Subaru Telescope
National Astronomical Observatory of Japan

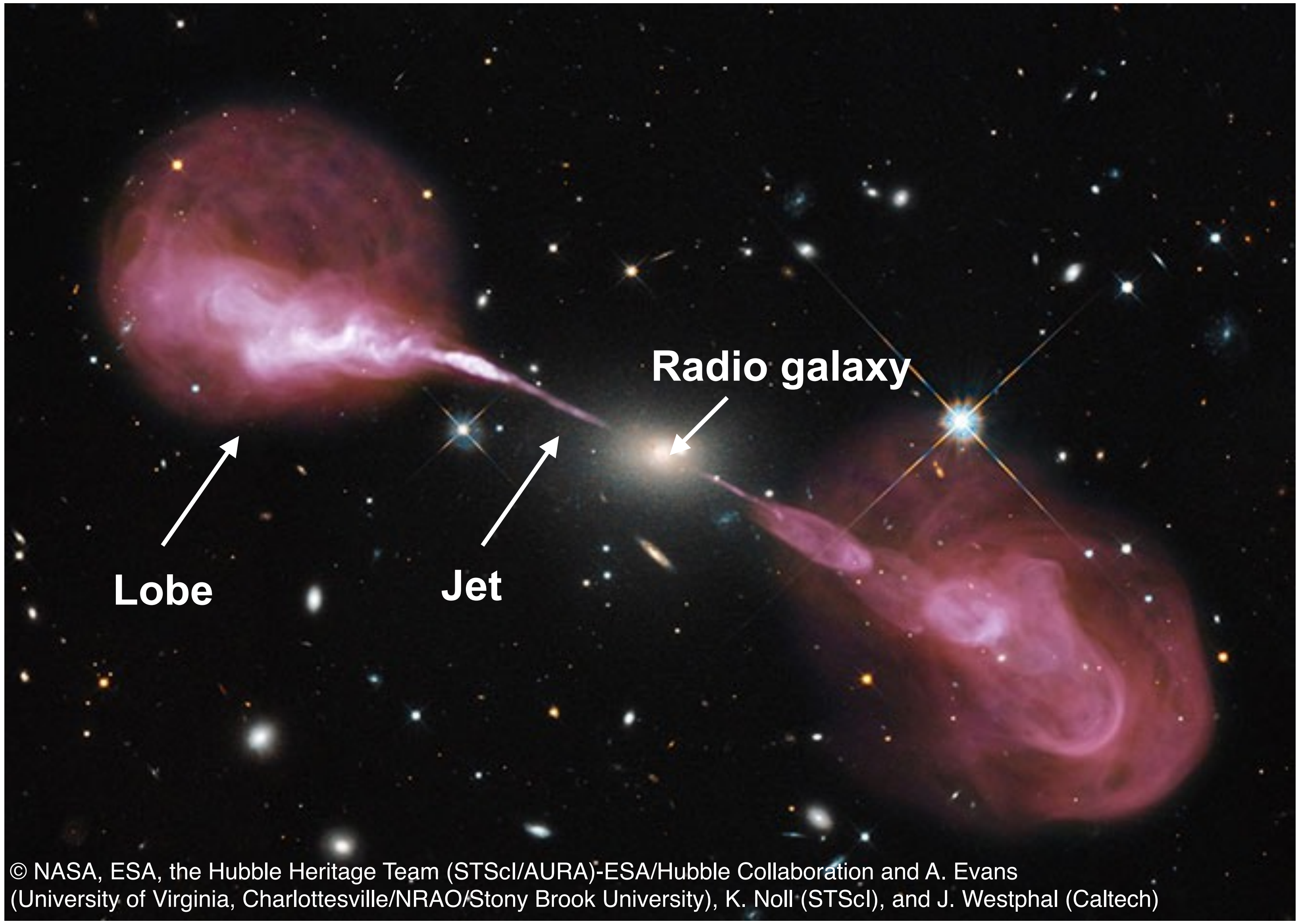
Uchiyama et al. 2021, accepted in ApJ, arXiv: 2112.01684
Uchiyama et al. 2022, to be submitted

A Wide and Deep Exploration of Radio Galaxies with Subaru HSC (WERGS). Statistical Characterization of Radio Galaxy Environments

Hisakazu Uchiyama
Ehime University

Collaborators
Takuji Yamashita, Jun Toshikawa, Nobunari Kashikawa, Kohei Ichikawa, Mariko Kubo, Kei Ito, Nozomu Kawakatu, Tohru Nagao, Yoshiki Toba, Yoshiaki Ono, Yuichi Harikane, Masatoshi Imanishi, Masaru Kajisawa, Chien-Hsiu Lee, Yongming Liang, Shogo Ishikawa, Toshihiro Kawaguchi, Akatoki Noboriguchi, and WERGS members

Radio galaxy and galaxy formation/evolution



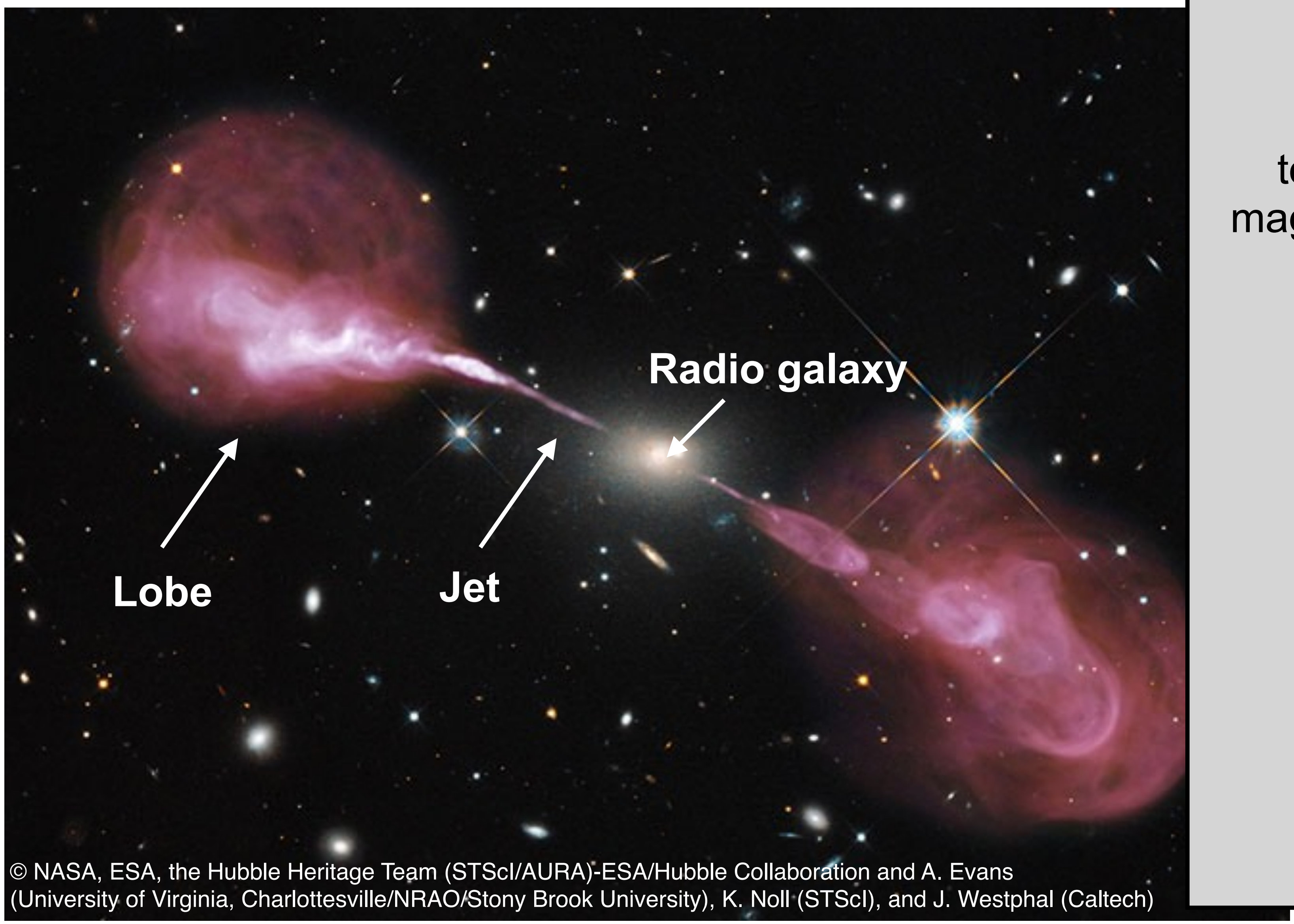
- Radio Galaxy (RG) :
  AGN launching radio jet/lobe

- Radio jets suppress gas cooling
  and thus star formation
  (e.g., Izquierdo-Villalba+18)

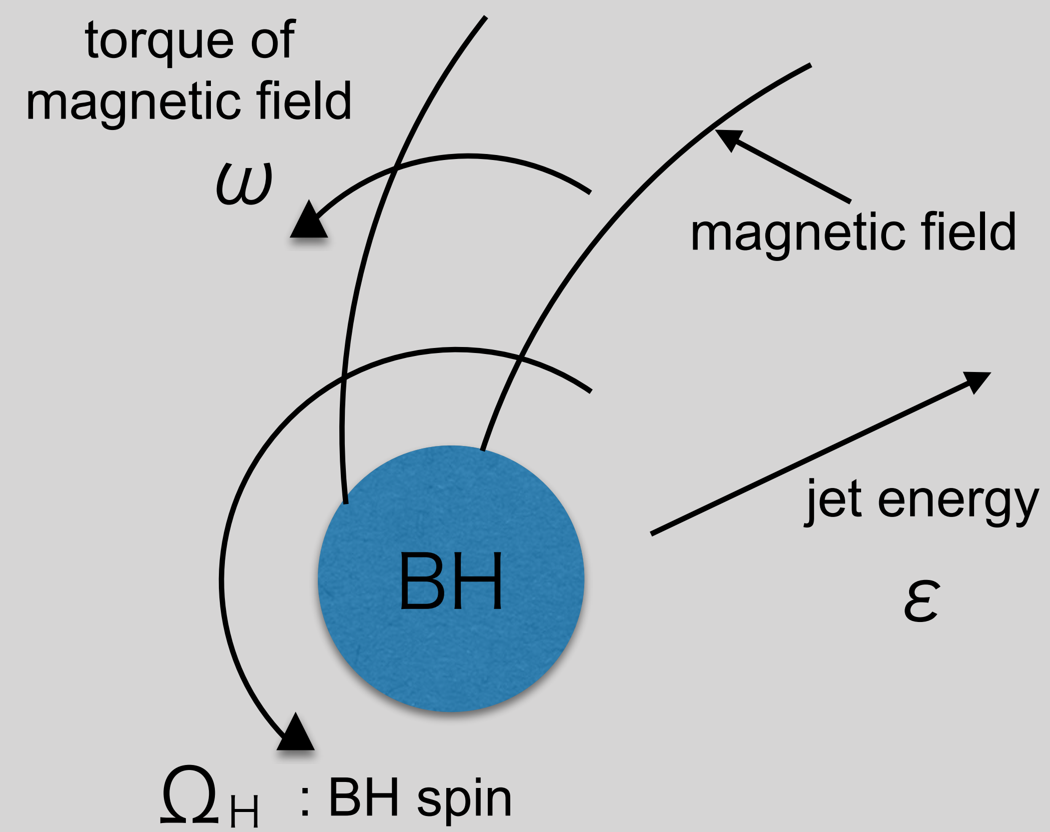
- Radio jets can extend to >1 Mpc
  (e.g., Jamrozy+14)
  → suppress star formation in
  not only the host galaxies
  but also the surrounding halos

→ In order to understand galaxy formation/evolution,
we need to understand **where** RGs appear/live.

Radio galaxy live in overdense region ?



Blandford-Znajek process
(Blandford and Znajek 1977)



$$\varepsilon \propto \omega \, (\Omega_H - \omega)$$

→ RGs are expected to appear in galaxy overdense regions or (proto)clusters preferentially ?

Previous studies and this study

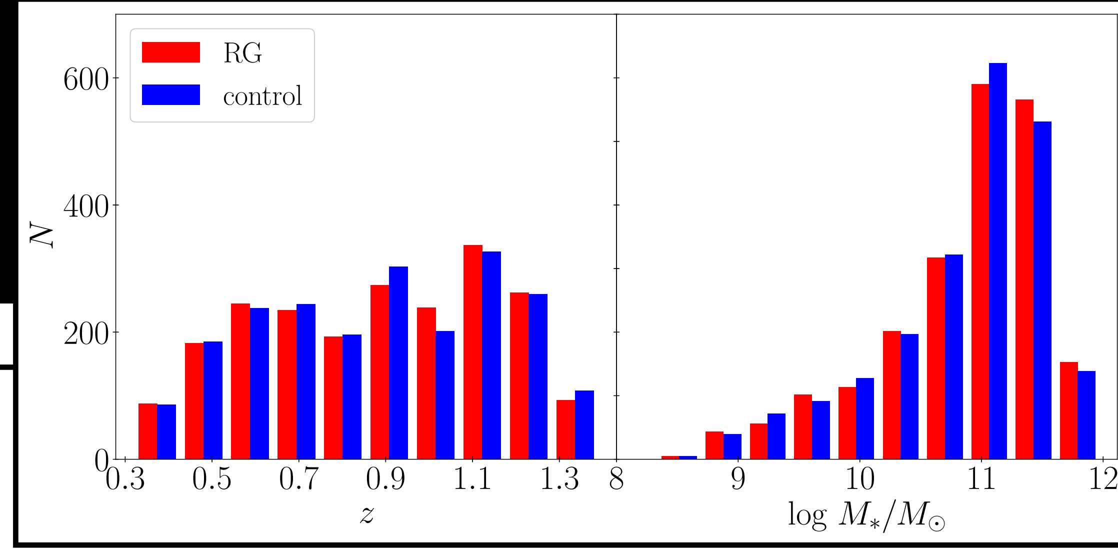
	z < 0.3	z > 0.3
Population	**massive** **elliptical** (e.g., Kron+85)	**proportion of radio galaxies hosted by less massive SFGs increase with redshift** (Donoso+09, Delvecchio+18)
Environment	**rich clusters** **overdense regions** (e.g., Venturi+07)	**overdense regions** - Kolwa+18 : SDSS Stripe 82 bias toward massive gals $M_* > 1e11$ M_{sun} - Malavasi+15 : COSMOS lack of statistical sample

We **statistically** characterize the RG environments at *z*>0.3, based on **HSC-SSP**.

Data and method

Data

Radio galaxies



- extract from **WERGS** (A Wide and Deep Exploration of Radio Galaxies with Subaru HSC ; Yamashita+18)
- WERGS is the very wide optical counter part survey (154 sq. deg) of radio galaxies with the optical depth down to i~26 based on HSC-SSP and FIRST data.

  → **2,170 radio galaxies** at photometric redshift (Mizuki; Tanaka+18) z = 0.3-1.4

Control galaxies

- photo-z galaxies (Tanaka+18) covering similar M_* and z but w/o radio detection.

Method

k-Nearest Neighbor method

$$1+\delta^k_{\mathrm{RG/control}} \equiv \frac{\Sigma^k_{\mathrm{RG/control}}}{\langle\Sigma^k_{\mathrm{Field}}\rangle}$$

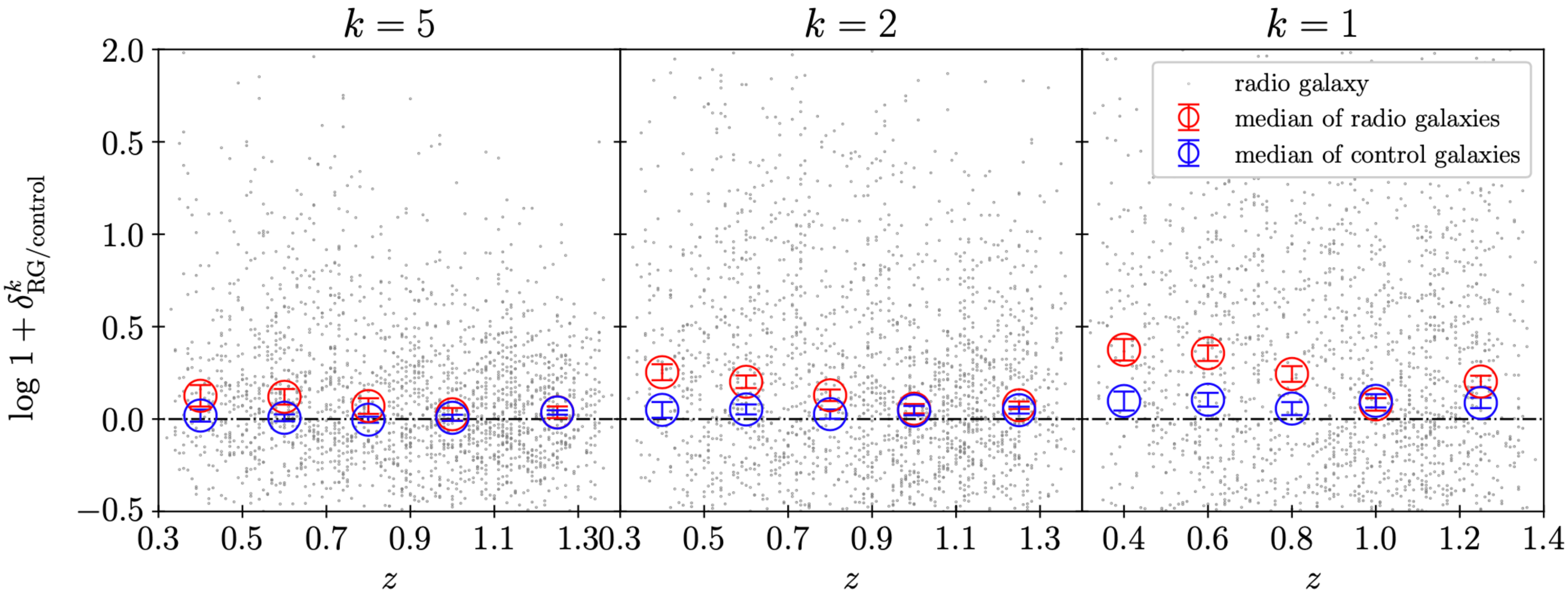
$$\Sigma^k_{\mathrm{RG/control}} \equiv \frac{k+1}{\pi d_k^2 C} \quad \mathrm{pkpc}^{-2}$$

dk : projected distance to k-th nearest photo-z galaxy

C : percentage of the area within radius dk that is not masked.

$\langle\Sigma^{N=k}_{\mathrm{Field}}\rangle$: average value of estimated for each photo-z galaxy within the redshift error of the relevant RG/control.

Result (1) redshift vs environment



- Spearman rank correlation test — control : no correlation
  RG : very weak negative correlation
- Average feature — z<0.7 : RGs reside in higher density than controls
  z>0.7 : RGs approach to average density

→ RGs tend to avoid the most overdense regions at high-z

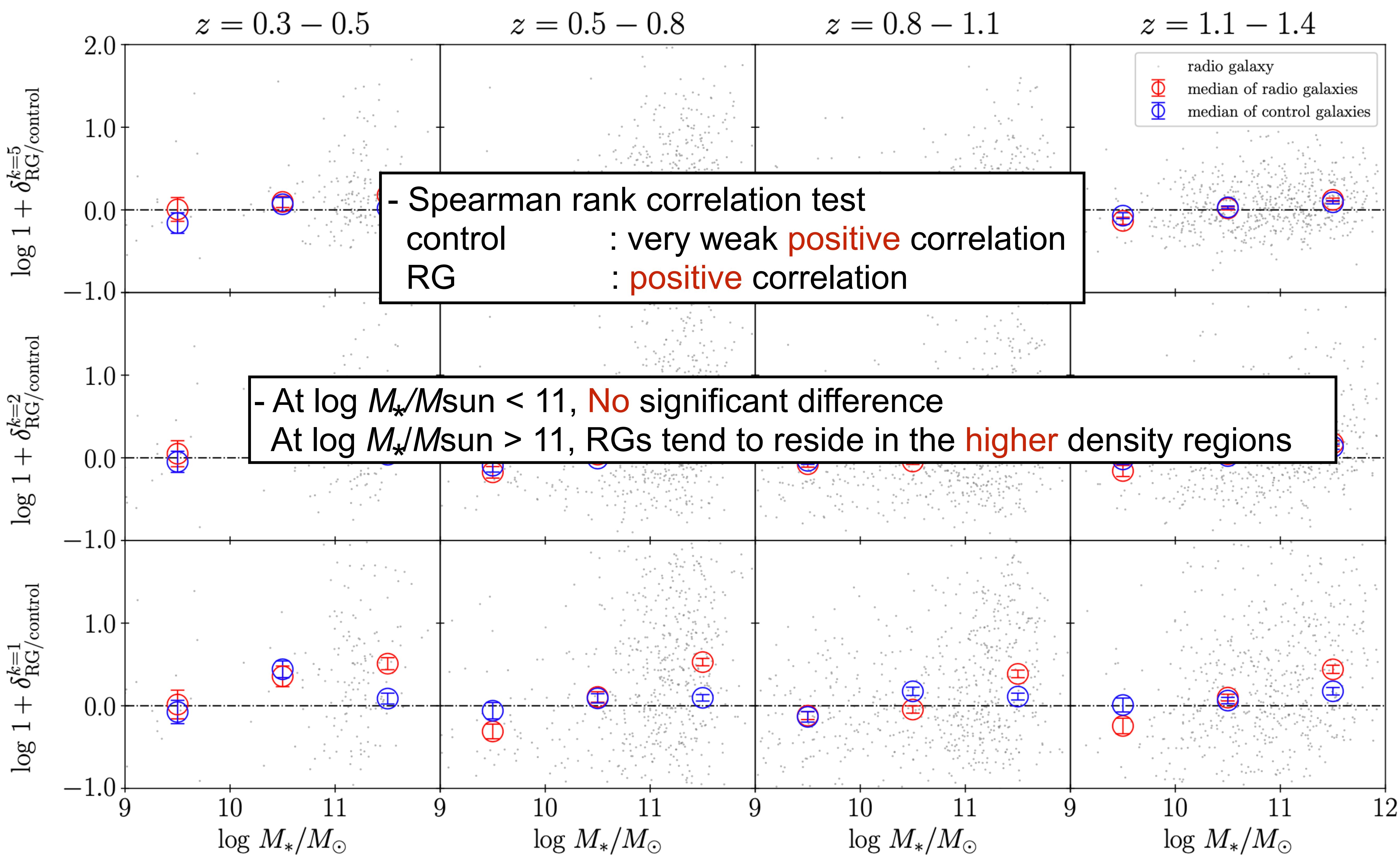
the population of less-massive RGs increase with redshift (e.g., Donoso+09)

(In fact, we find that the stellar masses of RGs decrease with redshift.)

- smaller k, larger enhance

→ related to short scale physics

Result (2) stellar mass vs environment

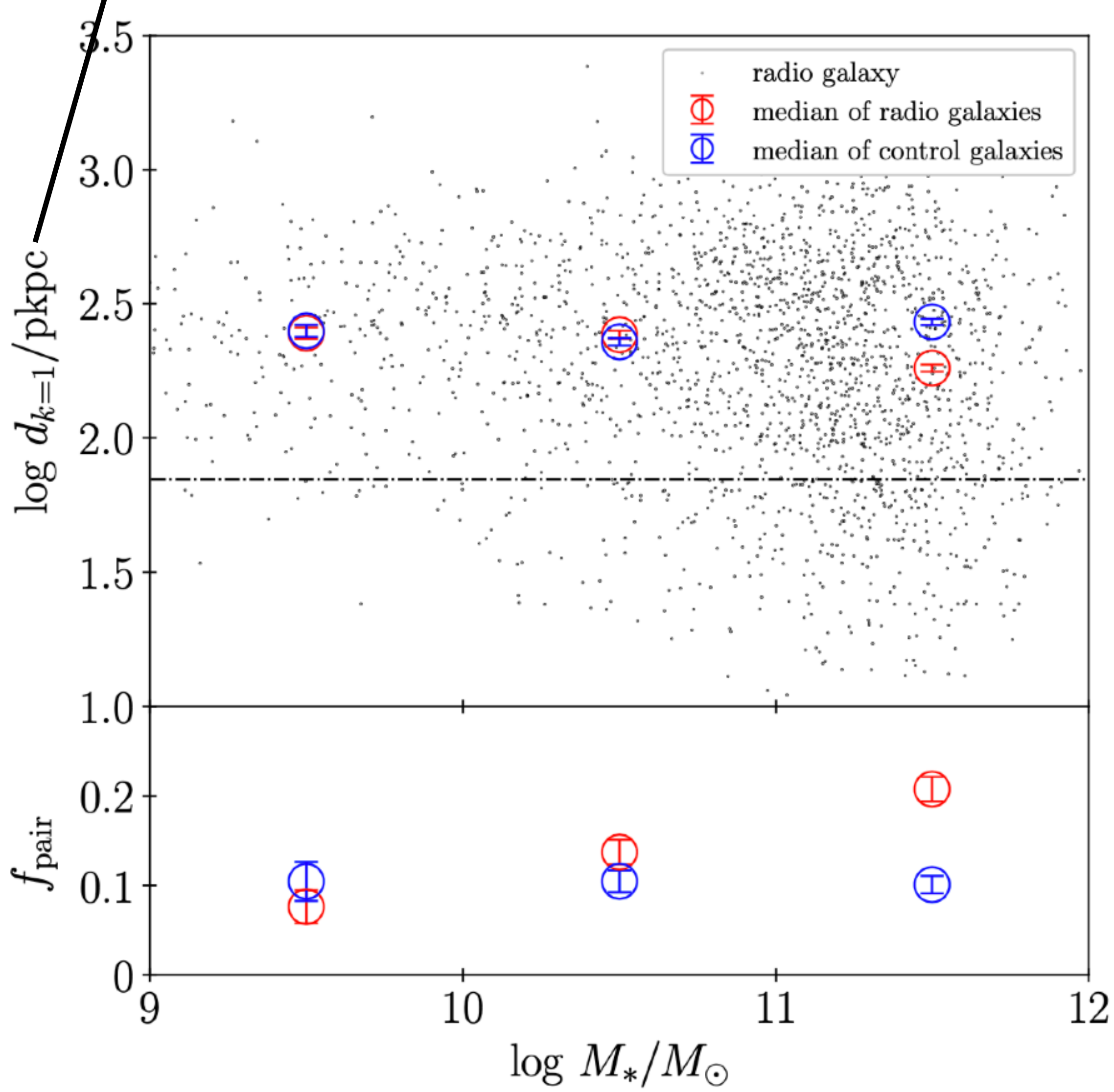


- Spearman rank correlation test
  control : very weak positive correlation
  RG : positive correlation

- At log M_*/Msun < 11, No significant difference
  At log M_*/Msun > 11, RGs tend to reside in the higher density regions

Discussion: Triggering of radio galaxy and Role of the local environment

$d_{k=1}$ [pkpc]; projected distance from RG/control to the nearest galaxies



- The major merger scale is <70 pkpc (Larson+16)

- pair fraction

$$f_{\rm pair}(M_*) = n_{d<70}(M_*)/n_{\rm tot}(M_*)$$

numerator : # of RG/control with $d_{k=1}$<70 pkpc
denominator : total # of RG/control

→ Implication :
massive-end radio galaxies are likely to be associated with mergers

- We also find that the local densities of RGs are negative correlated with the black hole accretion rates (sBHAR; Toba+19, Ichikawa+21).

These findings are consistent with a scenario:
massive RGs have already matured at z = 0.3-1.4 through galaxy mergers in the past, while less-massive RGs undergo active accretion just at this epoch by avoiding past mergers (e.g., Bower+17, Habouzit+17, Ichikawa+21).

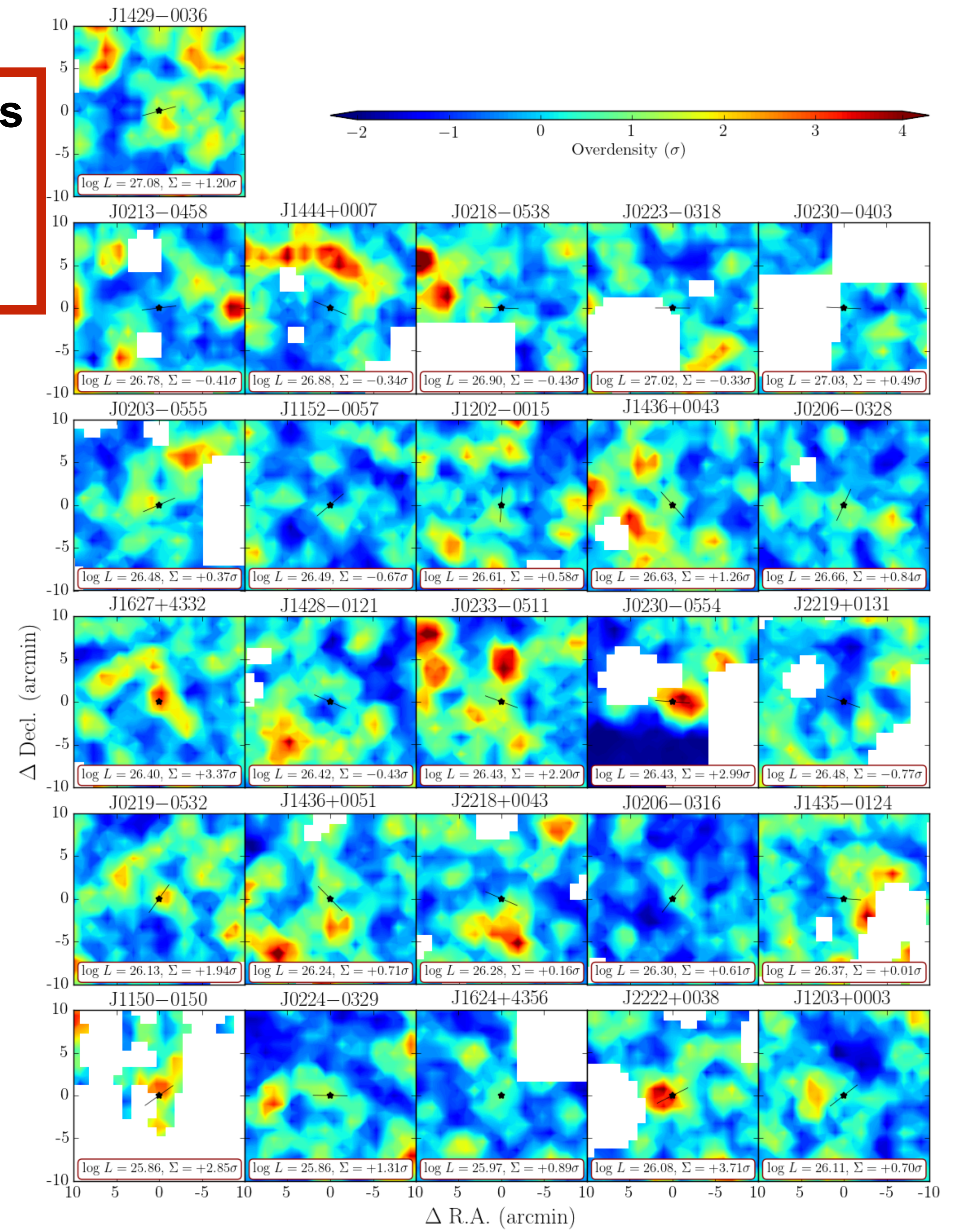
Environments of high-z RGs at z~4

We statistically characterize the environments of high-z radio galaxies (HzRGs) at z~4 by using galaxy surface density of g-dropout galaxies, based on HSC-SSP.

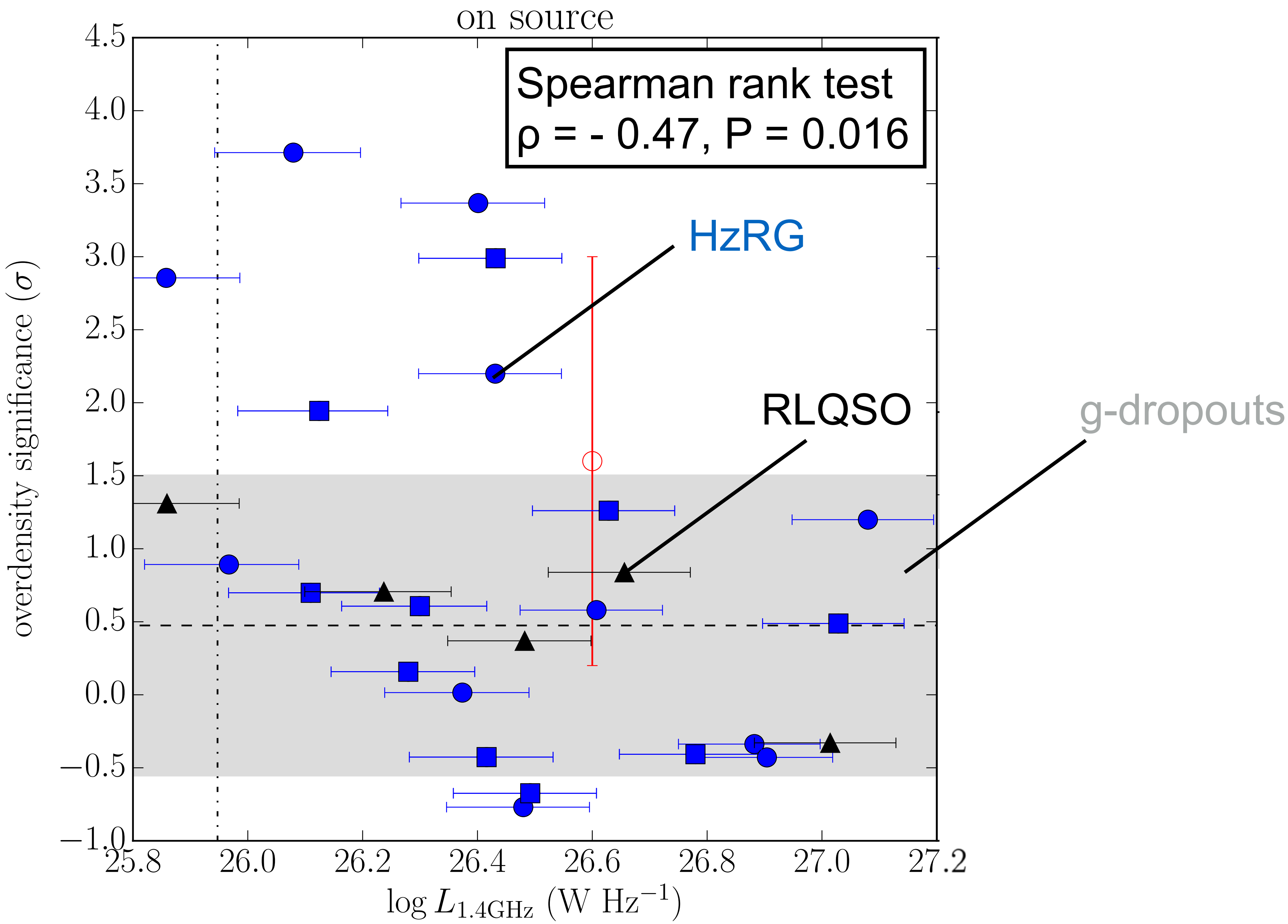
Uchiyama et al. 2021, accepted in ApJ
arXiv: 2112.01684

- **Surface density catalog (Toshikawa+18)**
  they select g-dropout galaxies in the Wide layer of S16A DR, and make galaxy surface density map

- **HzRGs (T. Yamashita et al., in prep.)**
  Matching g-dropouts (Ono+18) with FIRST
  → 21 HzRGs + 5 RLQSOs candidates

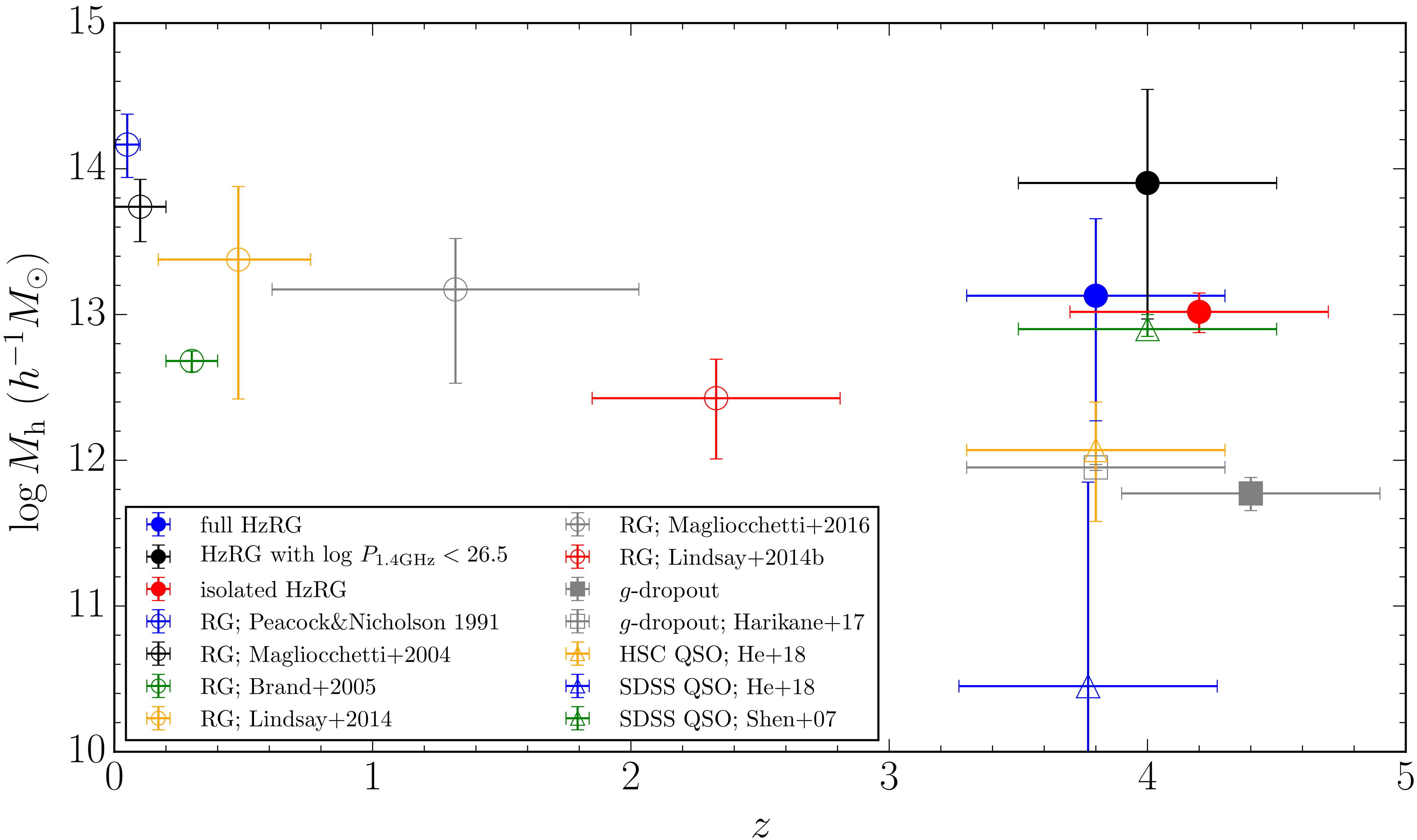


Dependency of overdensity on radio luminosity



- The surface densities around HzRGs are anti-correlated with their radio luminosities.
- In the radio-luminous regime (log $L_{1.4GHz}$ /(W/Hz) > 26.5), there are no significant difference between the densities around the HzRGs and the g-dropouts,
- at log $L_{1.4GHz}$ /(W/Hz) <26.5, HzRGs tend to reside in the denser regions than g-dropouts.

HzRG Halo mass from clustering analysis



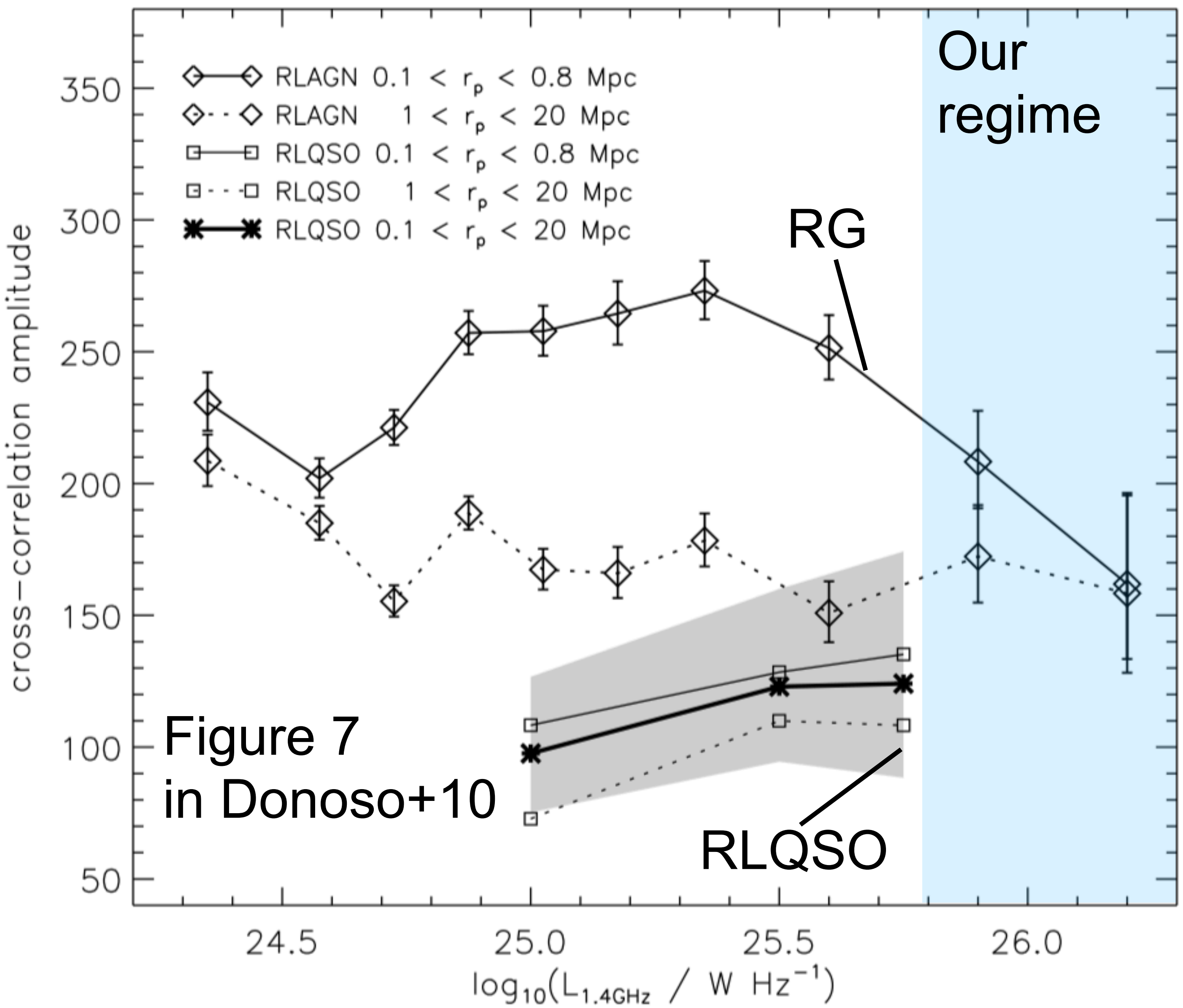
- The HzRGs are found to occupy more massive halos than g-dropout galaxies.
- This trend is more pronounced in the faint HzRGs.

Discussion: luminosity dependency

The densities/halo masses of our HzRGs are anti-correlated with their radio luminosities.

→ Our result is consistent with the scenario (e.g., Donoso+10)

Radio galaxies get younger and less massive as the radio-luminosity increases.



- at log L>25.3, the clustering strength of RLAGNs are anti-correlated with their radio luminosities
  → explained from the fact that the most luminous RGs are mostly classified into high-excitation RGs (HERGs) (e.g., Jackson&Wall+99)

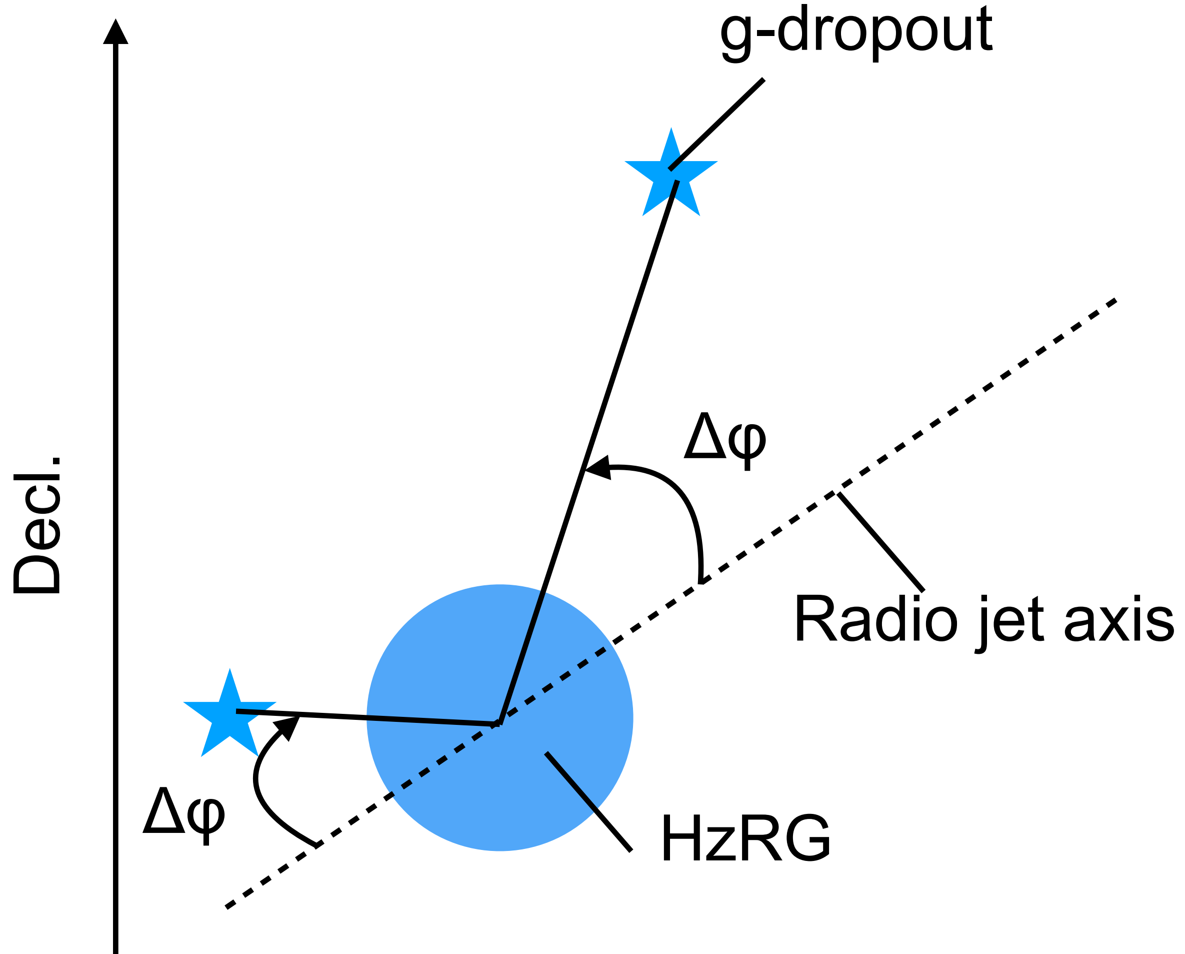
→ Our result is consistent with the scenario.

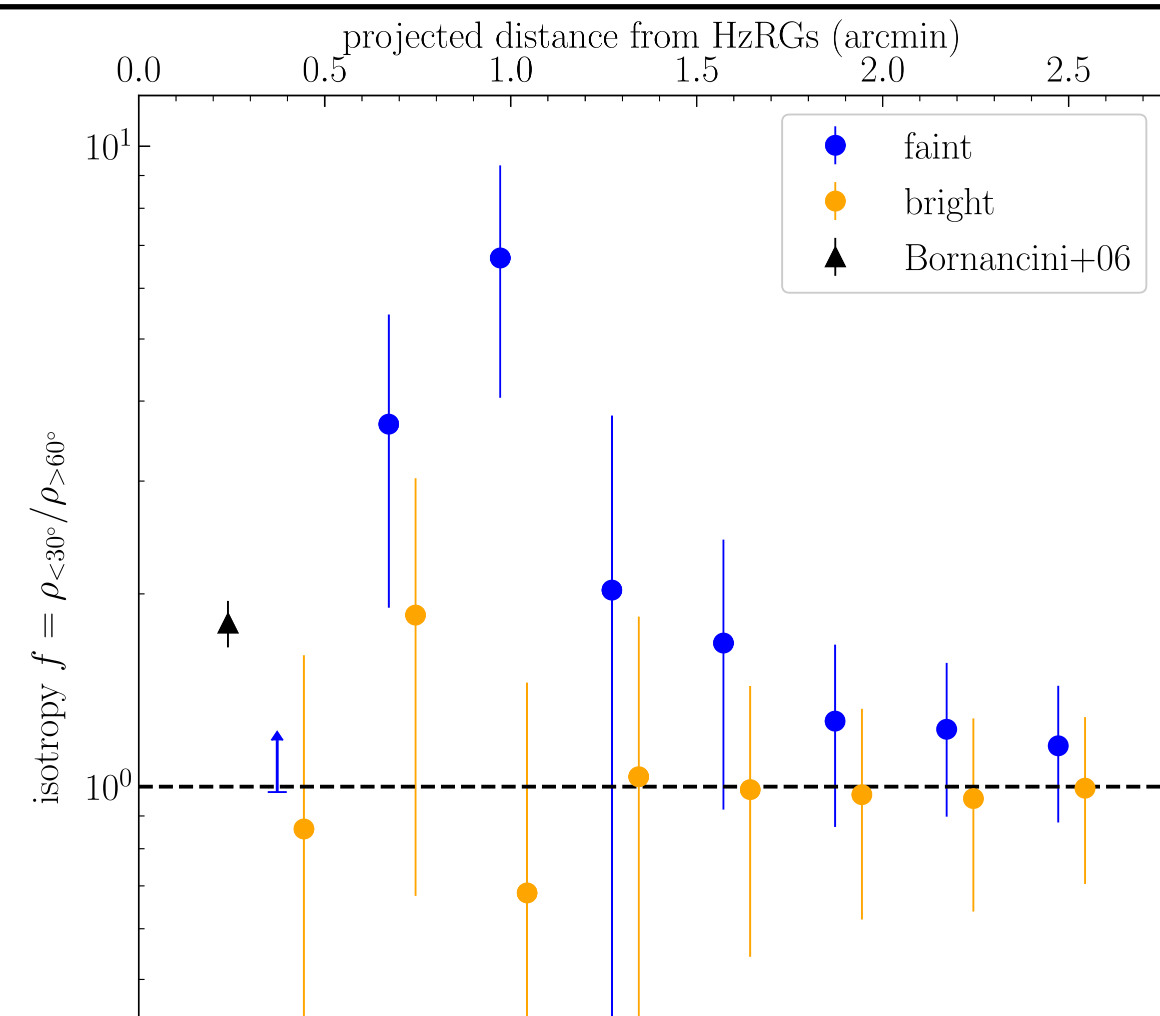
→ HzRGs get older and more massive as the radio-luminosity decreases.

Companion alignment

- isotropy parameter, **f(r) = N<30 (r)/ N>60 (r)** (e.g., Bornancini+06)

N<30 (r) and N>60 (r) : the number of galaxies with Δφ<30 and Δφ>60 deg within the projected radius of r arcmin centered on a HzRG
Δφ : the orientation of the galaxies for the radio major axis of a HzRG





- At r<400 pkpc, the surrounding galaxies tend to distribute along the radio major axis of the faint HzRGs.

→ Our findings imply **the onset of the filamentary structures around HzRGs at z ~ 4**

Summary

We statistically characterize the RG environments at z=0.3-1.4, based on HSC-SSP.

- RGs tend to avoid the most overdense regions at high-z
  → consistent with the scenario where the population of less-massive RGs increase with z
- We found that at log M < 11, the radio galaxies reside in the same density regions as controls, while, the radio galaxies reside in higher density regions compared to controls at log M > 11.
- In the case of k=1, this trend is more pronounced.
  → consistent with a scenario: massive RGs have already matured at z = 0.3-1.4 through galaxy mergers in the past, while less-massive RGs undergo active accretion just at this epoch by avoiding past mergers.

We statistically characterize the environments of high-z radio galaxies HzRGs at z~4 by using galaxy surface density of g-dropout galaxies, based on HSC-SSP.

- We found that the surface densities and halo masses of HzRGs are anti-correlated with their radio luminosities.

→ HzRGs get older and more massive as the radio luminosity decreases.

- At r<400 pkpc, the surrounding galaxies tend to distribute along the radio major axis of the faint HzRGs.

→ Our findings imply the onset of the filamentary structures around HzRGs at z ~ 4