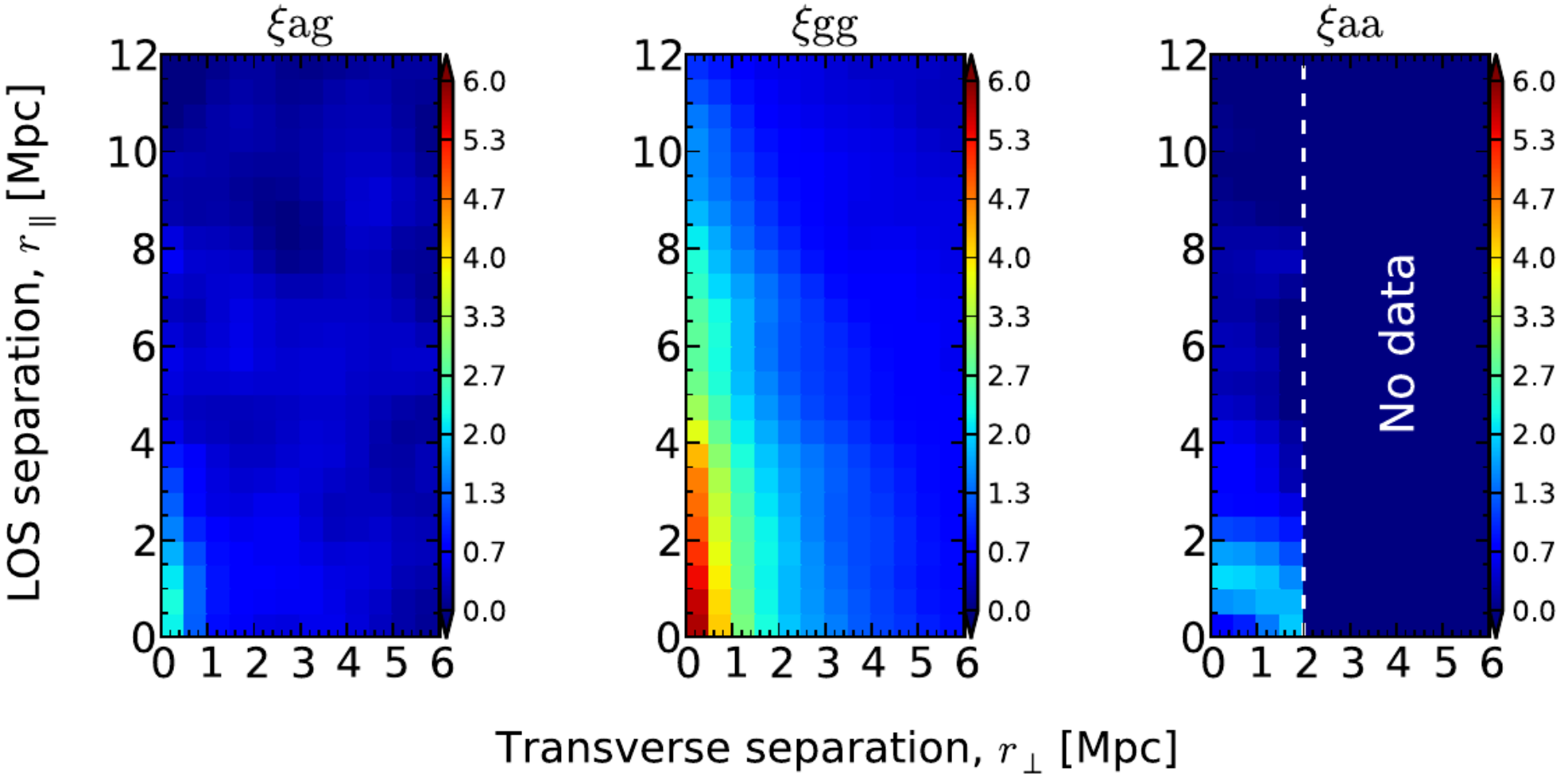
Well constrained measurements (small uncertainties)

Tejos+14

Part I:

Key results

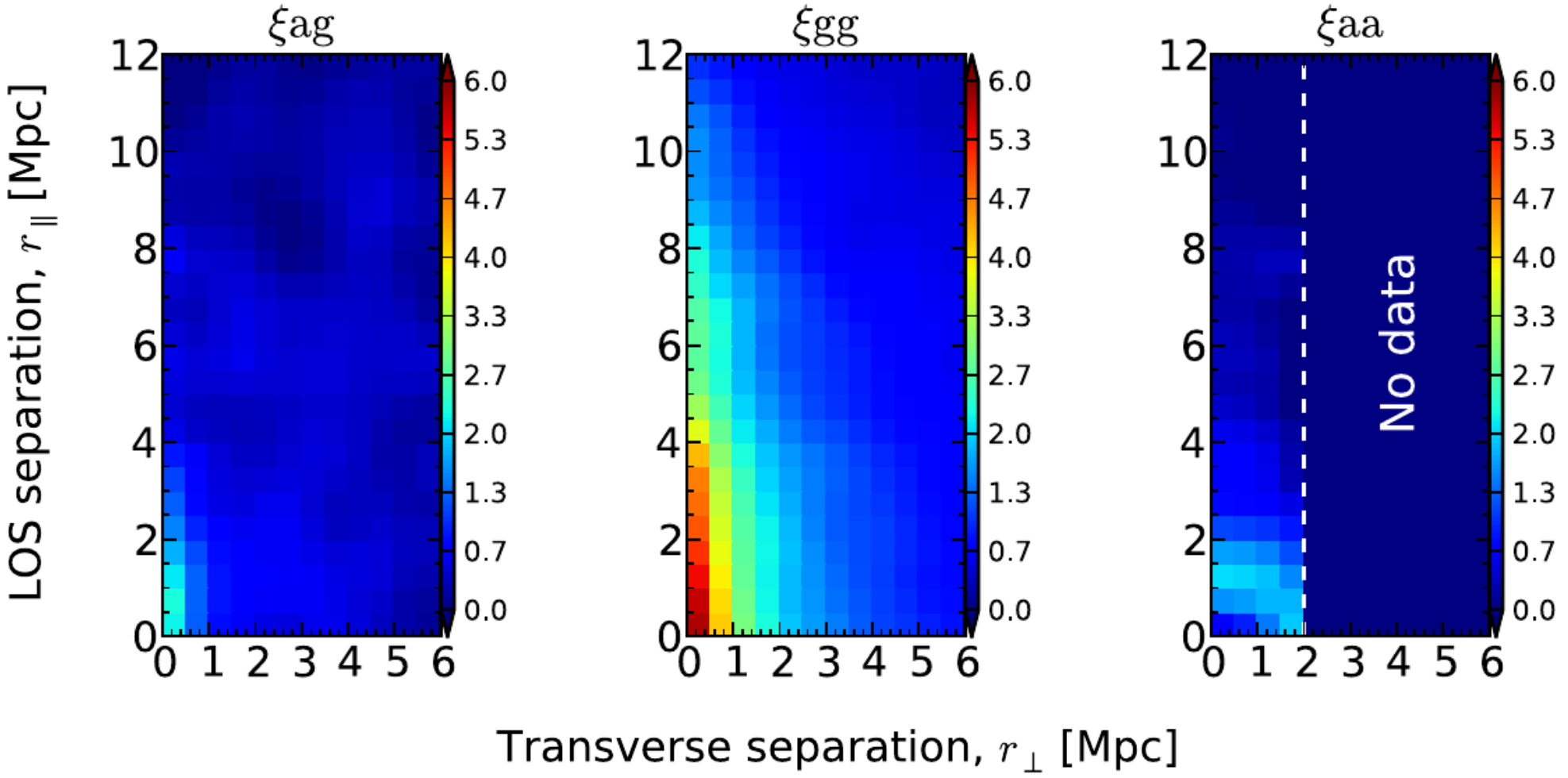
No strong outflow/inflow



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

Tejos+14

Test linear dependence



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

Tejos+14

Linear dependence

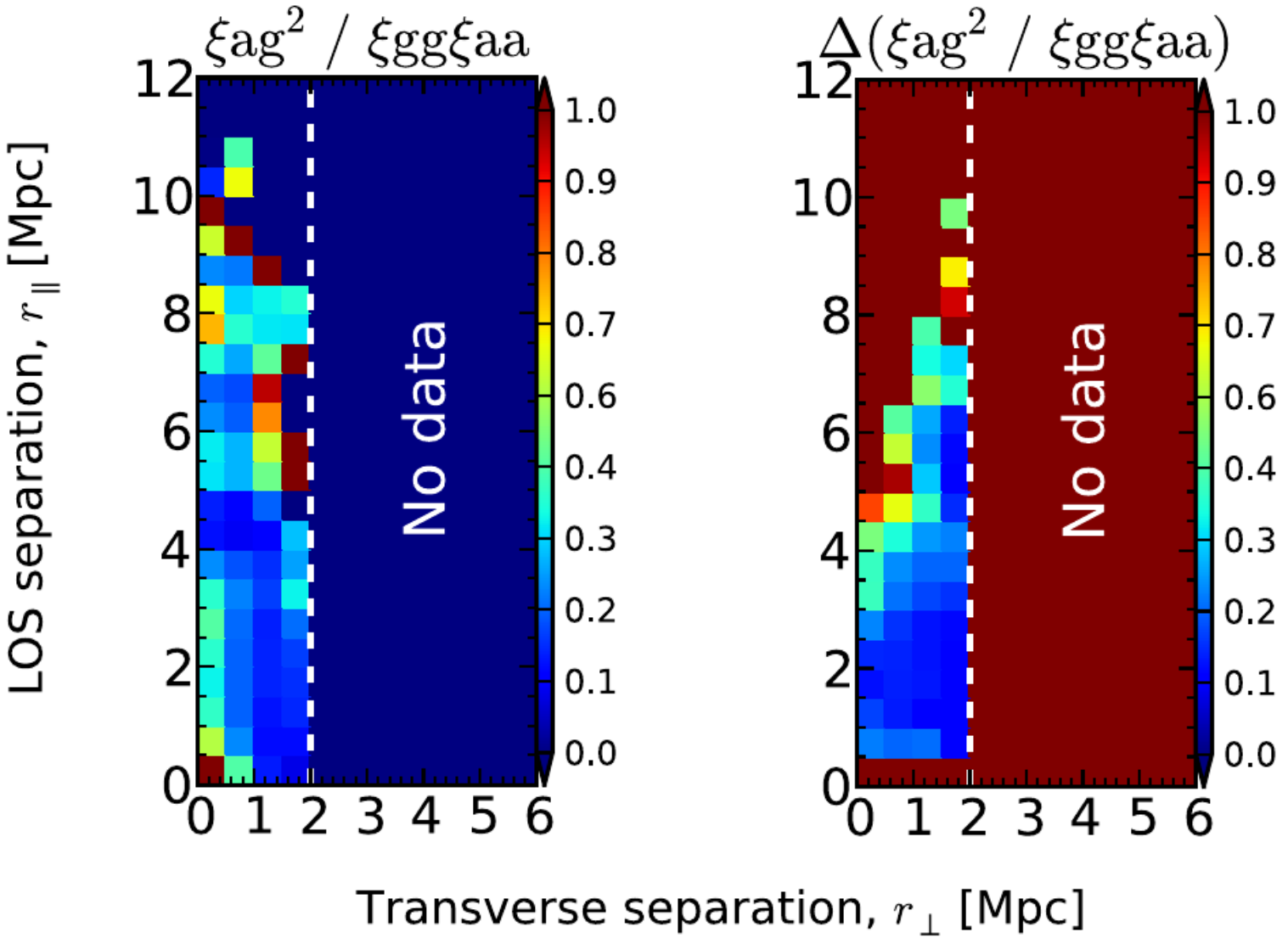
$$\xi_{\rm gg} = b_{\rm g}^2 \xi_{\rm DM}$$

$$\xi_{\rm aa} = b_{\rm a}^2 \xi_{\rm DM}$$

$$\xi_{\rm ag} = b_{\rm a} b_{\rm b} \xi_{\rm DM}$$

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

HI and galaxies do not trace same structures

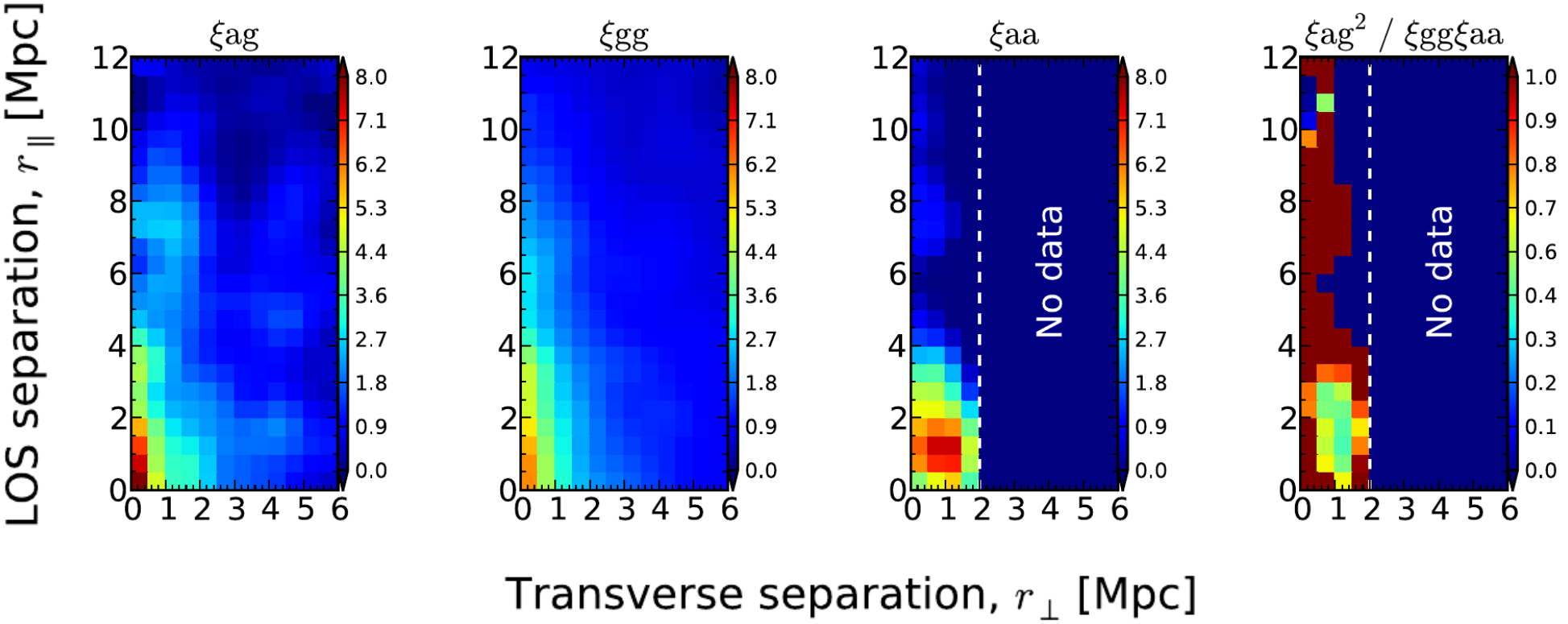


Tejos+14

Part I:

Subsamples

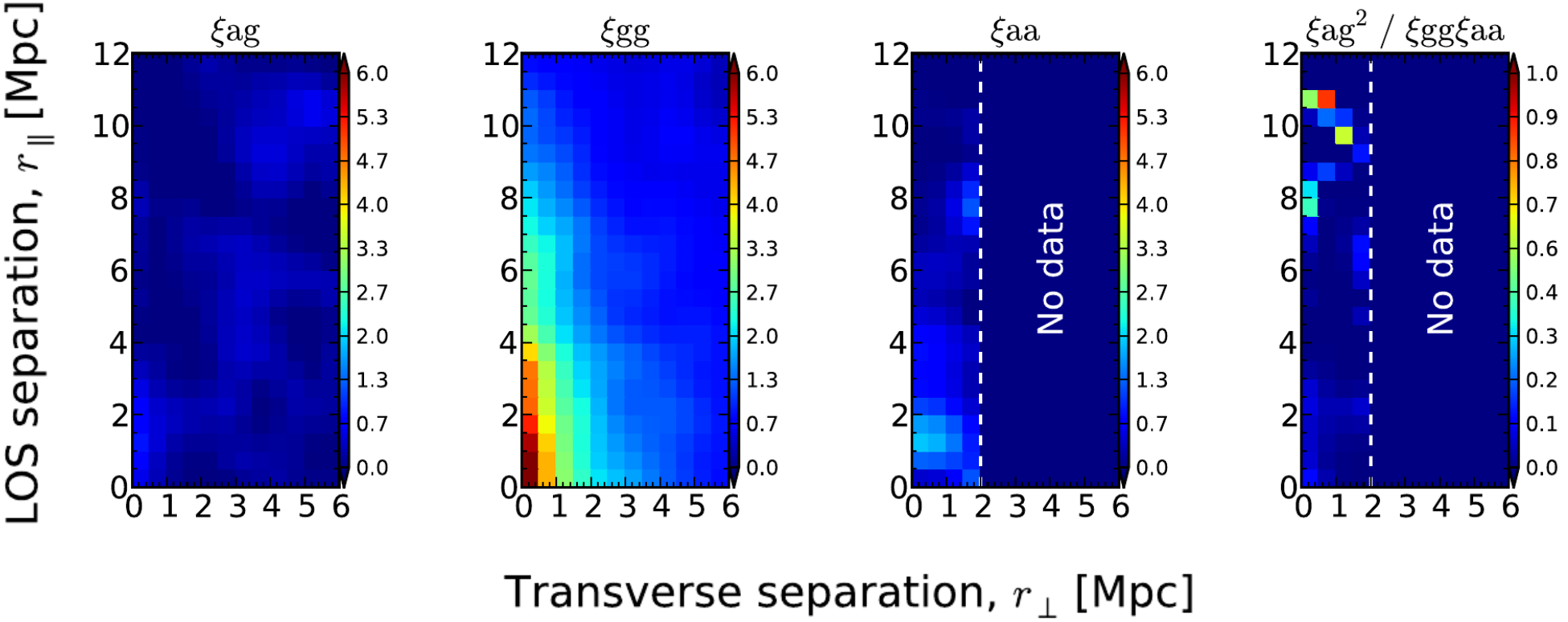
'Strong' HI systems and star-forming galaxies



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



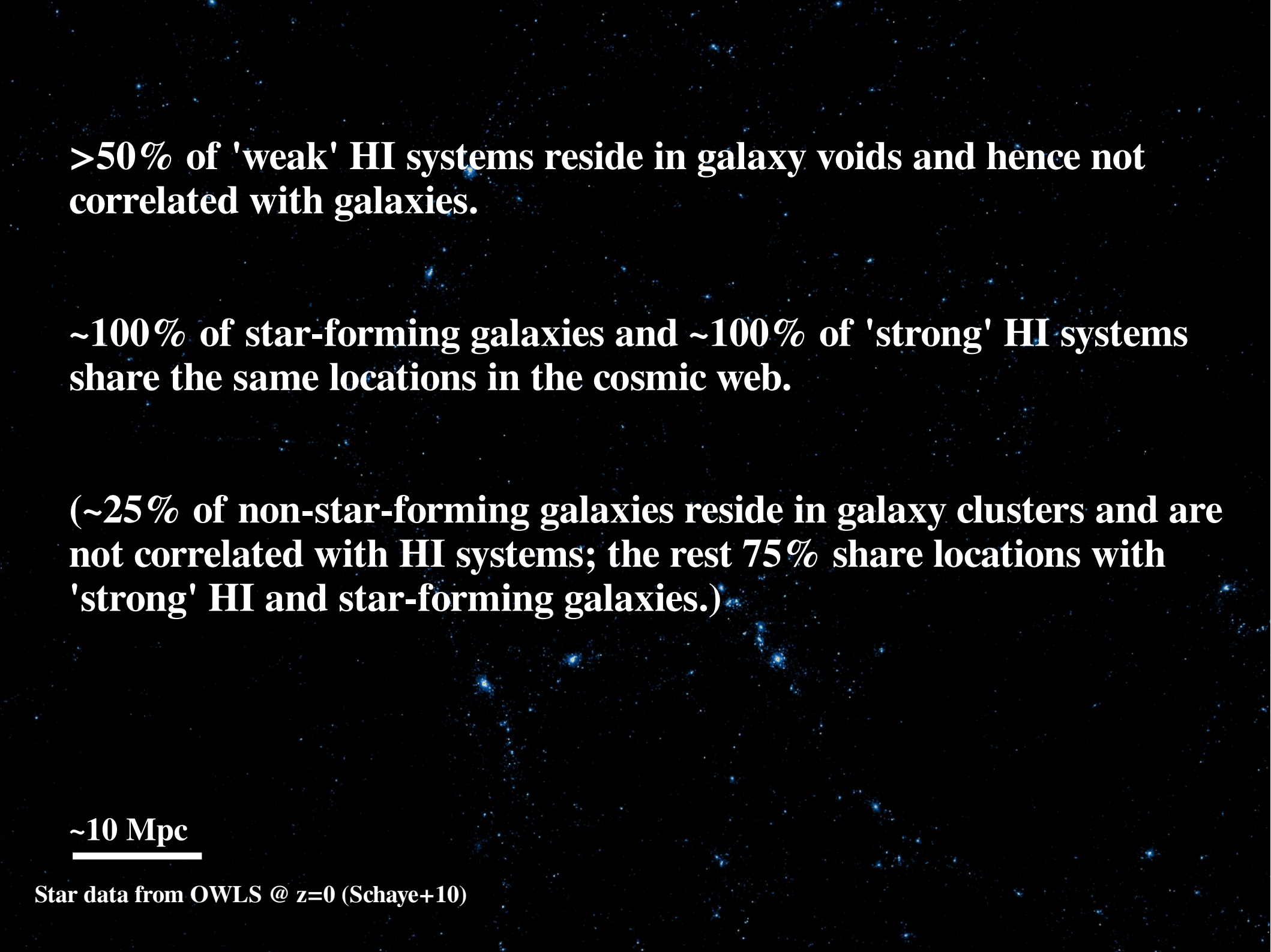
N_{HI}<10^{14} cm^{-2} HI systems and star-forming galaxies

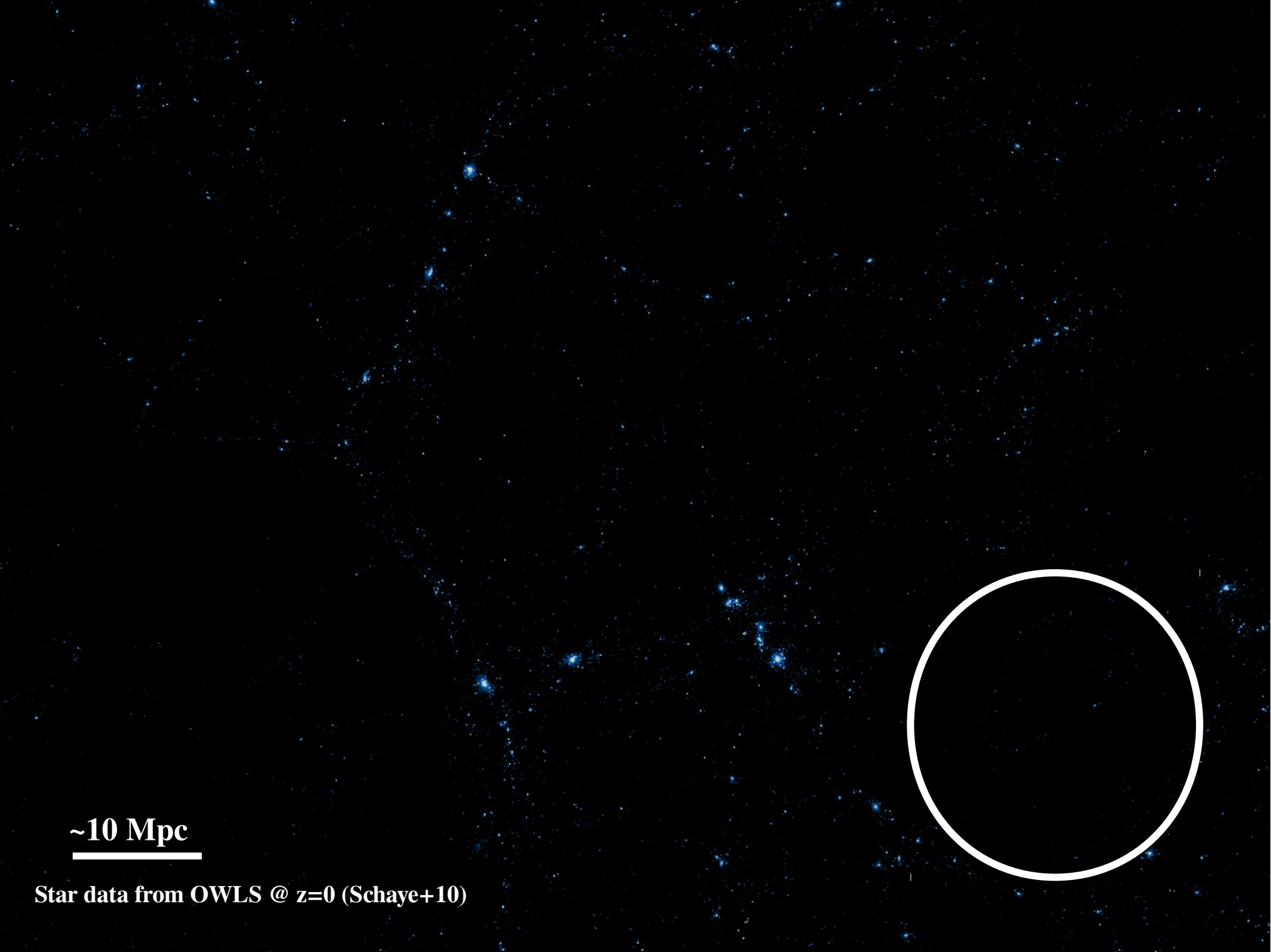
***do not* trace the same structures**

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)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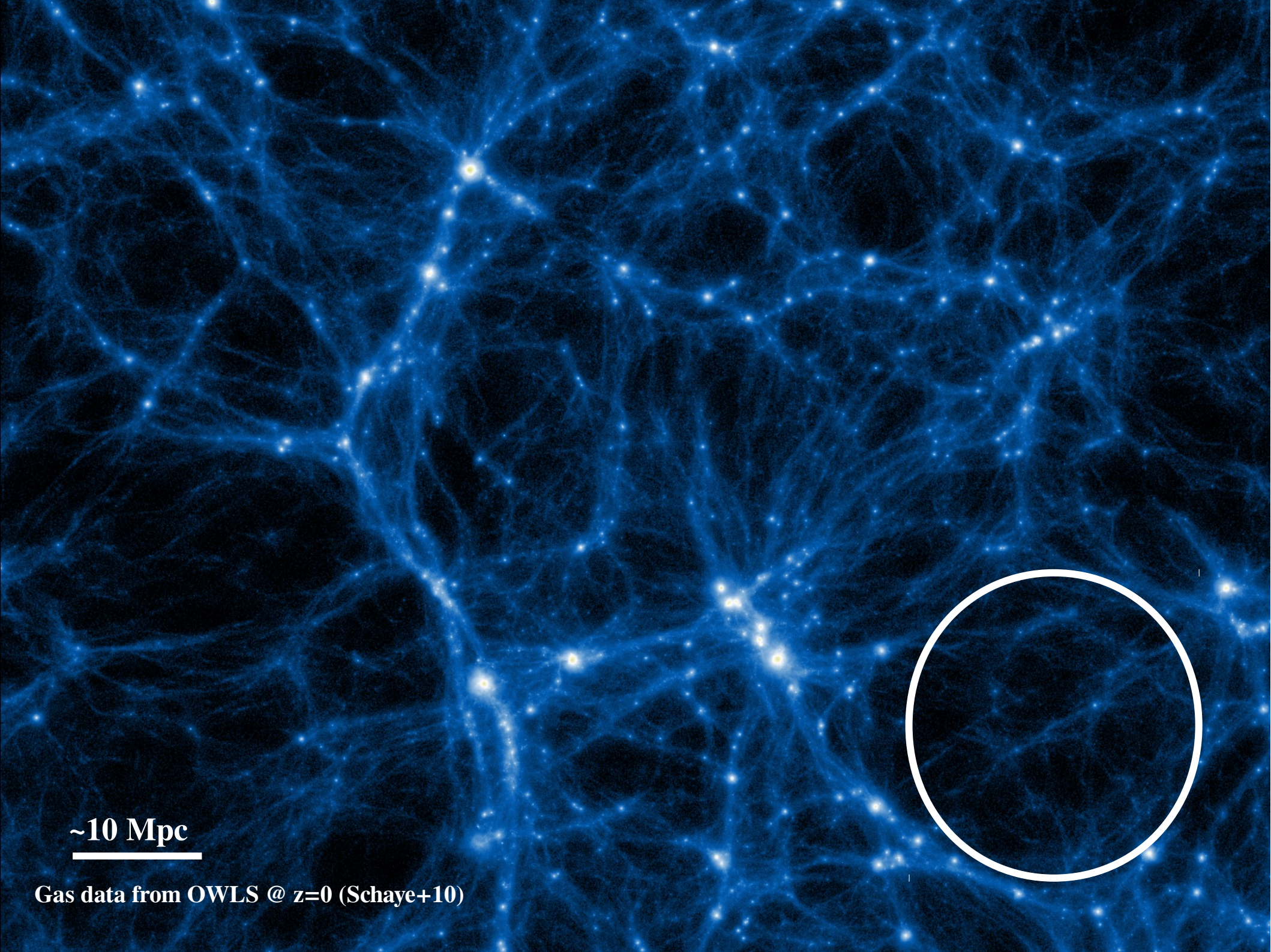
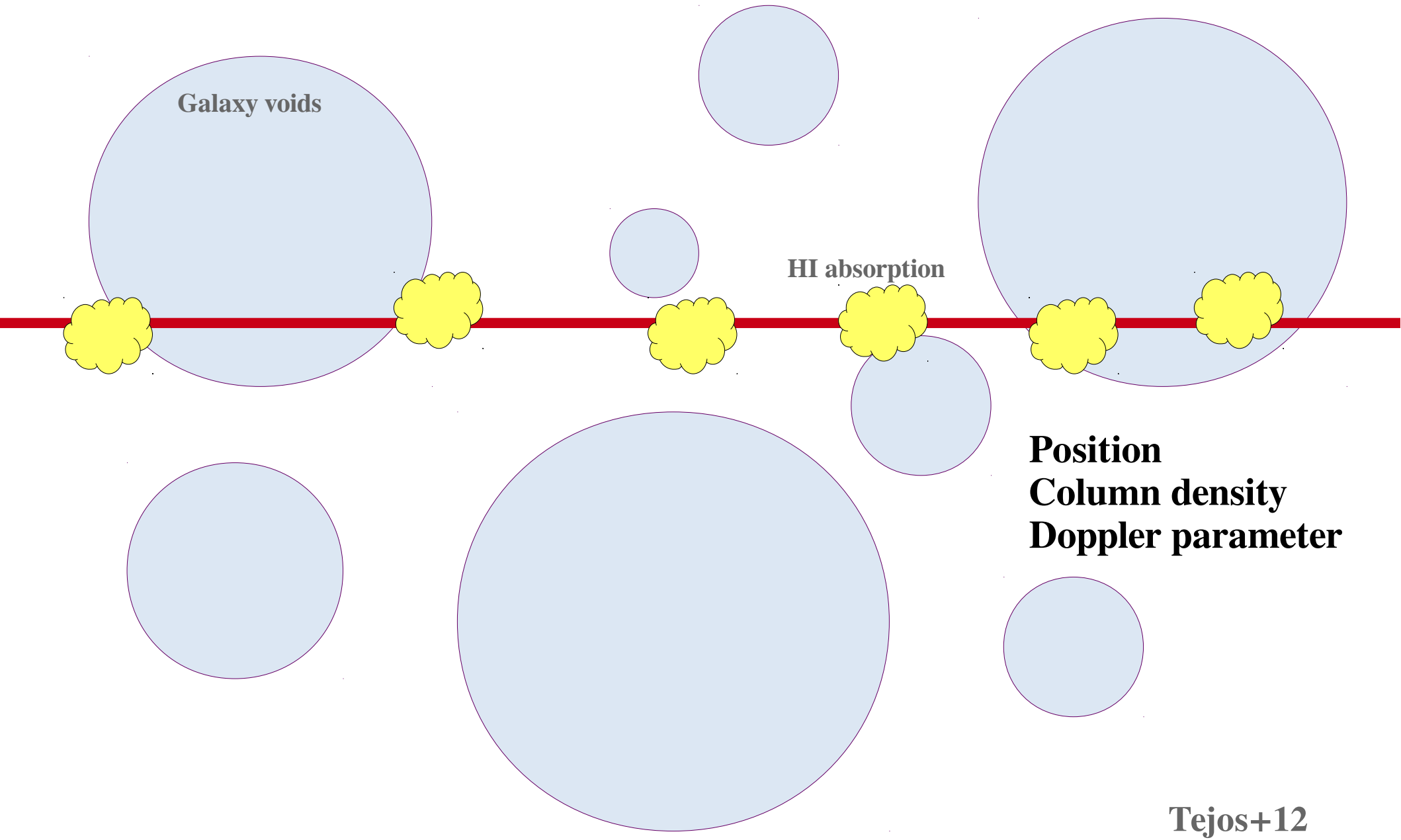

~10 Mpc
Gas data from OWLS @ z=0 (Schaye+10)

Part II:

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

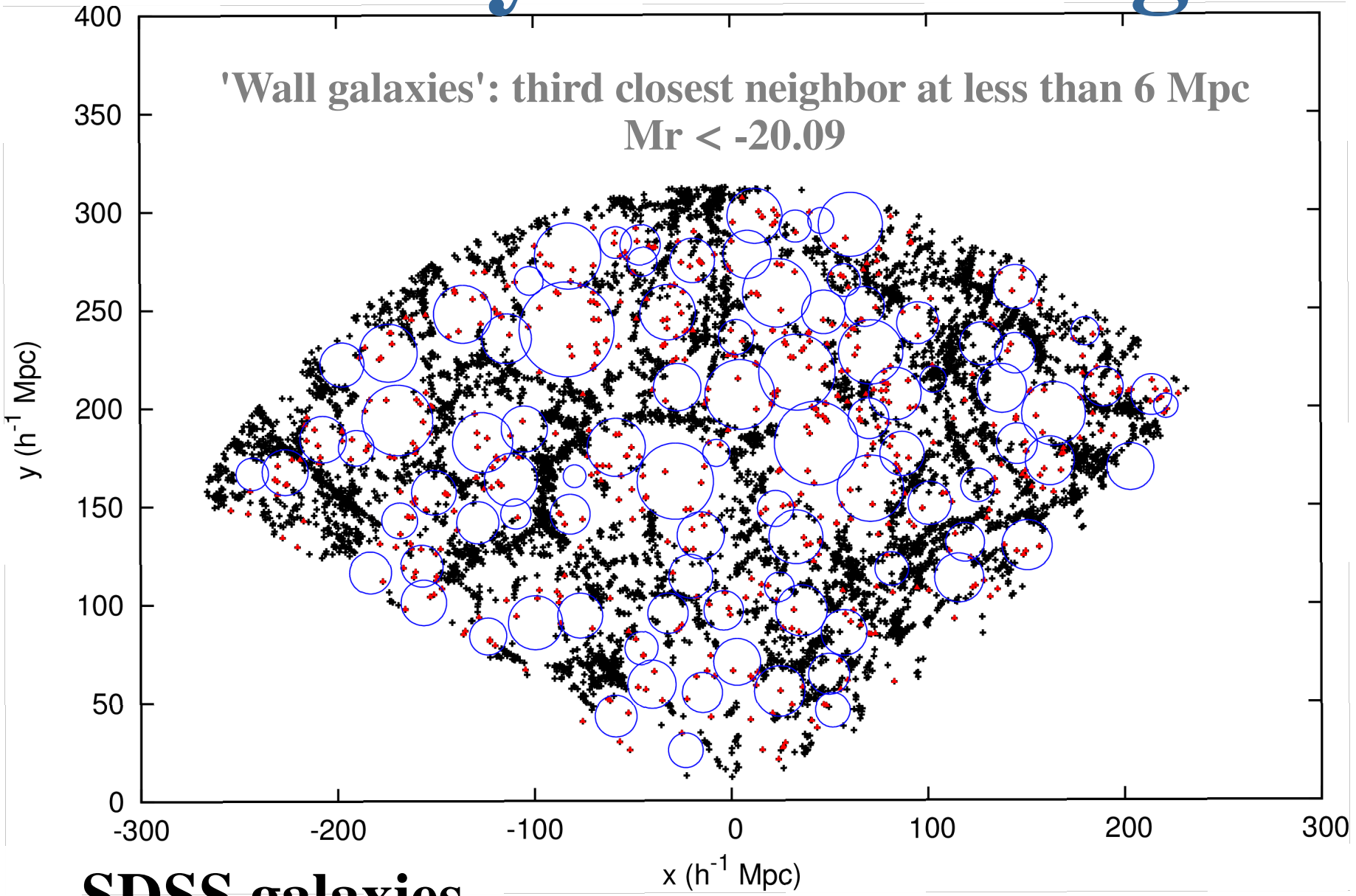
Experimental design



Position
Column density
Doppler parameter

Tejos+12

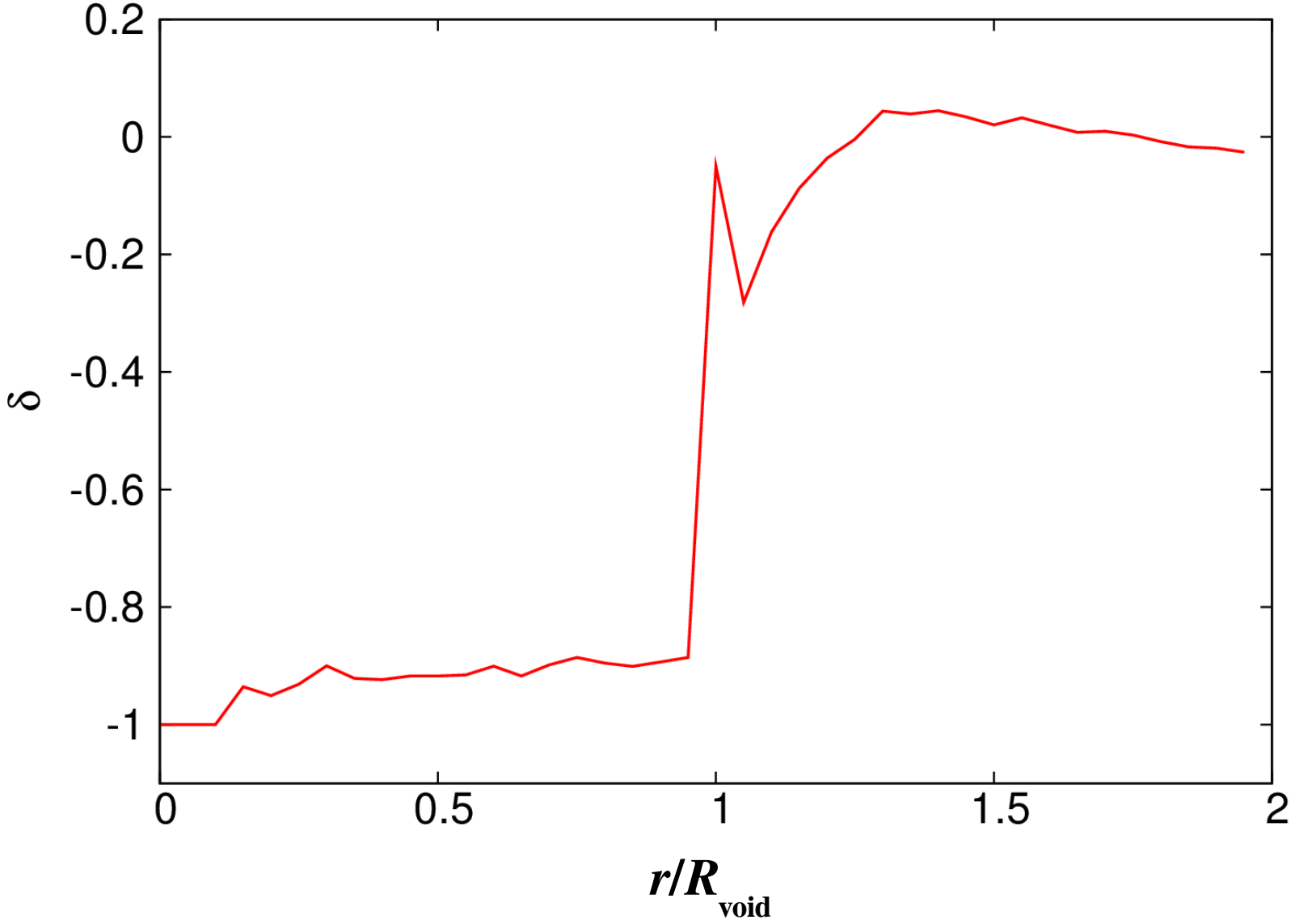
Galaxy void catalog



SDSS galaxies

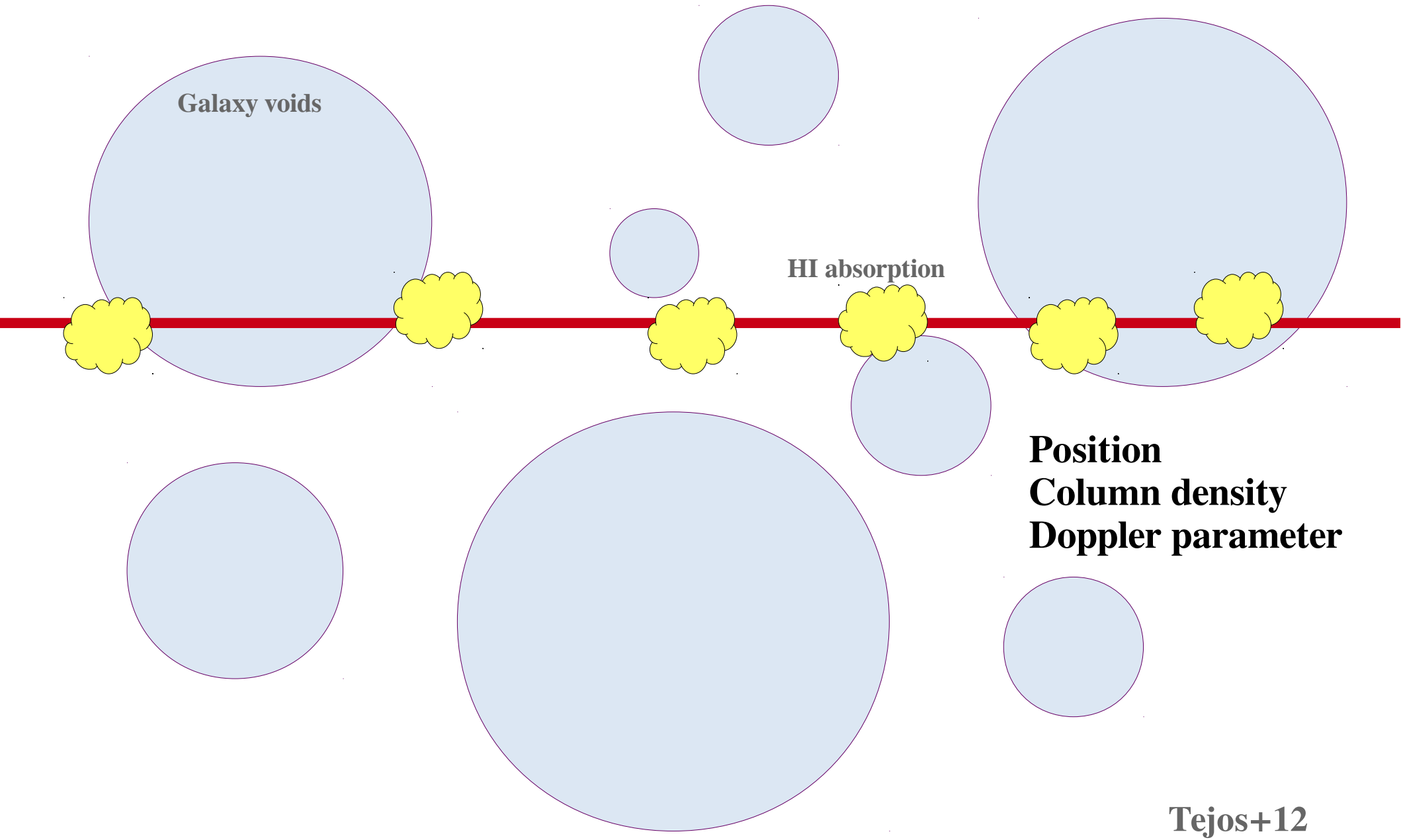
Pan+12

Galaxy void catalog



Pan+12

Experimental design



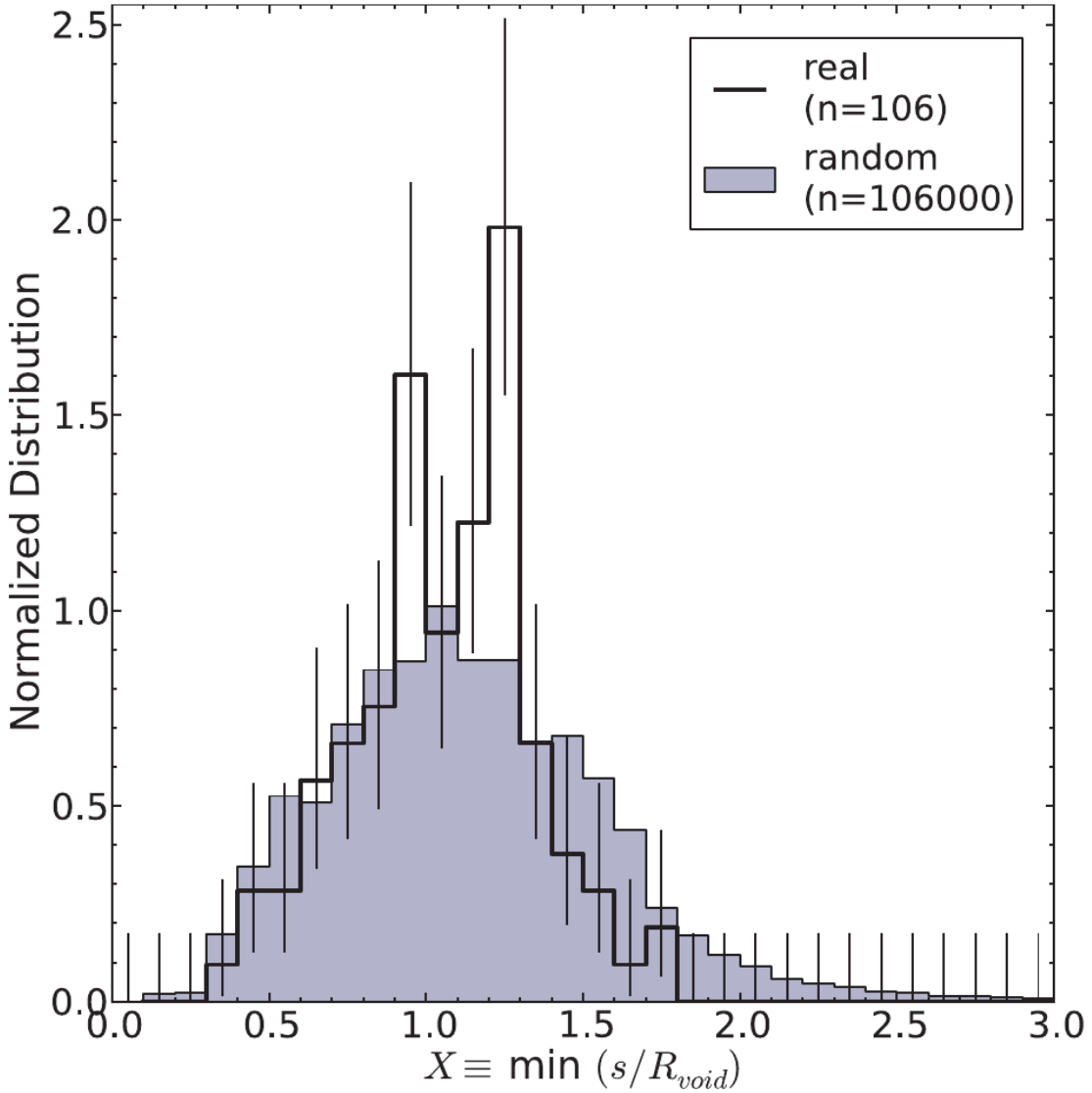
Position
Column density
Doppler parameter

Tejos+12

Part II:

Results

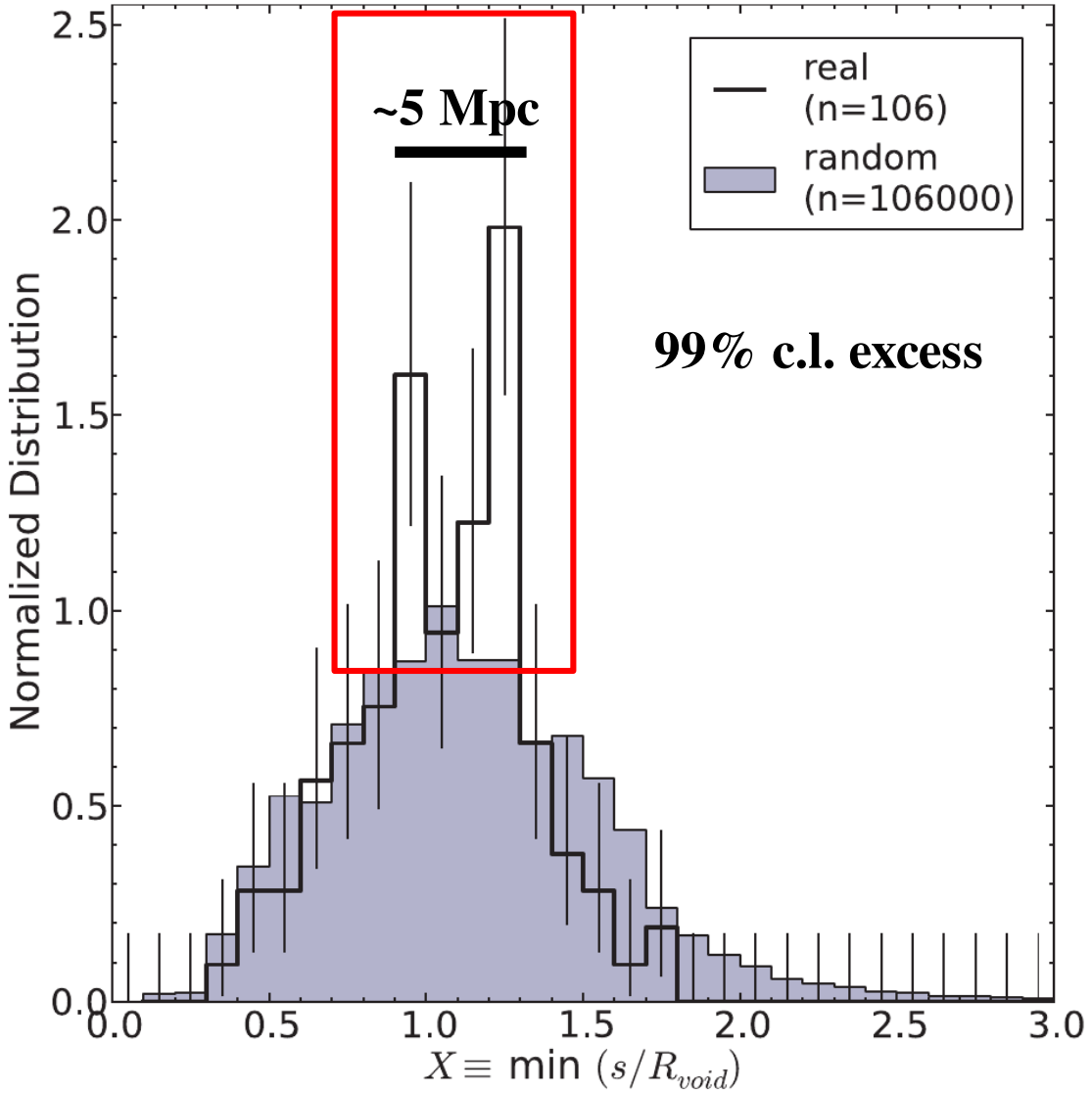
HI distribution w/r 'voids'



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

Tejos+12

HI distribution w/r 'voids'

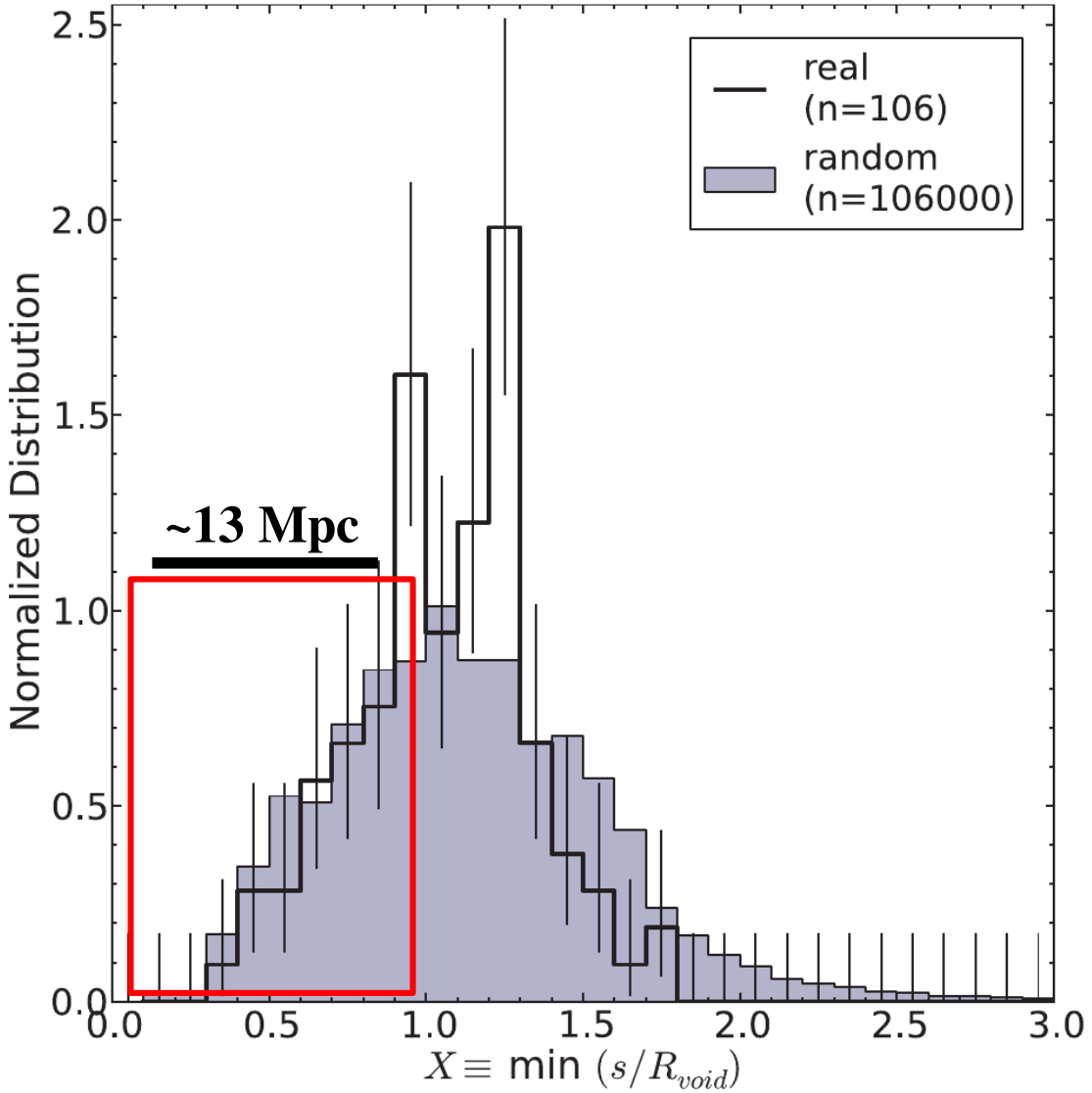


Statistically significant excess of HI at the edges of galaxy voids

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!

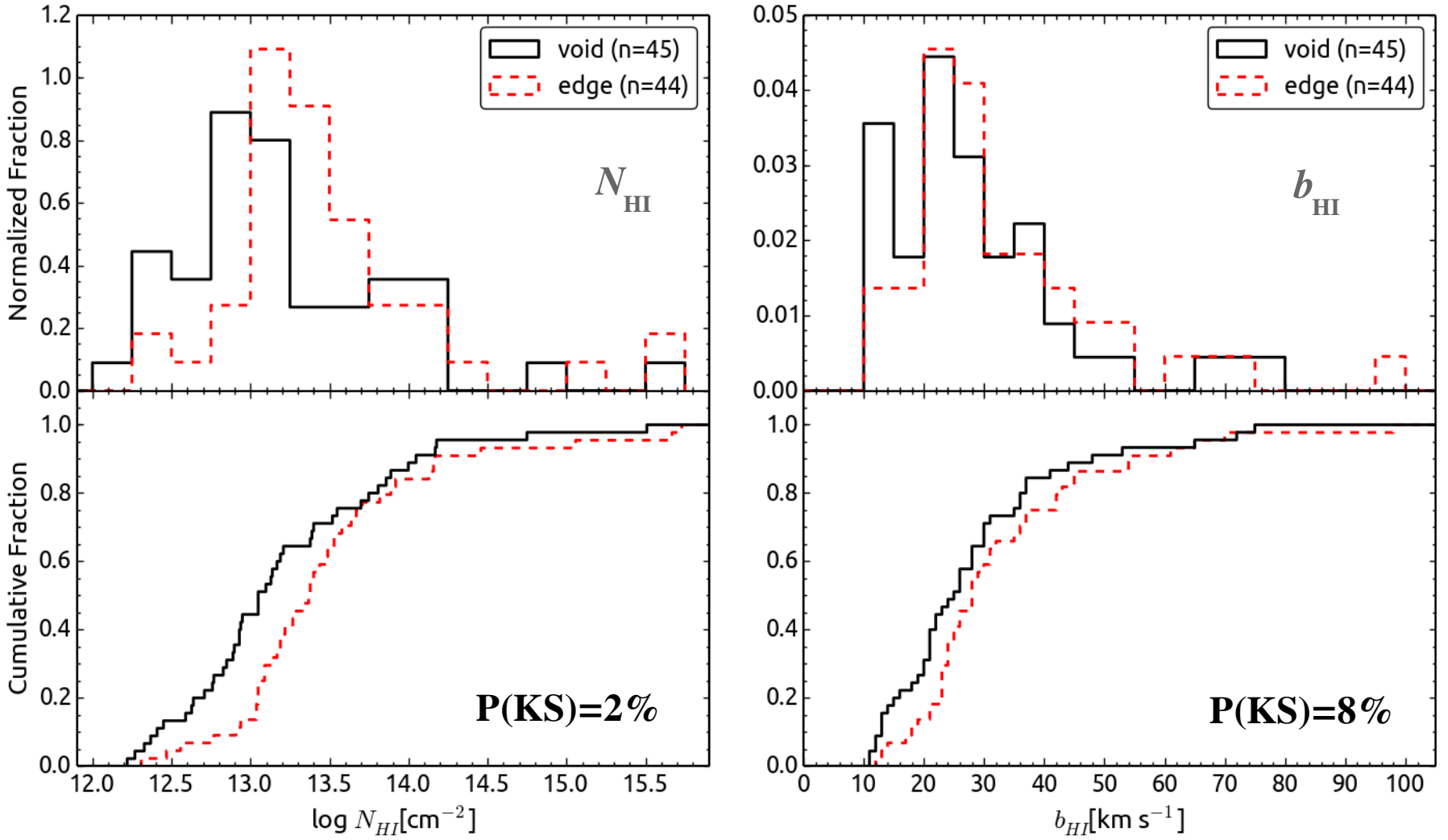
1054 galaxy voids at z<0.1 (Pan+12)
106 HI absorption systems (Danforth & Shull 2008)

Tejos+12

Part II:

Are their properties different?

Properties of HI w/r 'voids'



Mild trends present / no sharp transitions
These are theoretically expected

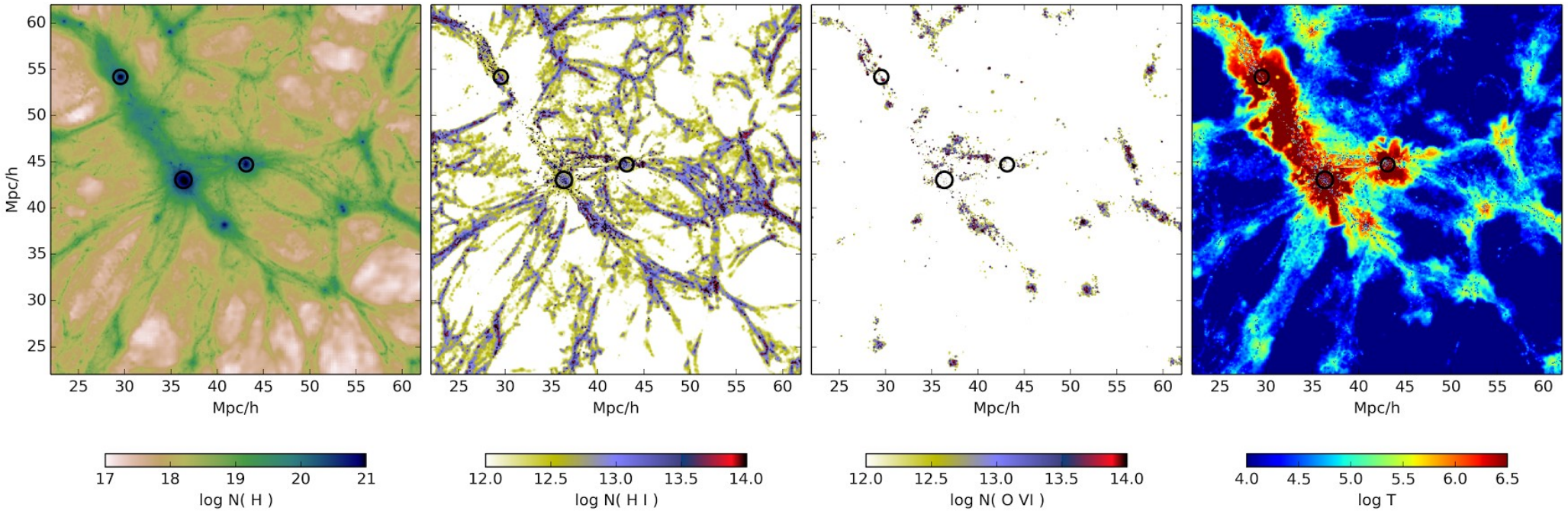
Tejos+12

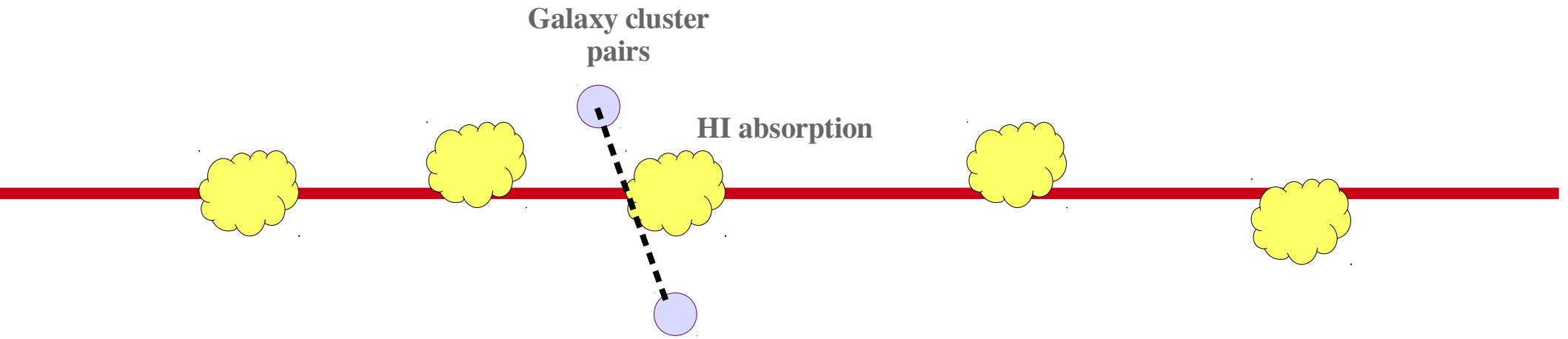
Part III:

The IGM in intercluster filaments at z<0.5

Experimental design

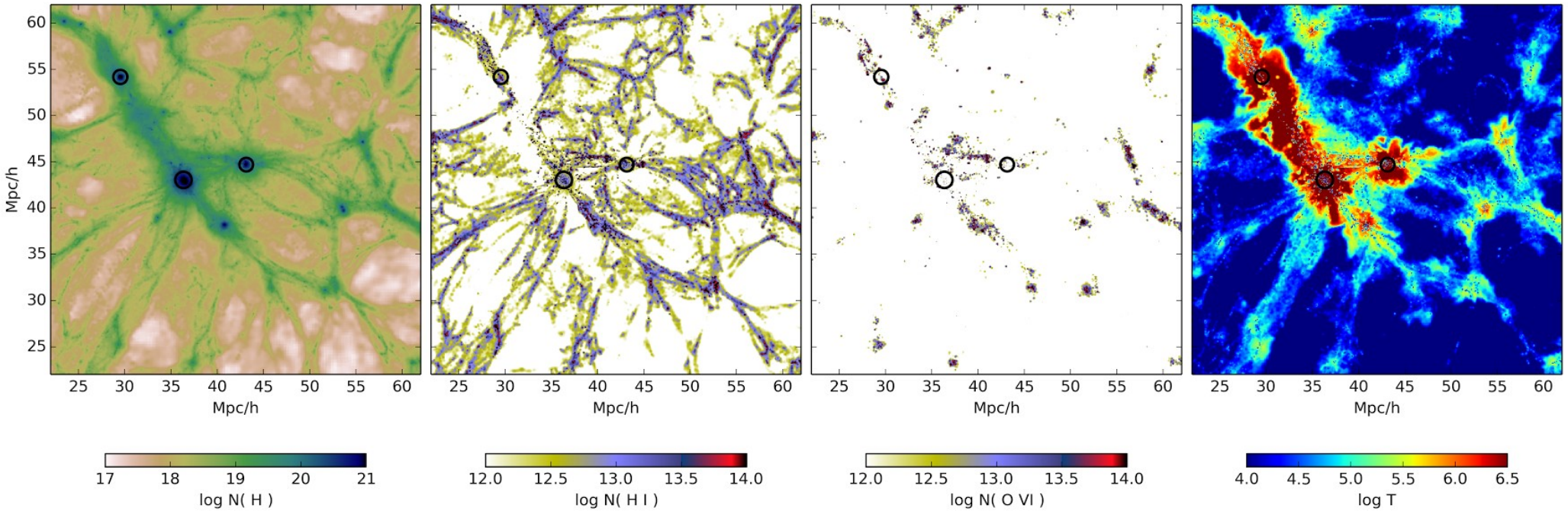
Data from OWLS (Schaye+10)

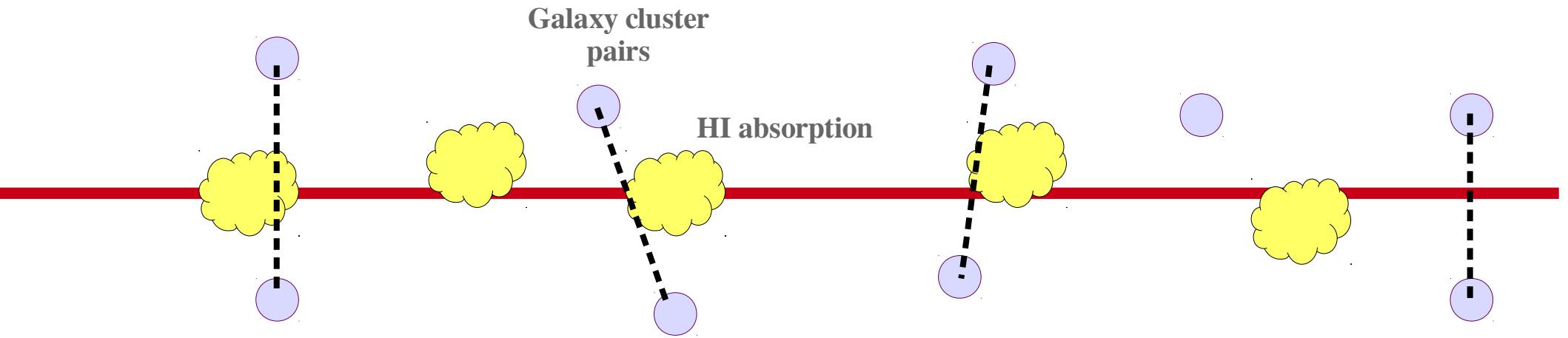




We need multiple probes

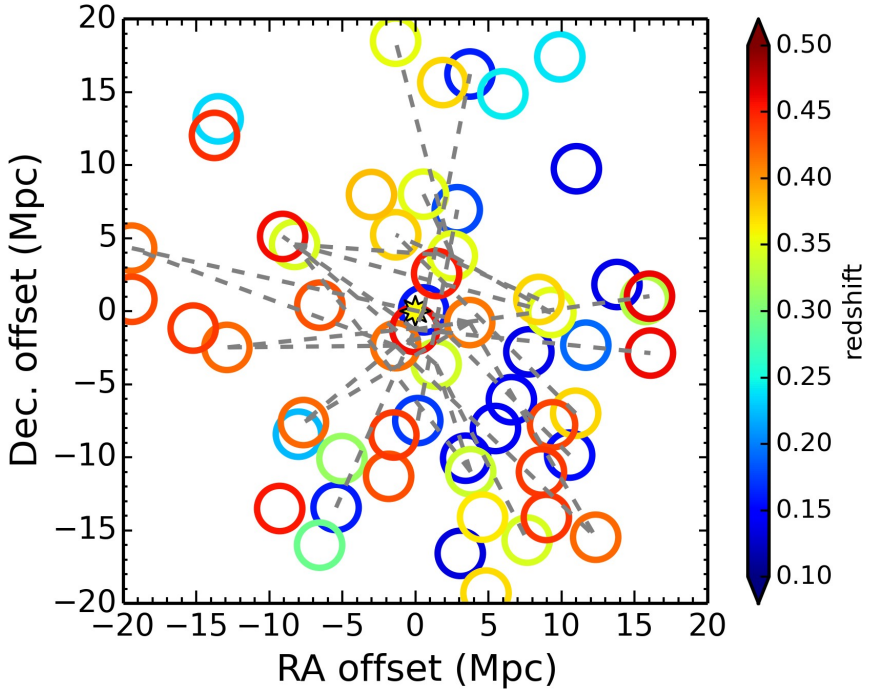
Data from OWLS (Schaye+10)

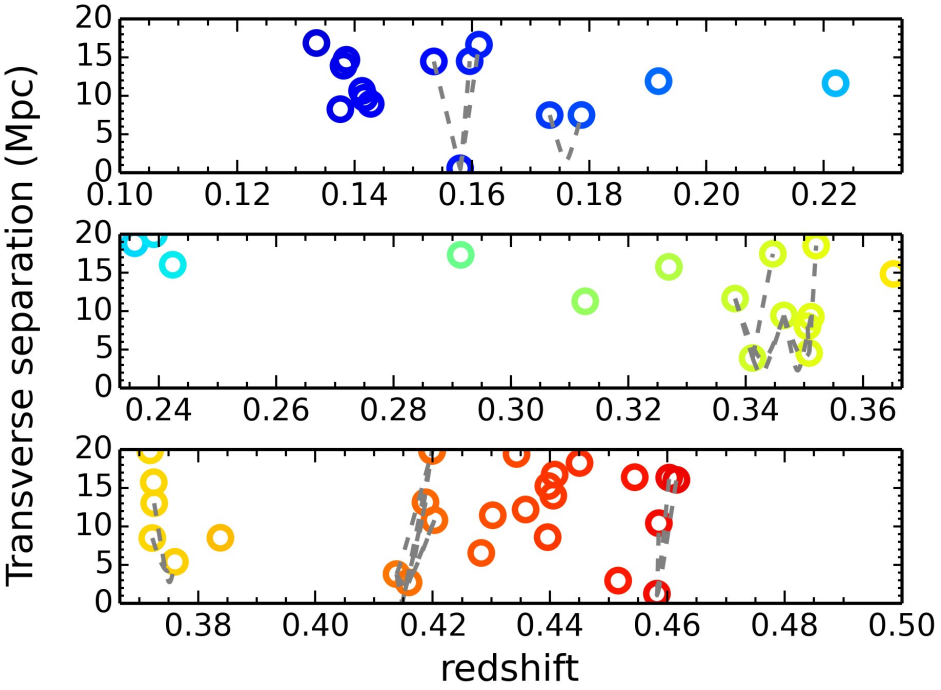




Unique dataset

- **HST/COS** (12 orbits)
- 1 QSO whose sightline intersects **7 independent (11 total)** cluster-pairs
- The random expectations are **~1 ± 1 independent (~1.6 ± 2.2 total)**
- Clusters from redMapper catalog (Rykoff+14)

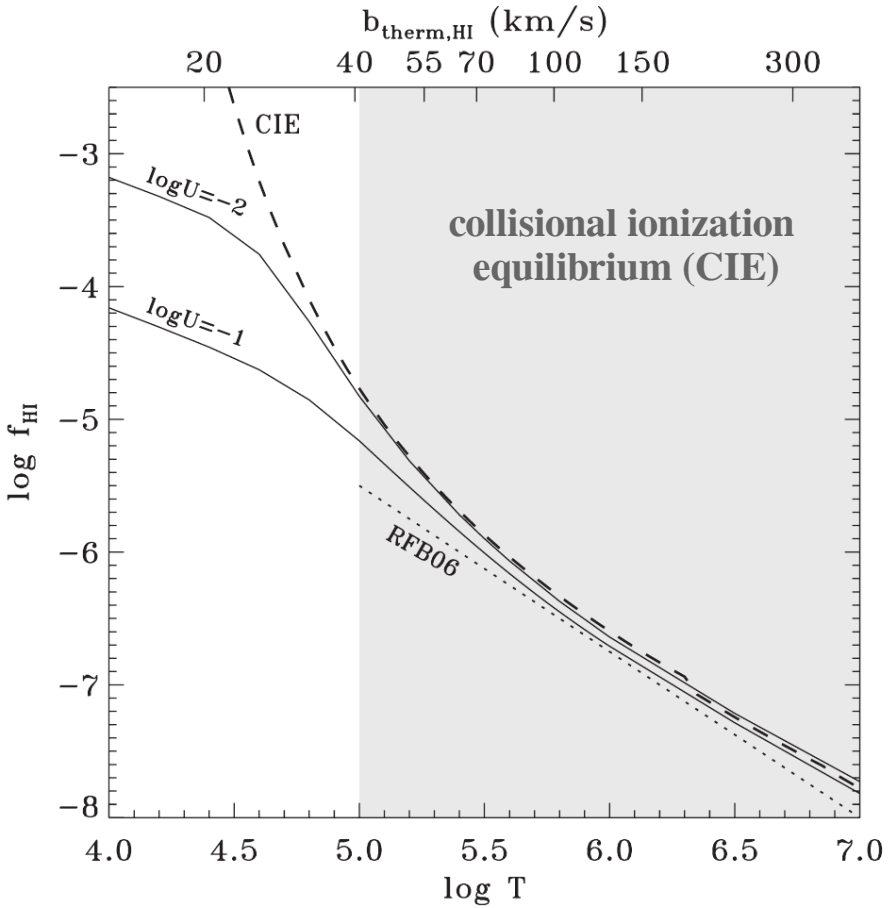




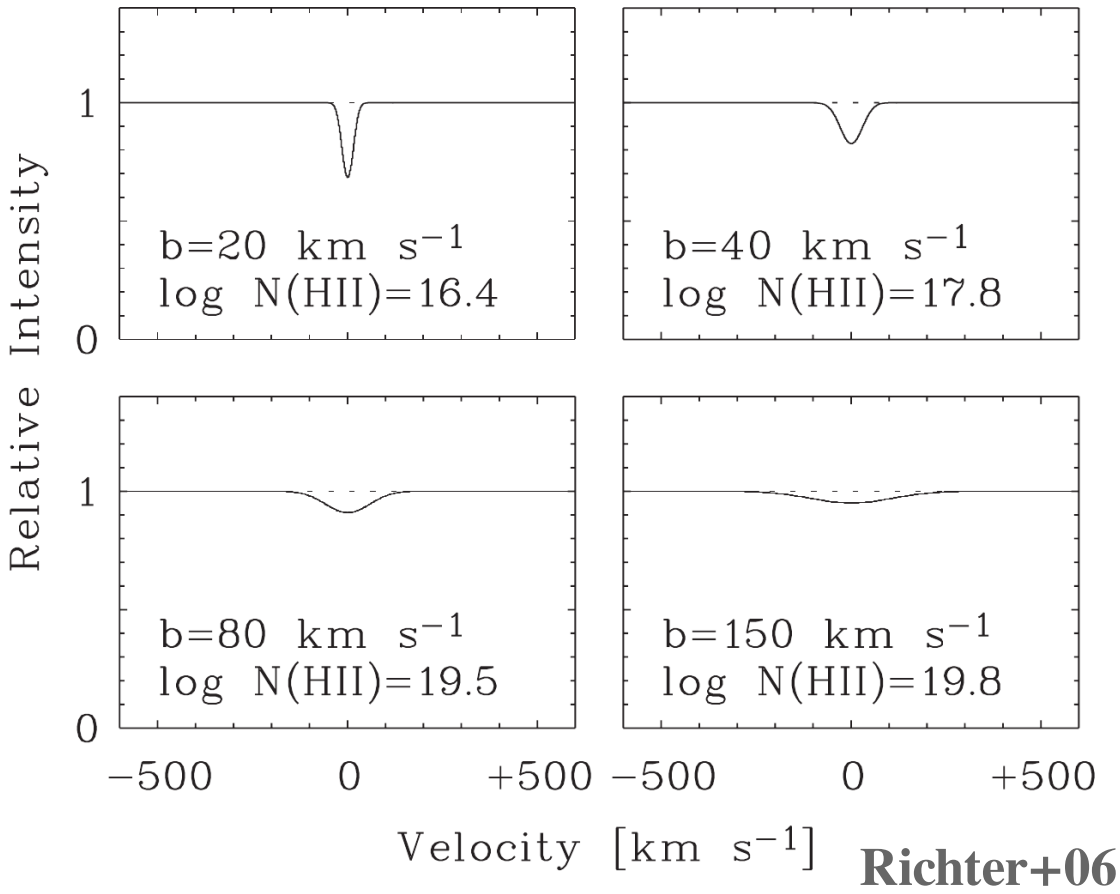
This is a highly exceptional sightline!

Tejos+ in prep.

Experimental challenge



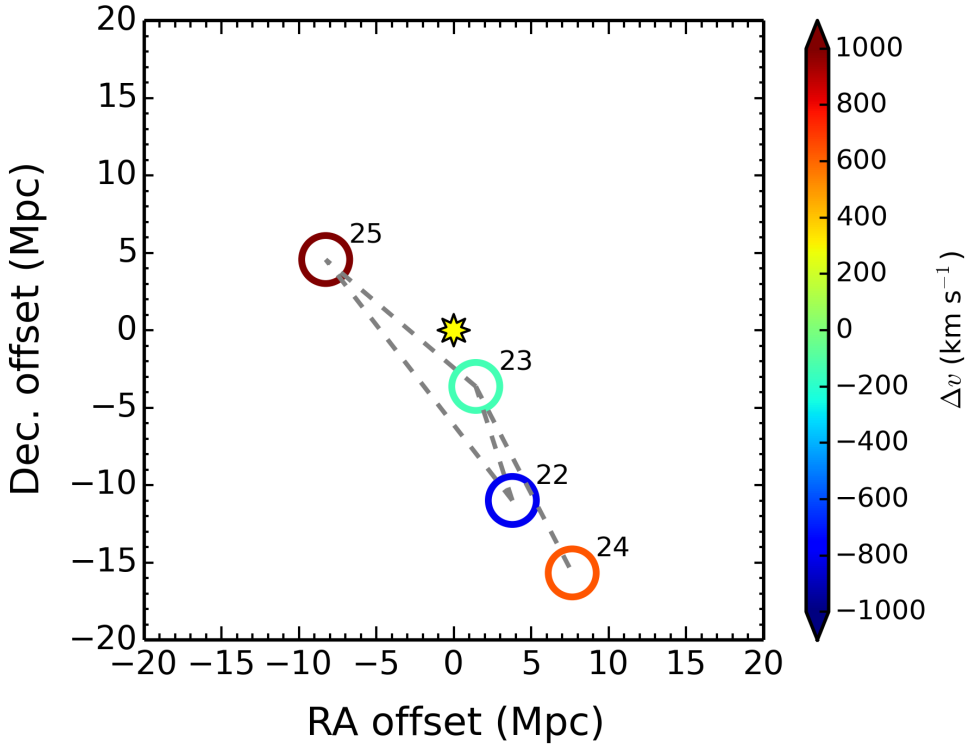
Danforth+10

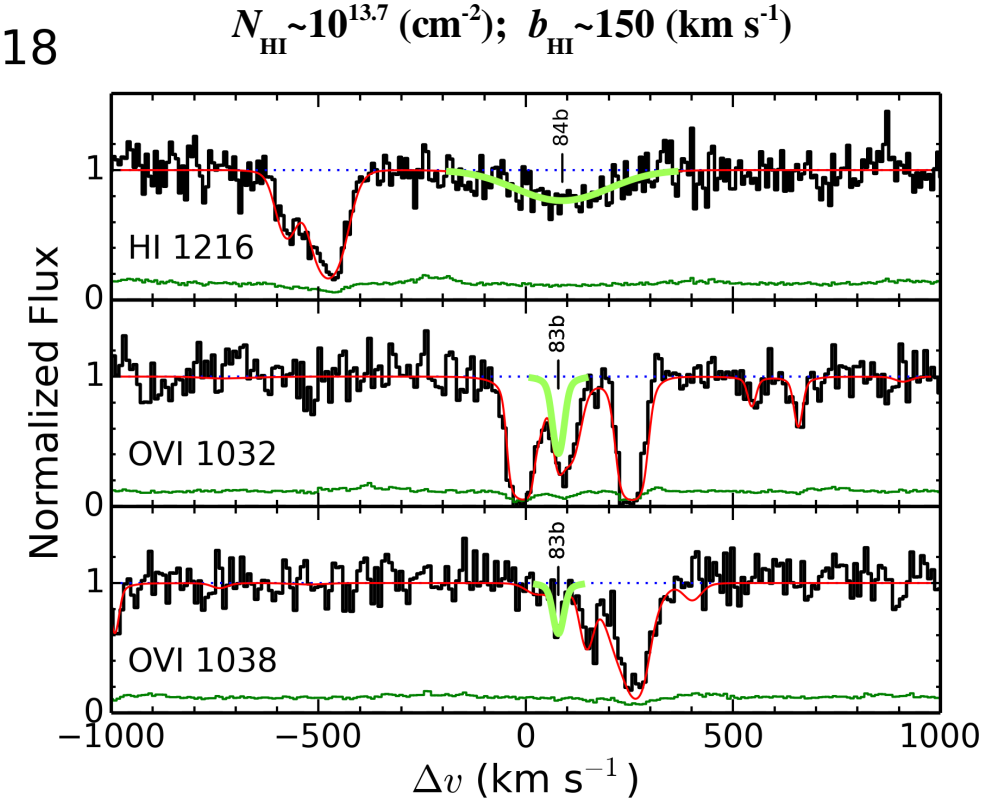


Richter+06

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

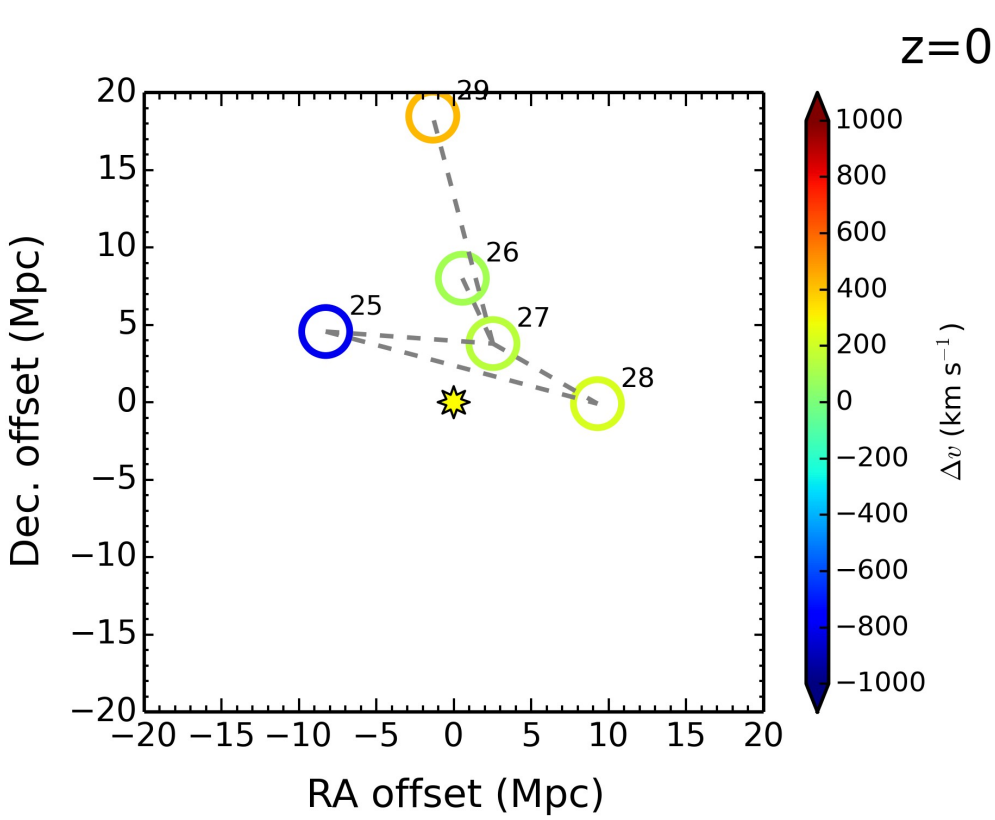
Examples

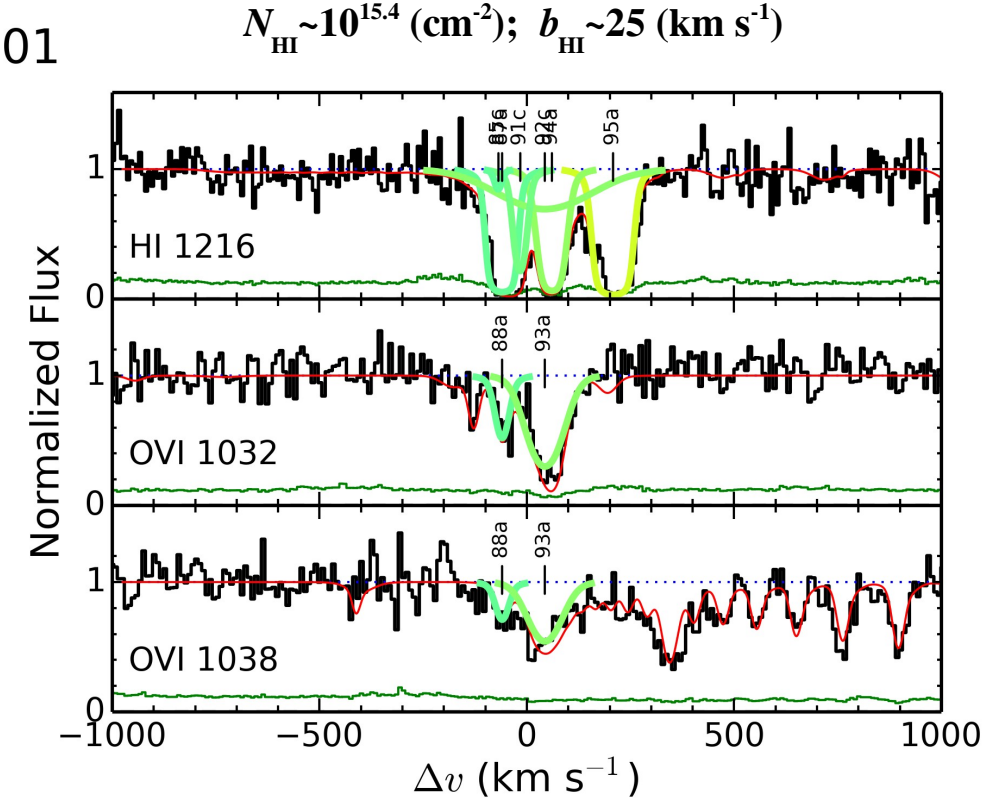




Tejos+15 in prep.

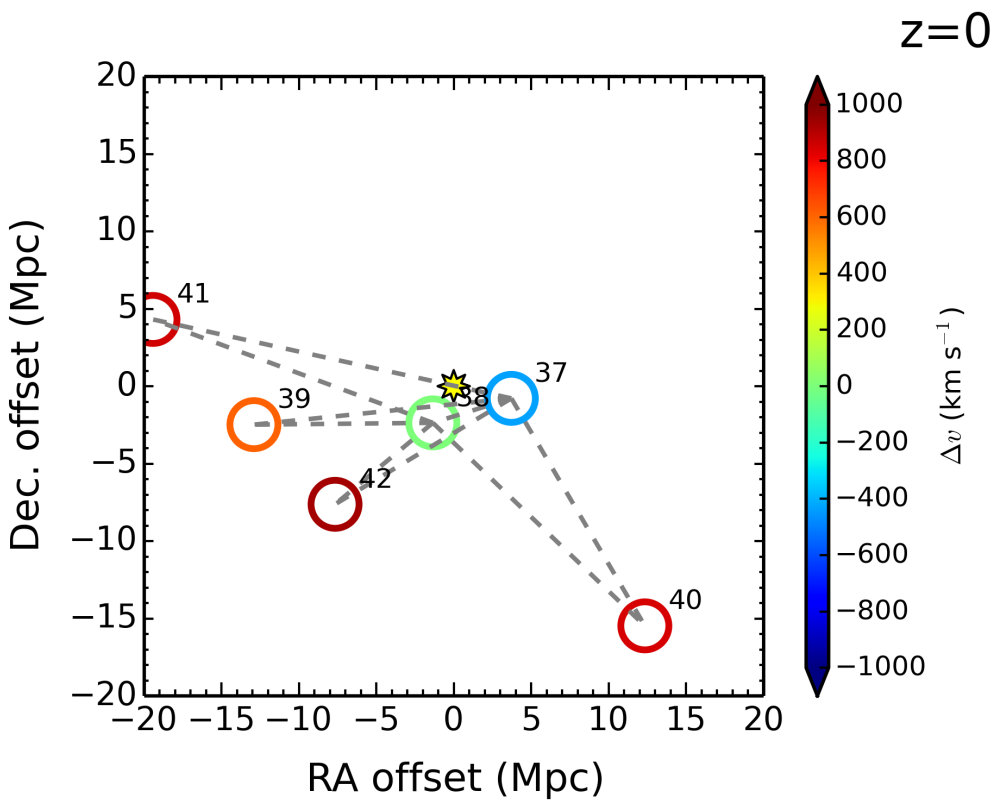
Examples

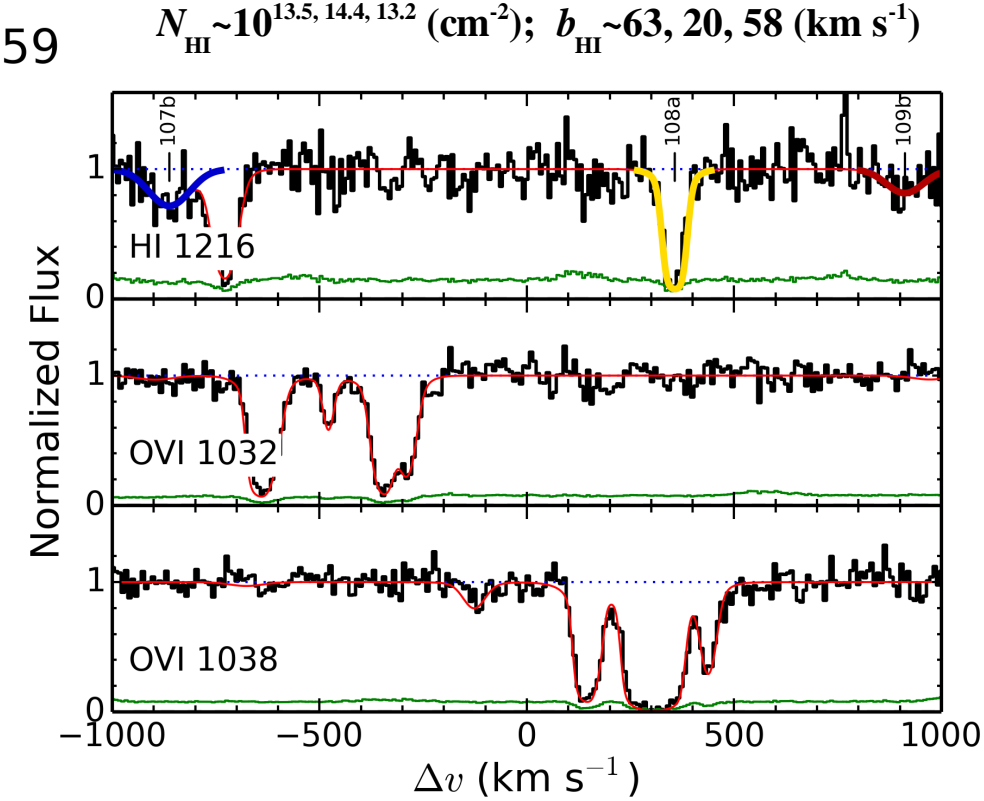




Tejos+15 in prep.

Examples





Tejos+15 in prep.

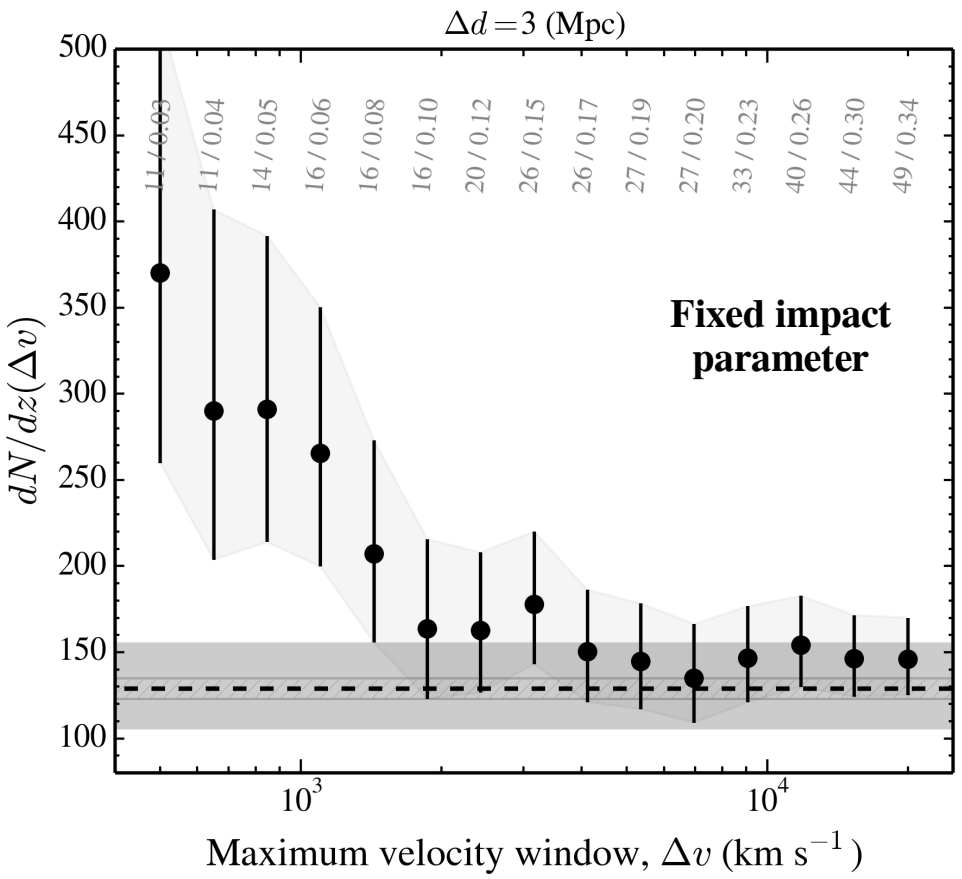
Part III:

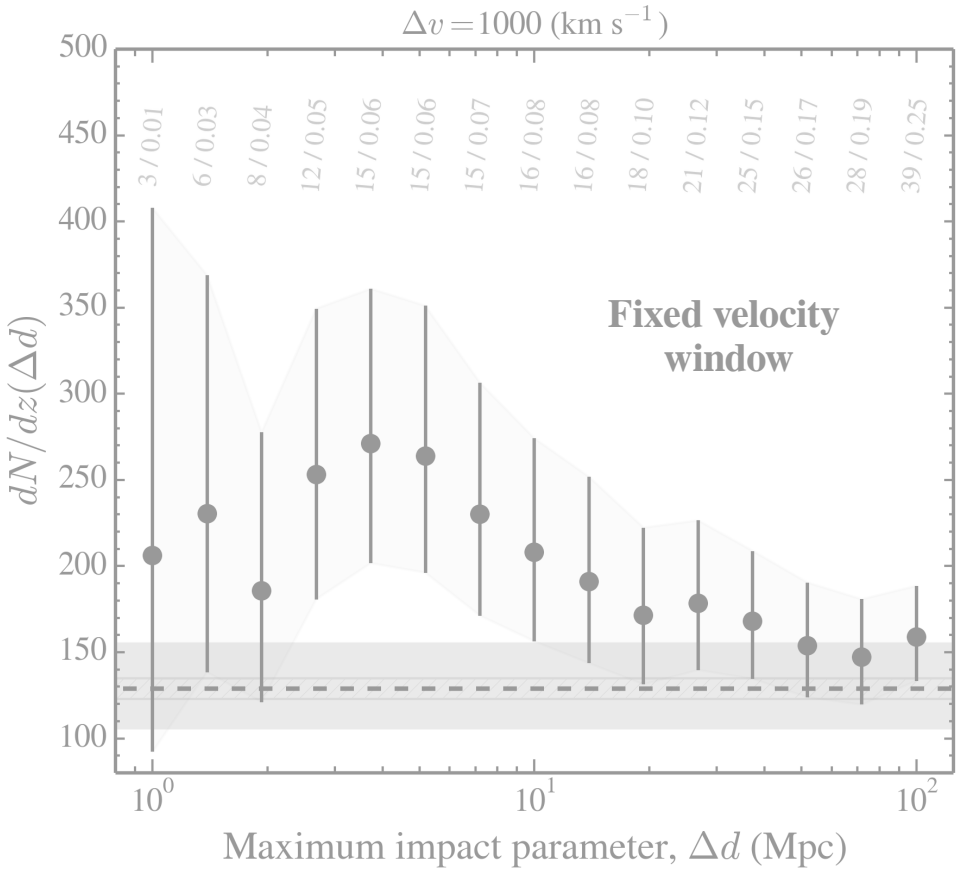
Results

HI in intercluster filaments

(W_r > 0.04 Å)

Total HI





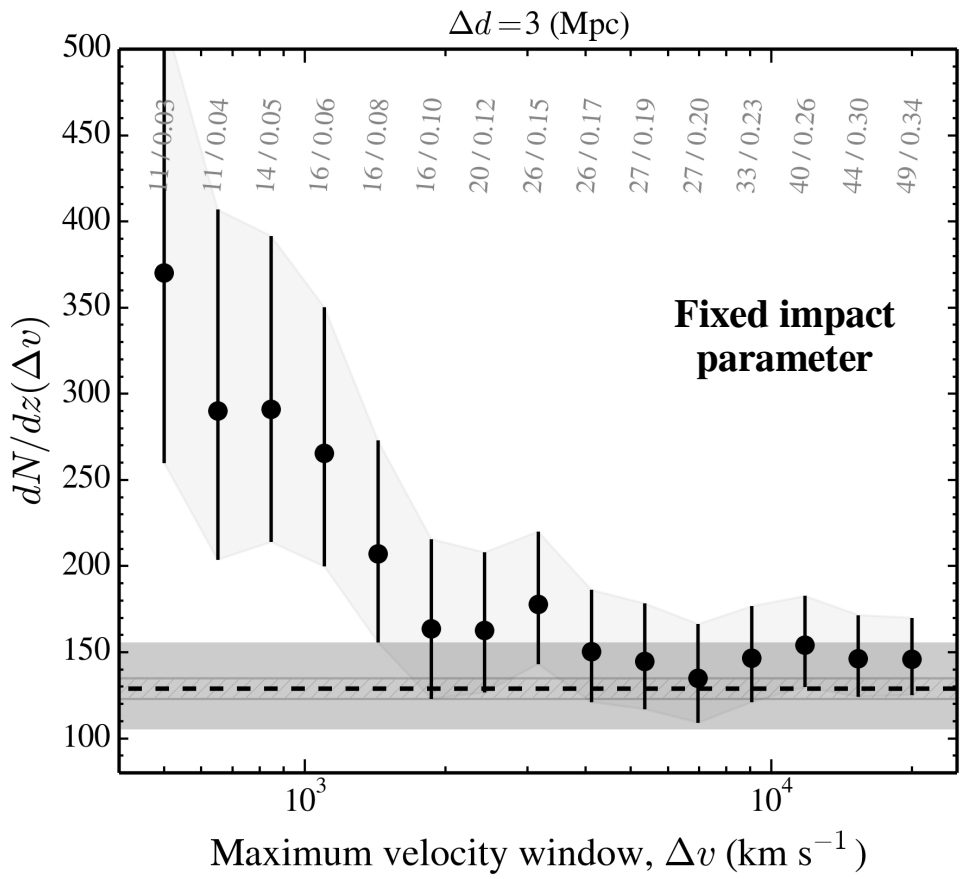
A factor of ~2 excess!

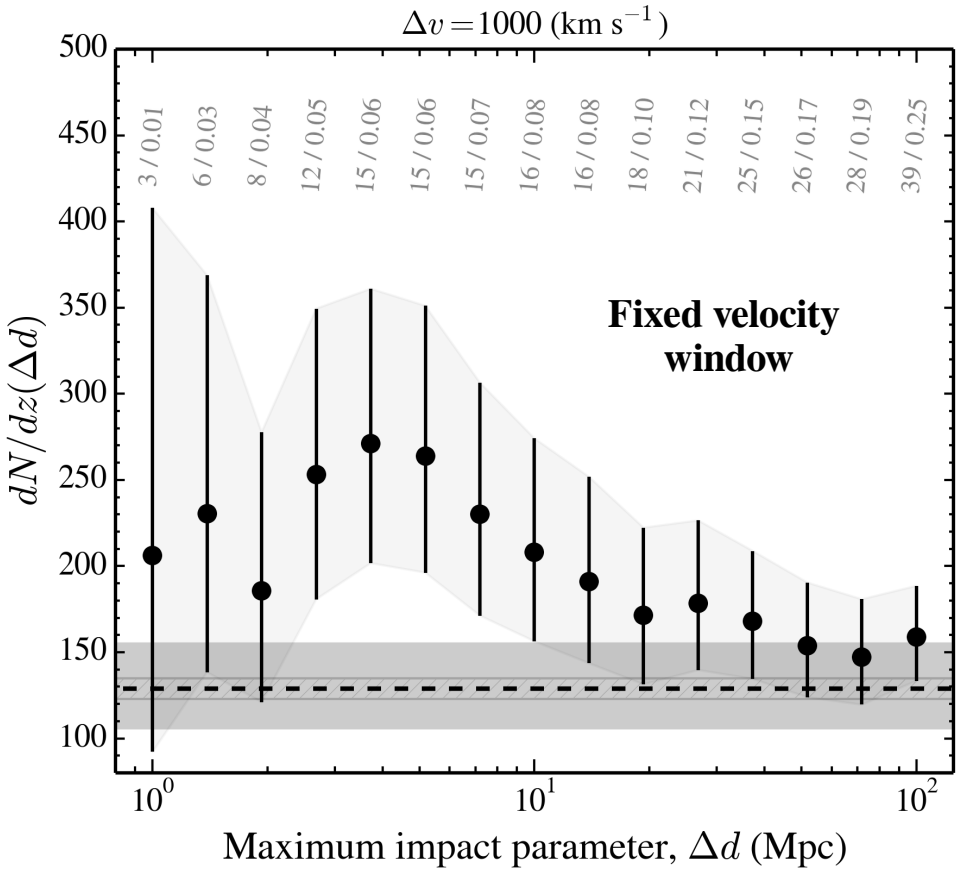
Tejos+ in prep.

HI in intercluster filaments

($W_r > 0.04$ Å)

Total HI

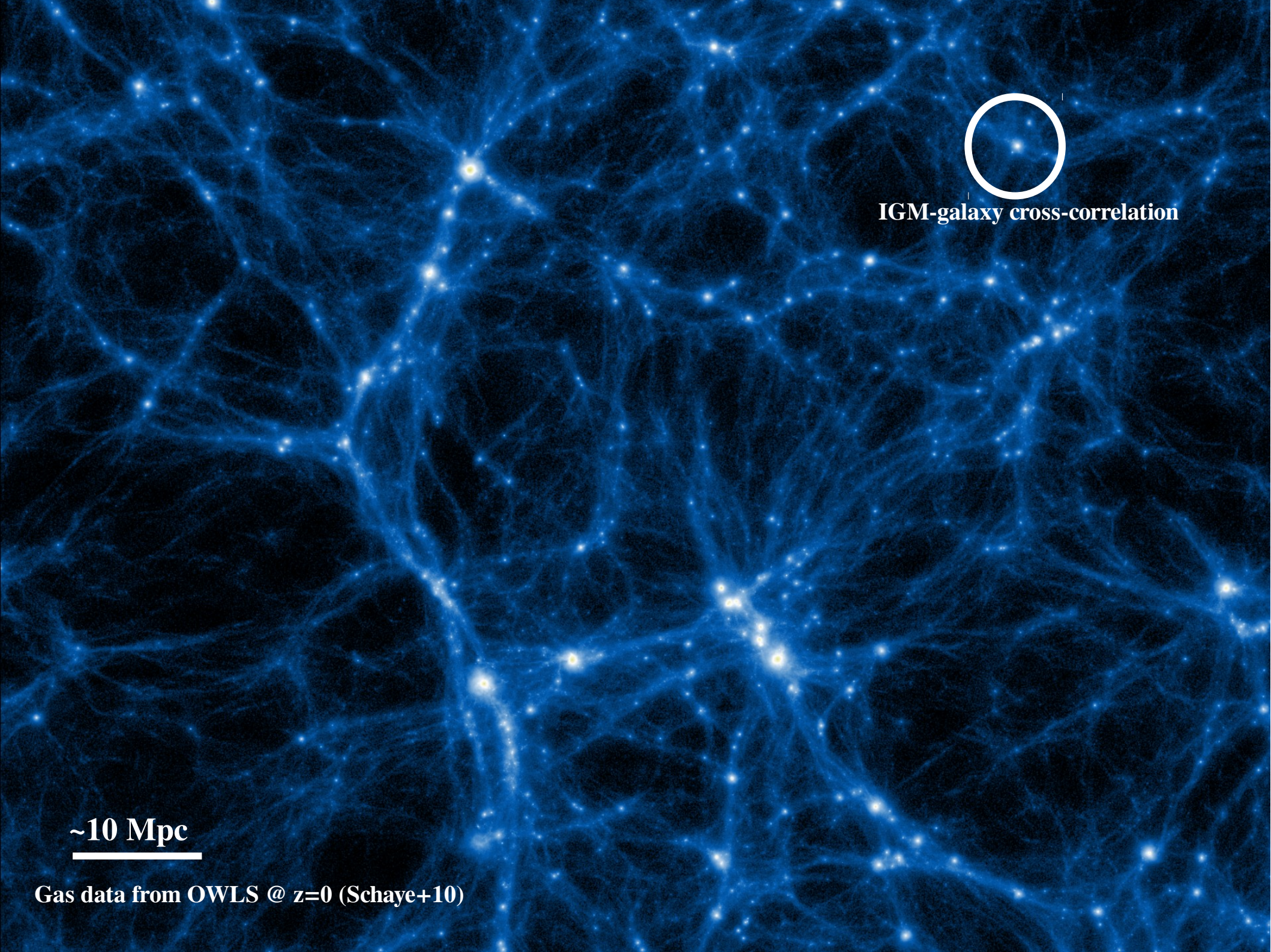


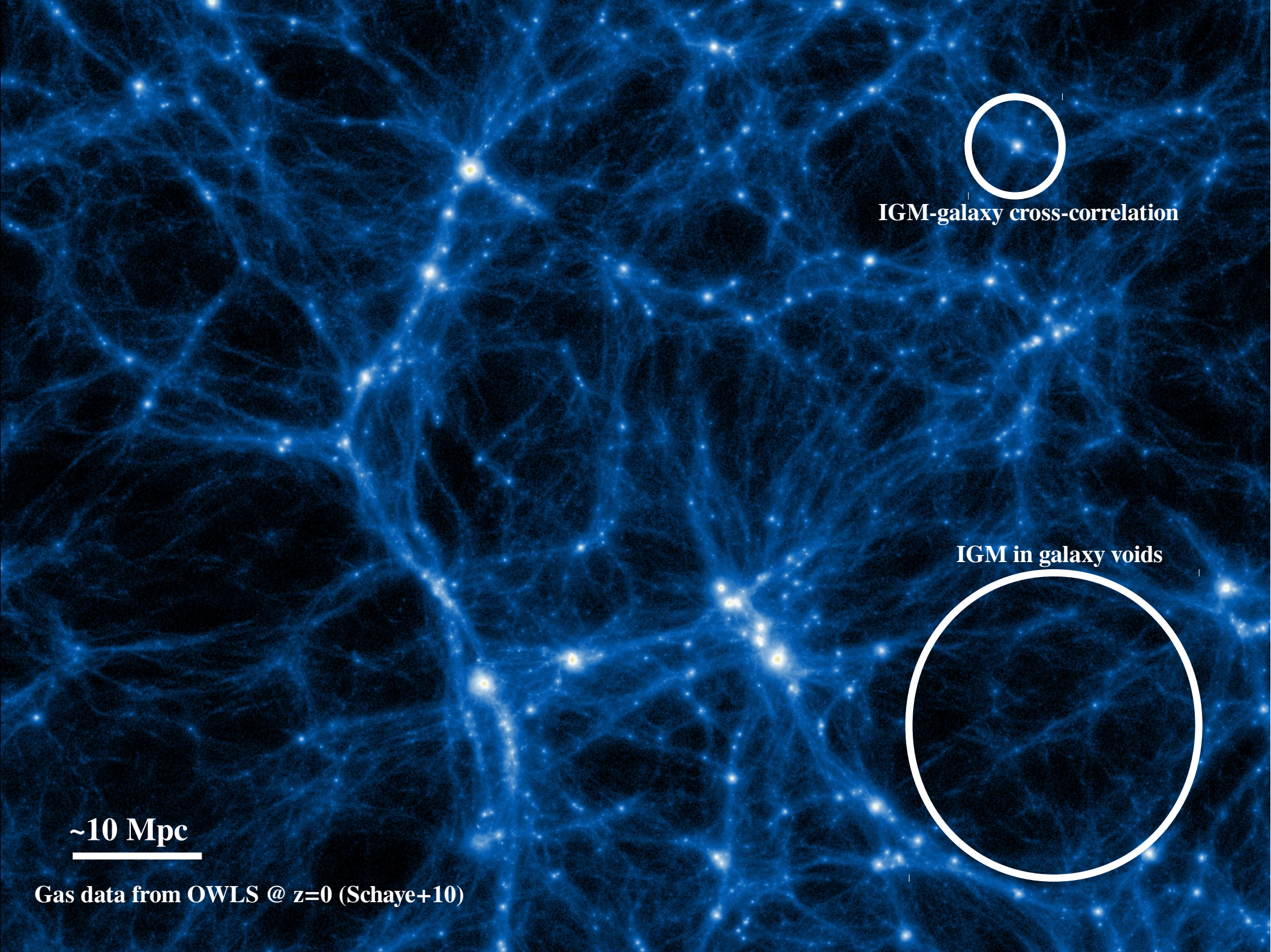


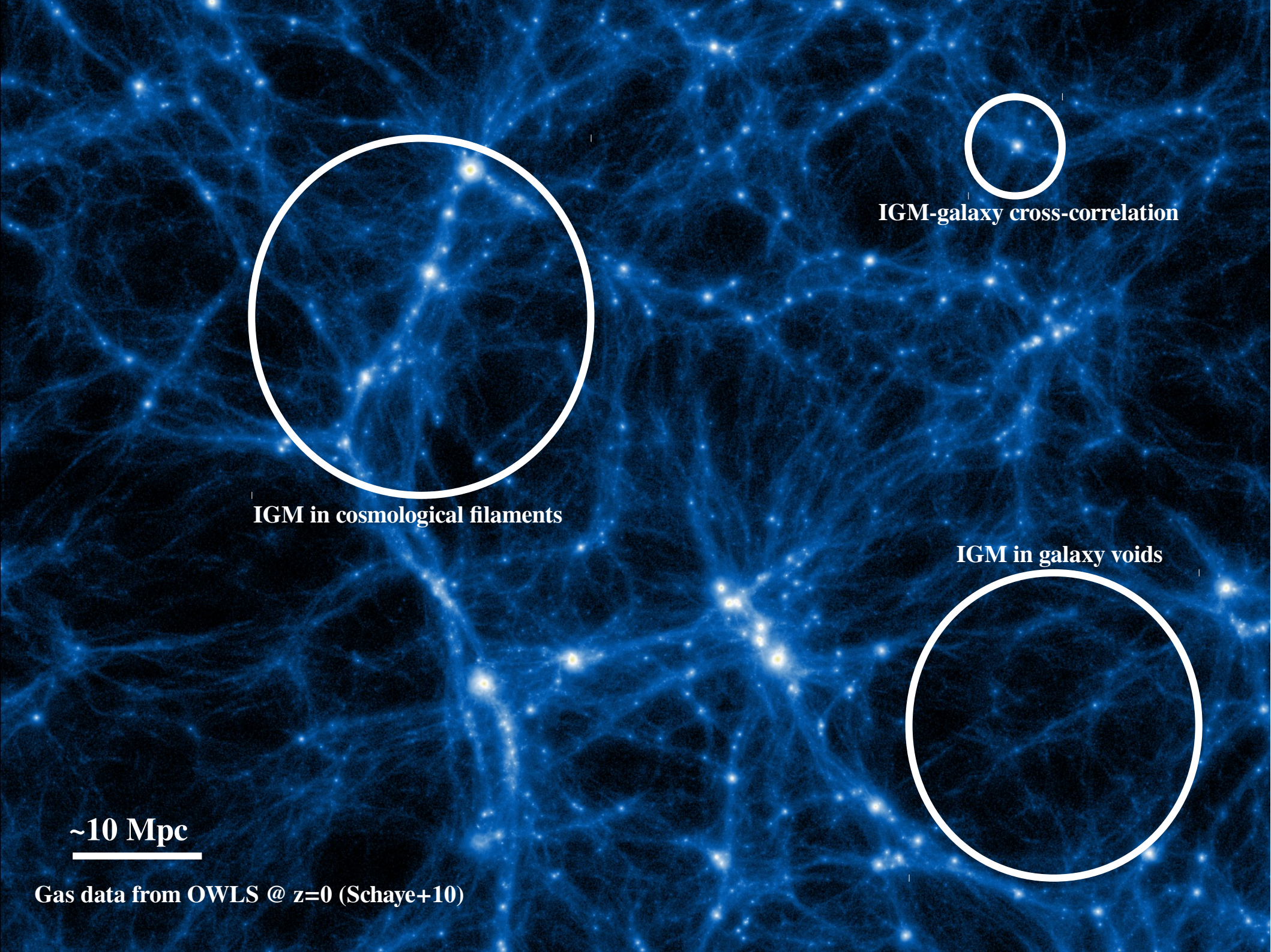
A factor of ~2 excess!

Tejos+ in prep.

Summary & Conclusions

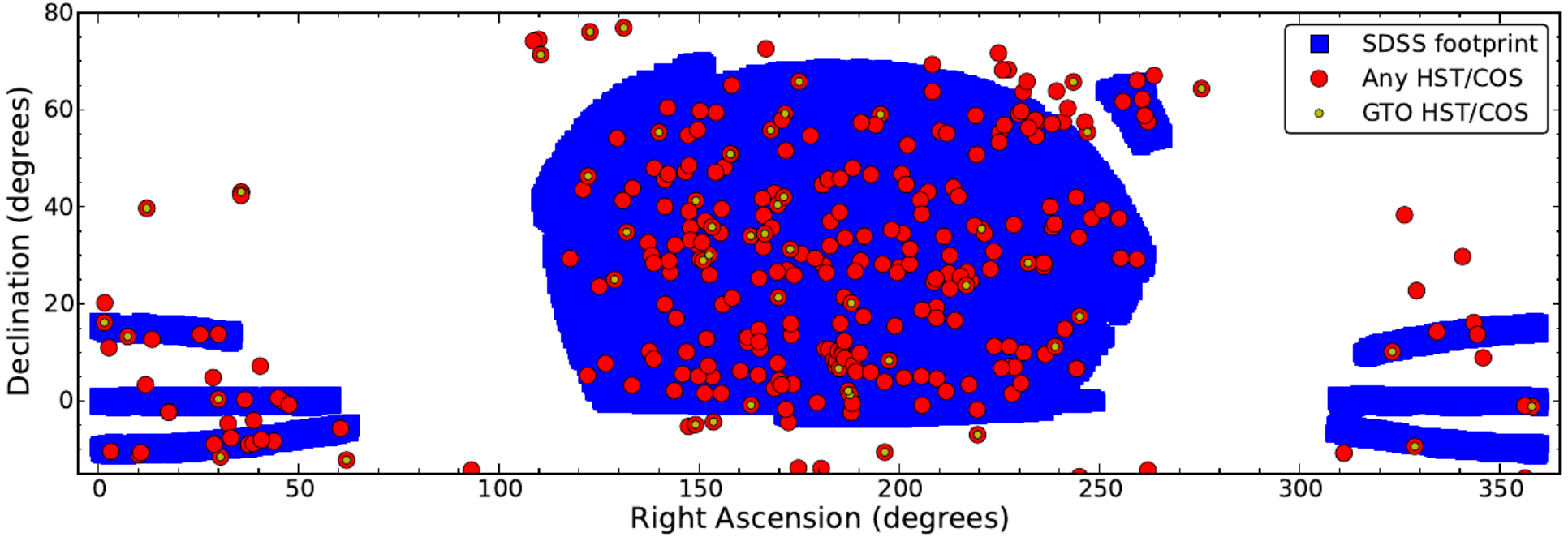

IGM-galaxy cross-correlation
~10 Mpc
Gas data from OWLS @ z=0 (Schaye+10)


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


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

Future work

Future work

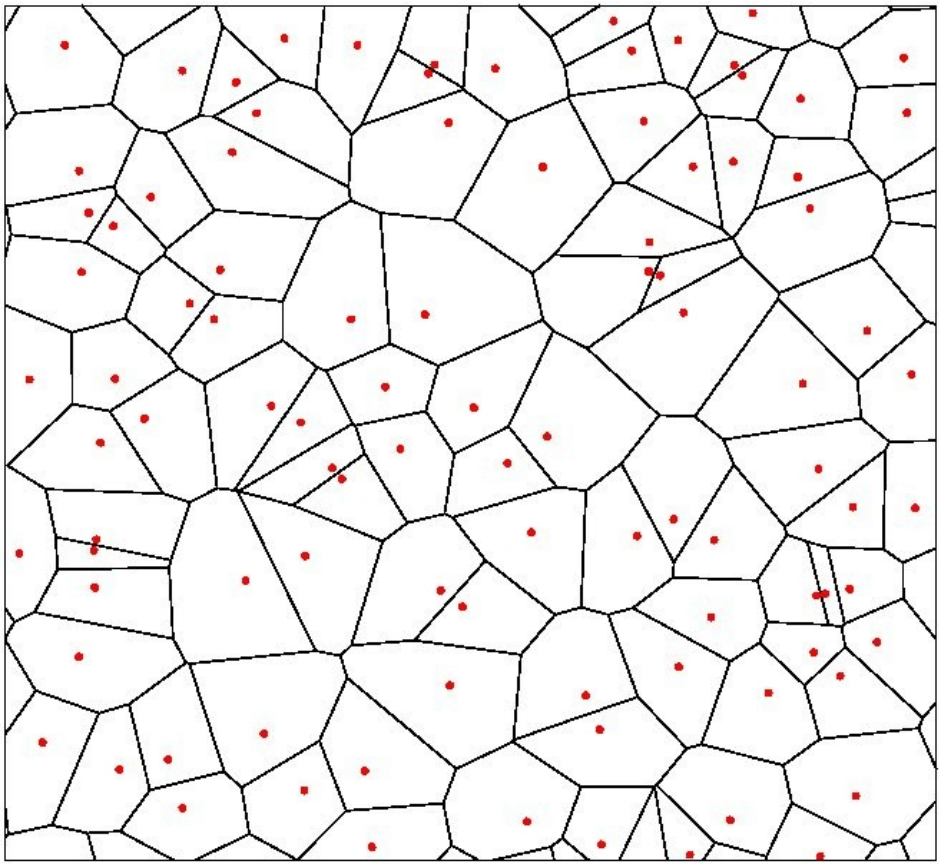


All these projects are currently being further developed with new data.

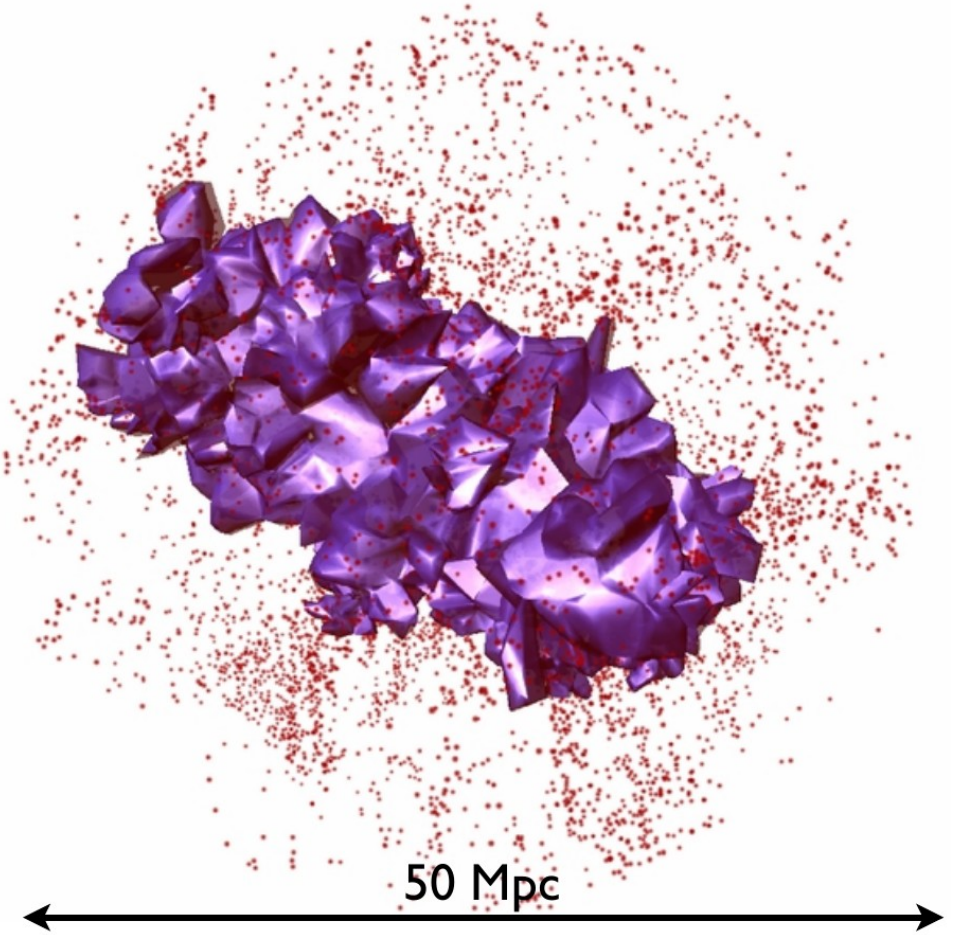
We will reduce statistical uncertainties, and will better constraint systematics.

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

Future work: Voids



Voronoi tesselation



Sutter+12

Recently awarded HST AR proposal (PI Tejos).

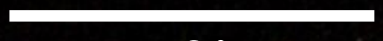
Future work: Filaments

Future work: Filaments

Recently awarded (PI Tejos):

VLT/MUSE
VLT/VIMOS
HST/COS

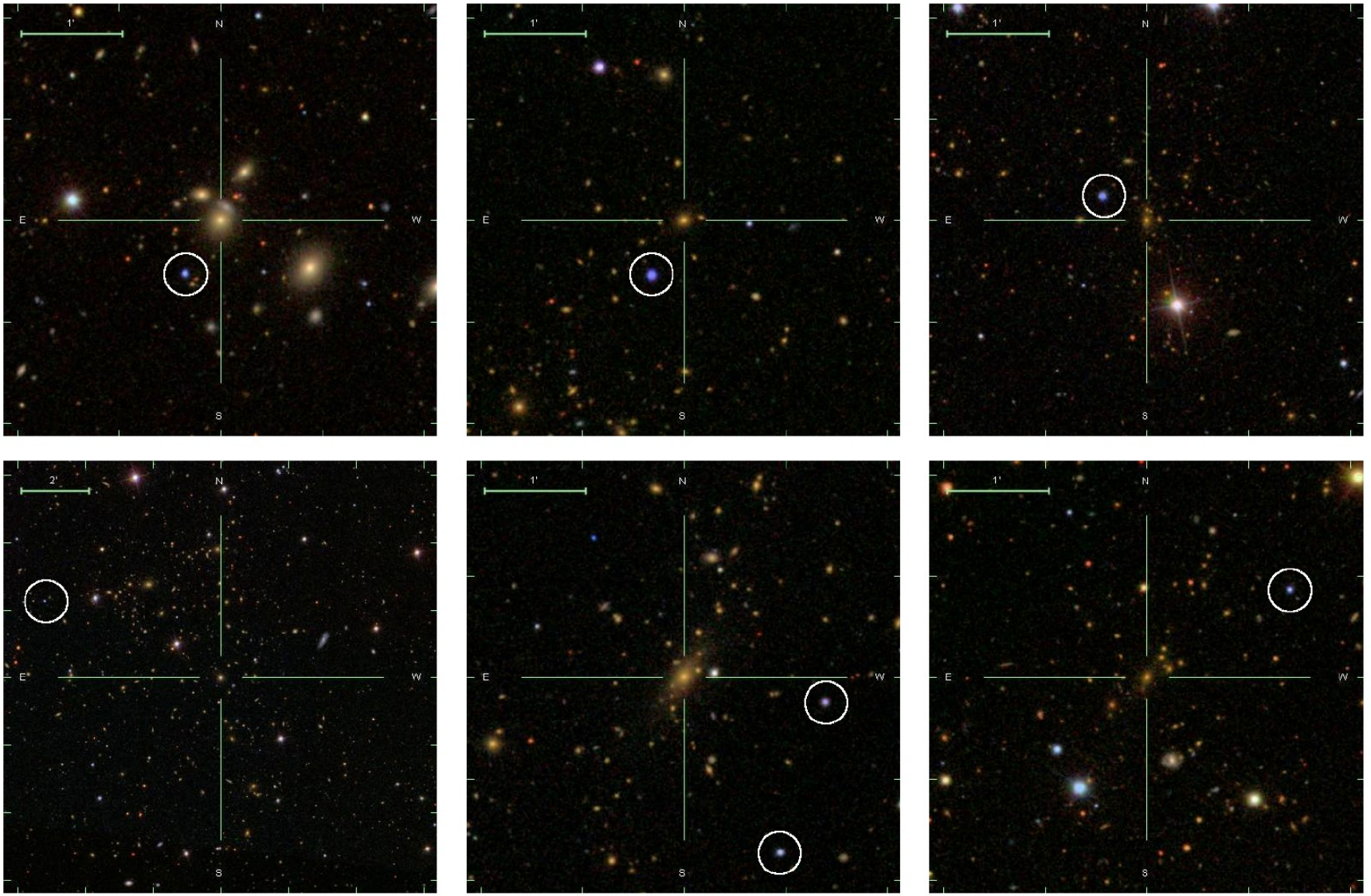
To map galaxies in these filaments and repeat the experiment in another field.



2'

~0.5 Mpc @ z=0.2
~1.0 Mpc @ z=0.5

Future work: Clusters

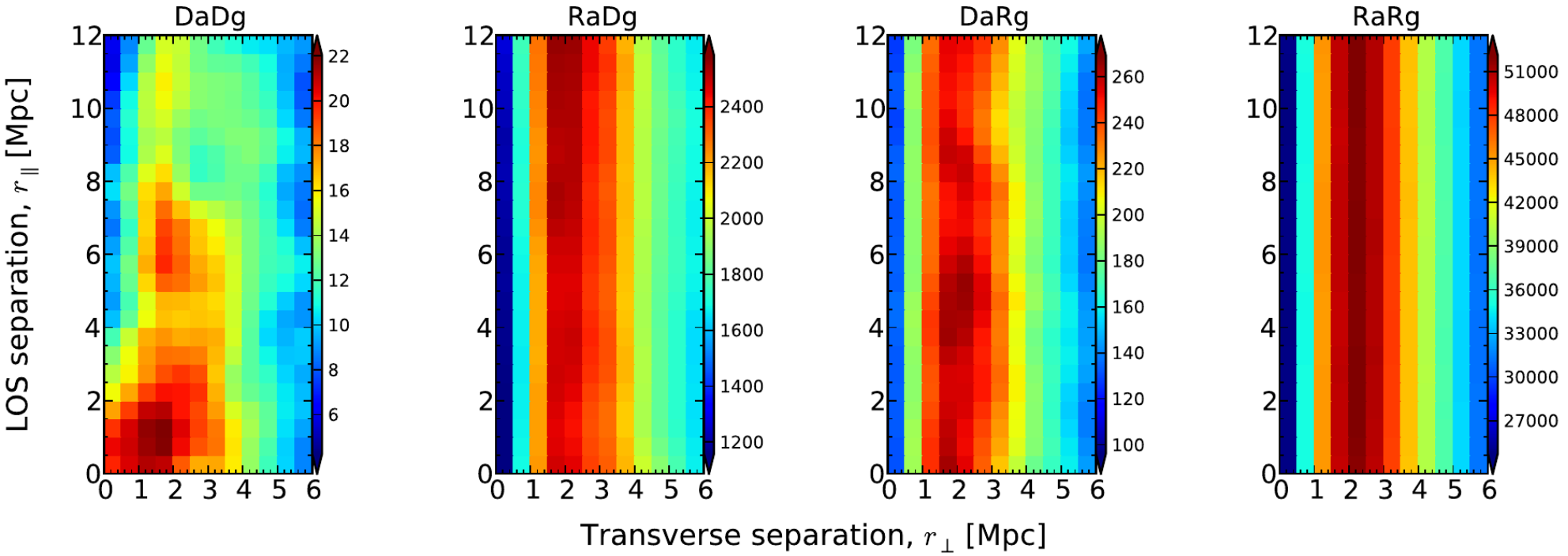


Recently awarded HST/COS (PI Tejos) to study galaxy clusters at 0.1< z <0.4

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.)**

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

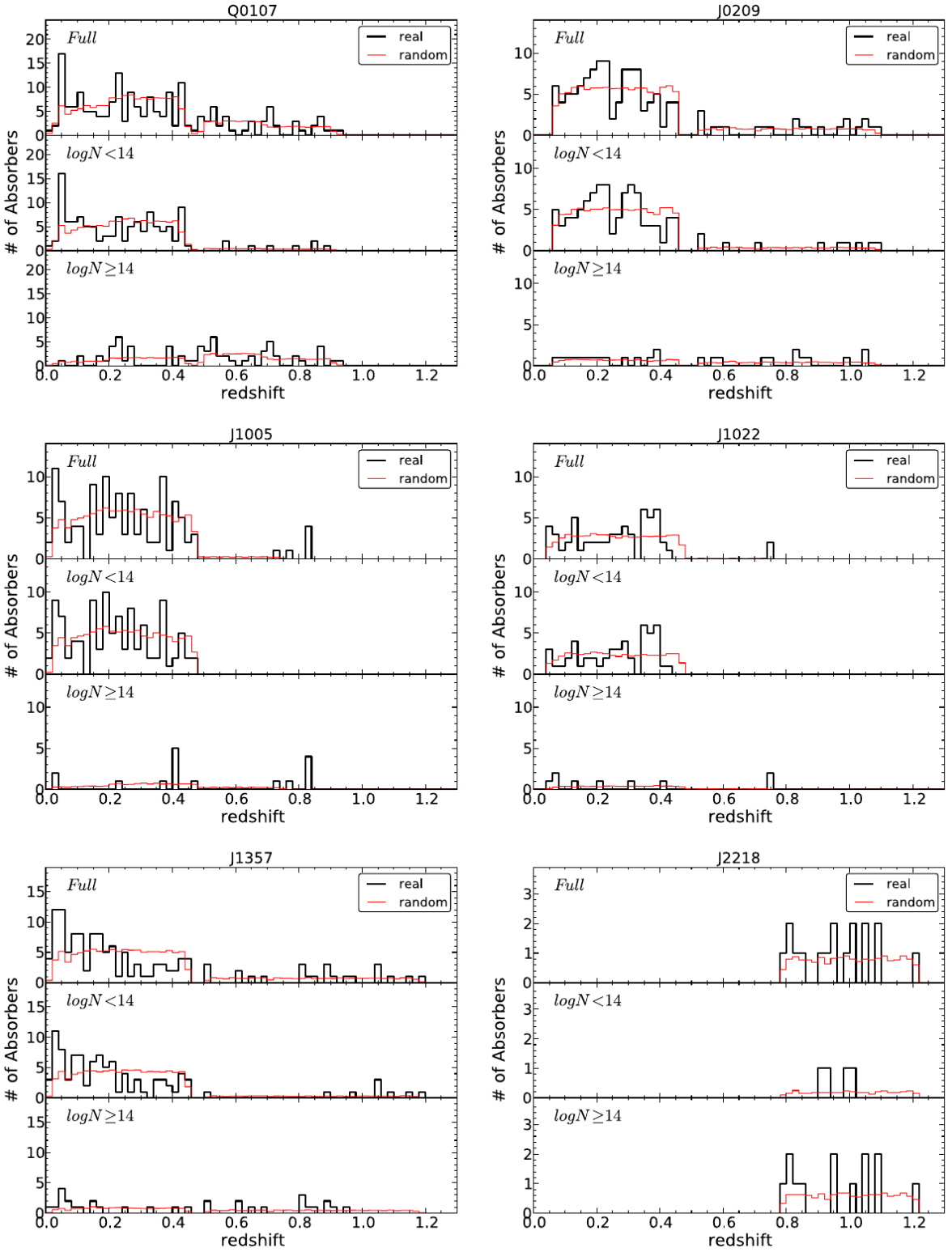
Samples

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

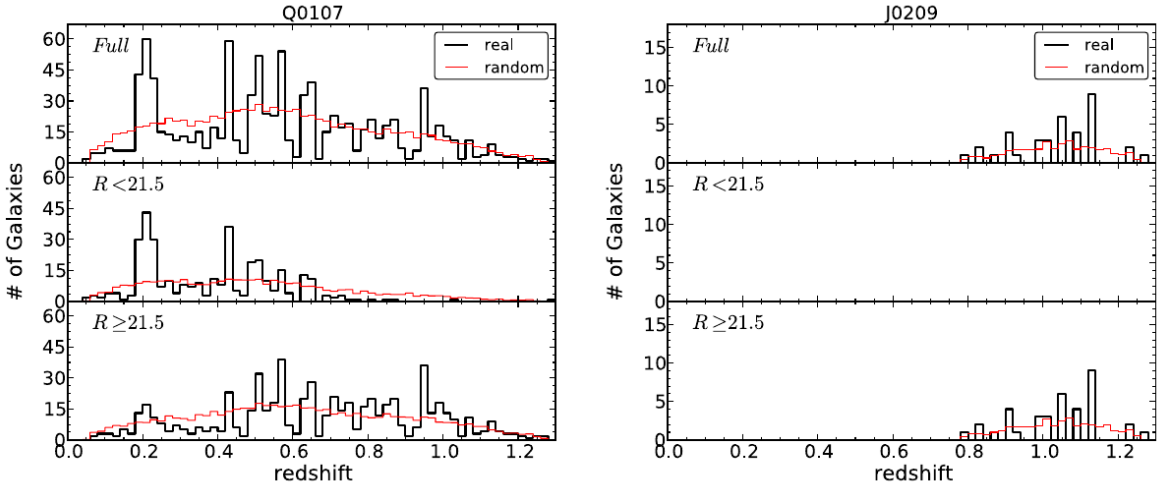
$10^{14} \leqslant N_{\rm HI} \lesssim 10^{17}$ cm^{-2} ('strong')
$10^{13} \lesssim N_{\rm HI} < 10^{14}$ cm^{-2} ('weak')

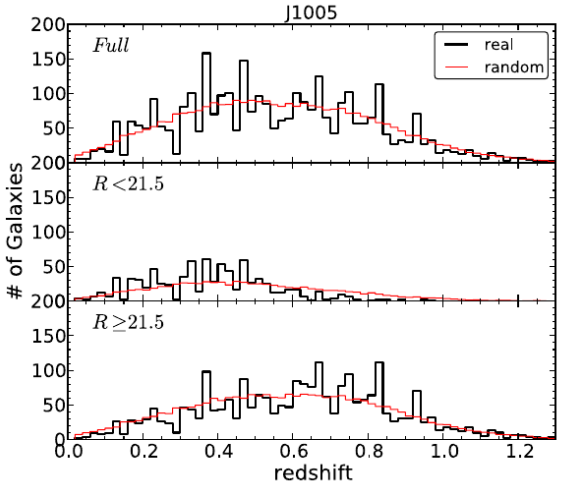
Tejos+14

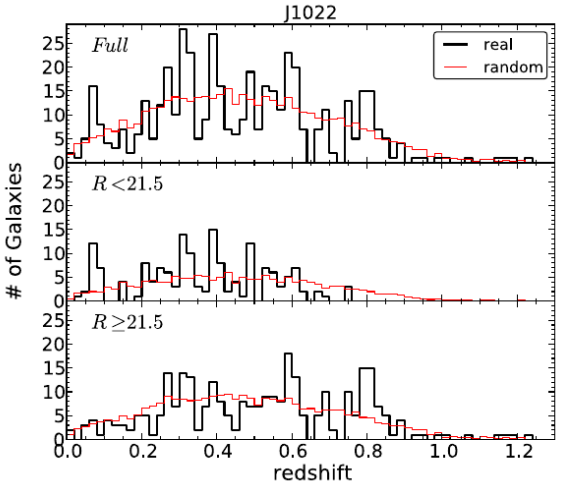


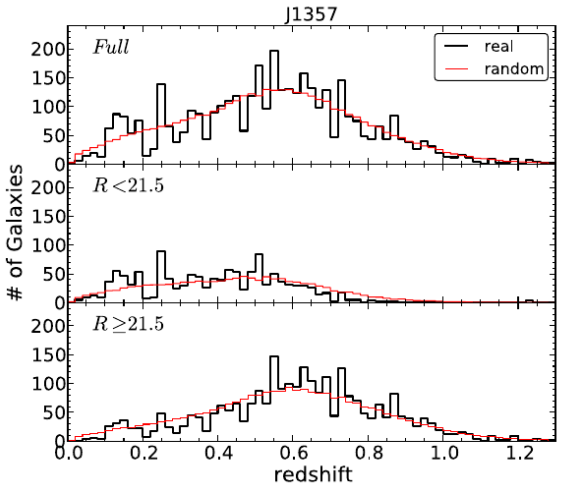
Selection function

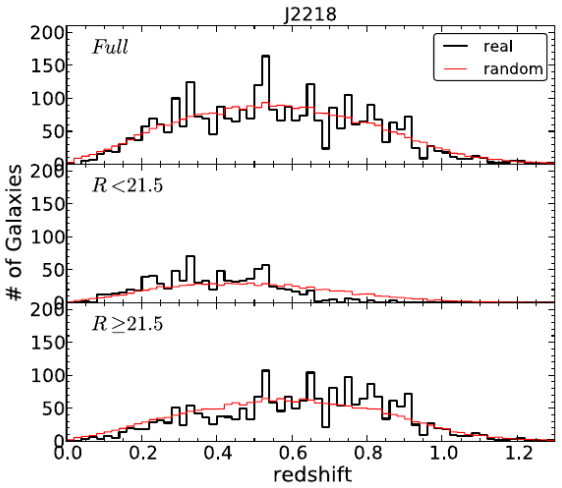
Tejos+14





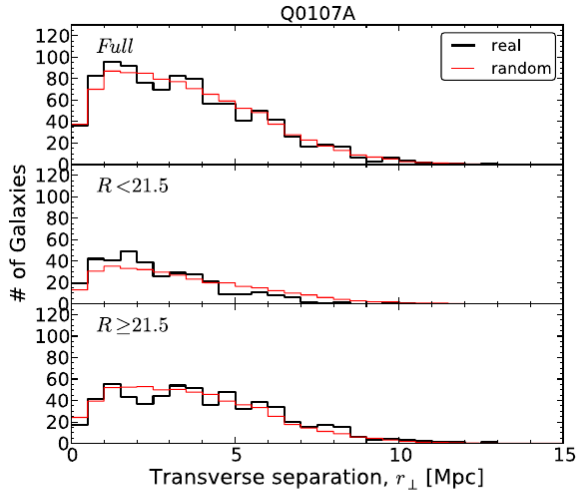


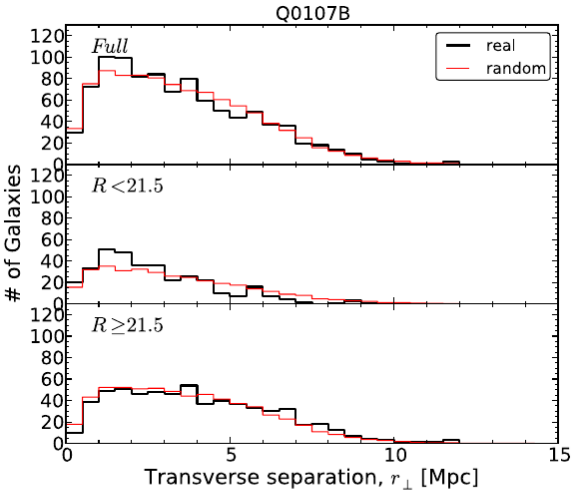


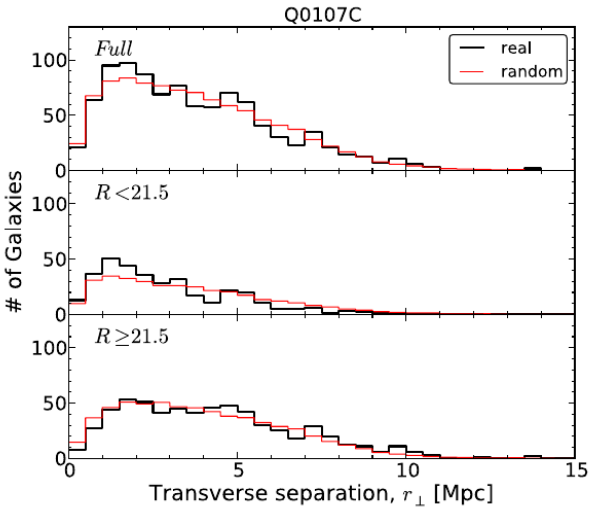


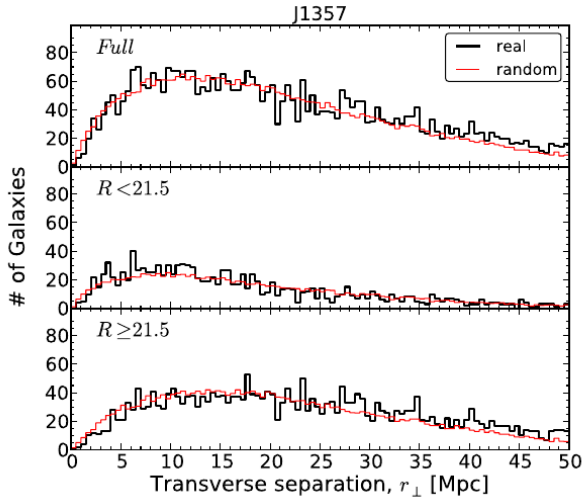
Selection function

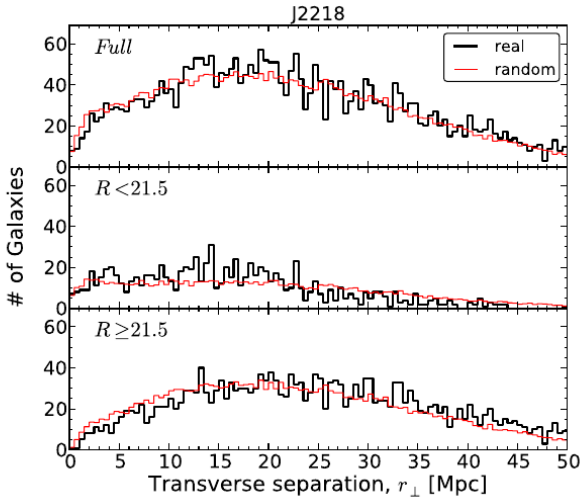
Tejos+14





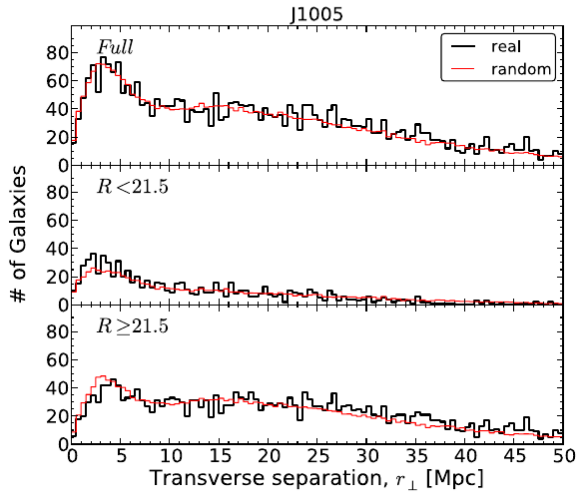


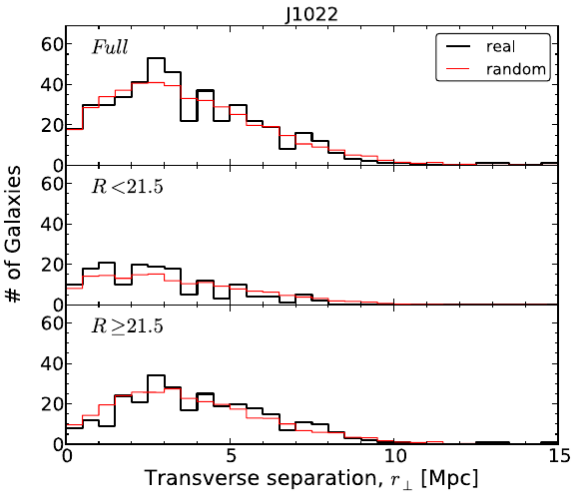


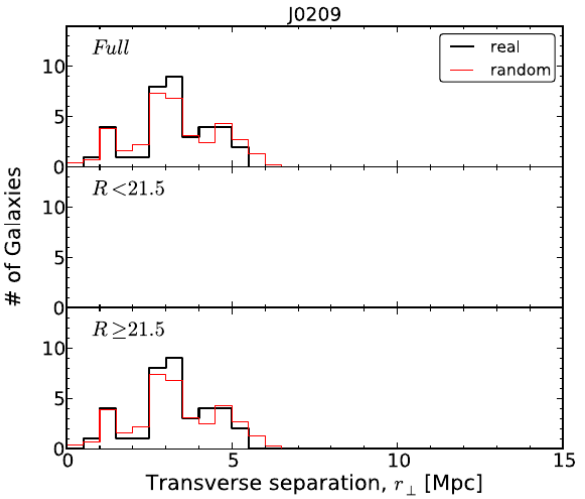


Selection function

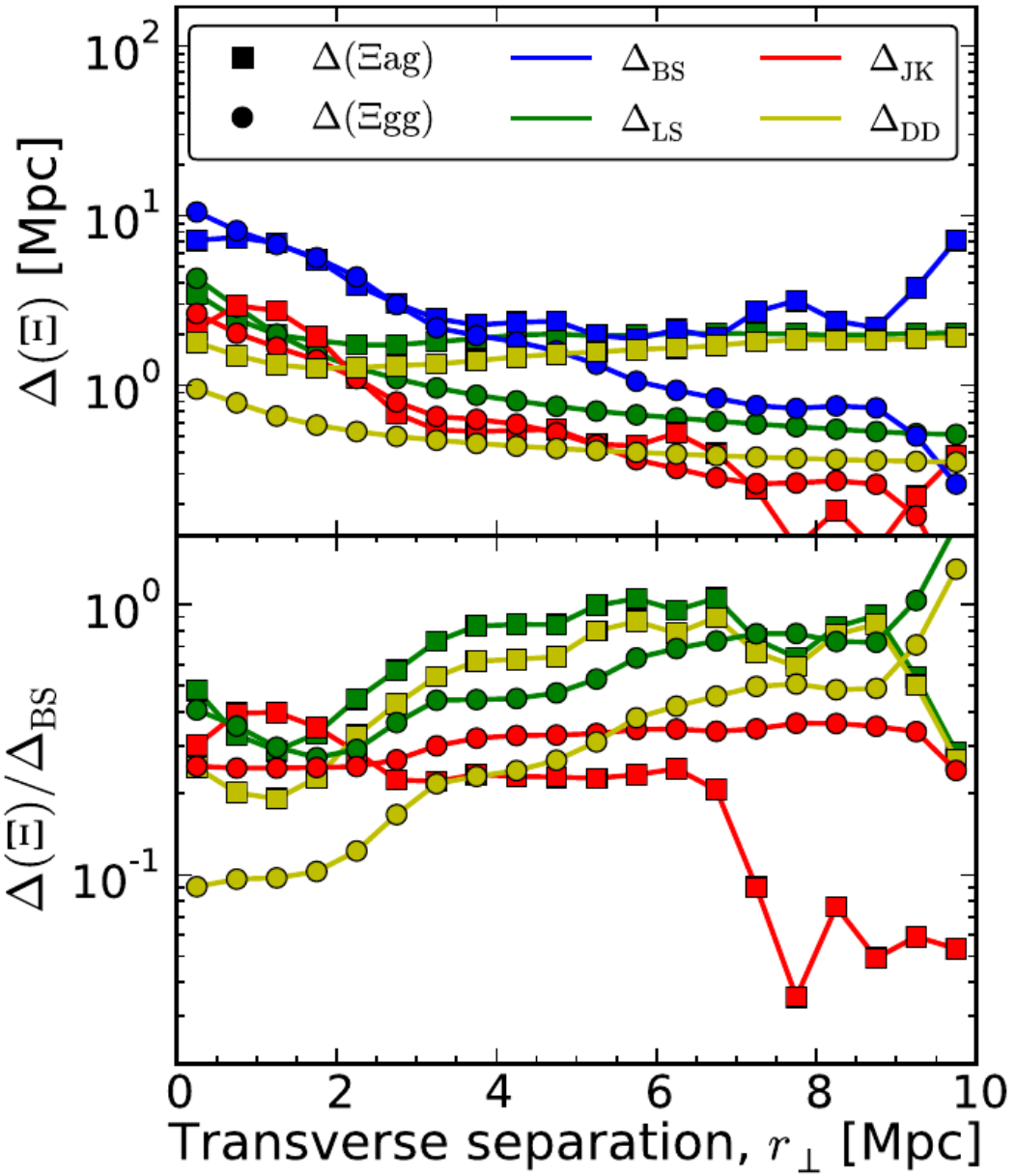
Tejos+14



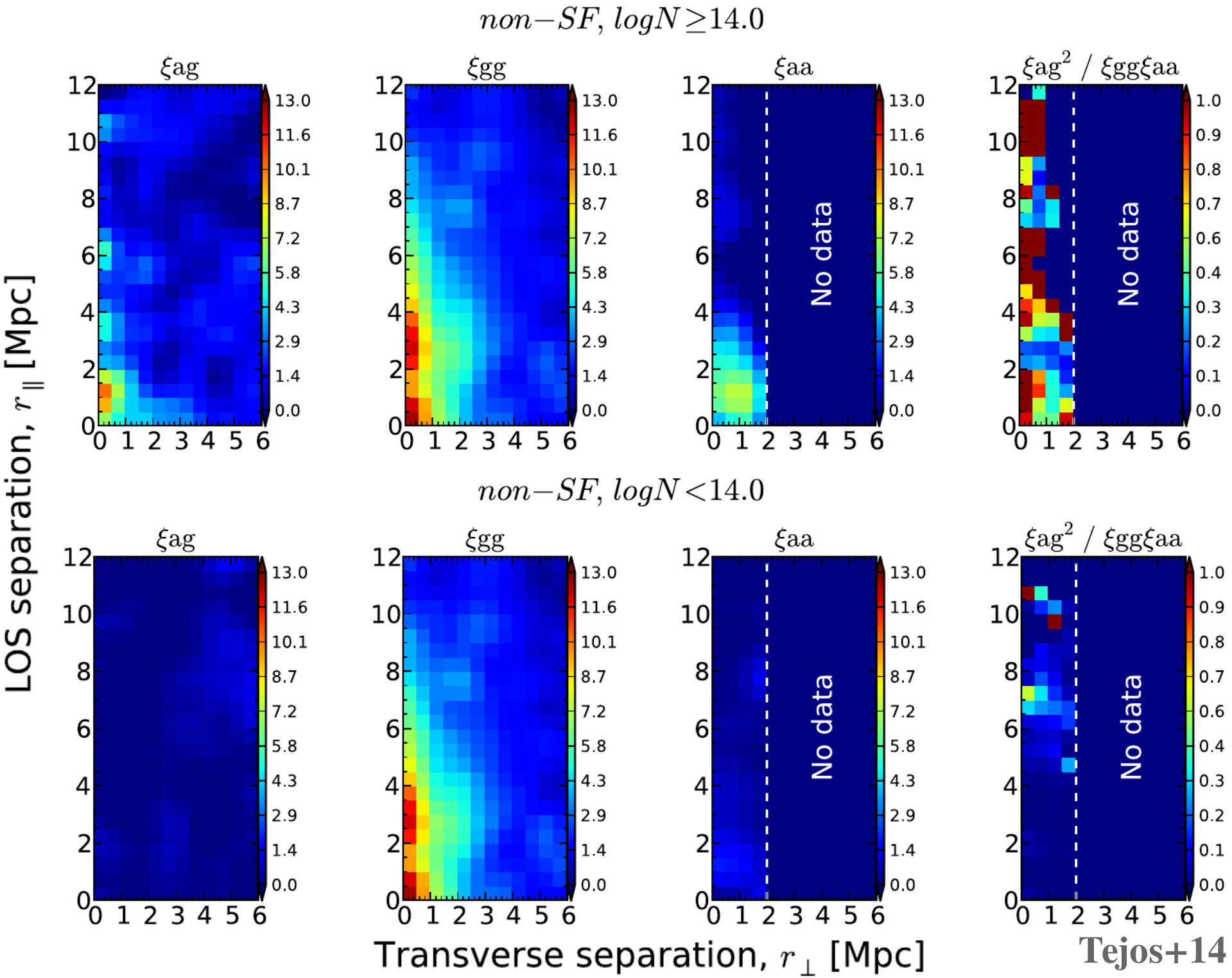


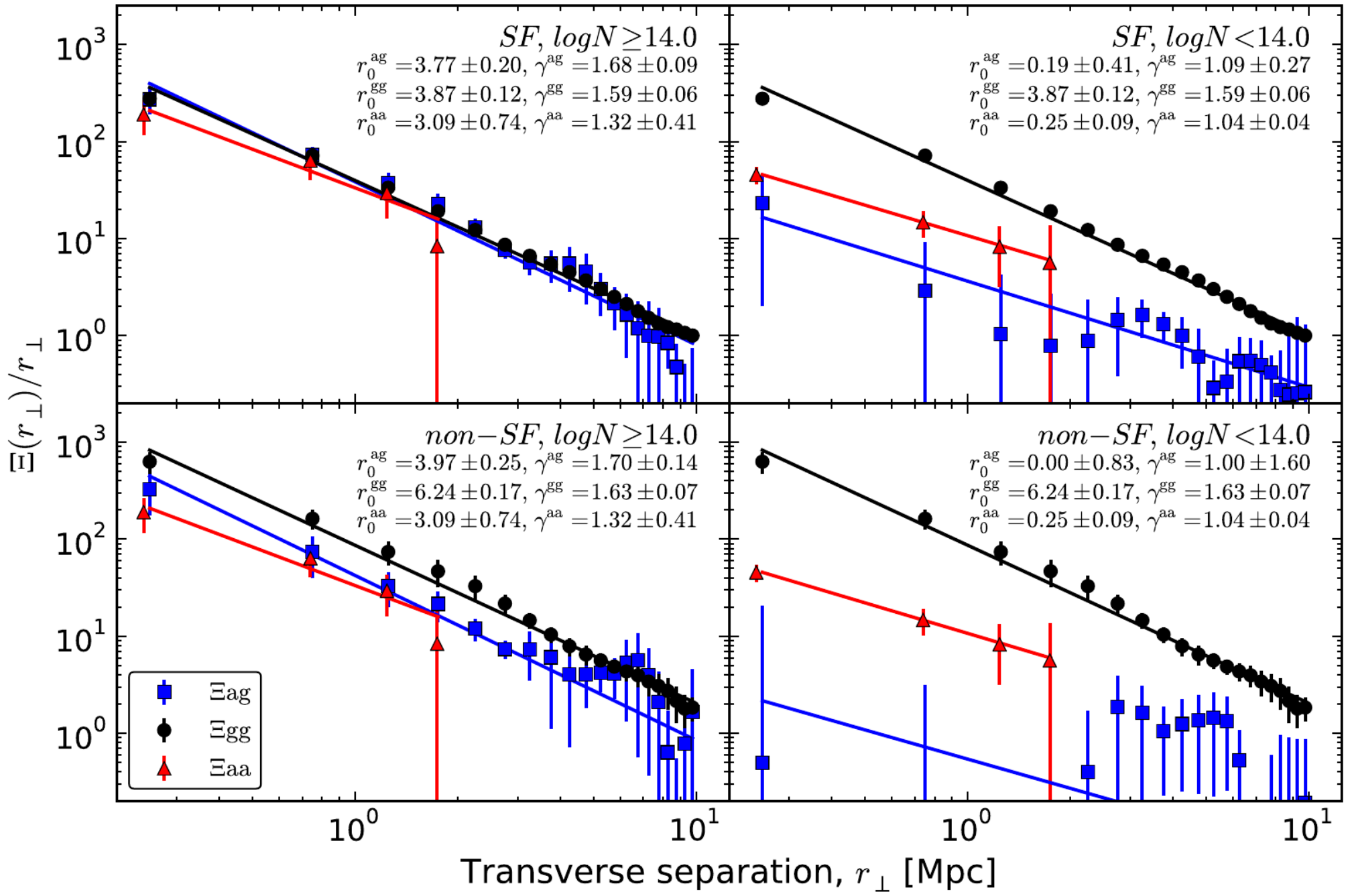


Uncertainties

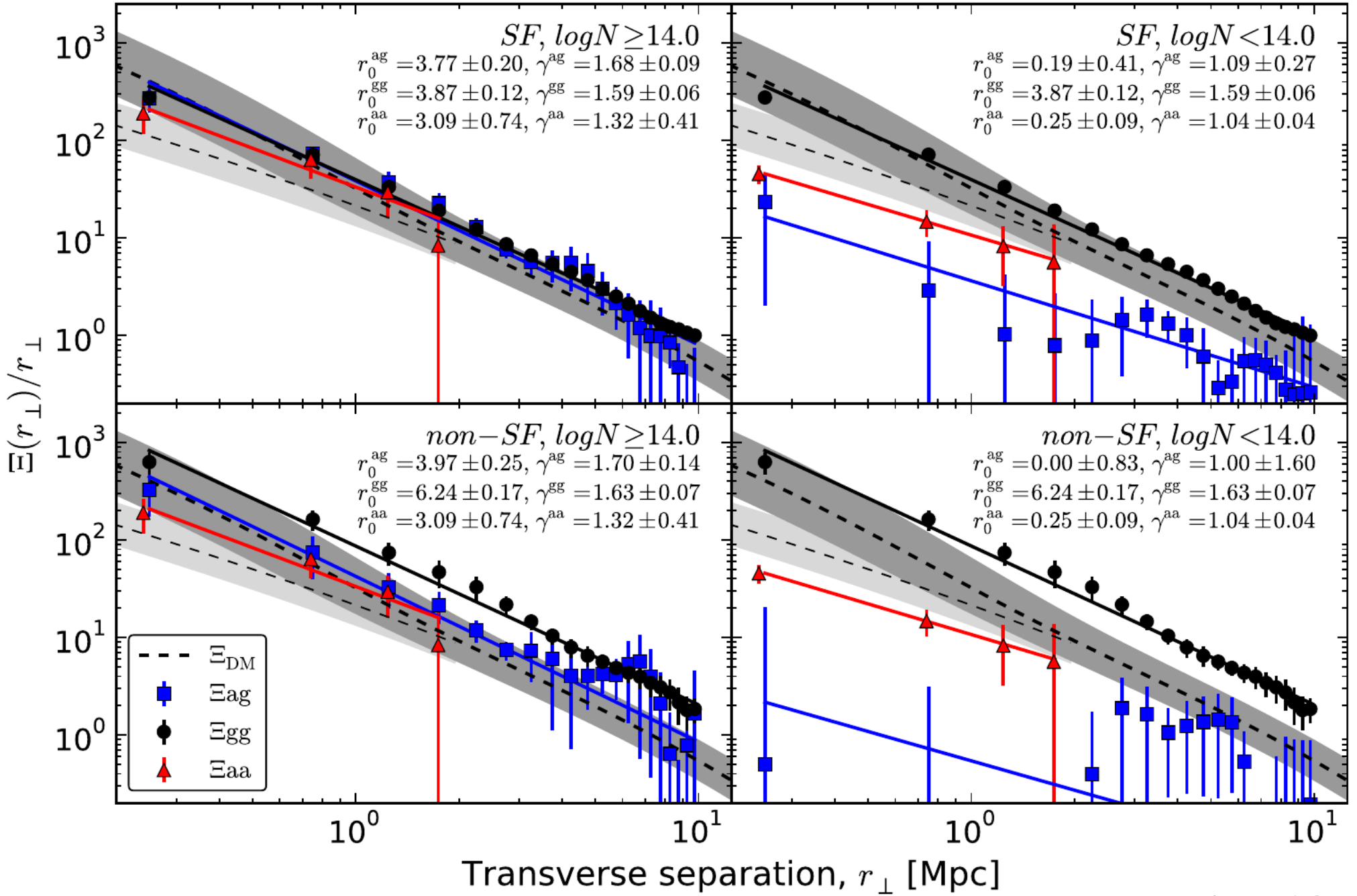


Tejos+14

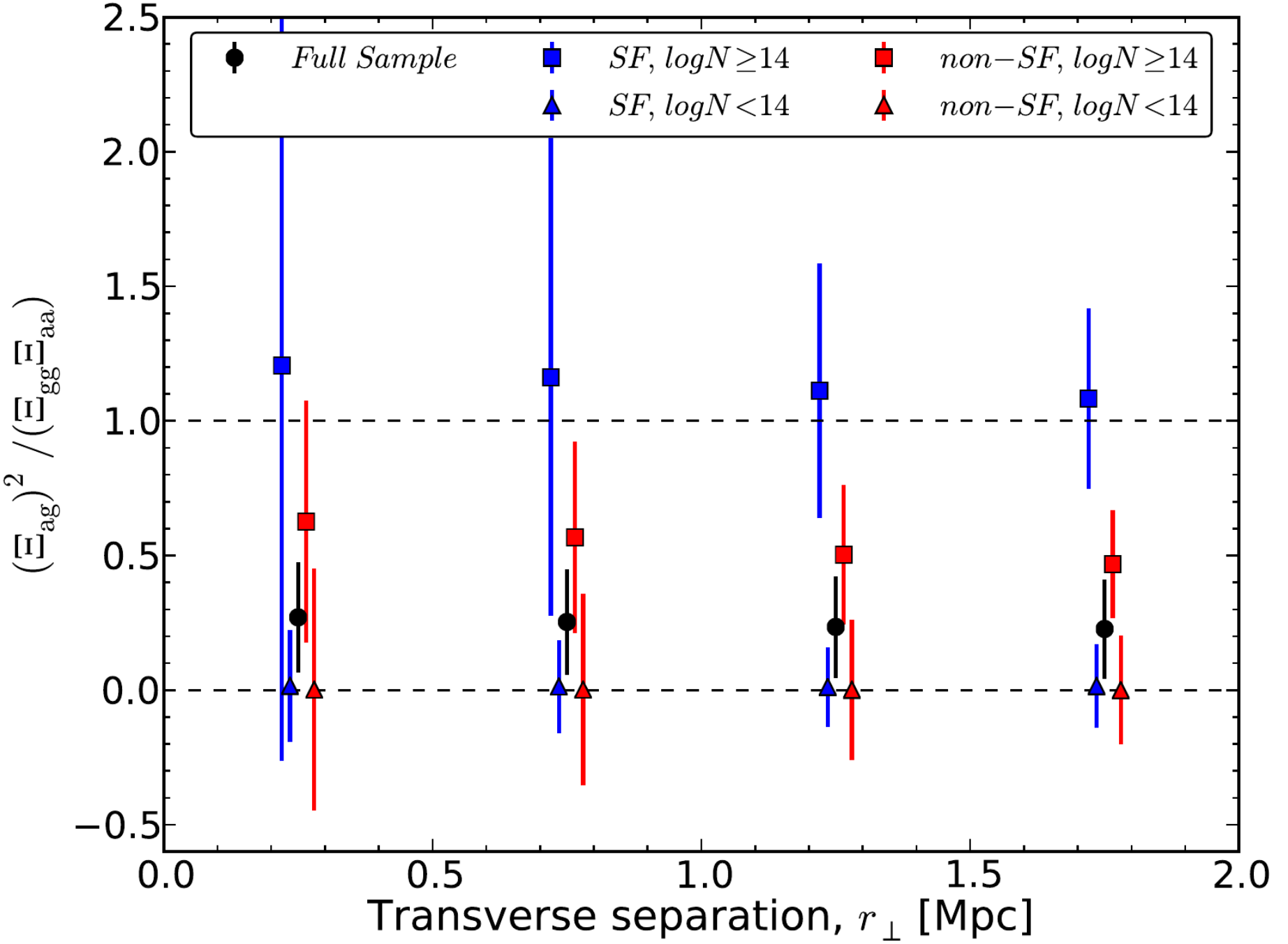

non−SF, logN ≥14.0
ξag
ξgg
ξaa
ξag² / ξggξaa
No data
No data
non−SF, logN <14.0
ξag
ξgg
ξaa
ξag² / ξggξaa
No data
No data
LOS separation, r∥ [Mpc]
Transverse separation, r⊥ [Mpc]
Tejos+14


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]

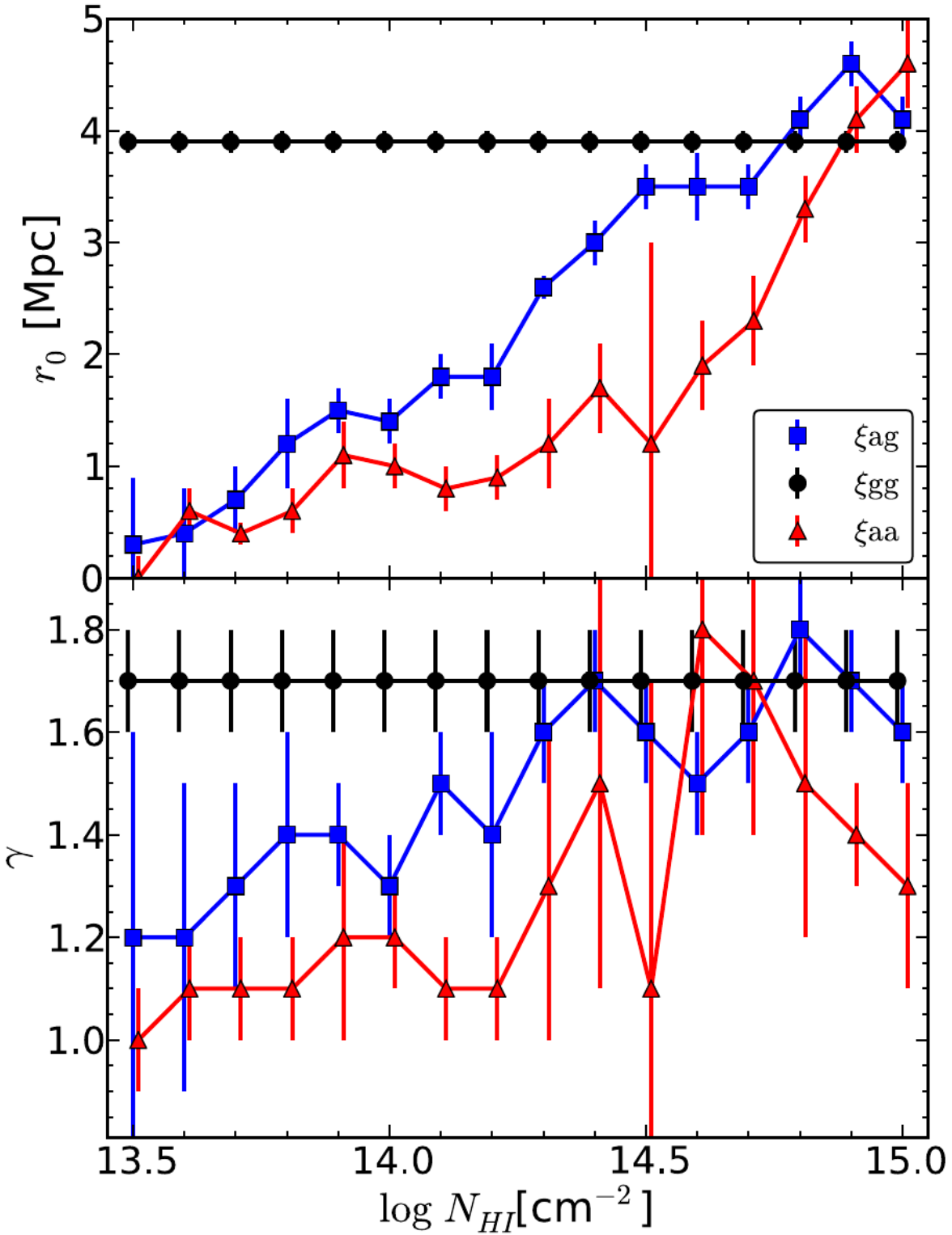
Tejos+14


SF, logN ≥14.0
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
Ξ_{DM}
Ξag
Ξgg
Ξaa
$[\Xi(r_\perp)/r_\perp]$
Transverse separation, $r_\perp$ [Mpc]

Tejos+14

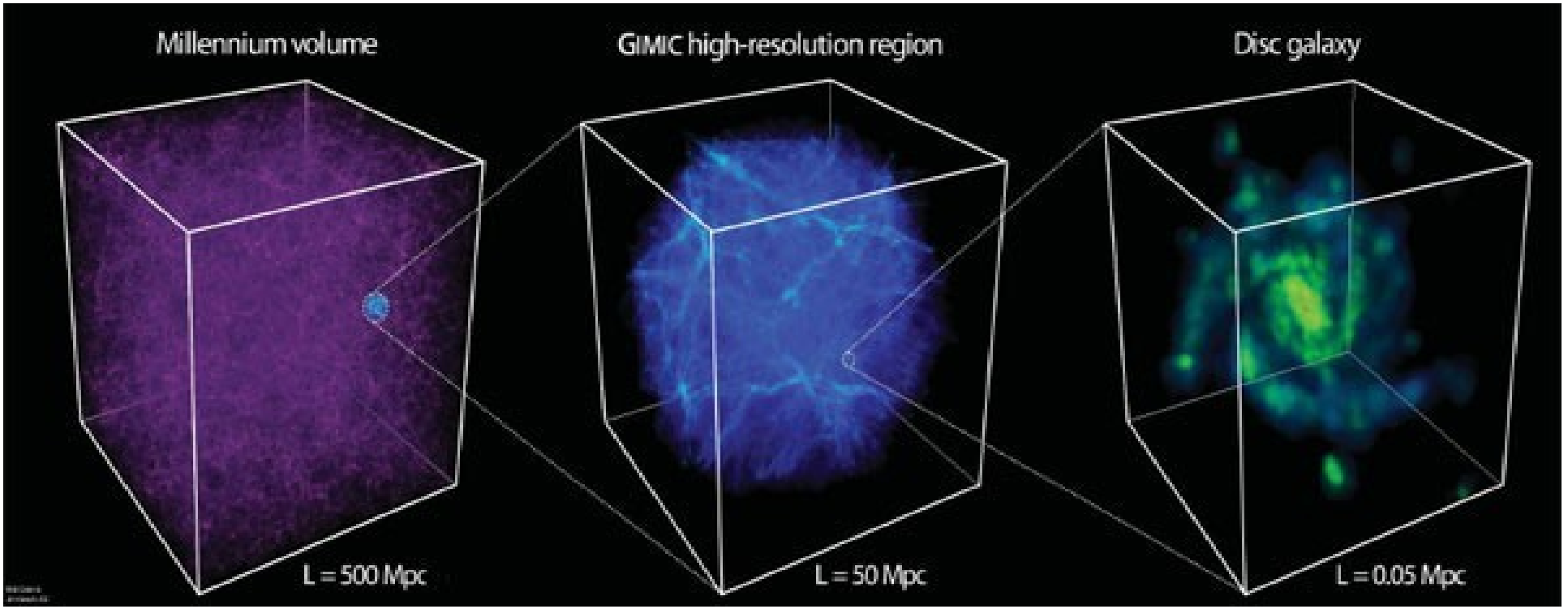

Full Sample
SF, logN≥14
non−SF, logN≥14
SF, logN<14
non−SF, logN<14
$(\Xi_{ag})^2 / (\Xi_{gg}\Xi_{aa})$
Transverse separation, $r_\perp$ [Mpc]
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
0.0
0.5
1.0
1.5
2.0

Tejos+14



Tejos+14

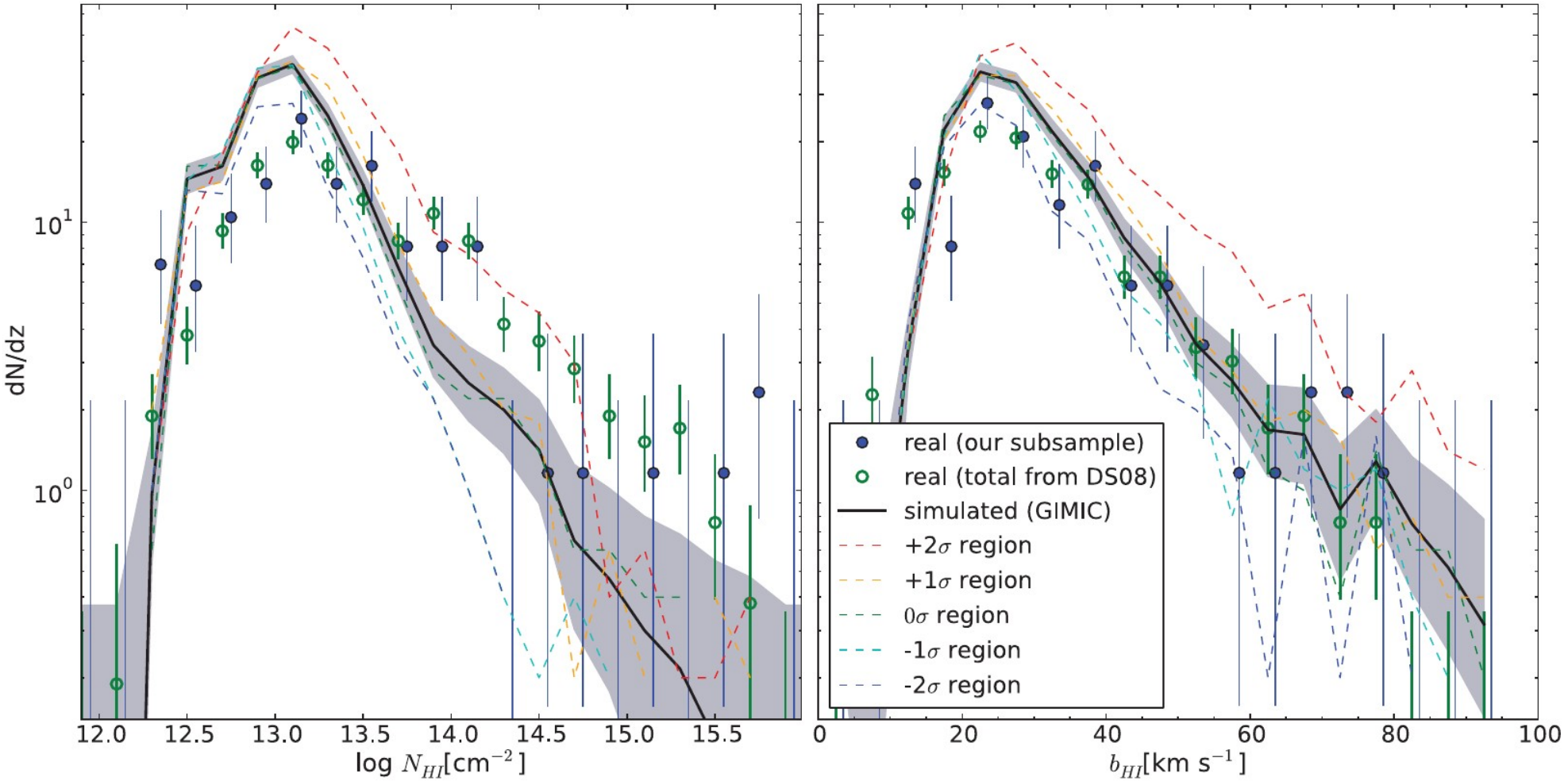
Comparison to simulations



GIMIC simulations (Crain+09)

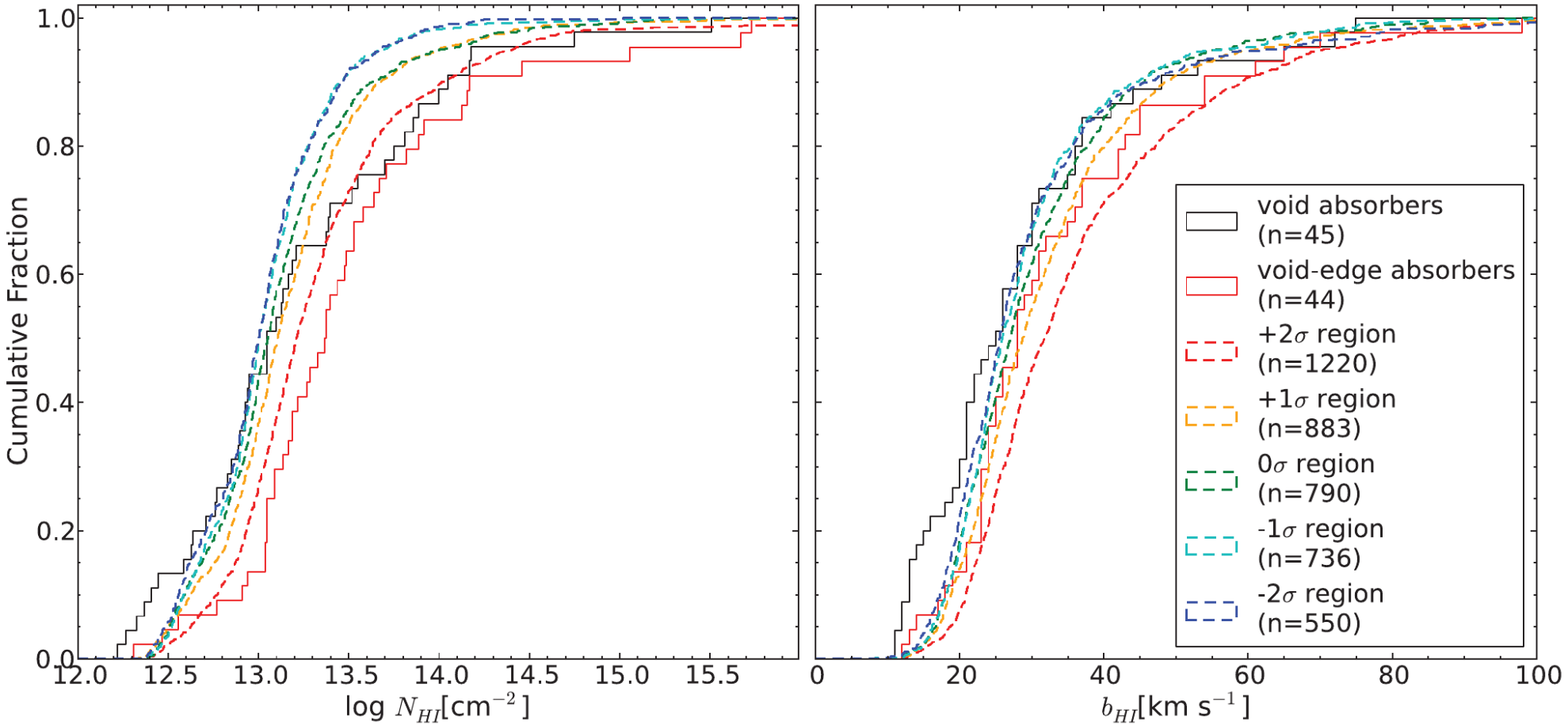
Tejos+12

Comparison to simulations

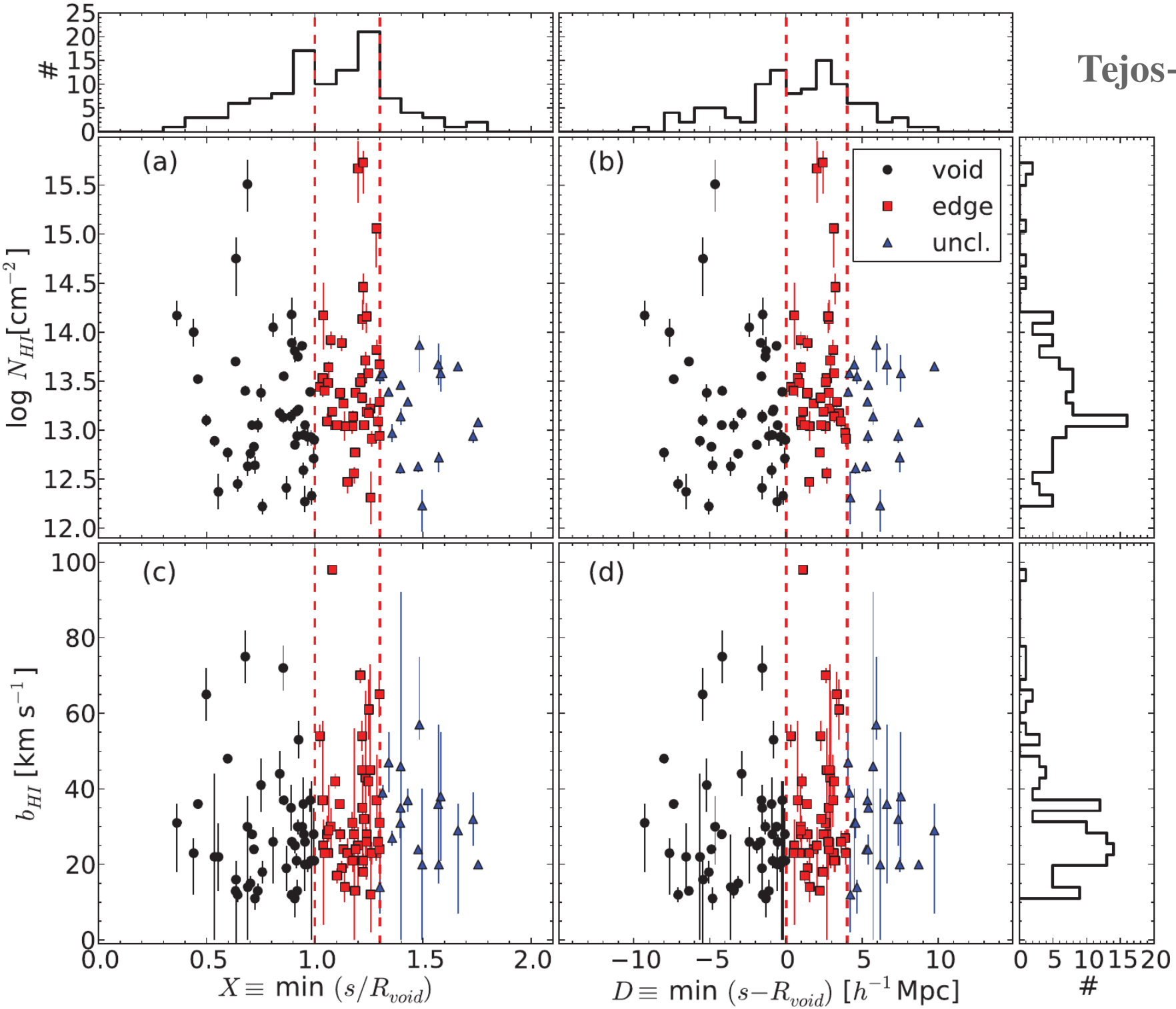


Tejos+12

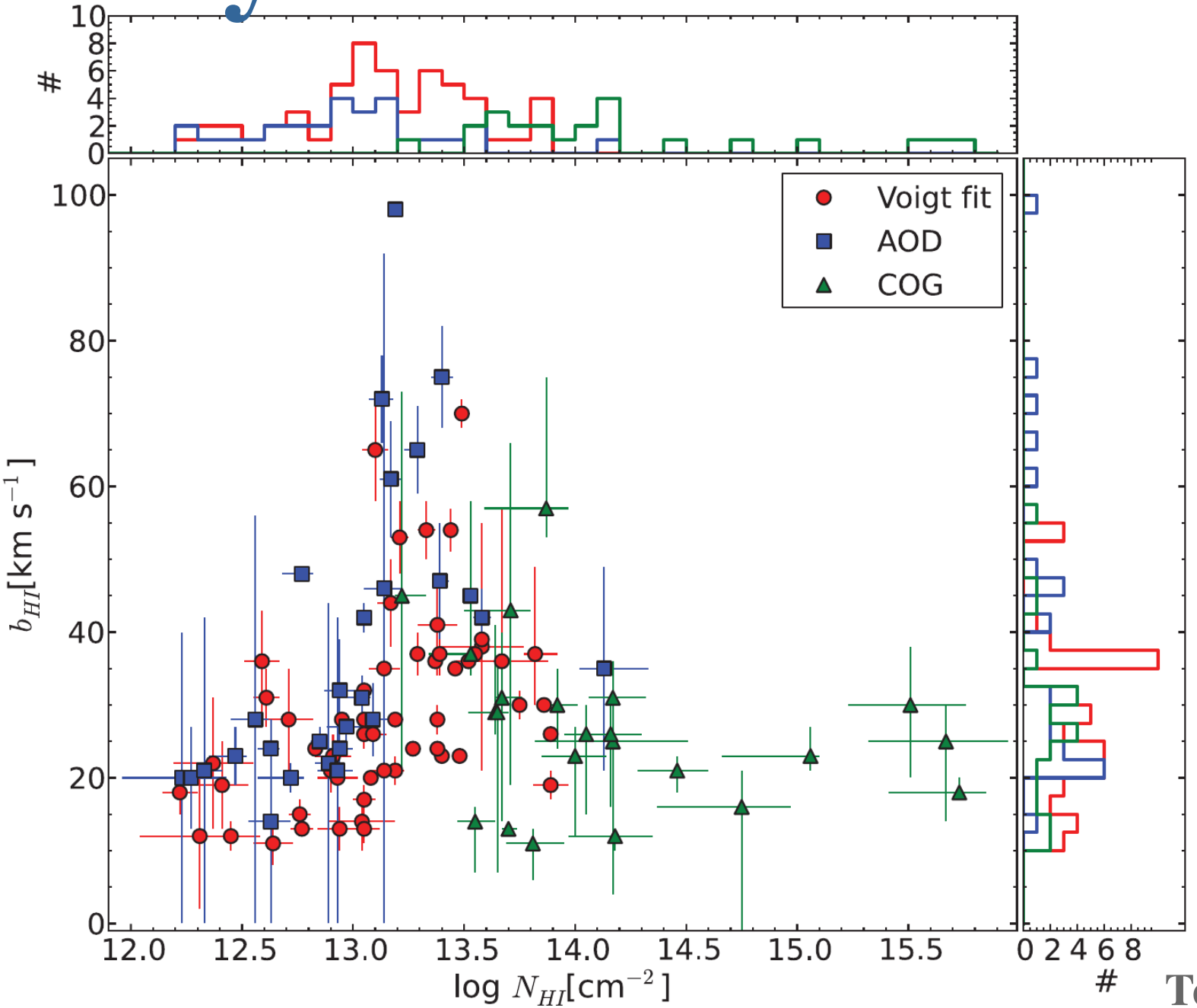
Comparison to simulations



Tejos+12

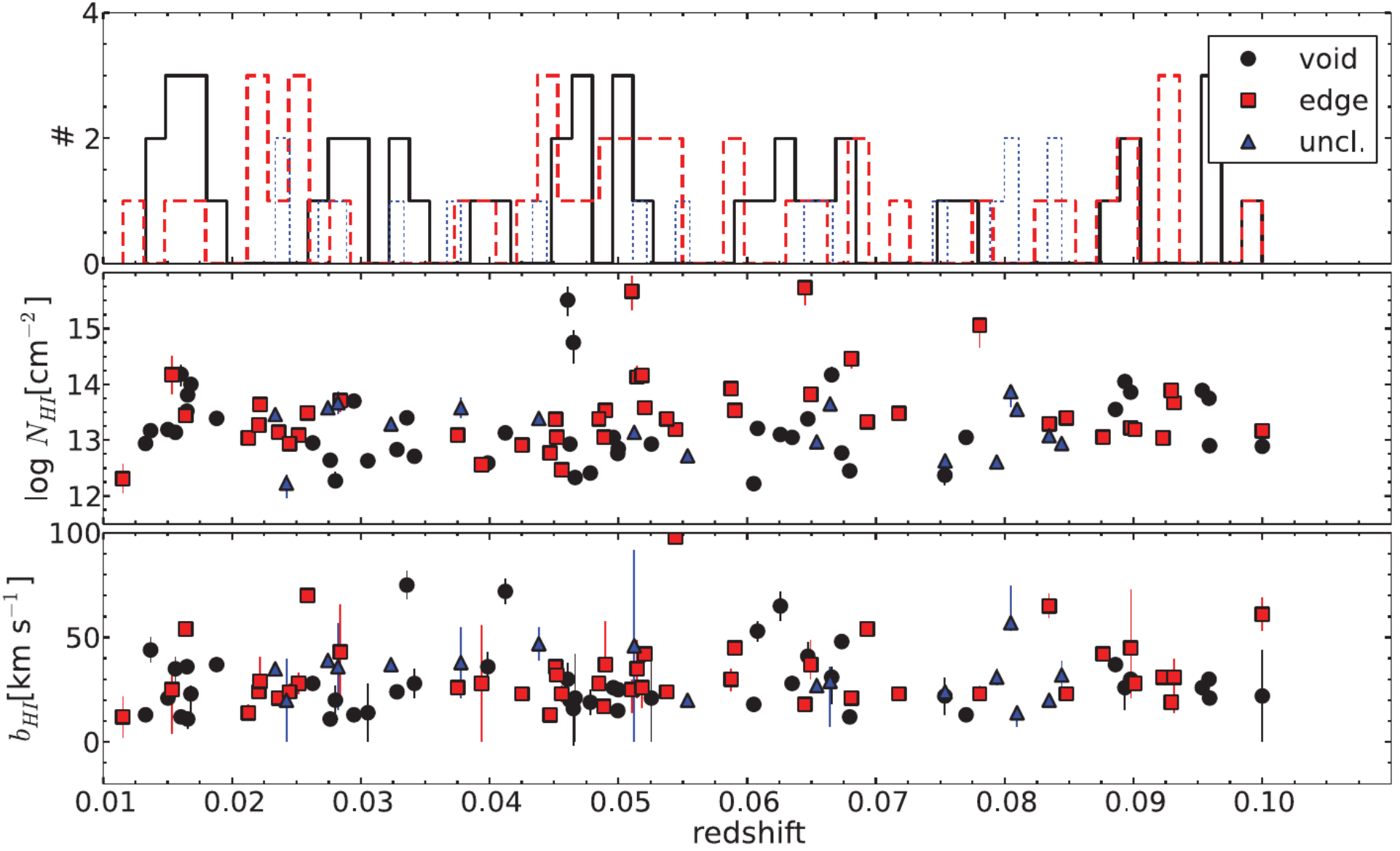

Tejos+12
(a)
(b)
(c)
(d)
void
edge
uncl.
log N_{HI}[cm^{-2}]
b_{HI} [km s^{-1}]
$X \equiv$ min (s/R_{void})
$D \equiv$ min $(s-R_{void})$ [h^{-1} Mpc]
#

Systematic effects



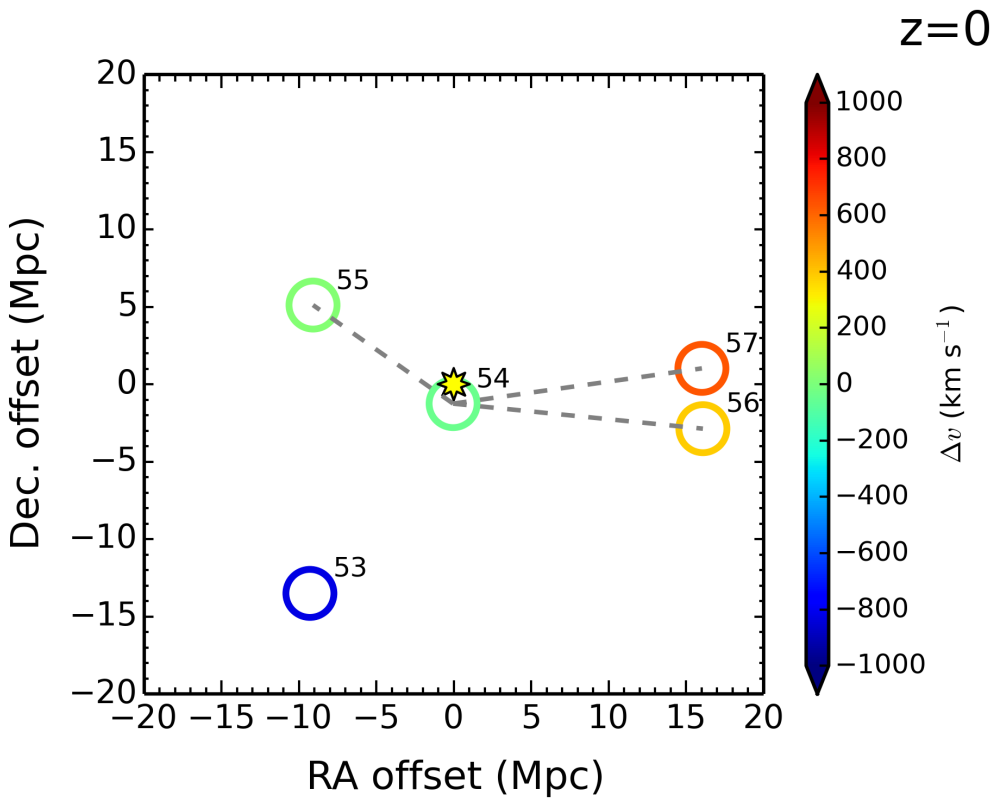
Tejos+12

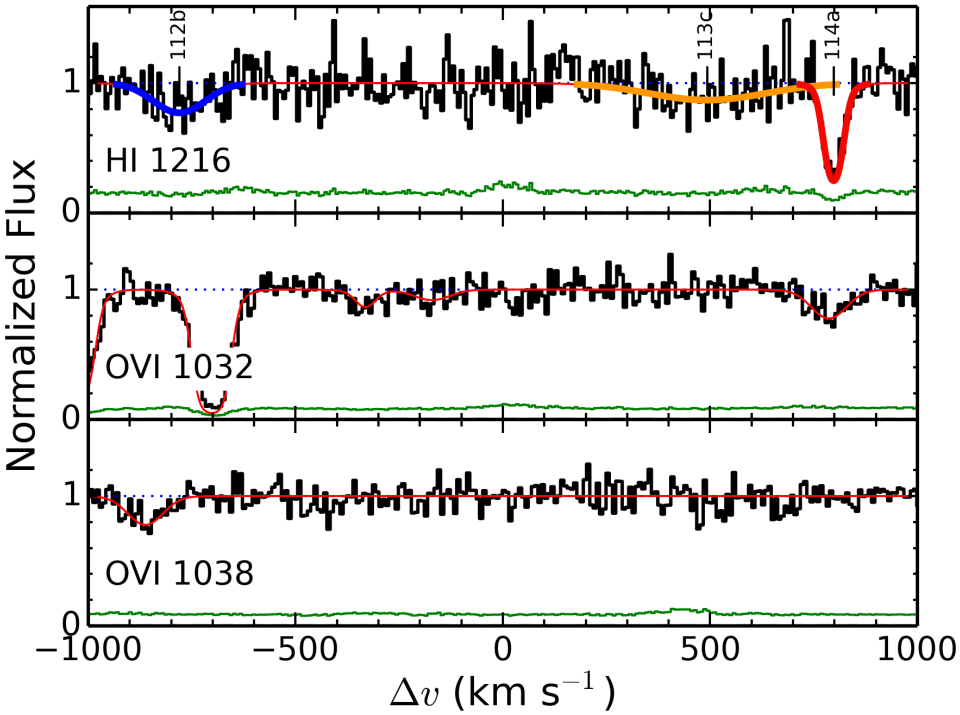
Systematic effects



Tejos+12

Examples





Tejos+14b in prep.

Future work