Investigation of Extremely Massive Quasar Environments via MMT Hectospec and SDSS

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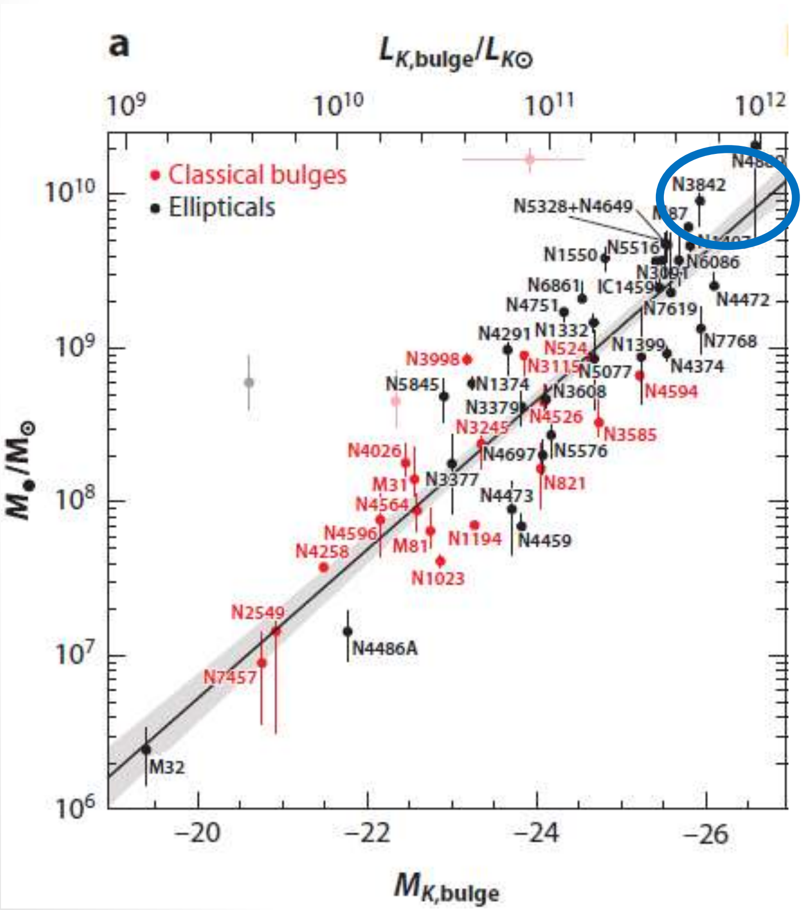
Feb 27, 2018

1. Introduction

Extremely massive black holes (**EMBH**s, M_{BH}~ $10^{10}M_{\odot}$) do exist.



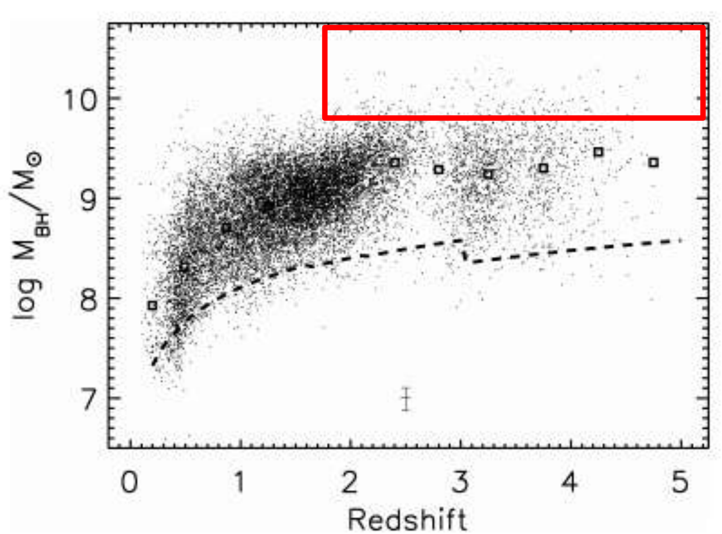
Kormendy & Ho (2013)

LETTER

doi:10.1038/nature10636

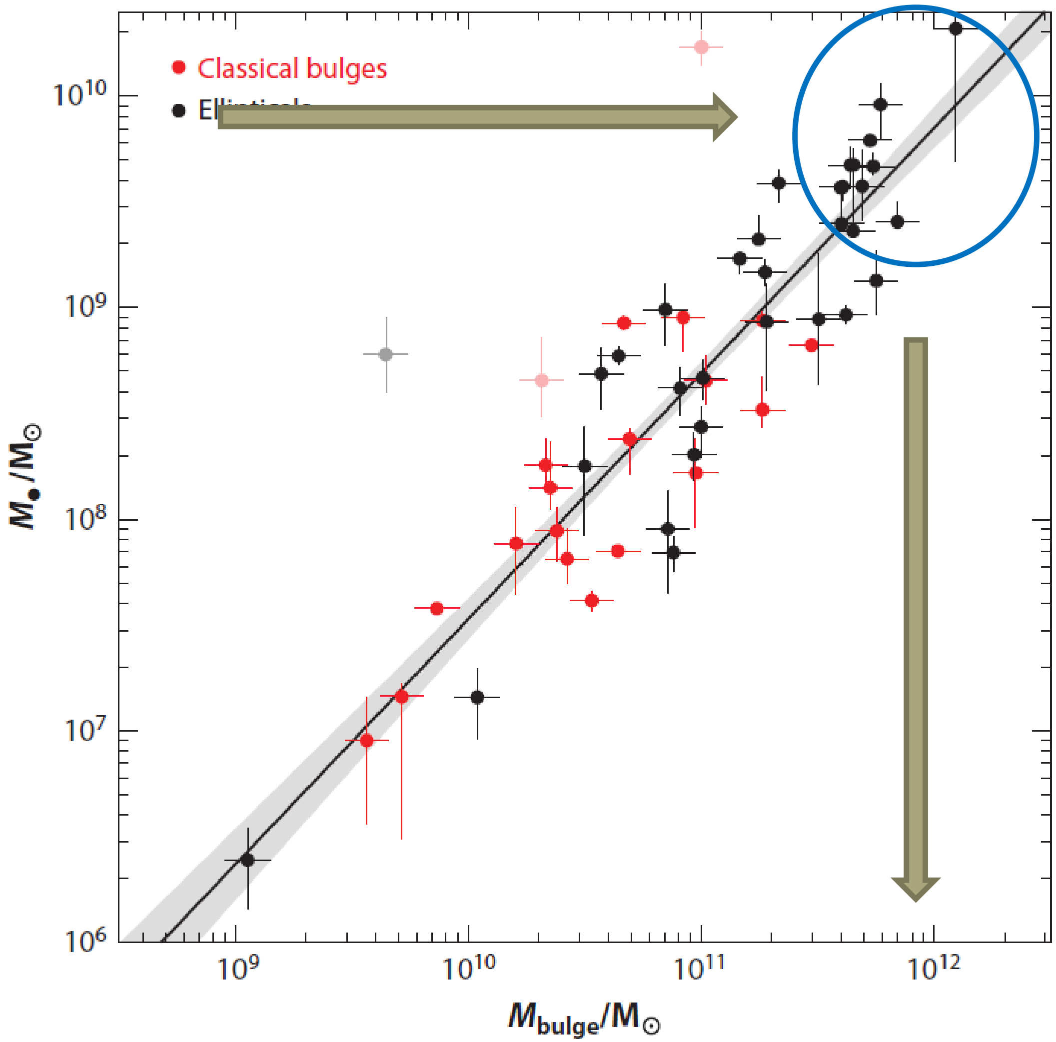
Two ten-billion-solar-mass black holes at the centres of giant elliptical galaxies

Nicholas J. McConnell, Chung-Pei Ma, Karl Gebhardt, Shelley A. Wright, Jeremy D. Murphy, Tod R. Lauer, James R. Graham & Douglas O. Richstone



Netzer (2003)

BH scaling relations suggest that EMBHs ($M_{BH} > 10^{9.4} M_{\odot}$) are in the most massive galaxies ($M_{star} > 10^{11.6} M_{\odot}$).



Kormendy & Ho (2013)

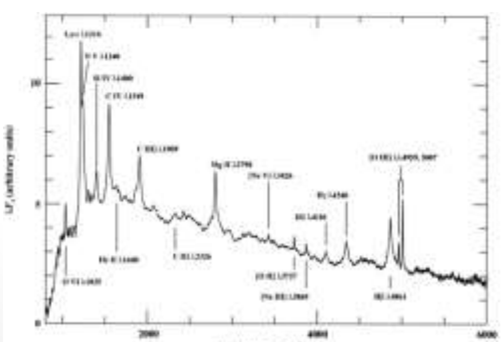
- The most massive galaxies are commonly found in dense environments like clusters.

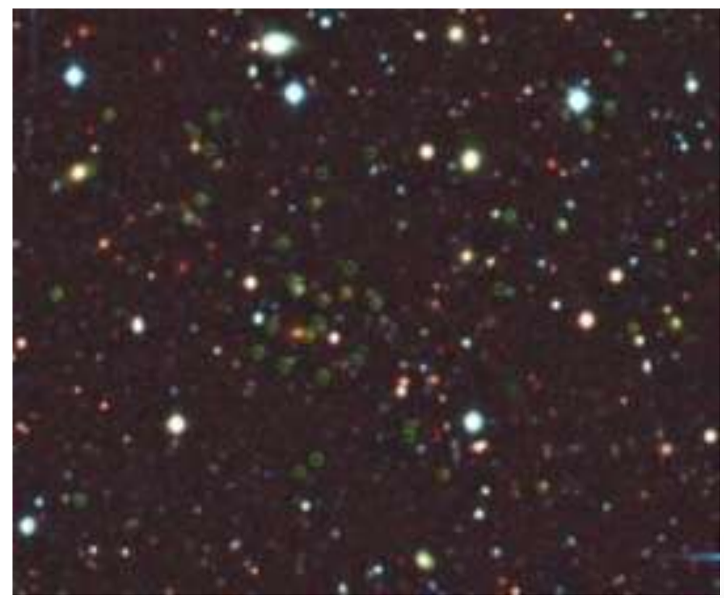
➔ One can expect that there is a close connection between active EMBHs (massive quasars) and dense environments.

If the close connection between active EMBHs (massive quasars) and dense environments is true,

1) EMBHs can grow at quasar phase even in cluster environments.

2) Massive quasars can be attractive signposts to discover galaxy clusters.





J.-W Kim, M. Im, S.-K. Lee & M. Hyun

Recent studies about quasar environments

- Quasars avoid rich clusters or highly dense environments.

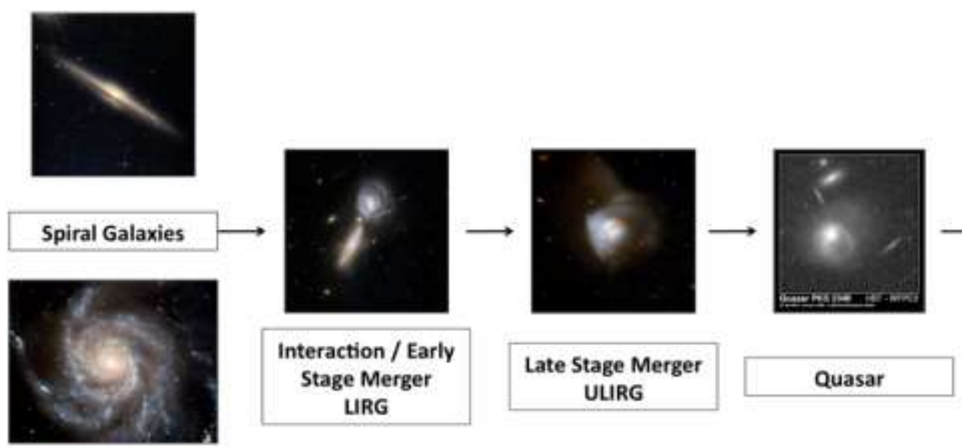
  (poor clusters or group; $\log(M_{halo}/M_{\odot}) \sim 12\text{-}13$)

  (Wold et al. 2001; Sochting et al. 2002, 2004; Coldwell & Lambas 2006; Hopkins et al. 2008; Lietzen et al. 2009; Fanidakis et al. 2012, 2013; Karhunen et al. 2014; Song et al. 2016)

- The moderate environments

  → Triggering mechanism of quasars: gas-rich merger/interaction processes

  (Kaumann & Haehnelt 2000; Canalizo & Stockton 2001; Sochting et al. 2002; Hopkins et al. 2008; Myers et al. 2008)



From CANDELS blog

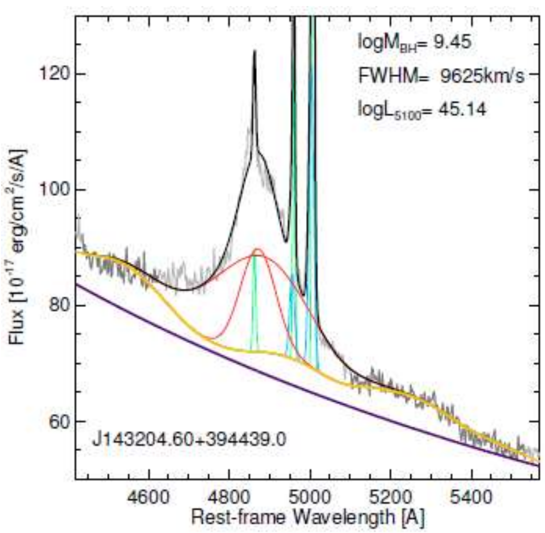
If active EMBHs turn out to be in moderate environments,

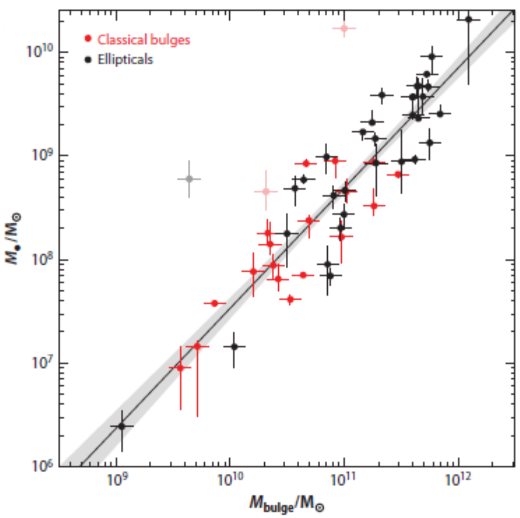
→ EMBHs grow by quasar phase at group scale then later they would combine with larger and denser structures.

Chance to examine

→ Uncertainty of black hole mass measurements at the massive end

→ BH scaling relation

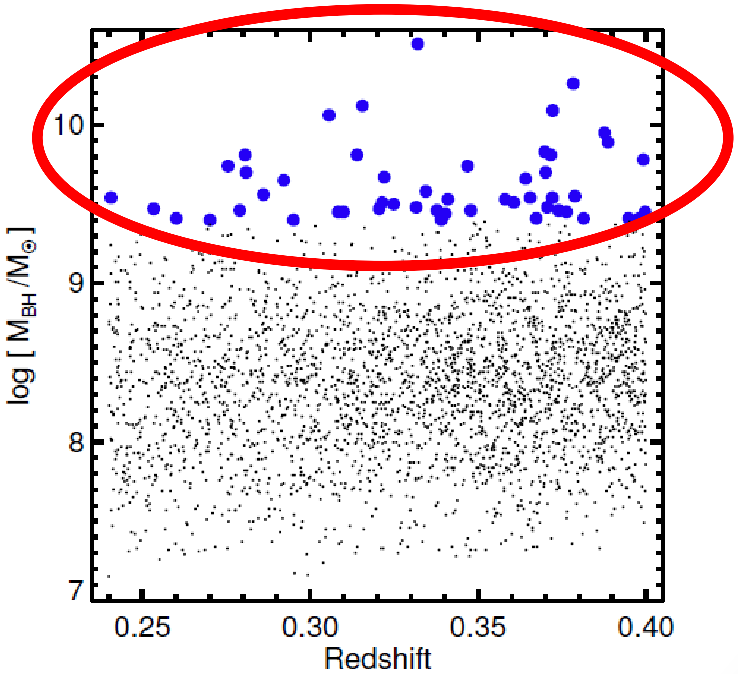




Kormendy & Ho (2013)

2. Sample

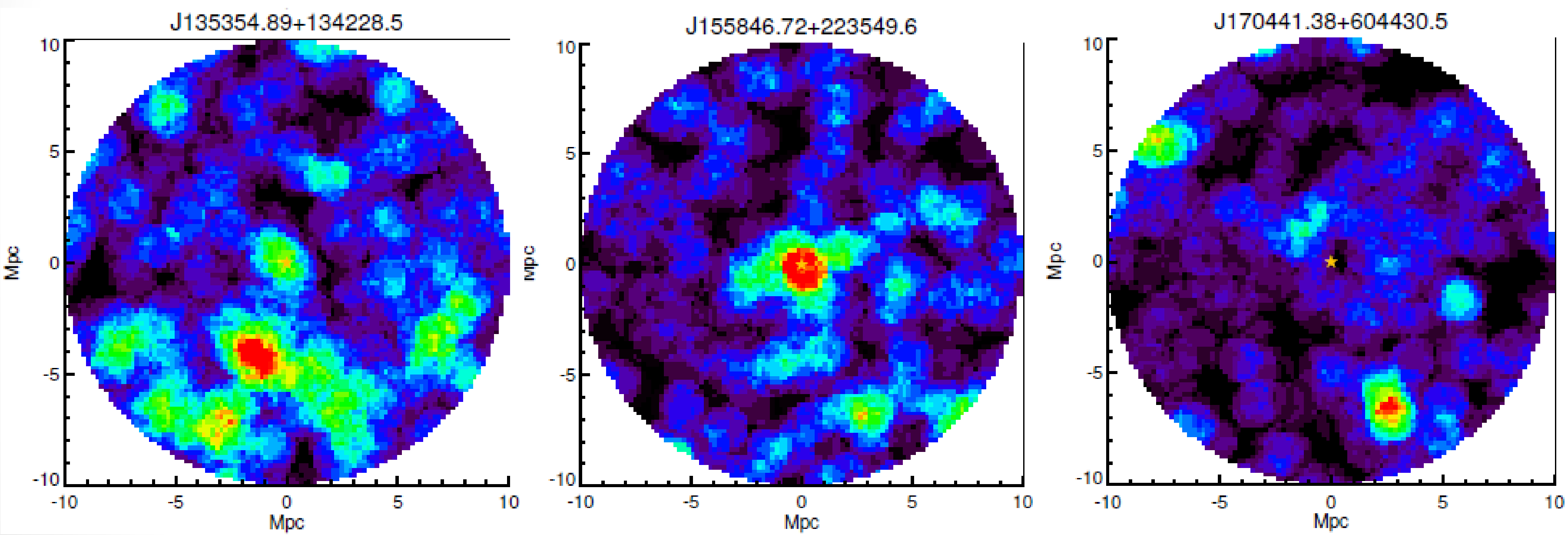
- SDSS DR12
- + Shen et al. (2011) quasar catalog
- + Mendel et al. (2014) galaxy catalog (Bugle + Disk decomposition)
- $0.24 \leq z \leq 0.40$



- **Massive quasars (52)**
- $\log(M_{BH}/M_{\odot}) \geq 9.4$

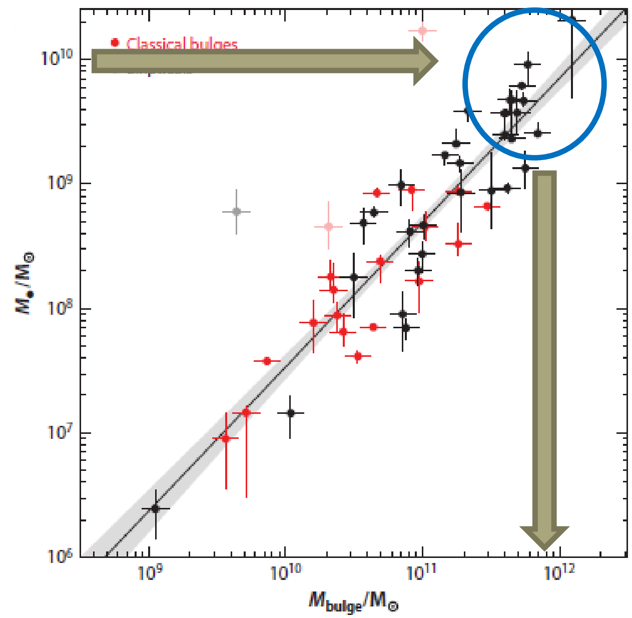
- For **three massive quasars**, we observed galaxies in the radius of ~ 0.5 degree from the quasars using **Hectospec on MMT** **(K-GMT Science Program 2015A)**.

4	Q1353+134	13:53:54.89	+13:42:28.5	$z = 0.3722$, log(MBH)=10.09, $R < 21.5$
5	Q1558+223	15:58:46.72	+22:35:49.6	$z = 0.3992$, log(MBH)=9.78, $R < 21.5$
6	Q1704+604	17:04:41.38	+60:44:30.5	$z = 0.3716$, log(MBH)=9.81, $R < 21.5$

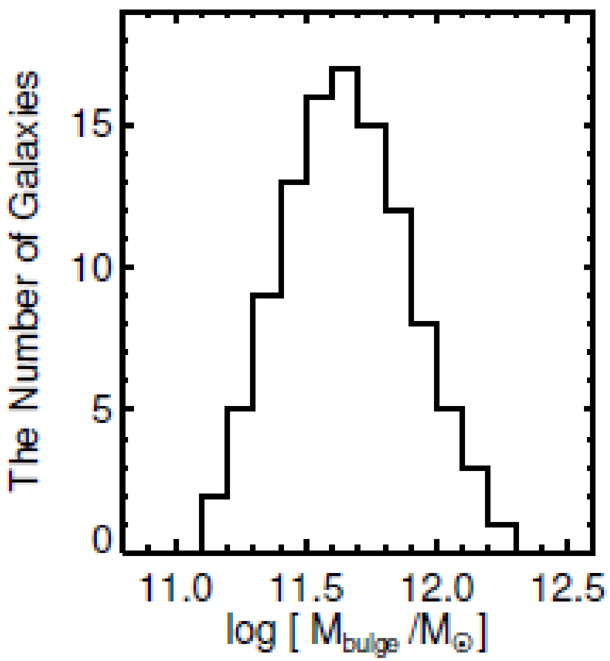


- **Mass-matched galaxies (massive galaxies):**

  Galaxies whose bulge stellar masses are matched with BH masses of 52 massive quasars through a scaling relation.



Kormendy & Ho (2013)



3. Environments Measurements

Overdensity

$$\delta = \frac{\Sigma_O - \Sigma_B}{\Sigma_B}$$

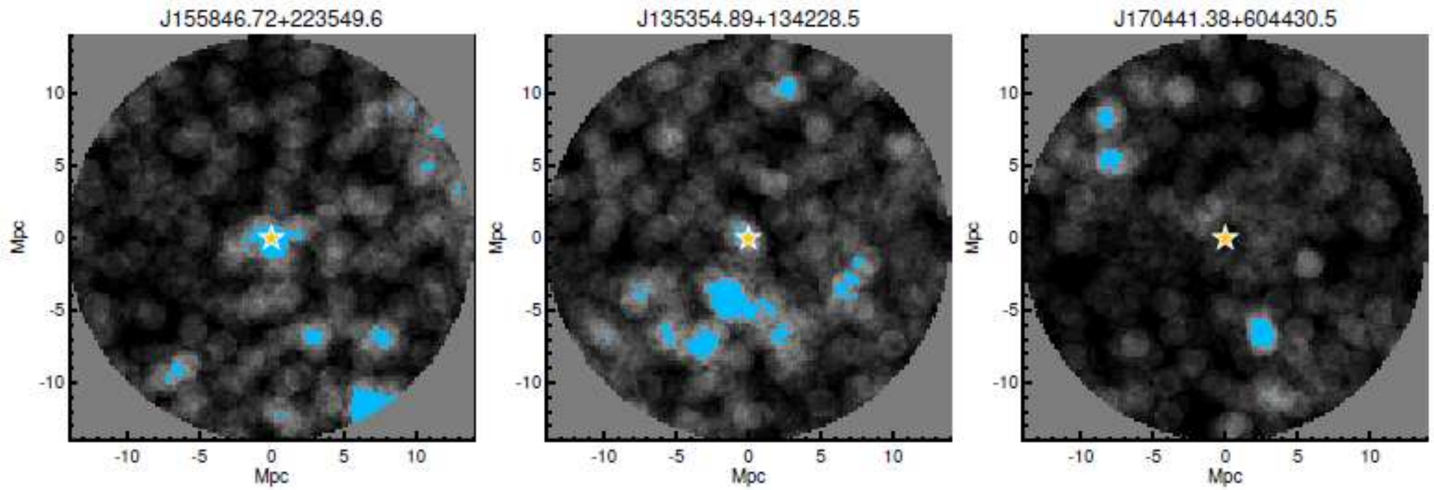
- Σ_O : Surface galaxy number density around a object
- Σ_B : Surface galaxy number density of background

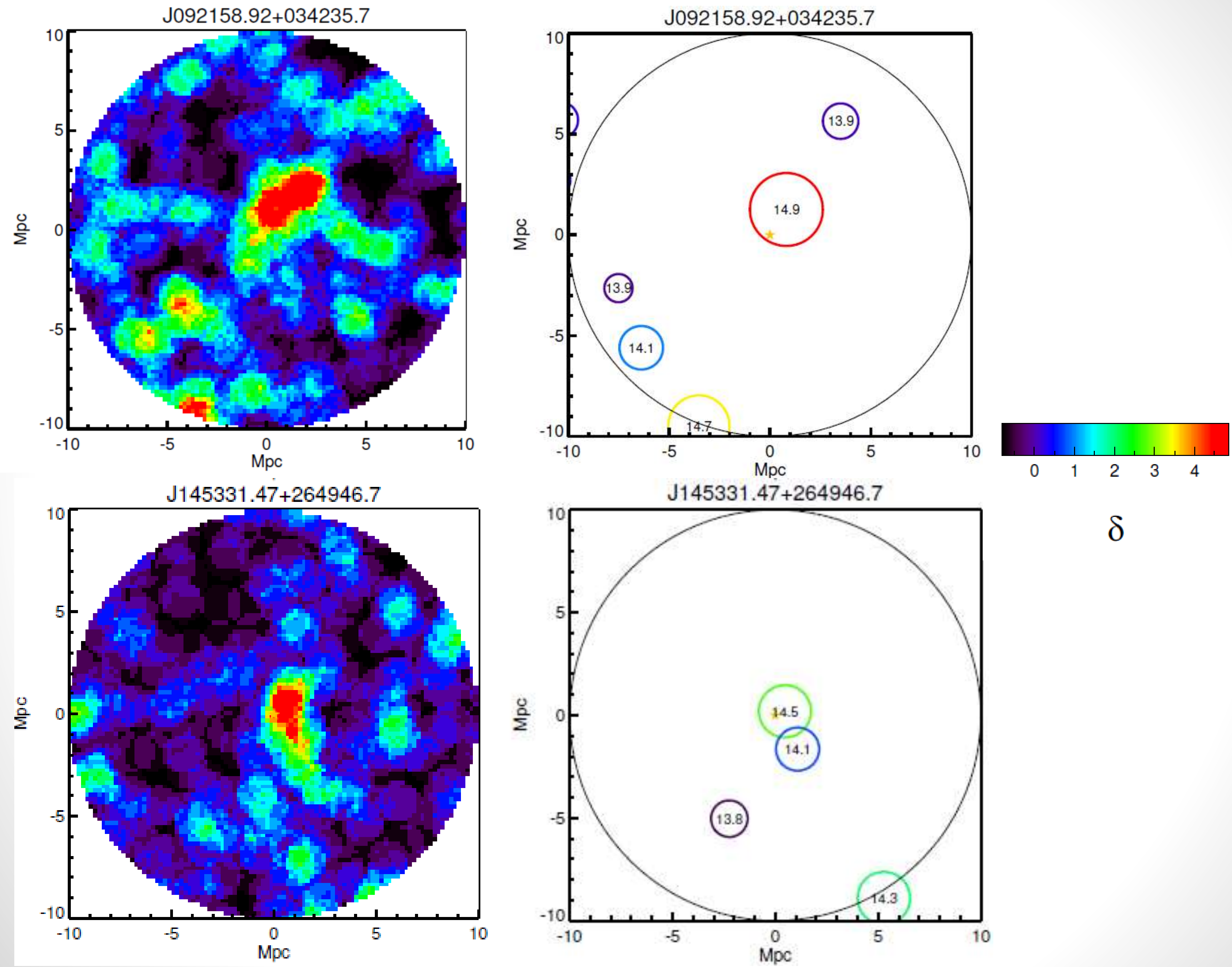
- r-band absolute mag < -19.8 (evolution corrected)
- Redshift slice: dv= $\pm$8500km/s (Δz/(1+z) = 0.028)

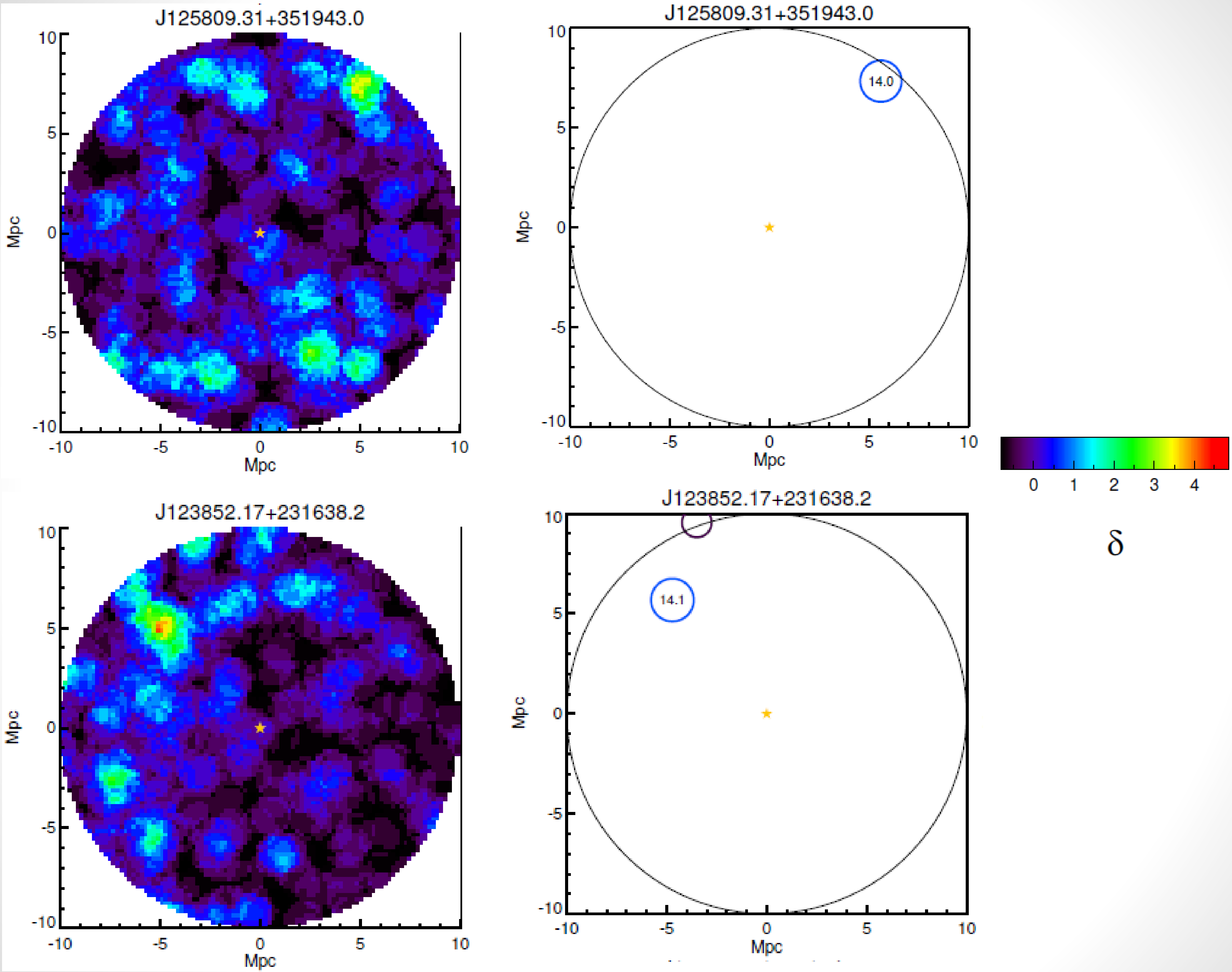
→ The rms value of the difference between the photometric redshifts and the spectroscopic redshifts.

4. Results

- **Overdensity maps for massive quasars**

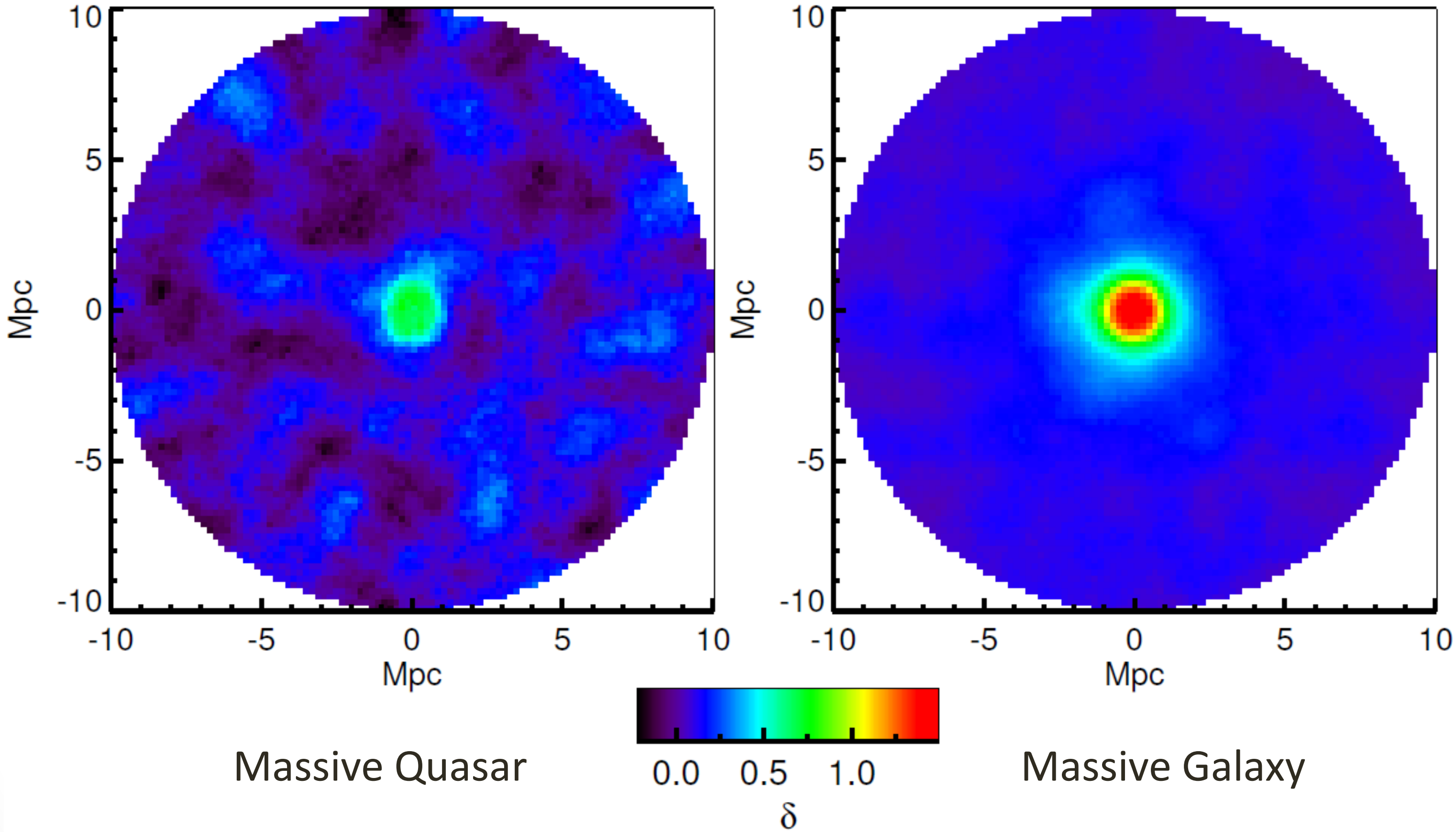



J092158.92+034235.7
J092158.92+034235.7
J145331.47+264946.7
J145331.47+264946.7
Mpc
14.9
13.9
13.9
14.1
14.7
14.5
14.1
13.8
14.3
δ


J125809.31+351943.0
J125809.31+351943.0
14.0
J123852.17+231638.2
J123852.17+231638.2
14.1
Mpc
0
1
2
3
4
δ

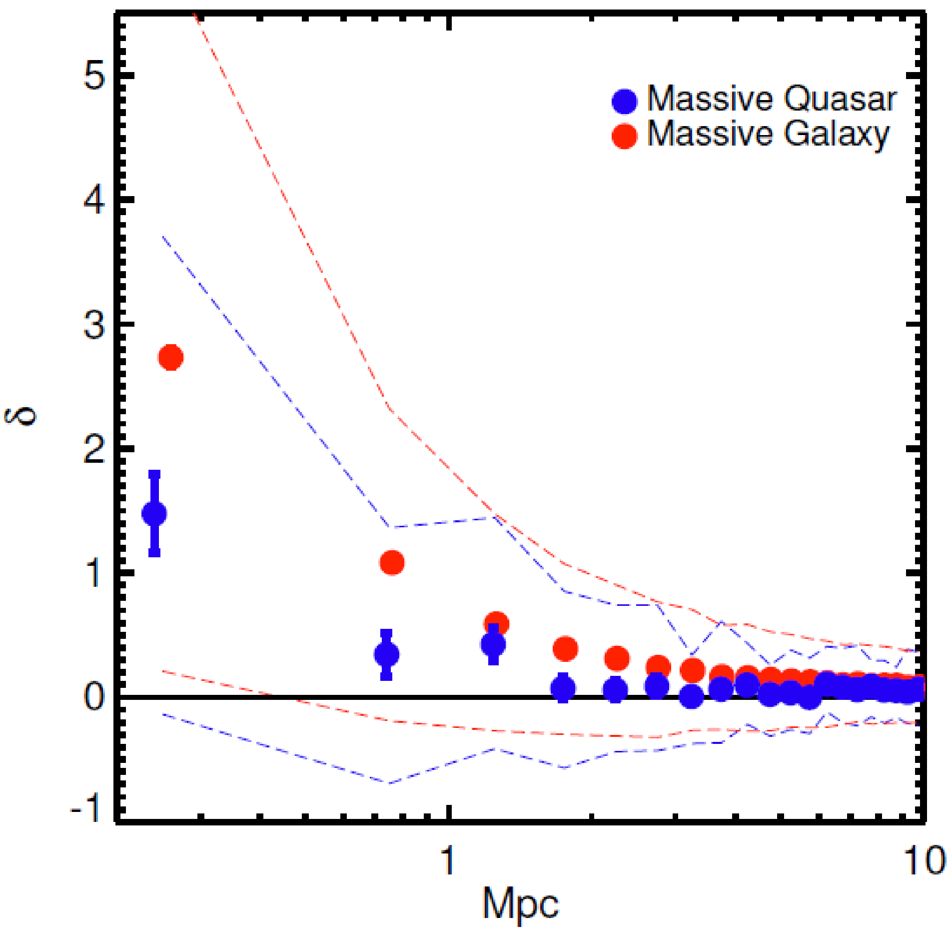
- **Comparison between environments of massive quasars and those of massive galaxies**

Average-combined overdensity maps



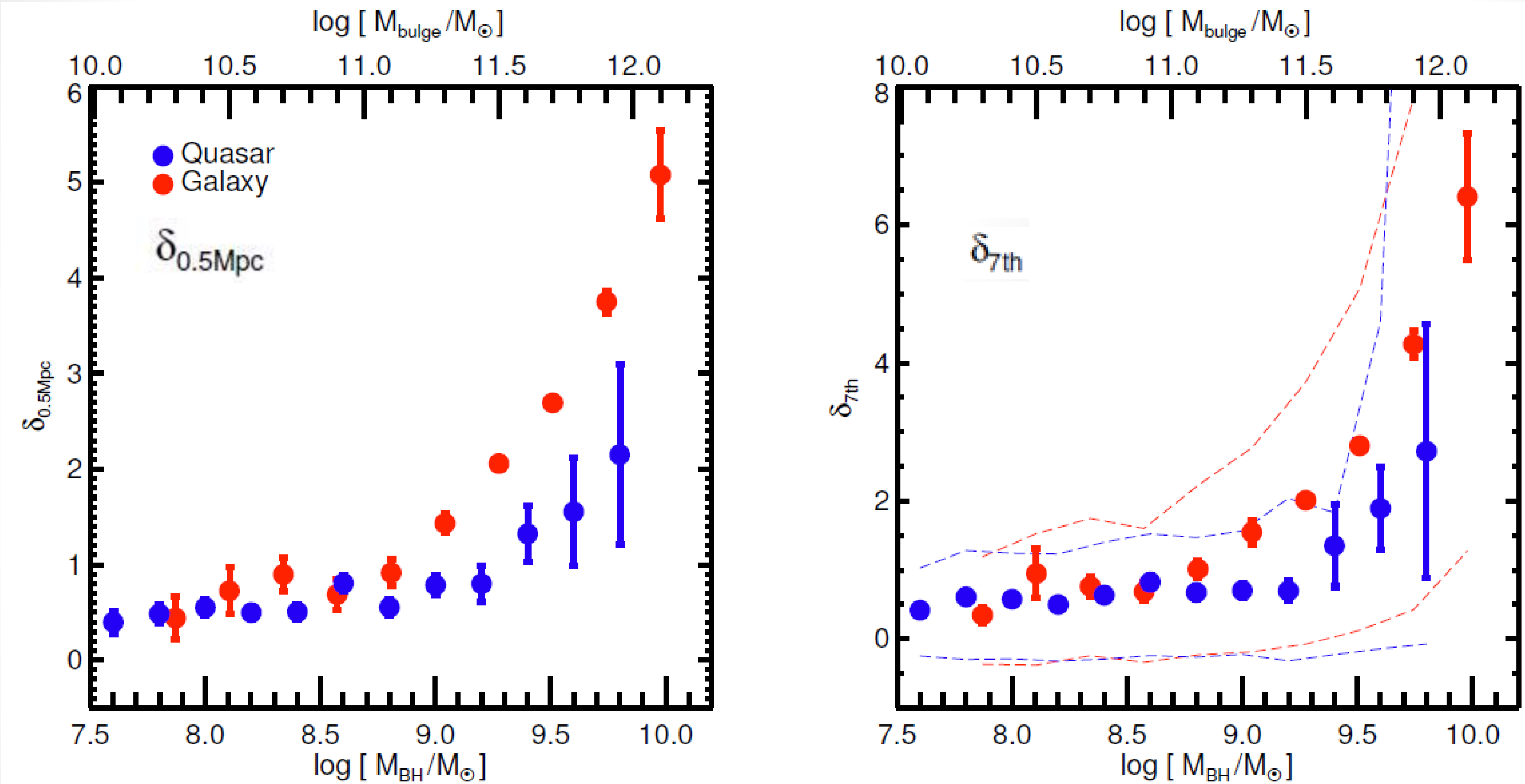
- **Massive galaxies are on average in ~2 times denser environments than the massive quasars are.**

Average overdensity as a function of radial distance



- **Massive galaxies reside in denser environments in large scale.**

Mass-overdensity relation



- **Mass-overdensity relation is steeper for galaxies.**

Cluster finding probability by searching around massive quasars or massive galaxies

- Matching with clusters of $\log(M_{halo}/M_{\odot}) \geq 14$ from the catalog of Wen et al. (2012)

- Matching radius: R_{200} of clusters
- Redshift slice: $\Delta z/(1+z) = 0.04$

  (phot-z gap used in Wen et al. (2012) to select cluster members)

- **9.6% for massive quasars with $\log(M_{BH}/M_{\odot}) \geq 9.4$**
- **40.1% for massive galaxies of $\log(M_{bul}/M_{\odot}) \geq 11.6$**

5. Why Their Environments are Different

1) They can have intrinsically different environments to each other.

2) The black hole mass can be a secondary proxy for the environments intrinsically.

3) Uncertainty of black hole mass measurements can be a reason for the environmental discrepancy.

1) They can have intrinsically different environments to each other.

Quasars prefer group like moderate environments.

(Kaumann & Haehnelt 2000; Canalizo & Stockton 2001; Sochting et al. 2002; Hopkins et al. 2008; Myers et al. 2008)

- Gas-rich mergers/interactions prefer group scale, moderate environments.

Proper encounter velocity and galaxy number density

& Galaxies in that environments have more cold gas than those in the highly dense environments

(Davies & Lewis 1973; Hashimoto & Oemler 2000; Solanes et al. 2001; Hopkins et al. 2008; Grossi et al. 2009; Catinella et al. 2013)

➔ *Massive quasar environments can be biased to underdense environments.*

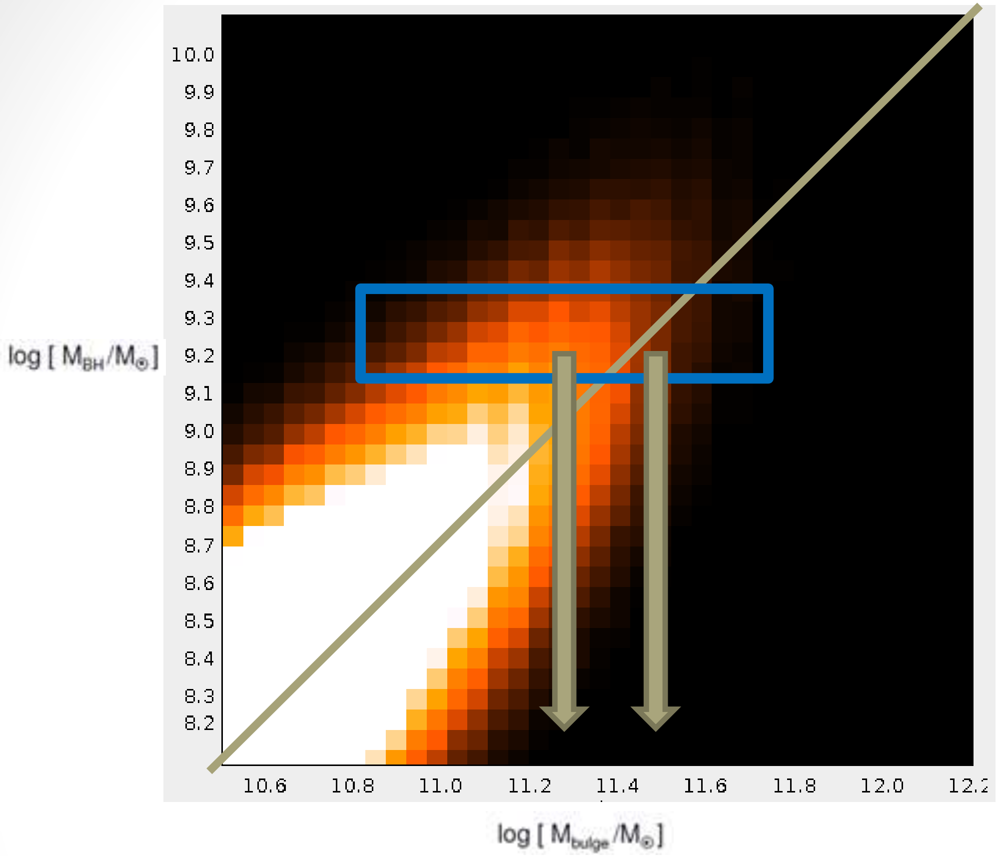
2) The black hole mass can be a secondary proxy for the environments intrinsically.

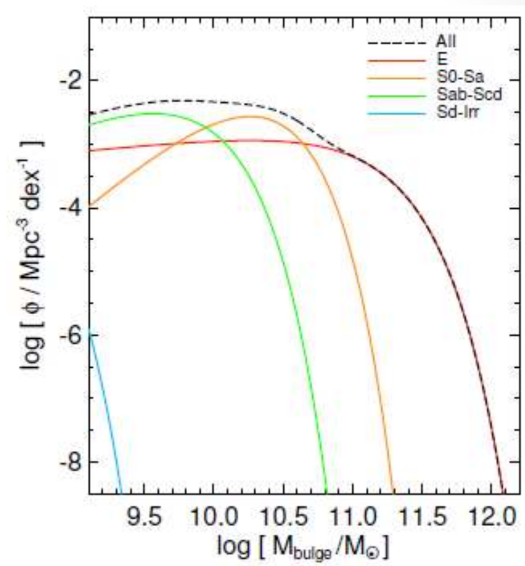
Two assumptions:

- The bulge stellar mass is a primary proxy for the environments.
- BH mass can be a secondary proxy for environments.

Because they are simply connected to the bulge stellar masses by the scaling relation and its intrinsic scatter.

- Combined effect of the intrinsic scatter and exponentially declining stellar mass function at high mass range



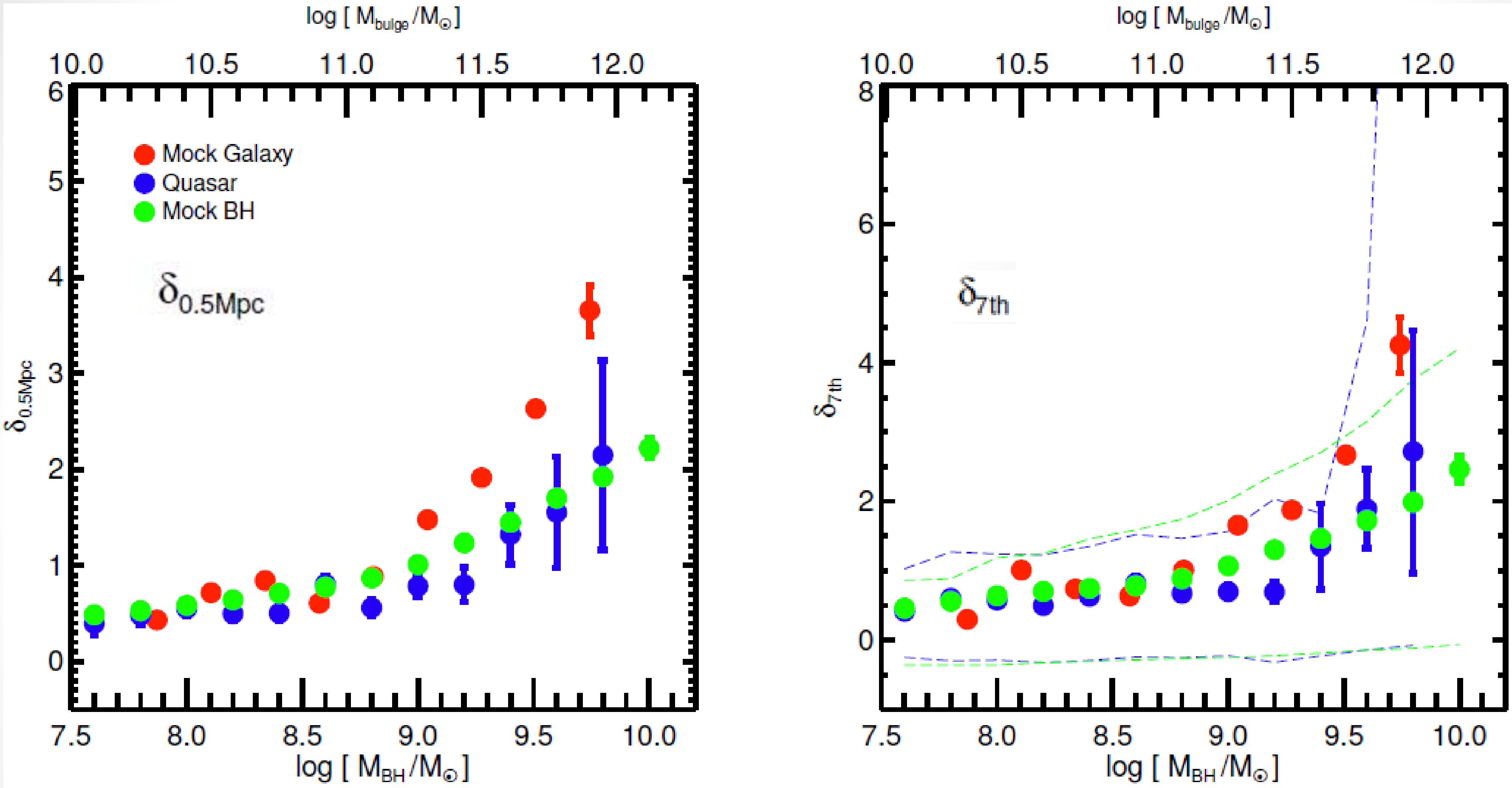


→ BH with a certain mass has a high probability to be in a less massive bulge (hence a lower overdensity).

➔ *Environmental discrepancy*

- Test it with a simple simulation of mock BHs.

Mass-overdensity relations of mock BHs and quasars



- **The environments of mock BHs overlap with those of real quasars even at the massive end.**

The bulge stellar mass is a primary proxy for the environments.

BH mass can be a secondary proxy for environments connected to the bulge stellar mass by the scaling relation and its intrinsic scatter.

➔ *The environmental discrepancy between massive quasars and massive galaxies can be explained simply.*

3) Uncertainty of black hole mass measurements can be a reason for the environmental discrepancy.

Two assumptions:

- Both bulge stellar masses and BH masses of quasars are comparably good proxies for environments.
- Uncertainty of BH mass measurements by the single epoch spectrum is ~0.3 dex larger than that of the bulge masses obtained by SED fitting.

- Every situation is **identical** to the previous case, except the **intrinsic scatter of the scaling relation** is replaced with **uncertainty of the BH measurements**.

- Combined effect of the uncertainty of BH mass measurements and exponentially declining stellar mass function at high mass range

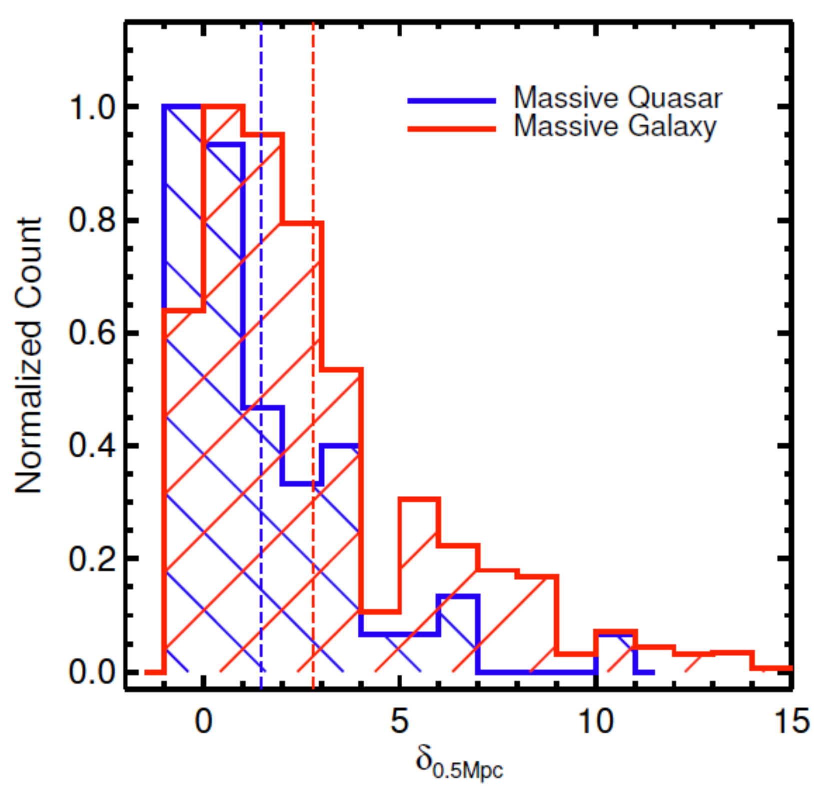
→ *Environmental discrepancy*

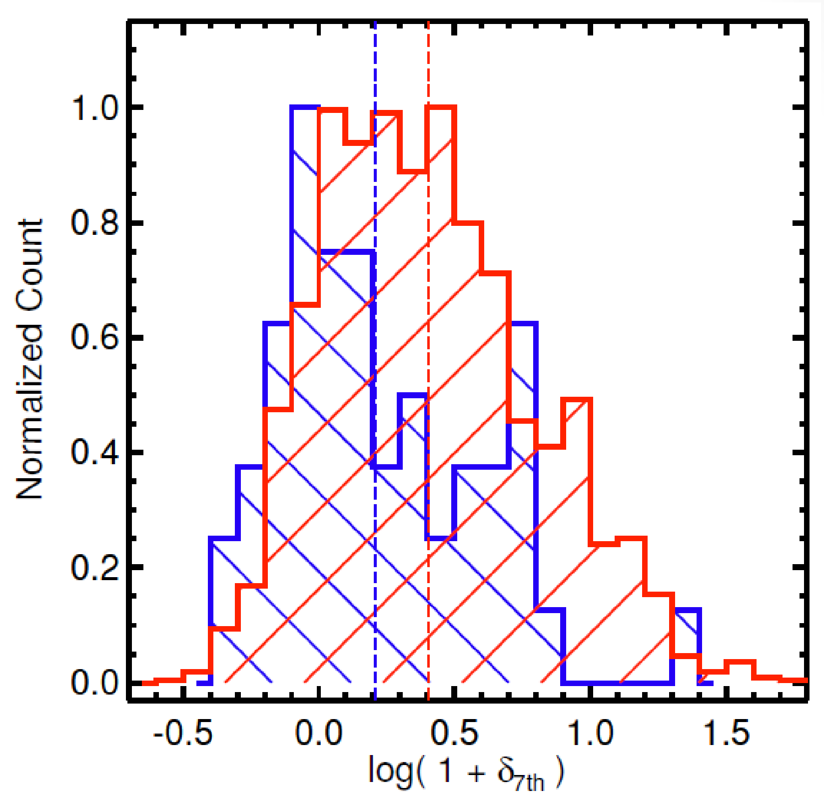
6. Summary

- We study environments of 52 extremely massive quasars with $\log(M_{BH}/M_{\odot}) \geq 9.4$ in $0.24 \leq z \leq 0.4$ via MMT Hectospec and SDSS.
- On average, massive quasars reside in more than ~2 times denser environments than less massive quasars with $\log(M_{BH}/M_{\odot}) < 9.0$.
- Massive quasars reside in ~2 times underdense environments compared to those of massive galaxies whose bulge stellar masses are matched with BH masses of massive quasars through a scaling relation.
- We discuss why the environments of massive quasars and those of massive galaxies are different.

  1) They can have intrinsically different environments to each other.
  2) The black hole mass can be a secondary proxy for the environments intrinsically.
  3) Uncertainty of black hole mass measurements can be a reason for the environmental discrepancy.

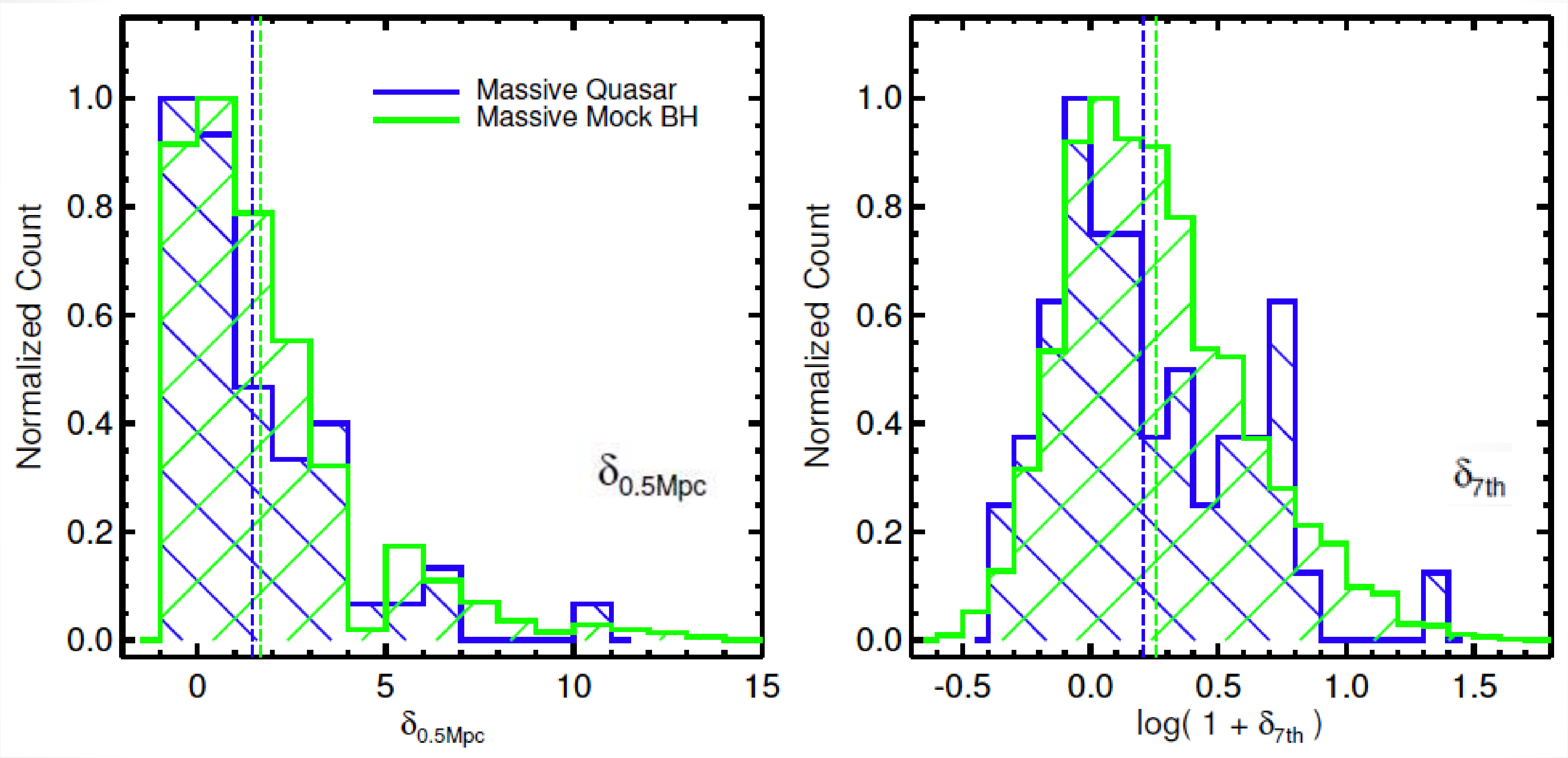
Overdensity histogram





- KS test probability: 2.5×10^{-4} for $\delta_{0.5Mpc}$ 3.8×10^{-4} for $\log(1 + \delta_{7th})$
- **Massive quasars and massive galaxies reside in essentially different environments.**

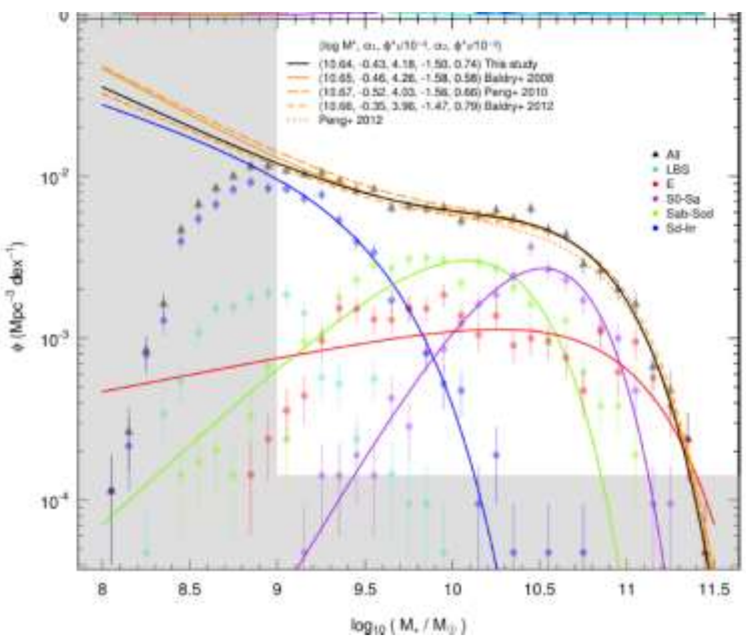
Environments of massive mock BHs and those of massive quasars both with $\log(M_{BH}/M_{\odot}) \geq 9.4$



- **Massive mock BHs and massive quasars have similar overdensity distributions to each other.**

- Constructing bulge mass function from stellar mass function by the method in Shankar et al. (2009)

- Using stellar mass functions for each Hubble type (Kelvin et al. 2014).

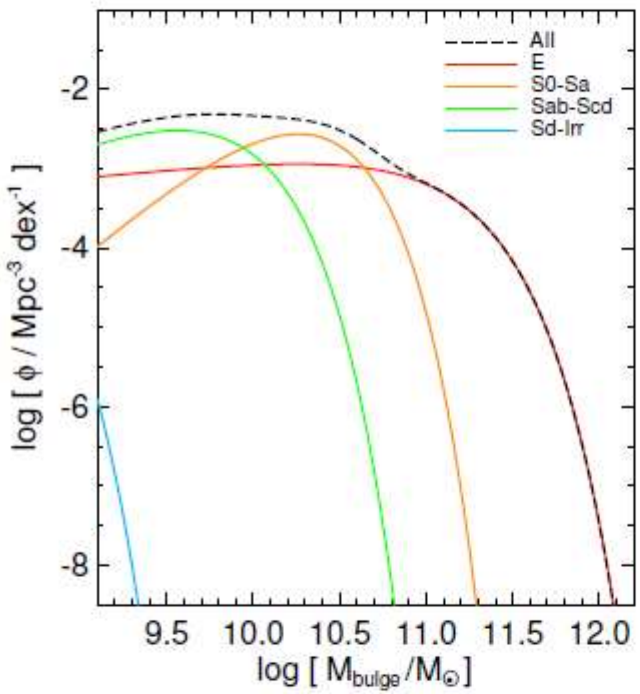


Kelvin et al. (2011)

- Hubble type fraction + B/T (bulge fraction) in Fukujita et al. (1998)

Parameter	E	S0	Sab	Sbc	Scd	Irr
Bulge fraction $\kappa(r)$	1	0.75	0.40	0.24	0.10	0
Morphology fraction μ(B)	0.11	0.21	0.28	0.29	0.045	0.061

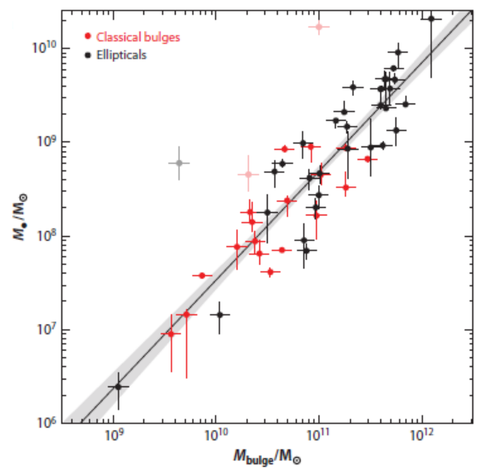
- Total stellar mass function → Bulge stellar mass function



- Generating mock bulges (~4,000,000) that follow the bulge stellar mass function.

- Assigning the environments to mock bulges in such a way that the mock bulges have real overdensity values of galaxies at their mass bins of 0.1 dex.

- Converting bulge stellar masses to mock BH masses using the scaling relation in Kormendy & Ho (2013).



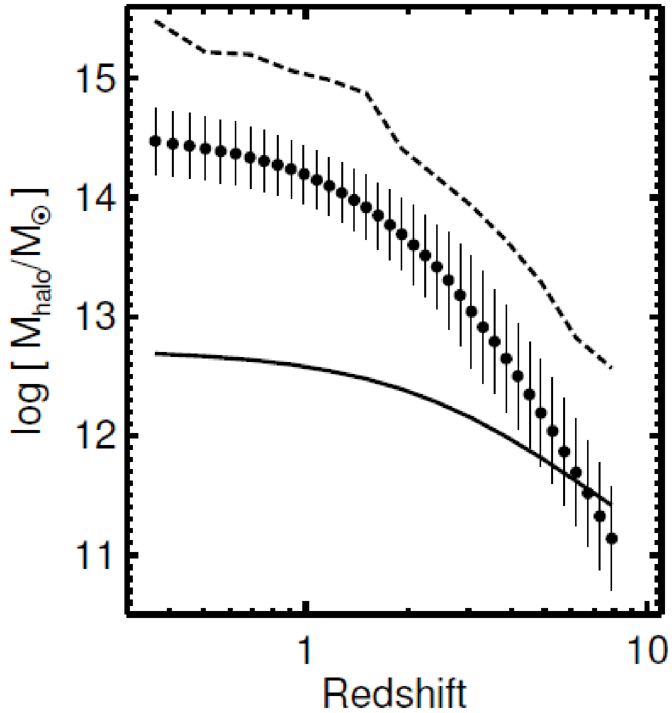
Kormendy & Ho (2013)

- The mock BH masses were scattered by adding a random Gaussian error with σ=0.28 dex (the intrinsic scatter of the scaling relation).

6. Predictions from ΛCDM galaxy formation simulation: role of high-redshift quasars as signposts for environments at high redshift.

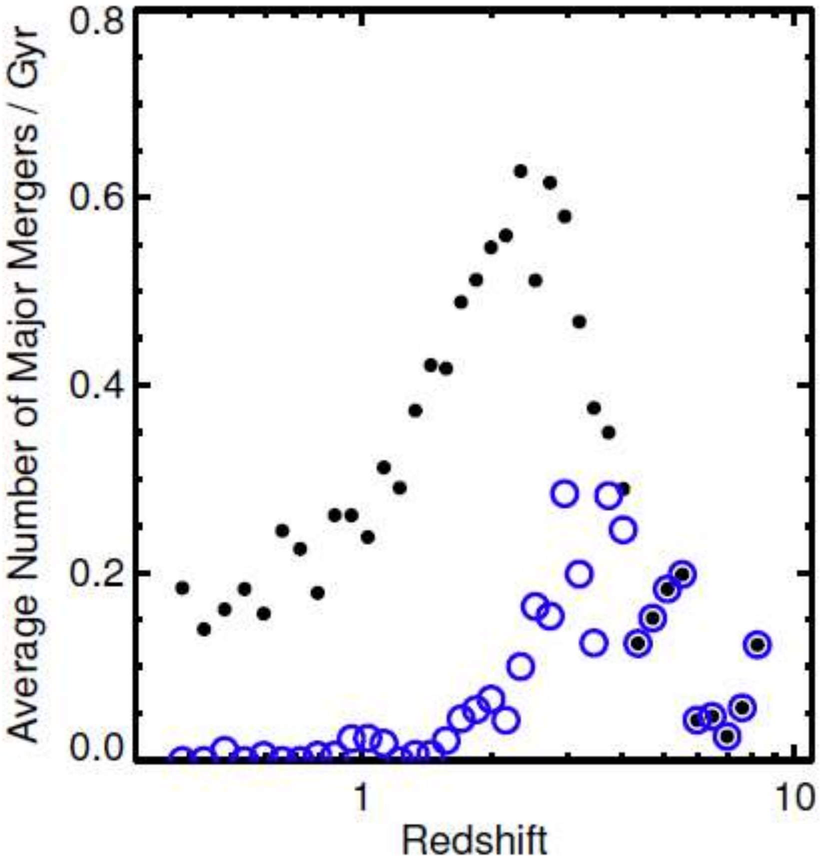
- ΛCDM galaxy formation simulation of Guo et al. (2011) based on the Millennium 1 Simulation (Springel et al. 2005)

- Where EMBHs have grown in their lifetimes
- Average Halo mass as a function of redshift for main progenitors of 492 EMBHs of $\log(M_{BH}/M_{\odot}) \geq 9.4$ at $z=0.36$.



- The EMBHs have resided in massive halos of $\log(M_{halo}/M_{\odot}) > 14$ from $z=2$ in their growing histories.
- The typical mass of halos at high redshift of $4<z<6$ is close to $\log(M_{halo}/M_{\odot})=12$.

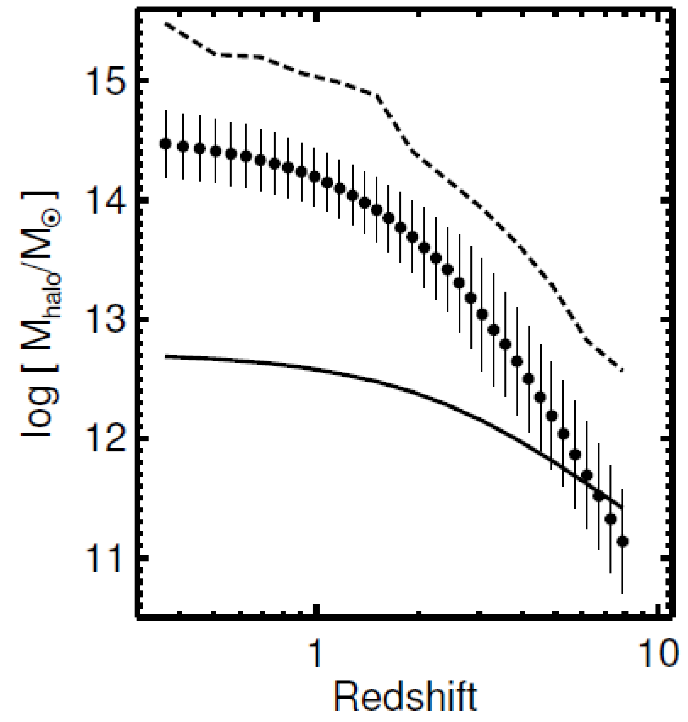
- Average number of **major mergers** (the black points) and gas-rich major mergers (the blue circles) the EMBHs have experienced in a Gyr.



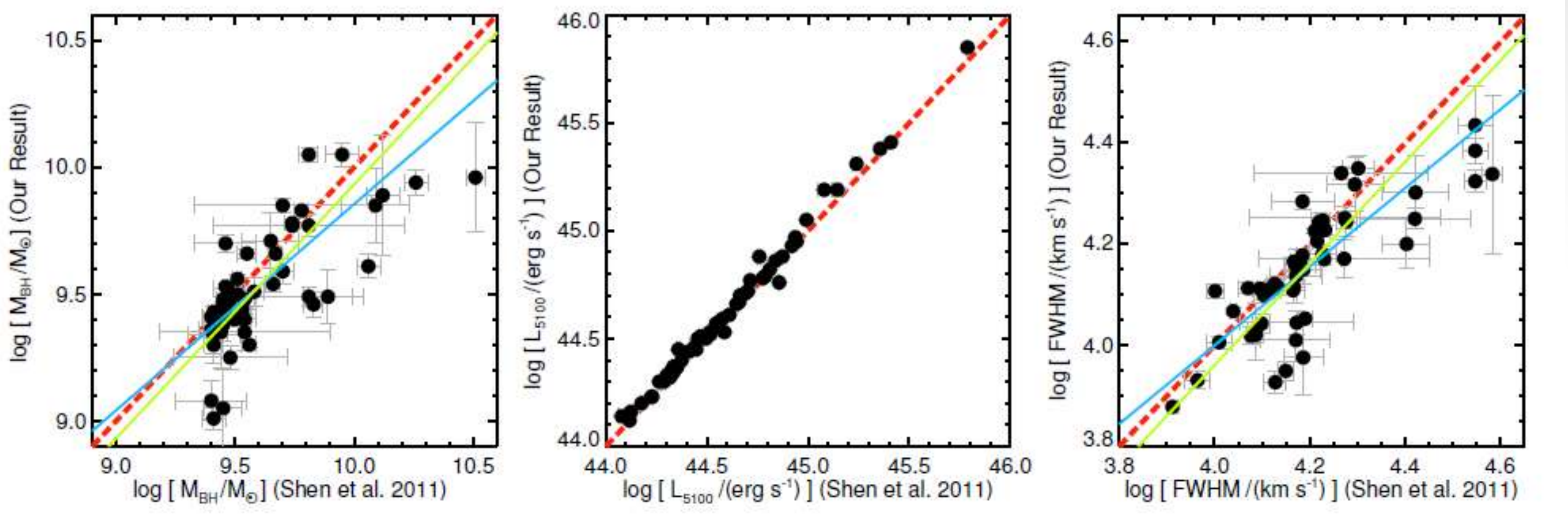
- Gas-rich major mergers are dominant at z>4.

- Fanidakis et al. (2013): **Main fueling mechanism for bright quasars** of $\log(L_{bol}/\mathrm{erg\ s^{-1}})>45$ in the moderate halo mass of $\log(M_{halo}/M_{\odot})\sim12$ at high redshift of **z>4** is gas-rich mergers (starburst mode).

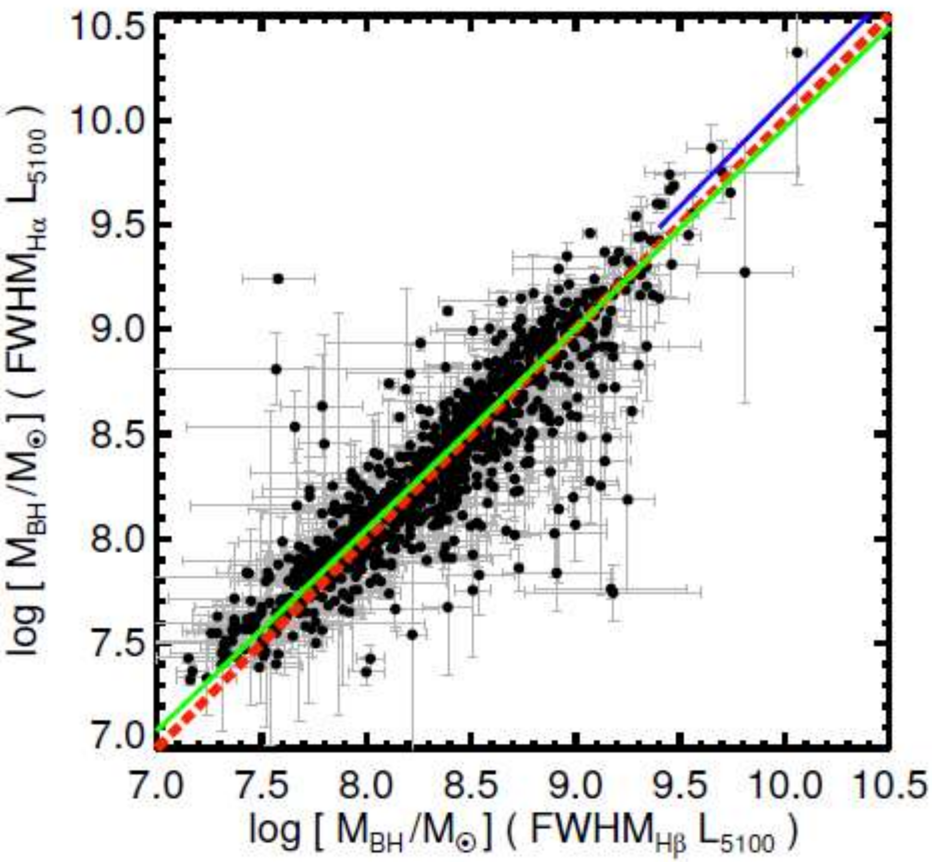
- ➔ We expect ~10 – 20% of the progenitors of the EMBHs grow by quasar phase at the epoch.



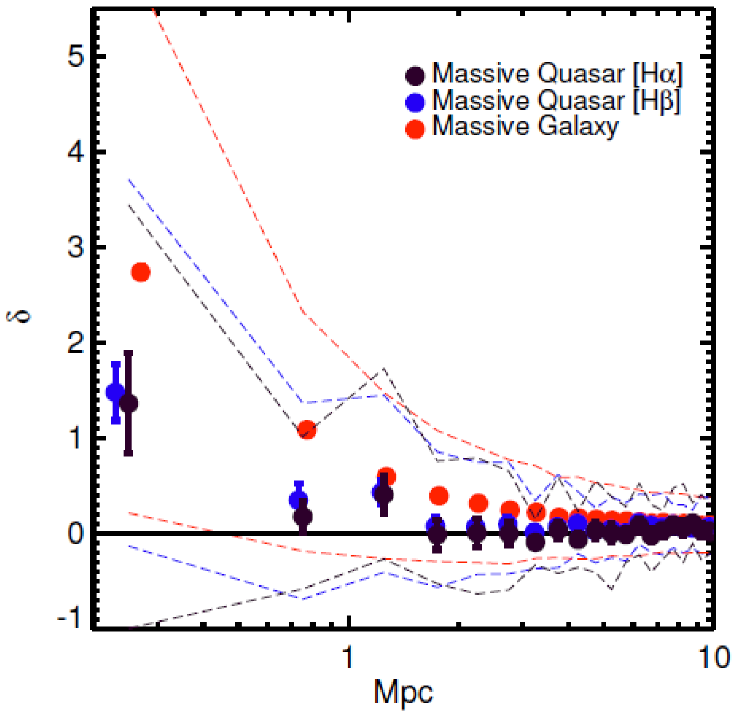
It is possible to find **proto-clusters by location of quasars at high redshift** of z>4 in consideration of the fact that the **descendants of the quasars reside in massive environments** like clusters.

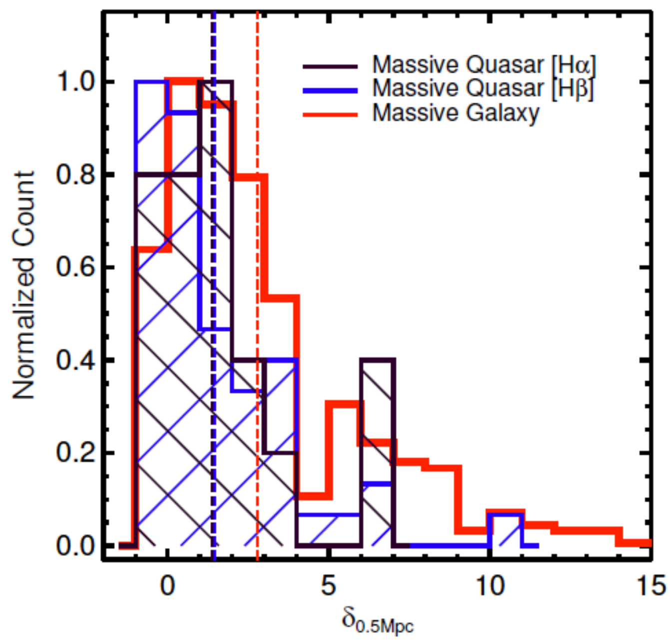


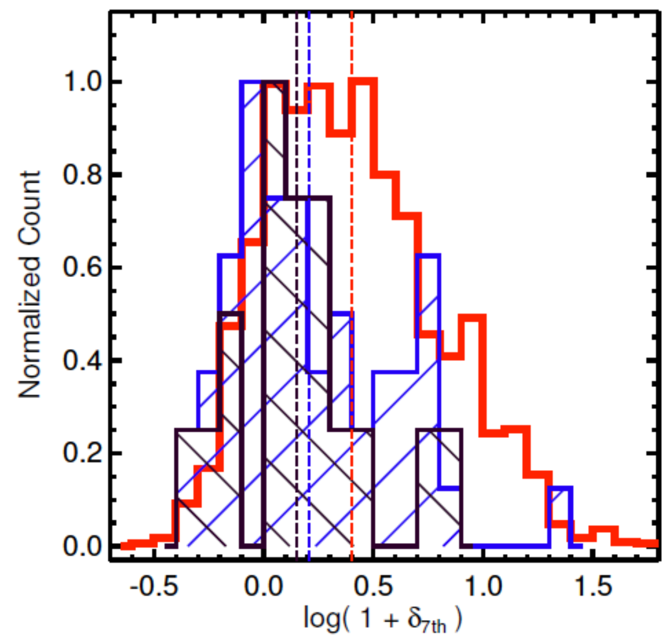
log [$M_{BH}/M_\odot$] (Our Result)
log [$M_{BH}/M_\odot$] (Shen et al. 2011)
log [L_{5100} /(erg s^{-1})] (Our Result)
log [L_{5100} /(erg s^{-1})] (Shen et al. 2011)
log [FWHM /(km s^{-1})] (Our Result)
log [FWHM /(km s^{-1})] (Shen et al. 2011)

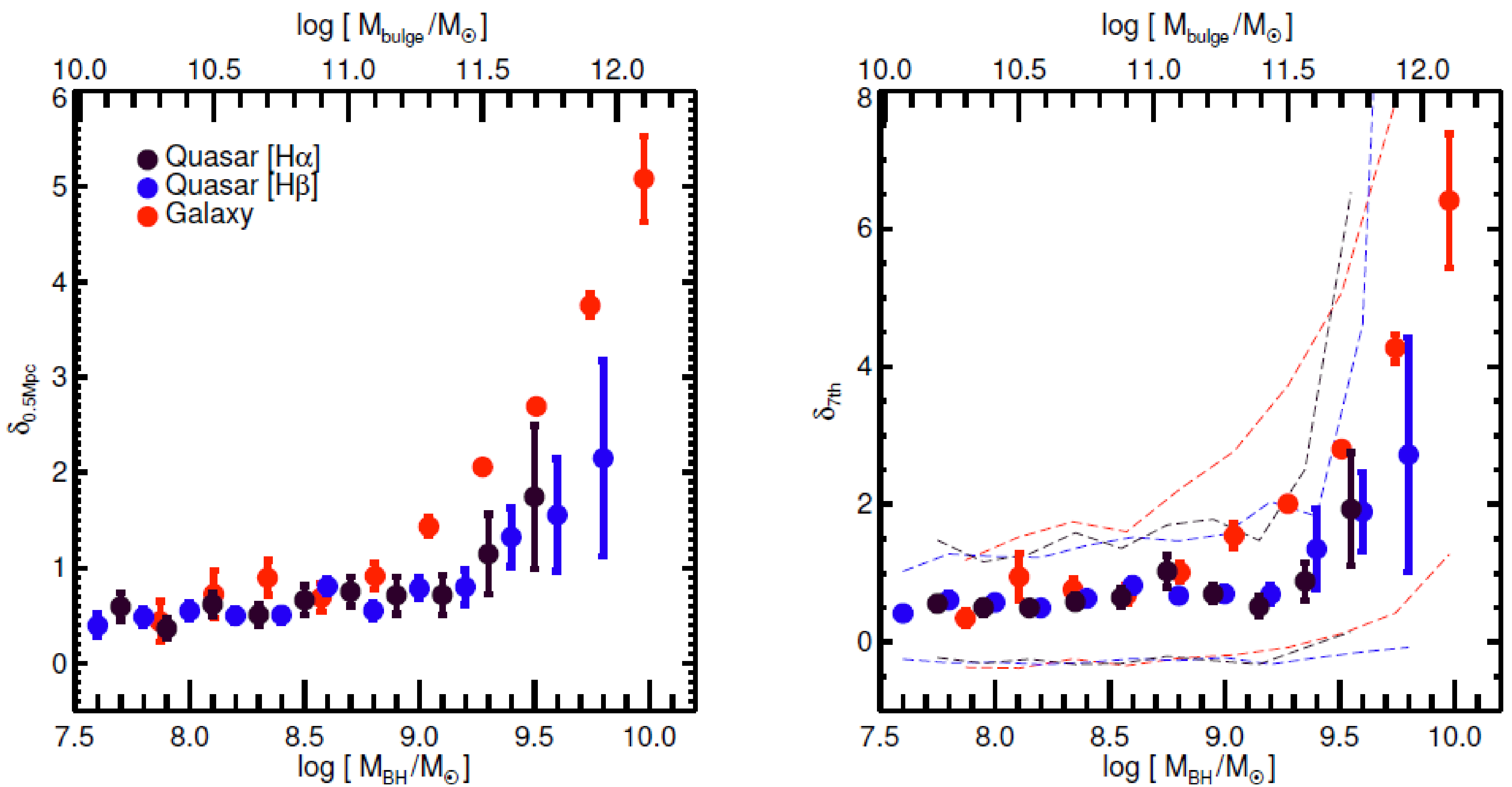


10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
log [M_BH /M_⊙] (FWHM_Hα L_5100)
7.0 7.5 8.0 8.5 9.0 9.5 10.0 10.5
log [M_BH /M_⊙] (FWHM_Hβ L_5100)

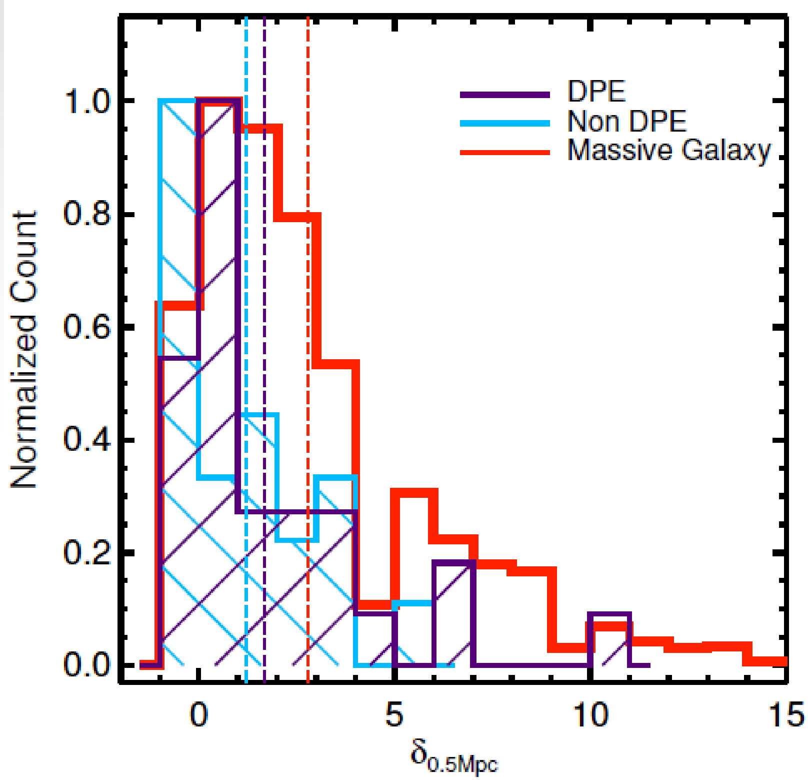

Massive Quasar [Hα]
Massive Quasar [Hβ]
Massive Galaxy
δ
Mpc
5
4
3
2
1
0
-1
1
10


Massive Quasar [Hα]
Massive Quasar [Hβ]
Massive Galaxy
Normalized Count
$\delta_{0.5Mpc}$
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15

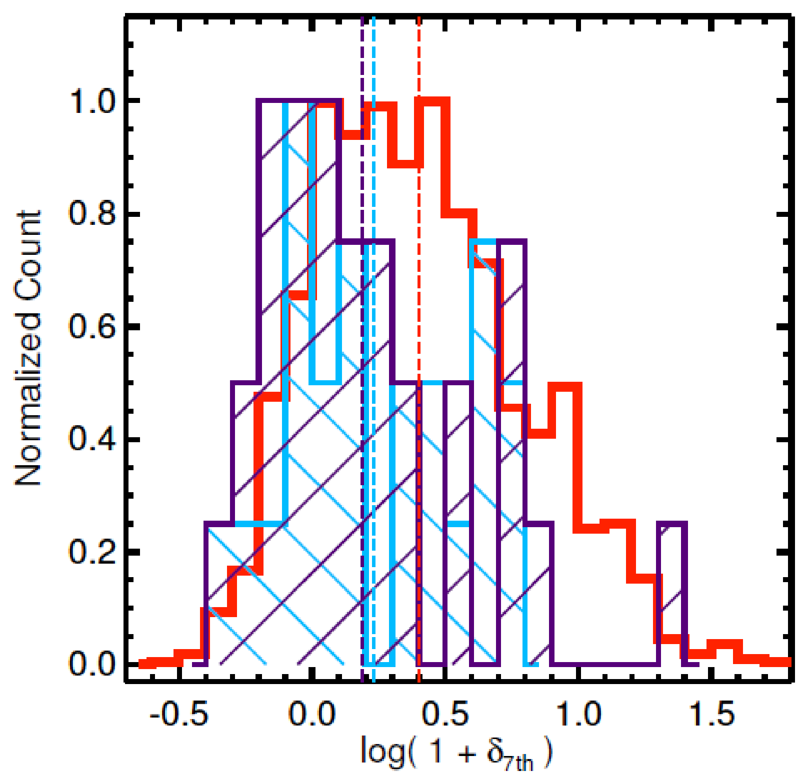

Normalized Count
log(1 + δ_{7th})
1.0
0.8
0.6
0.4
0.2
0.0
-0.5
0.0
0.5
1.0
1.5



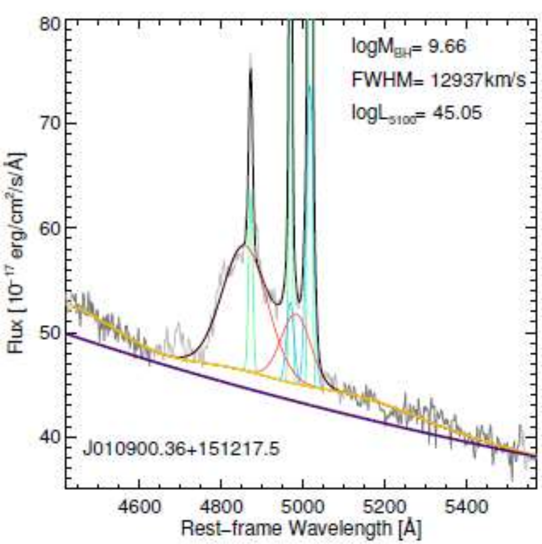
log [$M_{bulge}/M_\odot$]
10.0
10.5
11.0
11.5
12.0
Quasar [Hα]
Quasar [Hβ]
Galaxy
$\delta_{0.5Mpc}$
7.5
8.0
8.5
9.0
9.5
10.0
log [$M_{BH}/M_\odot$]
δ_{7th}



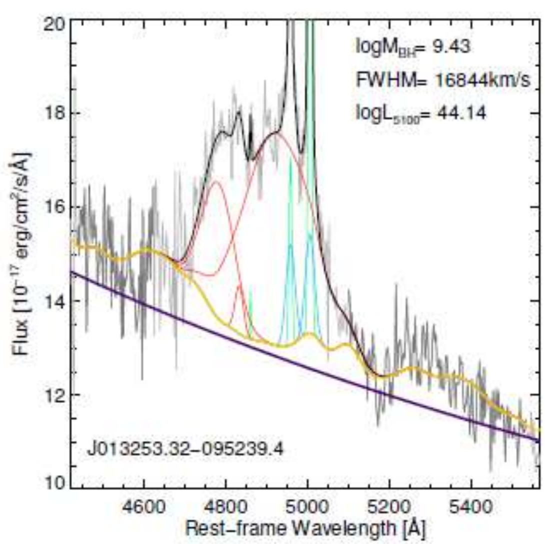
DPE
Non DPE
Massive Galaxy
Normalized Count
$\delta_{0.5Mpc}$



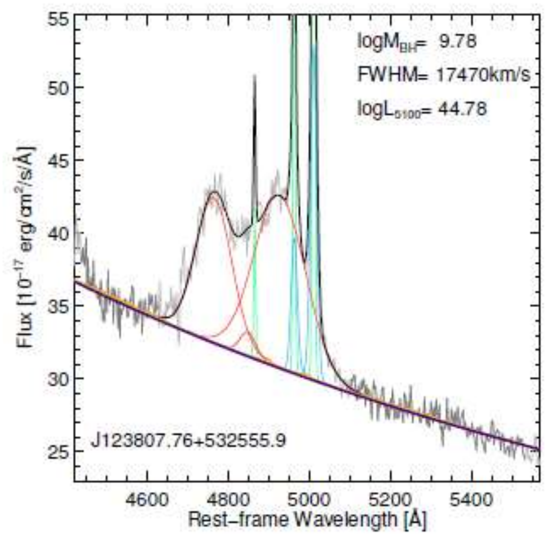
Normalized Count
log(1 + δ_{7th})



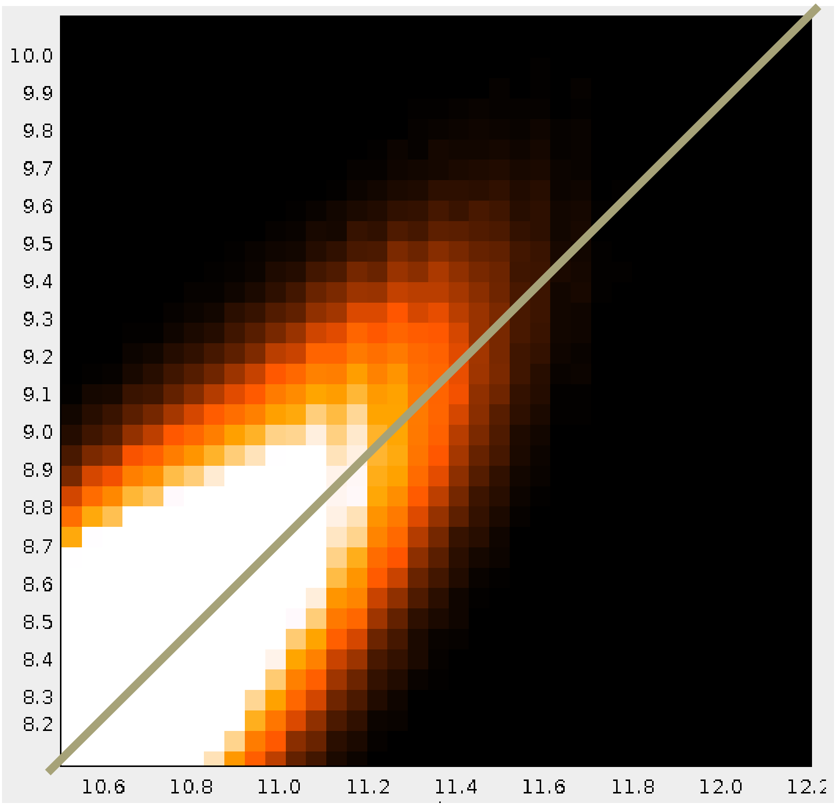
logM$_{BH}$= 9.66
FWHM= 12937km/s
logL$_{5100}$= 45.05
J010900.36+151217.5
Flux [10^{-17} erg/cm^2/s/Å]
Rest-frame Wavelength [Å]



logM$_{BH}$= 9.43
FWHM= 16844km/s
logL$_{5100}$= 44.14
J013253.32-095239.4
Flux [10^{-17} erg/cm^2/s/Å]
Rest-frame Wavelength [Å]



logM$_{BH}$= 9.78
FWHM= 17470km/s
logL$_{5100}$= 44.78
J123807.76+532555.9
Flux [10^{-17} erg/cm^2/s/Å]
Rest-frame Wavelength [Å]

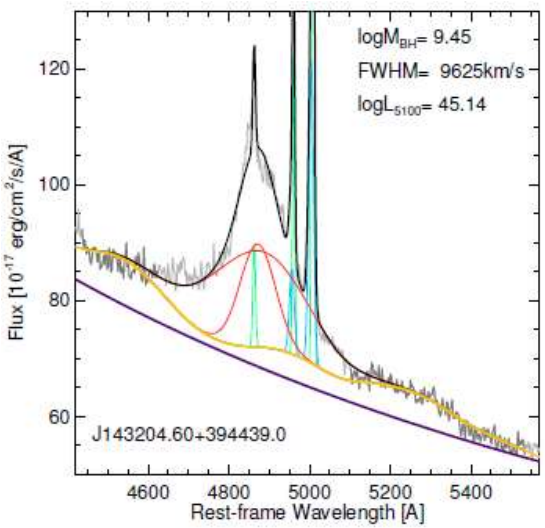

10.0
9.9
9.8
9.7
9.6
9.5
9.4
9.3
9.2
9.1
9.0
8.9
8.8
8.7
8.6
8.5
8.4
8.3
8.2
10.6
10.8
11.0
11.2
11.4
11.6
11.8
12.0

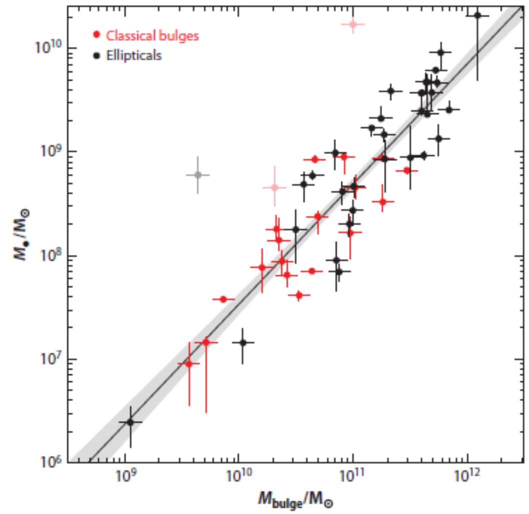
If active EMBHs turn out to be in moderate environments,

→ It can be suggested that EMBHs grow by quasar phase at group scale then later they would combine with larger and denser structures.

→ Uncertainty of black hole mass measurements at the massive end

→ Chance to examine the BH scaling relation





Kormendy & Ho (2013)