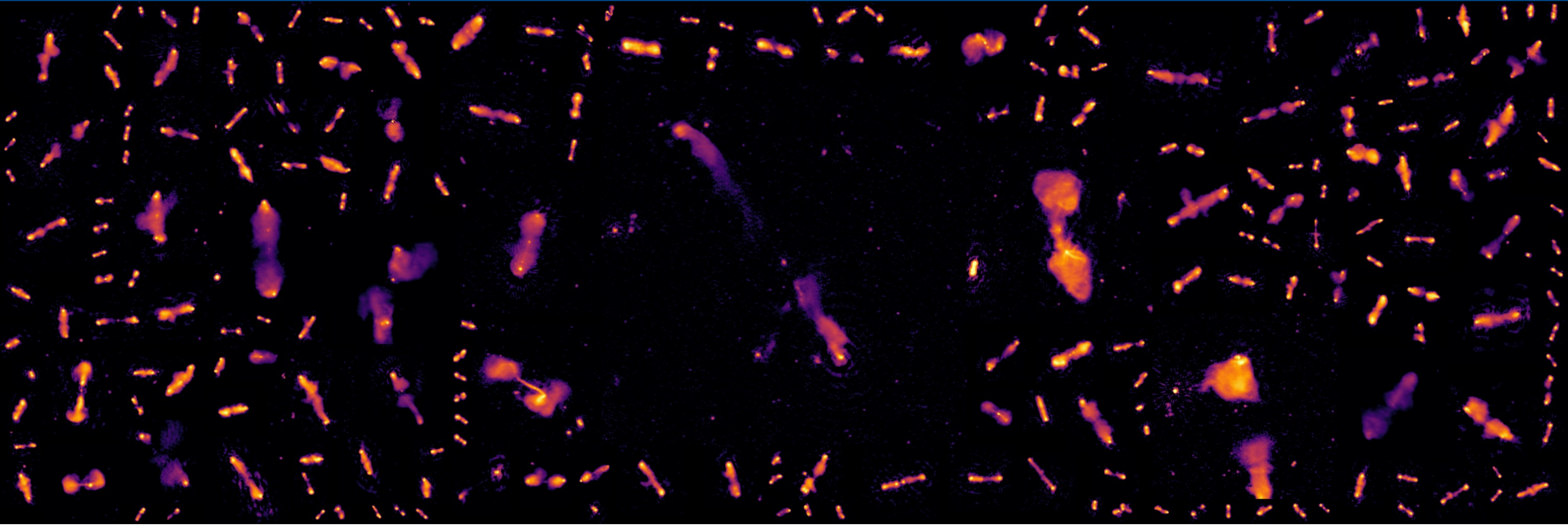
The largest samples of radio-luminous AGN from wide-area LOFAR surveys

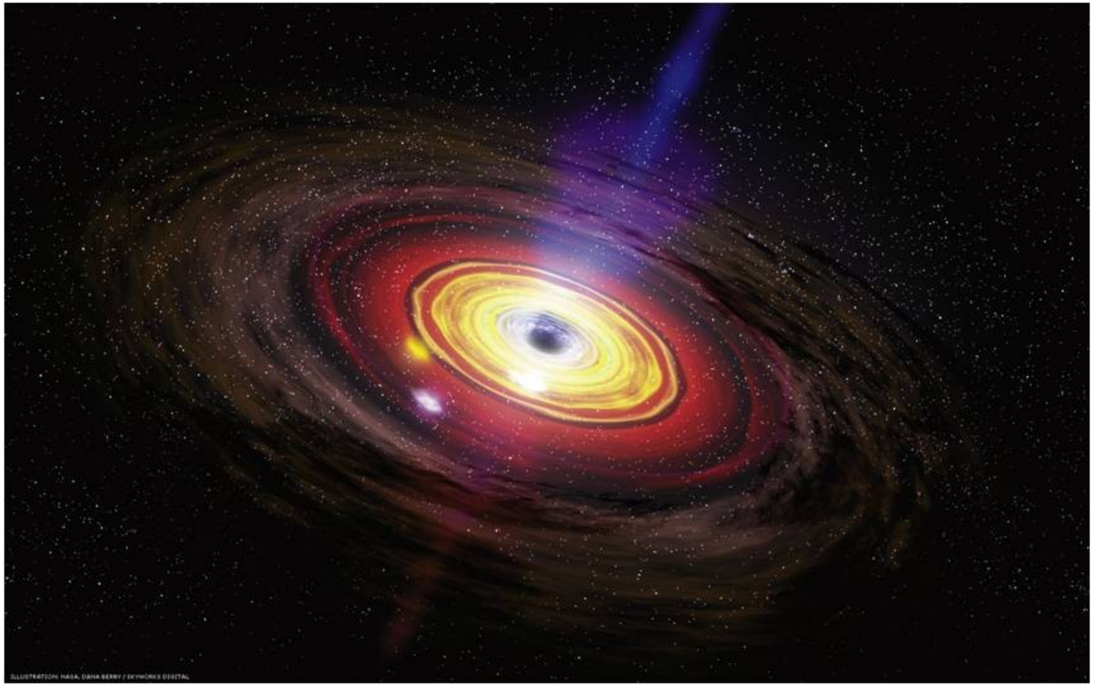


Martin Hardcastle

LFM Paris 23/09/25

Selecting AGN

- People generally think of AGN as being driven by thin-disk accretion on to a black hole as in the artist's impression below.
- But theoretically this can only happen in a restricted range of Eddington ratios between about 1 and 100%
- Below ~ 1% Eddington disks will not be radiatively efficient and will not be visible.
- Radiative AGN can only be between ~ 0.1 and 10 times the luminosity of their host galaxy (for typical M_{BH}/M_*)
- However if a radio jet is present, we can detect AGN down to much lower Eddington ratios… at a cost!

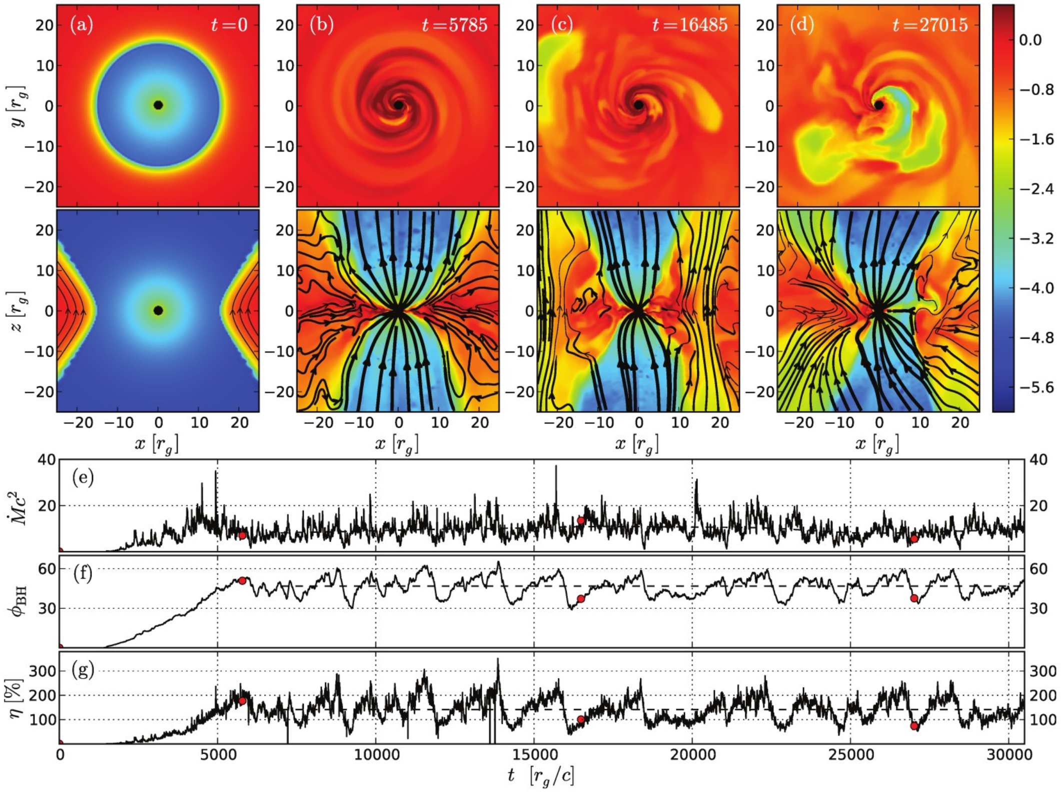


Jet generation

- General consensus that powerful jets are generated by a Blandford-Znajek type process in magnetized disks (e.g. Tchekhovskoy+11, right).
- Then jet power Q should be of order the B-Z power:

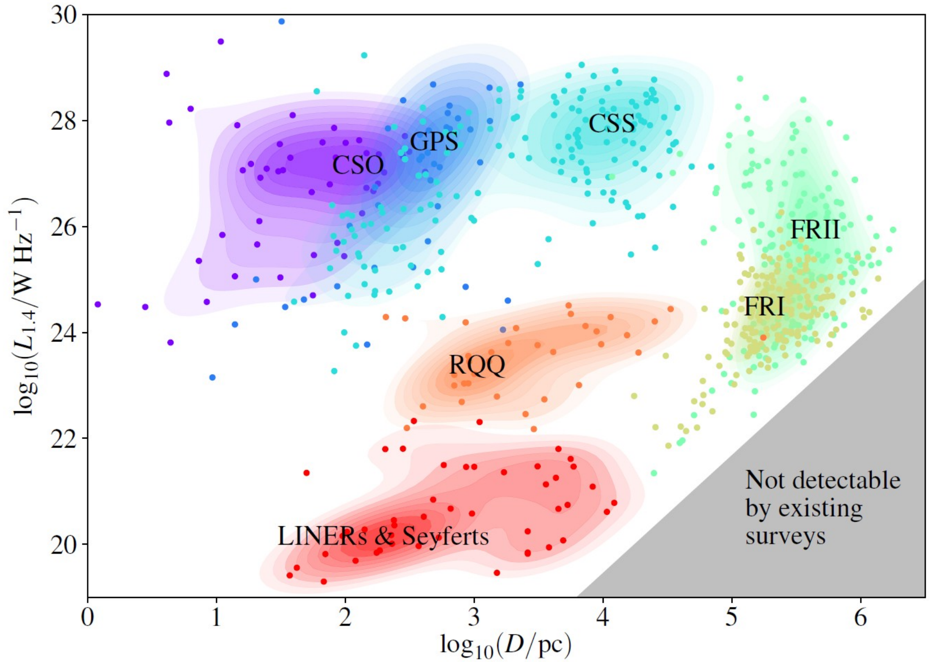
$$P_{\rm BZ} \approx \frac{\kappa}{\mu_0 c}\Omega_{\rm H}^2\Phi_{\rm H}^2$$

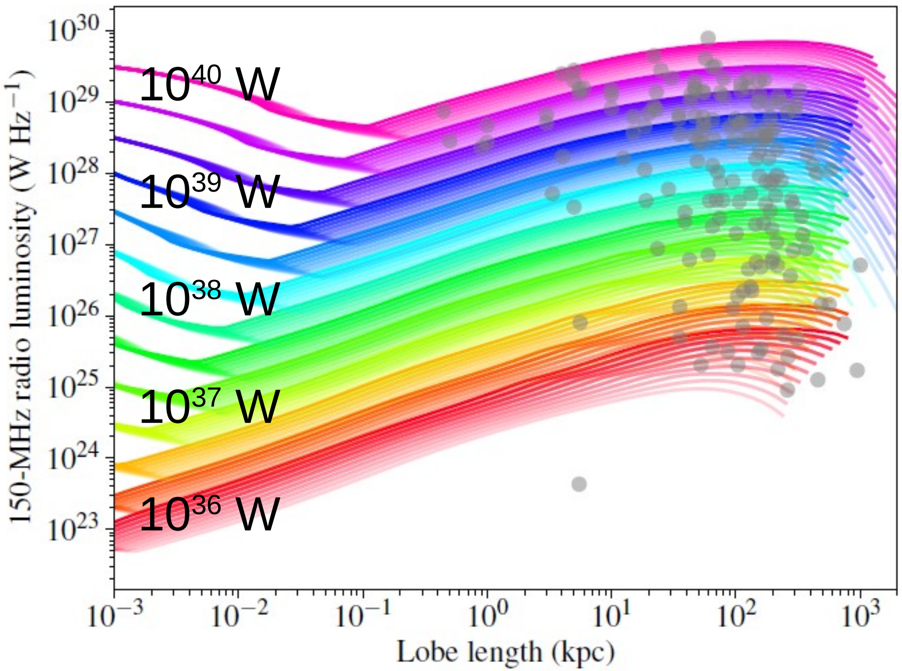
- Depends on spin and the integrated magnetic flux accreted onto the black hole, *not directly on mass accretion rate*
- Efficiency can exceed 100% for high spin!
- Spin/field dependence means that we can get a wide range of jet powers for a given accretion rate/RE luminosity, as observed (Mingo+14, Gürkan+19)
- Thin RE disks **can** form jets (Liska+22) but magnetic field geometry as well as spin are important
- Jets may be intermittent – long-term power spectrum not known



What do radio observations tell us about AGN?

- Simplest observables are radio luminosity and size
- But both must start at zero and evolve with time – size a proxy of age
- Evolution of radio sources gives tracks in the power/linear size diagram that depend on environment as well as other factors – so use radio luminosity with caution

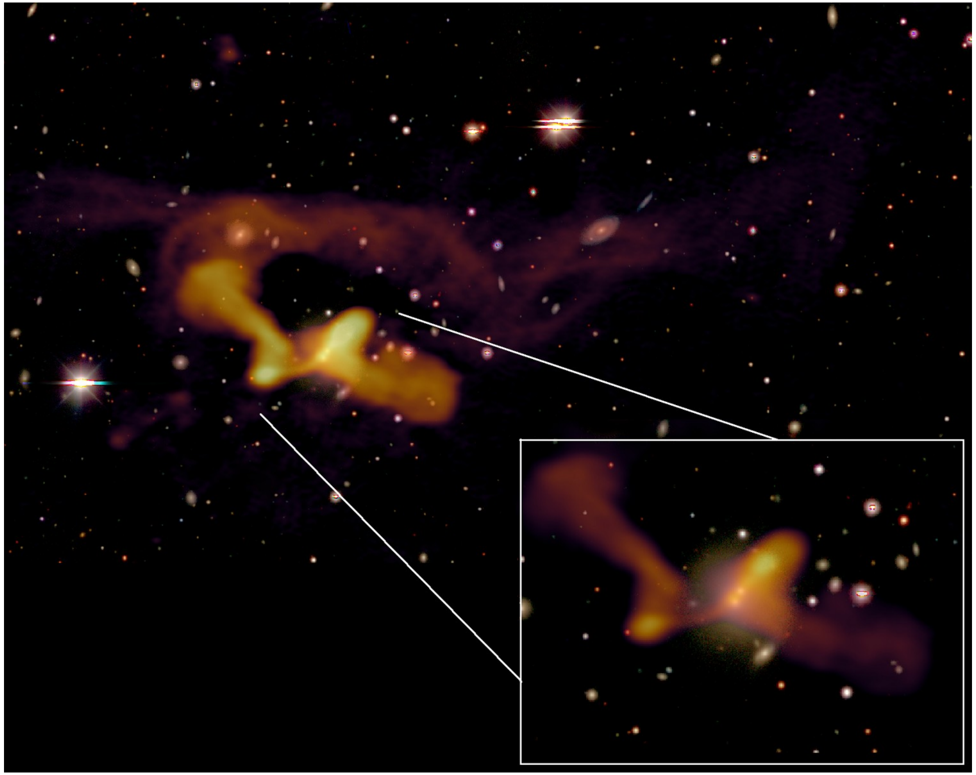


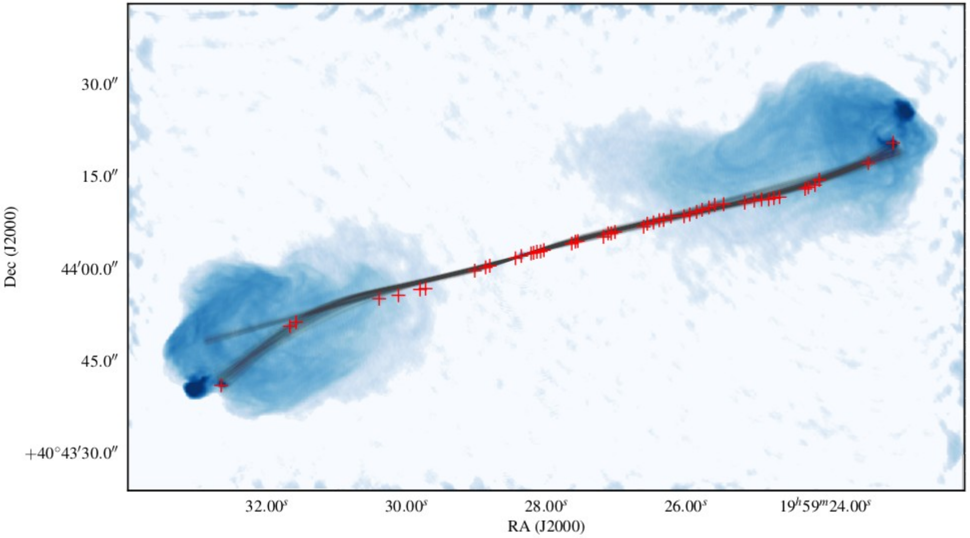


Left: schematic PD diagram from Hardcastle+Croston 20, after Jarvis+19 and An+Baan 11. Right: analytical modelling of PD tracks from Hardcastle 18b. Note different scales and frequencies on y axes.

Resolved sources and the 'fossil record'

- History of jet power evolution, but also directional changes and environment, encoded in large-scale structure of resolved sources
- Key information if we can find the sources and interpret them!

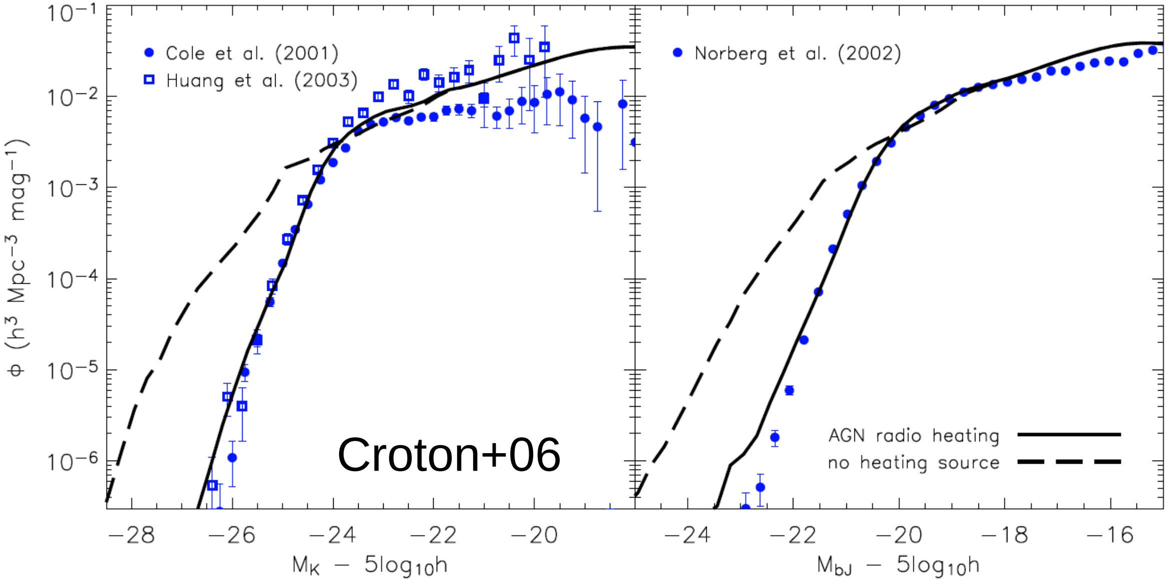




Left: X-shaped radio galaxy NGC326 seen with LOFAR (Hardcastle+19b). Above: Cygnus A overlaid with samples from MCMC precessing jet models (Horton+20).

Feedback and the galaxy formation context

- Cosmological models require ‘AGN feedback’ to regulate the growth of massive galaxies
- 'Cooling flow problem' requires heating to offset X-ray cooling
- Radio galaxies clearly are doing this in the local universe
- How can we *quantitatively* assess their global role over cosmic time & compare with model expectations?



- LoTSS gives us the large sample size with sensitivity to extended emission that we need to make progress
- 4.1 million sources in LoTSS DR2 are in the DESI Legacy survey area
- After much work we have an optical ID rate of 85% and a redshift rate of 58% (14% spectroscopic)
- Combines automated and visual inspection methods to deal with resolved AGN
- See arXiv:2309.00102
for many more details

A&A, 678, A151 (2023)
https://doi.org/10.1051/0004-6361/202347333

Astronomy & Astrophysics

The LOFAR Two-Metre Sky Survey

VI. Optical identifications for the second data release★

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Received 1 July 2023 / Accepted 29 August 2023

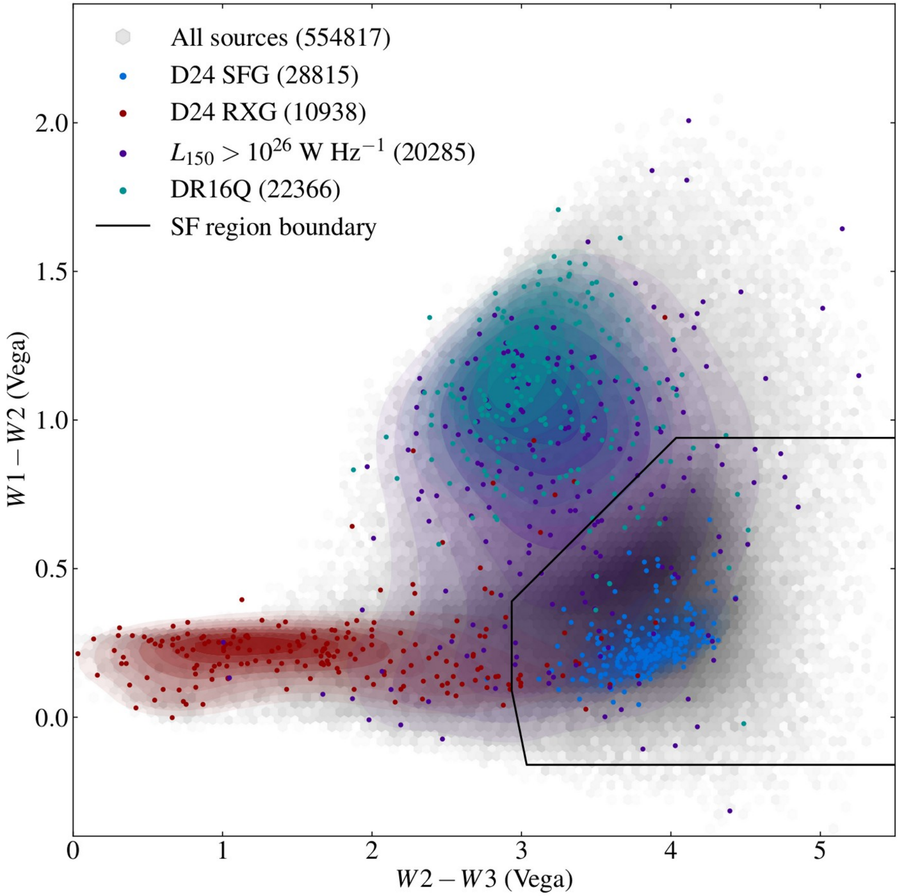
ABSTRACT

The second data release of the LOFAR Two-Metre Sky Survey (LoTSS) covers 27% of the northern sky, with a total area of ~5700 deg^2. The high angular resolution of LOFAR with Dutch baselines (6 arcsec) allows us to carry out optical identifications of a large fraction of the detected radio sources without further radio followup; however, the process is made more challenging by the many extended radio sources found in LOFAR images as a result of its excellent sensitivity to extended structure. In this paper we present source associations and identifications for sources in the second data release based on optical and near-infrared data, using a combination of a likelihood-ratio cross-match method developed for our first data release, our citizen science project Radio Galaxy Zoo: LOFAR, and new approaches to algorithmic optical identification, together with extensive visual inspection by astronomers. We also present spectroscopic or photometric redshifts for a large fraction of the optical identifications. In total 4 116 934 radio sources lie in the area with good optical data, of which 85% have an optical or infrared identification and 58% have a good redshift estimate. We demonstrate the quality of the dataset by comparing it with earlier optically identified radio surveys. This is by far the largest ever optically identified radio catalogue, and will permit robust statistical studies of star-forming and radio-loud active galaxies.

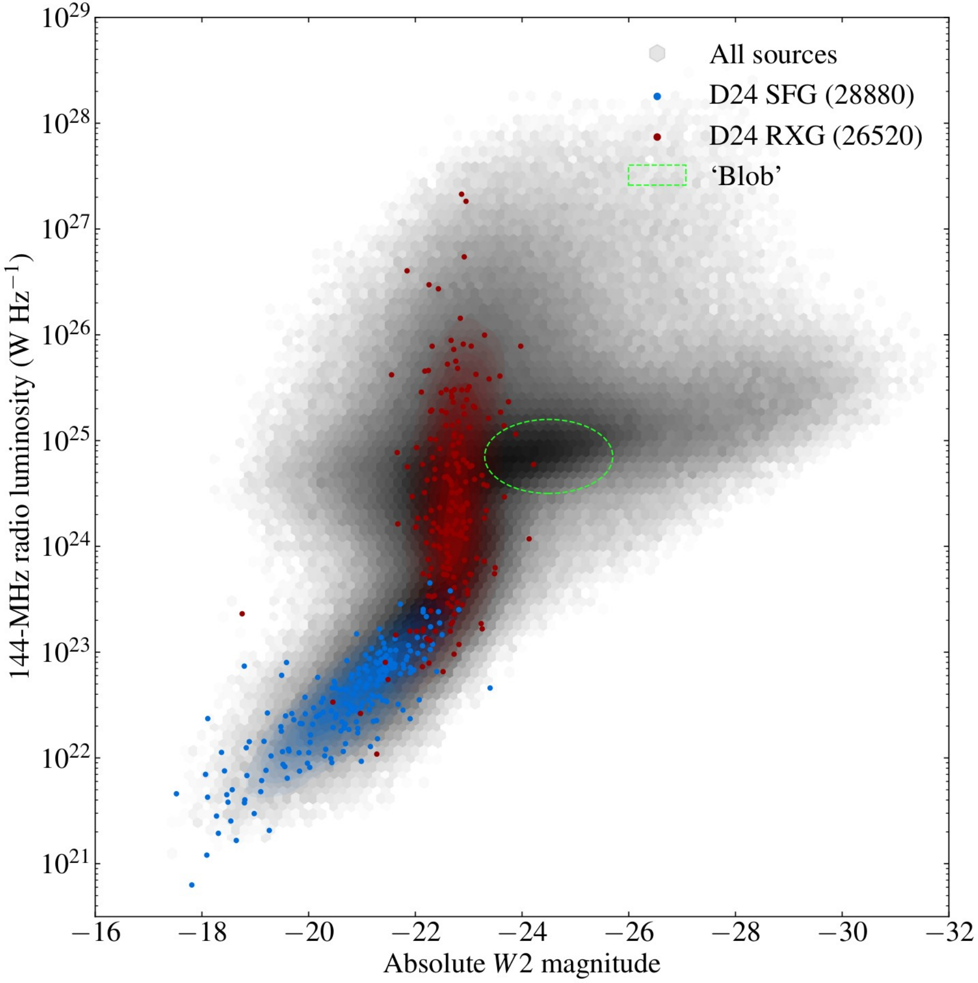
Key words. catalogs – radio continuum: galaxies

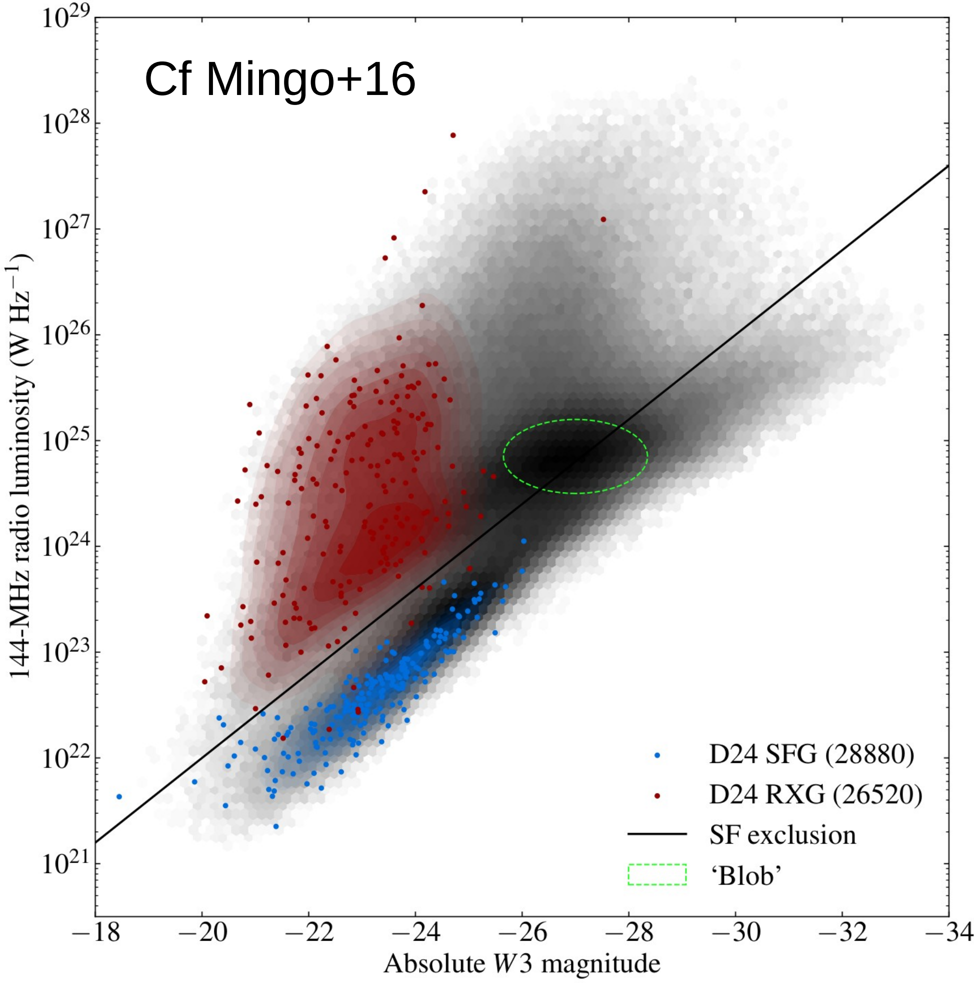
AGN selection and emission-line classifications

- Which of these sources are radio AGN?
- Drake+24 (D24: arxiv:2409:11465) used BPT-type emission-line diagnostics to classify 150k DR2 sources with SDSS spectra as radio-excess (radio luminosity exceeds expectation from Halpha) and HERG/LERG.
- Classification is consistent with expectations from WISE colour-colour plots
- Bright AGN and HERGs lie in the same location as SFG
- Not safe to select AGN as in Hardcastle+19 with cuts in WISE colour space!
- But W2/W3 vs radio luminosity is more interesting...

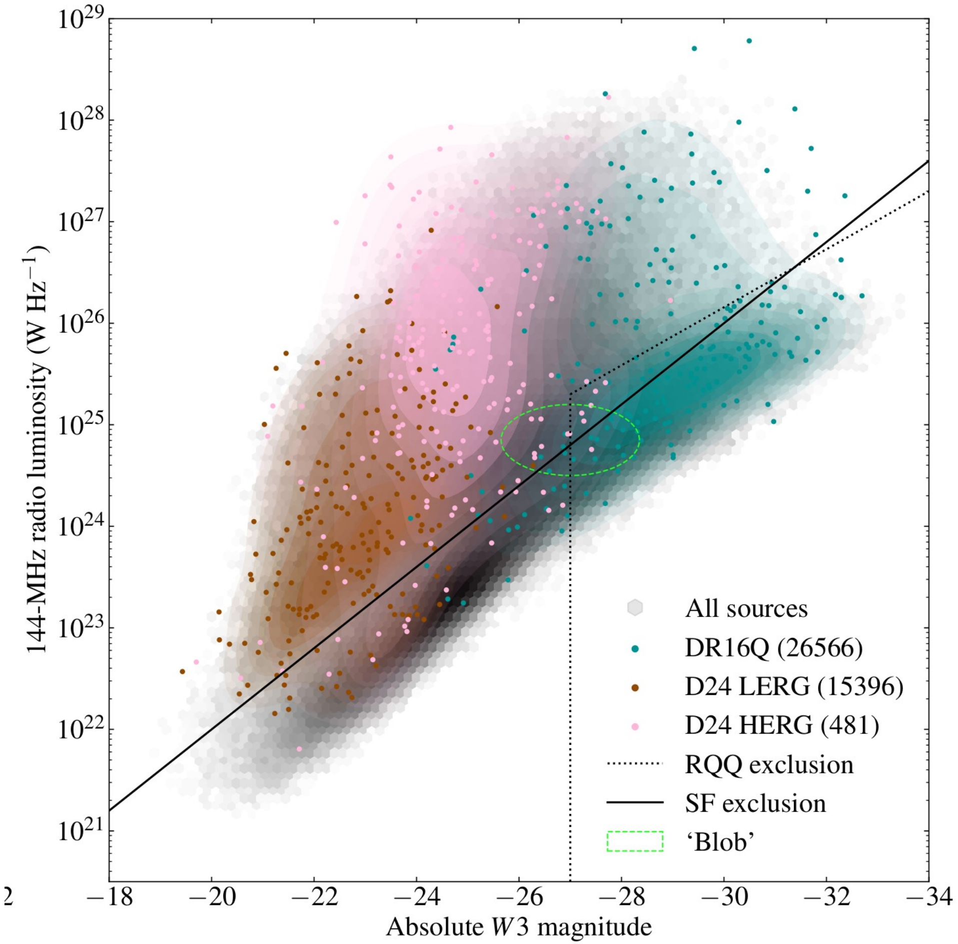


AGN selection and WISE absolute magnitude



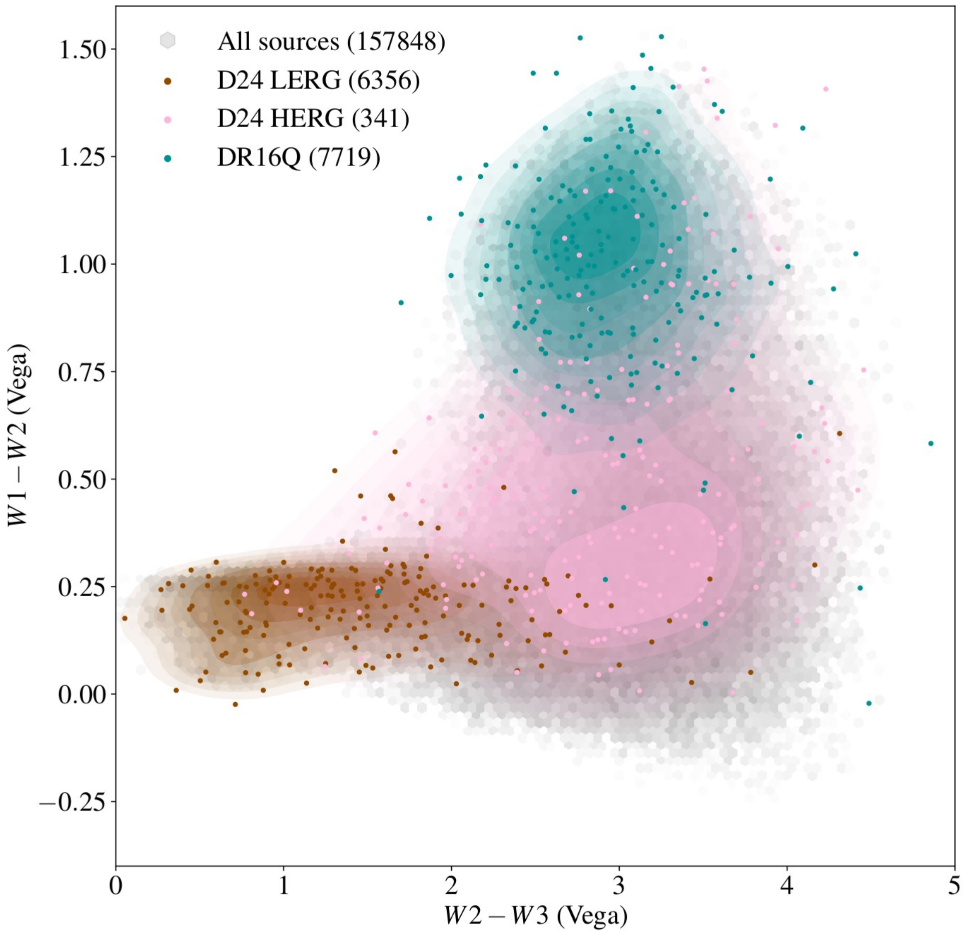


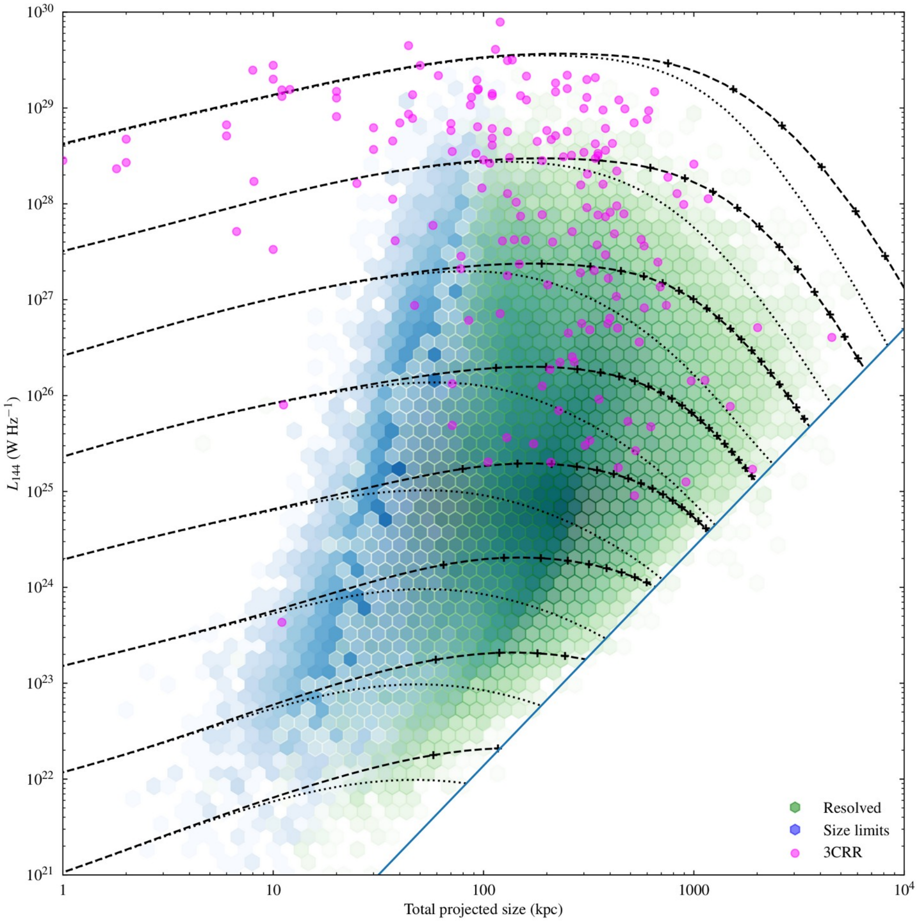
AGN selection



- Start from flux-complete sample with S > 1.1 mJy, good z > 0.01 (963,764 objects)
- W3-radio diagram allows us to select different classes of objects (although note that many objects are undetected in W3)
- Quasars and HERGs lie to the right of this plot (W3 luminosity from the torus – cf Gurkan et al 2014)
- SDSS DR16 quasars populate the far right including a clear 'RQQ' branch
- Not clear whether these should or should not be excluded! But we can remove them for consistency with Hardcastle+19
- Net result is a plot with two cuts in this space.
- Can decide whether a W3 detection is required or use limits – overall around 500,000 AGN.

AGN classification and evolution

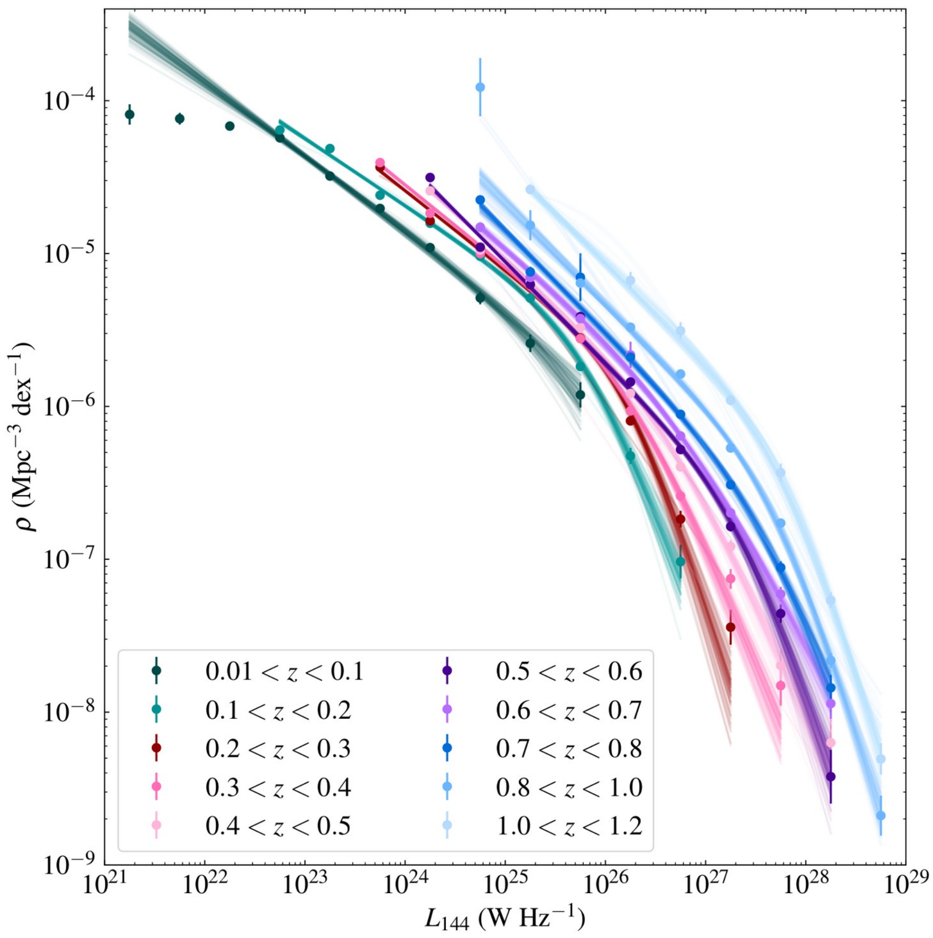


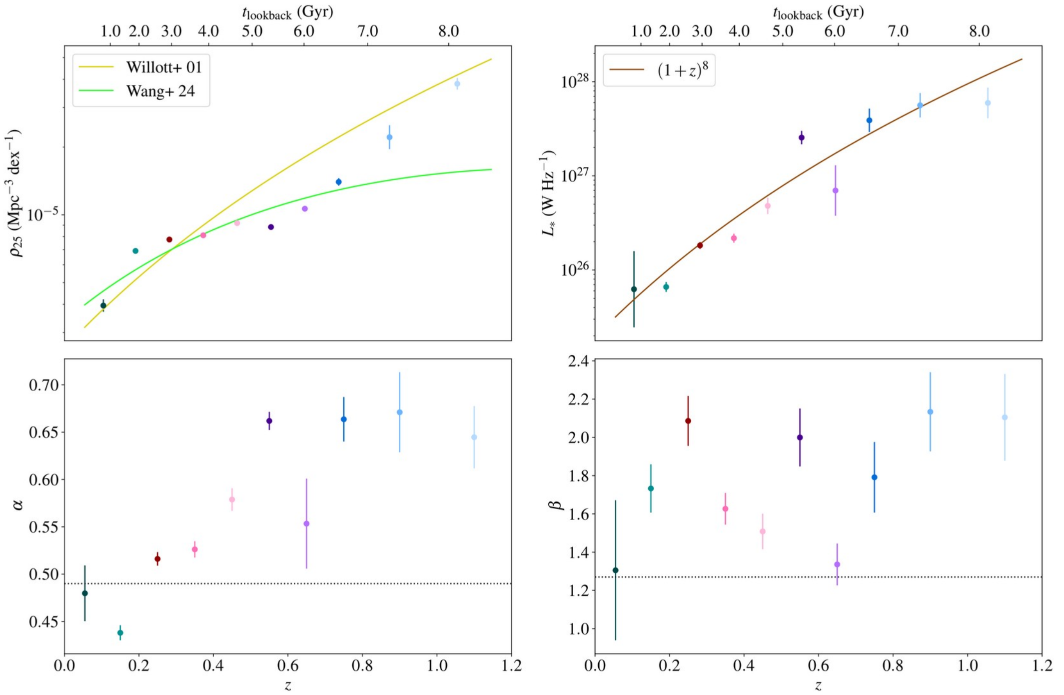


Hine & Longair 1979; Hardcastle+ 2007; Gürkan+ 2014

Baldwin 1982; Kaiser+ 1999; Hardcastle 2018

Radio luminosity functions

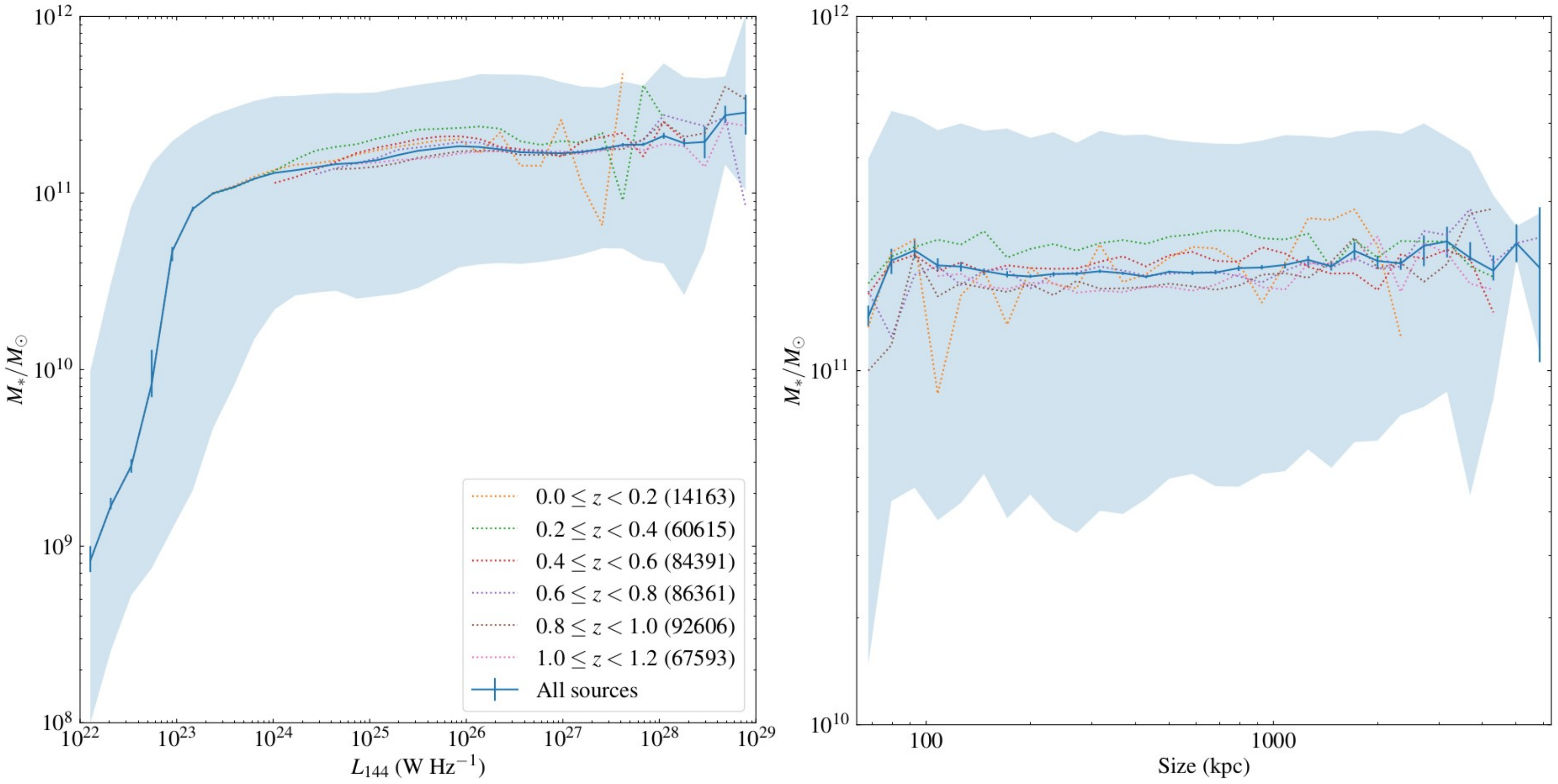




$$\rho(L) = \frac{C}{(L/L_*)^{\alpha} + (L/L*)^{\beta}}$$

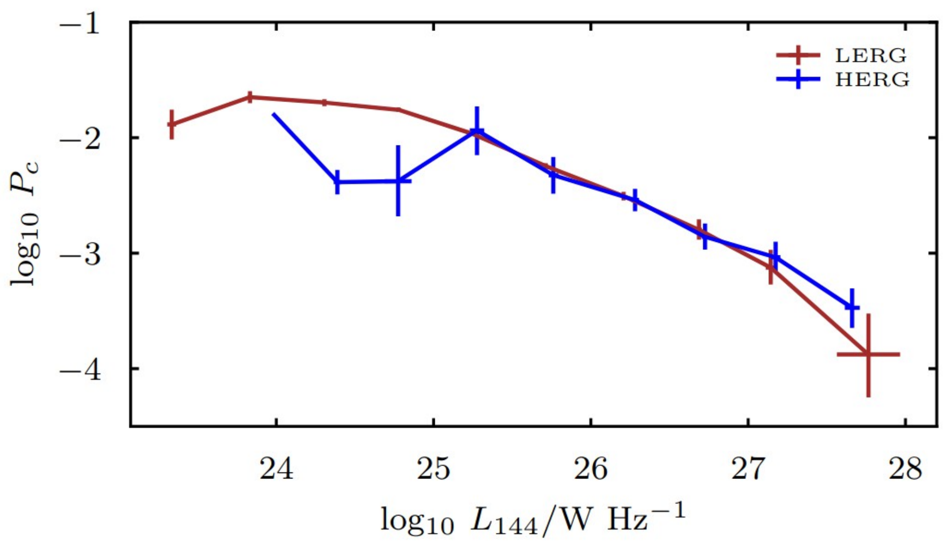
Luminosity functions with thousands of points per bin (rather than in total): strong evolution with *z*

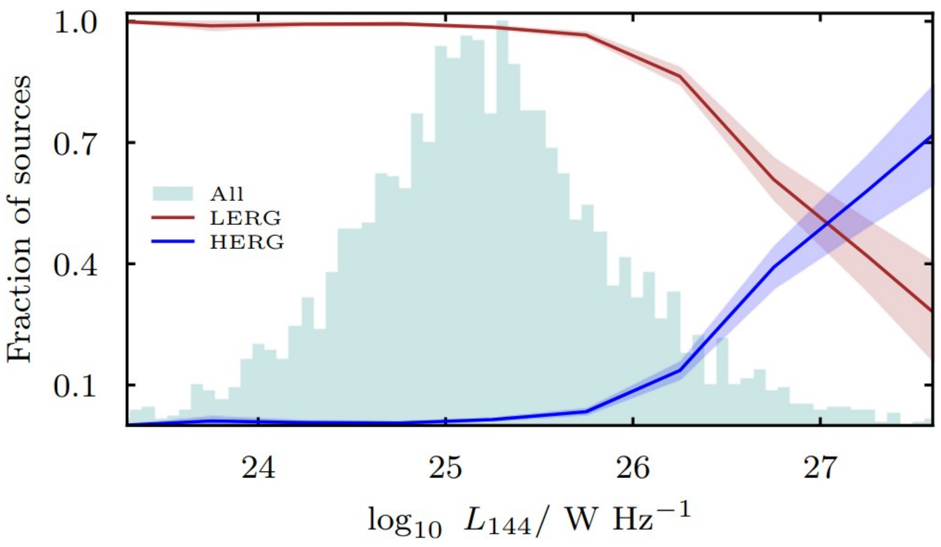
Masses: AGN host galaxy mass relation to luminosity and size



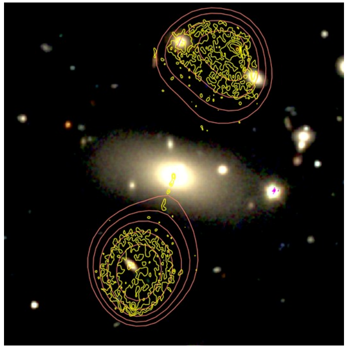
Emission-line classifications

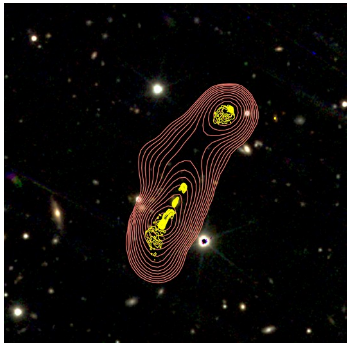
- Drake+24 have used SDSS to classify LoTSS DR2 sources (in preparation for WEAVE)
- We can use this information to look at the radiatively inefficient vs efficient radio AGN populations (distinguished by their emission lines)
- We can rule out models in which most or even a significant fraction of radiatively inefficient objects are remnants where the AGN has switched off. The radio sources are behaving the same way independent of their emission-line class, at high power (Chilufya+25)

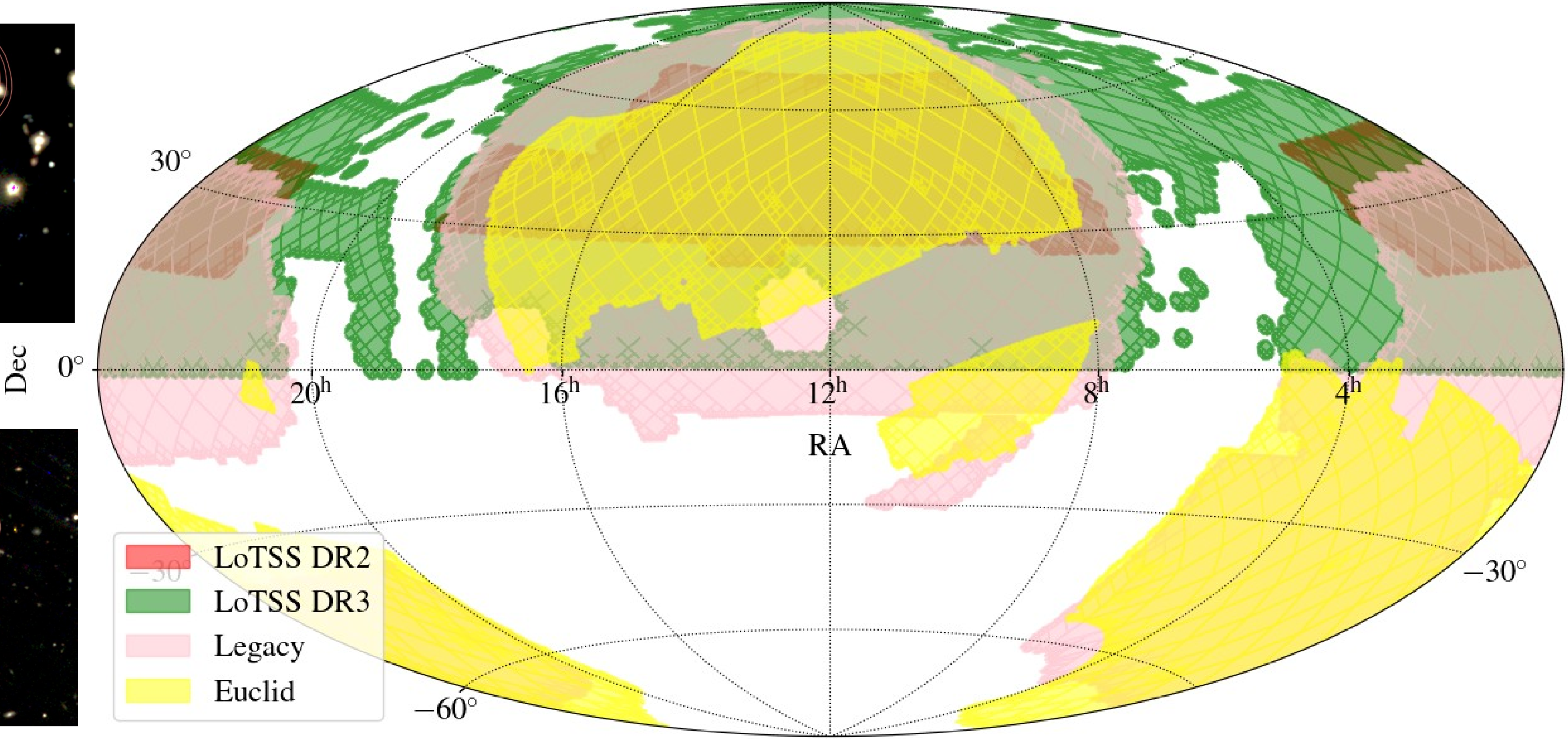




With combination of wide area from LoTSS/ILoTSS we should get the whole population of the most powerful radio sources out to z ~ 2







Summary

- DR2 optical ID catalogue exists: see Hardcastle+23 and https://lofar-surveys.org/
- Probably reasonably complete for bright radio AGN below z=1 and massive SFG with z<0.3
- We plan to keep updating the DR2 catalogue through and past the DR3 LoTSS release
- Improved method of AGN selection currently using WISE data – WEAVE and DESI will enable much more by providing emission lines (DESI work in prep!)
- ~ 500,000 sources should be enough for a lot of robust statistical analysis!
- See Hardcastle+25 arXiv:2504.09303 for more
- Work coming soon on jet power inference as a function of environment
- Watch this space for:
  - High-resolution imaging
  - Euclid optical IDs and high-z wide-field science