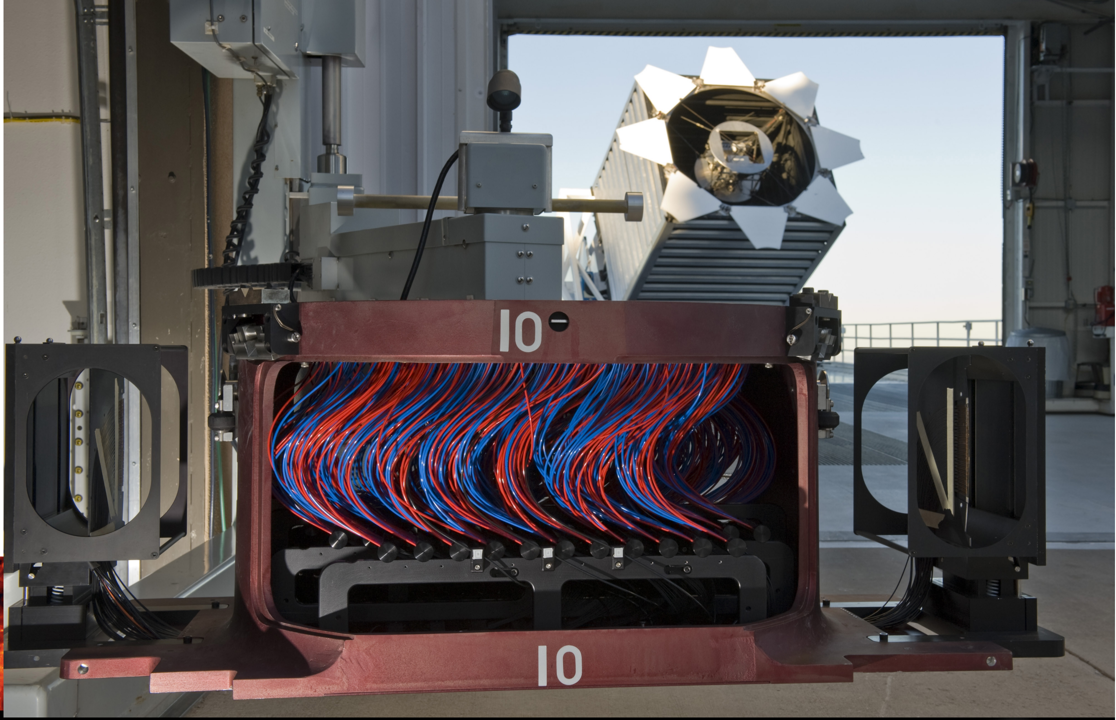
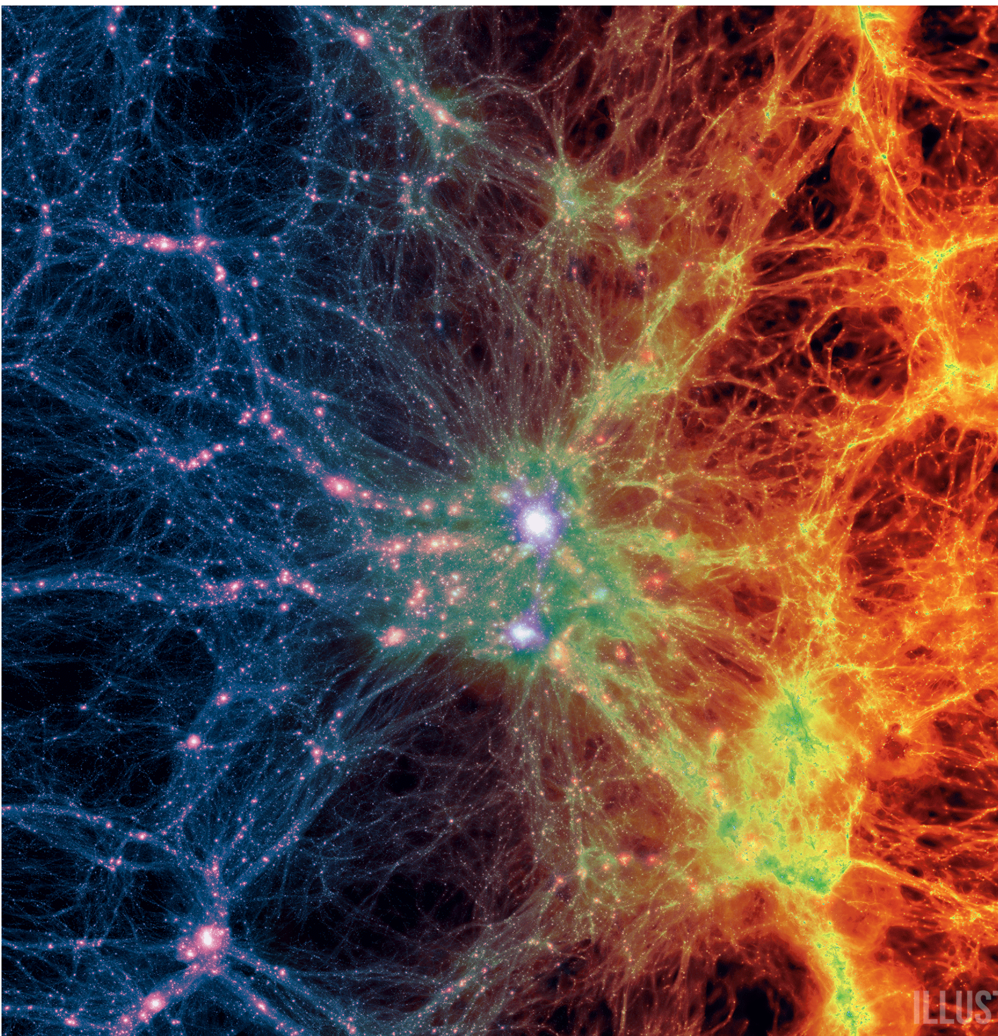
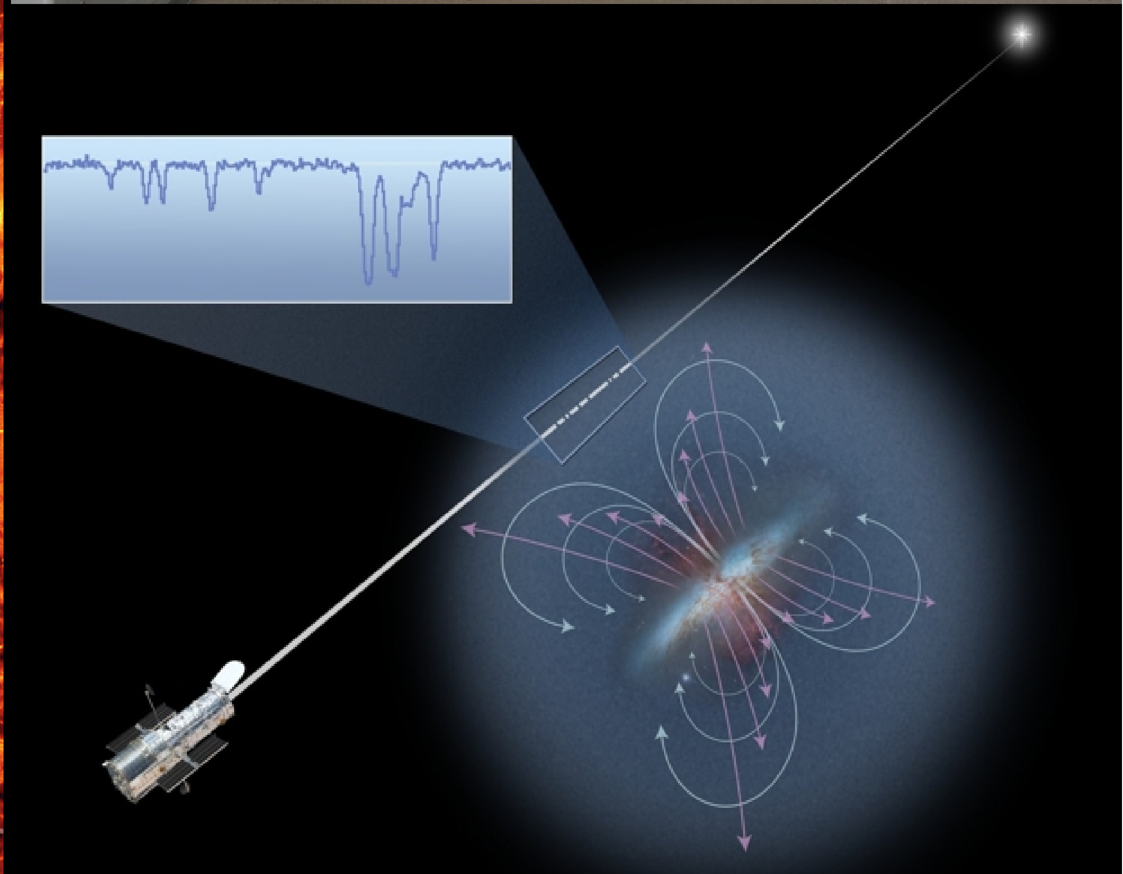
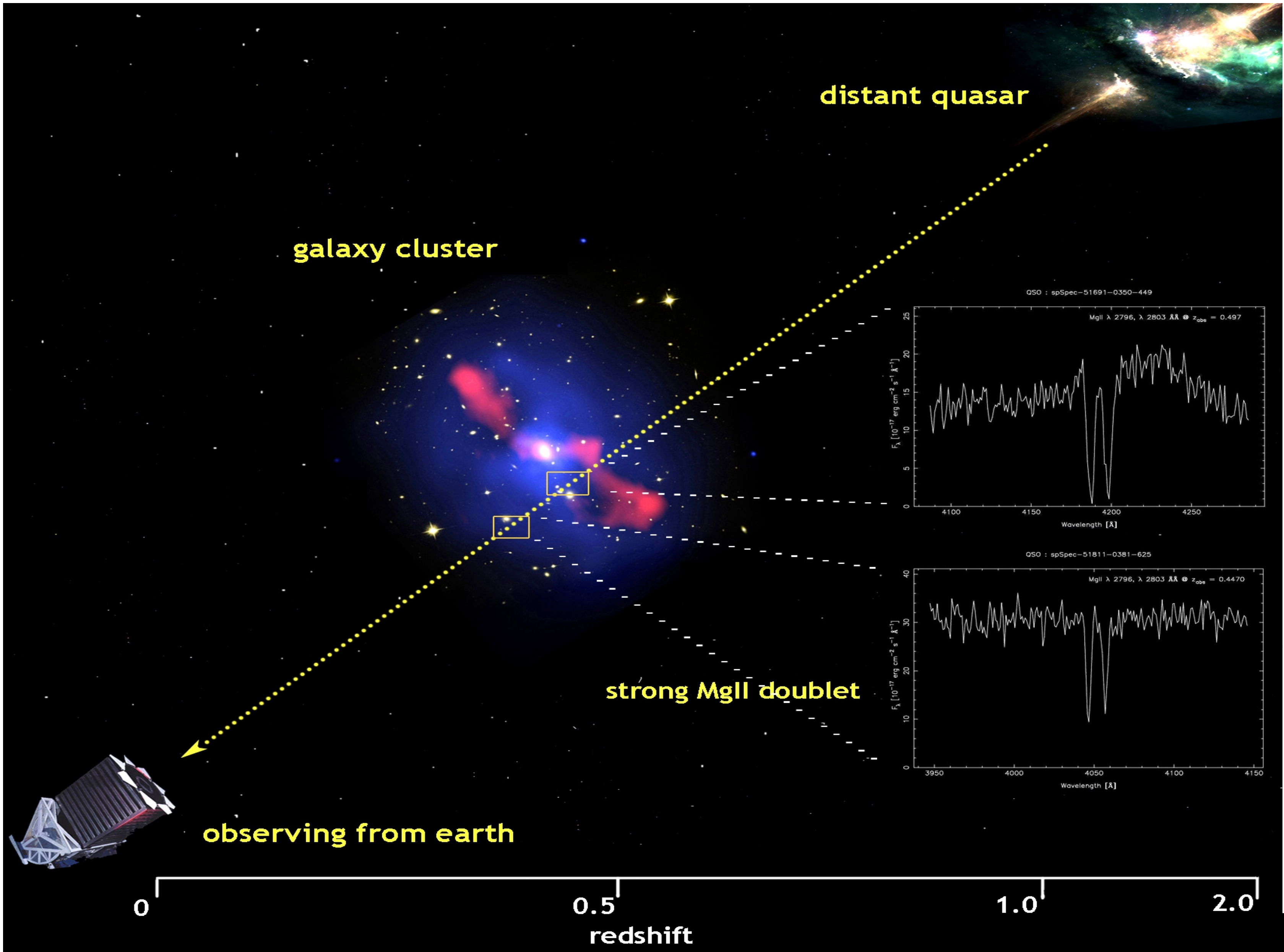
# THE GASEOUS STRUCTURE OF DARK MATTER HALOS

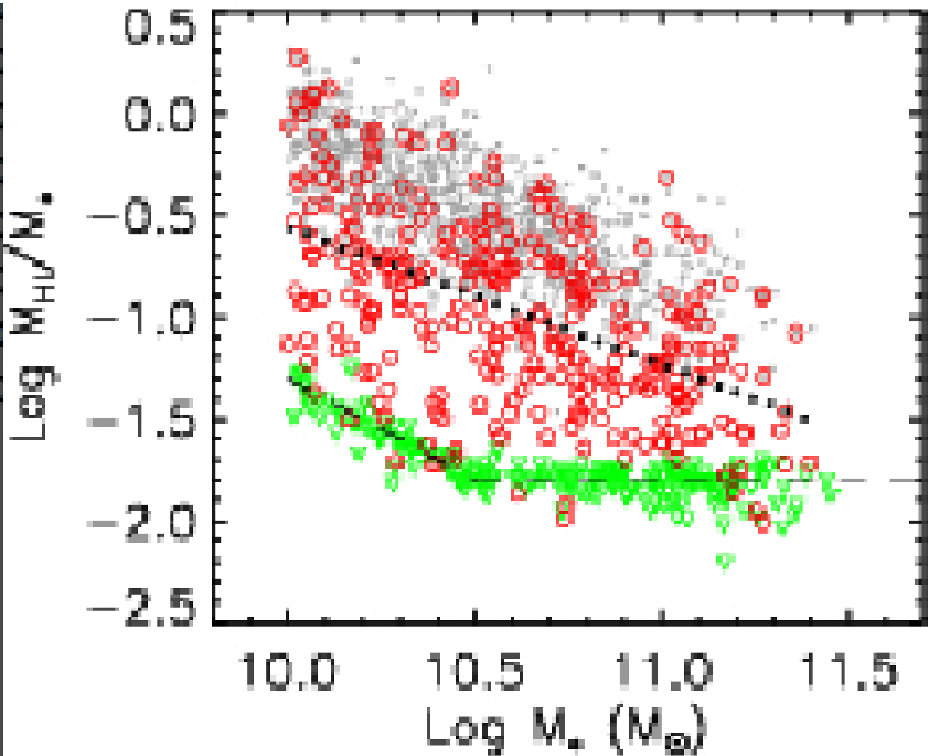




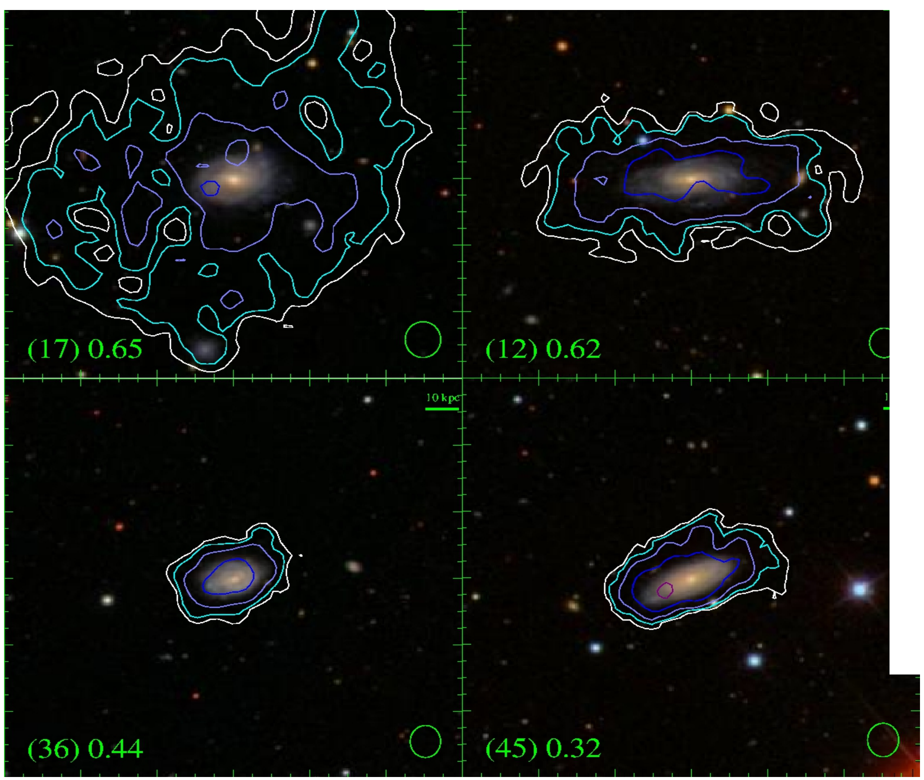
# QSOs probing the circumgalactic medium (CGM) : the properties of quasar absorption lines in the vicinity of galaxies of known redshift, mass, type, SFR, etc

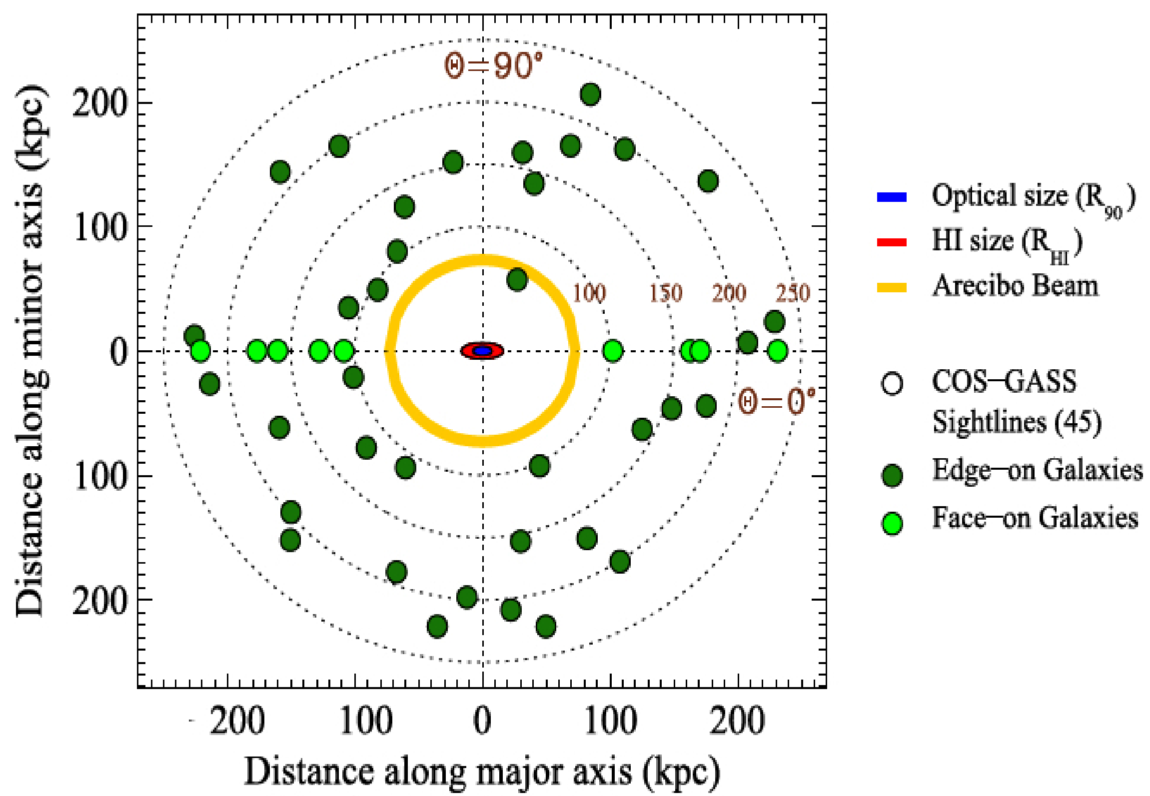


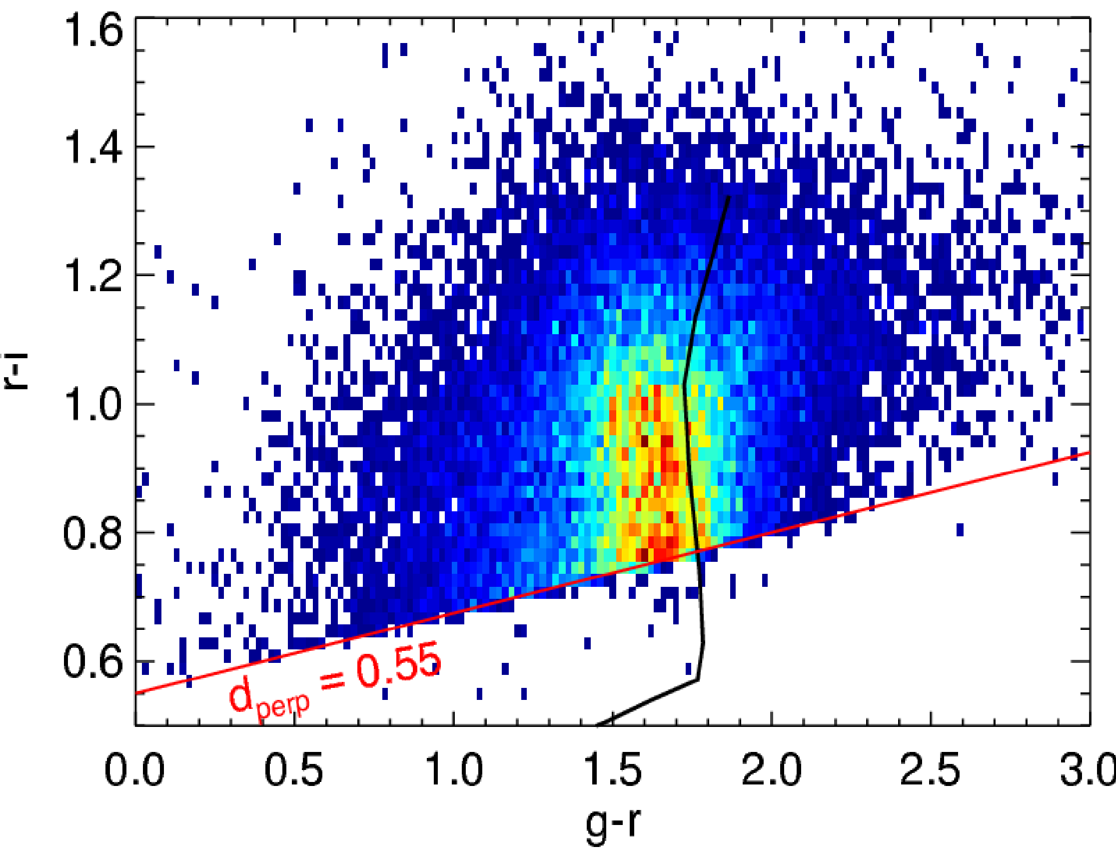


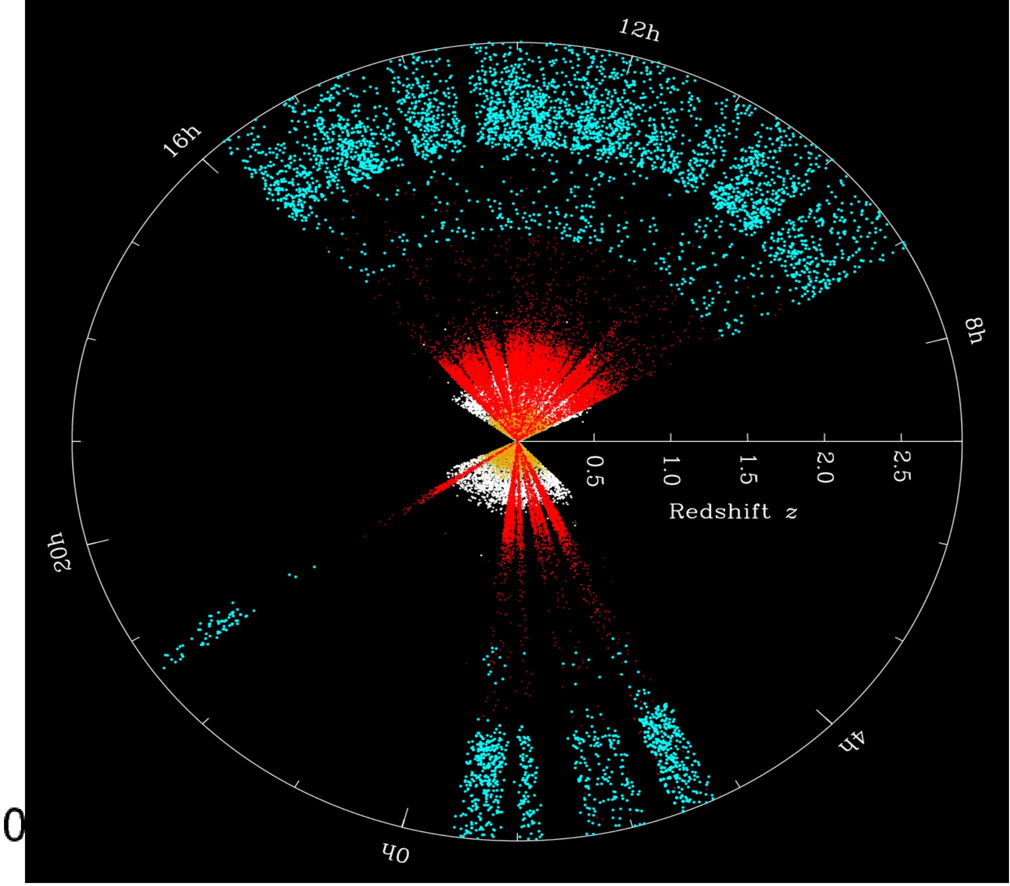

COS HST program to study the CGM around galaxies of known atomic gas content

in collaboration with S. Borthakur et al



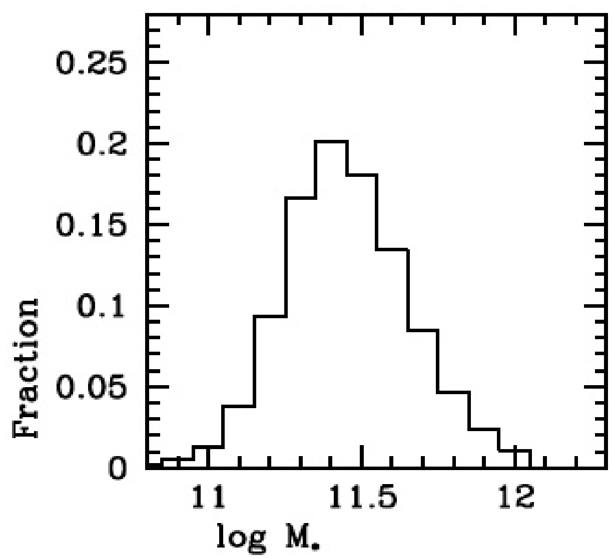



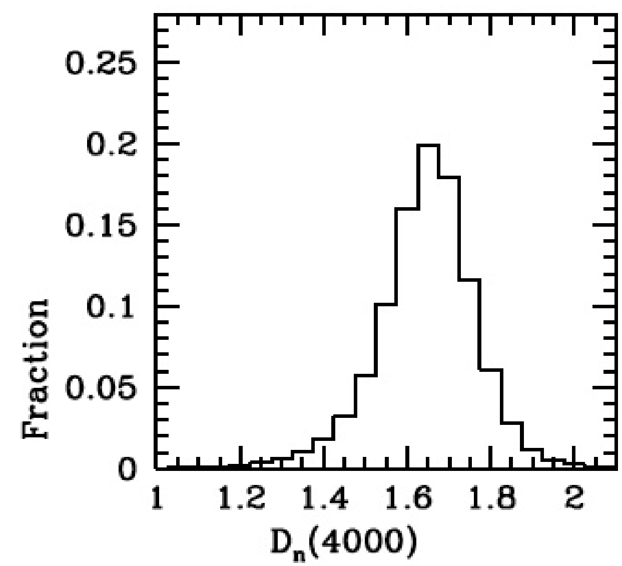



Ground-based telescopes
cannot access Lyman alpha
at low redshifts.
Tracers such as MgII used
Instead.

"CMASS" galaxy sample
from the BOSS (SDSS-III)
survey: massive galaxies
(log M*>11) with redshifts in
the range 0.4-0.8.

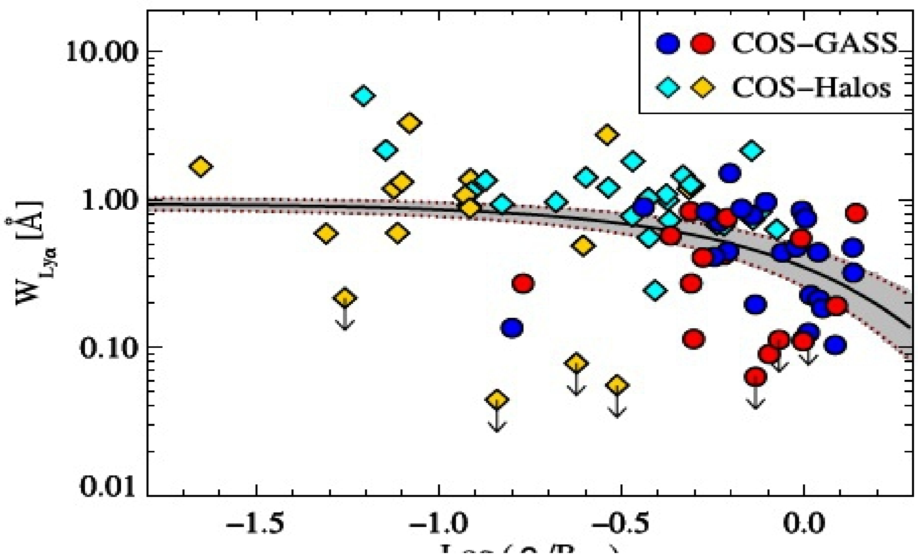


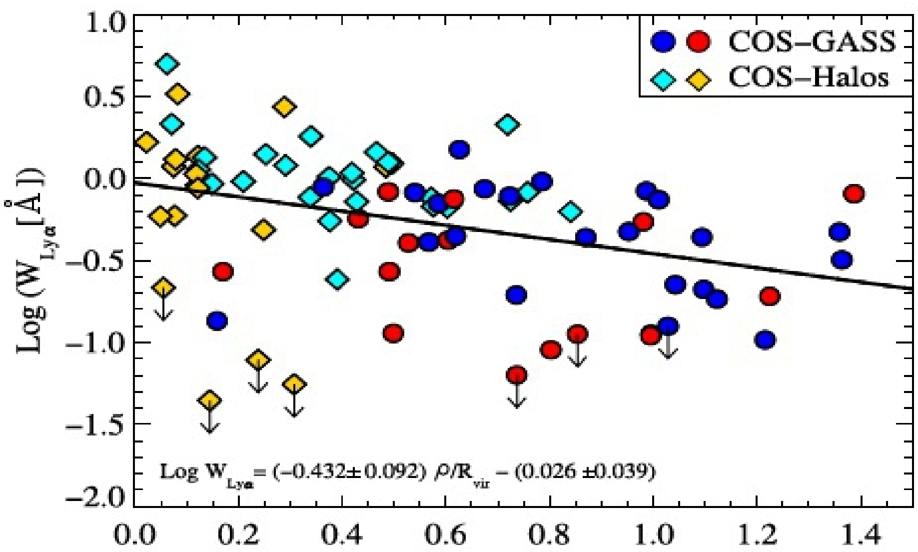



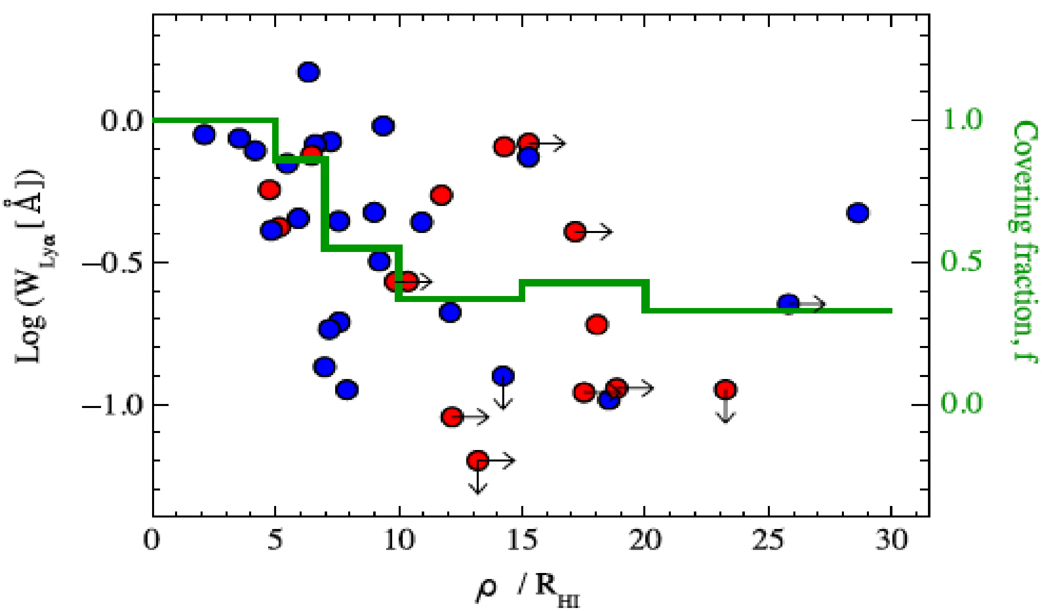
# MAIN RESULTS FROM COS-GASS

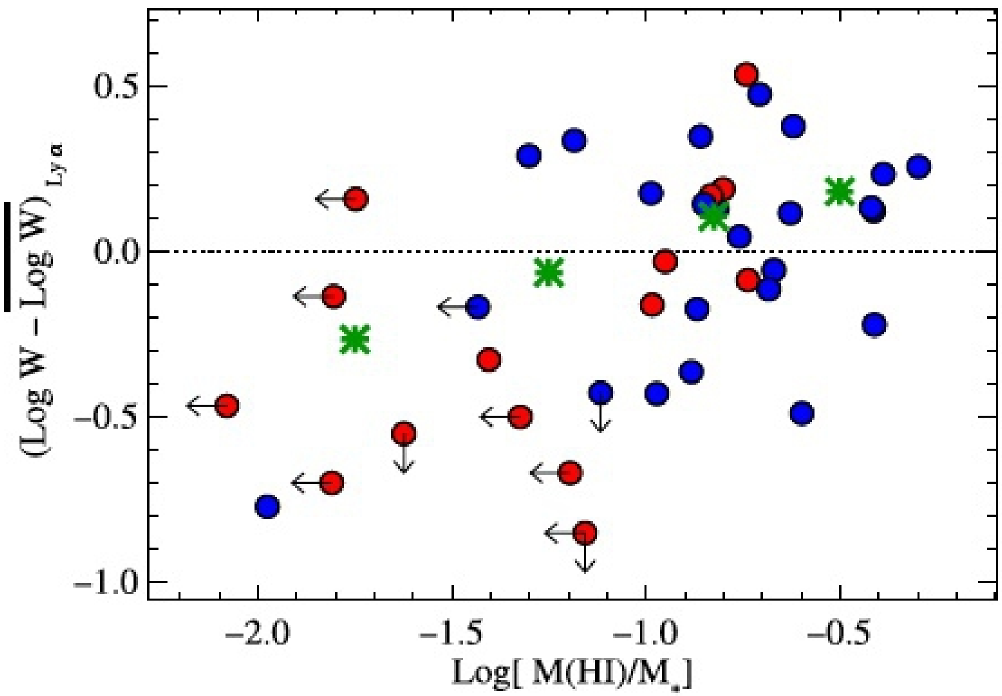
Borthakur et al 2015

1) Lyman alpha equivalent width decreases gradually as a function of radius out to the virial radius. “Covering fraction” of clouds is ~50% even at the virial radius.

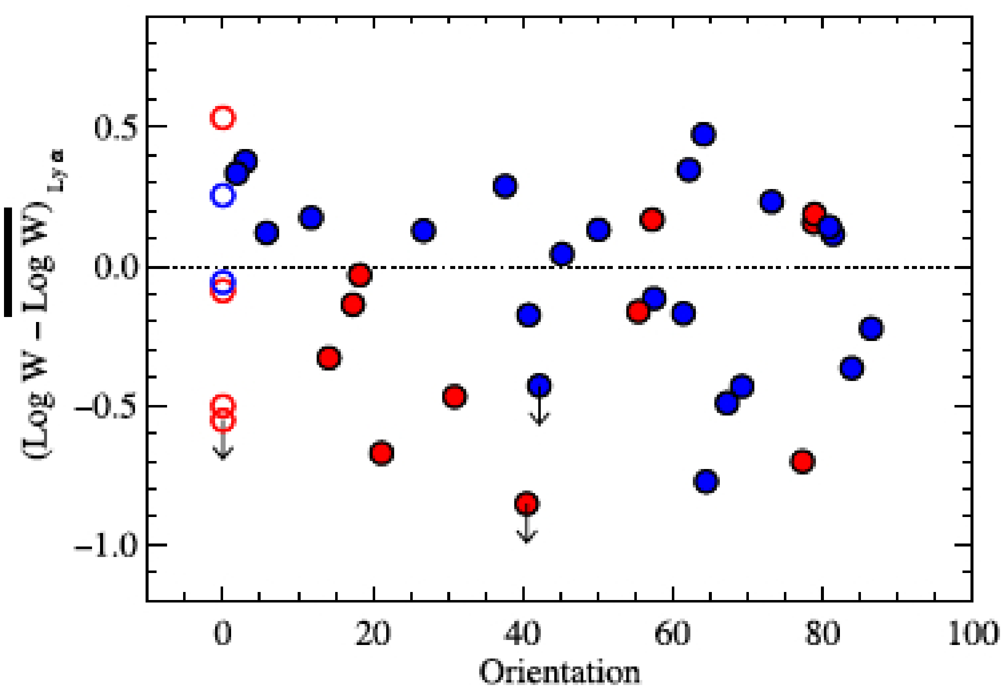


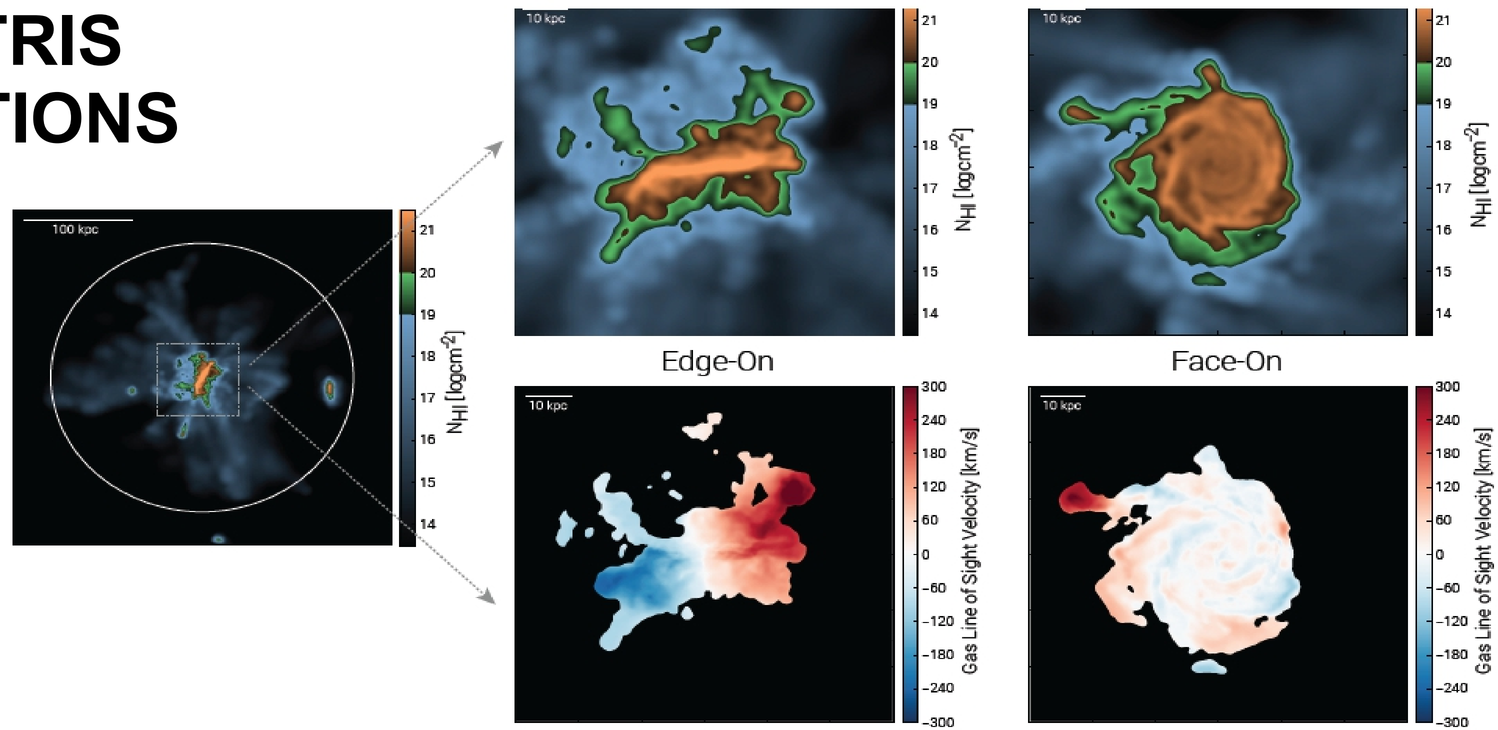


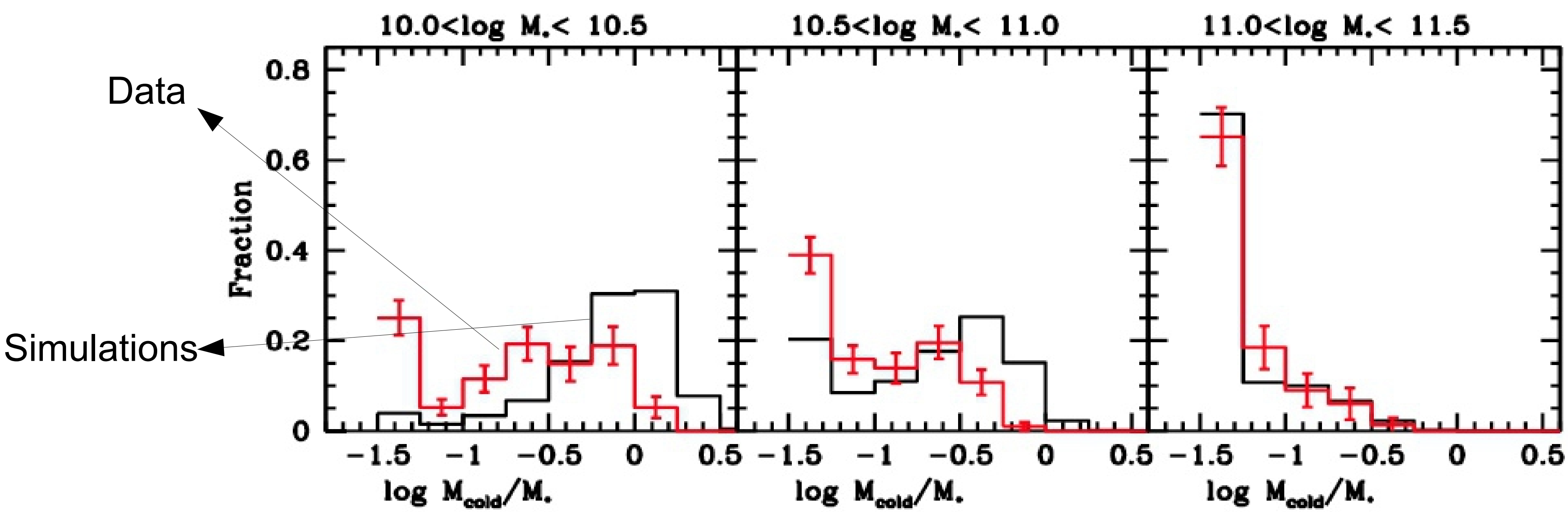

Significant correlation between Lyalpha EQW in the outer halo and HI gas mass fraction in the disk. Stronger than the correlation with SFR/M*



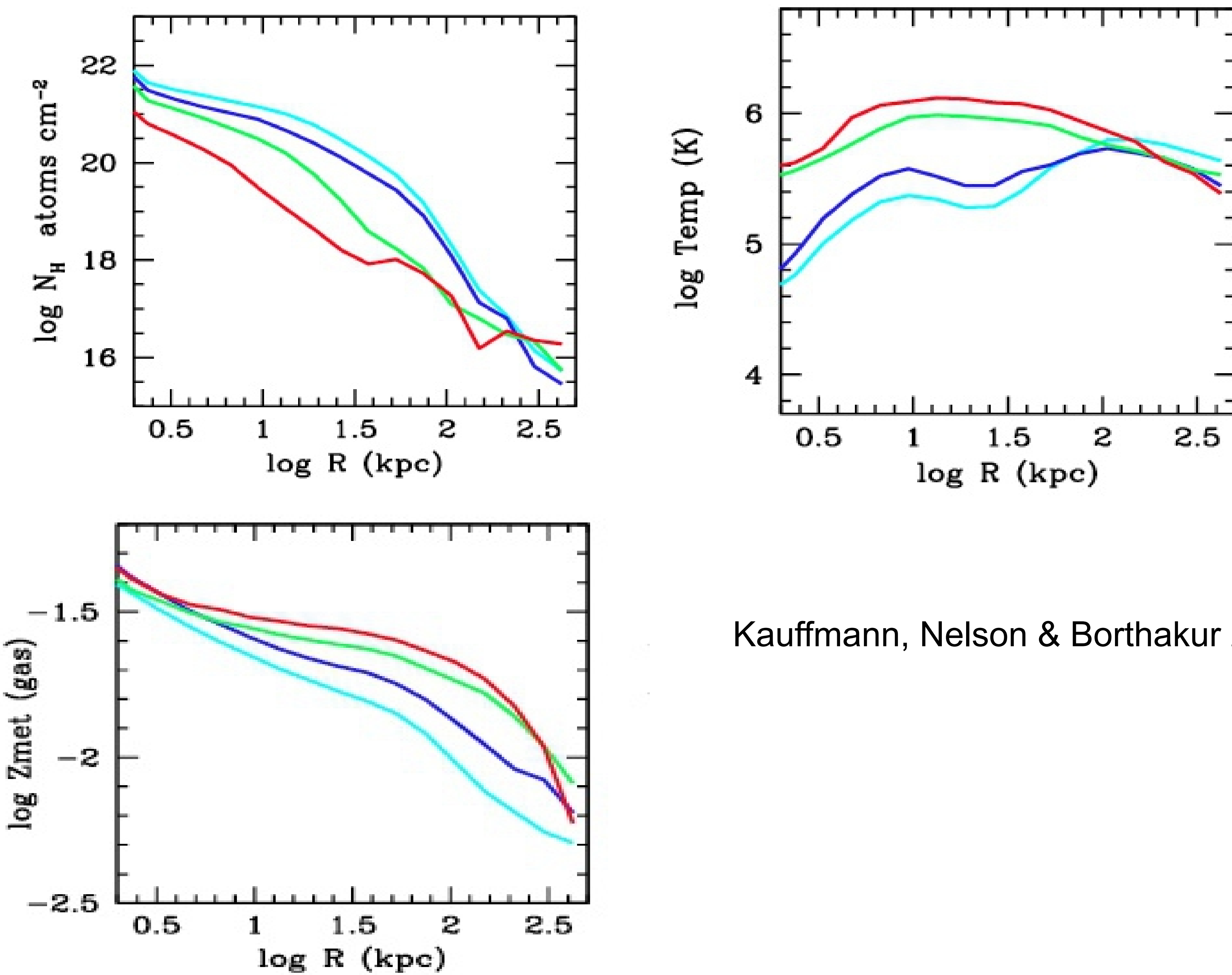

No correlation between Lyalpha EQW in the outer halo and orientation with respect to the disk

# COMPARISONS WITH ILLUSTRIS SIMULATIONS



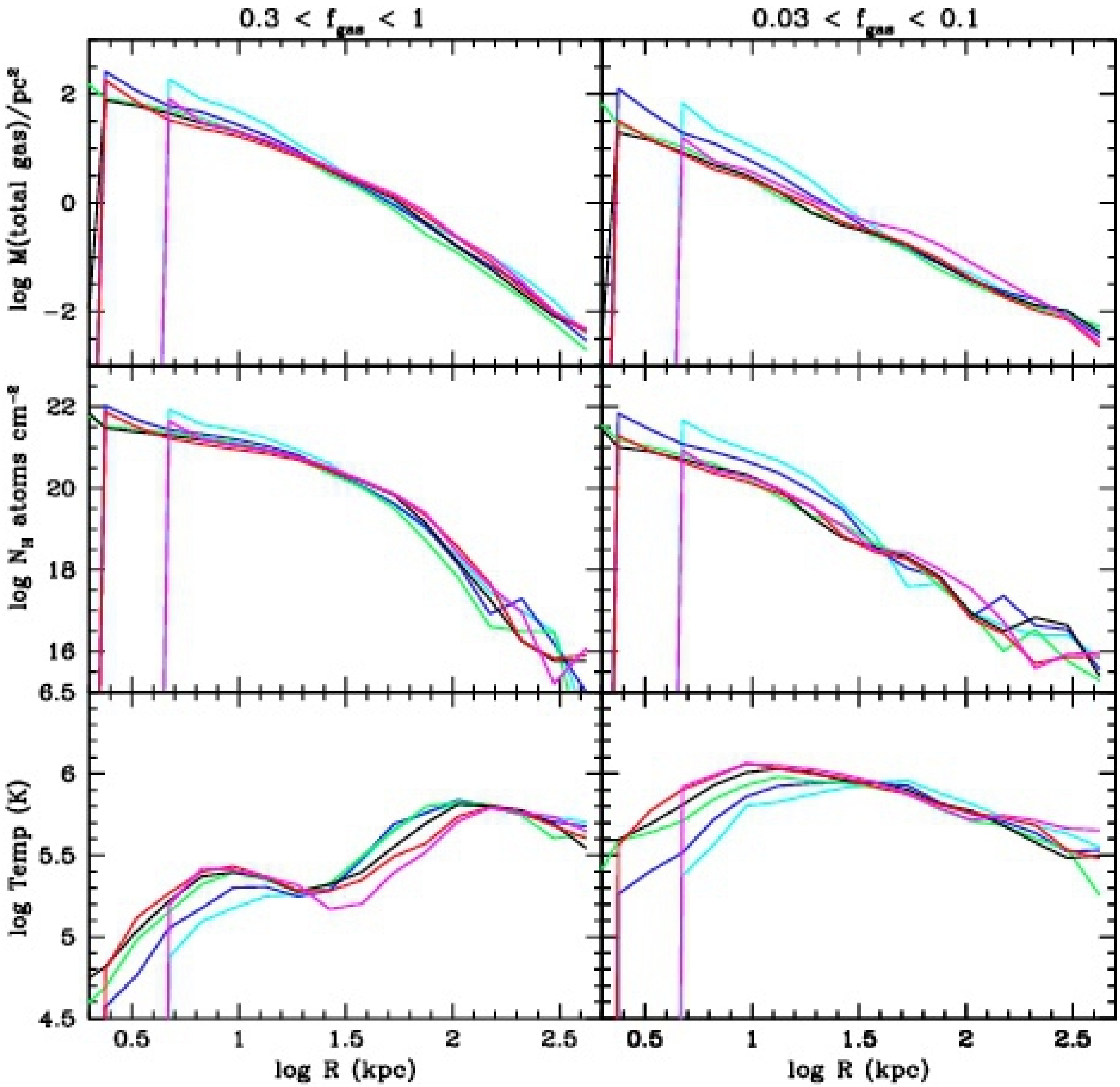



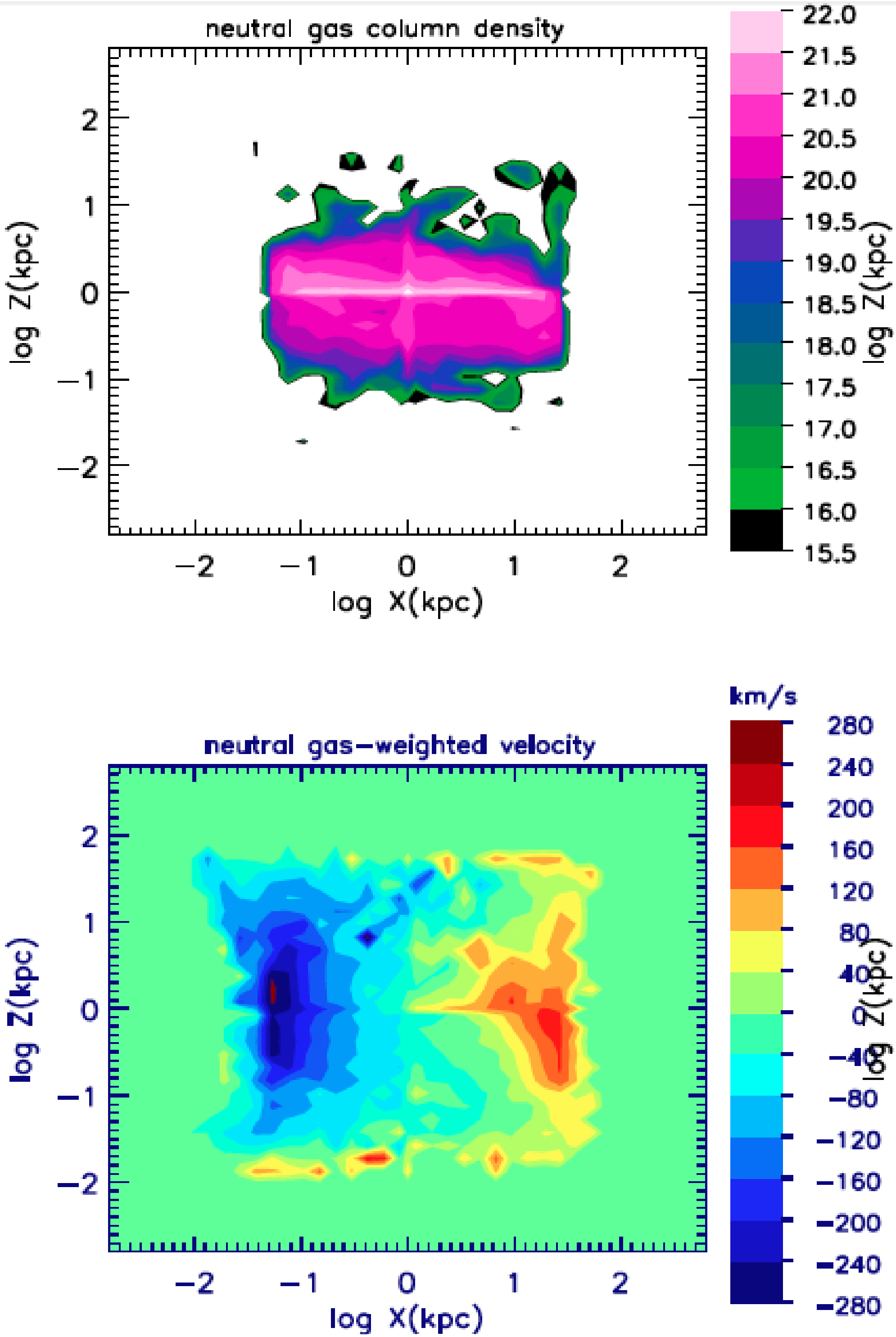
Correlations in average CGM properties (temperature, metallicity, neutral hydrogen column) with the gas mass fraction in the inner disk, persist out 100 kpc .




Kauffmann, Nelson & Borthakur 2016

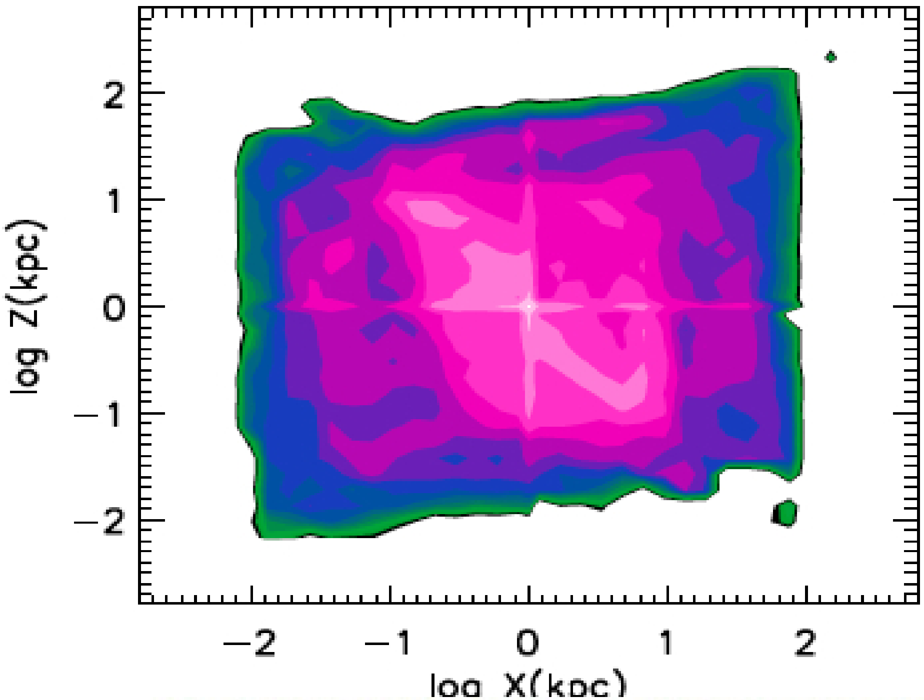
# Correlations in CGM properties with disk orientation only present at radii less than around 30kpc.

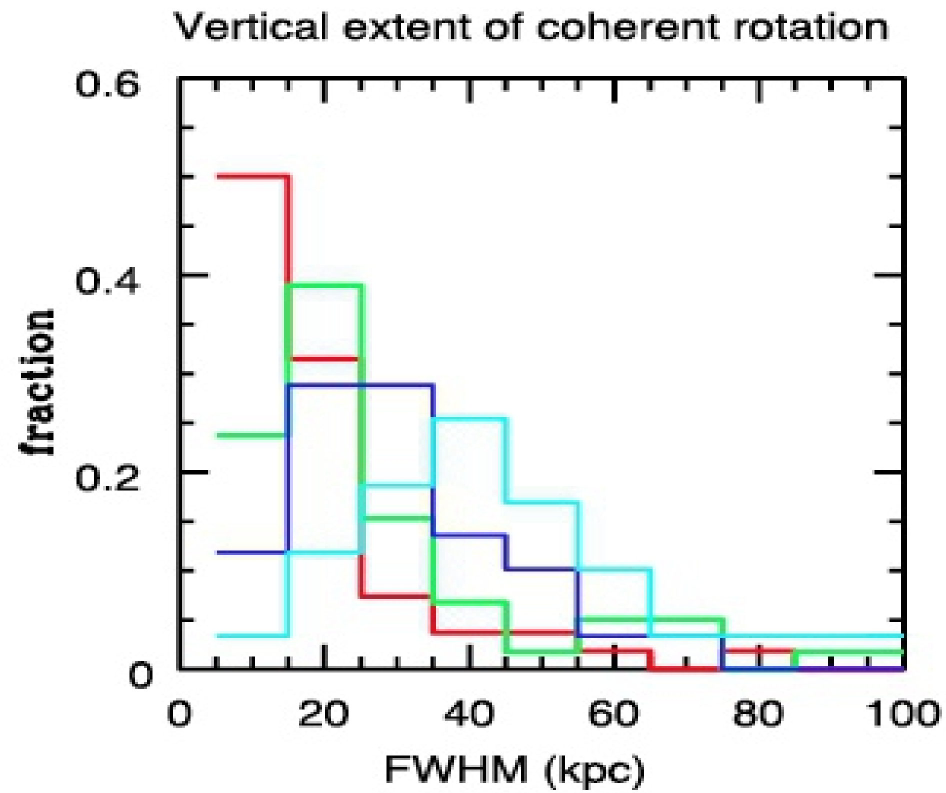


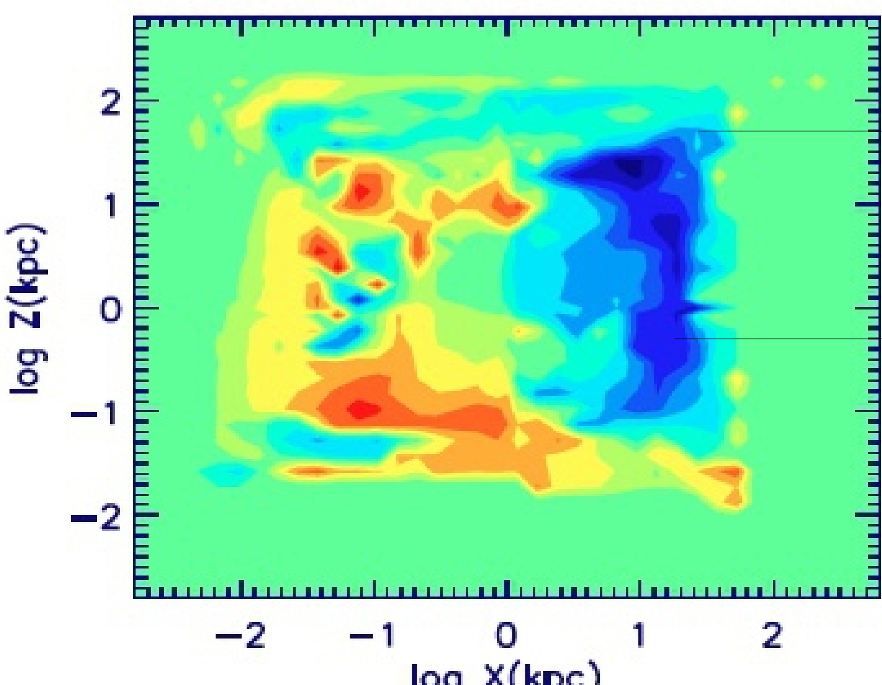



Gas around a galaxy similar to the Milky Way in gas—to-stellar mass ratio (10%)

# Gas around the most gas-rich galaxies (>30%)

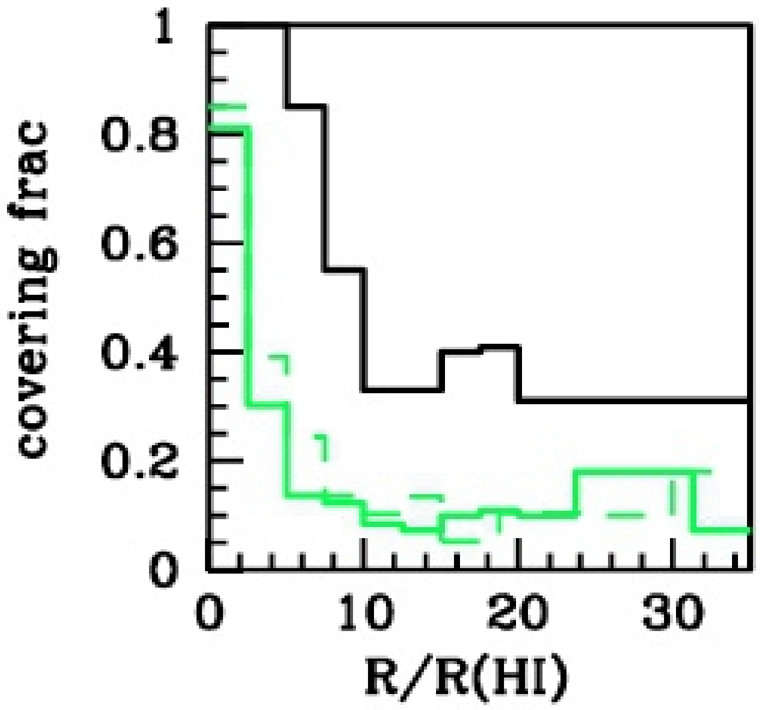


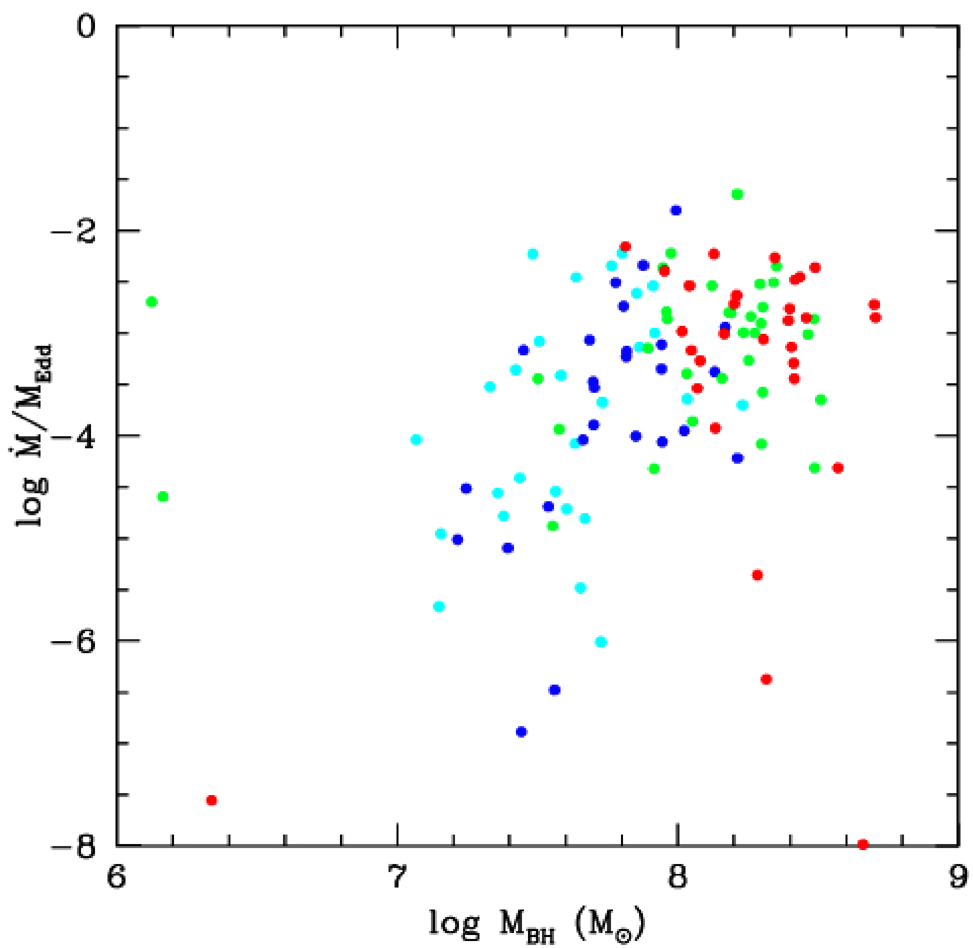




Coherence scale of the rotation

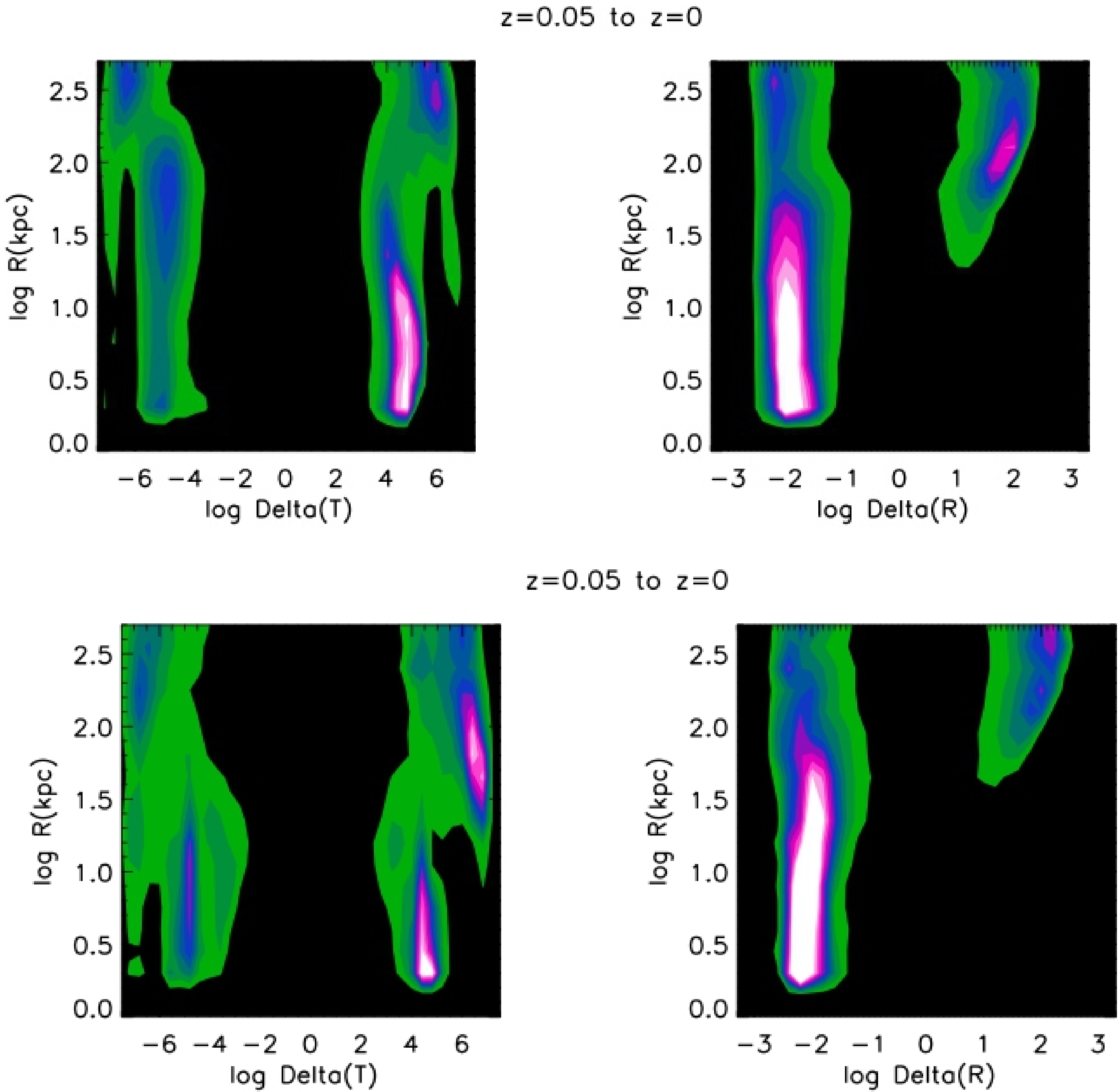
# Covering fraction of neutral gas too low in Illustris compared with data: effect of AGN feedback processes



Heating/cooling

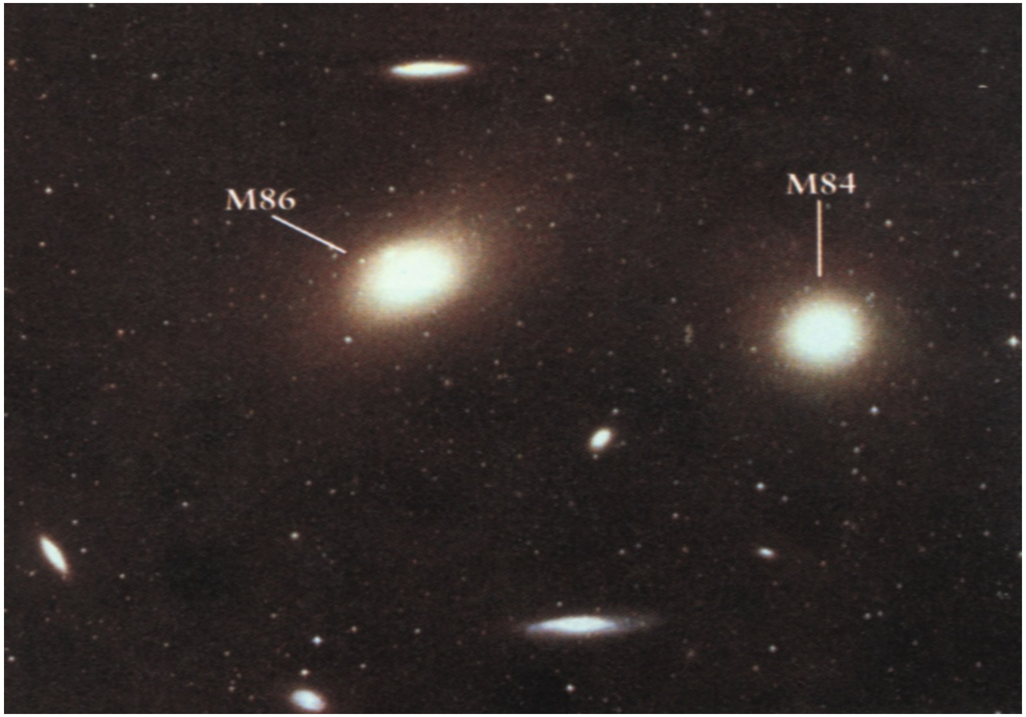
Inflow/outflow

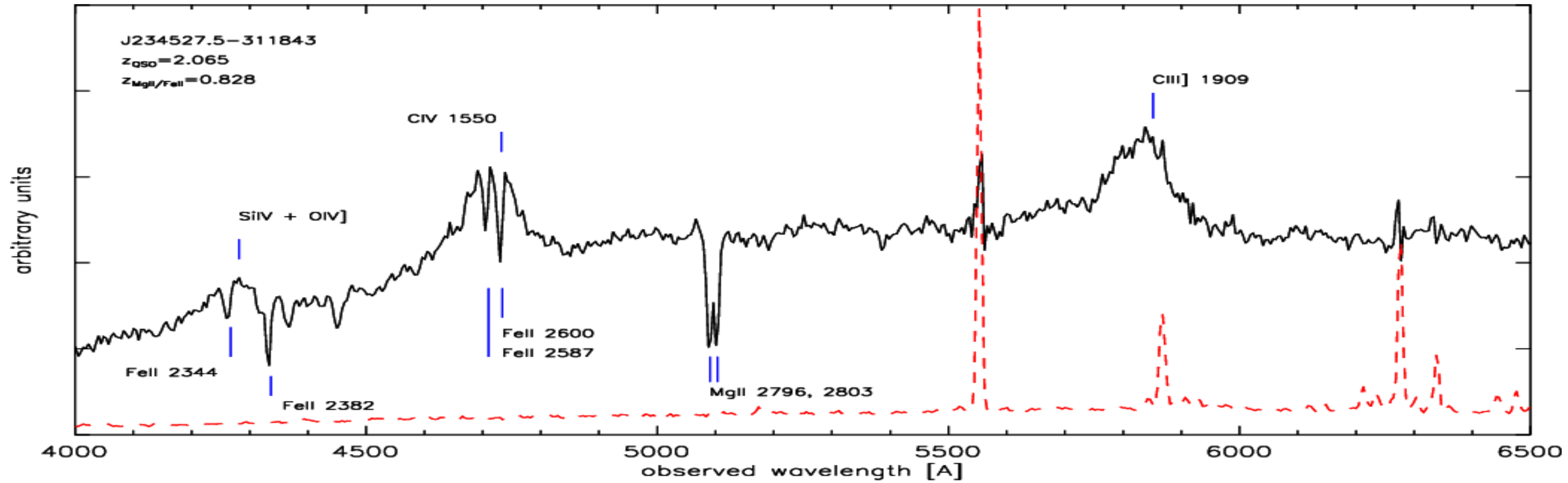



Gas-rich galaxies

Gas-poor galaxies

# MgII absorption lines around the most massive galaxies



Solar metallicity

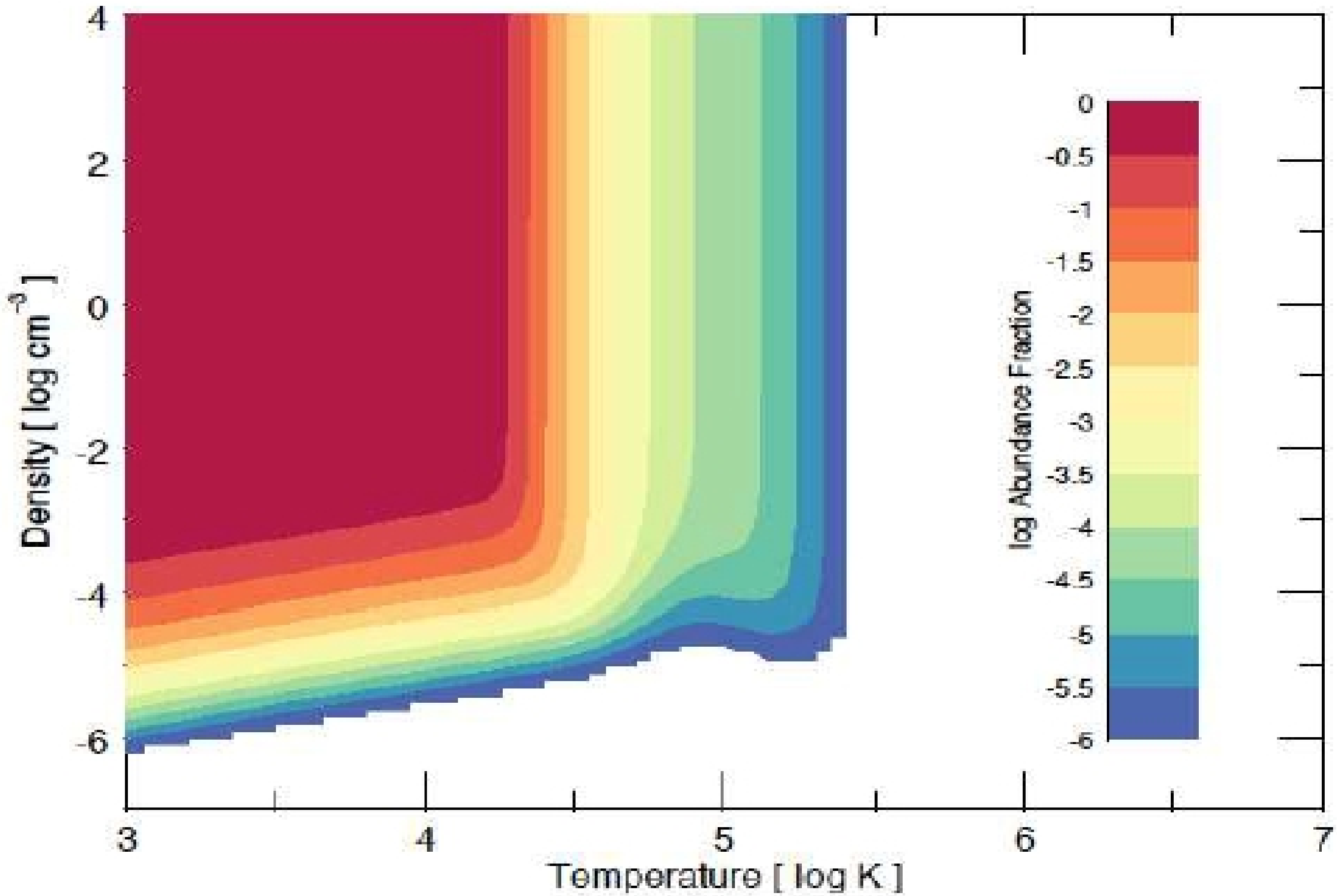
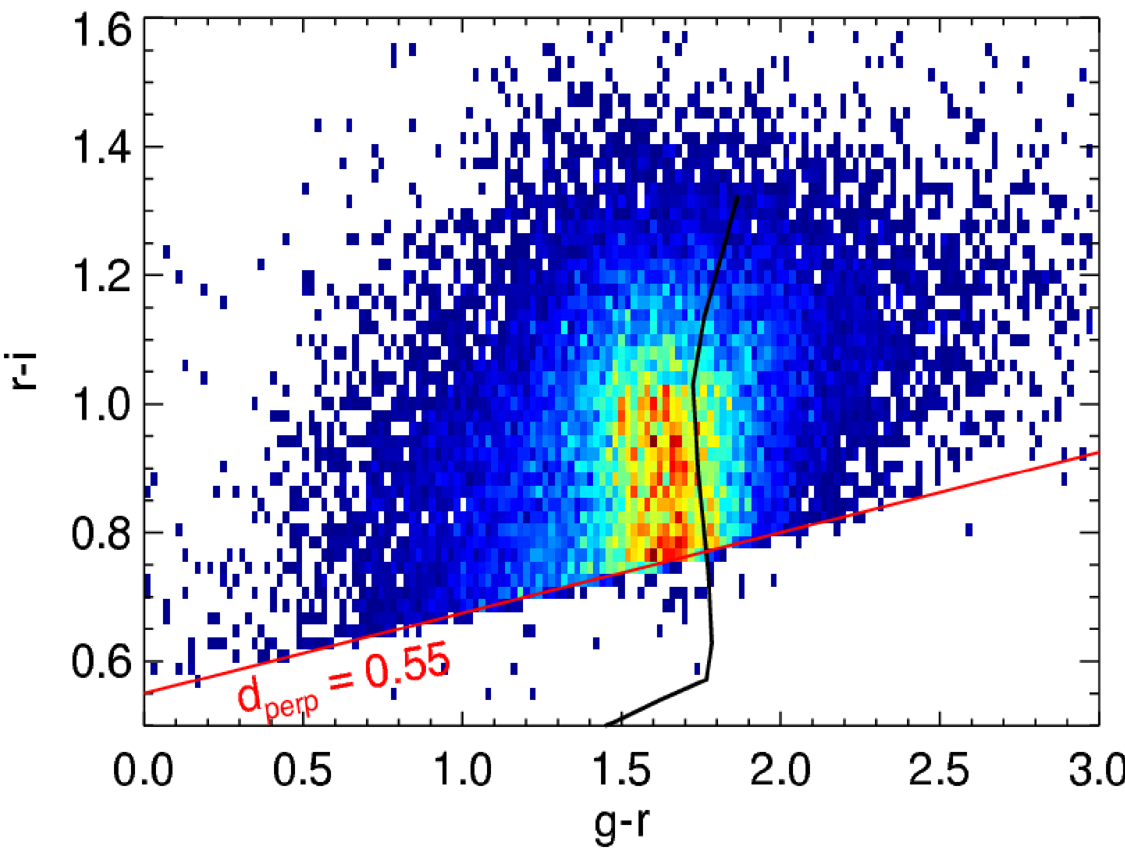
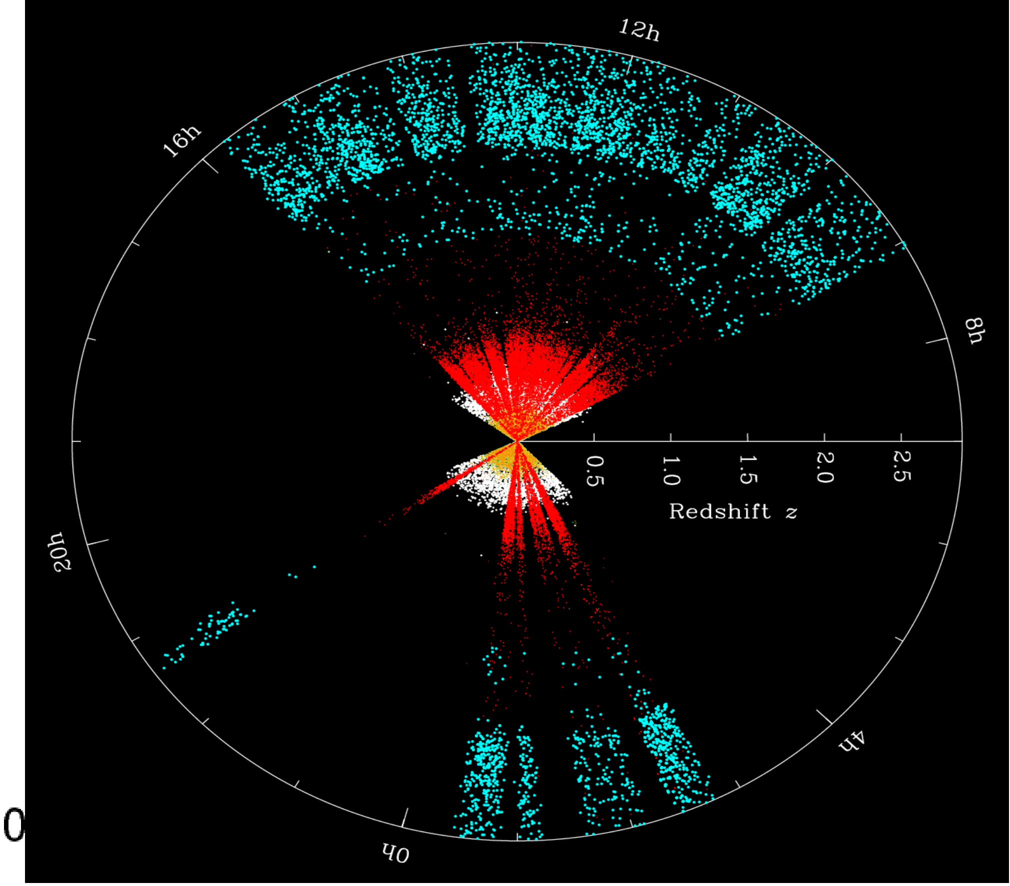
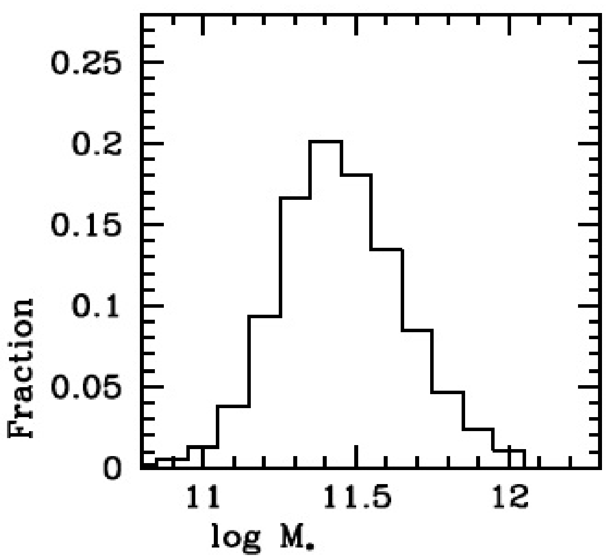


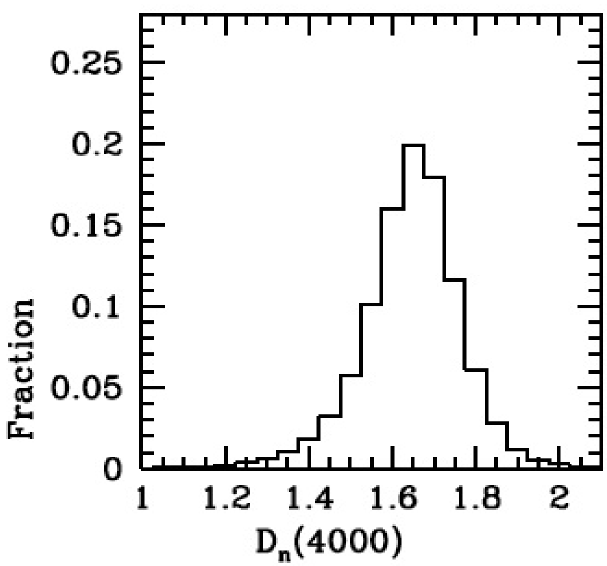

**Figure 8.** The fraction of Magnesium in the form of Mg II as a function of density and temperature as predicted by CLOUDY in single-zone mode, including both collisional and photo-ionization in the presence of a UV background (see text).



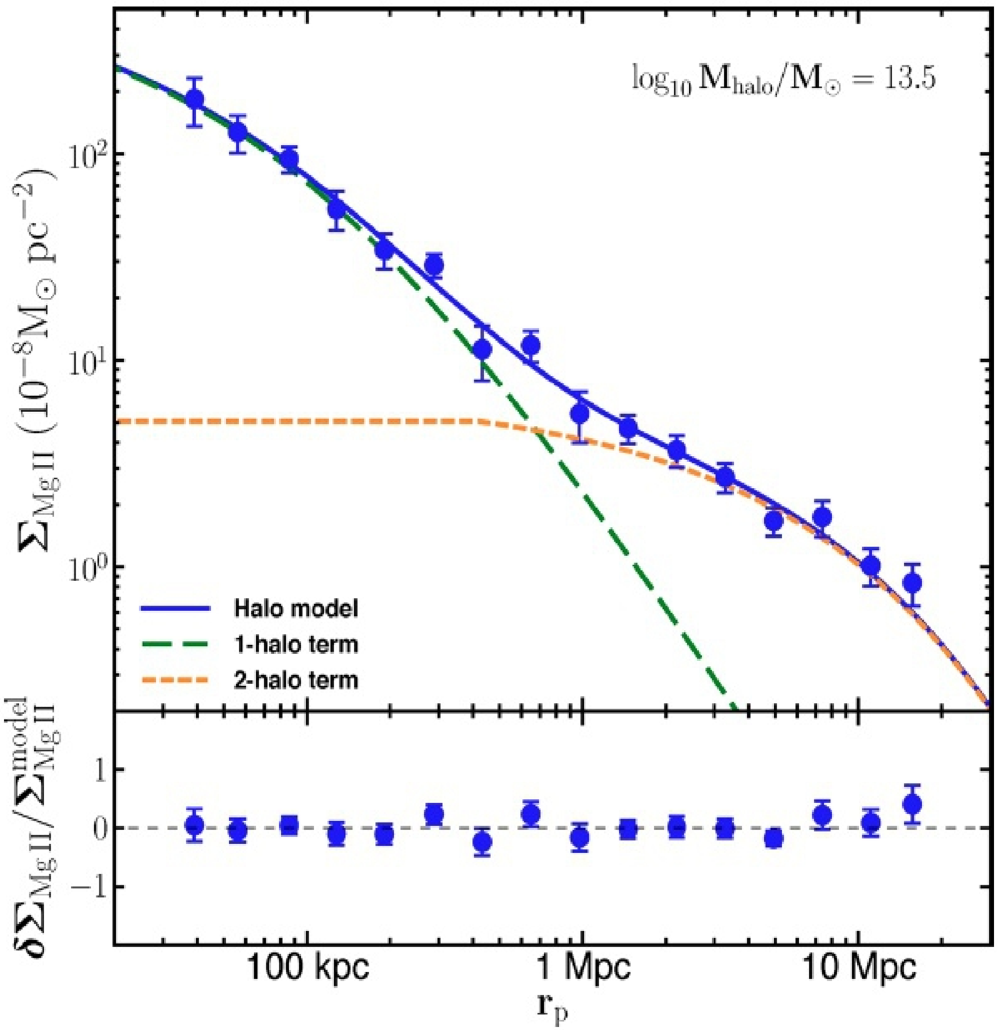




"CMASS" galaxy sample from the BOSS (SDSS-III) survey: massive galaxies (log M*>11) with redshifts in the range 0.4-0.8.

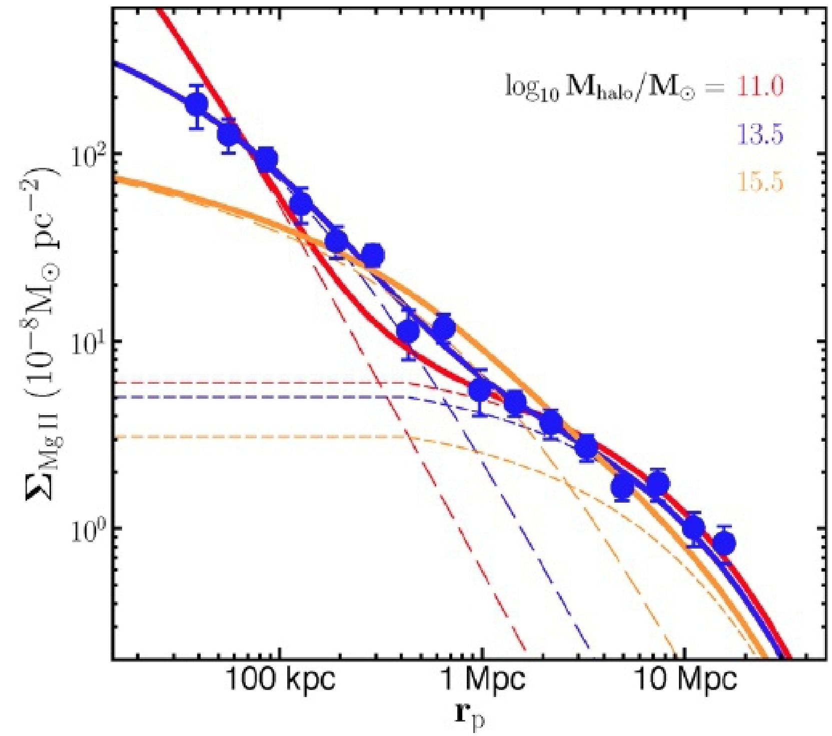


# Zhu & Menard (2014): the cross correlation between MgII systems and massive galaxies



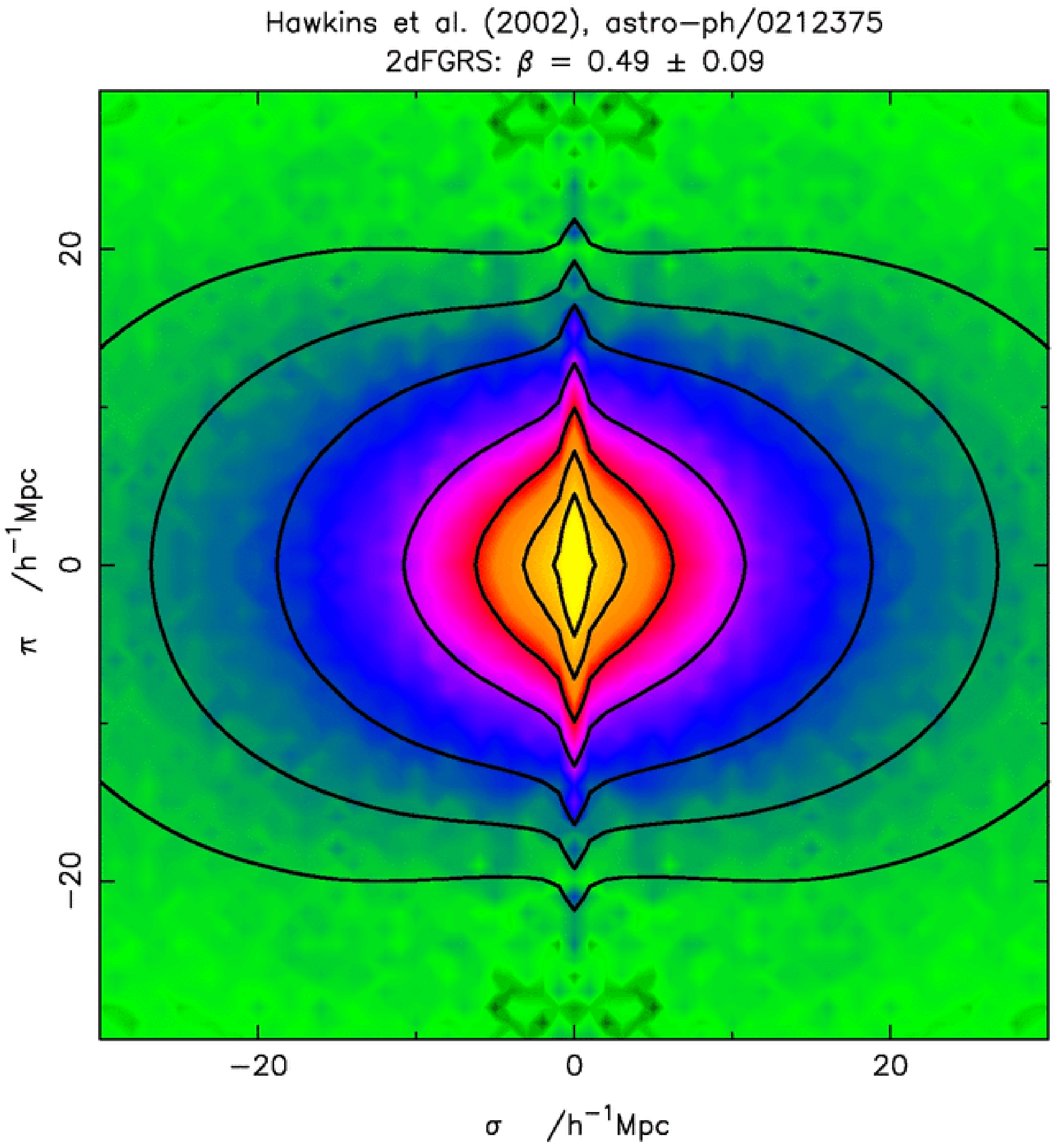

igure 5. The best fitting halo model. Upper panel shows the best fitting halo model, decomposed into one-halo and two-halo terms. Lower panel shows the ractional residuals. The halo model has three parameters: average LRG host halo mass $M_{halo}$, Mg II gas-to-mass ratio in the host halo $f^{1h}_{Mg\,II}$, and mean Mg II as-to-mass ratio of all galaxies $f^{2h}_{Mg\,II}$.




## Model:

Gas distribution is assumed to trace the dark matter distribution exactly, i.e. the gas density profile in a halo of mass M has the same NFW shape as the dark matter up to a normalization factor **f_gas(M**_halo). This model is shown to provide an adequate fit to the data if the average host halo mass of the galaxies is 10^13.5 **M⊙**.

# Evaluate clustering as a function of projected radius and velocity space separation.



Kauffmann et al 2017

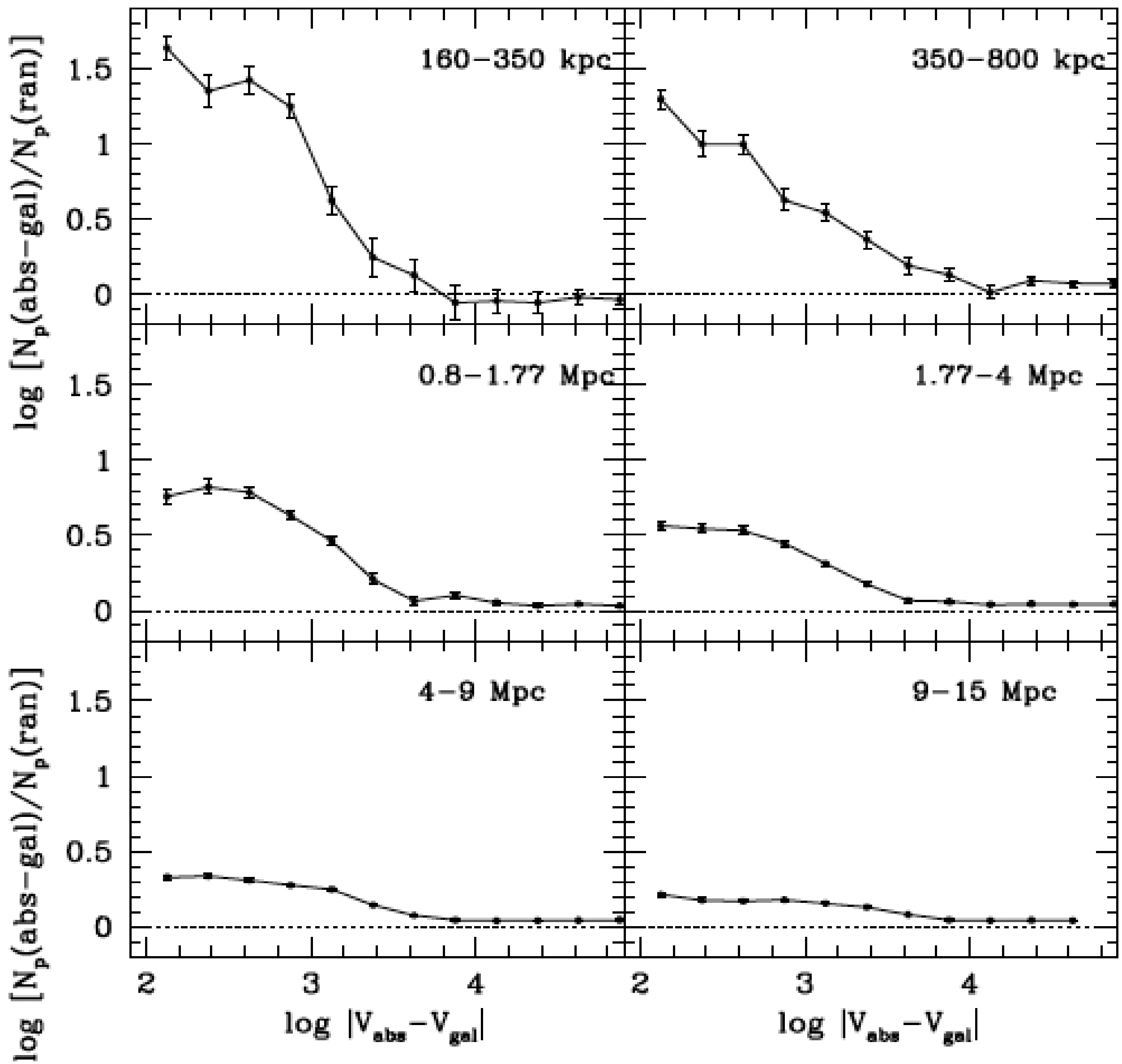
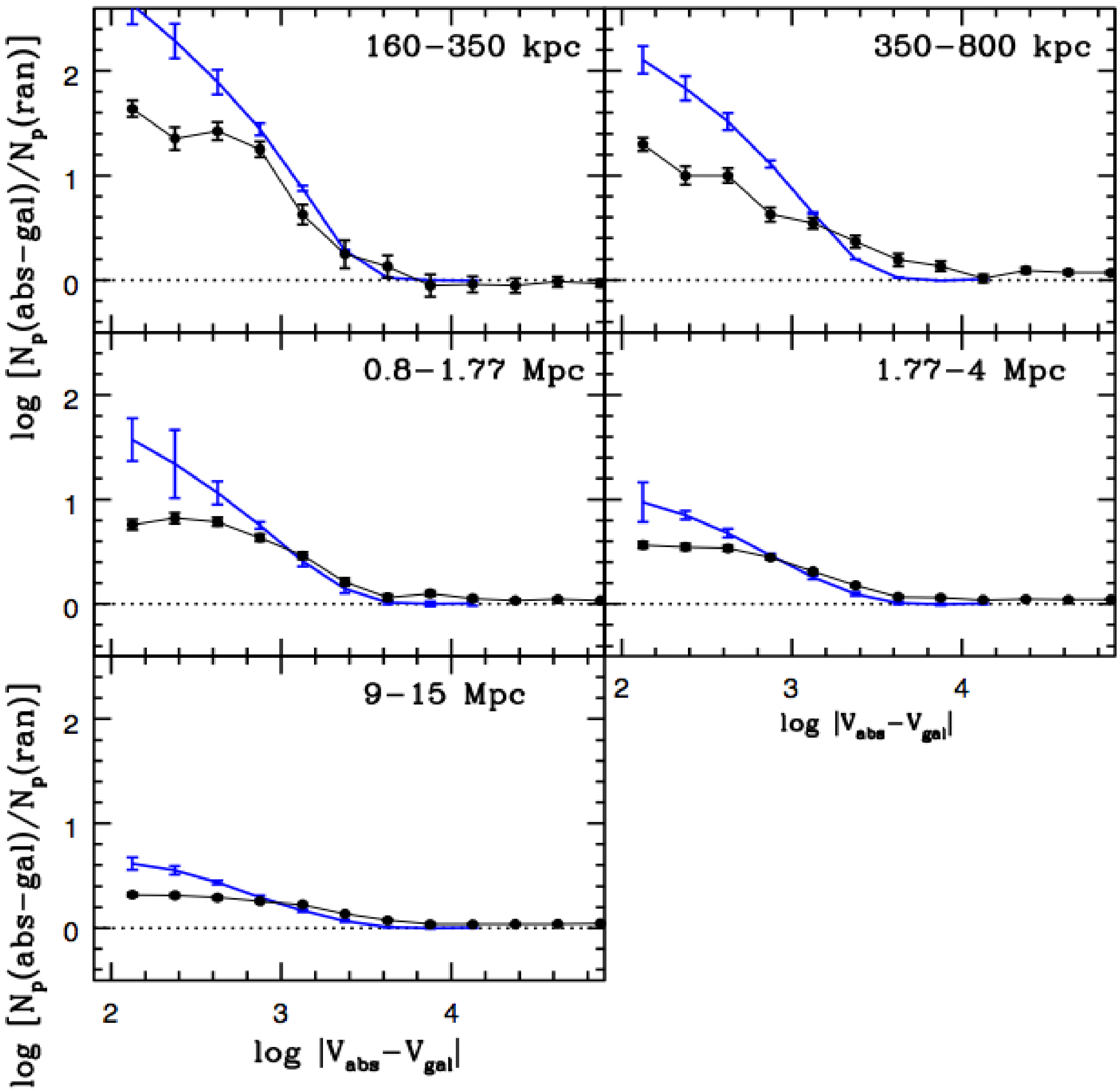
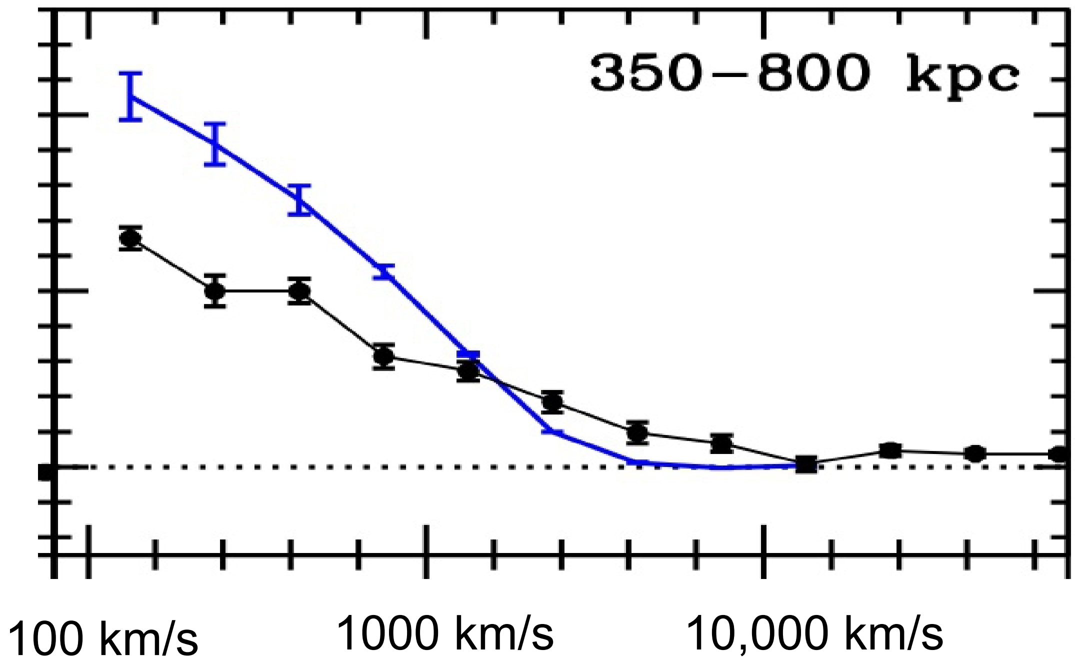


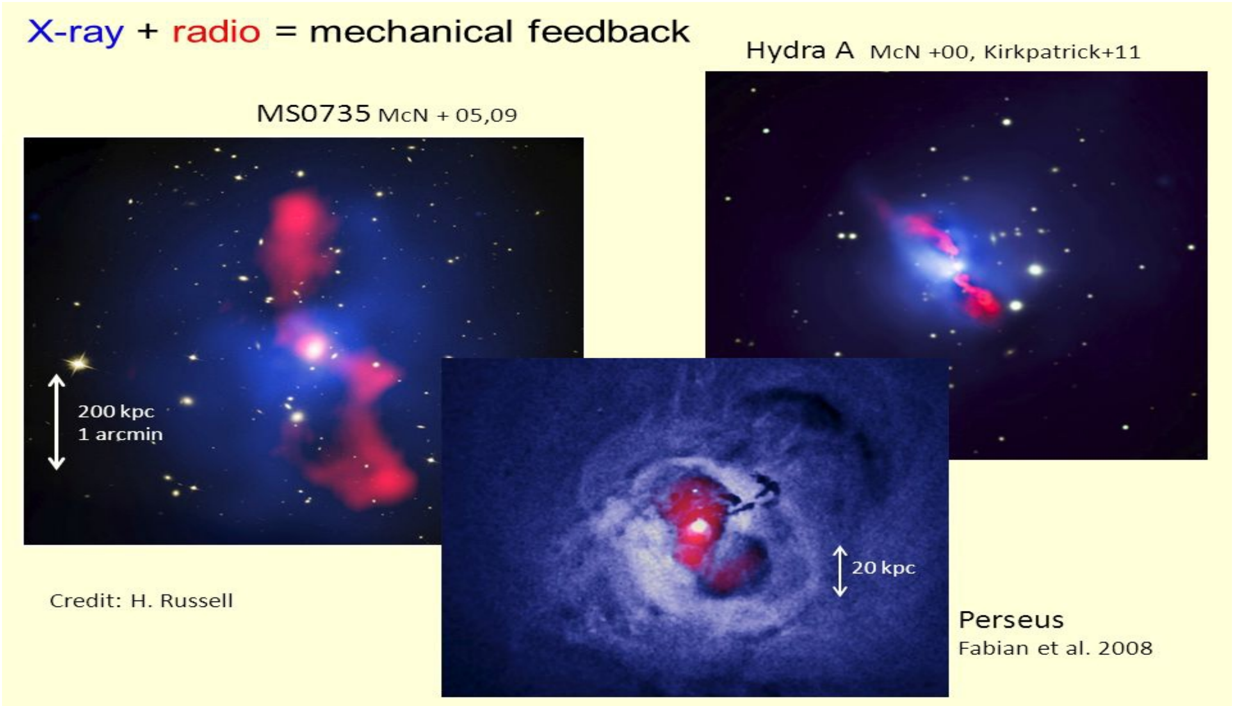

**Figure 3.** The logarithm of the number of galaxy-absorber pairs in the full CMASS sample divided by the average number of galaxy-absorber pairs in the random catalogues is plotted as a function of the absolute value of the velocity separation. Results are shown in 6 different bins in projected radius $R_p$.

**Compared to model:** MgII absorbers trace dark matter around CMASS-type galaxies in the Millennium Run simulation at z=0.55



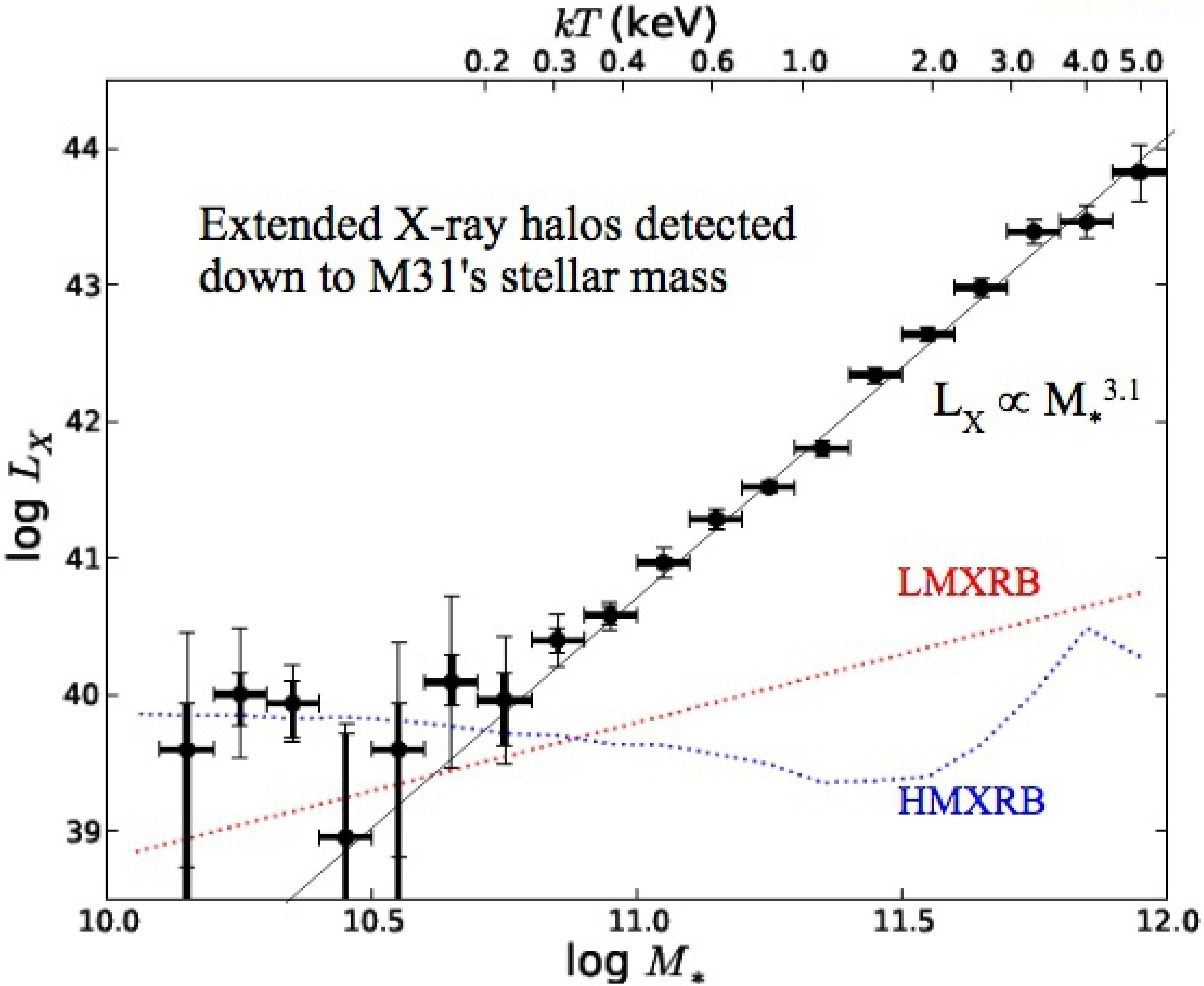
# Evidence that gas has been pushed out of dark matter halos



# Stacked Rosat X-ray signal from LBGs

Anderson et al 2015



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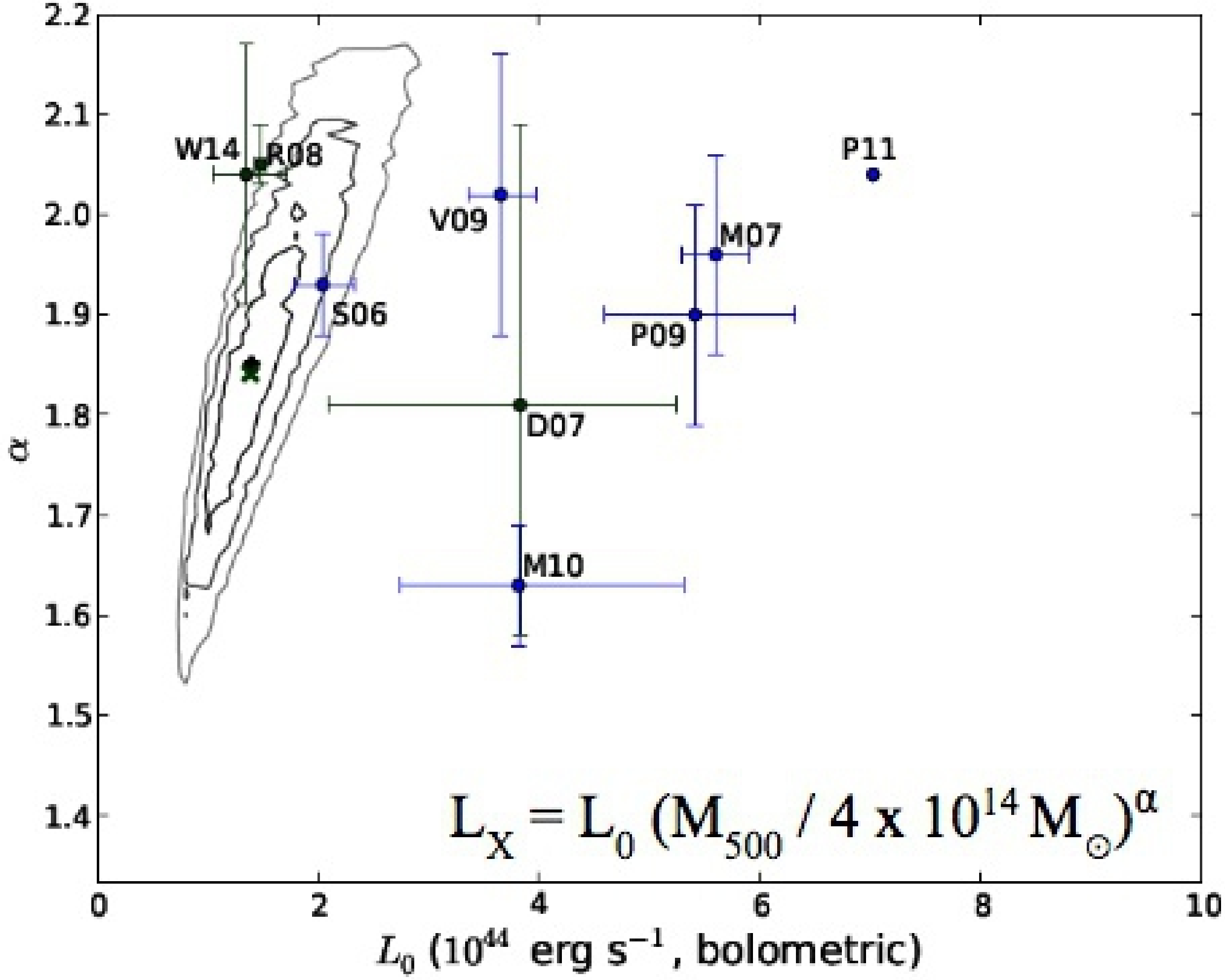
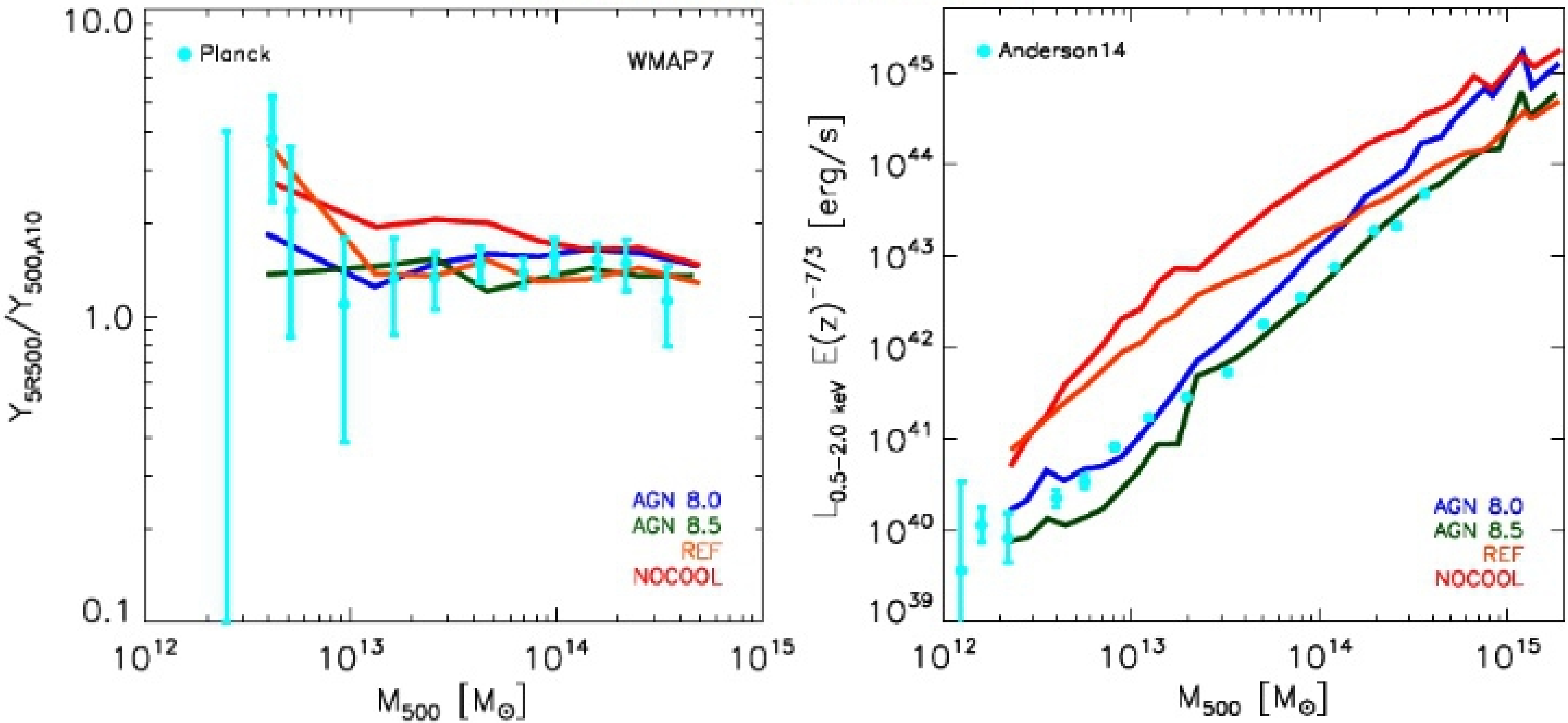



Anderson et al 2015

$\alpha = 4/3$ is expected for self-similar halos with constant baryon fraction

X-ray luminosity grows much faster with mass than this

Le Brun, McCarthy & Melin 2015




AGN feedback models provide better match to X-ray data

Observational data on the circumgalactic gas provides a potentially powerful means of constraining feedback processes in galaxy formation.

Complexity arises because halo gas spans a wide range in temperature and density, so multiple tracers are necessary for full understanding.

Because of the complexity of the feedback processes, hydrodynamical simulations are required to interpret the observations. Ideally, the comparisons should involve multiple simulations with different physical prescriptions.

We also need to move beyond zero'th order characterizations of gas properties (e.g. covering fraction, column density), to measures that can probe kinematics of the gas with respect to the central galaxy.