DECIPHERING THE LARGE-SCALE ENVIRONMENT OF RADIO GALAXIES IN THE LOCAL UNIVERSE

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Outline

This is the story of a question ... what is the meaning of the word "often"?

1. Please let me start with something "well-known": radio galaxy classification.
2. The connection between classification and environment.
3. A few details on the analysis carried out and the samples we used.
4. Results !!!
5. Future perspectives.

The FR classification of radio galaxies

Our radio Universe is populated by FR I and FR II radio galaxies

Mon. Not. R. astr. Soc. (1974) **167,** *Short Communication,* 31P–35P.

THE MORPHOLOGY OF EXTRAGALACTIC RADIO SOURCES OF HIGH AND LOW LUMINOSITY

B. L. Fanaroff and J. M. Riley

(Received 1974 March 6)

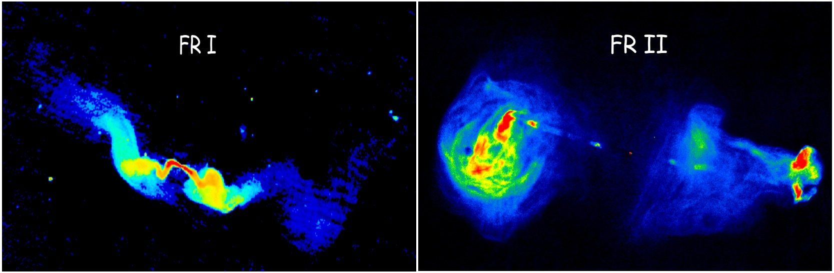
SUMMARY

The relative positions of the high and low brightness regions in the extragalactic sources in the 3CR complete sample are found to be correlated with the luminosity of these sources.

In 1974 Fanaroff & Riley introduced the first classification scheme of radio galaxies.
A criterion that is not only based on the RG morphological properties
but also related to their radio luminosities.
(radio morphology → power → cosmology)

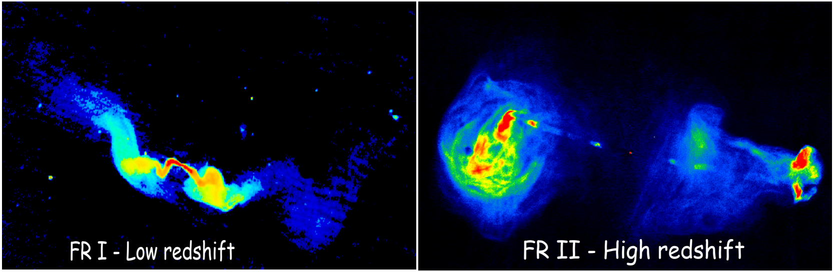
The FR classification of radio galaxies

The RGs were classified on the basis on the ratio R_{FR} of the distance between the regions of highest surface brightness on opposite sides of the central galaxy to the total extent of the source up to the lowest brightness contour.



Sources with $R_{FR} \leq 0.5$ were placed in Class I (i.e., FR I) and sources with $R_{FR} \geq 0.5$ in Class II (i.e., FR II). In particular, at GHz radio frequencies, FR Is show surface brightness higher toward their cores while FR IIs toward their edges.

The FR classification of radio galaxies



Fanaroff and Riley found that all sources with radio luminosity at 178 MHz

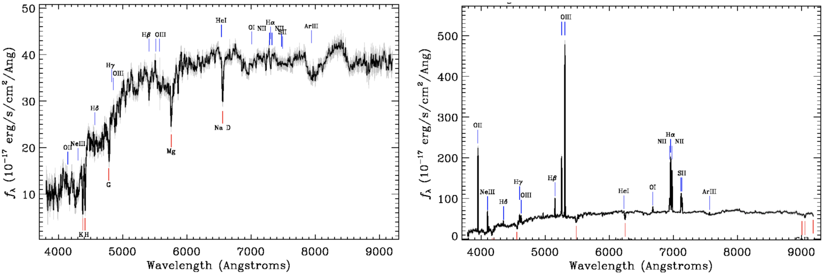
$$L_{178\text{MHz}} \leq 2 \times 10^{25} h_{100}^{-2} WHz^{-1} str^{-1} \qquad (1)$$

were classified as Class I while the brighter sources all were Class II.

This luminosity boundary between them is not very sharp, and there is some overlap in the luminosities of sources classified as FR I or FR II on the basis of their structures.

... and more recently also an optical classification

The RGs were classified on the basis on the emission lines in their optical spectra distinguishing between LERGs and HERGs.

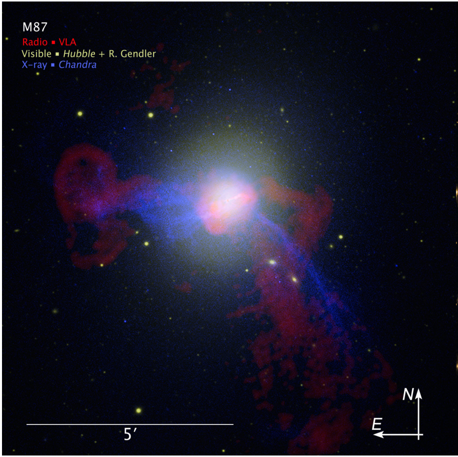


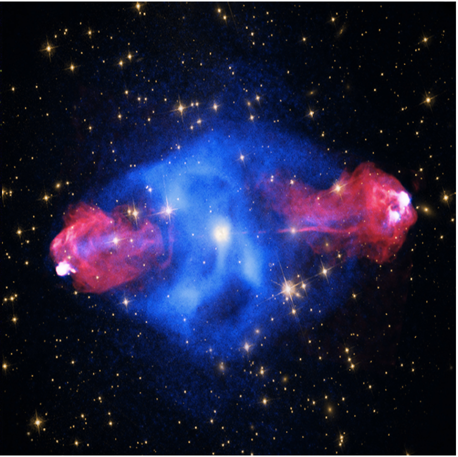
Most of the FR Is tend to be LERGs while a fraction of the FR IIs are indeed classified as HERGs, especially at high redshift.
The difference between HERG/LERG optical emission lines is not simply related to orientation effect but also reflects accretion modes (i.e., radiatively efficient vs inefficient).

The link with the large scale environment of radio galaxies

1. Have you ever seen an FR I radio galaxy in a group and/or a cluster of galaxies? Let's say in a galaxy dense/rich large-scale (0.5 Mpc scale) environment!
2. What about an FR II radio galaxy?
3. And what about HERGs and LERGs?

Of course we all did ... here some famous examples right?





In addition ...

We generally "believe" that:

FR I radio galaxies generally lie in galaxy-rich large-scale environments being **often** associated with galaxy clusters while FR IIs tend to live in small groups and/or more isolated.

More recently people tend to use the optical classification claiming "something similar" for LERGs and HERGs.

This brings the dichotomy between FR I and FR II and/or the one between LERGs and HERGs to a different level: interaction with their environment.

All correlated by a vast literature

... Prestage & Peacock (1988); Hill & Lilly (1991); Best (2004); Belsole (2007); Gendre et al. (2013); Ineson et al. (2013); Ineson et al. (2015); Miraghei & Best (2017); Ching et al. (2017), to name a few ...

Comparing claims arising from different analyses carried out with different techniques and on different samples requires extreme caution.

Biases in the methods adopted to estimate the cluster richness or even the association with a galaxy group or cluster could affect conclusions, as well as differences in the region sizes adopted to perform galaxy counts.

The possible presence of environment evolution with redshift makes not comparable high and low z analyses. Changes in HERG and LERG populations with redshift z and the lack of powerful sources in our local Universe must be taken into account when performing sample selections, as well as the Malmquist bias in flux limited catalogs.

Mendel *vs* Darwin

The main point we wish to address is summarized as follows:

What is the link between radio galaxy classifications and their environments?

In other words test if differences in the radio morphology and/or those linked to the accretion modes are affected by the large-scale environment.

Ingredients

1. First: let's find a FR I radio galaxy catalog and maybe even an FR II radio galaxy catalog.
2. Second: let's get a group and/or clusters of galaxies catalog ... maybe more than one and some clustering algorithms.
3. Third: mix them with care ... shake and let's see what you get.

What I meant with a radio galaxy catalog

Something we could not find and we built! → FIRST+NVSS+SDSS+WISE

FRI*CAT*: A FIRST catalog of FR I radio galaxies.

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ABSTRACT

We built a catalog of 219 FR I radio galaxies (FR Is), called FRI*CAT*, selected from a published sample and obtained by combining observations from the NVSS, FIRST, and SDSS surveys. We included in the catalog the sources with an edge-darkened radio morphology, redshift ≤ 0.15, and extending (at the sensitivity of the FIRST images) to a radius r larger than 30 kpc from the center of the host. We also selected an additional sample (sFRI*CAT*) of 14 smaller ($10 < r < 30$ kpc) FR Is, limiting to $z < 0.05$. The hosts of the FRI*CAT* sources are all luminous ($-21 \gtrsim M_r \gtrsim -24$), red early-type galaxies with black hole masses in the range $10^8 \lesssim M_{\rm BH} \lesssim 3\times10^9 M_\odot$; the spectroscopic classification based on the optical emission line ratios indicates that they are all low excitation galaxies. Sources in the FRI*CAT* are then indistinguishable from the FR Is belonging to the Third Cambridge Catalogue of Radio Sources (3C) on the basis of their optical properties. Conversely, while the 3C-FR Is show a strong positive trend between radio and [O III] emission line luminosity, these two quantities are unrelated in the FRI*CAT* sources; at a given line luminosity, they show radio luminosities spanning about two orders of magnitude and extending to much lower ratios between radio and line power than 3C-FR Is. Our main conclusion is that the 3C-FR Is just represent the tip of the iceberg of a much larger and diverse population of FR Is.

FRII*CAT*: a FIRST catalog of FR II radio-galaxies.

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ABSTRACT

We built a catalog of 122 FR II radio galaxies, called FRII*CAT*, selected from a published sample obtained by combining observations from the NVSS, FIRST, and SDSS surveys. We included in the catalog the sources with redshift ≤ 0.15, an edge-brightened radio morphology, and with at least one of the emission peaks located at radius r larger than 30 kpc from the center of the host.
The radio luminosity at 1.4 GHz of the FRII*CAT* sources covers the range $L_{1.4} \sim 10^{39.5} - 10^{42.5}$ erg s^{-1}. FRII*CAT* is formed by 90% of low and 10% of high excitation galaxies (LEGs and HEGs), respectively. The properties of these two classes are significantly different. FRII*CAT* LEGs are mostly luminous ($-20 \gtrsim M_r \gtrsim -24$), red early-type galaxies with black hole masses in the range $10^8 \lesssim M_{\rm BH} \lesssim 10^9 M_\odot$; they are essentially indistinguishable from the FR Is belonging to the FRI*CAT*. HEG FR IIs are associated with optically bluer and mid-IR redder hosts than the LEG FR IIs, and to galaxies and black holes smaller, on average, by a factor ~2.
FR IIs have a factor ~ 3 higher average radio luminosity than FR Is. Nonetheless, most (~ 90 %) of the selected FR IIs have a radio power that is lower, by as much as a factor of ~100, than the transition value between FR Is and FR IIs found in the 3C sample. The correspondence between the morphological classification of FR I and FR II and the separation in radio power disappears when including sources selected at low radio flux thresholds, in line with previous results. In conclusion, a radio source produced by a low power jet can be edge brightened or edge darkened, and the outcome is not related to differences in the optical properties of the host galaxy.

Finding a galaxy cluster catalog was easier but not super obvious and we used the Tempel+12 (T12) based on SDSS DR8 as well as the GMBCG (Hao et al. 2010) catalog based on the search of the red sequence around candidate BCGs.

... a few more definitions

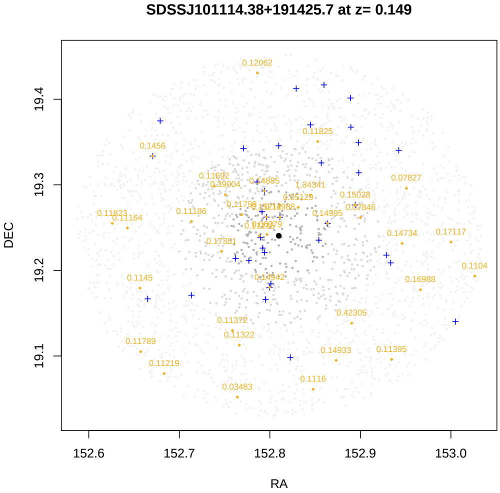
Cosmological neighbors: all the optical sources lying within the 2Mpc radius computed at the redshift of the central object z_{src} with all the SDSS magnitude flags indicating a galaxy-type object (i.e., uc=rc=gc=ic=zc=3), and having a measured spectroscopic redshift z, with $\Delta z = |z_{src} - z_{cl}| \leq 0.005$ (i.e., $\sim$1500 km/s).

Candidate elliptical galaxies: those SDSS sources, lying within the 2Mpc distance from the central radio galaxy, estimated at z_{src}, and having optical colors consistent with those of the quiescent elliptical source within $\Delta z < 0.005$ at 90% a level of confidence (KDE). Source selected as candidate elliptical galaxies do not necessarily have spectroscopic redshifts.

Mock sources: In our analysis we used a catalog of mock sources (labeled as MOCK), created shifting the position of each source in the radio galaxy catalogs several times, by a random radius between 2 and 3 degrees in a random direction of the sky, up to obtain 5000 fake sources/positions (more than one order of magnitude that the entire radio galaxy sample). We then removed from the MOCK sample all sources lying within 5" from the positions of real radio source.

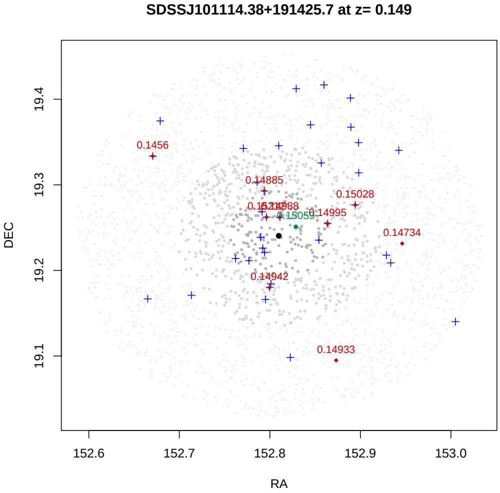
The large-scale environment from an optical perspective

Central radio galaxy, surrounding galaxies, sources with spectroscopic redshifts and candidate elliptical galaxies ... all within 2Mpc.



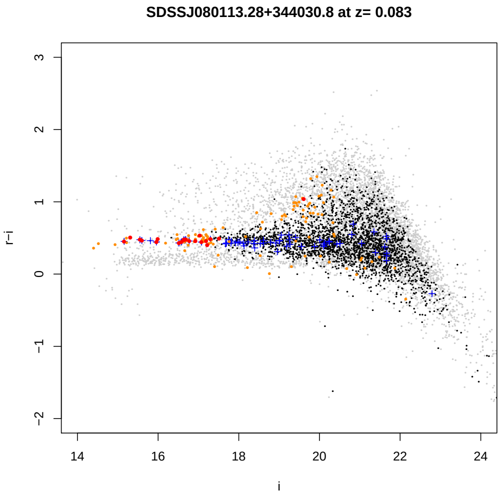
The large-scale environment from an optical perspective

Central radio galaxy, surrounding galaxies, cosmological neighbors, candidate elliptical galaxies and closest galaxy cluster/group ... all within 2Mpc.



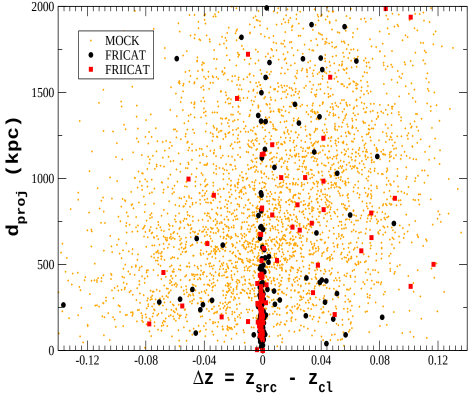
Red Sequence

just a check



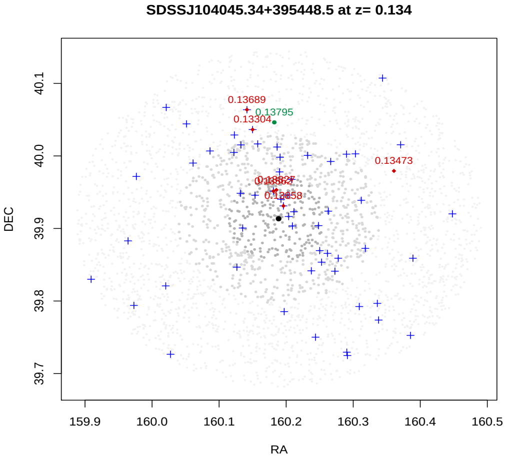
Cross-matching with a catalogs of groups and clusters

Using the T12 galaxy group/cluster catalog ...



Cross-matching with a catalogs of groups and clusters

need to recover some cases ... as well as those having $N_{gal} = 2$ (richness estimate in the T12 catalog).



Thresholds

Hereinafter we are going to consider a source living in a galaxy-rich large-scale environment when at least one of the following statement is verified.

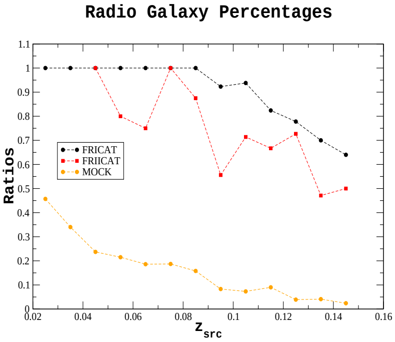
1. There is a group/cluster of the T12 catalog within 2 Mpc, with N_{gal} larger than 3 and with $\Delta z \leq 0.005$ or more than one group/cluster of galaxies with the same constraints but also having $N_{gal} = 2$ (Crossmatching).

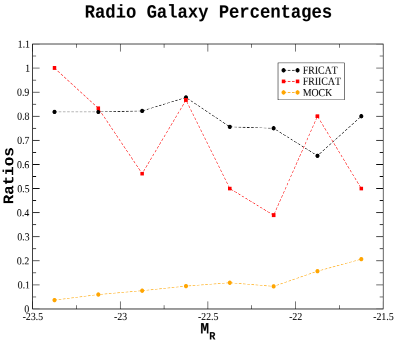
2. The number of cosmological neighbors is more than expected in random positions of the sky within a 5% threshold for the same redshift bin which the source belongs to. (Cosmological over-densities).

3. When the redshift difference Δz computed between that of the central source and the z_{cl} reported in the GMBCG is less than 0.005.

Results

Radio galaxies percentages ...

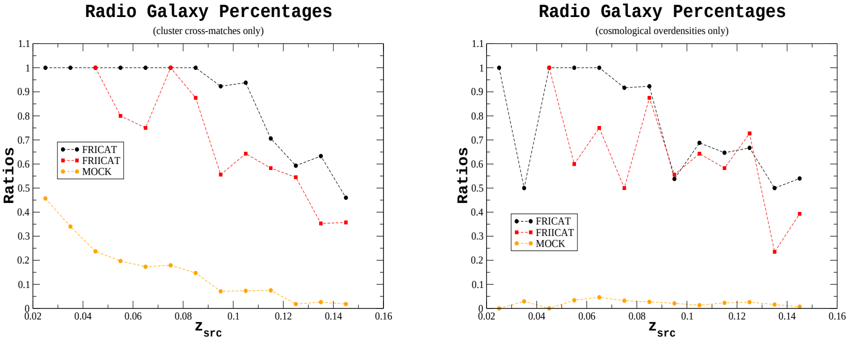




Same trend for FR Is and FR IIs. Both all well above what you expect in a random sample.

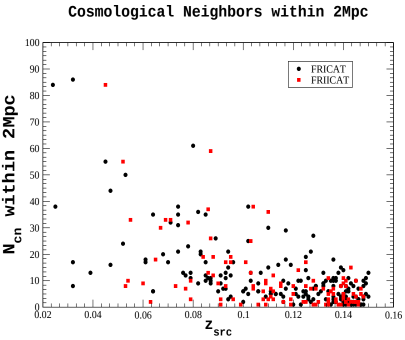
Results

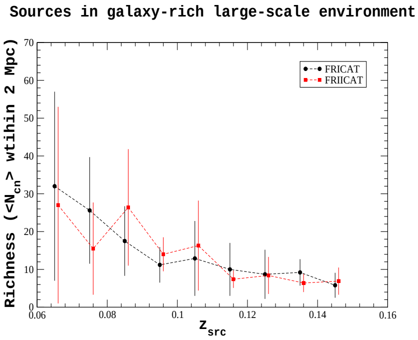
Highlighting the bias in the use fo the T12 catalog



Results

Richness

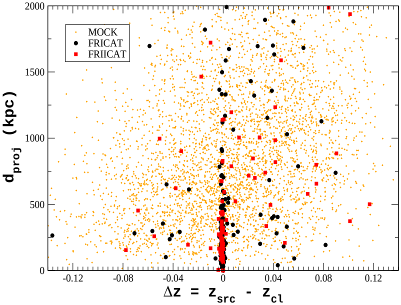


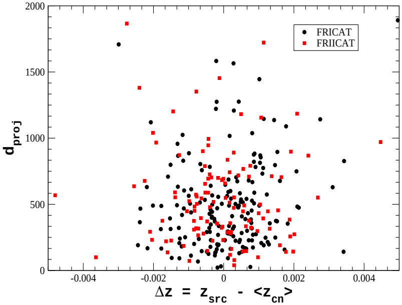


You see no differences between FR Is and FR IIs.

Results

The choice of Δz using cosmological neighbors

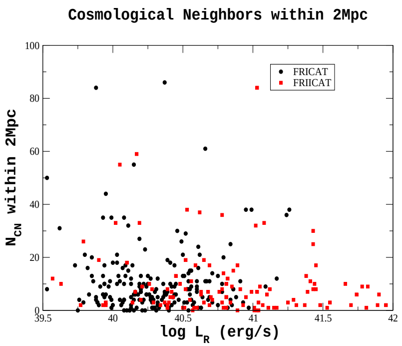


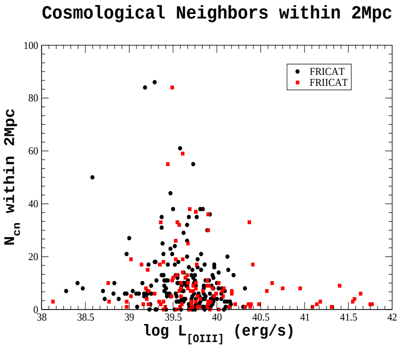


You see no differences between FR Is and FR IIs.

Results

Richness as function of luminosities

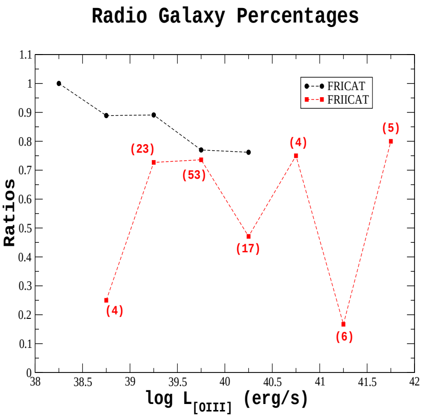




You see no differences between FR Is and FR IIs but also between HERGs and LERGs.

Results

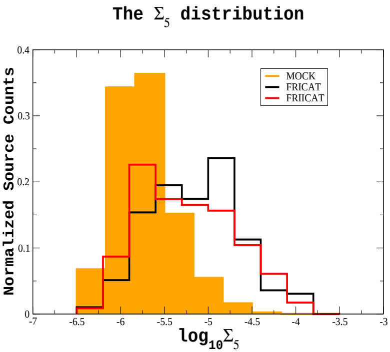
Fraction of radio galaxies as function of $L_{[OIII]}$

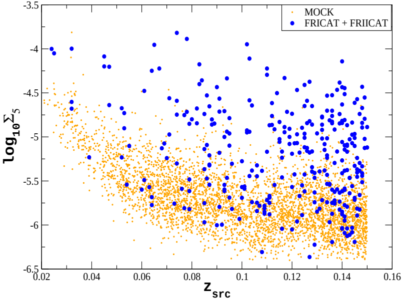


A few HERGs seems to do not live in galaxy rich environments this fraction is always of the order of 50%.

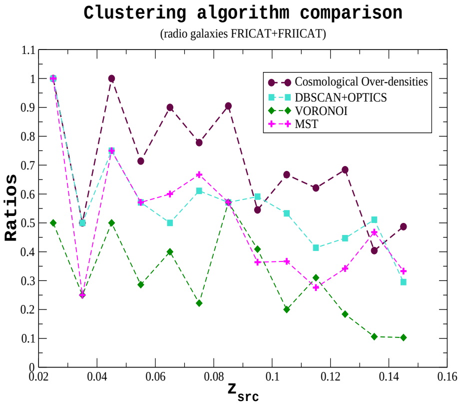
Results

and finally the $\Sigma_5 = \frac{5}{\pi r_5^2}$





Additional clustering algorithms



And the underlying idea of the “broken balance”.

Final claims

HERGs are found almost exclusively in low-density environments while LERGs occupy a wider range of densities, independent of FR morphology (Gendre et al. 2013).

Indeed we proved that LERGs and HERGs in the local Universe (at least up to $z_{src} \leq 0.1$) live in galaxy-rich large-scale environments with same richness. At higher redshifts it was not possible, for us, to establish a firm conclusion given the low number of HERGs in our catalogs.

Final claims

There is a significant overlap in the environment between LERGs and HERGs, and no clear driving factor between the FR I and FR II sources is found even when combining radio luminosity or accretion mode (Gendre et al. 2013).

Confirmed.

Final claims

FR Is radio galaxies lie in higher density environments, on average, than FR IIs (Miraghei & Best 2017).

On the contrary, we showed that fraction of FR Is living in galaxy-rich large-scale environments could be slightly larger than that of FR IIs, but the richness of their ambients is certainly consistent at all redshifts sampled by our analysis. The difference with respect to literature works could be due to radio source that are contaminants of selected samples, a bias that does not affect our radio galaxy catalogs.

Final claims

The environments of LERGs display higher density compared to the HERGs (Miraghei & Best 2017).

No difference were found in the environments of LERGs and HERGs in our analysis. The case of the FR II HERG SDSSJ131509.84+084053.3 having 11 cosmological neighbors within 1Mpc is a clear example of a galaxy-rich ambient for HERGs.

Final claims

High-luminosity radio galaxies with weak or no emission lines (LERGs) lie in more massive haloes than non-radio galaxies of similar stellar mass and color (Ching et al. 2017). The HERGs are typically in lower mass haloes than LERGs.

The distribution of the Σ_5 parameter for our radio galaxy catalogs (comparing FR Is with FR IIs or LERGs with HERGs) is not in agreement with this statement at least in the z_{src} range we carried out our analysis.

Final claims

At low redshifts, there is a correlation between radio luminosity and the cluster environment for LERGs but not for HERGs (Ineson et al. 2015).

No difference between the richness of their environments were indeed found as function of their L_R, not even between FR Is and FR IIs.

Final claims

Our final claim is also that all HERGs in our sample that lie in galaxy-rich large-scale environments are also BCG according to the luminosity distribution of the cosmological neighbors within 2 Mpc.

What's next?

1. Study different source classes: FR 0s, WATs, Compact FR II radio galaxies ... blazars!
2. Trying to obtain X-ray observations: IGM properties, IGM structure, statistical test of our methods and many more information that cannot be revealed with optical and infrared observations.
3. Extend the analysis at higher redshifts ... possible but problematic!

Fin

Thanks!

I told you this is the story of a question ... I did not say “I had the answer” !!!