The LOFAR-eFEDS survey: The incidence of radio and X-ray AGN and the disk-jet connection

Zsofi Igo

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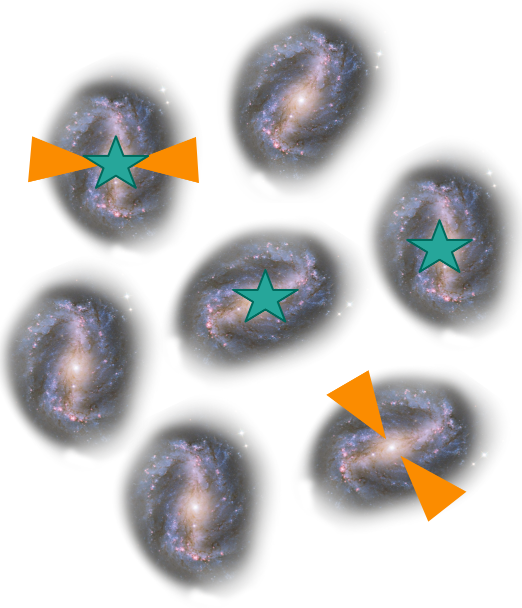
LOFAR Family Meeting - Leiden – 7th June 2024

What are AGN incidences? Why are they important?



Some relevant literature: Aird+2012, 2018, 2019; Heinz & Sunyaev 2003; Merloni+2003; Birchall+2021; Georgakakis+2017; Hardcastle & Croston 2020; Macfarlane+2021; Sabater+2019; Kondapally+2022, 2023, 2024; Mingo+2022; Hickox+2009; Saikia+2022; Willott+99, Hardcastle+2018, 2019.

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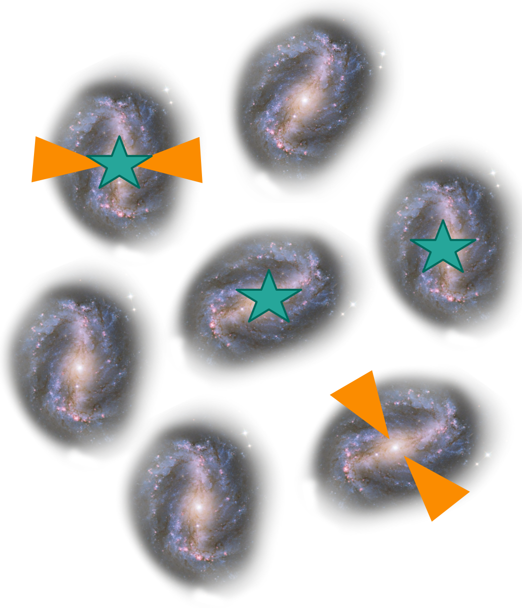

It can tell us about:

- Triggering, fueling and jet powering mechanisms of AGN with different properties (e.g. mass, environment, power, morphology etc...)
- Understand small-scale accretion physics through large statistical studies
- Power distribution and AGN feedback (essentially building luminosity functions)

Some relevant literature: Aird+2012, 2018, 2019; Heinz & Sunyaev 2003; Merloni+2003; Birchall+2021; Georgakakis+2017; Hardcastle & Croston 2020; Macfarlane+2021; Sabater+2019; Kondapally+2022, 2023, 2024; Mingo+2022; Hickox+2009; Saikia+2022; Willott+99, Hardcastle+2018, 2019.

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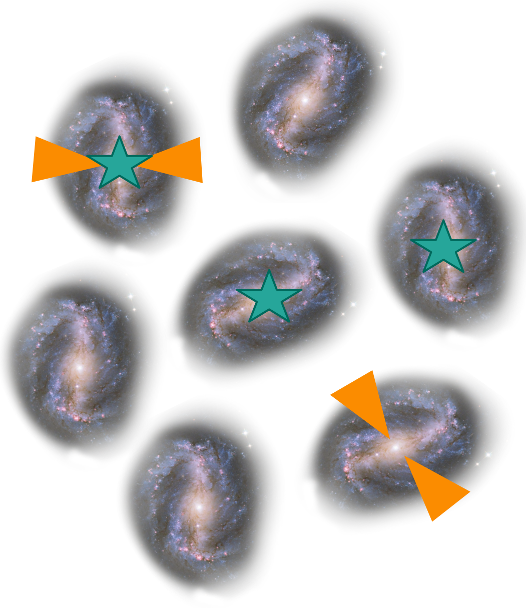

In this work:

- Study of 'AGN incidences' as functions of mass-scaled power indicators → luminosity/mass → λ_{Edd} and λ_{Jet}
- Focus on **X-ray** & **radio** regimes → tracing accretion input and kinetic output

Some relevant literature: Aird+2012, 2018, 2019; Heinz & Sunyaev 2003; Merloni+2003; Birchall+2021; Georgakakis+2017; Hardcastle & Croston 2020; Macfarlane+2021; Sabater+2019; Kondapally+2022, 2023, 2024; Mingo+2022; Hickox+2009; Saikia+2022; Willott+99, Hardcastle+2018, 2019.

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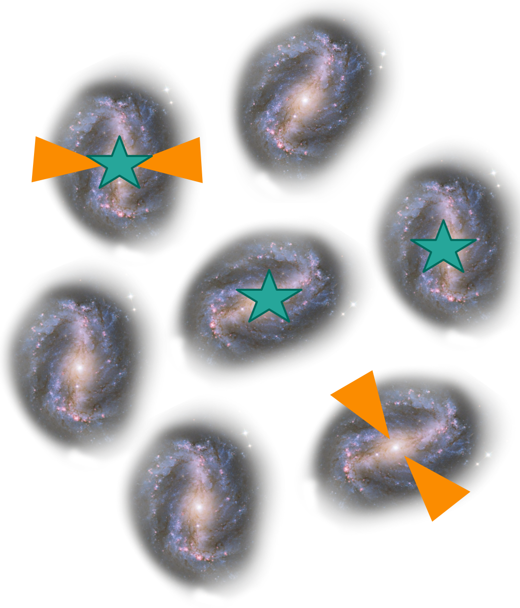

In this **presentation**:

- Study of 'AGN incidences' as functions of mass-scaled power indicators → [redacted] and λ_{Jet}
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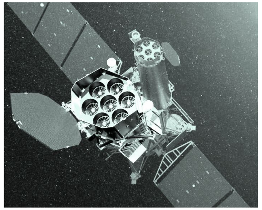
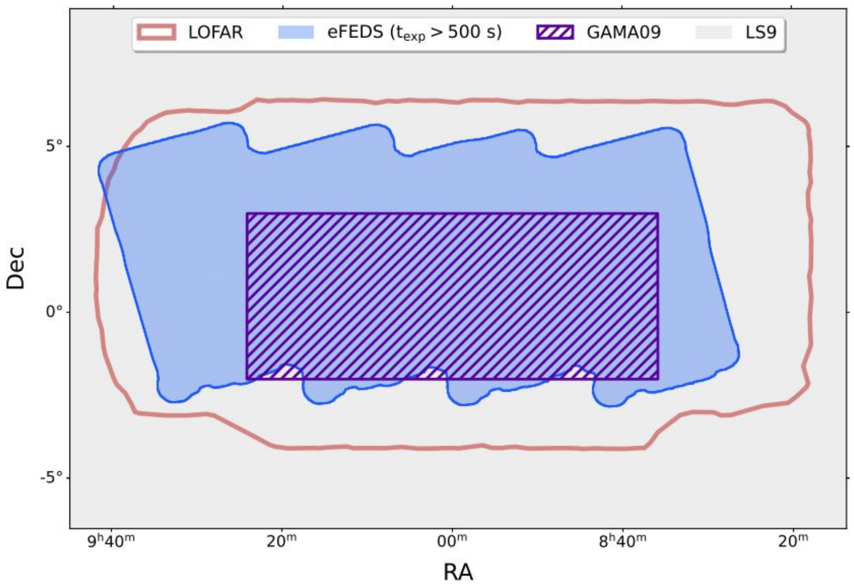
Data and Methods

The Catalogues





- **eROSITA eFEDS** (Brunner et al. 2021)
  - 140 deg^2 sky patch at final depth reached by 8 eROSITA All Sky Surveys - soft X-rays
- **DESI Legacy Imaging Surveys DR9** (Dey et al. 2019)
  - Optical survey with WISE data
  - Limiting AB mag in (g, r, z) = (23.95, 23.54, 22.50)
- **LOFAR - eFEDS field** (Igo et al. 2024, Pasini et al. 2022)
  - 144MHz, LoTSS DR1 processing, 8” x 9” resolution
  - RMS noise level ~ 150μJy/beam
- **GAMA09** (Driver et al. 2009)
  - Spectroscopic survey down to r<19.8 mag and z<0.4
  - Stellar mass and SFR calculated through SED fitting

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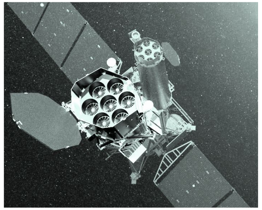
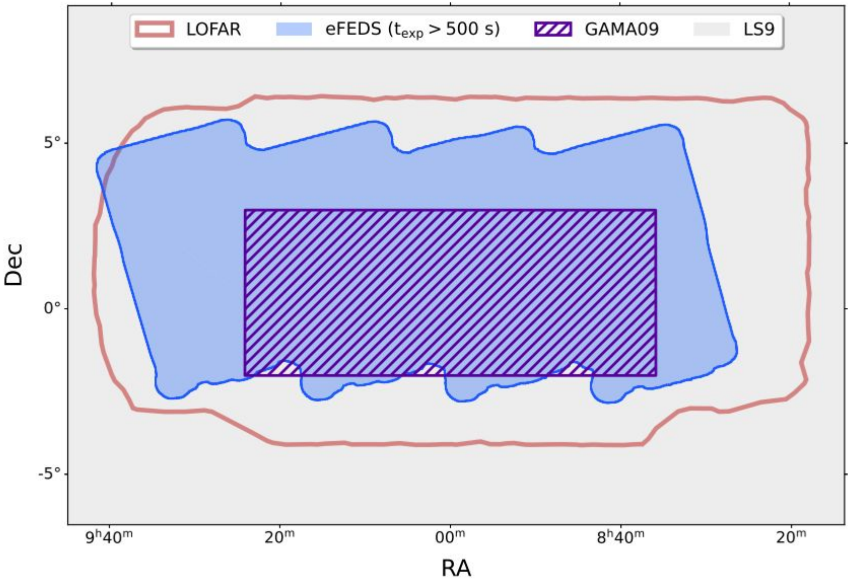
The Catalogues





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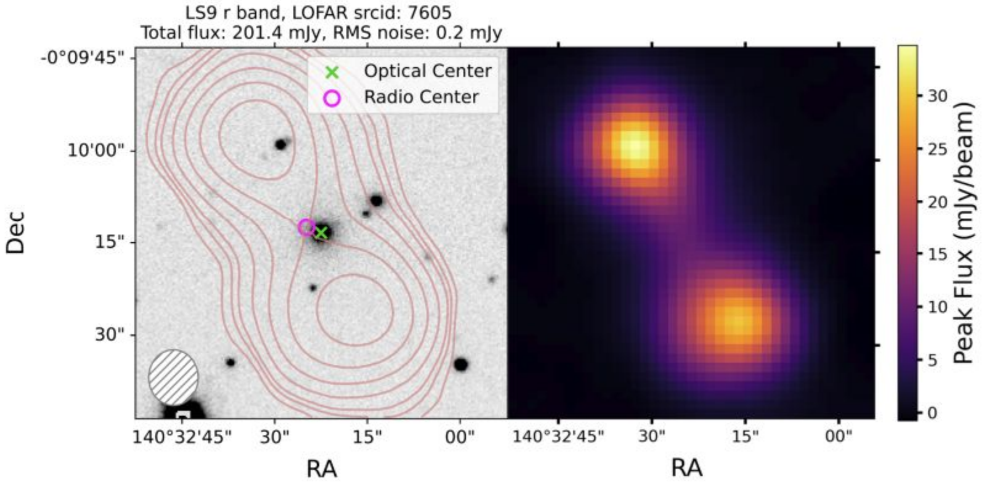
LOFAR-eFEDS value-added catalogue is publicly available!

Methods

1. Find optical counterparts to X-ray and radio detections using NWAY



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Methods

1. Find optical counterparts to X-ray and radio detections using NWAY

2. Create complete, volume-limited radio AGN sample
    a. Ensure completeness in stellar mass and radio luminosity
    b. Characterize radio morphology: compact and complex ?
    c. Find origin of radio emission: star formation vs. AGN processes?
    d. Characterize host galaxy: quiescent and star forming?

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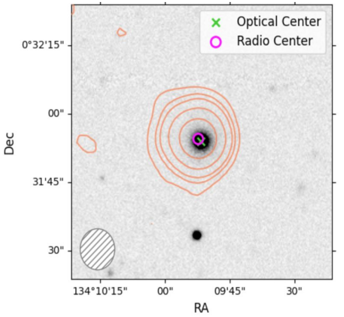
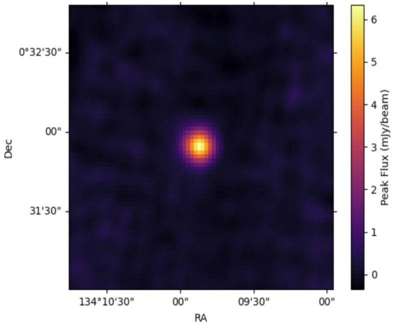
Characterizing Radio Morphology

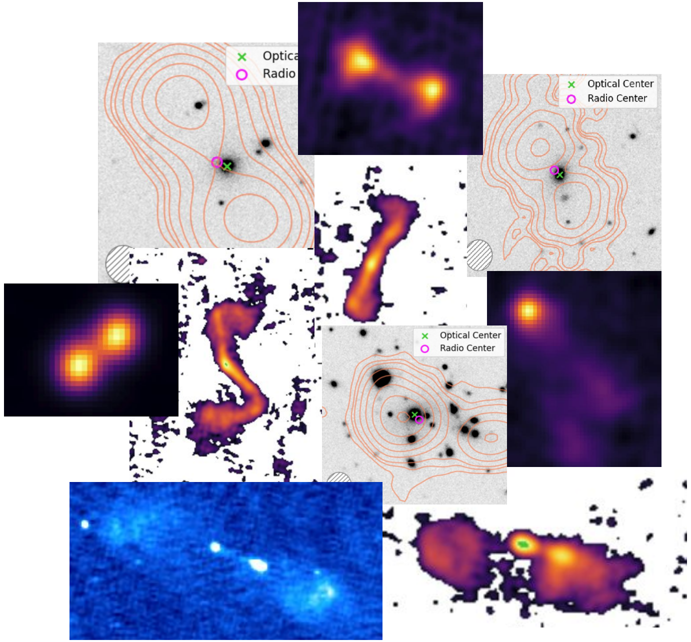
Compact

1) S_code=S
2) $F_{TOT}/F_{Peak} < 3.6$
3) Maj < 19.1”
4) Isolated: no NN within 45”





Complex



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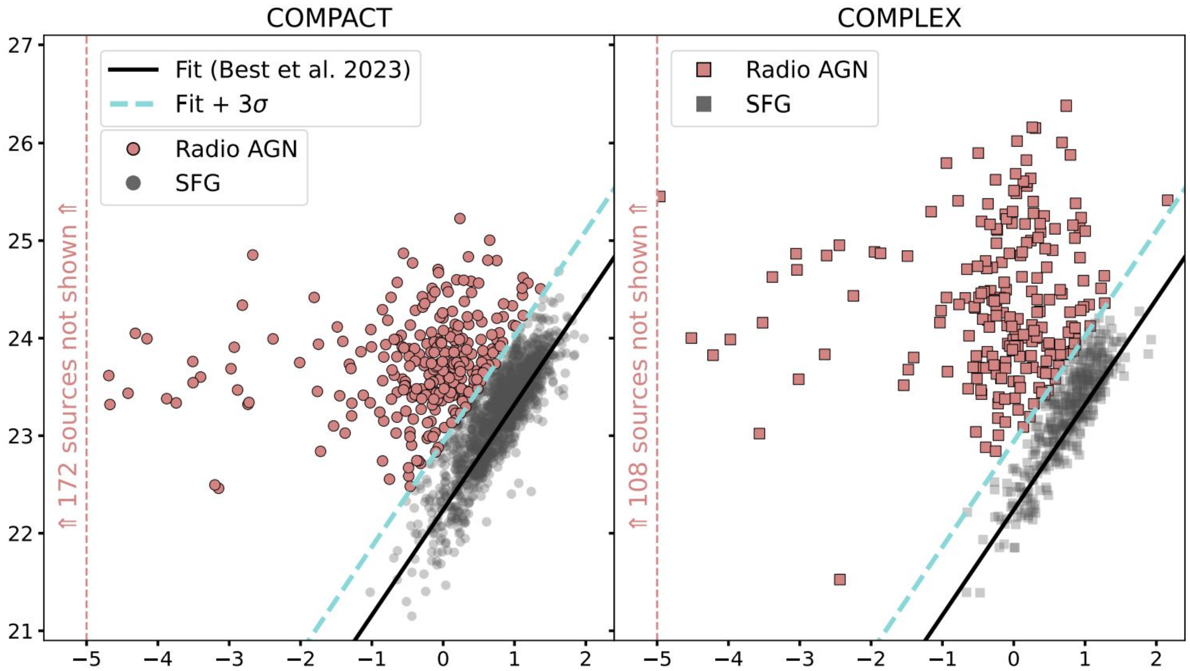
Distinguishing Radio AGN from SF Galaxies



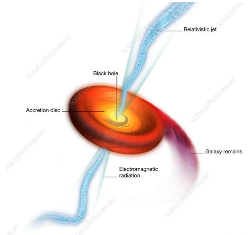
Radio Luminosity

Star formation Rate

Igo et al. (2024)

Radio emission can come from a variety of processes! LOFAR, at 144MHz, also probes large scale diffuse emission → picks up SF

vs.



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3. **Calculate incidence of AGN: M*–z binning**

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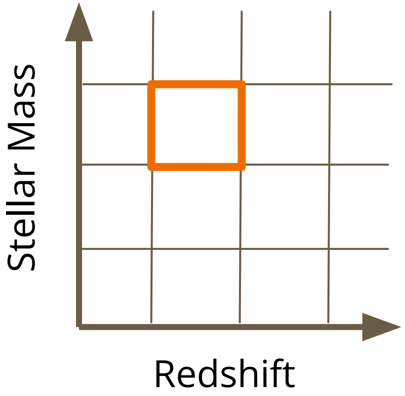
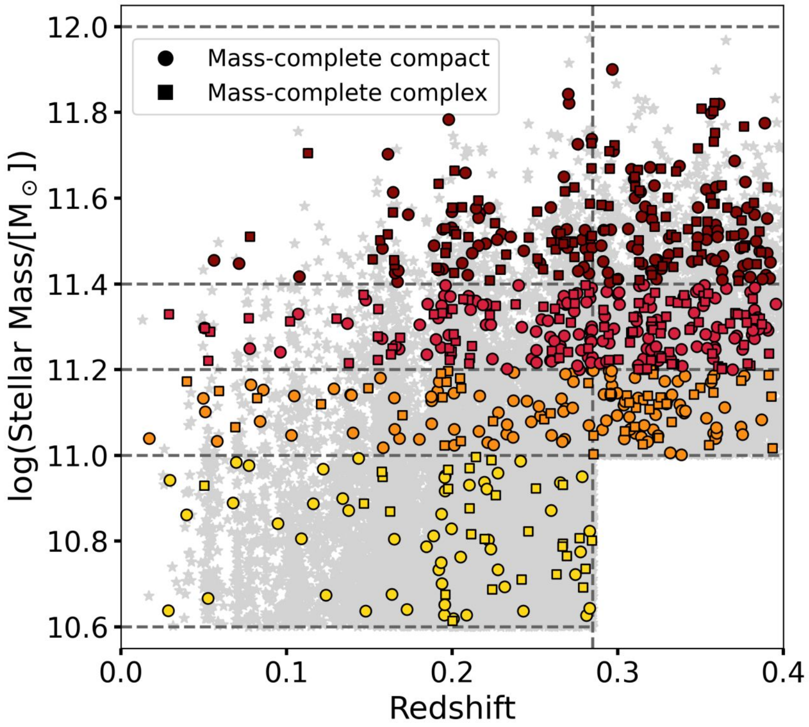
Calculating incidence of AGN: M*–z binning





1. Bin up target sources and GAMA parent galaxies

Target sources: radio or X-ray detected AGN

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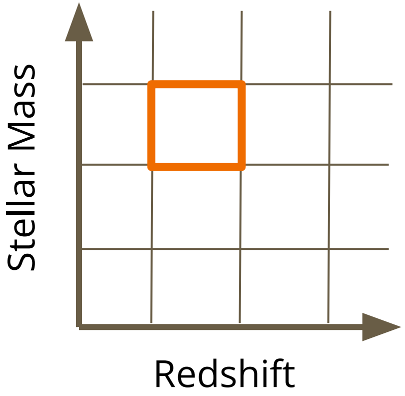
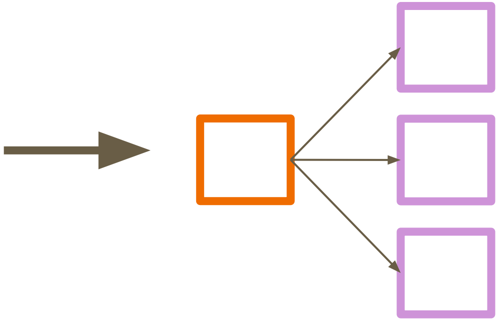
Calculating incidence of AGN: M*–z binning

For each M* – z bin…





1. Bin up target sources and GAMA parent galaxies

Target sources: radio or X-ray detected AGN

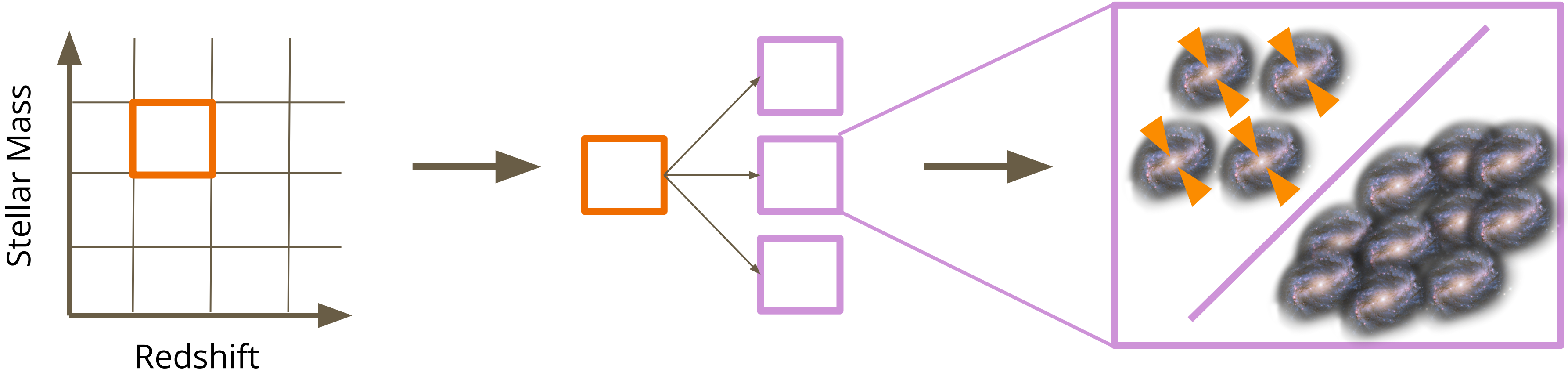
2. Bin up target sources in **further parameters of choice**:

e.g. λ_{Jet}

Calculating incidence of AGN: M*–z binning

For each M* – z bin...

Fraction in given bin =



1. Bin up target sources and GAMA parent galaxies
Target sources: radio or X-ray detected AGN

2. Bin up target sources in **further parameters of choice**:
e.g. λ_{Jet}

3. Calculate fraction of target sources wrt. GAMA parent sample of galaxies

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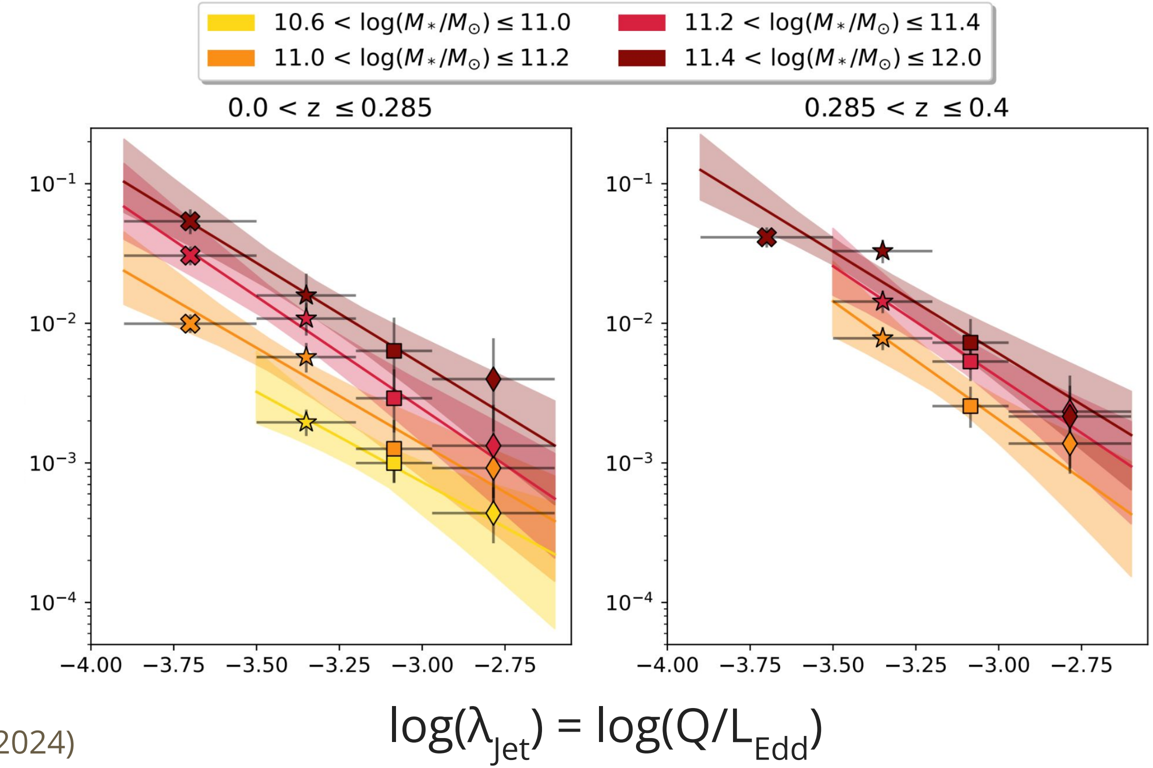
Results

Incidence of radio AGN

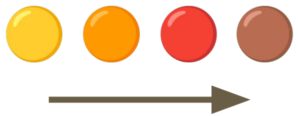
Incidence of compact radio AGN: specific BH kinetic power



L_R / M_* → Q/L_{Edd}

Jet power = $Q \propto L_R^{0.68}$

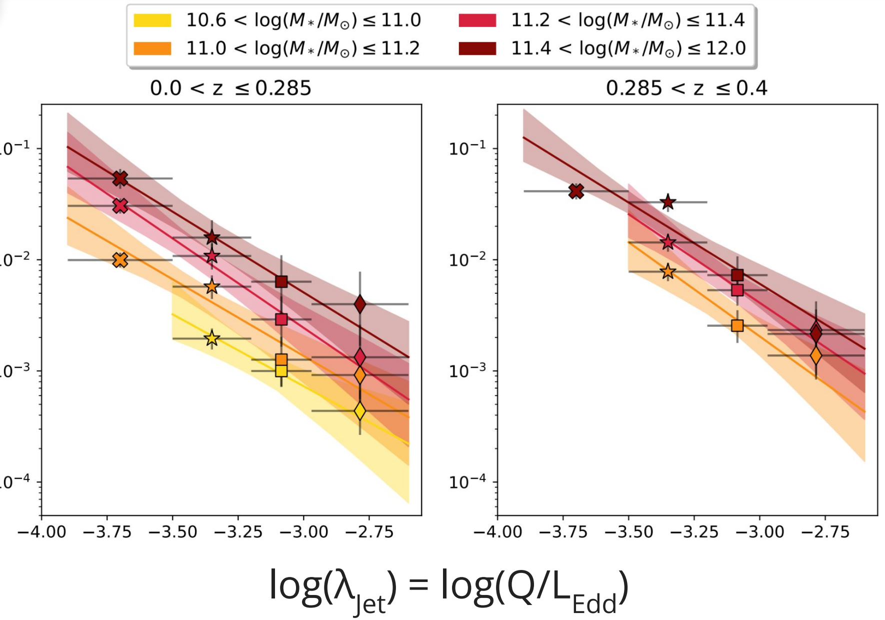
Heckman & Best 2014



Increasing stellar mass bins

Igo et al. (2024)

Incidence of compact radio AGN: specific BH kinetic power



Igo et al. (2024)

Main takeaways for compact-only results:

1) Higher mass galaxies are more likely to host compact radio AGN

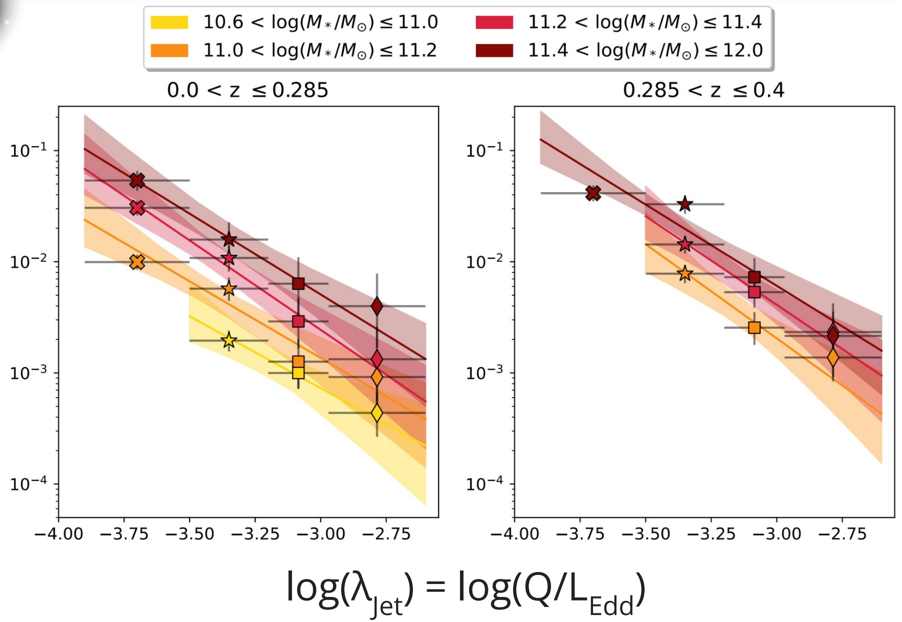
Small mass-dependence of jet powering.

2) Steep, but still approx. constant, power law slope (around – 1.5)

It is not only high mass galaxies which host high power jets and vice versa.

(ask me later for how this may connect to accretion modes or how it looks for radio AGN in quiescent versus star-forming galaxies!)

Incidence of compact radio AGN: specific BH kinetic power



Igo et al. (2024)

What about complex radio AGN?

Main takeaways for compact-only results:

1) Higher mass galaxies are more likely to host compact radio AGN

Small mass-dependence of jet powering.

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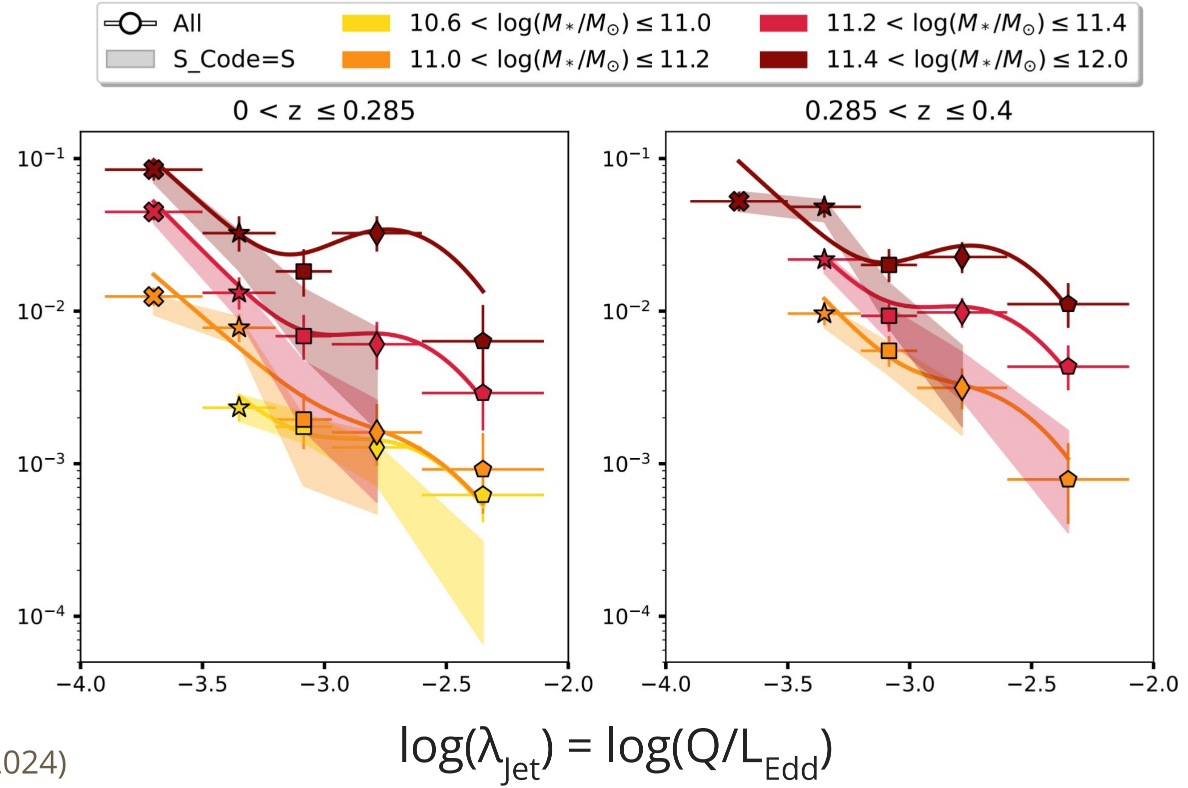
Incidence of radio AGN: Compact and Complex

Fraction of galaxies hosting **compact and complex** radio AGN



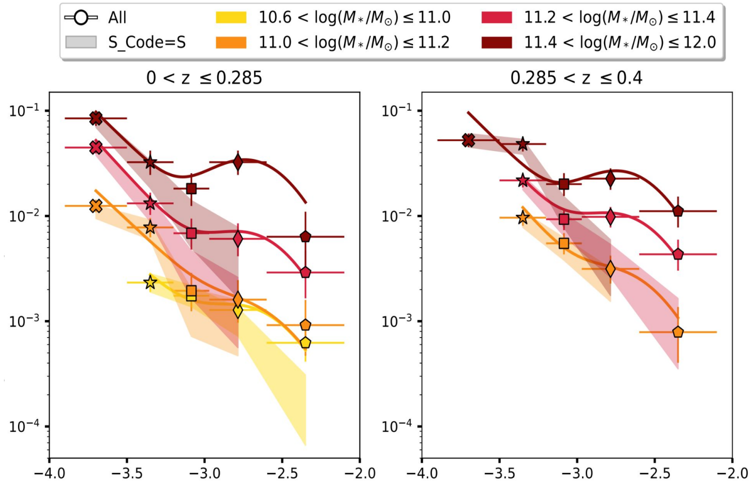
Increased mass dependence and different jet power dependence

Increased incidence at high λJet flattens the distribution
→due to large physical size (>60kpc) and multiple component radio AGN

Igo et al. (2024)

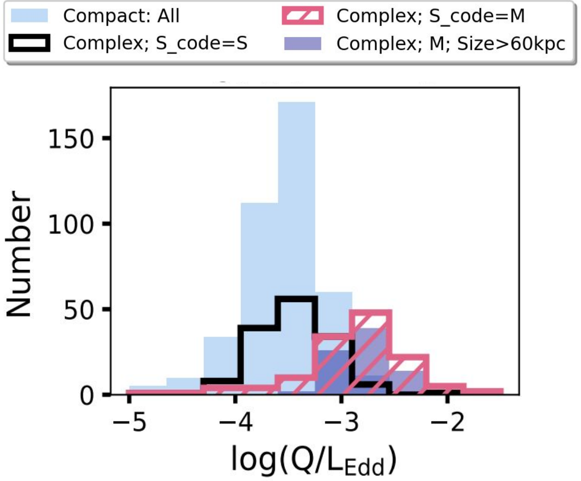
Incidence of radio AGN: Compact and Complex

Fraction of galaxies hosting **compact and complex** radio AGN



$\log(\lambda_{Jet}) = \log(Q/L_{Edd})$

Igo et al. (2024)



Increased incidence at high λJet flattens the distribution →due to large physical size (>60kpc) and multiple component radio AGN

BUT not due to such high power, large radio AGN lying in denser environments (ask me more later!)

Why?
→ Single LR–Q relation too simplistic? Further dependence on: α_r, jet particle content, radio morphology, spin?
→ Differing lifetime functions? e.g. large, powerful radio AGN are longer-lived (Hardcastle+18, 19); origin of radio in low power sources (e.g. Panessa+2019)?

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Summary

1) **First time probing the incidence of radio AGN as a function of mass-scaled jet power, using a well-characterized, complete, spectroscopic sample and splitting between different radio morphologies.**
2) **Incidence of compact radio AGN has a small mass- and steep jet power dependence.**
3) **Incidence of compact and complex radio AGN has a larger mass and flatter jet power dependence.**

Check out the full paper if you are interested in:

- New value-added catalogue of radio AGN in a rich multiwavelength field
- Incidence of quiescent vs. star-forming radio AGN
- Incidence of X-ray detected AGN → universal AGN fueling and triggering mechanism
- Using incidence analysis to analyse the balance of power in different accretion modes

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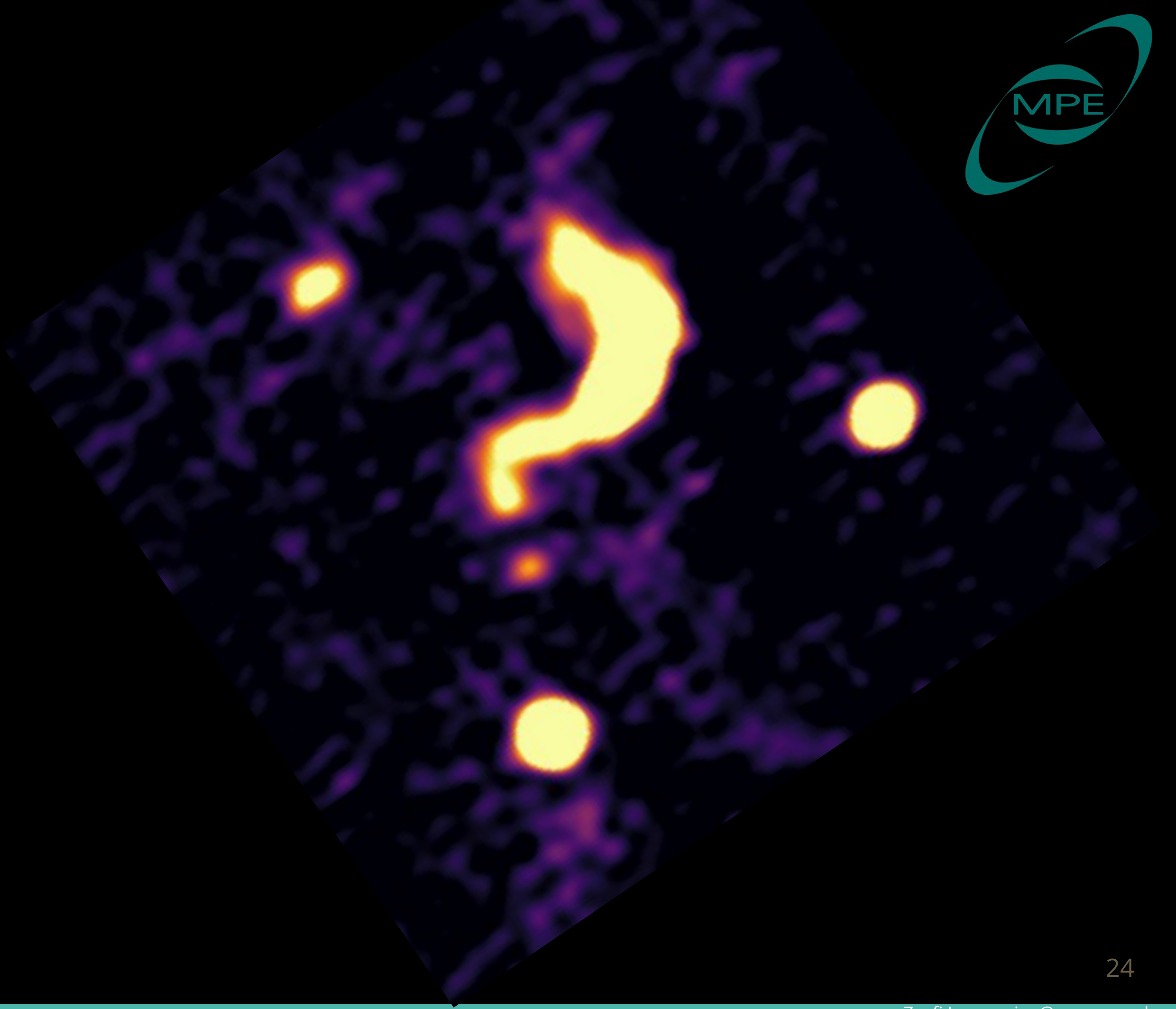
Any questions?



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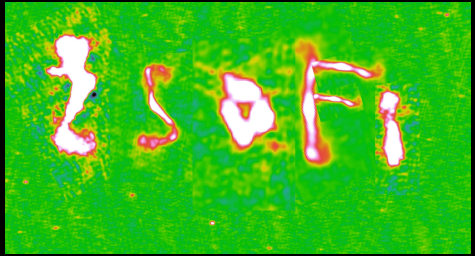

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Yes, the images are real LOFAR cutouts

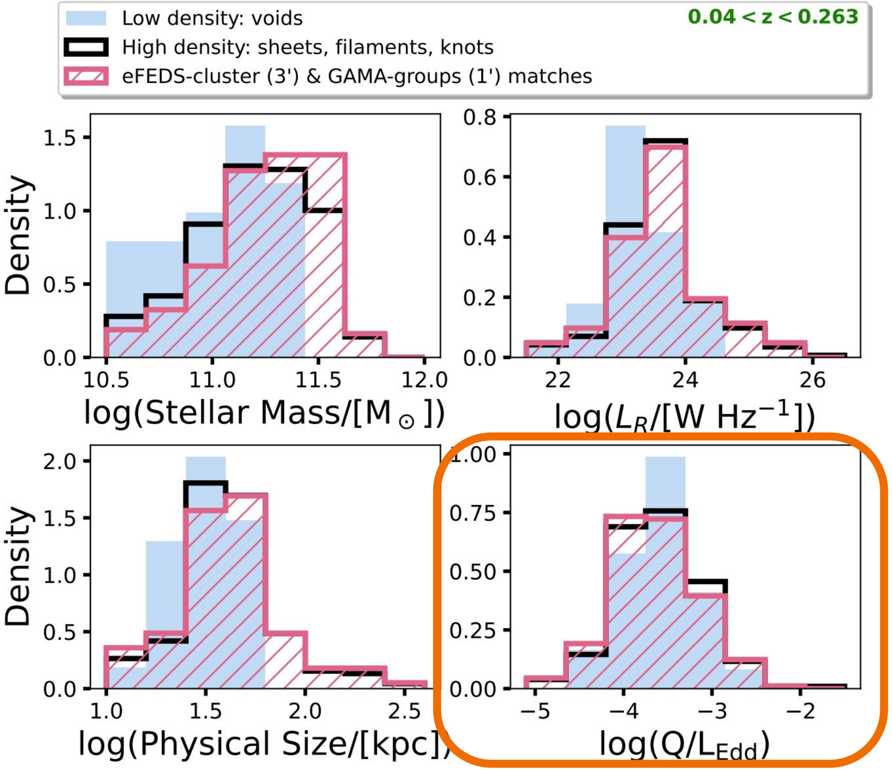
Extra Slides

Larger Scale Environment: Effect on Jet Power?

GAMA value added catalogue: voids, **sheets, filaments, knots**

Matches to GAMA groups (1') and eFEDS cluster (3') catalogues → dense environment

Conclusion: The increased incidence at the highest jet powers is not due to those AGN preferentially lying in denser environments (i.e. to powerful complex radio AGN residing in more massive haloes)



Igo et al. (2024)

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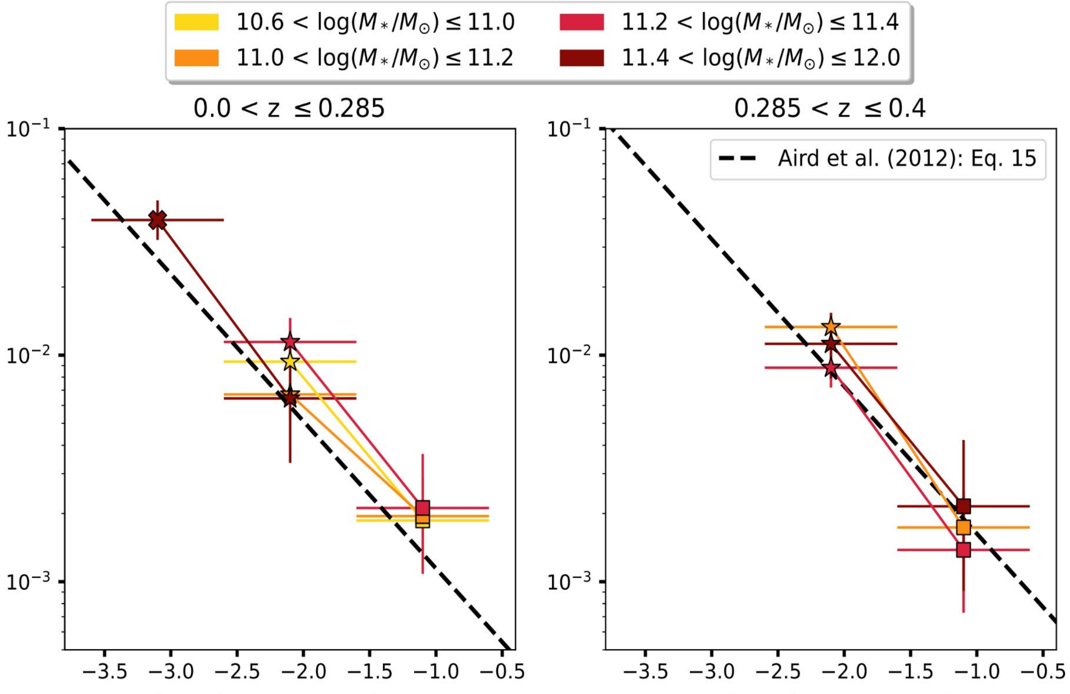
Mass-Invariant AGN Triggering and Fueling in X-rays

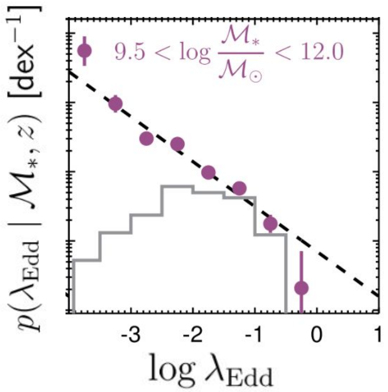
Fraction of galaxies hosting X-ray AGN



$\log(\lambda_{Edd}) = \log(L_{bol}/L_{Edd})$

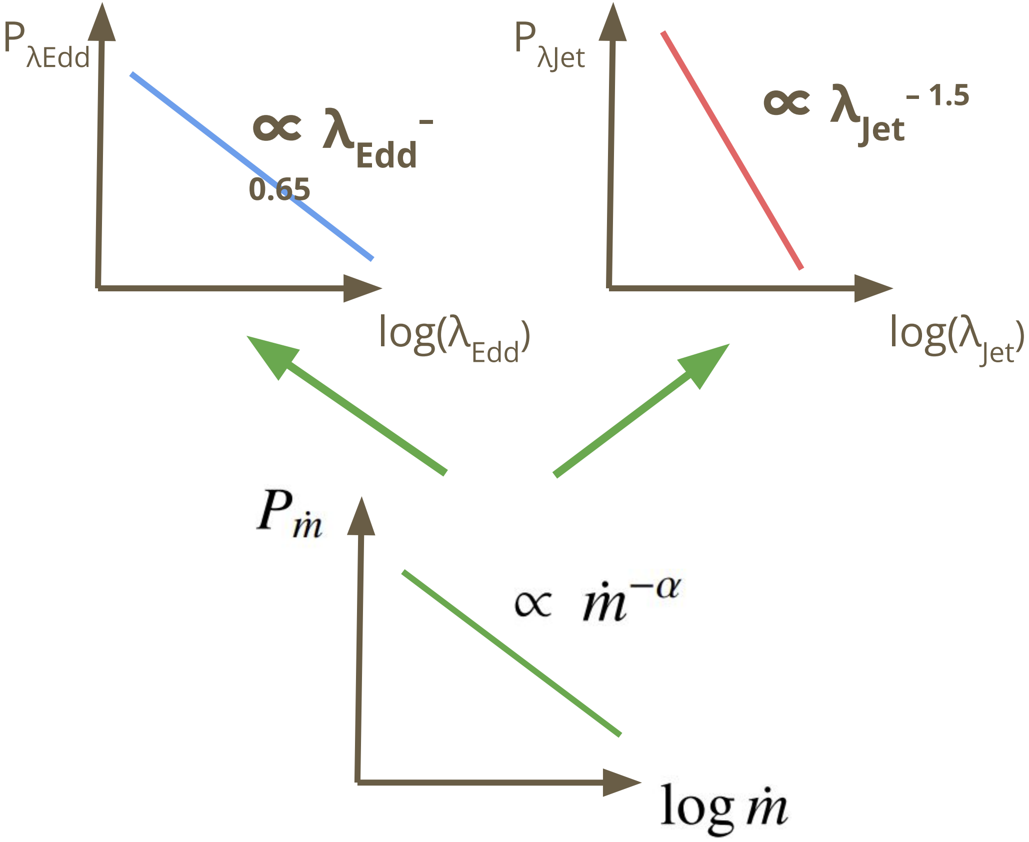
Igo et al. (2024)

“The same underlying physical processes are responsible for triggering and fueling AGN activity in all moderately massive galaxies.” (Aird et al. 2012)



$L_{bol}/L_{Edd} \propto L_X/M_*$

Incidence analysis and average accretion modes



$$\lambda_{\mathrm{Edd}} \propto \begin{cases} \dot m, & \dot m > \dot m_{\mathrm{crit}} \\ \dot m^2, & \dot m < \dot m_{\mathrm{crit}} \end{cases}$$

Assuming an **intrinsic power-law distribution of accretion rates** is responsible for the observed power-law distributions of the incidence of X-ray and (compact) radio AGN

⇒ the X-ray incidence is expected to flatten at low accretion rates

⇒ the compact radio AGN trace an inefficient accretion mode.

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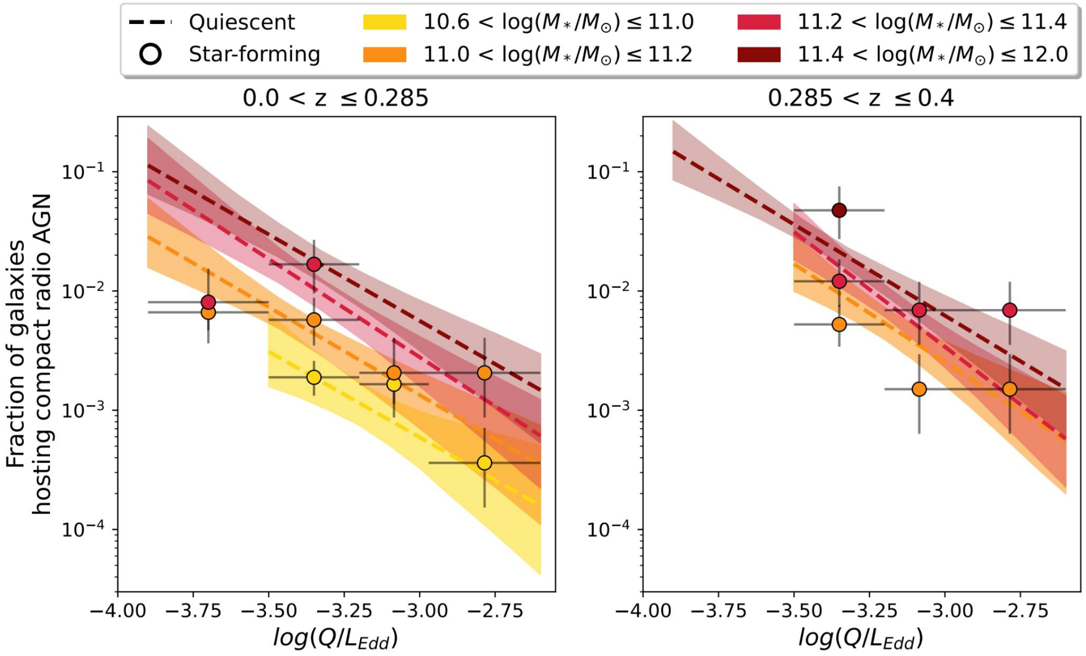
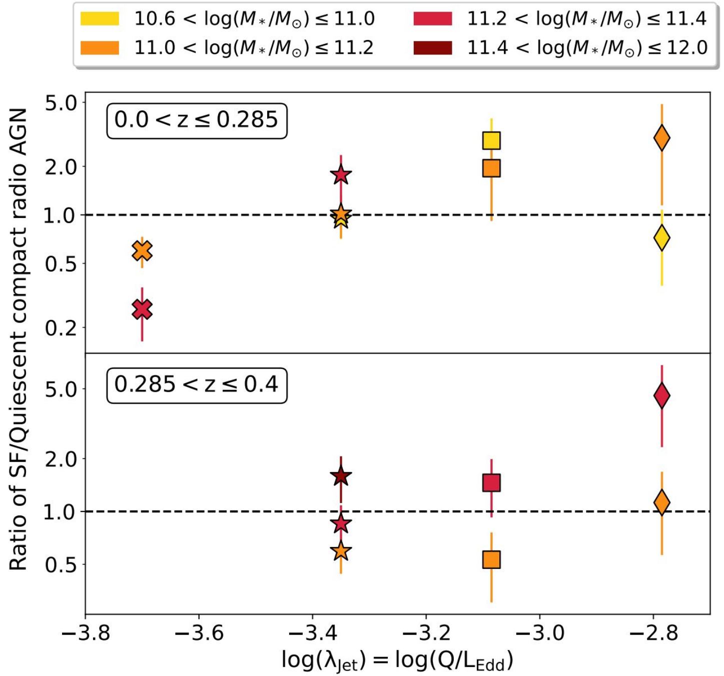
Quiescent vs. Star-forming radio AGN incidence





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Balance of Power

Igo et al. (2024)

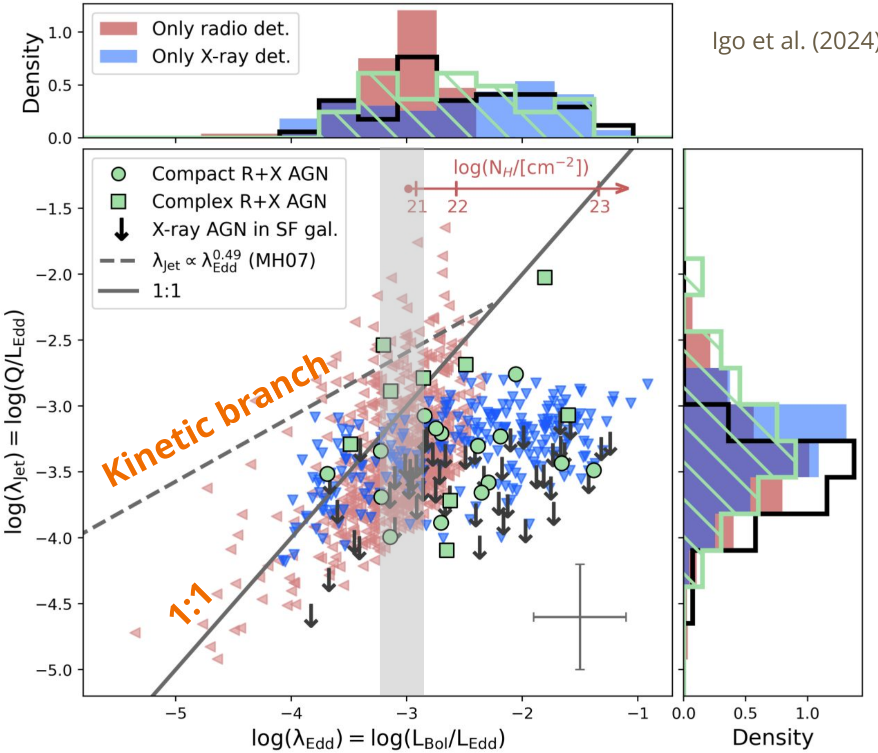
Kinetic power

$$Q = 2.8 \times 10^{37} \left(\frac{L_{1.4\mathrm{GHz}}}{10^{25}\ \mathrm{W\ Hz^{-1}}} \right)^{0.68} \mathrm{W}$$

$$\lambda_{\mathrm{Jet}} = \frac{Q}{L_{\mathrm{Edd}}}$$

CAUTION

Kinetic branch, see Merloni & Heinz 2007



Hard to disentangle different accretion states with this sample

Radiative power

$$\lambda_{\mathrm{Edd}} = \frac{25\, L_{\mathrm{X,Hard}}}{1.26 \times 10^{38}\ \mathrm{erg\ s^{-1}}\ (0.002\ \mathrm{M_*})/\mathrm{M_\odot}}$$

Absorption corrected 2-10 keV luminosity obtained from spectral fitting

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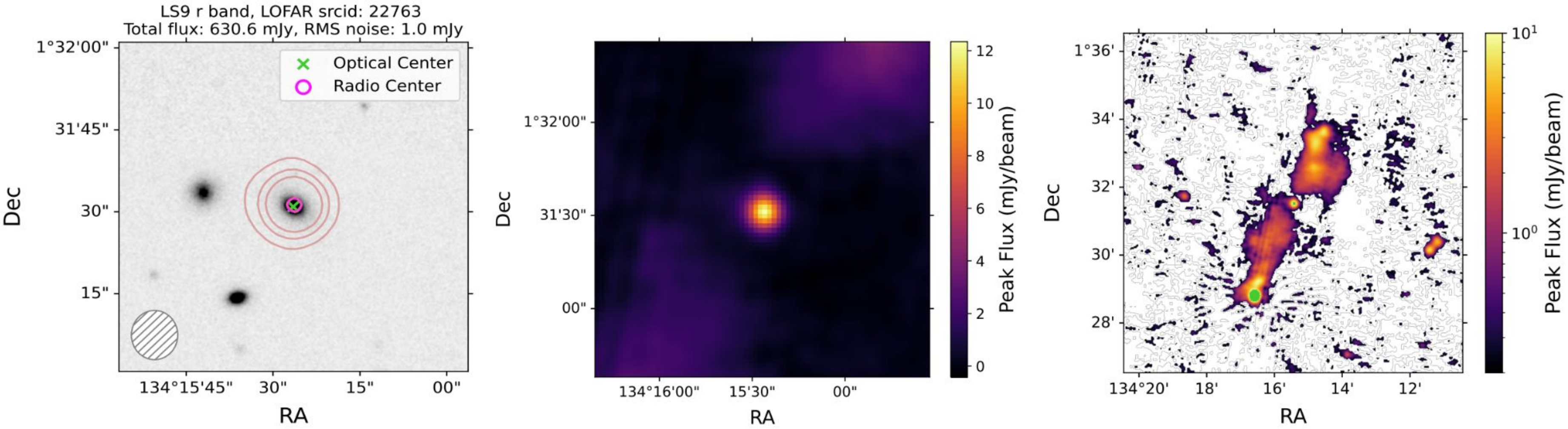
LS9 r band, LOFAR srcid: 22763
Total flux: 630.6 mJy, RMS noise: 1.0 mJy
Optical Center
Radio Center
1°32'00"
31'45"
30"
15"
Dec
134°15'45"
30"
15"
00"
RA
1°32'00"
31'30"
00"
Dec
134°16'00"
15'30"
00"
RA
Peak Flux (mJy/beam)
1°36'
34'
32'
30'
28'
Dec
134°20'
18'
16'
14'
12'
RA
Peak Flux (mJy/beam)

Redshift

log(Stellar Mass/[$M_\odot$])	$0 < z \leq 0.285$: # GAMA galaxies	# LOFAR-det.	# eFEDS-det.	# LOFAR & eFEDS det.	$0.285 < z \leq 0.4$: # GAMA galaxies	# LOFAR-det.	# eFEDS-det.	# LOFAR & eFEDS det.
11.4 – 12.0	420	96 (22.9%)	22 (5.2%)	3 (0.7%)	779	123 (15.8%)	28 (3.6%)	6 (0.8%)
11.2 – 11.4	1263	111 (8.8%)	33 (2.6%)	6 (0.5%)	2003	119 (5.9%)	28 (1.4%)	4 (0.2%)
11.0 – 11.2	2910	72 (2.5%)	47 (1.6%)	4 (0.1%)	3395	80 (2.4%)	31 (0.9%)	1 (0.0%)
10.6 – 11.0	10692	81 (0.8%)	136 (1.3%)	0 (0.0%)				

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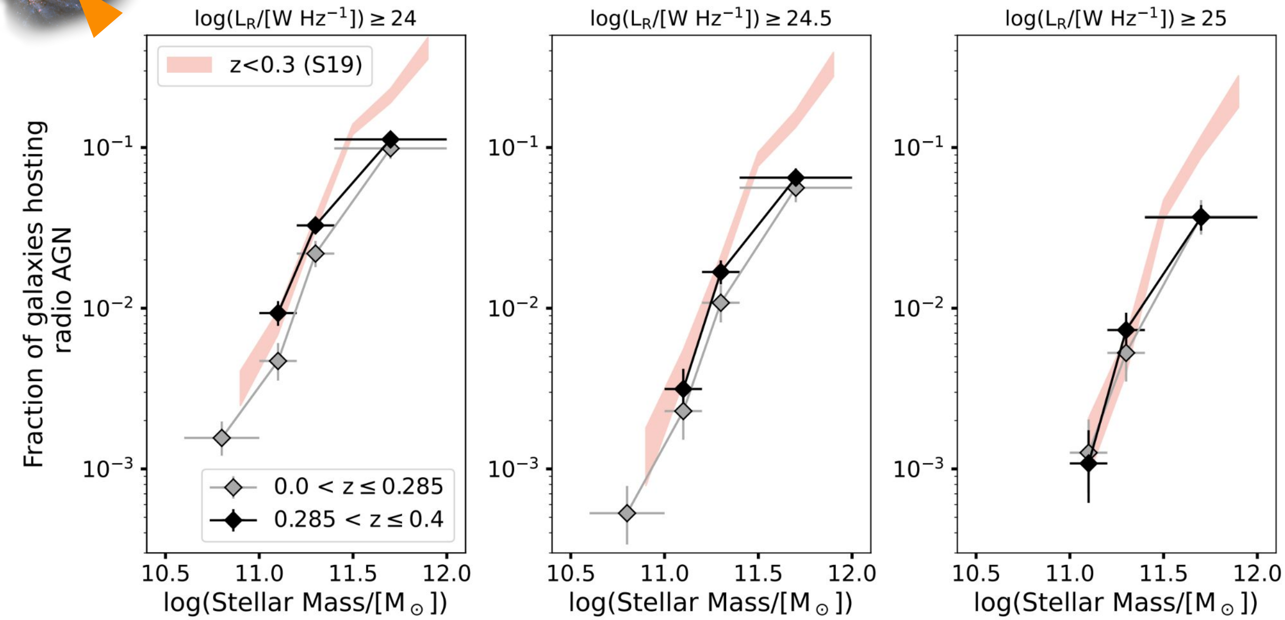
Incidence of radio AGN as a function of stellar mass



Steep dependence on stellar mass

HOWEVER: Incidence as a function of M* is prone to **SELECTION EFFECTS**, due to underlying jet power distribution and survey flux limits.

Need to compute incidence as a function of **mass-normalized jet power (λ_{Jet})**!

Igo et al. (2024)

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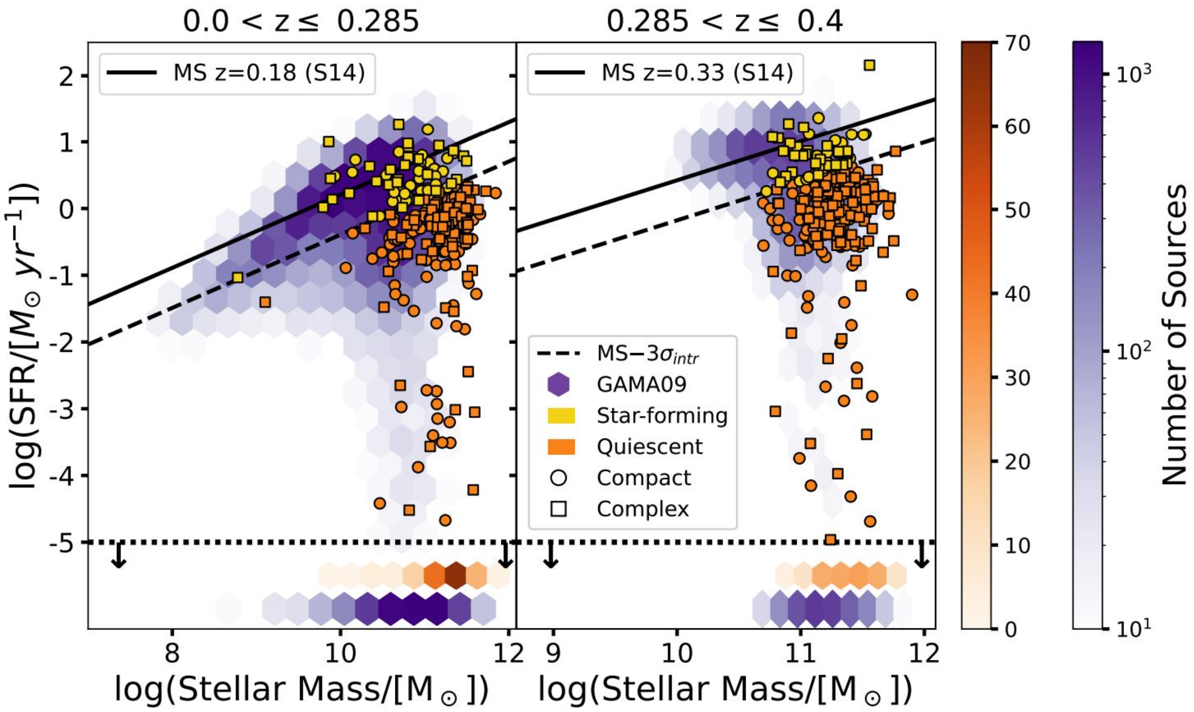
Characterizing host galaxy: quiescent or star-forming?



Igo et al. (2024)

- Redshift dependent relation between host galaxy star formation rate and stellar mass **(Speagle et al. 2014)**
- Sources **3-sigma** below this relation are **quiescent galaxies**