Links of AGN with environment through cosmic time

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ABSTRACT: We investigate two methods probing the environmental dependence of AGN activity. We first measure the prevalence of AGN in a protocluster at z~1.62. We find that the AGN fraction is enhanced relative to the field; a reversal of the suppression of AGN found in clusters at low z. Complementary to this case study, we statistically measure the typical large-scale environments of AGN using the two-point correlation function. We find that AGN prefer group-like environments of DM halo masses of 10^{12-13} $M_\odot$ regardless of z and Lx.

1. AGN-environment connection

★ Two methods of probing environmental dependence of AGN as a function of z:

- **Fractions of galaxies hosting AGN in dense environments and field**
- **Large-scale environment preferences of AGN through correlation functions**

★ In order to probe the high-z galaxy density field in which AGN are embedded, we require data sets that provide a unique combination of depth and area. The UDS and COSMOS fields probe L* galaxies out to z~4 over large scales (>100x100 comoving Mpc).

★ AGN are identified using deep Chandra and XMM observations.

2. AGN activity in a high-z protocluster

★ AGN activity is suppressed in clusters at low z. In Krishnan+17, we show that this turns into an enhancement at high z (see **Figure 1**).

★ We find a factor of ~2x AGN enhancement in a z~1.62 protocluster (Papovich+10, Hatch+16).

★ The AGN fraction among massive galaxies (M*> 10^{10} $M_\odot$) in the protocluster is 17% vs 8% in the field.

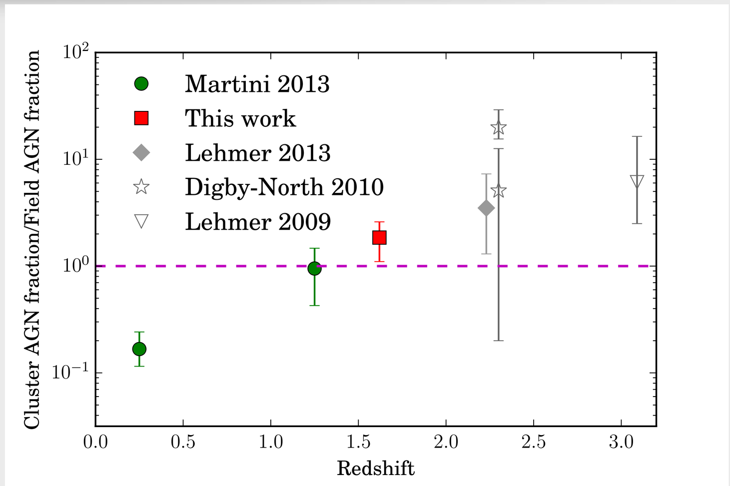

Figure 1: *Cluster AGN fraction relative to field AGN fraction as a function of redshift (Krishnan+17). There is a reversal in the local anti-correlation after z > 1.25. The magenta dashed line indicates an equal cluster and field AGN fraction.*

★ The overdensity is concentrated in the centre of the protocluster, of which half is due to the overdensity of massive galaxies in the centre.

★ AGN merger rates are higher in protocluster than field, but other properties are similar.

3. Two-point correlation functions (2pcf)

★ 2pcf can measure the clustering of a sample using excess numbers of pairs above random.

★ Simplest form of 2pcf is shown by **Figure 2**: $w(\theta) = GG(\theta)/RR(\theta) - 1$

★ A reliable auto-correlation function (ACF) requires large numbers of AGN pairs.

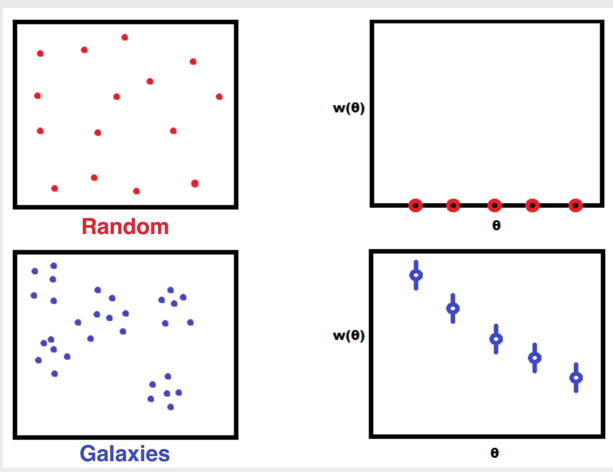

Figure 2: *Simple w(θ) according to a random distribution (red points) and a galaxy distribution (blue points)*

★ We infer reliable ACFs using the **cross-correlation** technique between AGN and the more numerous underlying galaxy population in the UDS and COSMOS fields.

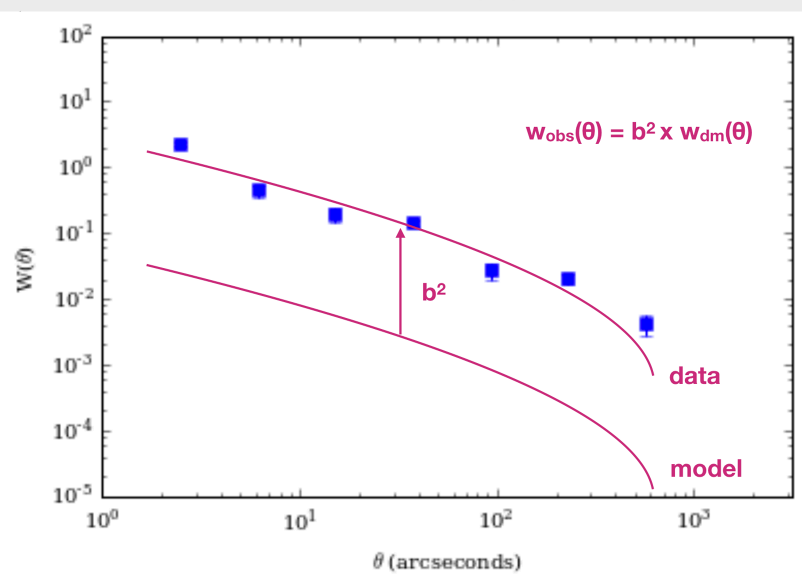

Figure 3: *Fit dark matter CF (model) to observed CF (data) to obtain 'b'. Compare b_{ccf} to b_{tracer} to obtain b_{AGN}.*

★ Galaxies & AGN are **biased** tracers of the underlying structure in mass.

★ Higher bias 'b' implies that AGN are more strongly clustered and reside in higher mass dark matter halos.

★ We measure 'b' by scaling dark matter CF to the observed AGN CF by b^2.

4. AGN prefer group-like environments

★ We perform the clustering analysis on our AGN sample split into redshift bins corresponding to equal cosmic time intervals: 0.5 < z < 0.8, 0.8 < z < 1.3, 1.3 < z < 2.1, 2.1 < z < 4.5.

★ We plot our bias measurements in Figure 4, where the individual COSMOS and UDS measurements are shown in cyan and green respectively.

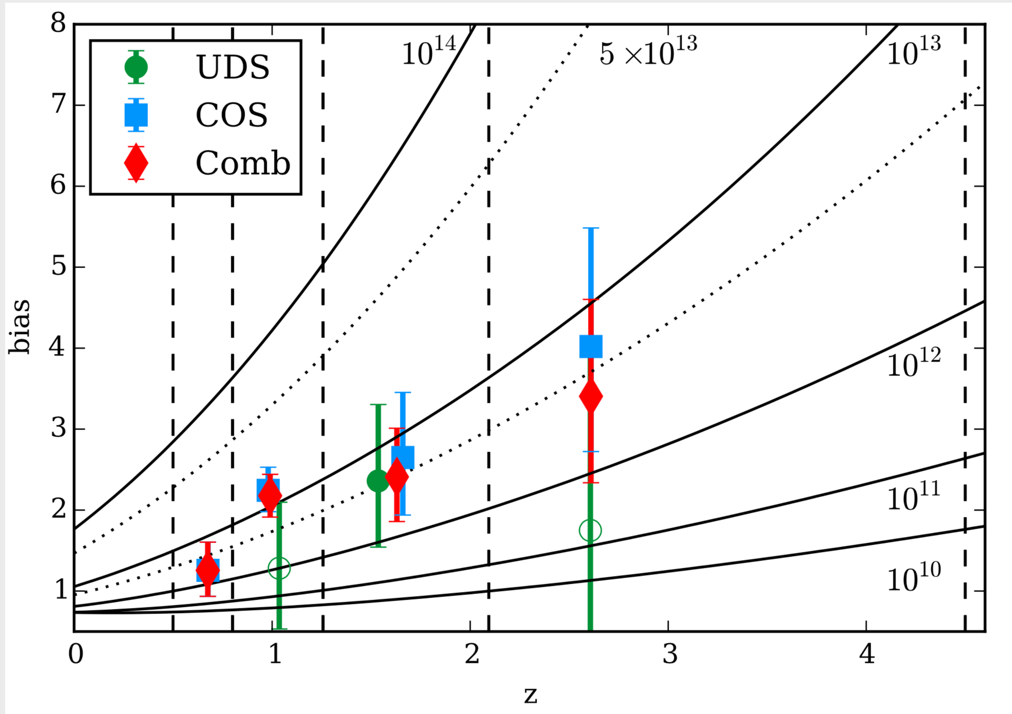

Figure 4: *Bias of X-ray AGN in the UDS (green) & COSMOS (cyan), as a function of redshift. Open symbols denote results derived using sample sizes of fewer than 50 (less reliable). The combined measurements are shown in red. The redshift evolution of dark matter halos corresponding to given masses are shown by the black lines, and are annotated by their corresponding halo masses in solar mass units. Dashed lines indicate redshift intervals (Krishnan et al. in prep).*

★ Interestingly, as shown by **Figure 4**, X-ray AGN show no difference in the typical dark matter halo mass as a function of redshift, as all AGN preferentially reside in 10^{12-13} $M_\odot$.

★ Dark matter halos of 10^{12-13} $M_\odot$ are typical of groups.

★ AGN appear to be preferentially triggered in group and protocluster environments. This may be due to velocity dispersions encouraging mergers/interactions (e.g. Popesso+06).

★ These mergers may be responsible for directly triggering the AGN, or alternatively, for building up the bulge mass (which is in turn correlated with AGN growth).

★ We then probe the connection between the power of the black hole and large-scale environment by splitting our AGN into low, medium, and high X-ray luminosity bins.

★ In **Figure 5**, we plot our bias measurements of AGN with hard band (2–10 keV) X-ray luminosities measured in erg s^{-1} in bins of $10^{43.2} \leq Lx < 10^{43.8}$, $10^{43.8} \leq Lx < 10^{44.4}$, and $10^{44.4} \leq Lx < 10^{45.0}$ in brown, purple, and green respectively.

★ Our results imply that the power of the black hole has no dependence on the large-scale environment.

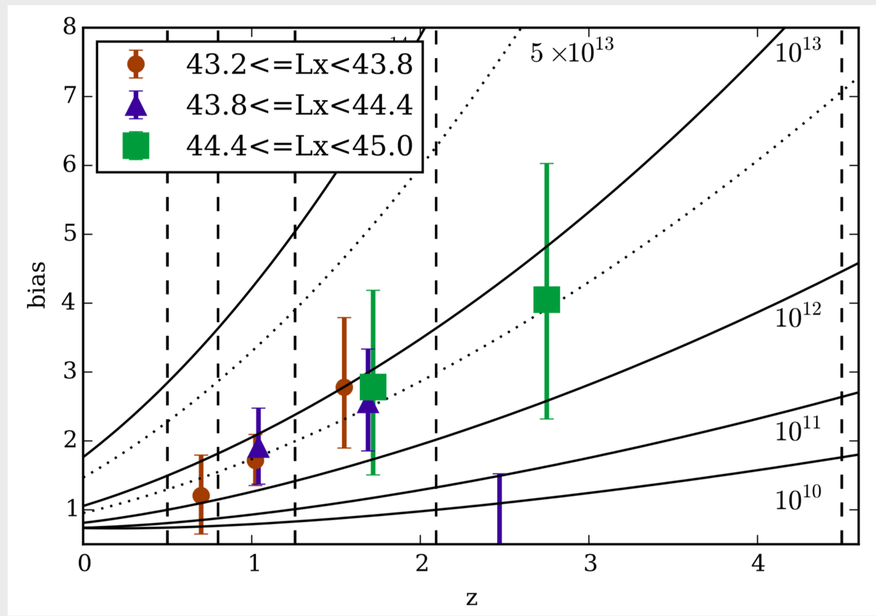

Figure 5: *Bias of X-ray AGN as a function of z, splitting the AGN sample by hard band X-ray luminosity. Although the AGN are more powerful at high redshift, we can see that there is no difference in the characteristic halo mass hosting low, medium, and high X-ray luminosities (Krishnan et al. in prep).*

★ Although AGN prefer environments corresponding to 10^{12-13} $M_\odot$, their luminosities and gas accretion rates appear to depend solely on the availability of fuel.

★ Higher redshift galaxies within 10^{12-13} $M_\odot$ halos perhaps accreted cold gas at higher rates leading to higher luminosities.

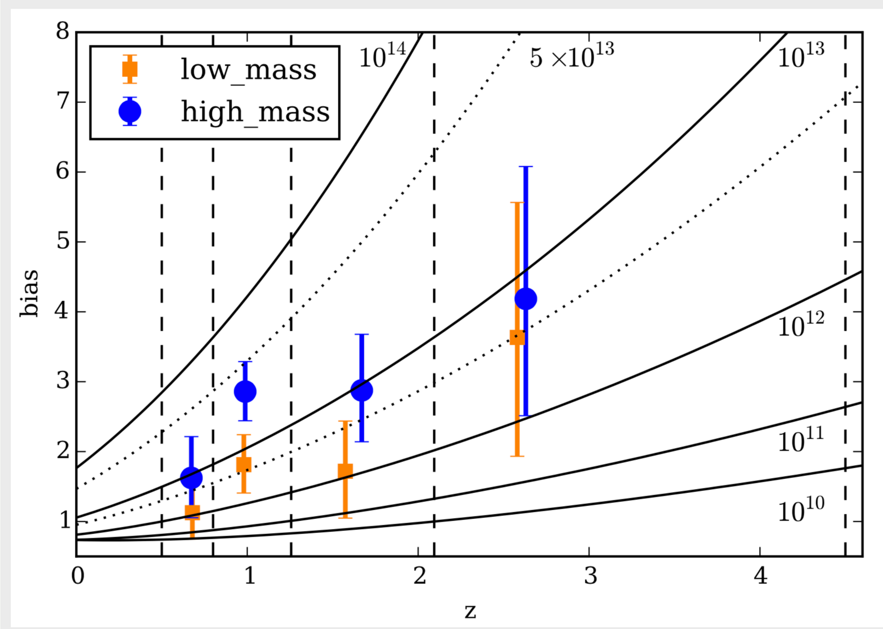

Figure 6: *Bias of low mass (orange squares) and high mass (blue circles) AGN in the UDS & COSMOS, as a function of redshift. We see that high mass AGN are more clustered than low mass AGN, most significant at z~1 (Krishnan et al. in prep).*

★ We finally split our sample by stellar mass. From **Figure 6**, we can see that AGN hosted in high mass galaxies (blue circles) have bias values corresponding to higher DM halo masses, compared to AGN hosted in low mass galaxies (orange squares).

★ However, we find that AGN in high mass hosts have a higher passive fraction than AGN in low mass hosts, and we know that passive galaxies preferentially reside in higher mass DM halos (e.g. Hartley+13).

★ We also find that star-forming AGN split into high and low mass hosts have near-identical bias values.

★ Therefore this excess in bias is likely due to an increased passive fraction in the high mass sample.

SUMMARY

1. We investigate the AGN-environment connection through 2 methods: AGN fractions in clusters and two-point correlation functions (2pcf).

2. AGN activity is enhanced in a z~1.6 protocluster, reversing the AGN suppression in low-z clusters.

3. We use 2pcf to compute the AGN bias and the typical characteristic halo mass hosting AGN.

4. We find that AGN of all luminosities and redshifts prefer group-like environments. AGN in high-mass host galaxies are more strongly clustered, but this trend is driven by the increased fraction of passive galaxies.

AGN activity is typical of group-like environments at all redshifts out to z~4.5!