AGN Through the Eyes of the LOw Frequency ARray

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Durham University

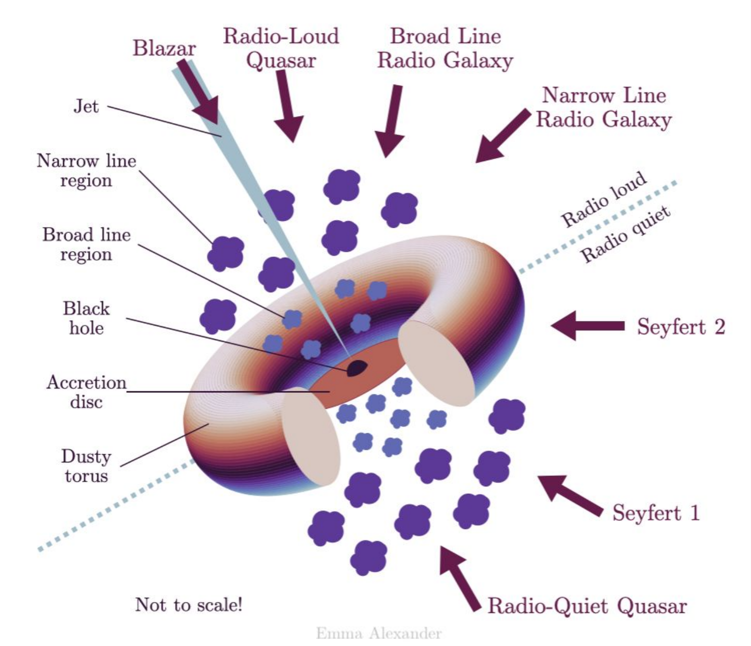
Active Galactic Nuclei

Most galaxies have a **Supermassive Black Hole** (SMBH) at the center

If a SMBH shows signs of accretion it is known as a **Active Galactic Nuclei (AGN)**

So powerful that they alter the evolution of a galaxy

AGN Unification model (Urry and Padovani 1995) demonstrates the multiple components within an AGN e.g torus, accretion disk, broad line region

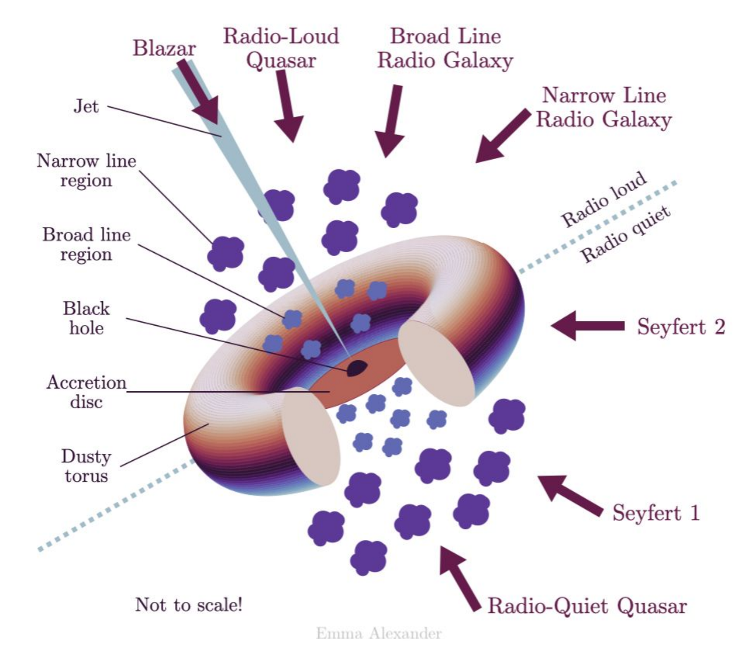


(Emma Alexander)

Active Galactic Nuclei

Radio-Loud - High radio to optical flux density ratio - **Large Scale Jets**

Radio-Quiet - Small radio to optical flux density ratio - 90% of the AGN population is Radio Quiet



(Emma Alexander)

AGN at Radio Wavelengths

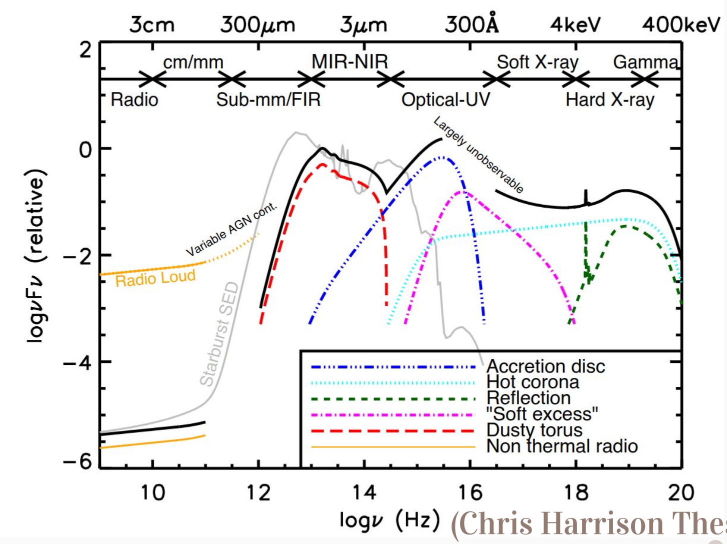
Most frequencies have emission from multiple AGN components e.g accretion disc or corona

At radio wavelengths we can study the **non-thermal emission** and the emission is **not affected by dust** obscuration

So we can probe the central region which can not be done at other wavelengths

And of course **radio jets**

(NASA/CXC/SAO)

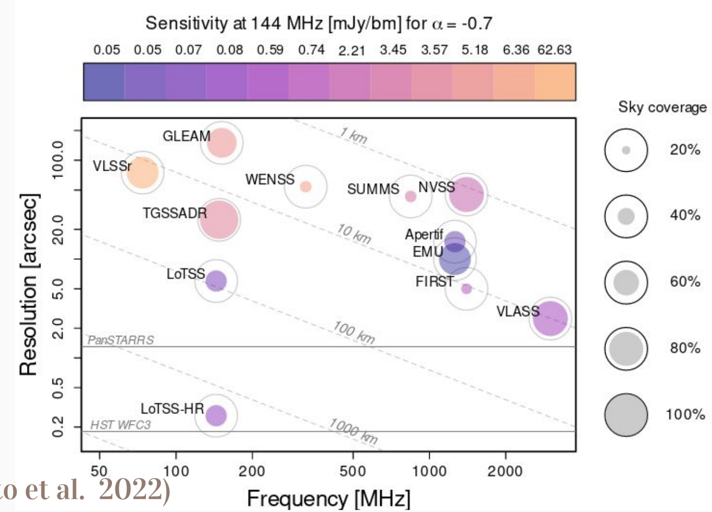


(Chris Harrison Thesis)

AGN with LOFAR

LOFAR provides **high sensitivity at low frequencies**.

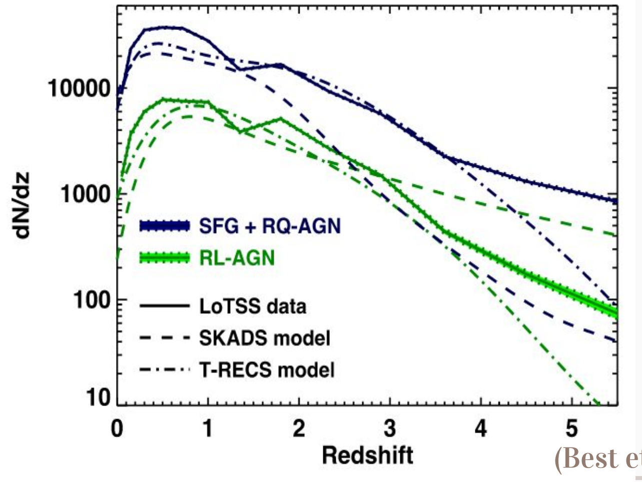
Add international stations to further improve resolution similar to optical instruments



(Morabito et al. 2022)

Allowing faint radio population to be studied including Radio Quiet AGN at redshift 5

No longer limited to local Radio Quiet and Radio Loud AGN



(Best et al. 2023)

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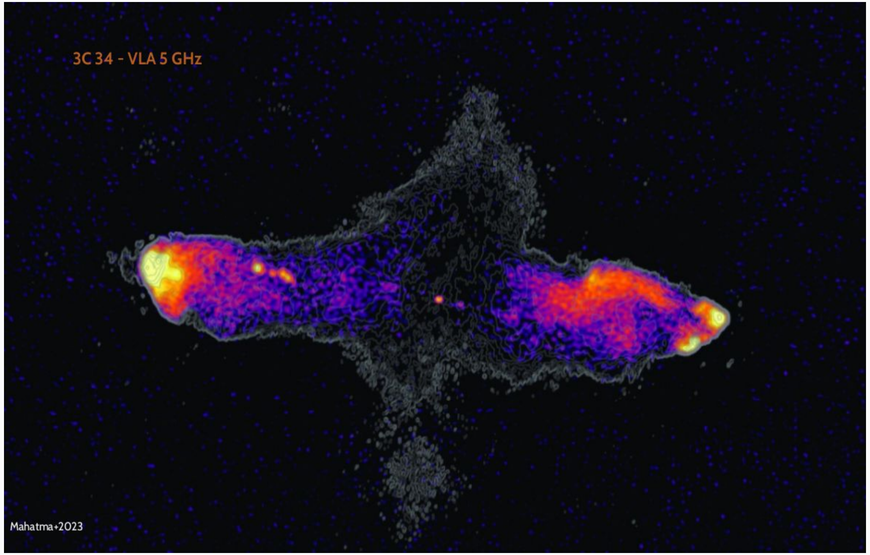
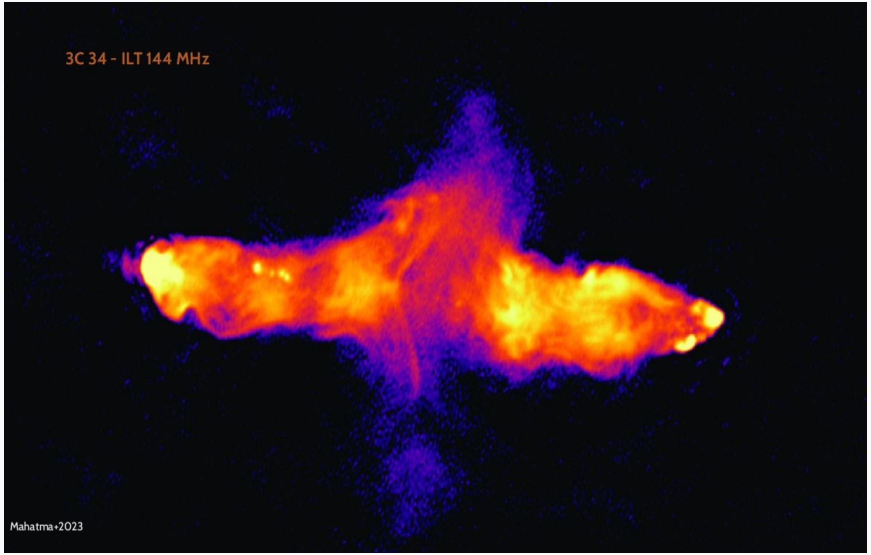
AGN with LOFAR

We can also probe older, more diffuse emission





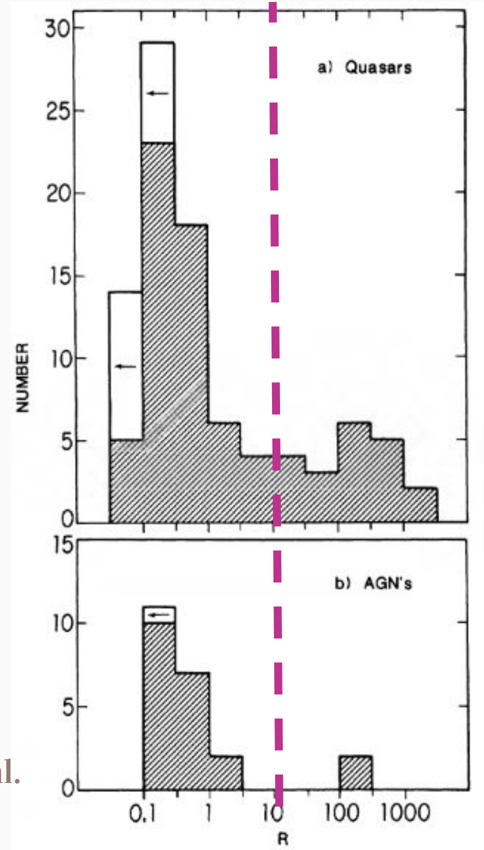
(Mahatma et al. 2023)

Radio Loud vs Radio Quiet

Radio-Loud - High radio to optical flux density ratio - **Large Scale Jets**

Radio-Quiet - Small radio to optical flux density ratio - 90% of the AGN population is Radio Quiet

Previously limited to Radio Loud AGN or local Radio Quiet - **Clear divide** in Kellerman et al. 1989 using VLA at R = 10

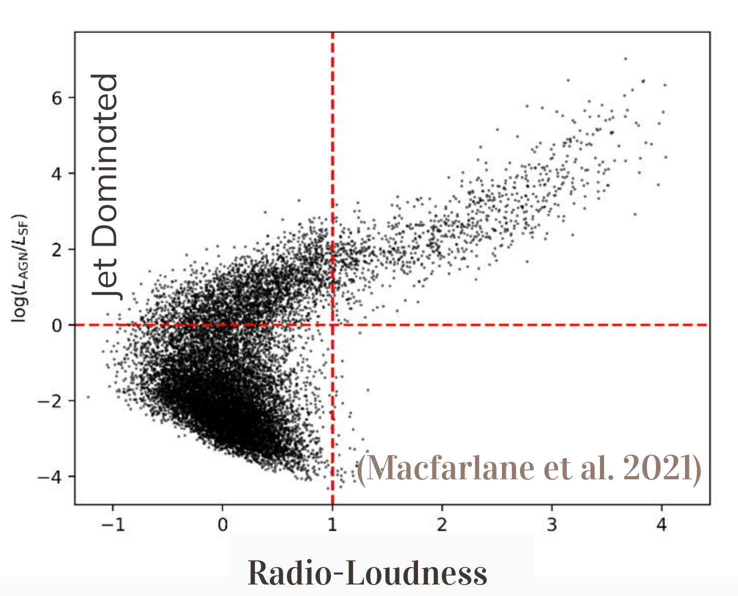


(Kellerman et al. 1989)

Radio Loud vs Radio Quiet

Increasing number of Radio Quiet sources with **LOFAR** quickly demonstrated **lack of a dichotomy** (Gürkan et al. 2019)

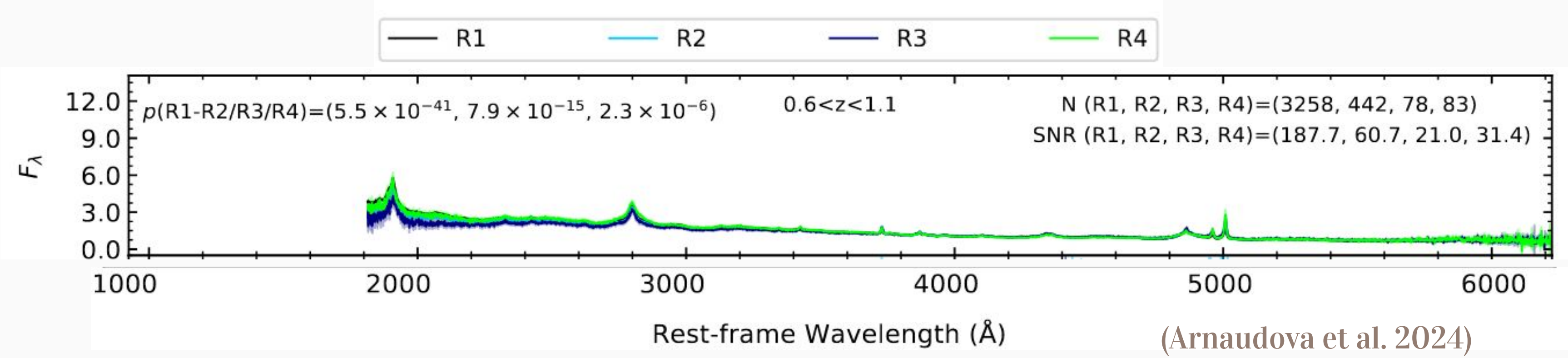
Macfarlane et al. 2021 shows that introducing the radio-loudness cut off (L5GHz/L4400 = 10) **misses out jet-dominated AGN.**



Radio Loud vs Radio Quiet

Increasing number of Radio Quiet sources with **LOFAR** quickly demonstrated **lack of a dichotomy** (e.g. Gürkan et al. 2019, Macfarlane et al. 2021)

Arnaudova et al. 2024 uses median stacking techniques to compare Radio Loud and Radio Quiet optical spectra, finding **Radio Loud appear more reddened**. However **gradually increasing radio-loudness provides a smooth transition** to redder spectra.
Not a clear Radio Loud cut.



(Arnaudova et al. 2024)

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FR Morphology

Fanaroff and Riley (1974) separated AGN into two morphology classes

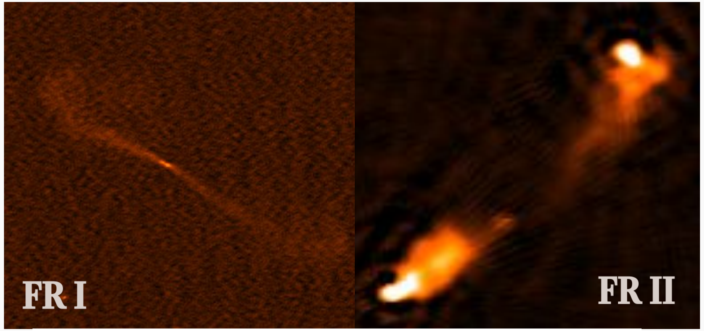
Luminosity cut can be made between the two classifications

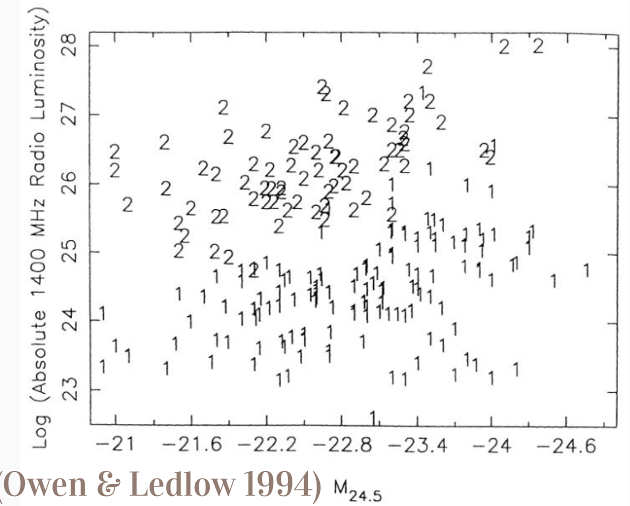
Associated with different accretion modes (Jackson & Rawlings 1997)

FR I - bright central regions with diffuse emission towards jet termini - **radiatively inefficient** (LERGs)

FR II - bright hotspots within the lobes - associated with higher radio luminosity - **radiatively efficient** (HERGs)

(E. Escott)





(Owen & Ledlow 1994)

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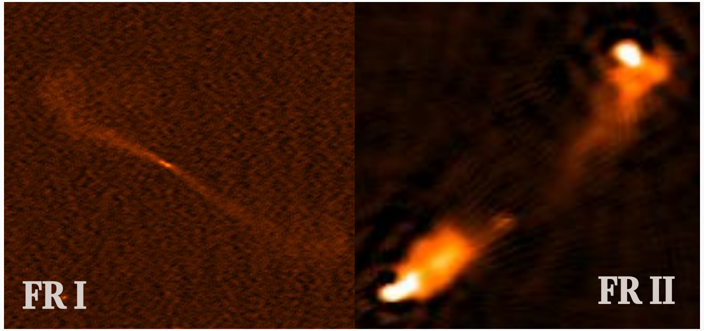
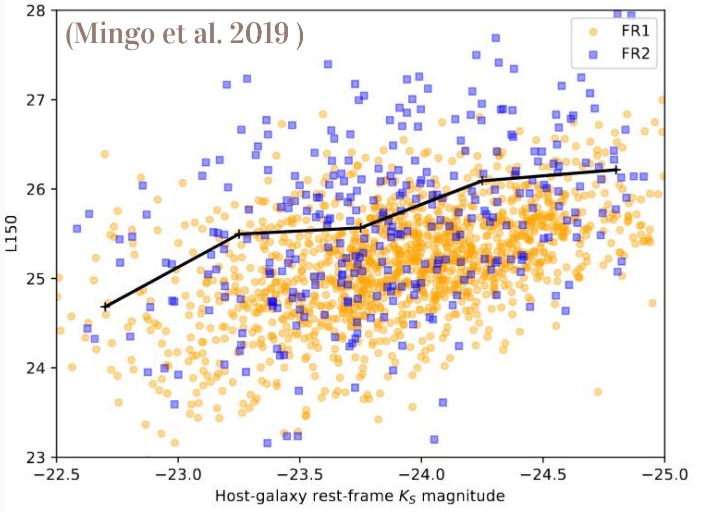
FR Morphology

(E. Escott)





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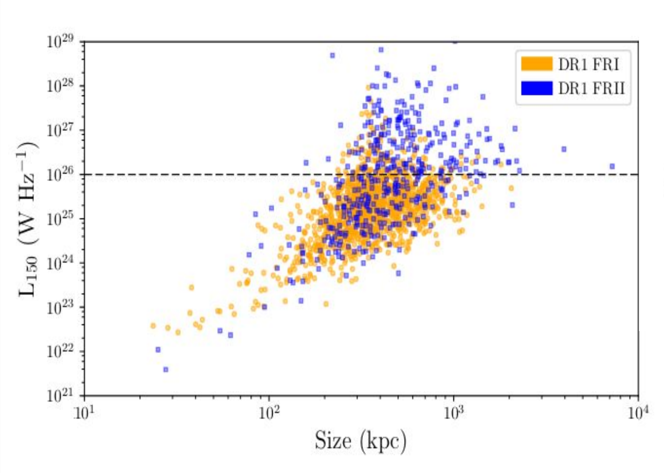
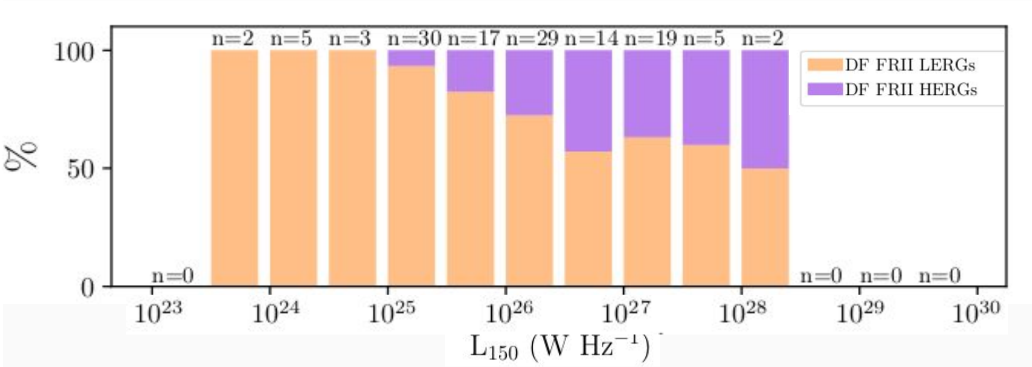
FR Morphology

Mingo et al. 2019, 2022 uses the **luminosity cut** in LoTSS Deep Fields and DR1 and shows a **massive overlap** between FR1 and FR2

Mingo et al. 2022 discovers FR classes **do not relate to the central engine** - mostly independent of accretion mode. FR classes could relate to Stellar Mass

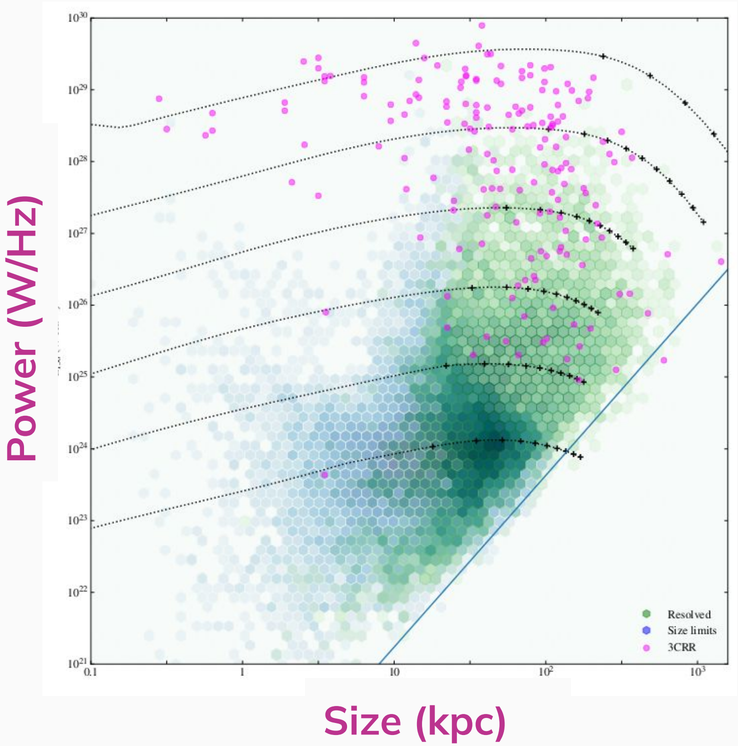




(Mingo et al. 2022)

Radio Loud Sizes

Hardcastle et al. 2019 - **P-D diagram** of DR1 Radio Loud AGN of resolved and unresolved sources with evolutionary tracks depending on jet powers.



(Hardcastle et al. 2019)

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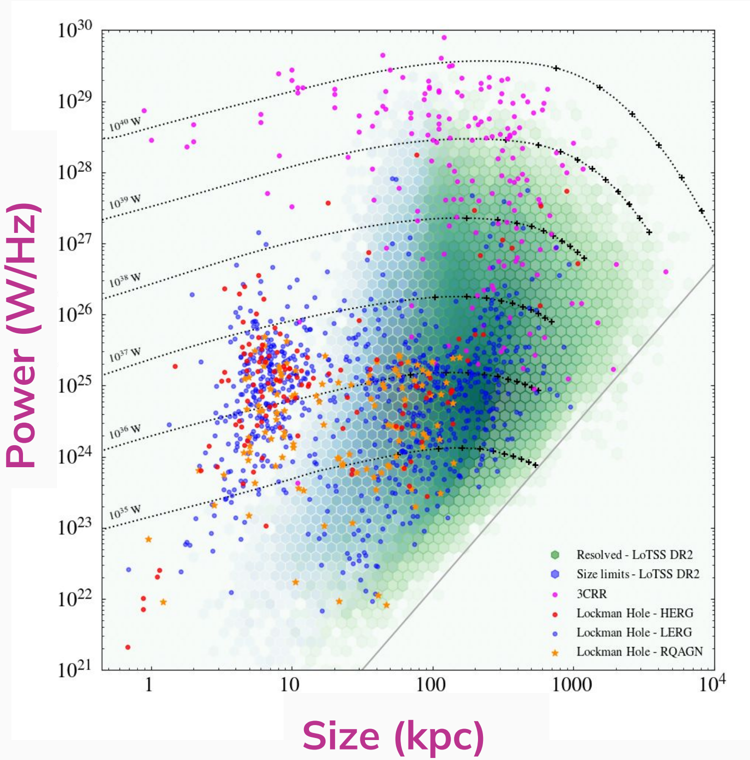
Radio Loud Sizes

Hardcastle et al. 2019 - **P-D diagram** of DR1 Radio Loud AGN of resolved and unresolved sources with evolutionary tracks depending on jet powers.

Pierce et al. in prep - **updated size measurements from 0.3” Lockman Hole image** (Sweijen et al. 2022, in prep). Resolves many of the previously unresolved AGN - occupy a new parameter space

Chilufya et al. 2024 - compact Radio Loud AGN with high resolution VLA images - do not occupy a special place in P-D diagram



(Pierce et al. in prep)

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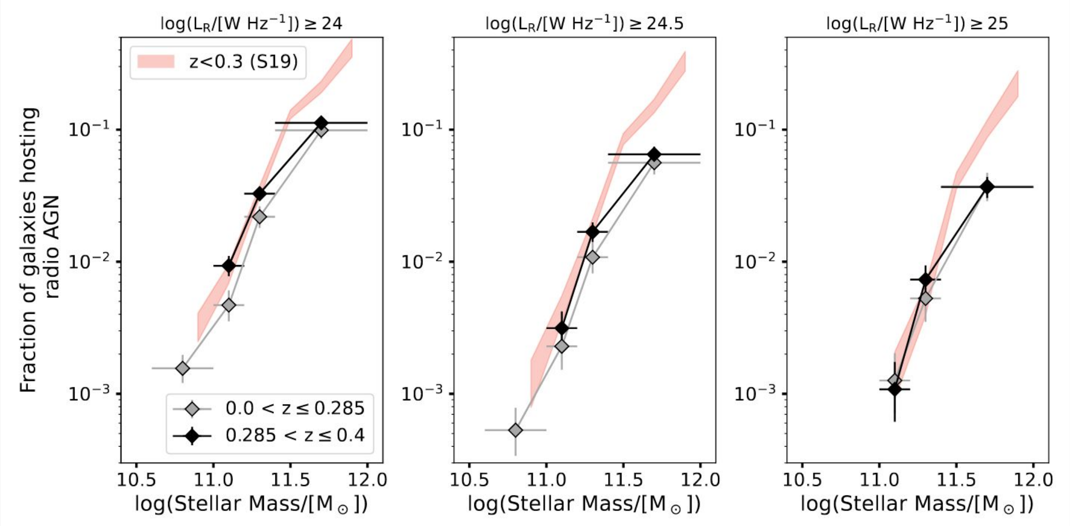
Radio Loud Activity

Sabater et al. 2019 - **Local Radio Loud AGN are always turn on**

Igo et al. 2024 - Large sample of Radio Loud AGN in the eFEDs field. Confirms more massive galaxies are more likely to be turned on - see next talk!

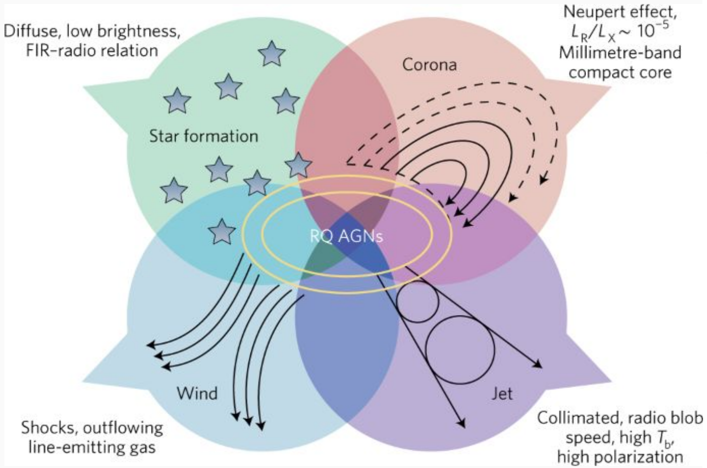


(Igo et al. 2024)

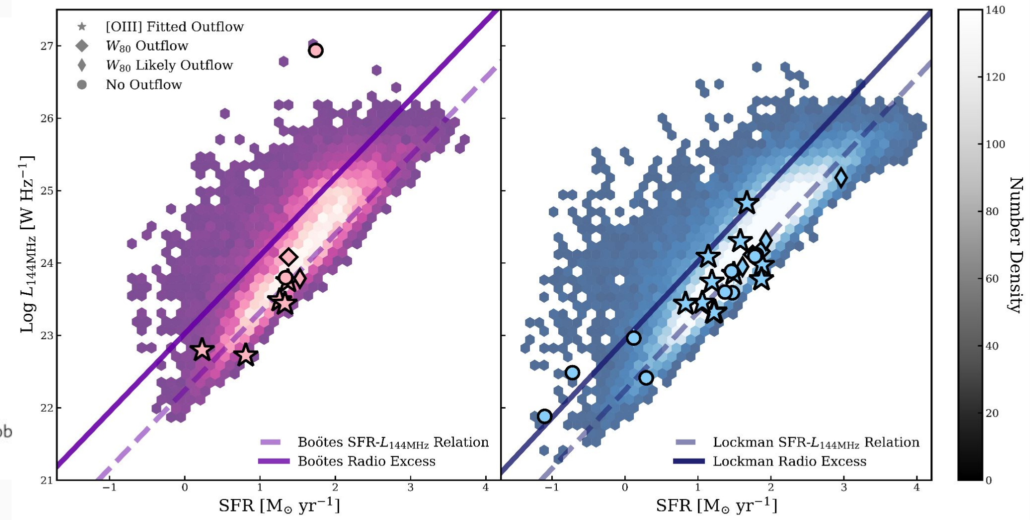
Radio Quiet Emission

Origin of radio emission from Radio Quiet AGN is currently unknown - it could be produced from jets, star formation or winds (see Panessa et al. 2019 for a review)

Need high resolution to determine radio emission (Escott et al. in prep)



(Panessa et al. 2019)



(Escott et al. Submitted)

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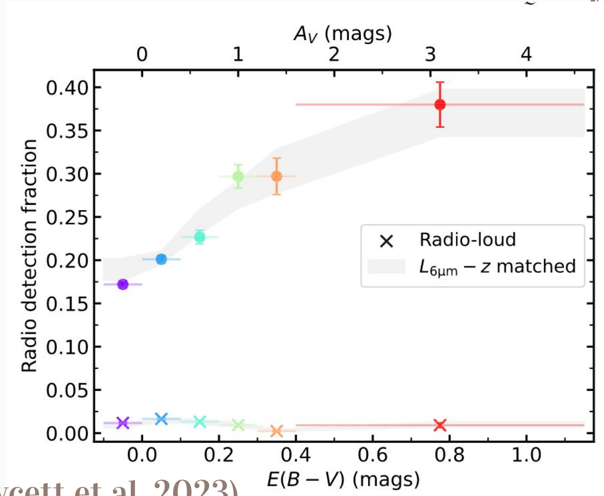
Red Quasars

Klindt et al. 2019 - Using FIRST found **red quasars are more likely to be radio detected**

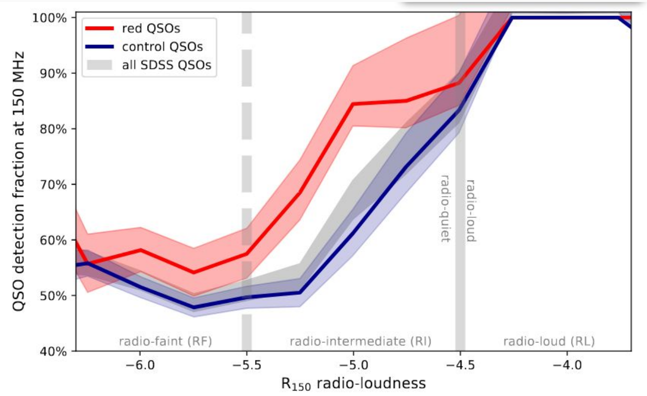
See Bohan Yue's talk for his work on red quasars

This is confirmed using DR2 after matching for redshift and AGN luminosity



(Fawcett et al. 2023)

Previous results showing radio enhancement in red quasars is greater at radio intermediate luminosities confirmed using the Deep Fields

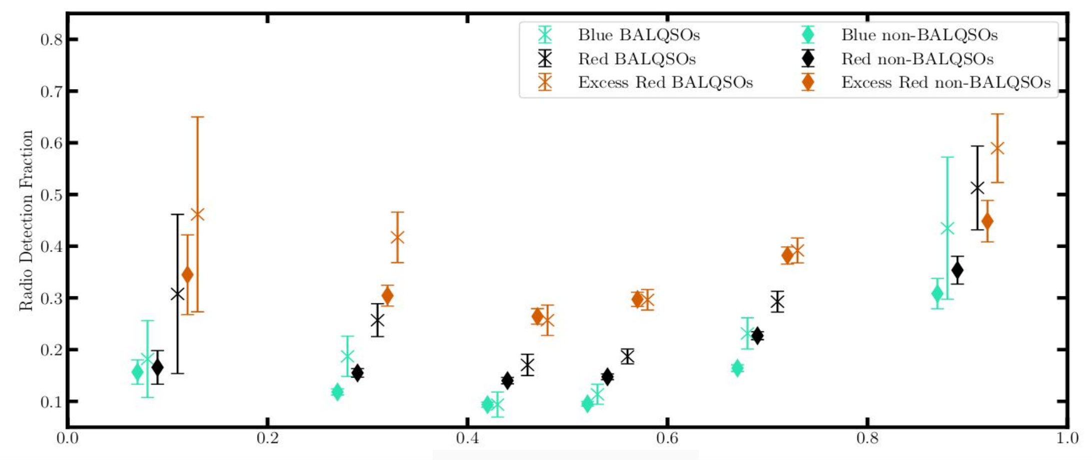


(Calistro Rivera et al. 2024)

Outflows - BALQSOs

Broad Absorption Line Quasars (BALQSOs) show absorption in Si IV and C IV which have been linked to disk winds

BALQSOs are more likely to be radio detected than non-BALQSOs, even more so as reddening is increased. BALQSOs are more intrinsically red but reddening can not fully explain increased radio detection



Wind Strength

(Petley et al. 2024)

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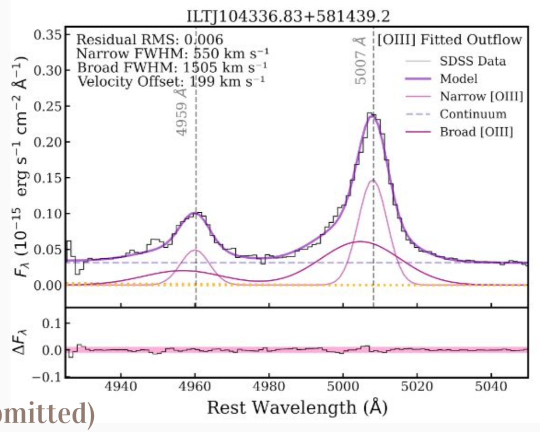
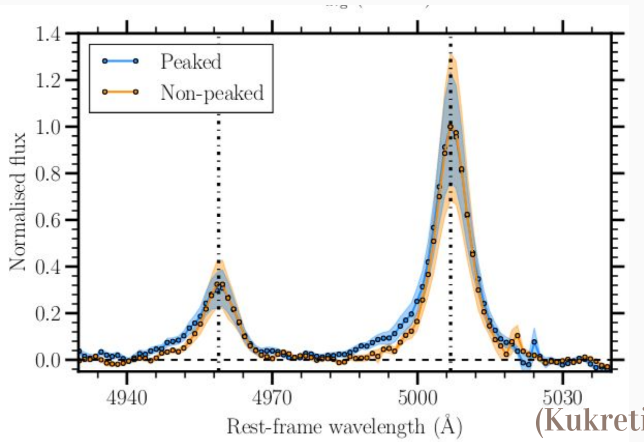
Outflows - [O III]

[O III] 5007 Å can be used to trace, warm ionised gas outflows. If a broad, blueshifted component is fit to [OIII] then this is indicative of an outflow

Using LOFAR (144MHz), FIRST (1400MHz) and VLASS (3000MHz) obtains spectral indices to split sample into peaked and non-peaked spectral sources. Stacks [OIII] in SDSS spectra and finds **peaked sources show an outflowing component whereas non-peaked do not**



(Escott et al. Submitted)



(Kukreti et al. 2023)

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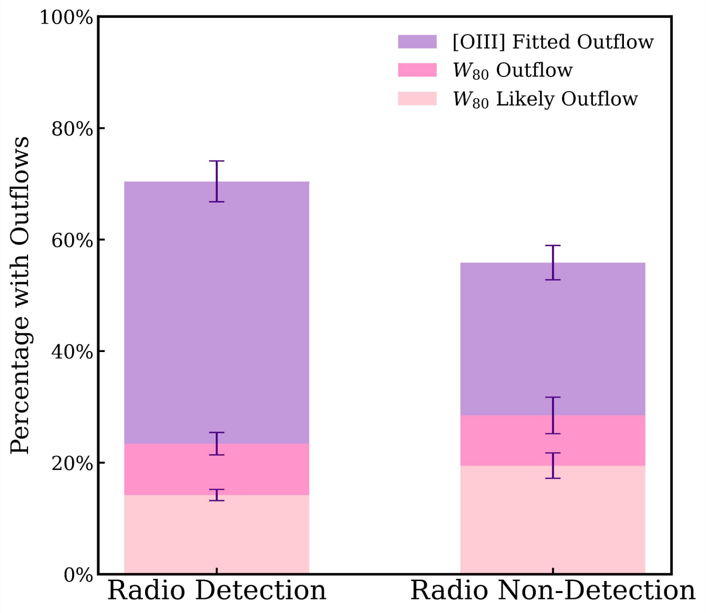
Outflows - [O III]

[O III] 5007 Å can be used to trace, warm ionised gas outflows. If a broad, blueshifted component is fit to [OIII] then this is indicative of an outflow.

Escott et al. Submitted - Sample of SDSS spectra with a population with detections from LoTSS Deep Fields. Using both spectral fitting and W80 measurements - find **higher prevalence of [OIII] outflows in radio detected than radio non-detected AGN.**

Using median stacking find an enhanced in the outflowing component in radio detected AGN after normalising for the [OIII] core component.

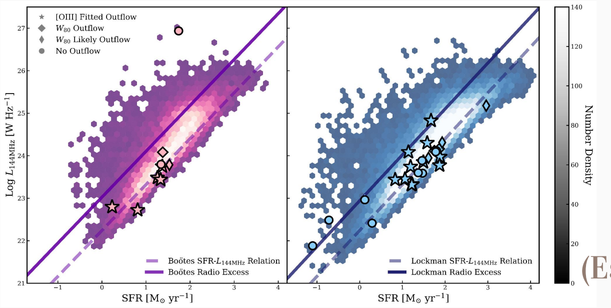


(Escott et al. Submitted)

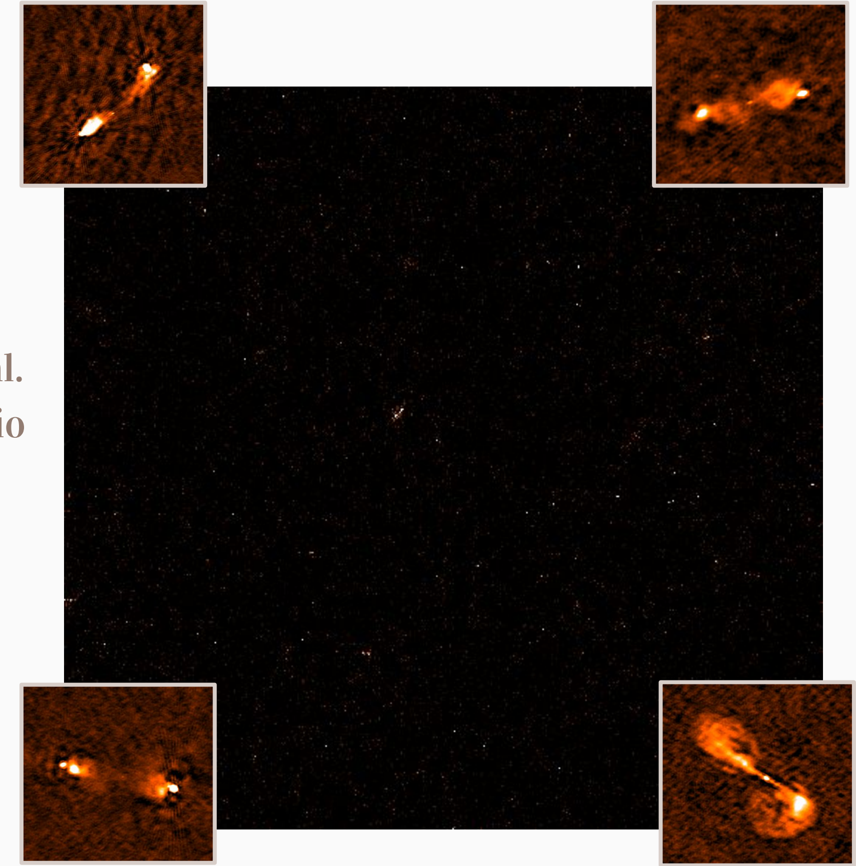
Outflows - [O III]

Reducing the **Böotes Deep Field with International station** to obtain a 0.3” widefield image.

Using these high resolution **morphologies alongside brightness temperature** measurements (Morabito et al. 2022) determine origin of radio emission of these radio quiet AGN.



(Escott et al. Submitted)



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Summary

LOFAR has allowed for a rapid increase in knowledge in the field of AGN

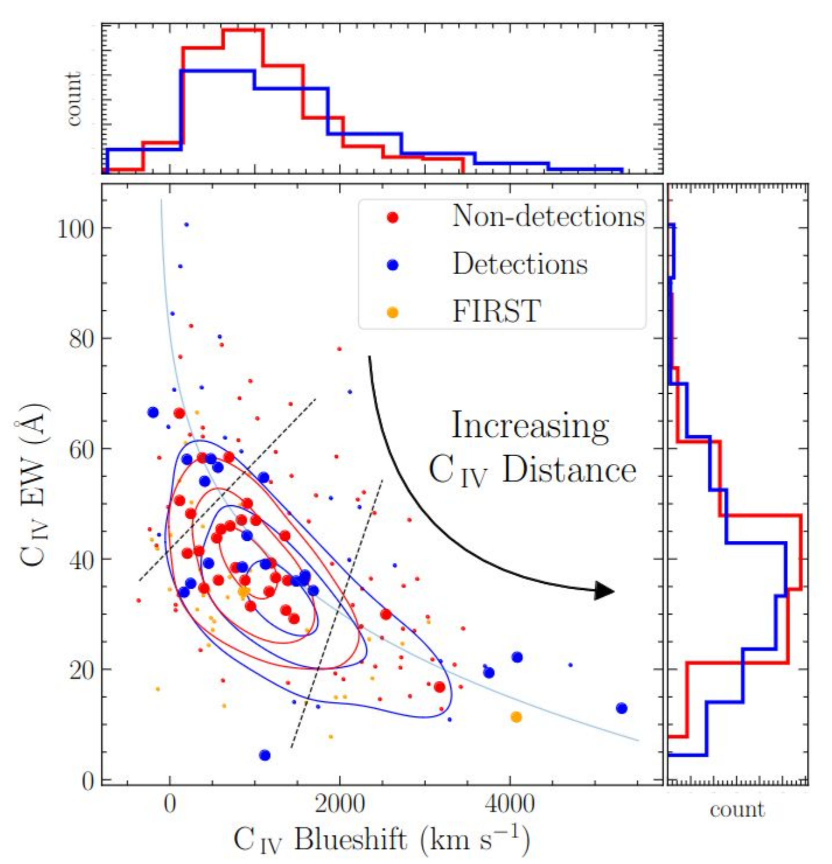
Furthered our understanding of the Radio Loud/Quiet Dichotomy, Radio AGN morphologies, and sizes

Expanded our knowledge of red quasar, BALQSOs and outflows

By including sub-arcsecond images we are probing a new regime of AGN Physics!

Keep doing great science!

Outflows - BALQSOs



Wind strength = C IV distance

(Richards et al. 2021)