Global energetics and feedback as probed by AGN incidences

Zsofi Igo

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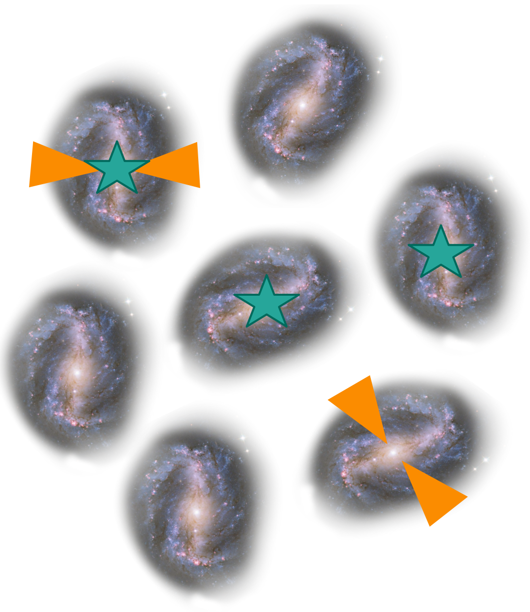
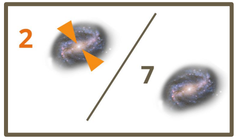
Collaborators: A. Merloni, D. Hoang, J. Buchner, T. Liu, M. Salvato, R. Arcodia, S. Bellstedt, M. Brüggen, J.H. Croston, F. de Gasperin, A. Georgakakis, M.J. Hardcastle, K. Nandra, Q. Ni, T. Pasini, T. Shimwell, J. Wolf

18th Potsdam Thinkshop – 14th July 2025

What are AGN incidences? Why are they important?





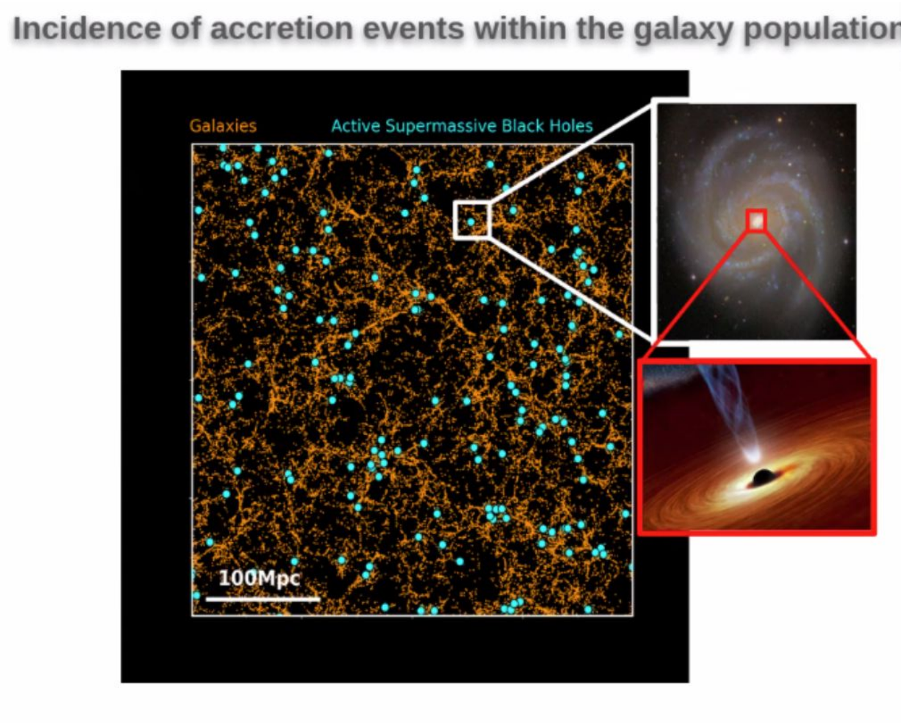


Figure courtesy of A. Georgakakis

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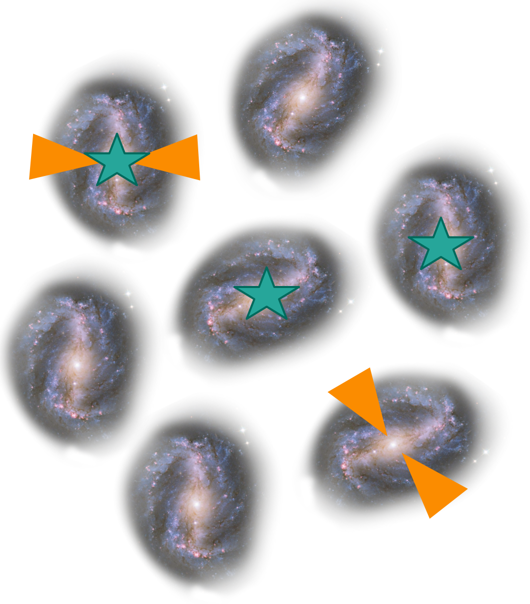

It can tell us about:

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

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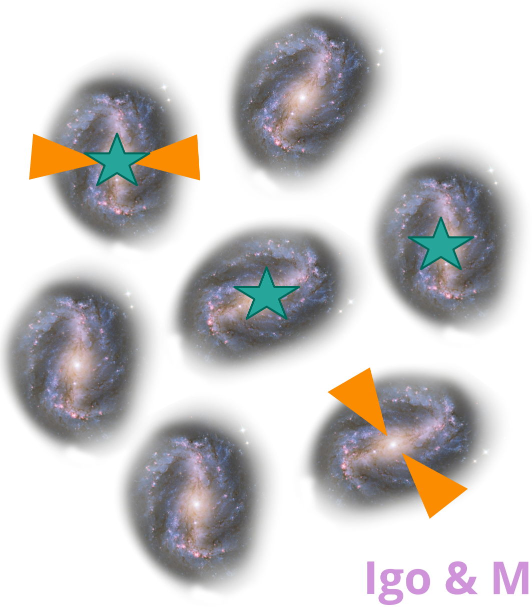

Igo & Merloni (2025)

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Igo et al. 2024

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Data and Context

The incidence of radio and X-ray AGN and the disk-jet connection

Igo et al. 2024

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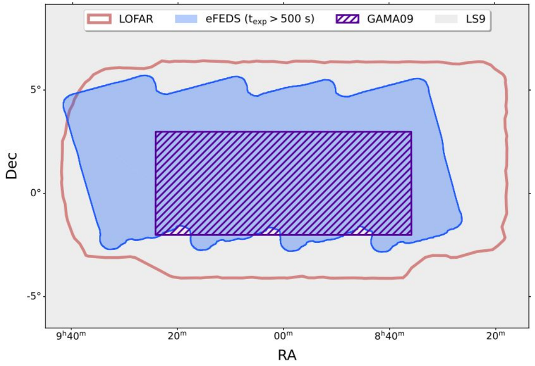

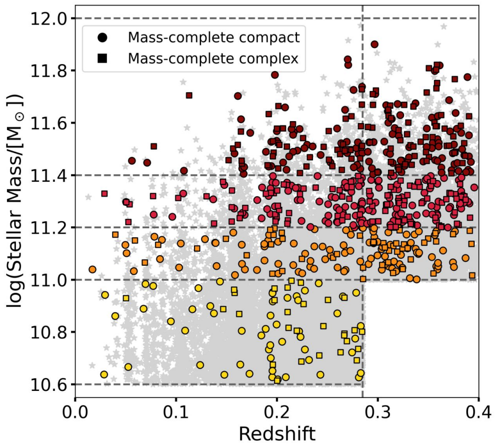

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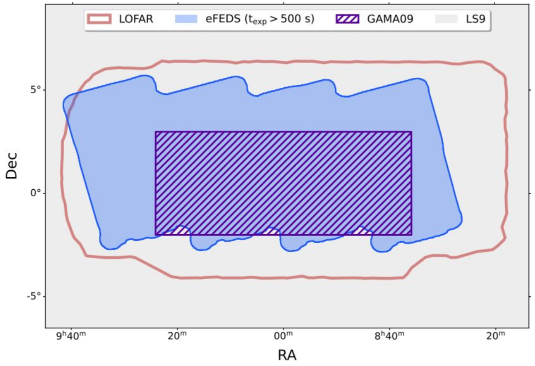

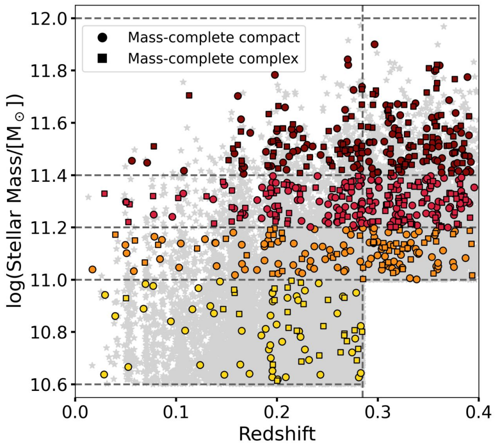

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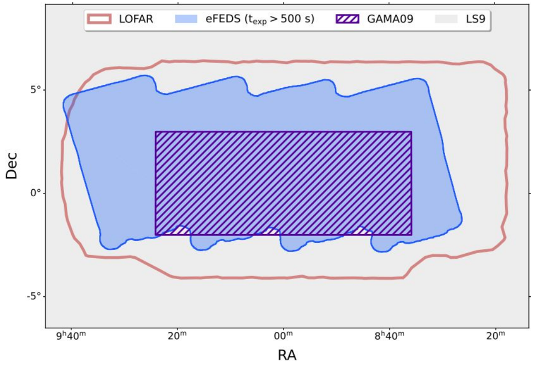
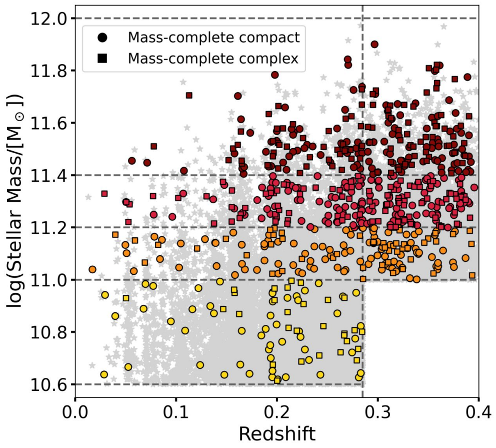
- **Sample properties:**
  Massive galaxies: $10.6 < \log(M_*/M_\odot) < 12$
  Low redshift: $z < 0.4$
  Large samples: 682 radio AGN; 325 X-ray AGN
  (X-ray results not covered in this talk, but ask me later!)





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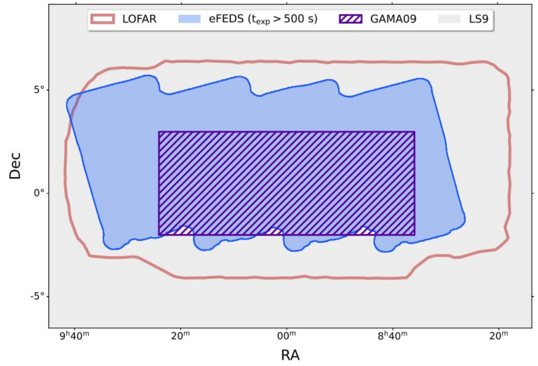
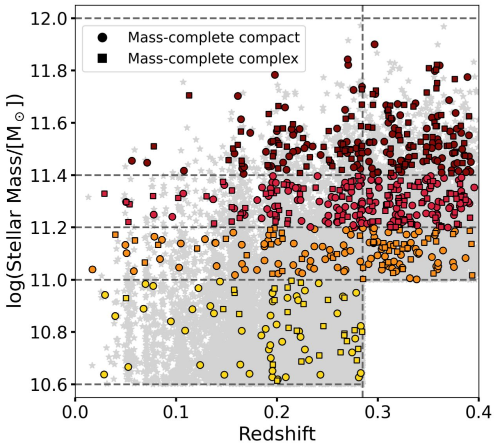
- **Goal:** Study AGN incidence as a function of mass-scaled power indicators, i.e. luminosity/mass → λ_{Jet}





Goal: Study AGN incidence as functions of mass-scaled power indicators

Igo et al. 2024

Specific Black Hole Kinetic power

$L_R / M_* \rightarrow Q/L_{Edd}$

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

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

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Goal: Study AGN incidence as functions of mass-scaled power indicators AND RADIO MORPHOLOGY

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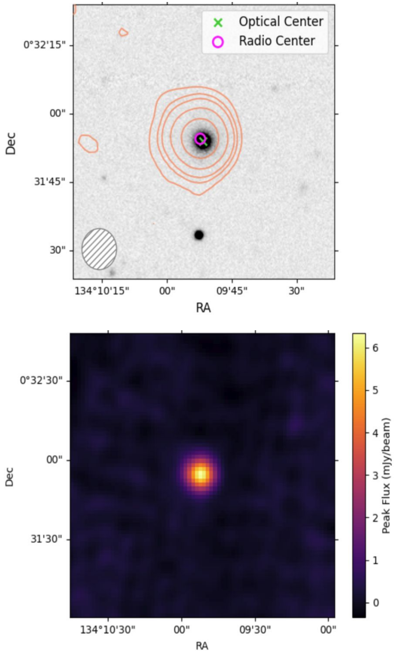
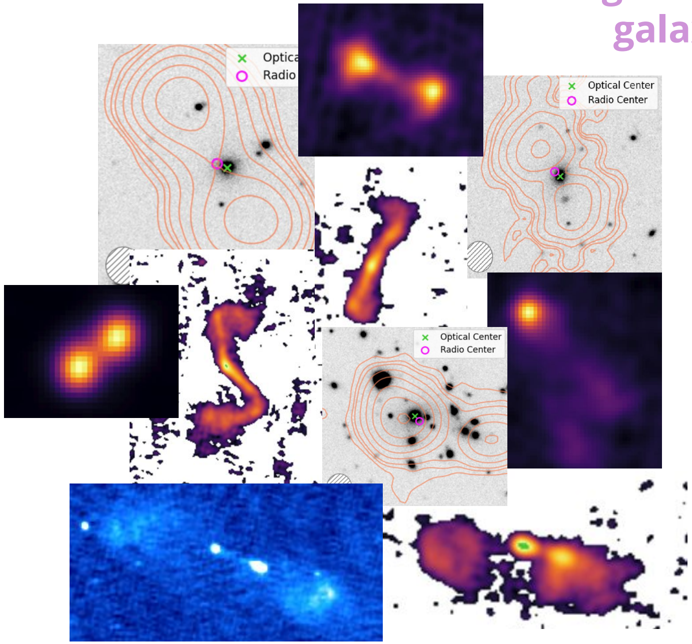
Compact

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



Complex

often >40 kpc in physical size! i.e. larger than typical galaxy sizes



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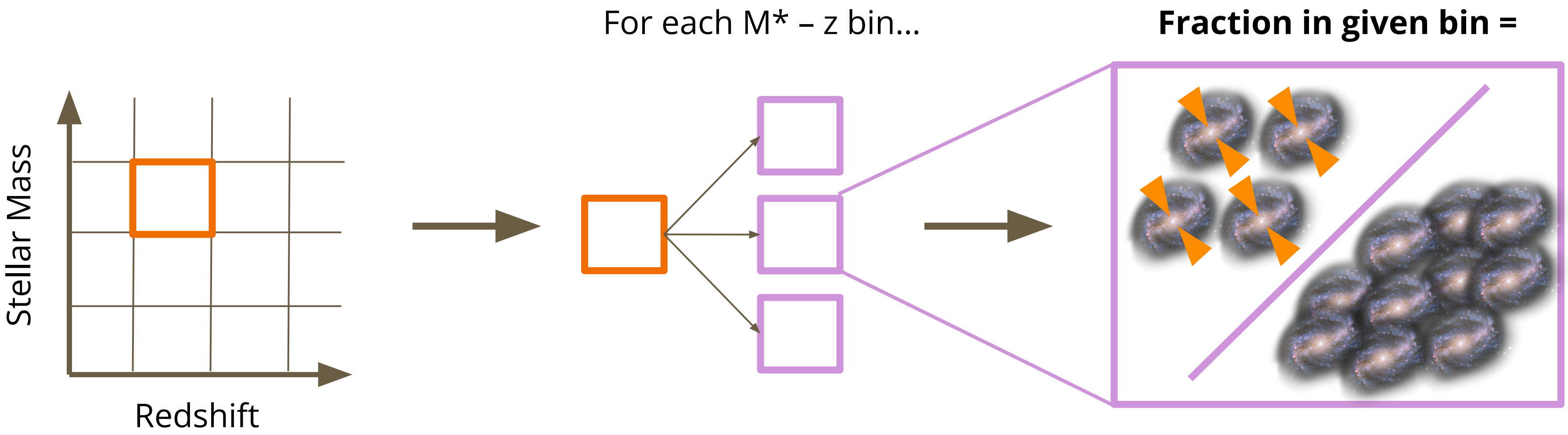
Calculating incidence of AGN: M*–z binning



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

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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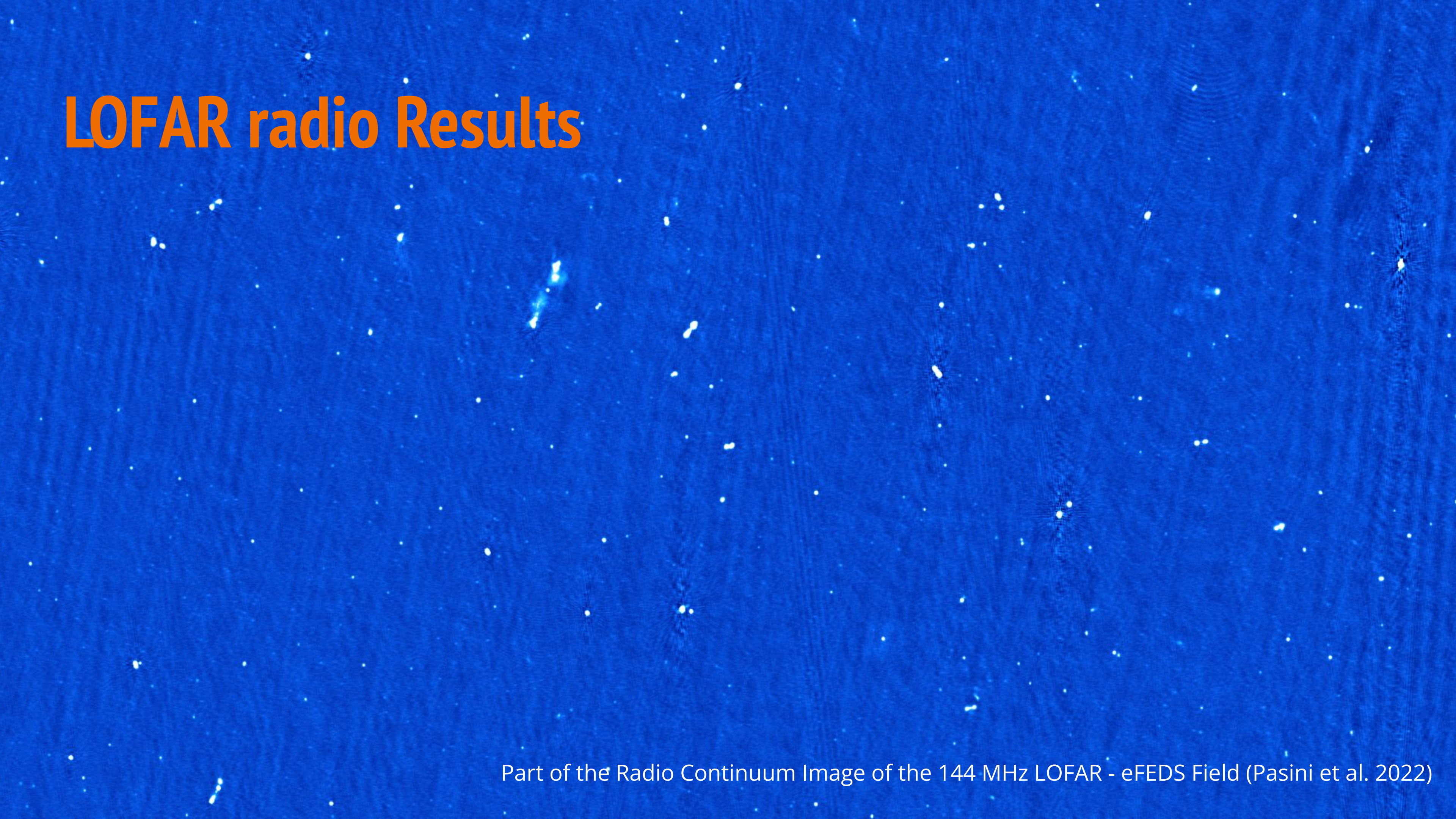
LOFAR radio Results

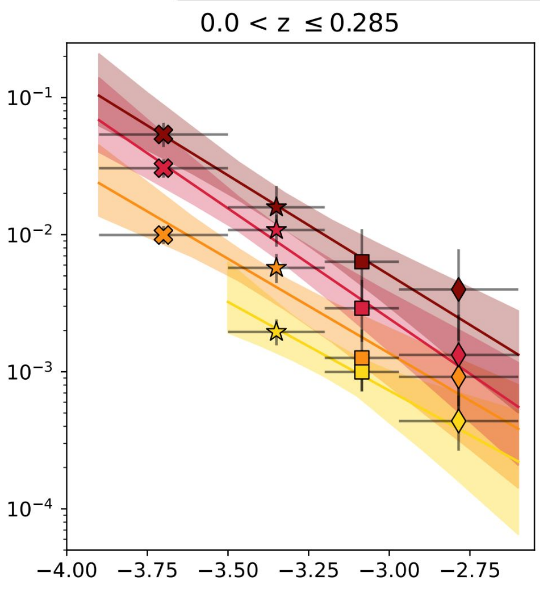


Part of the Radio Continuum Image of the 144 MHz LOFAR - eFEDS Field (Pasini et al. 2022)

Incidence of compact radio AGN: mass-scaled jet power λ_{Jet}

Igo et al. 2024

Fraction of galaxies hosting **compact** radio AGN



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

(Showing only lower redshift bin)

$10.6 < \log(M_*/M_\odot) \leq 11.0$

$11.0 < \log(M_*/M_\odot) \leq 11.2$

$11.2 < \log(M_*/M_\odot) \leq 11.4$

$11.4 < \log(M_*/M_\odot) \leq 12.0$

increasing stellar mass

increasing Jet power

$L_R / M_* \rightarrow Q/L_{Edd}$

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

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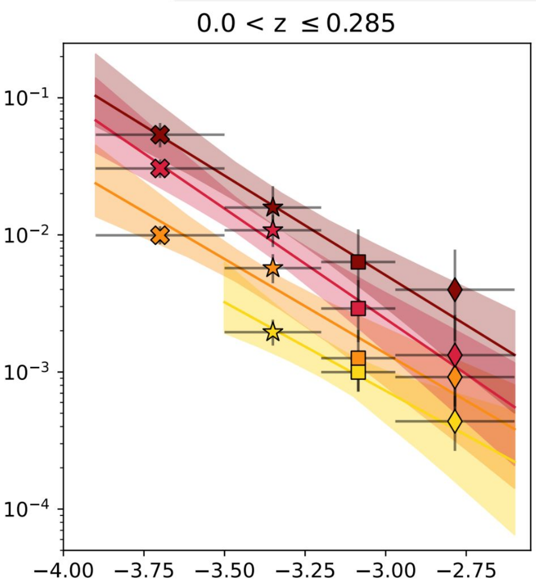

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Higher mass galaxies are more likely to host compact radio AGN

increasing stellar mass

(Showing only lower redshift bin)

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Igo et al. 2024

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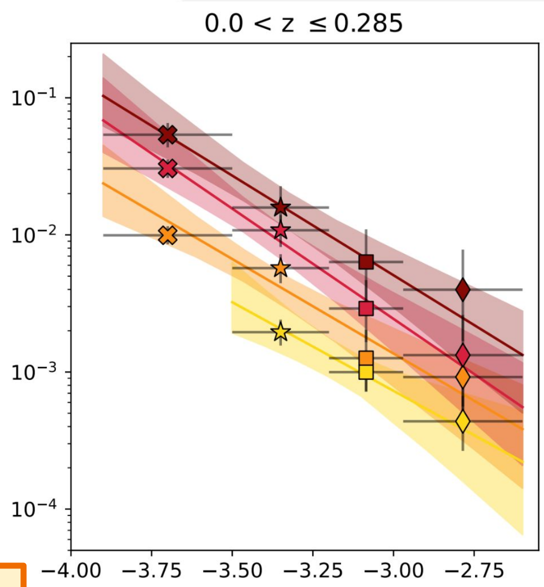

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increasing stellar mass

increasing Jet power

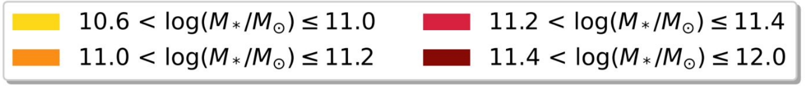
What about complex radio AGN?

$\mathbf{L_R / M_* \rightarrow Q/L_{Edd}}$

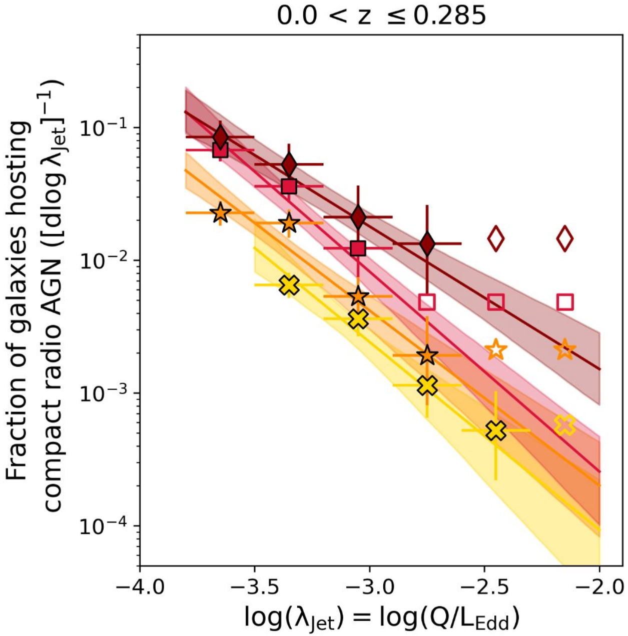
Jet power: $Q \propto L_R^{0.68}$

Radio morphology affects incidence of radio AGN !

Igo et al. 2024



<u>**Compact-only**</u> radio AGN →**steep** distribution, smaller mass dependence



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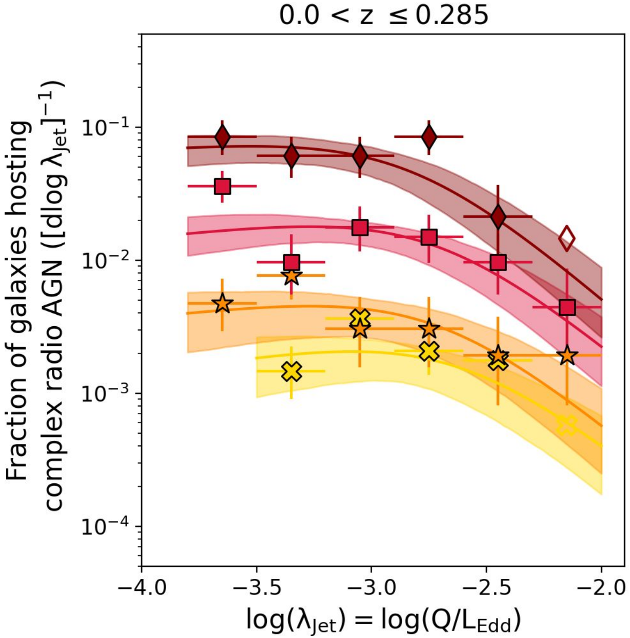

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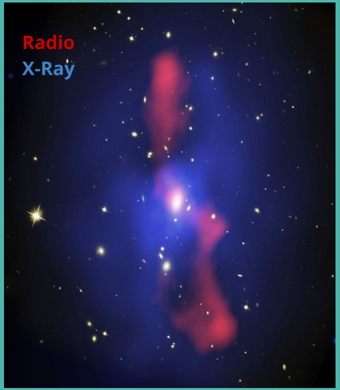
Global energetics of radio AGN kinetic feedback in the local universe



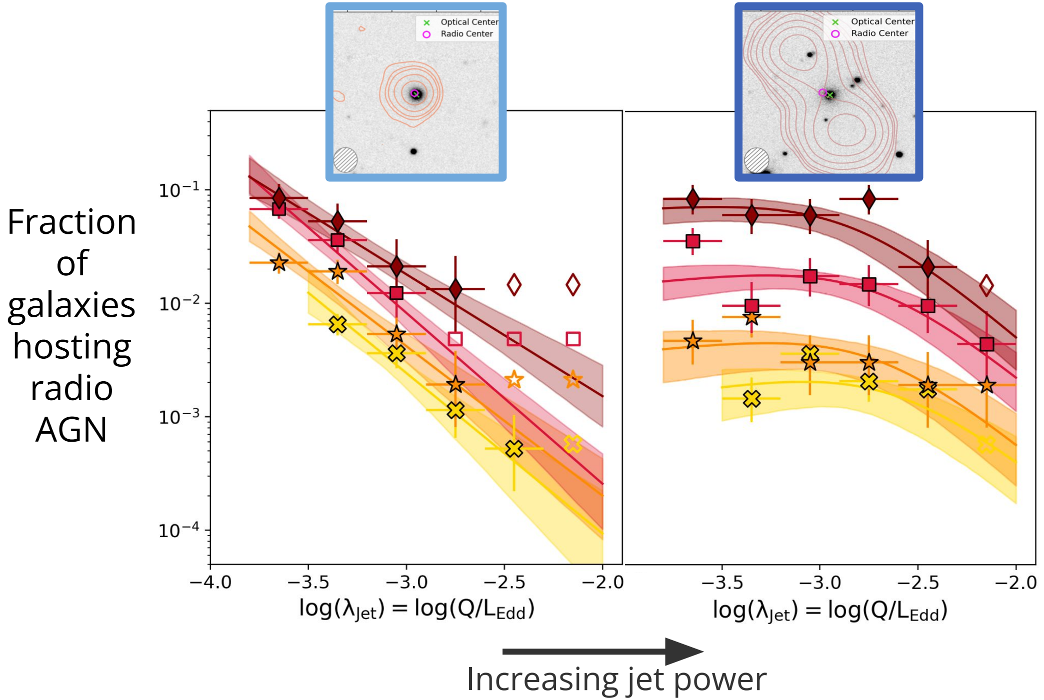
AGN feedback in Galaxy Cluster MS 0735
McNamara+ 2005, 2009

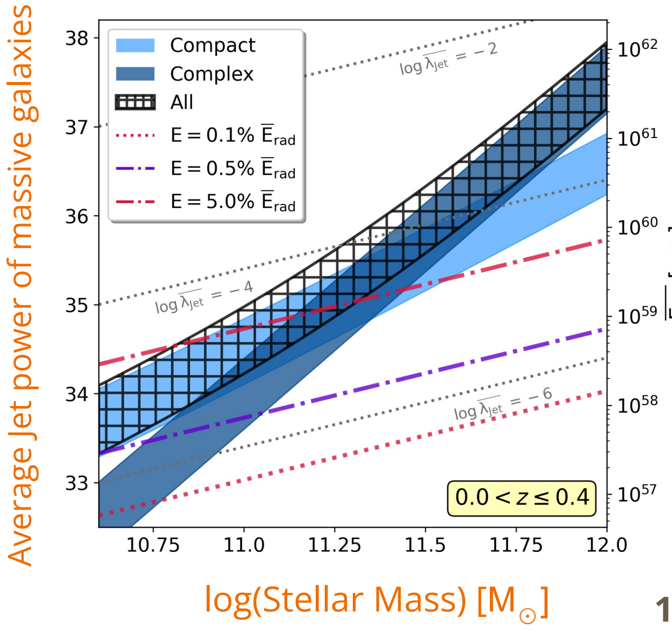
See also recent work by e.g. Buchner 2024, Heckman & Best 2023b, Kondapally+ 2023

AGN Feedback in massive galaxies via jets

Igo et al. (2024), Igo & Merloni (2025)

AGN incidence studies are very powerful ⇒ Global energy budget of radiative and kinetic feedback





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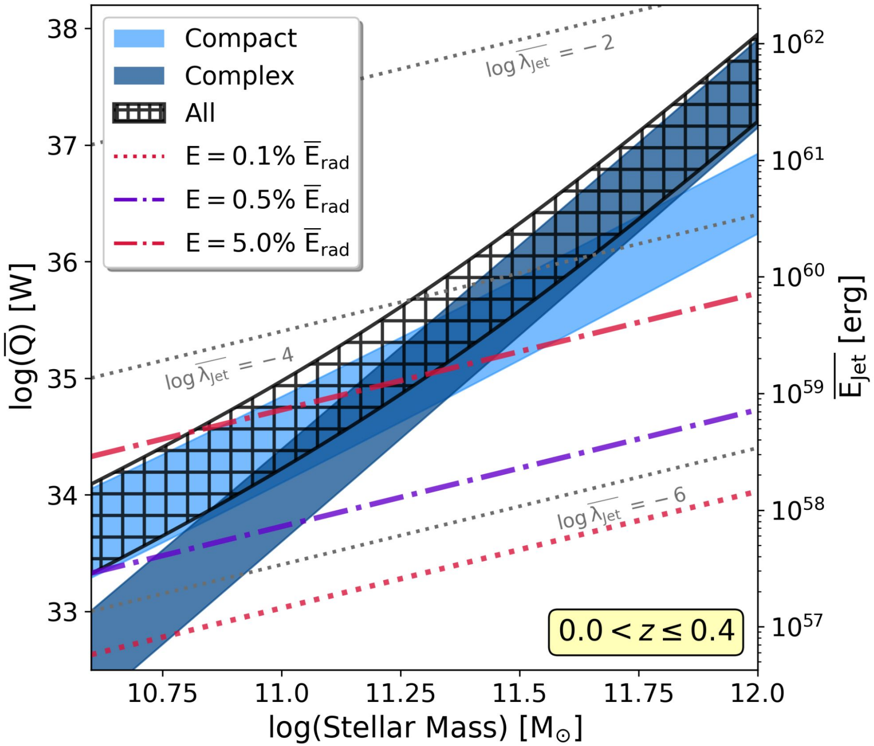
Average Jet Power of Massive Galaxies

Igo & Merloni 2025



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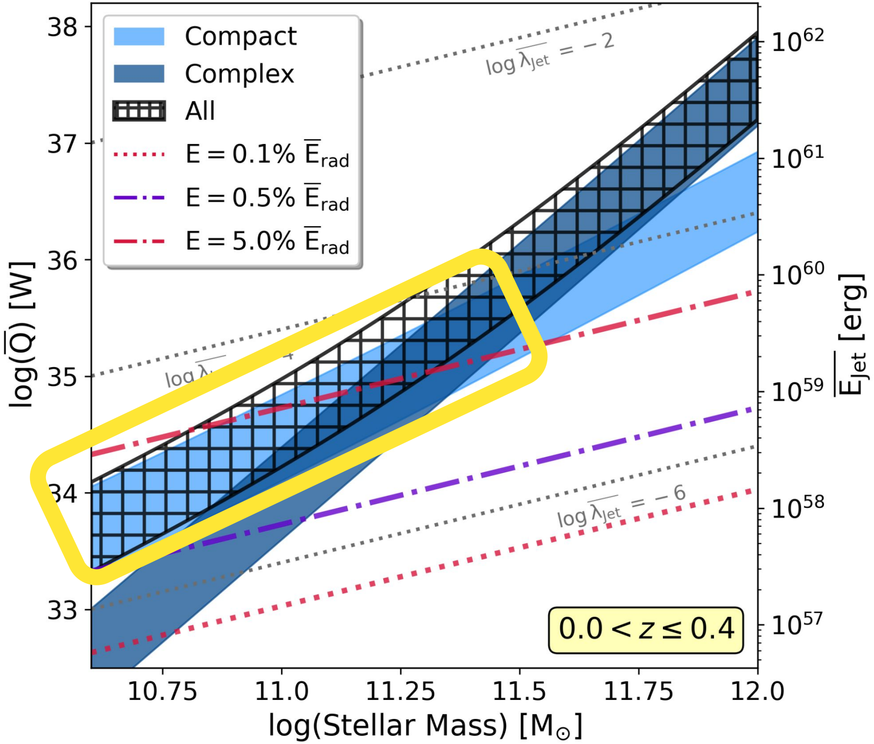
Average Jet Power of Massive Galaxies

Igo & Merloni 2025

Results:

- **Compact** (small, <40 kpc) radio AGN dominate feedback budget over a large range of massive galaxies **up to $\log(M_*/M_\odot) < 11.5$**



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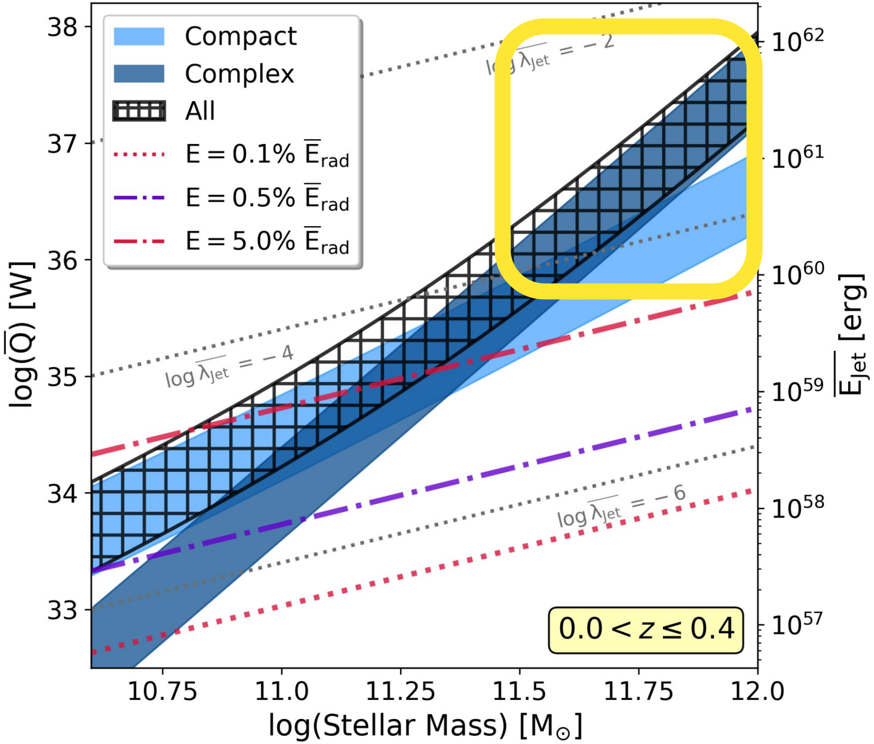

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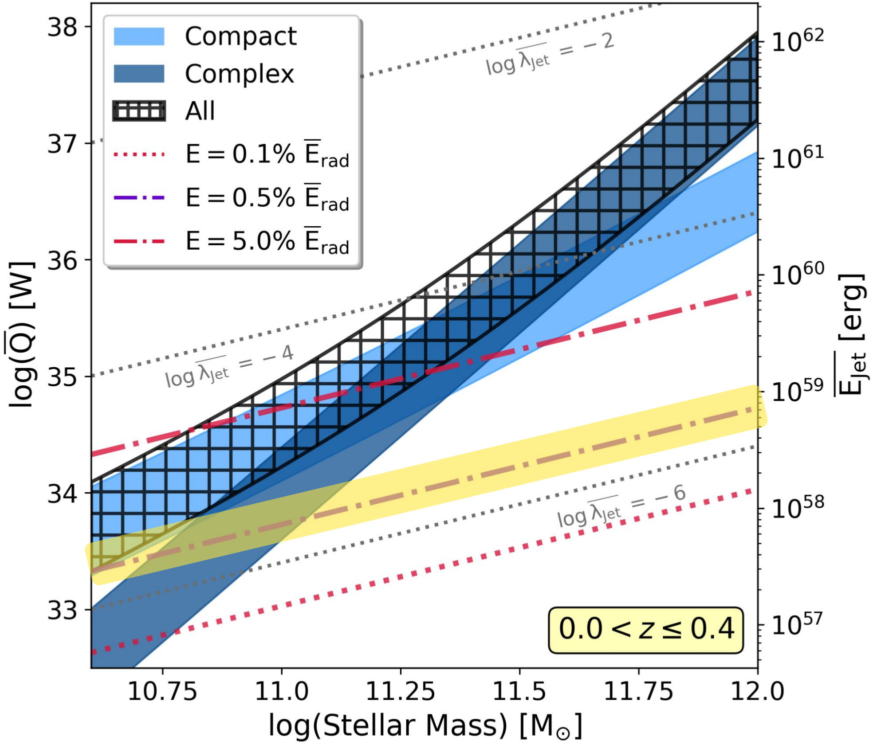
- In comparison: **Dashed-dot purple line** is **0.5%** of the **average AGN radiative energy output**, canonical frac. that can efficiently couple to the surrounding medium, producing feedback effects from multi-phase winds - see review in Heckman & Best 2023 (+ Di Matteo+2005 → 5%, red dot-dashed)



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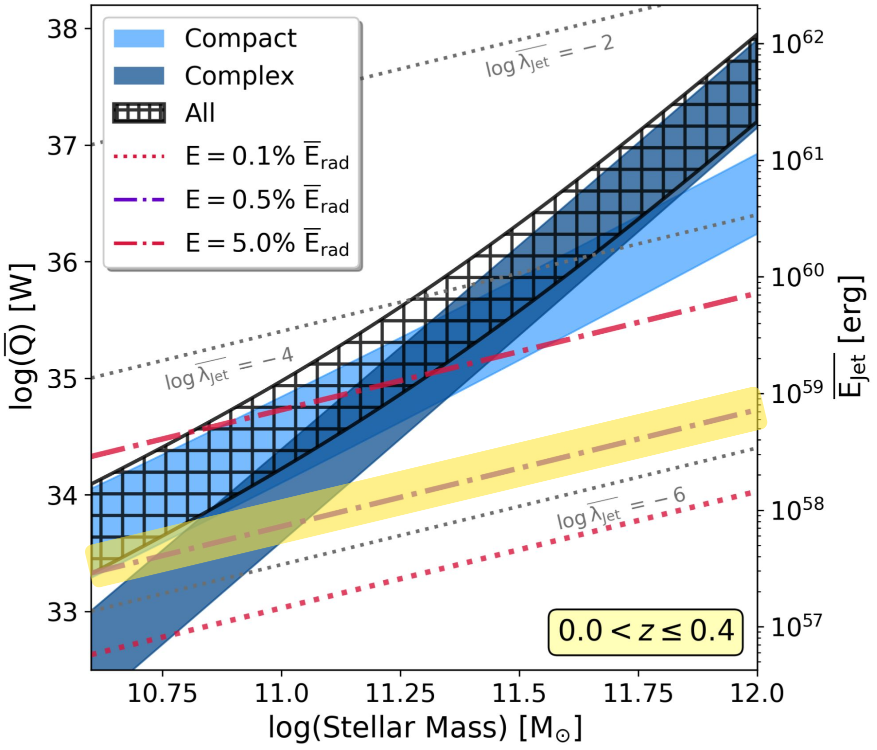

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(e.g. Somerville+2008, Croton+2016)

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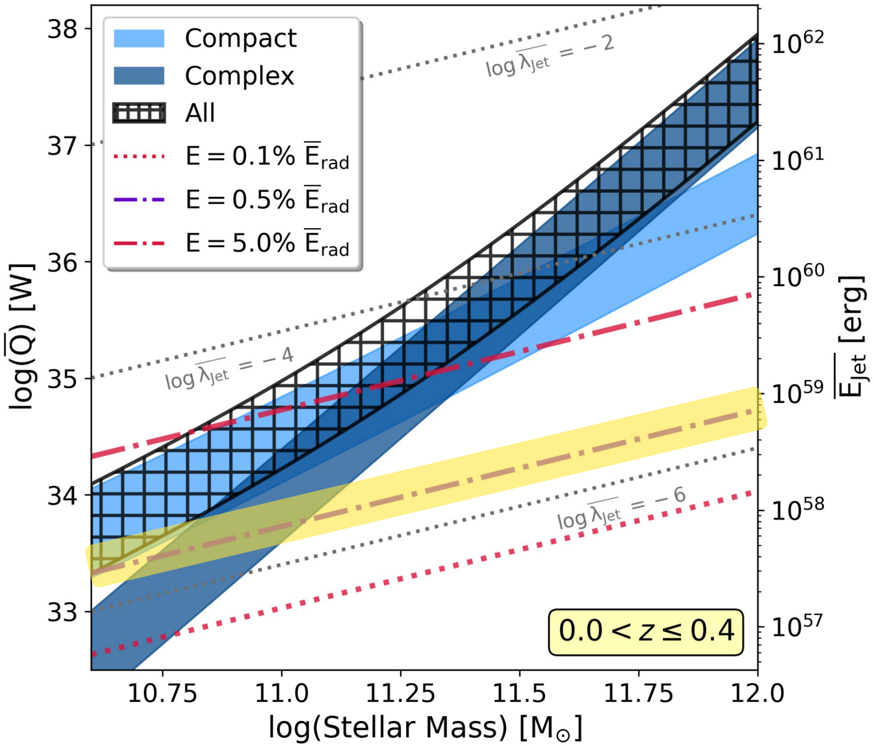

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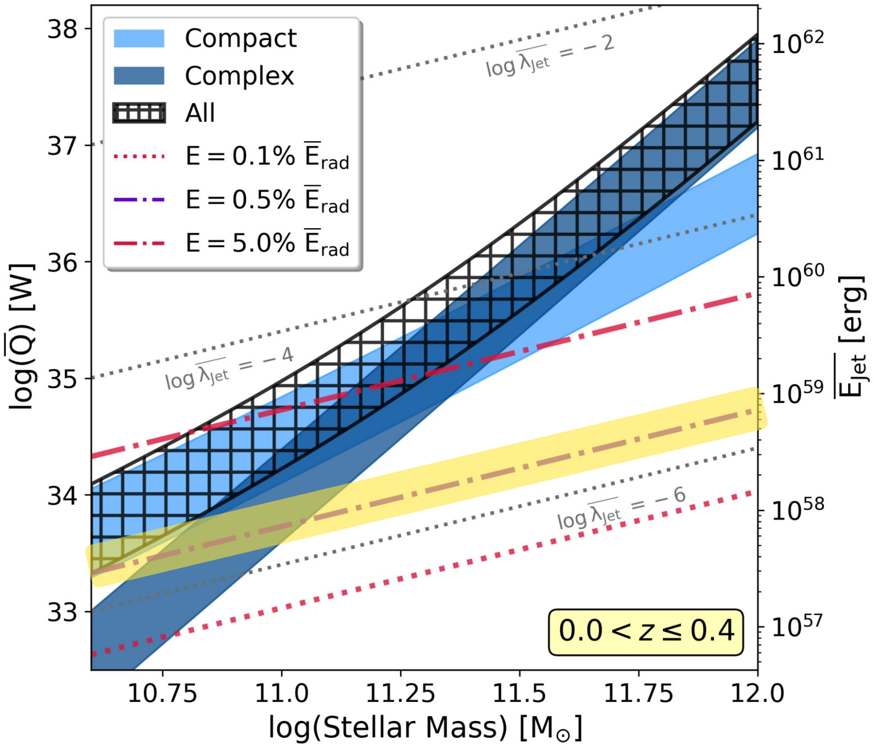

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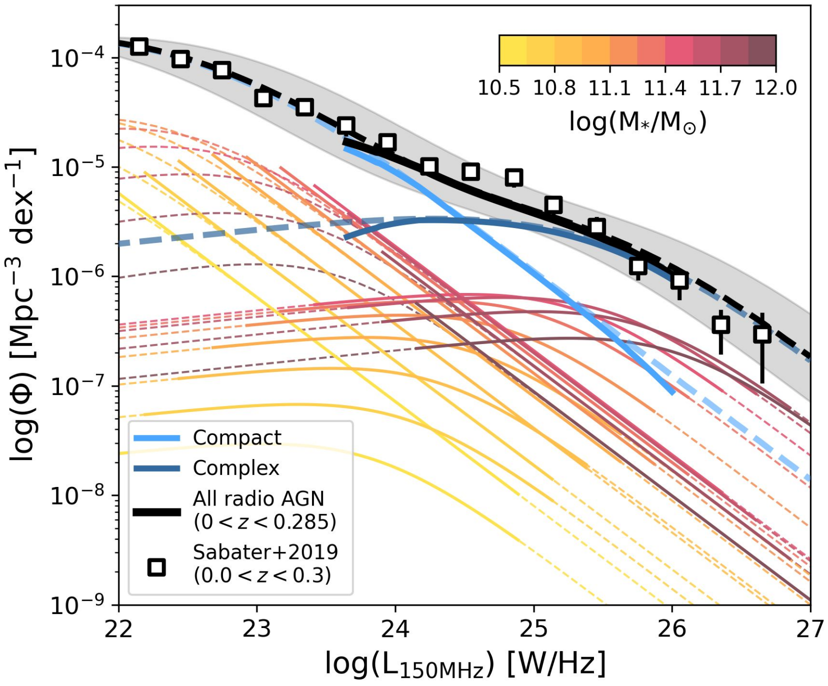
From Radio AGN incidences to Radio Luminosity Functions

Igo & Merloni 2025

- Convolve radio AGN incidence with the stellar mass function (Bernardi+2018) → recover the radio luminosity function (RLF)
- **RLF in agreement with literature**
- We decompose the RLF, for the first time, into different stellar mass *and* radio morphology contributions → useful for disentangling degeneracies in **AGN feedback simulations**



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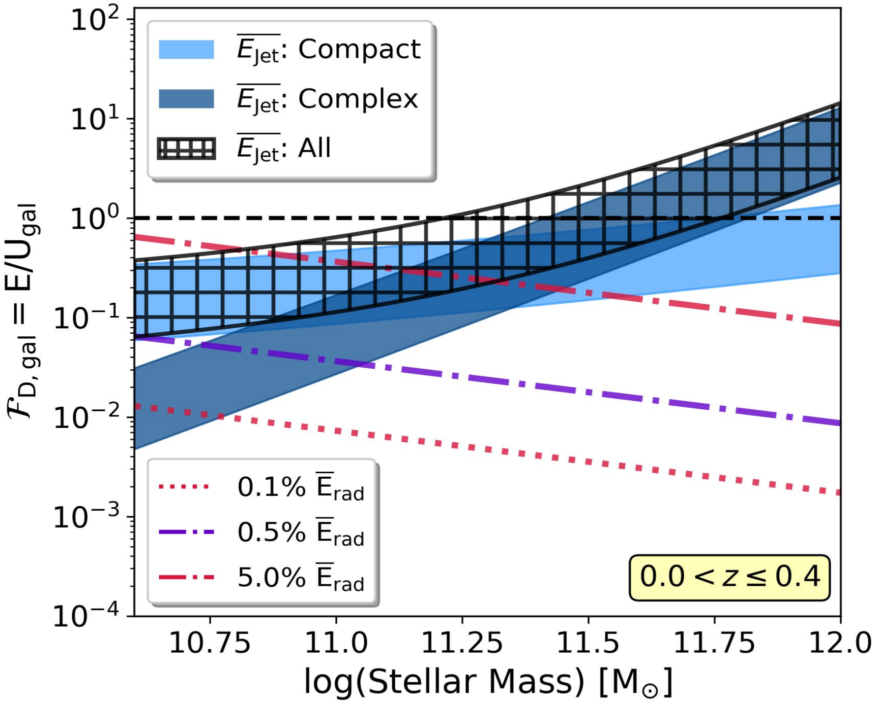
Radio AGN as "disruptive" feedback agents in galaxies

Igo & Merloni 2025

<u>Y- axis:</u> Avg. **Jet kinetic energy** compared to the **binding energy** of the <u>GALAXY</u>



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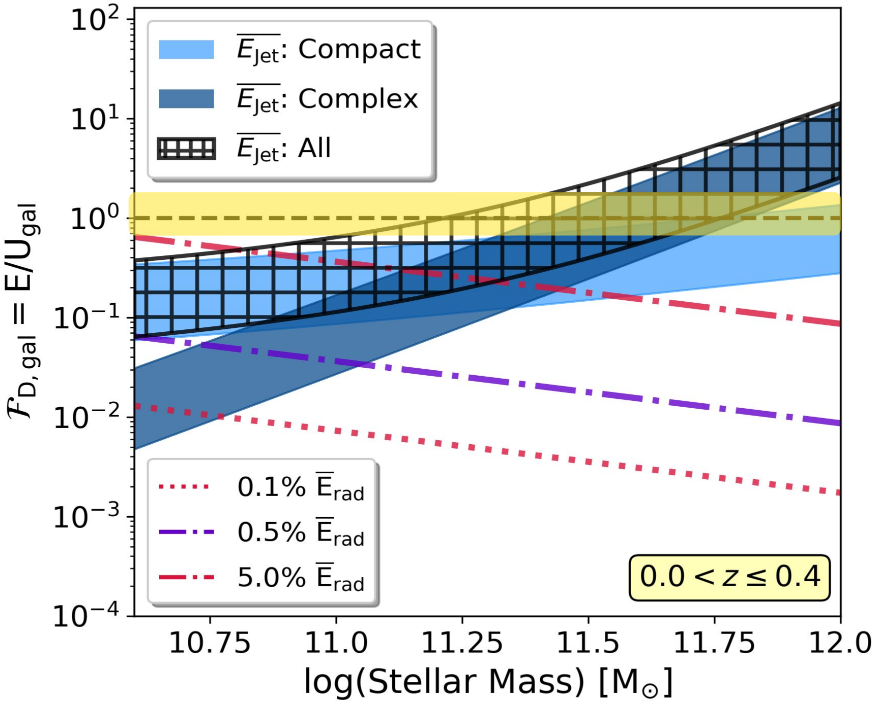
Jet kinetic energy == Galactic binding energy



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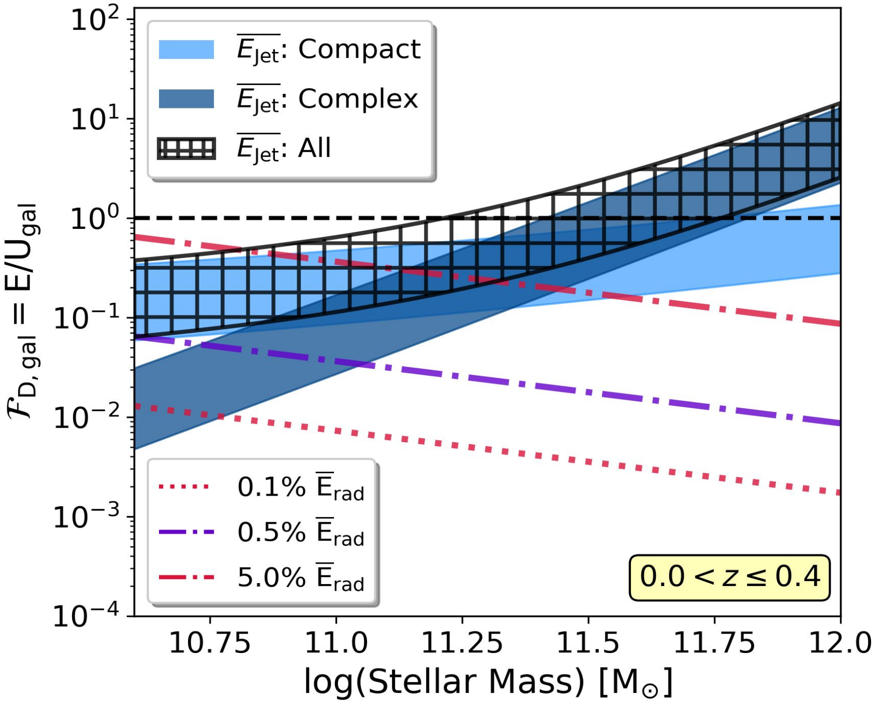
Results:

- **Compact radio AGN** provide 20-80% of the galaxies’ binding energies across the mass range

- **Complex radio AGN** in massive galaxies provide energy in excess of binding for $\log(M_*/M_\odot) > 11.5$
  <u>Caveat:</u> what are the **scales** at which the energy is released? (see next slide)

- Again, **radiative feedback via winds** is sub-dominant compared to kinetic feedback



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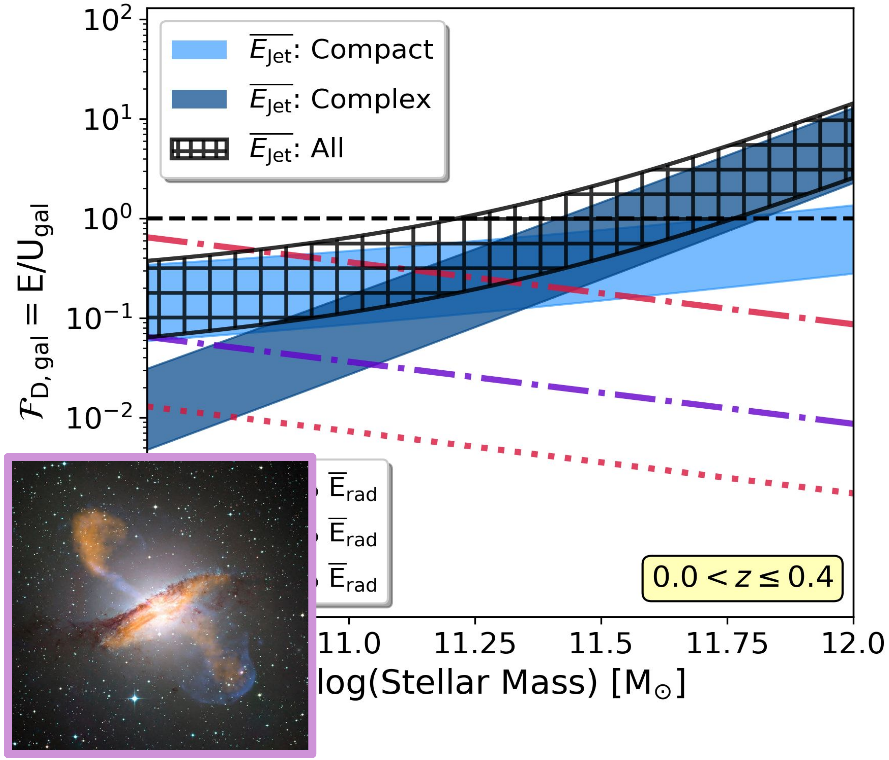

Cen A - radio galaxy

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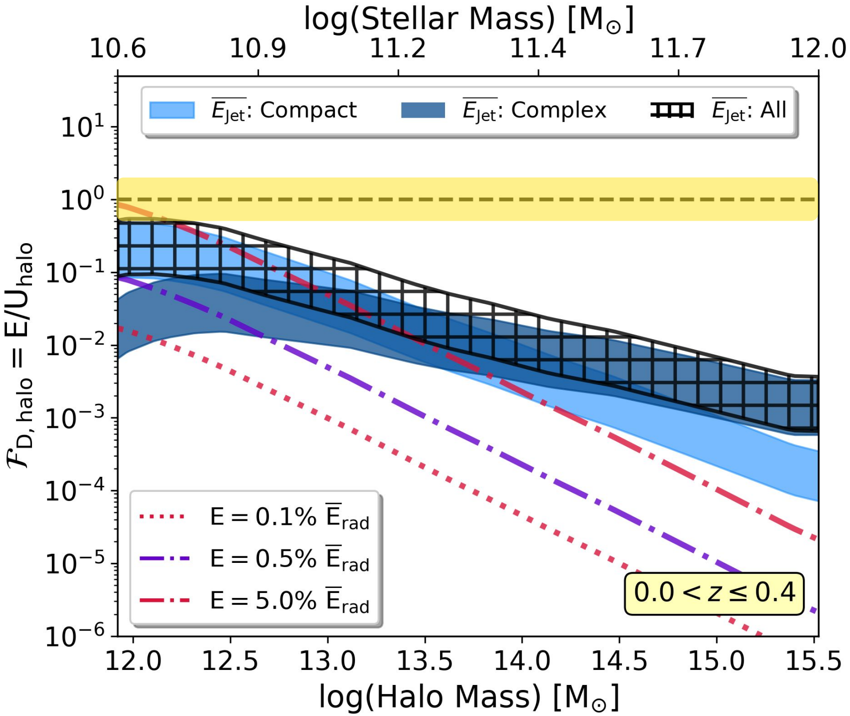
Radio AGN as "disruptive" feedback agents in halos

Igo & Merloni 2025

<u>Y- axis:</u> Avg. **Jet kinetic energy** compared to the **binding energy** of the <u>HALO</u>

Jet kinetic energy == Halo binding energy



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Radio AGN as "disruptive" feedback agents in halos

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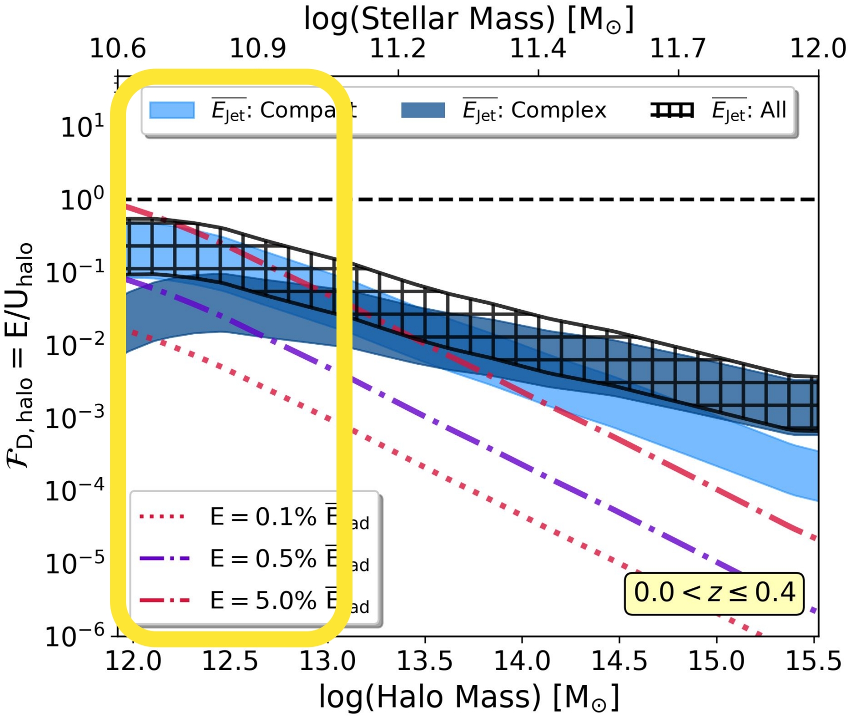
Y- axis: Avg. **Jet kinetic energy** compared to the **binding energy** of the HALO

Note: Convert $M_* \rightarrow M_{halo}$ using Girelli et al. 2020

Stellar mass range covers systems such as:

- **Isolated galaxies**



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Radio AGN as "disruptive" feedback agents in halos

Igo & Merloni 2025

<u>Y- axis:</u> Avg. **Jet kinetic energy** compared to the **binding energy** of the <u>HALO</u>

Note: Convert $M_* \rightarrow M_{halo}$ using Girelli et al. 2020

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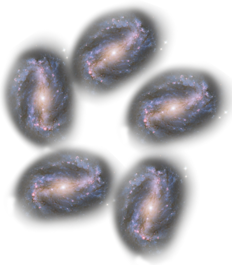

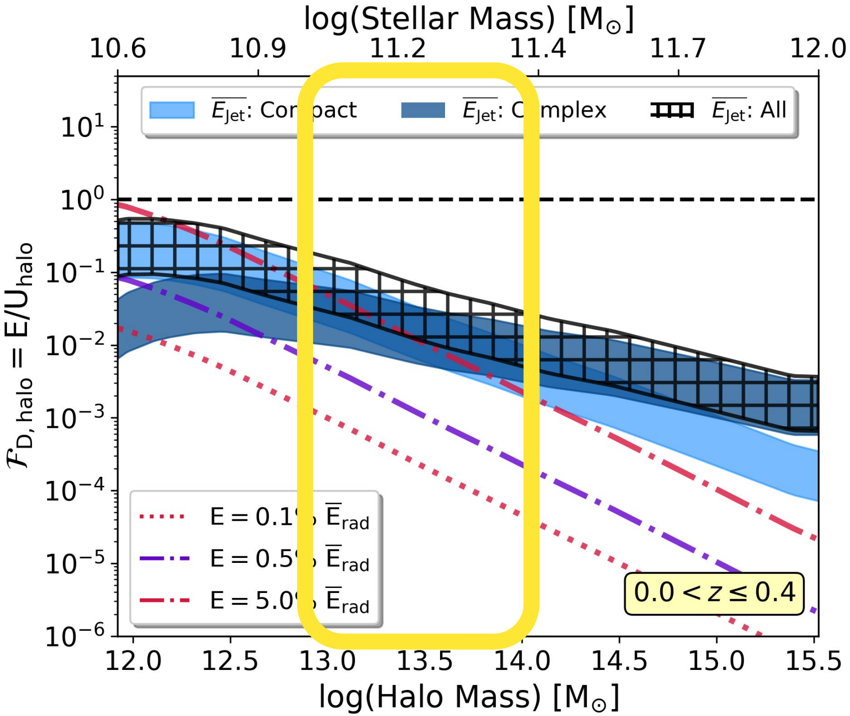

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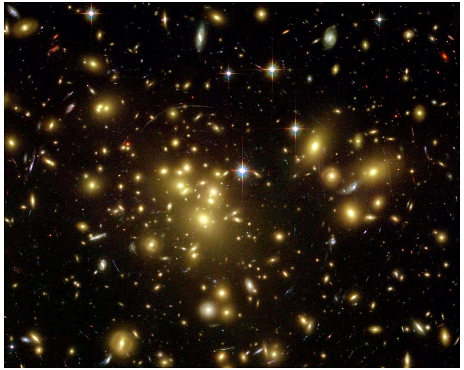
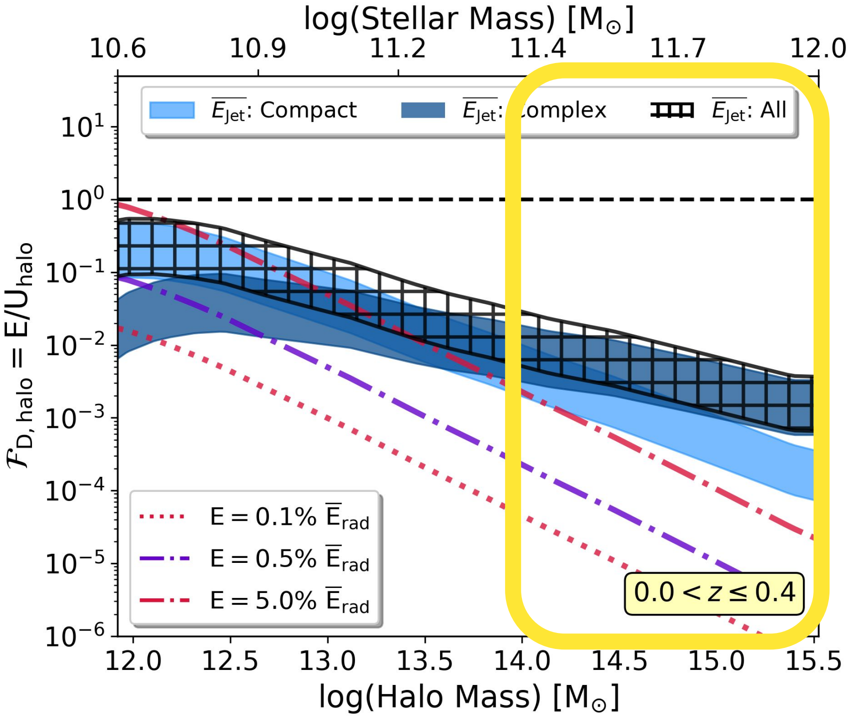
Stellar mass range covers systems such as:

- Isolated galaxies
- Groups of galaxies
- **Clusters (containing ~10-1000 galaxies)**



Galaxy Cluster Abell 1689



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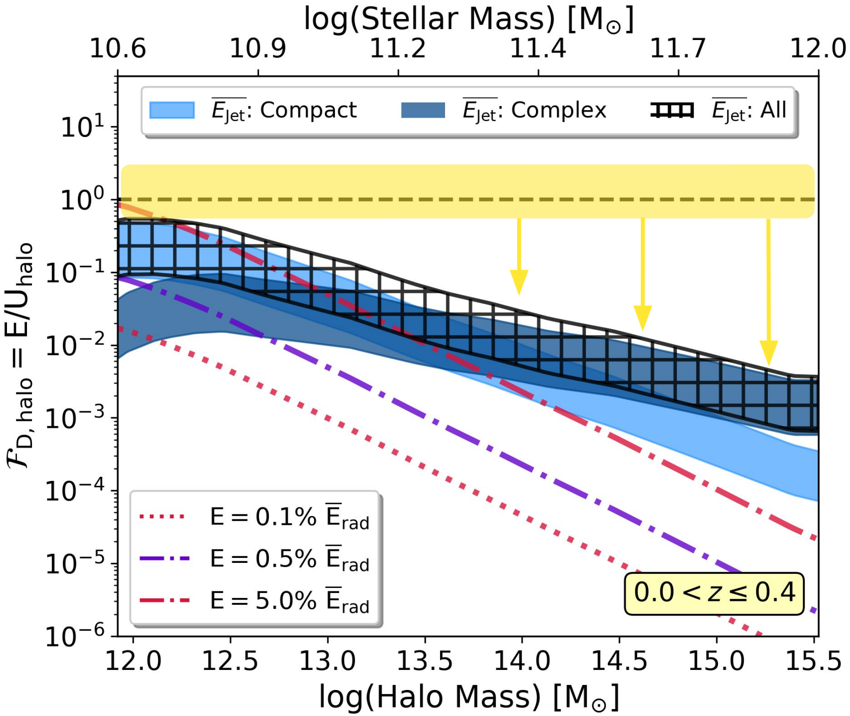
Results:

- Both **compact** and **complex** radio AGN reach at most 1-20% of the halo's binding energies at lowest mass scales and around 0.05-0.2% at the highest mass scales.
- **Not enough to unbind entire halos!** Makes sense as we observe such halos in the universe



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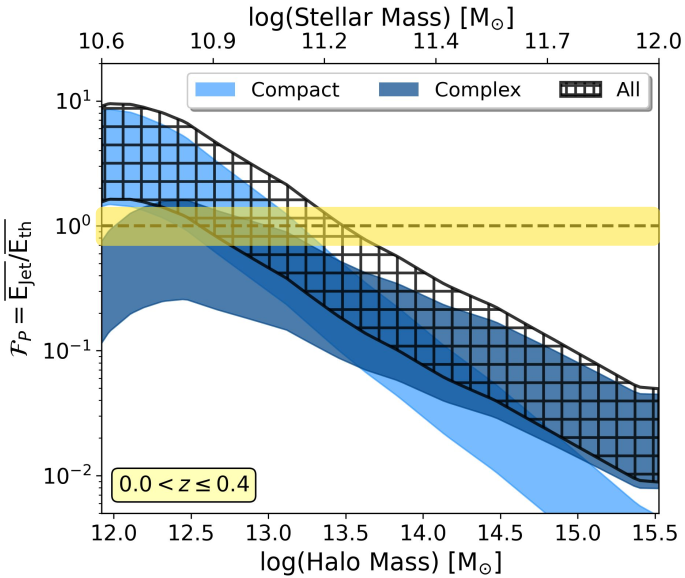
Radio AGN as "preventative" feedback agents

Igo & Merloni 2025

Radio AGN jets can also act to **heat the surrounding gas,** thereby **preventing star formation**

Determine thermal (cooling) energy of halo (**Lovisari et al. 2021**: k_bT vs M_{halo} vs L_{bol})
<u>Y- axis:</u> Avg. **Jet kinetic (heating) energy** compared to the **thermal (cooling) energy** of the <u>HALO</u>



Jet kinetic energy == Halo thermal energy

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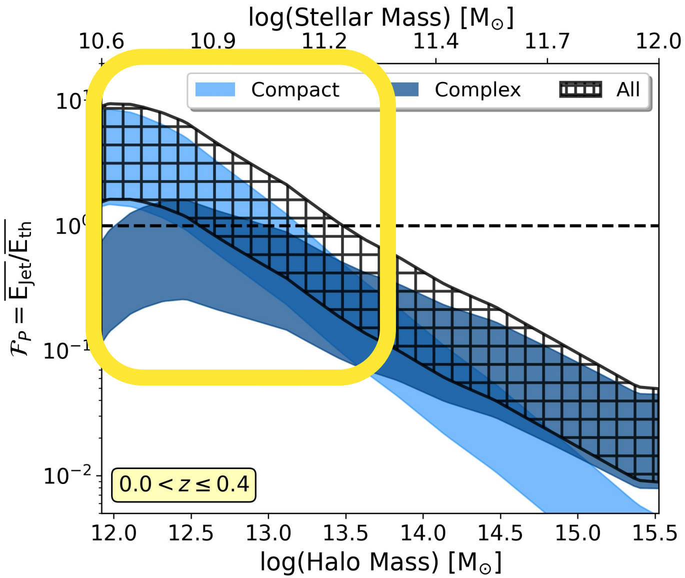

In galaxy and small-group regime → kinetic energy from radio AGN jets can ***globally*** **impact the thermodynamical balance** in the host halo

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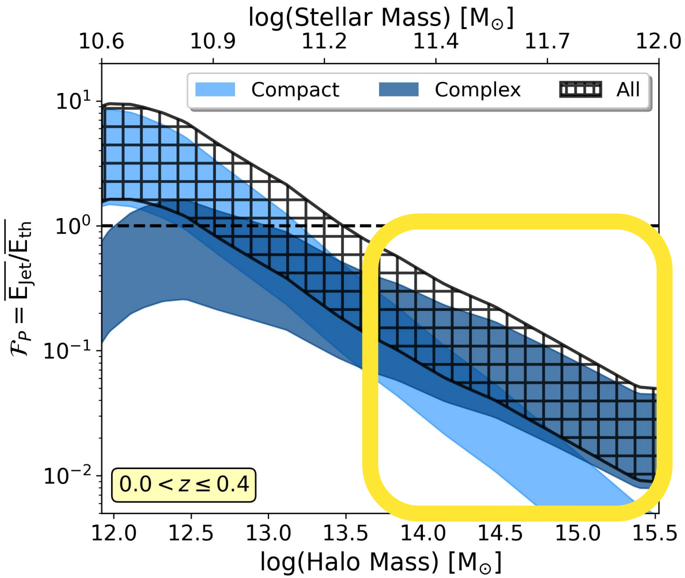

In large-group and cluster regime:
E_{Jet} is only ~1-10% of thermal cooling energy
→ **no global impact**, as jet energy is too low

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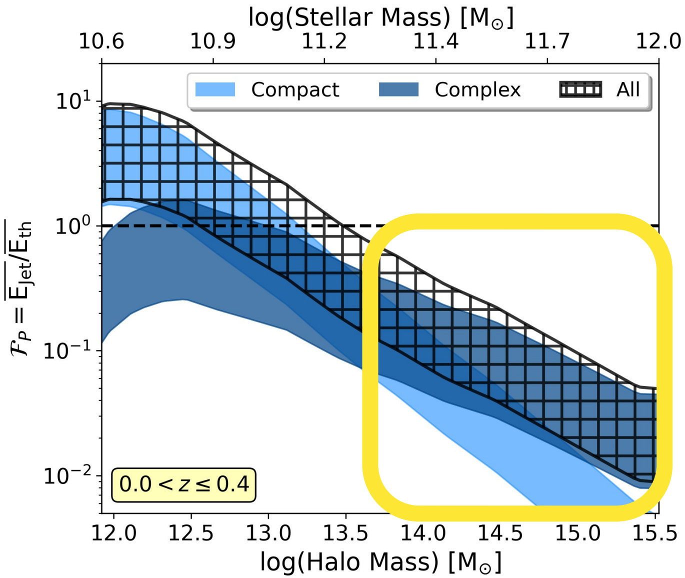

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HOWEVER …

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Jets are much smaller than host halos ⇒ Where is energy released?

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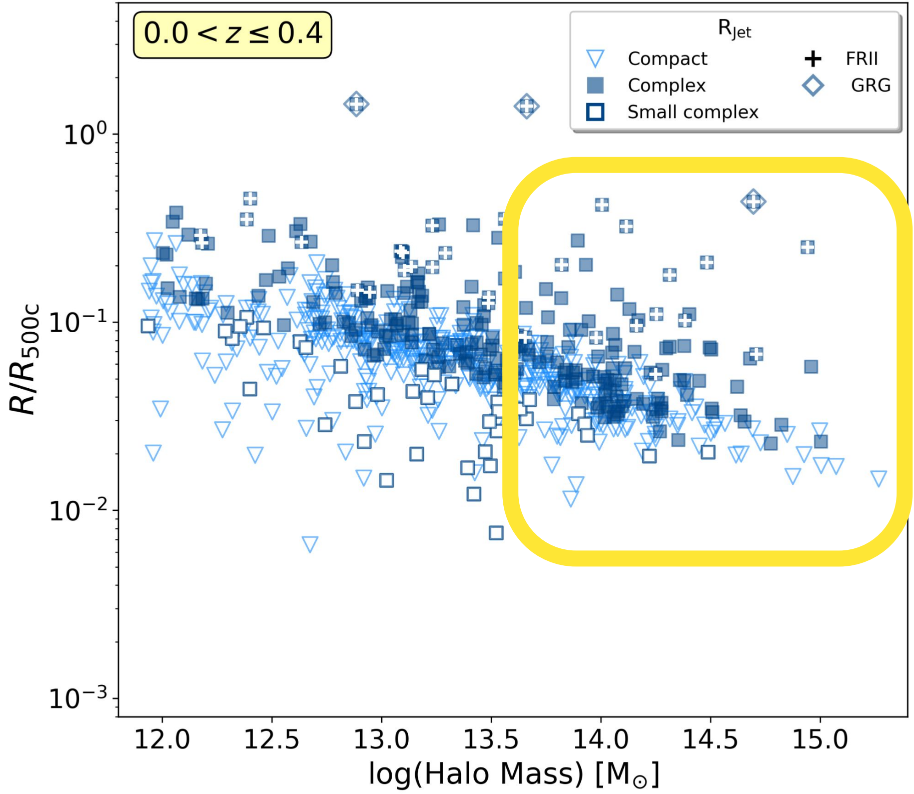

Result:

In the cluster regime:
→R_{Jet} reaches only ~2-10% of R_{500}

Makes sense that **jets cannot exert GLOBAL impact** on their host halo as **halos are simply too large** compared to the physical sizes of radio AGN jets

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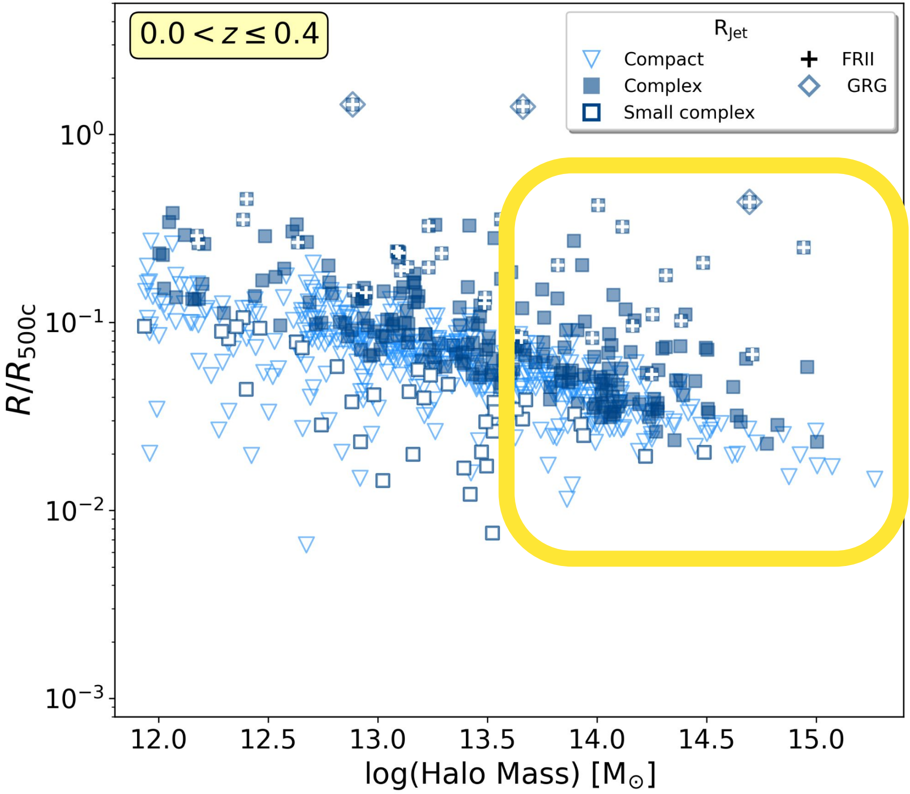

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A comparison of the **energy released in a volume defined by the size of the jet** shows that the **jet heating** does have a **significant local impact** on **offsetting central cooling flows in even the most massive clusters** (see extra slides)

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Summary

1. The LOFAR-eFEDS survey provides a complete (and reliable) census of radio and X-ray AGN in massive galaxies at low-redshift.

2. Through radio AGN incidence studies, we show that kinetic feedback from radio AGN (and especially from compact radio AGN!) dominates over any plausible inventory of radiatively-driven feedback for massive galaxies in the local universe.

3. Radio AGN cannot fully unbind their host galaxies nor host halos, but their jet kinetic energy can impact the global thermodynamical heating and cooling balance in small halos and significantly contribute to offsetting local cooling flows in even the most massive clusters.

LOFAR-eFEDS value-added catalogue is publicly available!

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Any questions?

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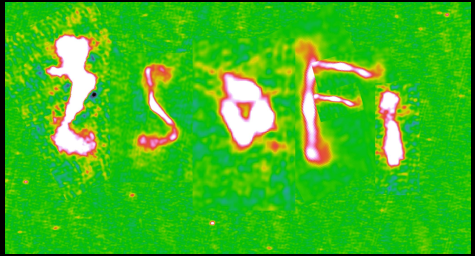

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Yes, the images are real LOFAR cutouts