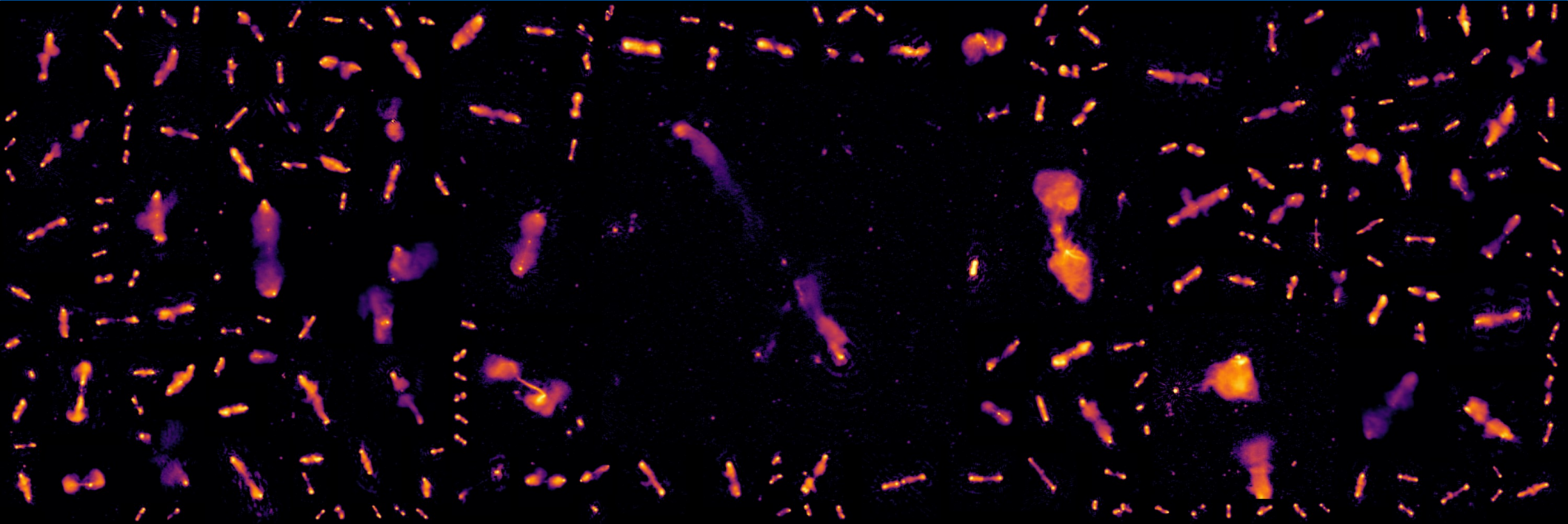


Radio AGN populations: morphology, energetics and evolution



Martin Hardcastle

INAF PhD School “Francesco Lucchin”, Bertinoro, October 2026

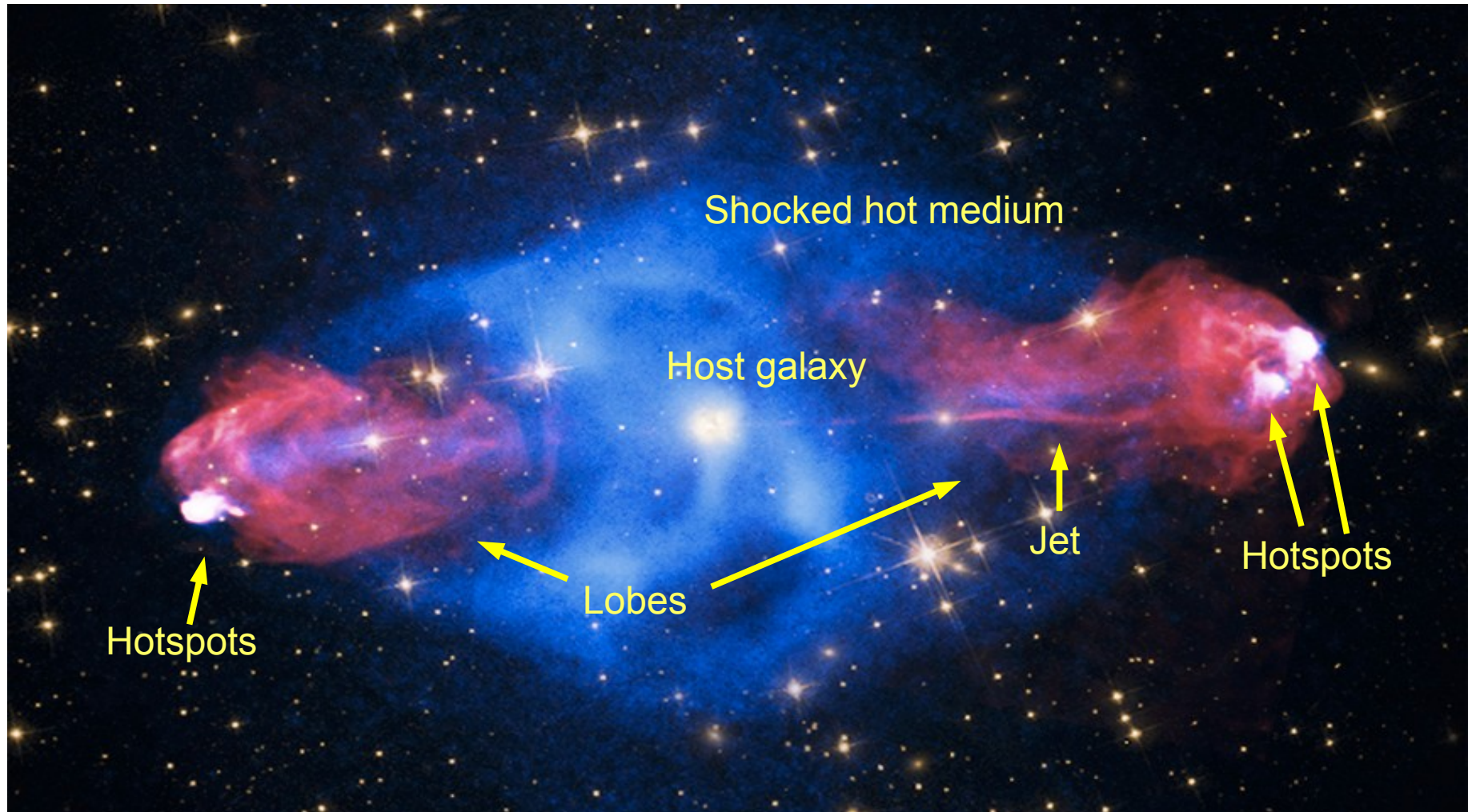


University of
Hertfordshire **UH**

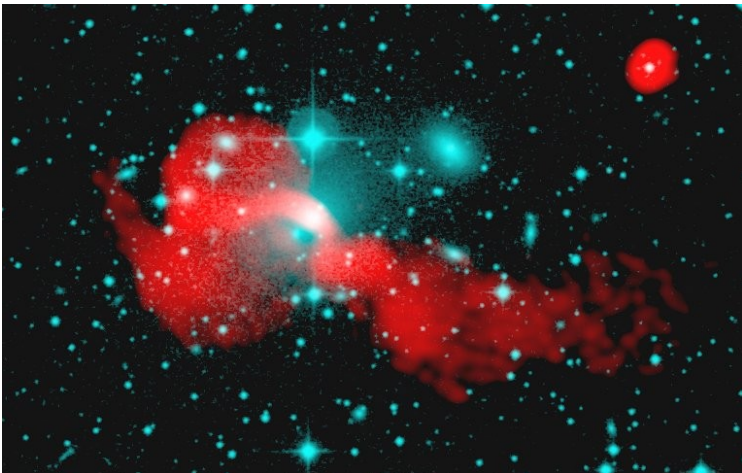
Section 1: The morphological zoo of radio-loud AGN

- Recap: the large-scale structures of radio AGN
- FRI vs FRII
- Other types of extended sources
- Giant radio galaxies
- Compact and low-luminosity populations
- What does morphology tell us about physics?

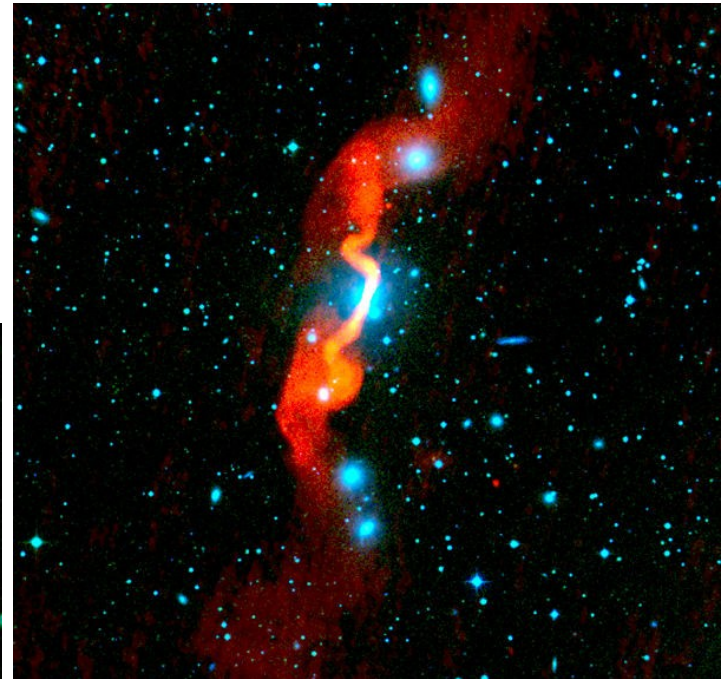
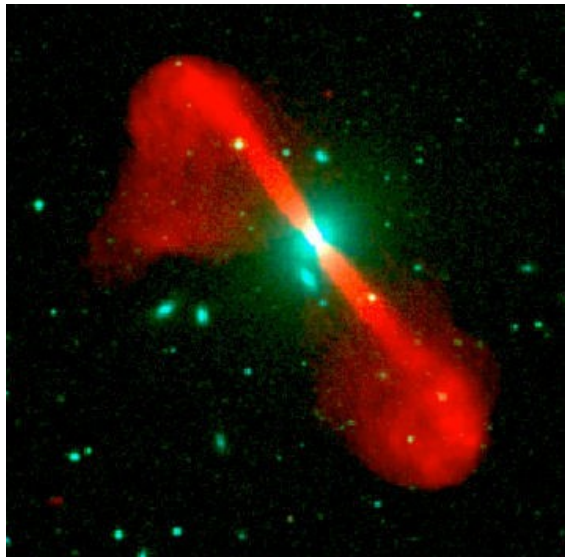
The large-scale structures of radio AGN



The large-scale structures of radio AGN

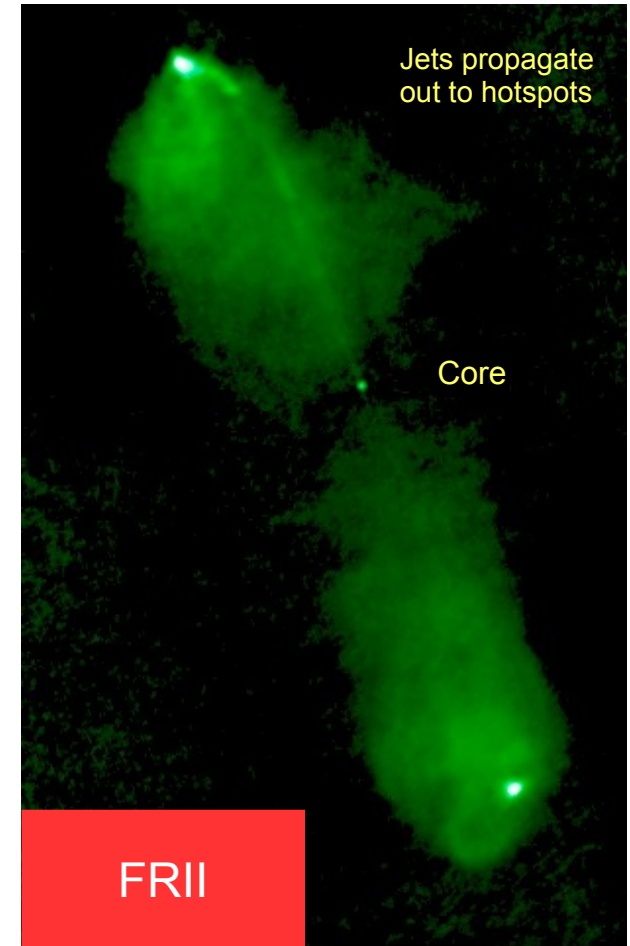
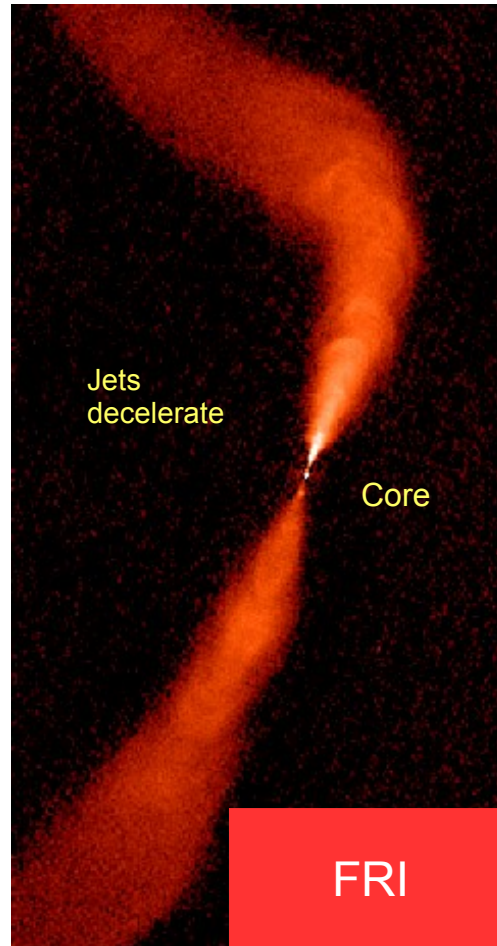


Sometimes we see
plumes instead of lobes,
and hotspots are not
always present...



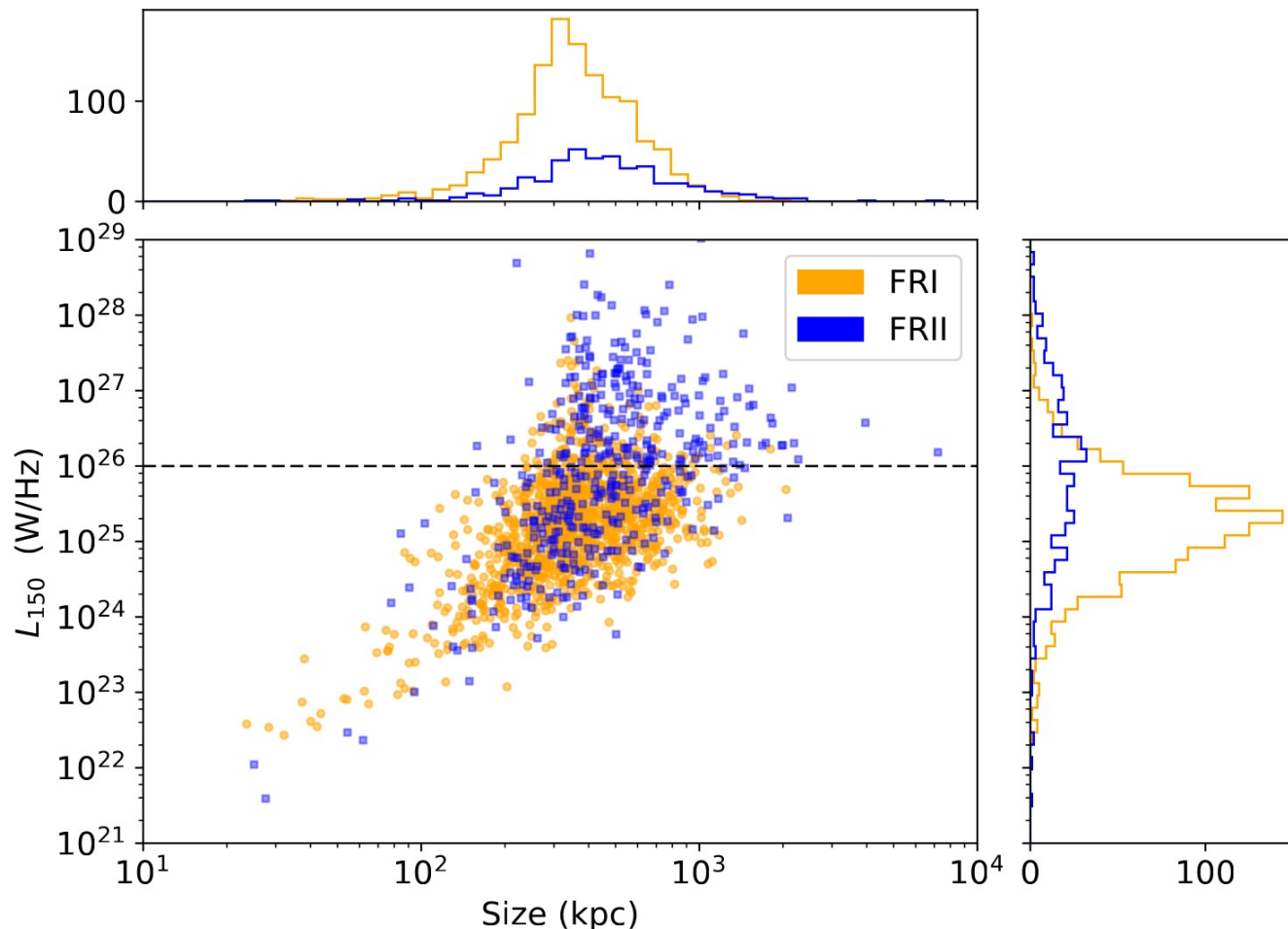
Fanaroff-Riley classification

- Fanaroff & Riley 74
- Morphological classification:
 - If a source is brighter towards the middle than the edges, it is a class I radio galaxy (FRI)
 - If it is brighter towards the edges than the middle, it is a class II radio galaxy (FR II)
- This distinction is important because it appears to encode physics!
- Most FRIs have low radio luminosity ($< 10^{26}$ W/Hz at 150 MHz). Most FR IIs have high radio luminosity.
- The most luminous radio galaxies are all FR IIs.
- Classification made in the 1970s with rather low-quality radio images... high-quality images reveal physical differences



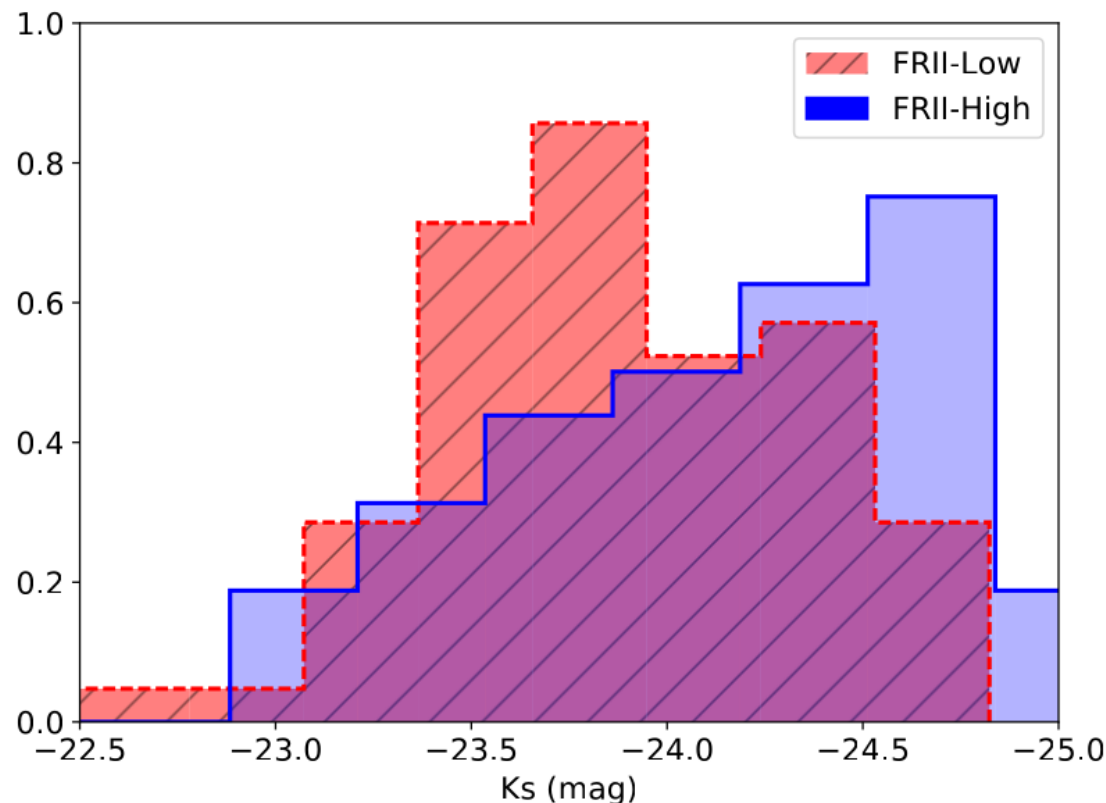
Fanaroff-Riley classification revisited

- Mingo+19
- Automatic classification of sources in the LOFAR surveys
- **Most** FRIs are below the Fanaroff-Riley luminosity threshold
- Significant number of FRIs are below it
- **Some** of these 'FRIs' have clear hotspots with high-resolution imaging (Barkus+26)
- Low-luminosity FRIs lie on average in less massive galaxies...

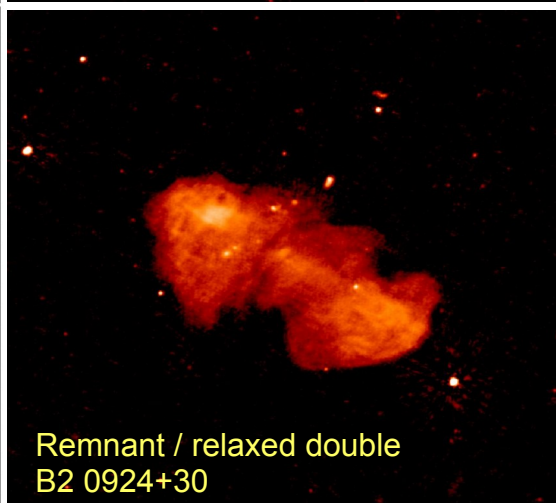
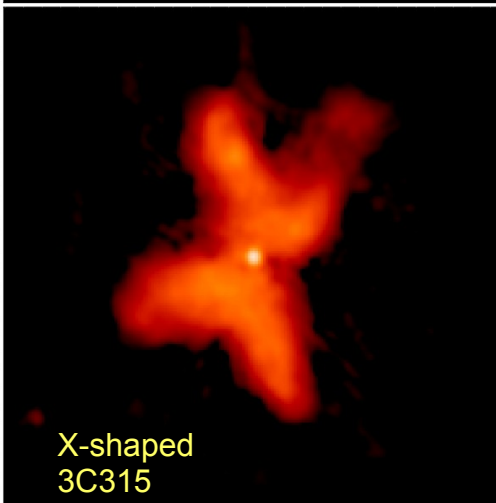
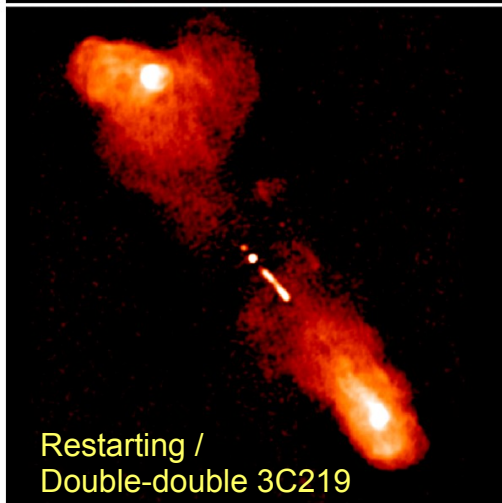
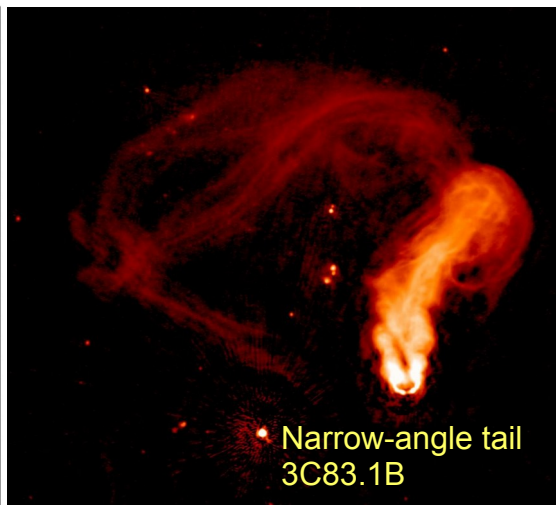
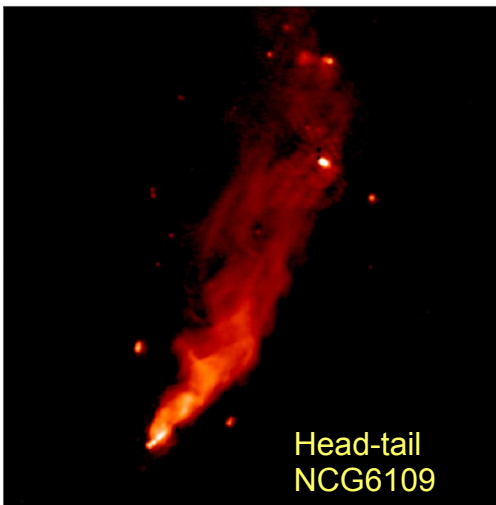
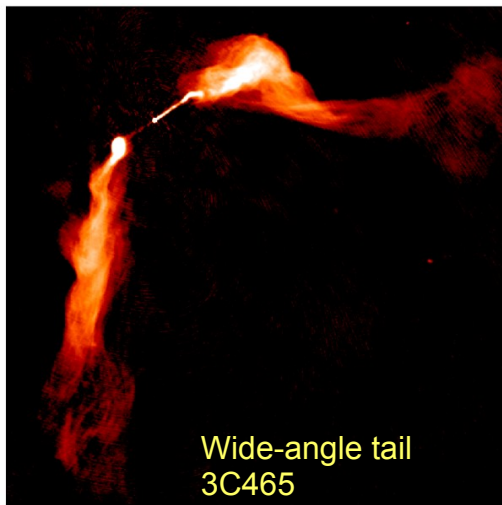


Fanaroff-Riley classification revisited

- Mingo+19
- Automatic classification of sources in the LOFAR surveys
- **Most** FRIs are below the Fanaroff-Riley luminosity threshold
- Significant number of FRIs are below it
- **Some** of these 'FRIs' have clear hotspots with high-resolution imaging (Barkus+26)
- Low-luminosity FRIs lie on average in less massive galaxies...



Some other classes



Source classes and physics

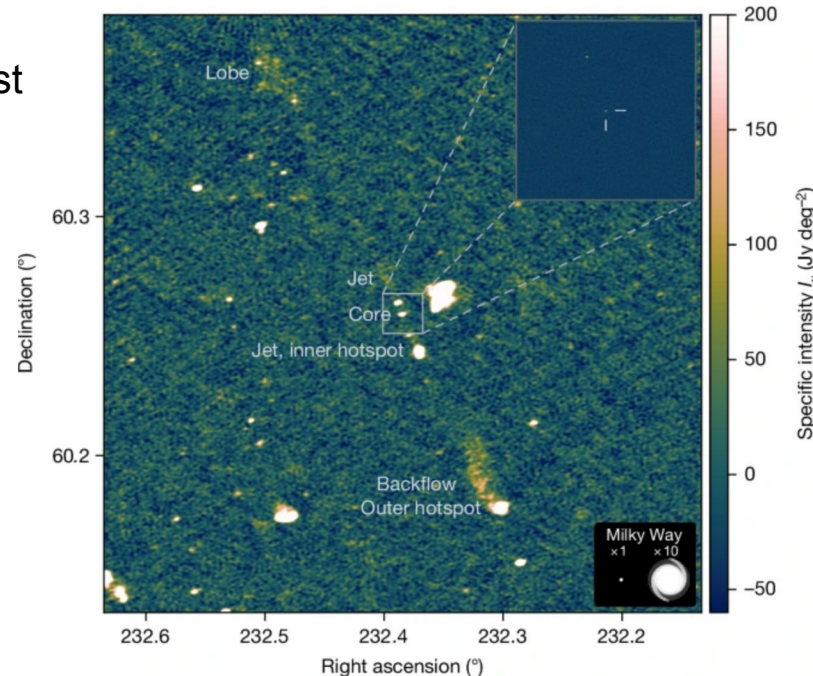
Source type	Has core?	Has narrow one-sided jets and hotspots?	Has lobes?	Has plumes?	Bent?	Radio luminosity
Classical FRII	Yes	Yes	Yes	No	No	Mostly high
Wide-angle tail	Yes	Yes	No	Yes	Sometimes	Medium
Lobed FRI	Yes	No	Yes	No	No	Low
Plumed FRI	Yes	No	No	Yes	Sometimes	Low
Narrow-angle tail	Yes	No	No	Yes	Yes	Low
Head-tail	Yes	No	No	Yes	Yes	Low
Remnant	No	No	Yes	No	No	Medium to low

Some clues:

- Only luminous sources have FRII-style fast jets and hotspots.
- Only low-power sources transition to bent plumes
- Only plumes can bend
- All active source types have cores

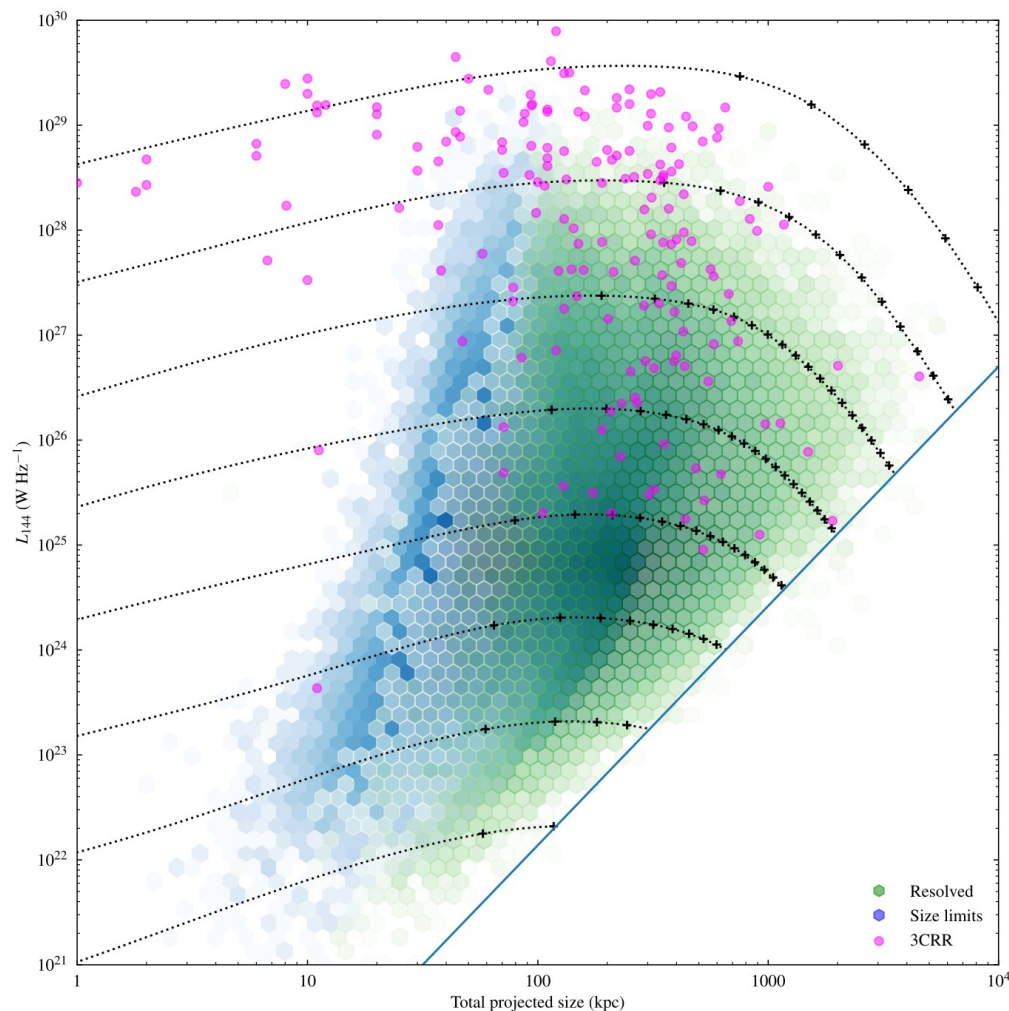
Giant radio galaxies

- Somewhat arbitrarily defined as being anything larger than 700 kpc
- Used to be rare, but now tens of thousands are known
- Largest sources are now ~ 6 Mpc (e.g. Oei+24)
- This implies stability of jets over very long timescales.
- GRGs are mostly FRIs at the largest sizes (due to observational limitations)



The compact source population

- A good way of representing the evolution of radio AGN is a power-linear size plot (PD diagram). We will see this several times again.
- The vast majority of radio AGN are unresolved at scales of a few arcsec
- Implies $\sim$ sub-10kpc spatial scales
- Detailed investigation shows that many are much smaller than this (e.g. Chilufya+ 23)
- This is the ‘compact source population’ – sometimes called FR0s because they can’t be classified (e.g. Baldi 23)
- Large numbers of compact sources have implications for life cycles – see Marisa’s talk



What does morphology tell us?

- We know radio sources expand over time, so **size** is a proxy for age – the wide range of sizes from sub-kpc to Mpc tells us that not all sources are the same age.
- But not all sources that are the same size are the same age!
- **FR class** correlates with radio luminosity, which is presumably a proxy for jet power
- From jet physics we know that **hotspots** are an indication of fast jets (no deceleration)
- Strong **bending** seems likely to be an indicator of interaction with the external medium
- To make all this quantitative though we need models of radio source evolution...

Section 1 summary

- Wide variety of morphological classes in the radio
- Some relationship between morphological class and radio luminosity, but it's complicated
- Sources come in a wide variety of shapes and sizes from sub-kpc to > 1 Mpc.

Section 2: radio source evolution models

- History of evolutionary models (see Turner & Shabala 23)
- How we understand the evolution of radio source size and luminosity
- The effects of jet power and environment



History of evolutionary models

- Key early work by Scheuer 74 and Blandford & Rees 74
- Although details were not correct, the idea of growth balanced against ram pressure of the external medium (assumed uniform), the evolution of lobes and the driving of shocks were consistent with what we now know 50 years later
- Constraints on external environments and even good radio images did not exist yet!
- Jet power Q was fundamental...

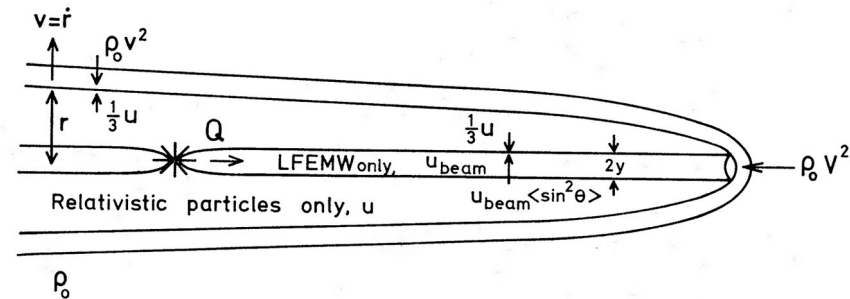
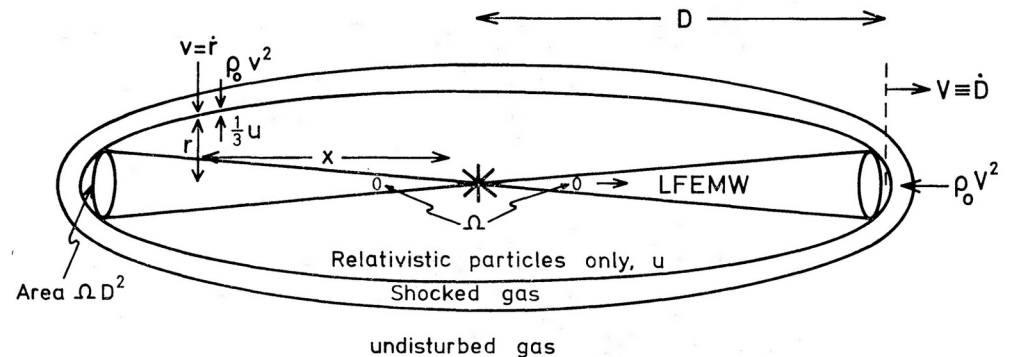
MODELS OF EXTRAGALACTIC RADIO SOURCES WITH A CONTINUOUS ENERGY SUPPLY FROM A CENTRAL OBJECT

P. A. G. Scheuer

(Received 1973 October 29)

SUMMARY

This paper explores the dynamics of radio source models in which energy is carried from a nucleus to the radio components by a relativistic beam. Only a small fraction of the energy supply can be radiated away from the tip of the beam, and the rest lingers on in a cavity surrounding the beam. For the dynamical development of the source it is not of great importance whether the 'beam' consists of strong electromagnetic waves or of fast particles with or without magnetic fields, or even if the energy is supplied from a moving massive object instead of the tip of a beam. If the energy in the cavity contains both fast electrons and magnetic fields, then the cavity rather than the tip of the beam is likely to be the site for the greater part of the radio emission. When the lateral expansion of the cavity becomes subsonic, the outer parts of the cavity swell at the expense of the parts nearest the massive nucleus, where the thermal gas pressure is higher.

FIG. 4. *Model B.*

History of evolutionary models

- Next important steps by Kaiser & Alexander 97 and co-workers
- Assume power-law atmospheres and self-similar expansion

Mon. Not. R. Astron. Soc. **286**, 215–222 (1997)

A self-similar model for extragalactic radio sources

Christian R. Kaiser[★] and Paul Alexander[★]

MRAO, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE

Accepted 1996 November 1. Received 1996 October 29; in original form 1996 March 21

ABSTRACT

An analytical model for extragalactic radio sources with pressure-confined jets is presented. We show that the properties of the bow shock and of the gas surrounding these objects force the sources to grow in a self-similar way provided the density in the external atmosphere falls less steeply than $1/d^2$. Results from observations and numerical simulations are used to develop a self-consistent model for the large-scale structure of FR II objects. The jets in these sources are shown to be stable against turbulence for the observed properties of FRIIs and the divide between FRI and FR II objects in jet power is reproduced. The overall dynamics of a source are derived as a function of time and depend on the external density, the jet power and the scaleheight of the external atmosphere. Derived dynamical ages are consistent with observed spectral ages.

Key words: galaxies: active – galaxies: jets.

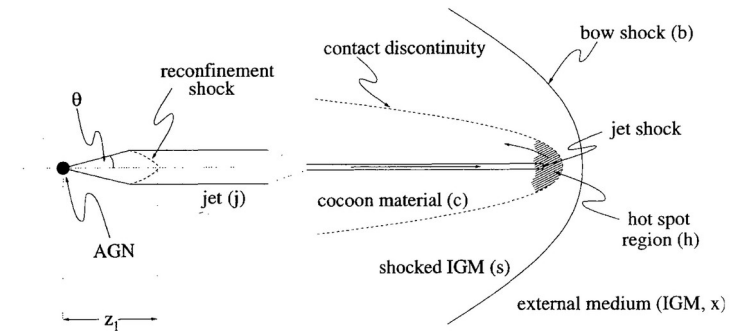


Figure 1. Basic elements of a radio source. The letters in brackets are the indices used for quantities in the indicated regions.

History of evolutionary models

- Kaiser+ 97 first to try to put models on a PD diagram
- Environments of sources still not well known, but now we can estimate jet powers from evolutionary tracks
- Model effects of radiative losses
- Assumption of self-similarity means that the shape of the sources cannot evolve
- Power-law environments are somewhat chosen to permit this and not necessarily realistic

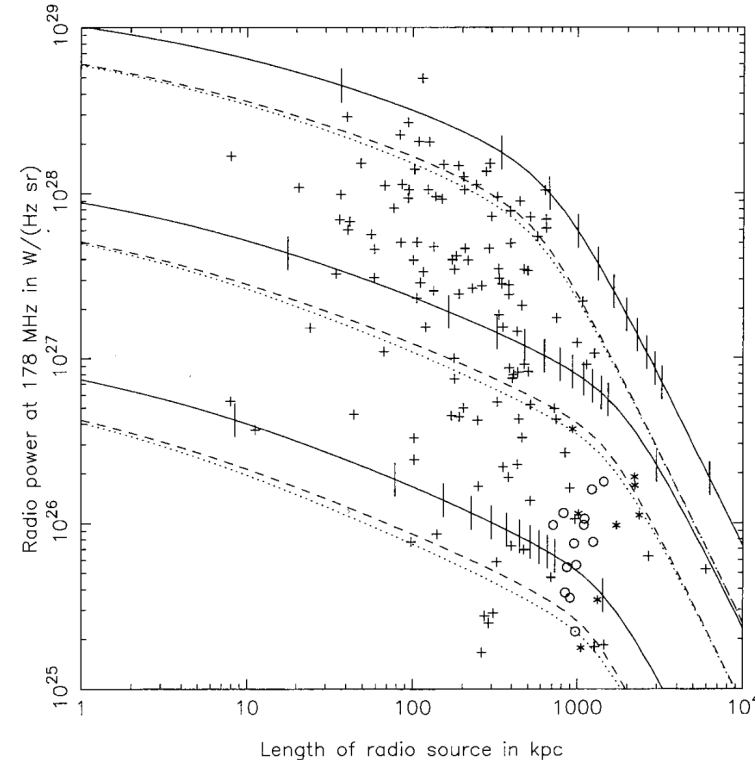
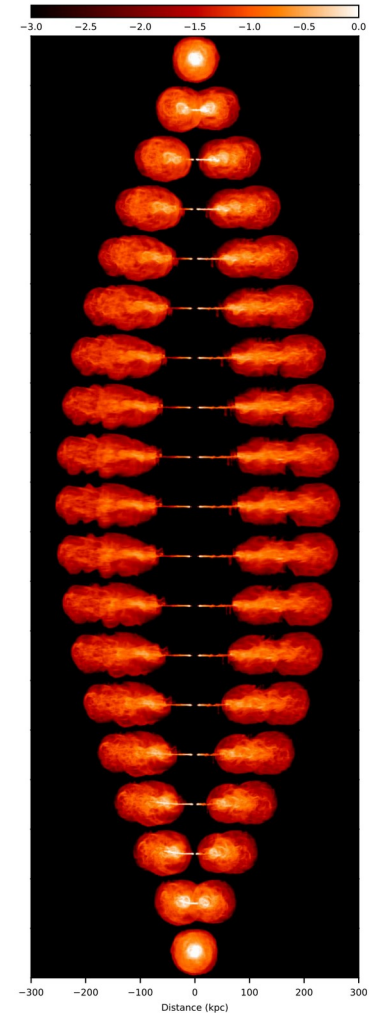
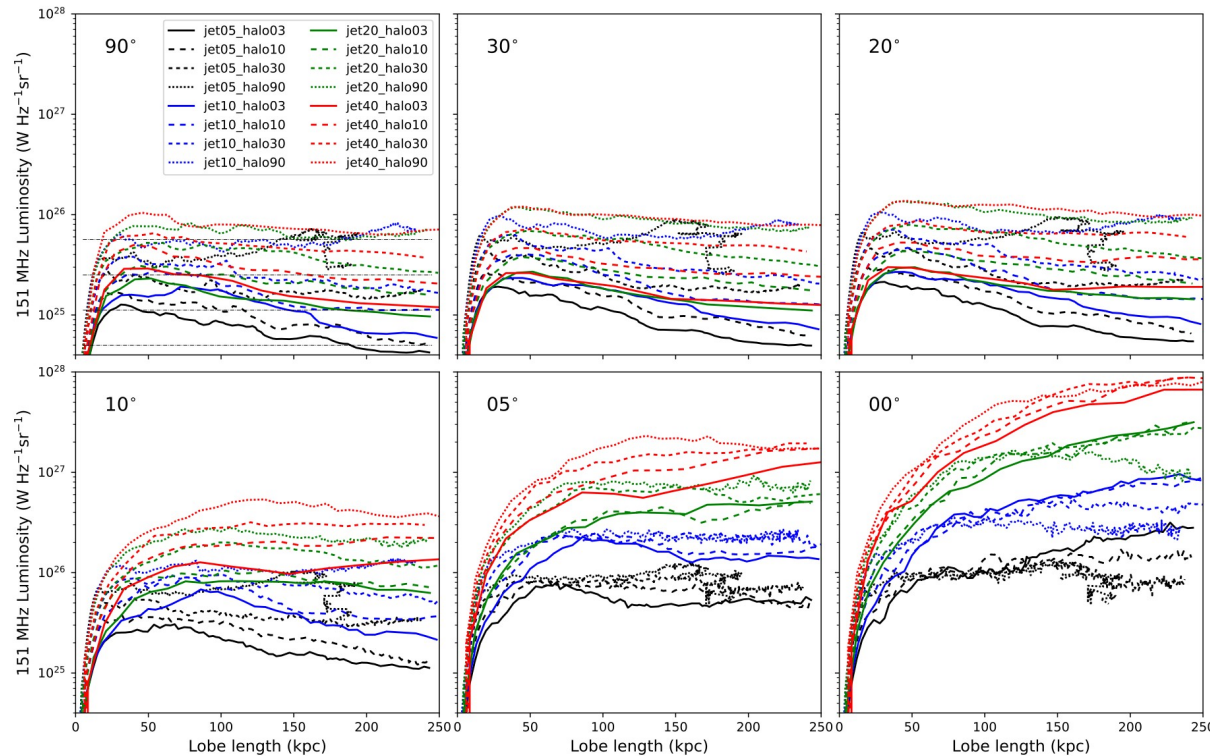


Figure 1. Evolutionary tracks for three FR II sources. The upper curves are for $Q_0 = 1.3 \times 10^{40}$ W and $z = 2$, the curves in the centre are for $Q_0 = 1.3 \times 10^{39}$ W and $z = 0.5$, and the lower curves are for $Q_0 = 1.3 \times 10^{38}$ W and $z = 0.2$. The other parameters for all sets of curves are: $R = 2$, $\rho_0 = 7.2 \times 10^{-22}$ kg m $^{-3}$, $a_0 = 2$ kpc, $\beta = 1.9$ and $k' = 0$. Solid curves are for case 1, dashed curves for case 2, and dotted curves for case 3 (see text). The vertical lines on the solid curves are time markers. The first marker on the left indicates a lifetime of 10^6 yr of the respective source model. The next 10 markers are for every 10^7 yr up to 10^8 yr. At the last marker the source is 2×10^8 yr old. Crosses are observed sources above 10^{25} W Hz $^{-1}$ sr $^{-1}$ taken from Laing et al. (1983), stars are sources from Subrahmanyan et al. (1996), and circles are sources from Cotter et al. (1996).

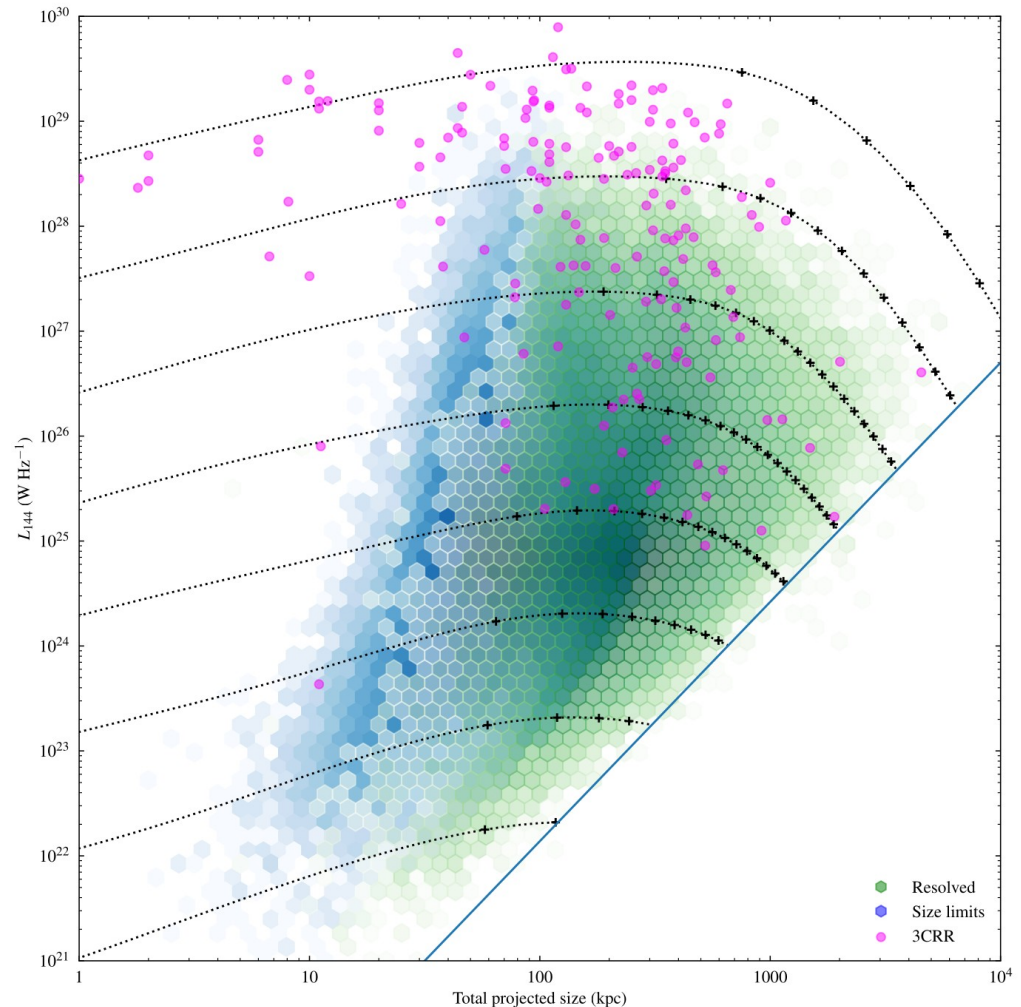
History of evolutionary models

- Hardcastle & Krause 13, 14 (see movie earlier) used full numerical modelling of representative environments and jet powers to investigate the relationship of source evolution with environment, abandoning self-similarity
- Latest versions of this work from Stimpson+ 23 – different tracks for different powers, environments and orientations (but no losses)



History of evolutionary models

- Numerical modelling revealed the need for semi-analytic models that could handle realistic environments and source physical conditions.
- Three models on the market today are those of Turner & Shabala 15, 23, Hardcastle 18, Beltran-Palau+ 25
- These can all make predictions for the evolution of radio AGN in the P-D diagram, or, for a given set of AGN parameters, predict the distribution of observables (Beltran-Palau+ 26)
- Right, the distribution of AGN in the P-D diagram from Hardcastle+ 25 with tracks from the Hardcastle 18 dynamical model
- Radiative losses are not generally self-consistently modelled in terms of dynamics (but see Hardcastle 26)



Semi-analytic modelling

- To give a flavour of how the models work...
- Hardcastle 18 model concentrates on the dynamics of the shocked shell and assumes that a constant fraction of the energy supplied by the jet goes there. Therefore works best for FRII-type sources
- These assumptions lead to differential equations based on the shock jump conditions for the evolution of the shocked shell that can be solved numerically, allowing the size and radio luminosity to be calculated
- See Turner + Shabala 23 for a comparison of this with other models

$$\frac{dR}{dt} = c_s \sqrt{\frac{(\Gamma_s + 1)(p_R/p_{\text{ext}}(R)) - (1 - \Gamma_s)}{2\Gamma_s}}$$

$$p_R = \frac{\epsilon Q R}{2cV_L} + \frac{(\Gamma_j - 1)\xi Q t}{V_L}$$

$$\frac{dR_{\perp}}{dt} = c_s \sqrt{\frac{(\Gamma_s + 1)(p_{R_{\perp}}/p_{\text{ext}}(R_{\perp})) - (1 - \Gamma_s)}{2\Gamma_s}}$$

$$p_{R_{\perp}} = \frac{(\Gamma_j - 1)\xi Q t}{V_L}$$

$$L_{\text{radio}} = J(\nu)V = \frac{C}{I} \frac{E_{\text{lobe}}}{1 + \zeta + \kappa} \nu^{-\frac{(q-1)}{2}} B^{\frac{(q+1)}{2}}$$

General trends from models

- Source size always grows with time. The largest sources require $\sim$ Gyr ages. Giant sources are just the longest-lived ones
- Radio luminosity rises, stays flat and then falls at late times due to a combination of lobe evolution and radiative (inverse-Compton losses).
- Lobe internal pressures, shocked shell pressures and densities, and magnetic field strengths fall with time
- Higher jet power means faster growth: denser environment means slower growth.
- Higher jet power means more radio luminosity: denser environment means more radio luminosity
- Radiative losses can be significant compared to the jet power particularly at late times

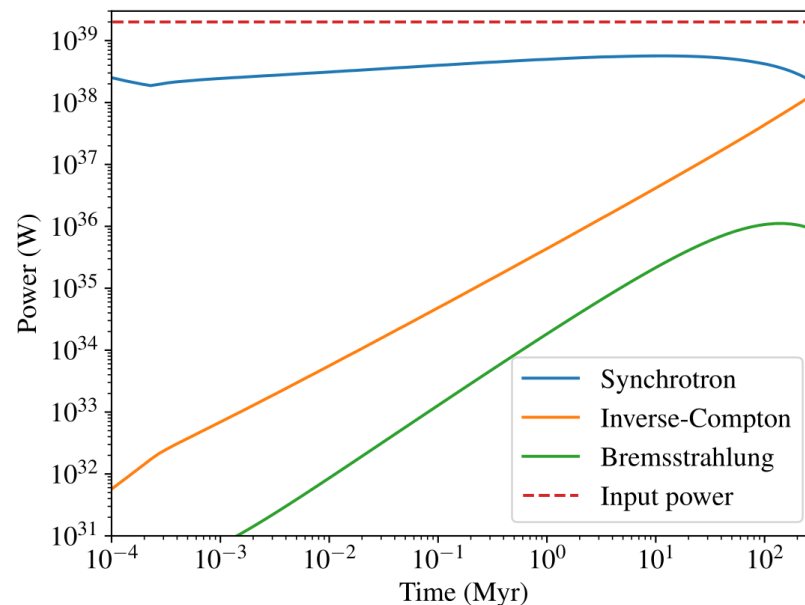
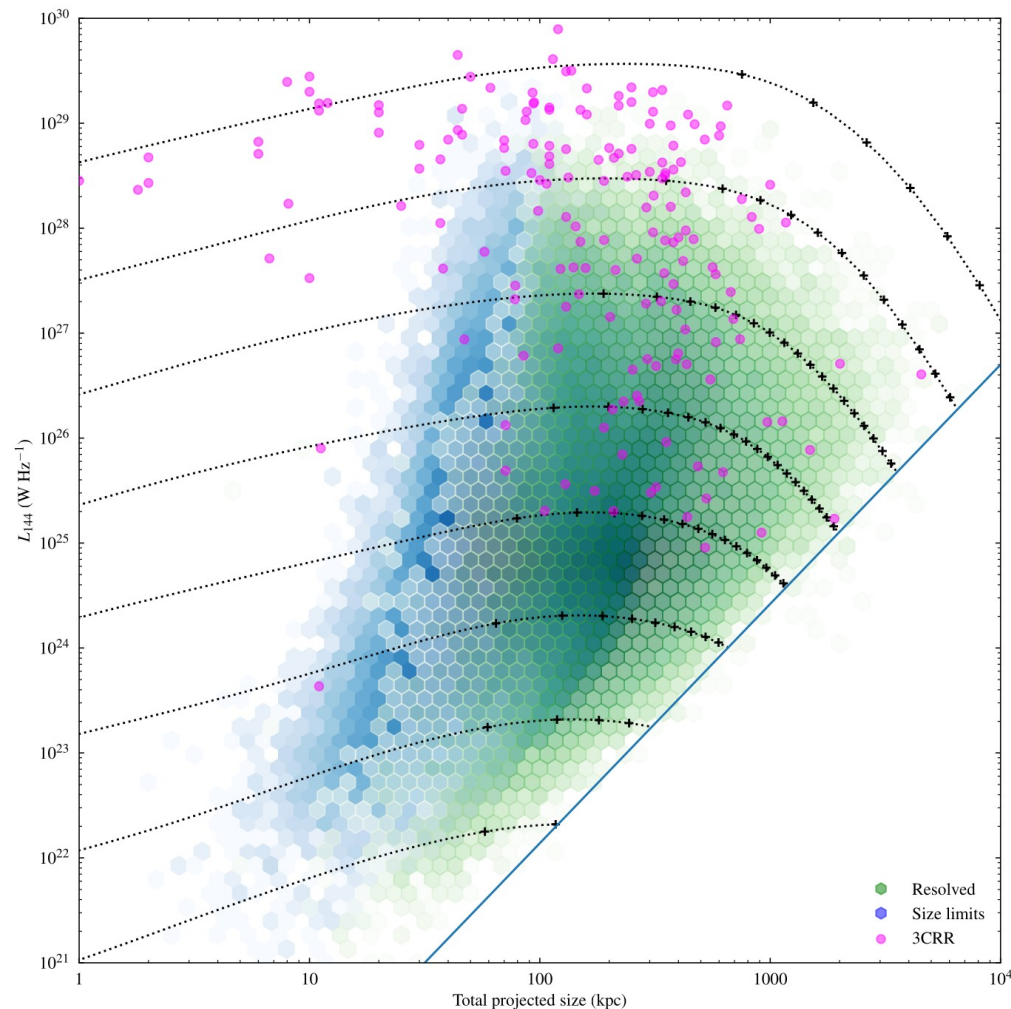


Figure 7. Radiative losses compared to the input jet power as a function of time for the $Q = 2 \times 10^{39}$ W jet discussed in the text. Plotted are the (constant) jet power, the synchrotron loss rate from the lobes, the inverse-Compton loss rate from the lobes at $z = 0$, and the thermal bremsstrahlung loss rate from the shocked shell.

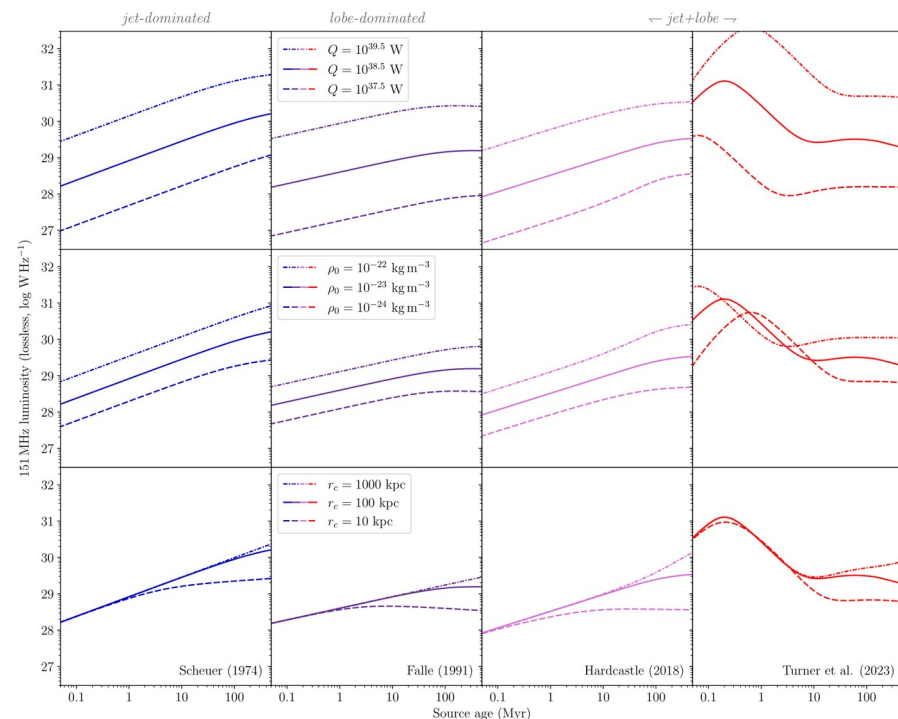
The distribution of source sizes

- The preponderance of small sources can only be explained in these models if **most sources die young** and therefore don't grow to large sizes
- Some intriguing ideas that some sources have a different triggering mechanism (TDEs from massive stars) and therefore can't live long (Readhead +24)
- Possibly also there is radio emission not from jets in some of these sources, e.g. winds in radio-quiet quasars (see e.g. Panessa+ 19).
- The role of evolving particle content through entrainment etc would influence the evolution of sources in these models and needs to be better explored.



Section 2 summary

- Radio source models have evolved from simple beginnings to be capable of matching what we know about environments and physical conditions in radio AGN
- All models predict evolution in radio luminosity with time/source length, and radio luminosity scaling with jet power, but details vary (Turner & Shabala 23).
- Distributions of source lifetime, jet power and environment can be used to make these models predict the overall radio source population and compare with observations.

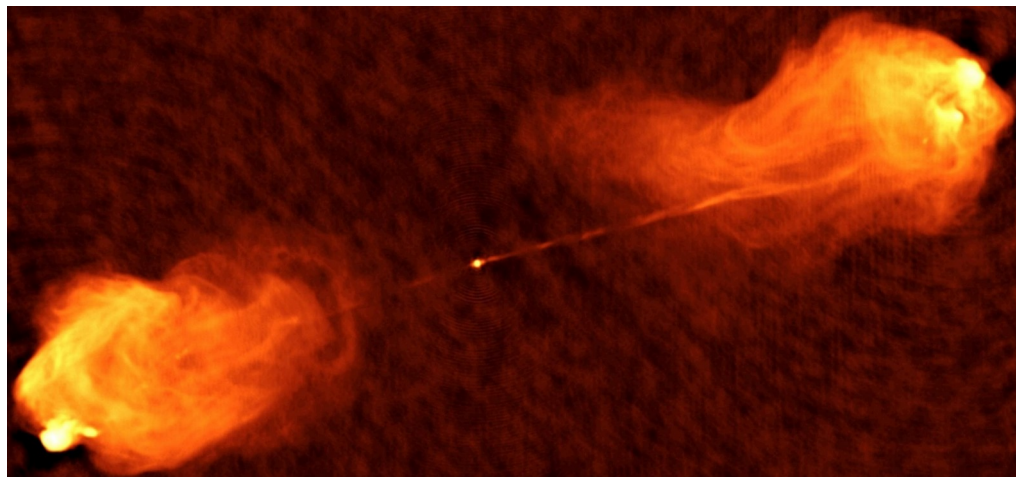


Section 3: Jet power

- How to calculate the jet power?
 - Lobe energetics
 - Cavity energetics
 - Shocked gas energetics
 - Age estimates
 - Scaling relations from age and power estimates
 - Dynamical models: scaling relations and inference
 - Jet deceleration models
 - Jet bending models
 - The issue of particle content
- How jet power compares to accretion power

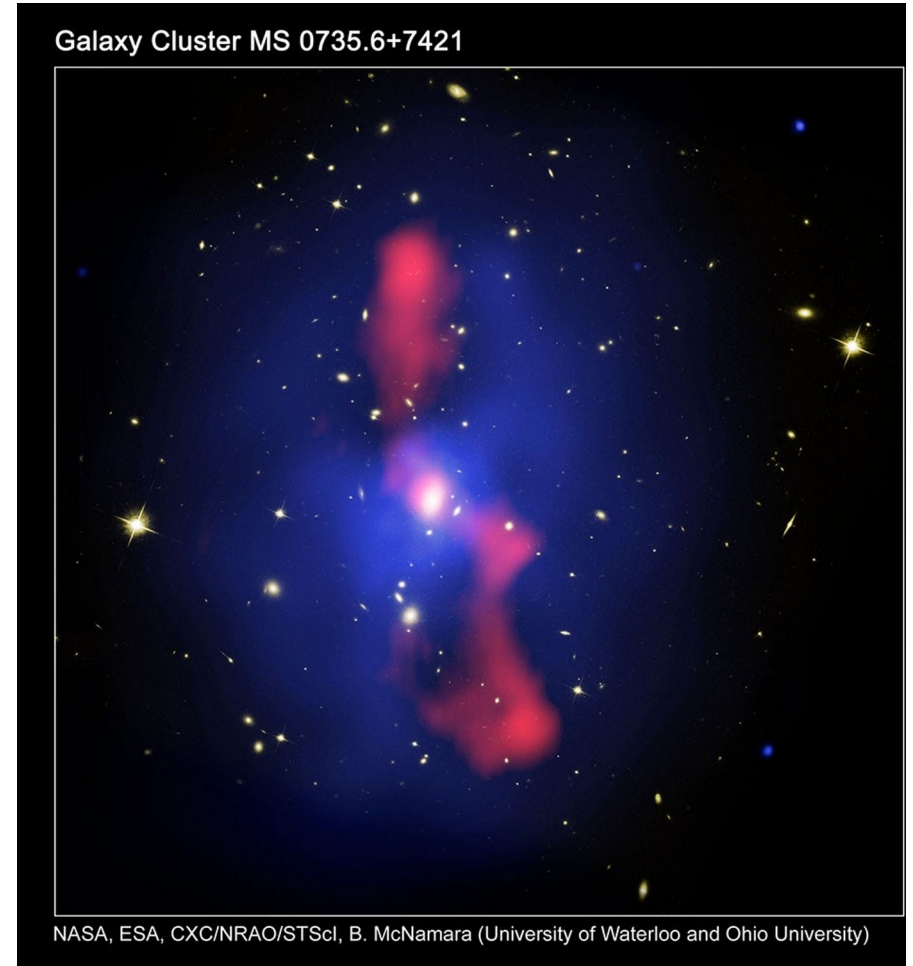
Lobe energetics

- From observations of radio lobe we can infer volume and internal energy density
- If inverse-Compton is available we can estimate magnetic field, else use equipartition/minimum energy (makes a difference of a factor ~ 5)
- Make some assumption about non-radiating particle content
- Ignores work done on the external medium (but could also assume a similar amount of energy in the shocked shell, e.g. Ineson+17)
- Requires source to be well resolved or dimensions can't be measured



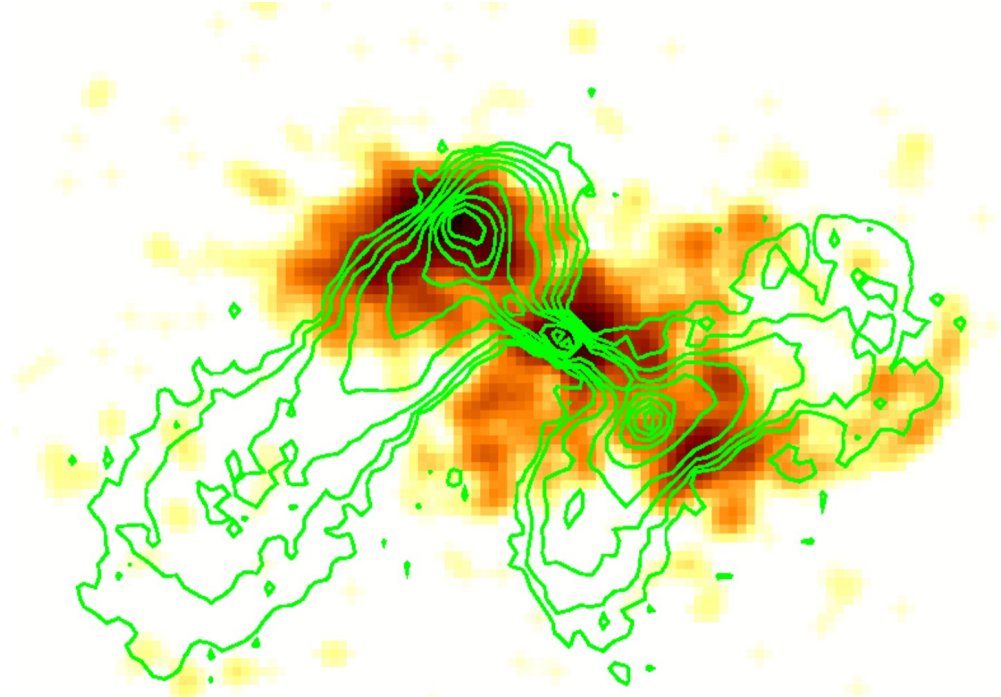
Cavity energetics

- Find a cavity in X-ray observations
- Assume that the energy to inflate the cavity is given by $p dV$ work in adiabatic expansion, i.e. $E = 4pV$
- Estimate external pressure p from X-ray observations
- Underestimate if the lobe expansion drove a shock
- Robust to assumptions about particle content since the external pressure is known



Shocked gas energetics

- Explicitly measure the energy in lobes and shocked shell
- Requires observations good enough to pick out the shocked gas and distinguish it from other X-ray-emitting material
- May work best in very poor environments (e.g. Hardcastle+ 12, right)
- Unusual to be able to see shocked shell and inverse-Compton emission at the same time so guesses have to be made



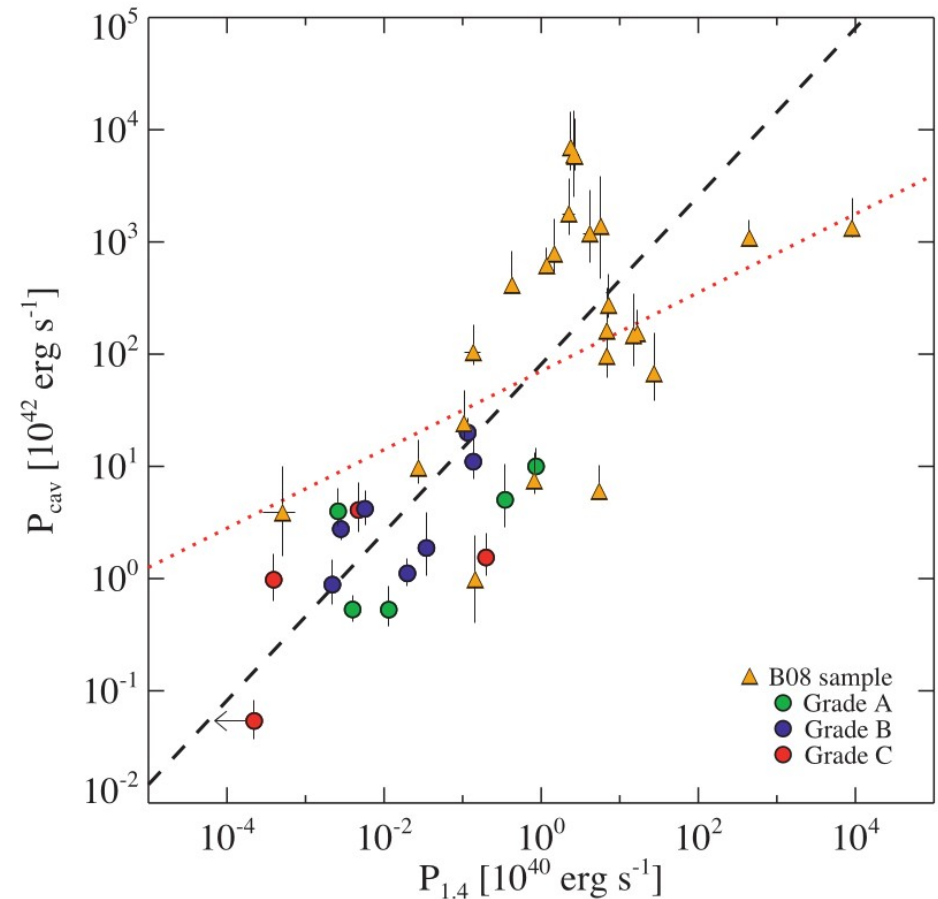
Phase	Mass ($M_{\odot}$)	Ref.	Internal energy (erg)	Kinetic energy (erg)	Contribution to total (erg)
Hot gas	7×10^7	1	6×10^{56}	3×10^{56}	6×10^{56}
Emission-line gas	4×10^5	2	—	2×10^{54}	2×10^{54}
Cold gas	10^7	2	—	4×10^{55}	4×10^{55}
Magnetic field in hot gas	—	1	$> 10^{55}$	—	10^{55}
Lobes	—	1	$> 3 \times 10^{56}$	—	3×10^{56}
Total					10^{57}

Age estimates

- Generally difficult
 - Spectral ages – but need magnetic field and these are generally much younger than dynamical ages, particularly with equipartition field, so overestimates power
 - Dynamical ages from e.g. direct speed estimates from optical emission lines – not usually possible
 - Sound crossing or buoyancy timescales – generally too long if the source is driving a shock, so underestimates power
- Any attempt to do this involves a resolved source, or at least a source size estimate which we don't always have => even more difficult for the overall population

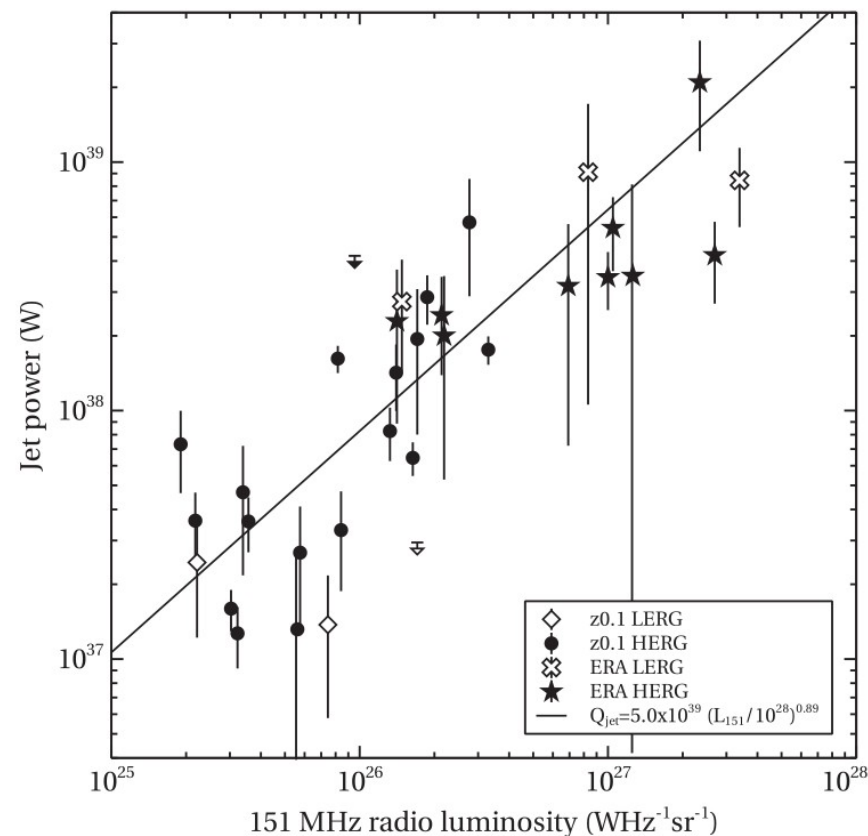
Scaling relations from age and power estimates

- The most widely used empirical scaling relations relate radio luminosity to cavity power, e.g. Cavagnolo+ 10
- Not actually clear that there is a genuine relationship here! (e.g. Godfrey & Shabala 16)
- If there is, E is estimated from 4pV (may be an underestimate) and age from buoyancy (may be an overestimate) so that powers will generally be systematically low
- Calibrated with low-power FRI-type radio galaxies



Scaling relations from age and power estimates

- Ineson+17 use X-ray observations to constrain actual lobe pressures (inverse-Compton) and dynamics based on pressure balance, and obtain a similar scaling relation which should be applicable generally to FR II radio galaxies.
- This relation does not agree well with the Cavagnolo one!

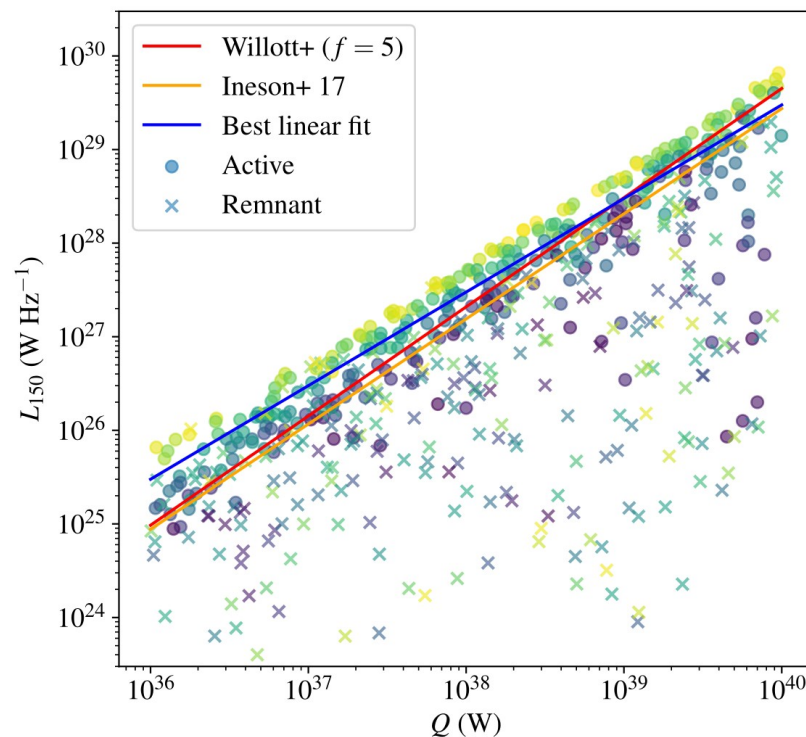


Dynamical models

- Early attempts to estimate jet power from dynamical models (e.g. Willott+99) assumed power-law environments and equipartition and neglected work done on the external medium to get a single luminosity/jet power relation independent of time – traditionally multiplied by a fudge factor $f^{3/2}$ to account for some of the missing energy
- We have seen though that dynamical models predict environment-dependent and time-dependent radio luminosity variation for constant Q (e.g. Hardcastle 18). Scaling relations can be adjusted to work well with these dynamical models on average but will be uncertain for individual sources

$$Q \simeq 3 \times 10^{38} L_{151}^{6/7} \text{W},$$

where L_{151} is in units of $10^{28} \text{W Hz}^{-1} \text{sr}^{-1}$.



Dynamical models and inference

- Hardcastle+ 19 showed that you can use dynamical models to do bulk inference of radio source properties – although without environmental information which was not available
- The model essentially takes a lifetime and jet power (and unknown environment) for many sources and derives the expected jet power for a given location on the P-D diagram (and a given redshift since source evolution depends on z). Note the variation in Q for constant L_{150} !
- Working on taking the environment into account...

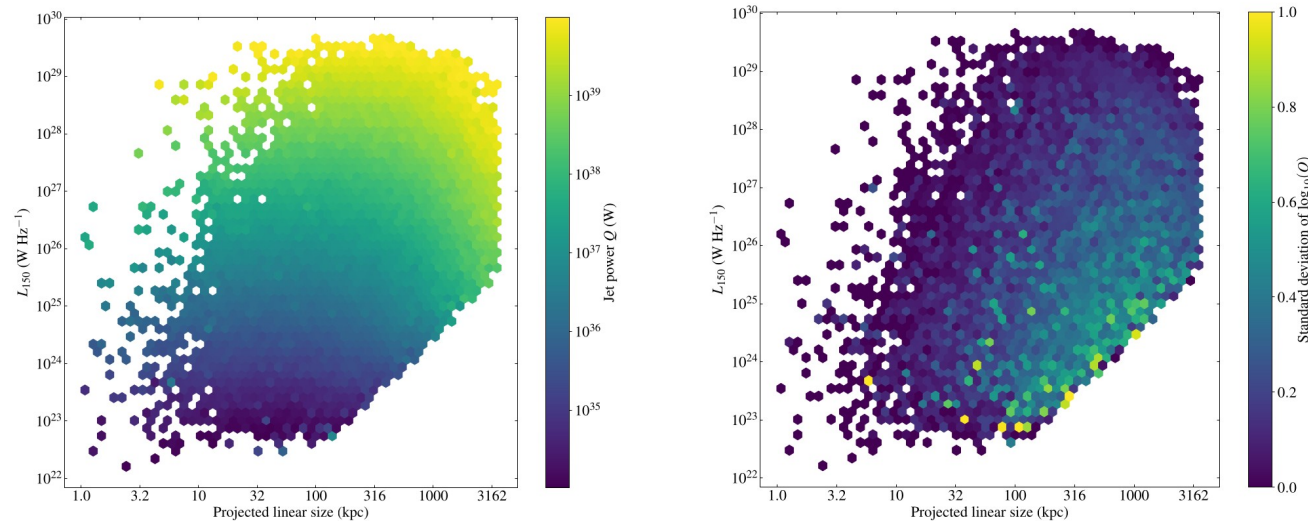
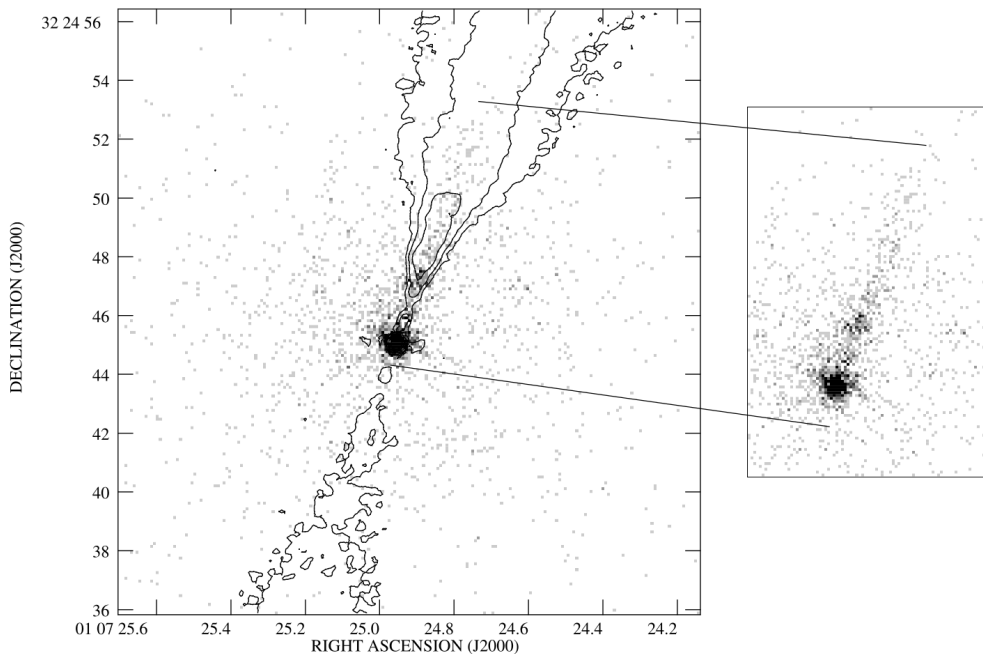


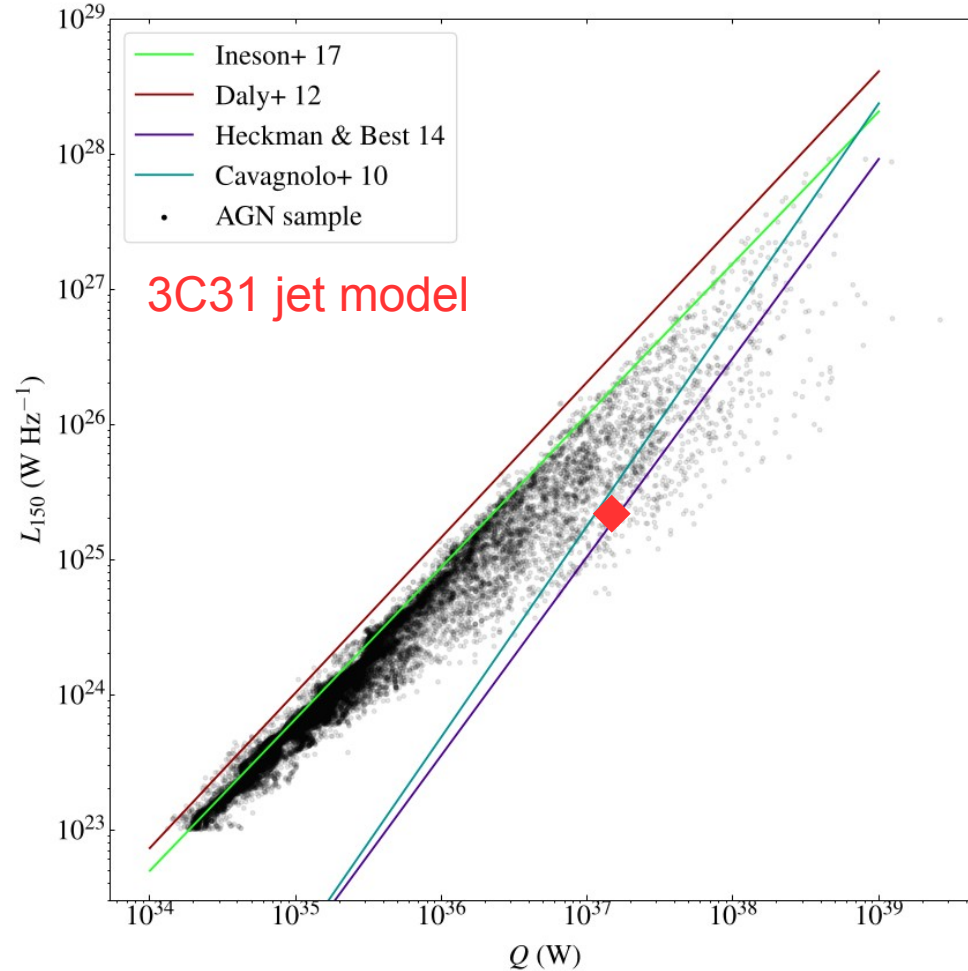
Fig. 11. Left: mean jet power Q as a function of radio luminosity and projected linear size for the full simulated sample over all redshifts. Right: standard deviation of $\log_{10}(Q)$ for each bin in the left-hand panel, showing the scatter in the inference introduced by different environments, projection angles, ages and redshifts. See the text for details of the modelling.

Jet deceleration modelling

- Modelling of jet deceleration constrains jet pressure, density and speed directly if an external pressure measurement is available
- Best measurement for a powerful FRI radio galaxy is $(0.9 - 1.4) \times 10^{37}$ W (Laing & Bridle 2002)
- This sets a normalization for this type of object but unfortunately is hard to repeat without detailed modelling.

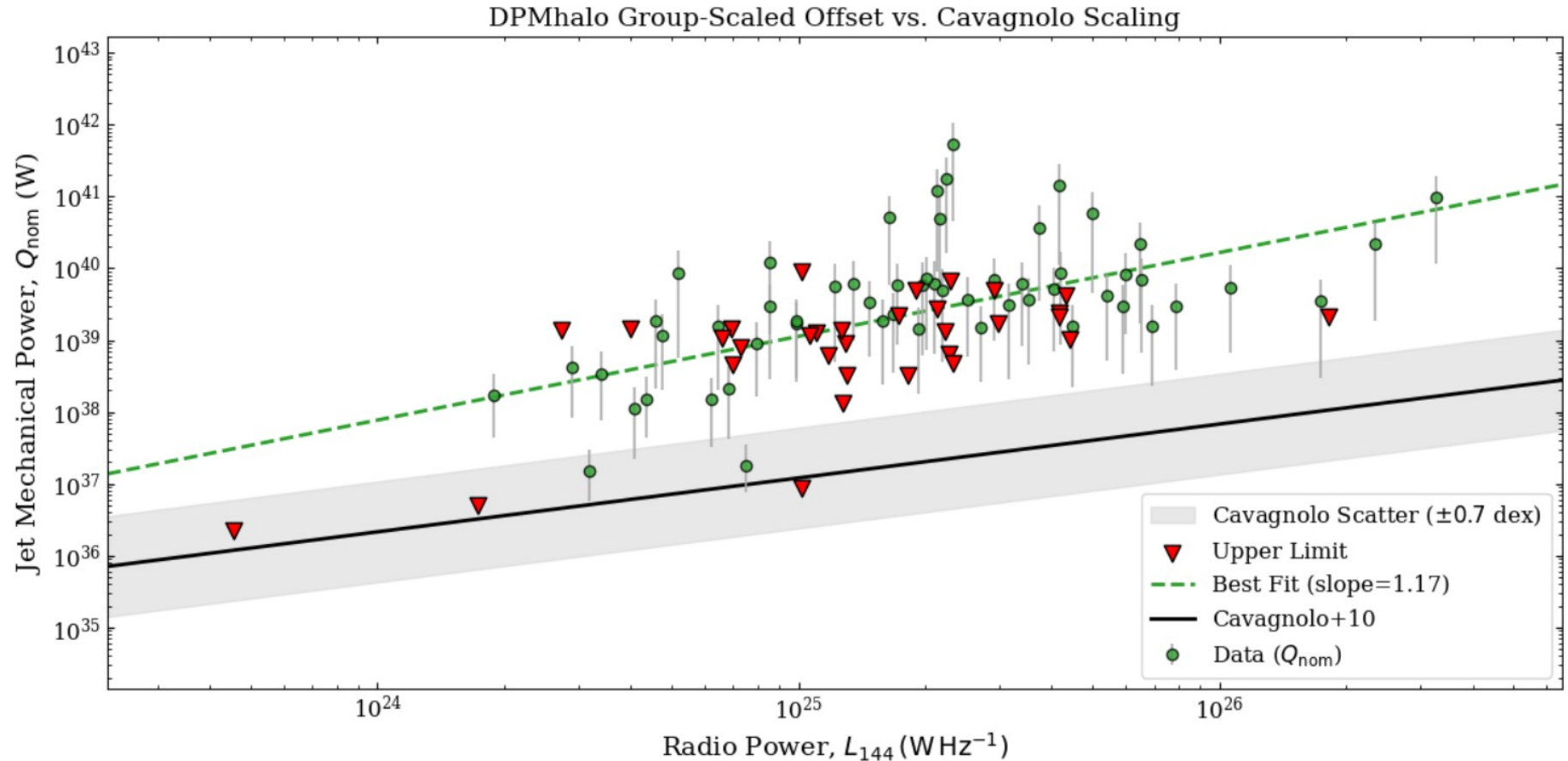


Inference models vs others



Jet bending modelling

- Estimates from jet bending in narrow-angle tails... powers significantly above the Cavagnolo relation!
Ong'alo+ in prep

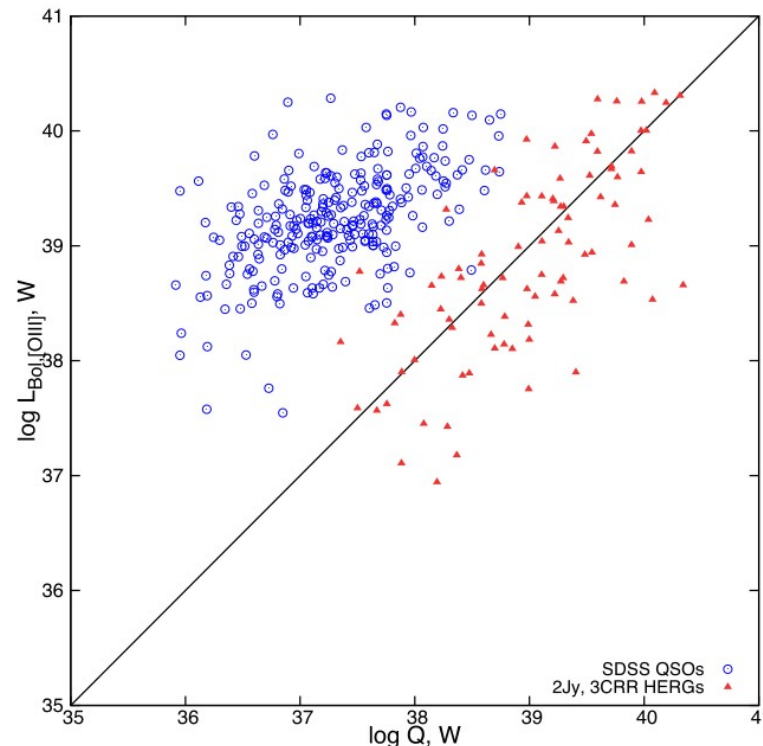


The issue of particle content

- Essentially the different models disagree because they make different assumptions about non-radiating particle content.
- Cavagnolo+ models are calibrated on objects where we believe the non-radiating particle content is probably substantial
- Ineson / dynamical models are calibrated on objects where we believe it may be negligible
- As all the energy in the non-radiating particles must have come up the jet this makes a big difference to jet power.
- The true answer is probably some combination of the two...

How jet power compares to accretion power

- This is difficult because there are many sources where we can't easily measure the accretion power.
- Where we can measure it, we already saw this plot from Mingo+14
- In the most powerful radio-loud AGN, the estimated jet power can be equal to or exceed the accretion power estimate. These could be cases where black hole spin energy is being efficiently tapped by the jet
- In lower-power radiatively efficient AGN the jet power can be orders of magnitude less for a given accretion power/accretion rate
- Note that the bolometric synchrotron losses are always significantly less than the jet power...



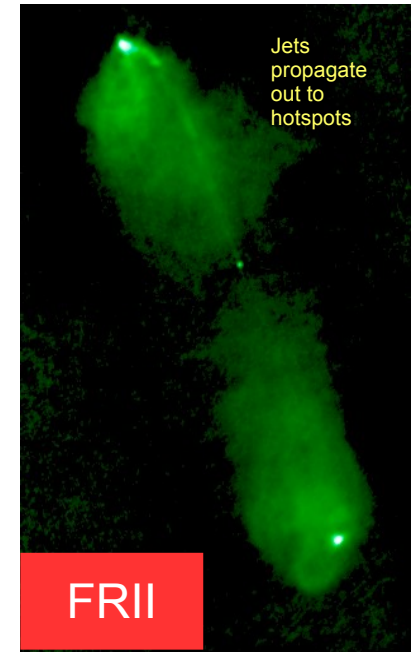
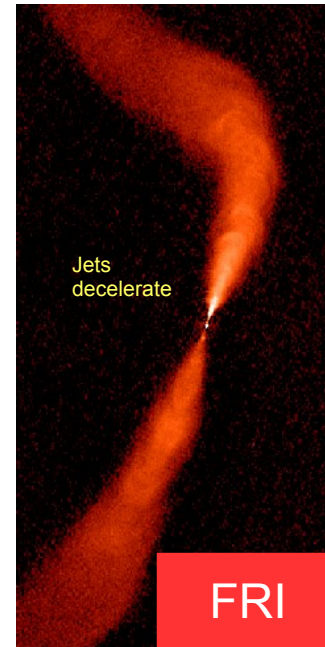
Section 3 summary

- Measuring jet power usually involves measuring an energy content and a timescale
- Both of these are difficult, so jet power estimates vary widely
- Methods include direct calorimetry and modelling
- Ballpark estimates consistent with most models are that FRI jets are at or below around 10^{37} W and FR II jets are in the range 10^{36} - 10^{40} W – but substantial uncertainty and scatter.
- Jet power estimates a key ingredient in feedback models (see Marisa's lecture this afternoon)

Section 4: What controls radio source morphology and properties?

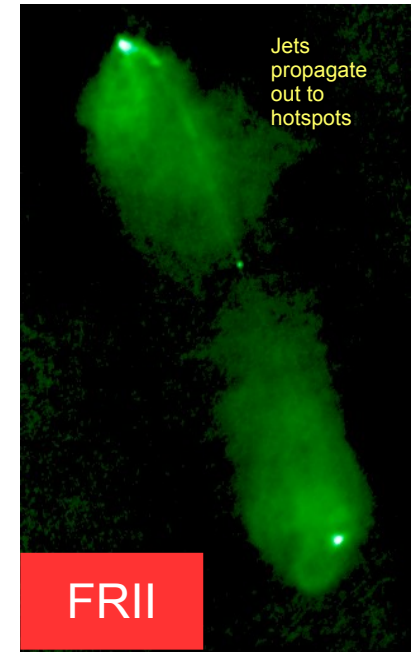
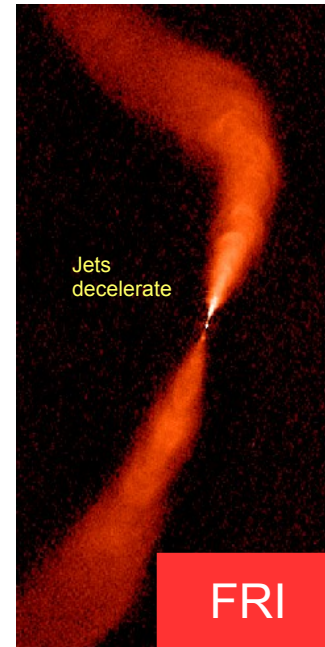
- FRI and FRII
- Lobes, plumes and bending
- Accretion modes?
- Orientation and beaming

(Thanks to Stas Shabala for a very instructive talk a couple of weeks ago in Kenya which has clarified my thinking on this)



FRI and FR II

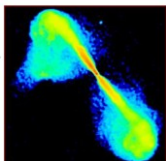
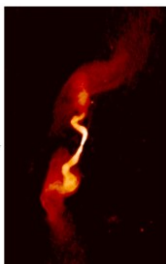
- Do we have the necessary physics to explain the FRI/FR II dichotomy?
- Suppose the ingredients are jet power, host galaxy, and host environment (the latter two are correlated)
- We know:
 - FRIs typically have lower radio luminosity and lower jet power than FR IIs
 - Particle acceleration takes place in FRI jets and FR II hotspots (this is where energy is dissipated)
 - The FRI/FR II boundary is related to host galaxy mass
- It is reasonable to conclude that *the balance between jet power and material entrained from the host galaxy determines whether an object has an FRI or an FR II-type jet* (e.g. Bicknell 84).
- Higher jet powers or lower galaxy masses favour jets that can escape the host galaxy at supersonic speeds and will go on to form hotspots.



- FRI jets may decelerate through
 - ISM entrainment (Bicknell 84, Bicknell 94, Bodo 95, Perucho & Marti 07) – requires the jet to be able to entrain external material across the boundary layer.
 - Stellar-wind mass loading (Phinney 83, Komissarov 94, Bowman+ 96, Wykes +13, Perucho 20) – must happen at some level but possibly not enough to decelerate the most powerful jets?
 - Kink instability (Begelman 98, Tchekhovskoy+Bromberg 16) – requires strong magnetic fields.
- FRII jets have enough power that even though they must at a minimum be affected by stellar wind entrainment, they still escape the host galaxy.
- Possible that stellar winds decelerate the jets of FRIs enough to make turbulent entrainment through a boundary layer effective.
- Stellar winds depend not just on the mass of the host galaxy but also the age of the stellar population, so predictions are complex.

Lobes, plumes and bending

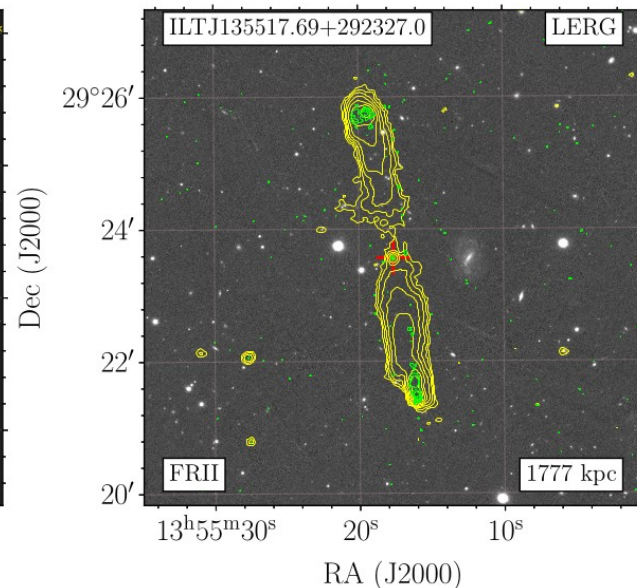
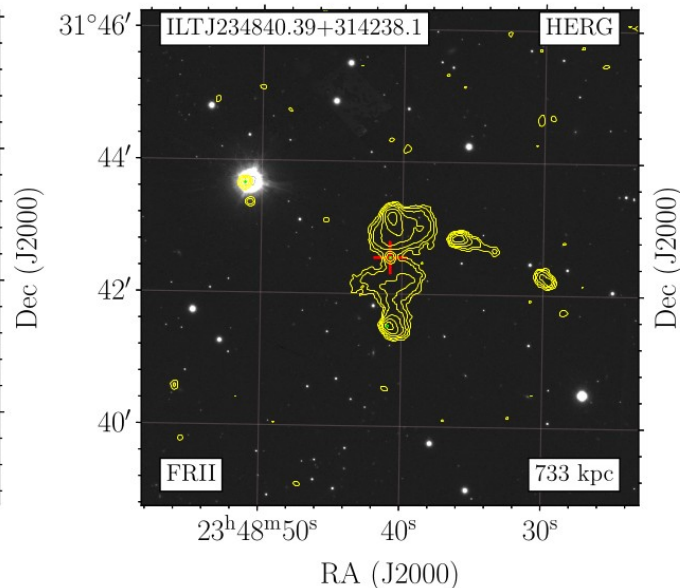
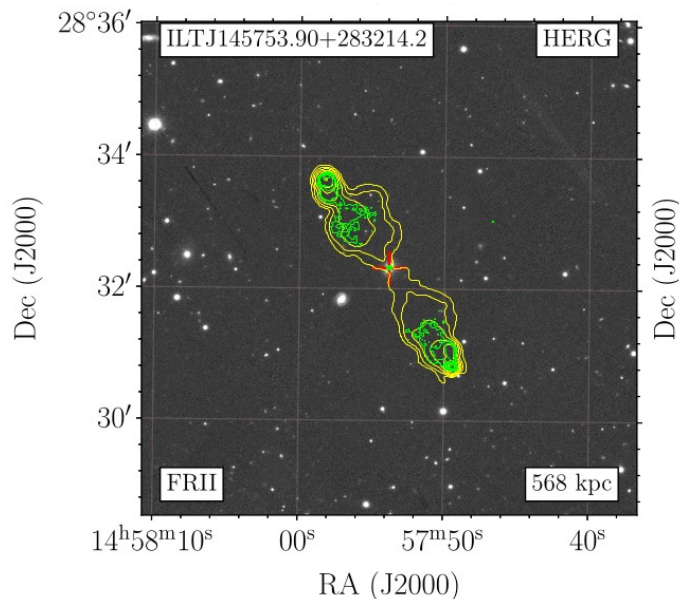
- Recall our morphological table
- Both FRIs and FRIIs effectively have 'plumed' versions
- This is likely the transition between supersonic and buoyant expansion of the *lobes*
- Once the lobes are buoyant, they will turn into plumes – this will happen on smaller scales in denser environments and for less powerful jets
- Every source starts off with an FRII-type jet, lobes and hotspots. FRI jets develop through interaction with the host galaxy. Lobes turn to plumes once the lobe expansion speed is slow enough
- Significant bending starts once the lobes are no longer supersonic (so only low-power objects).



Source type	Has core?	Has narrow one-sided jets and hotspots?	Has lobes?	Has plumes?	Bent?	Radio luminosity
Classical FRII	Yes	Yes	Yes	No	No	Mostly high
Wide-angle tail	Yes	Yes	No	Yes	Sometimes	Medium
Lobed FRI	Yes	No	Yes	No	No	Low
Plumed FRI	Yes	No	No	Yes	Sometimes	Low
Narrow-angle tail	Yes	No	No	Yes	Yes	Low
Head-tail	Yes	No	No	Yes	Yes	Low
Remnant	No	No	Yes	No	No	Medium to low

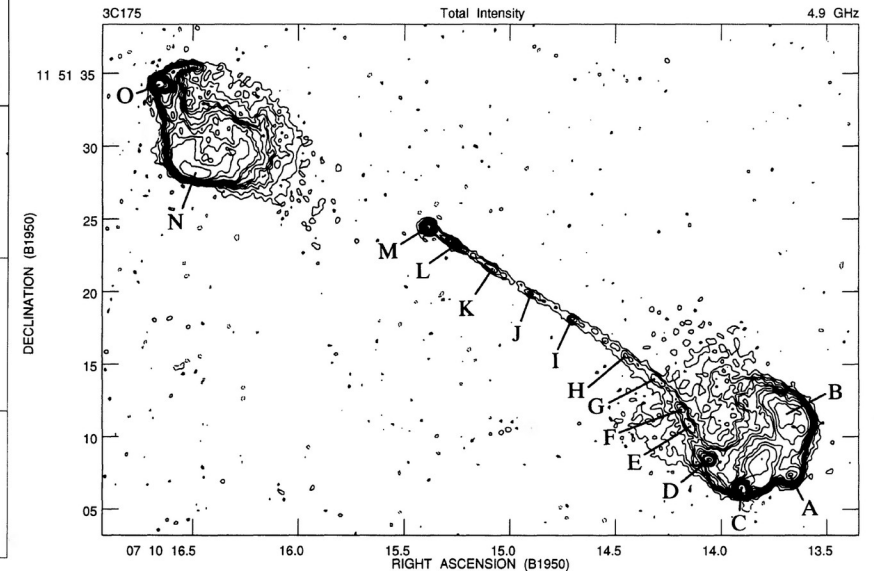
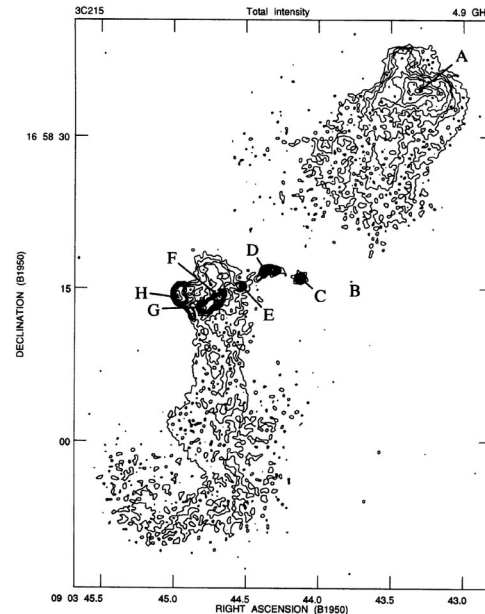
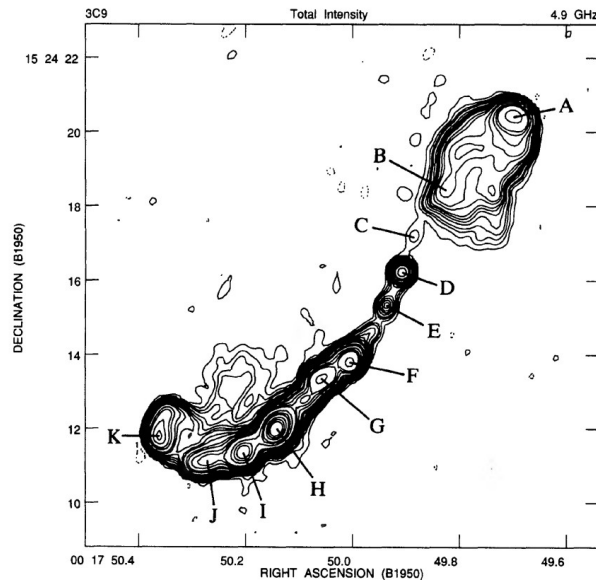
Accretion modes

- We know that AGN can come in radiatively inefficient or efficient versions depending on the Eddington-scaled accretion rate
- FRIs are almost all radiatively inefficient (LERGs).
- FRIs can be radiatively inefficient (LERGs) or radiatively efficient (HERGs). The most powerful FRIs are usually HERGs.
- There is no apparent effect of accretion mode on FRII morphology or other properties. It is not possible to tell RI or RE FRIs apart by eye (Chilufya+25, examples below). This makes sense if the FRI/FRII physics is about jet disruption on kpc scales (Hardcastle+Croston 20).
- FRIs favour lower-density environments (hence less massive BHs) and more powerful jets, but the transition between FRI/FRII and HERG/LERG does not have to happen at the same place (and in fact it does not).



Orientation and beaming

- Due to lack of time we have not covered classical unified models for radio galaxies and radio quasars (Barthel 1989, Antonucci 93)
- However, to summarize in a sentence, it is known (Laing 88, Garrington+88) that radio quasars have their jets aligned closer to the line of sight than normal RE radio galaxies (HERGs).
- This means that radio quasars are more strongly affected by Doppler boosting and projection effects, giving them bright cores and very one-sided, often apparently distorted jets (e.g. Bridle+94, below)



Section 4 summary

- With what we have learned about radio source dynamics we can now understand the basic morphological features of the radio AGN population
 - FRI/II or jet/hotspot on the basis of jet deceleration within the host galaxy
 - Lobes/plumes on the basis of the termination of supersonic advance speed of the lobes and the dominance of buoyancy in the external medium
- Complications arise from beaming, from restarting jet activity and from interactions so strong with the external medium that the original source structure is erased.

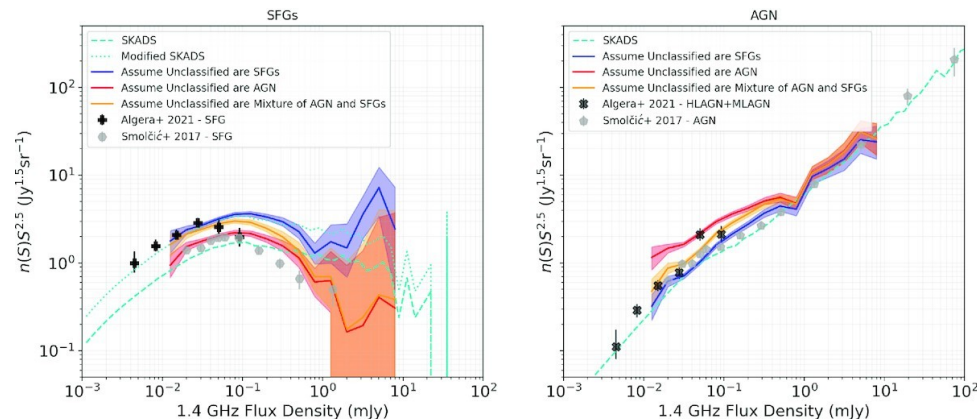
Section 5: populations and cosmological evolution

- How do we select radio AGN?
- What selection effects are present in the population we do see?
- How does the population evolve?
 - The radio luminosity function
 - The kinetic (jet power) luminosity function
- Open questions and future work

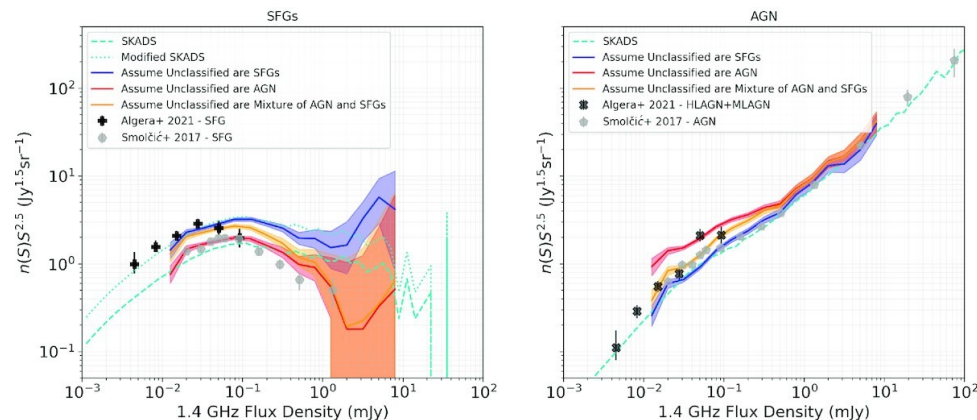
How do we select radio AGN from surveys?

- AGN completely dominate the bright radio source population but at the faint end they overlap with star-forming galaxies
- At resolutions of a few arcsec most radio sources are unresolved => can't use morphological selection
- Selection on the basis of radio luminosity and star formation rate or some proxy will miss some AGN activity
- Optical identifications become challenging at high z and are needed to find redshifts and do physics
- Ideally use high resolution (Morabito+25), but not widely available and not foolproof
- Estimate ~ 1000 radio AGN per square degree on the sky (Hardcastle+ 25)

Right: Hale+23



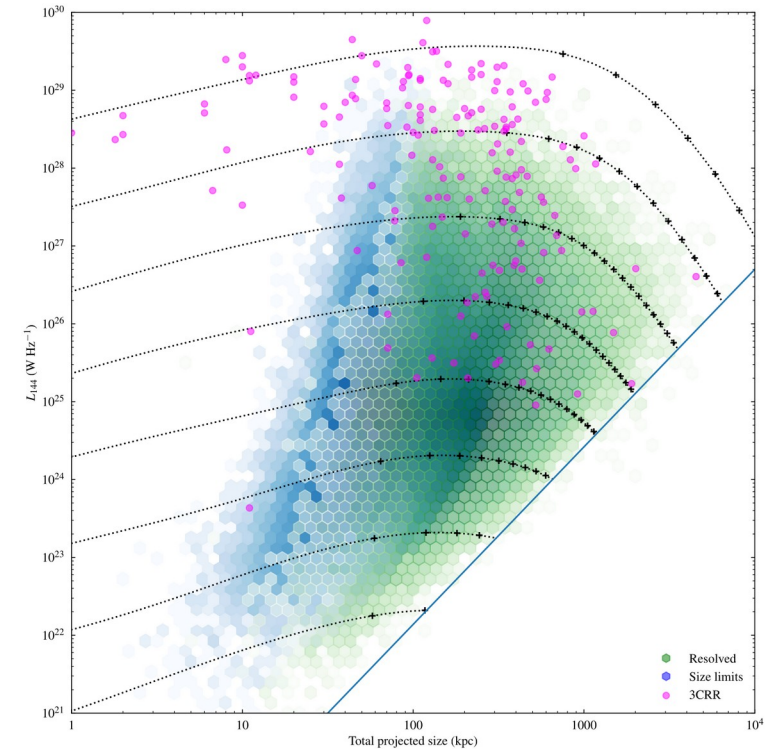
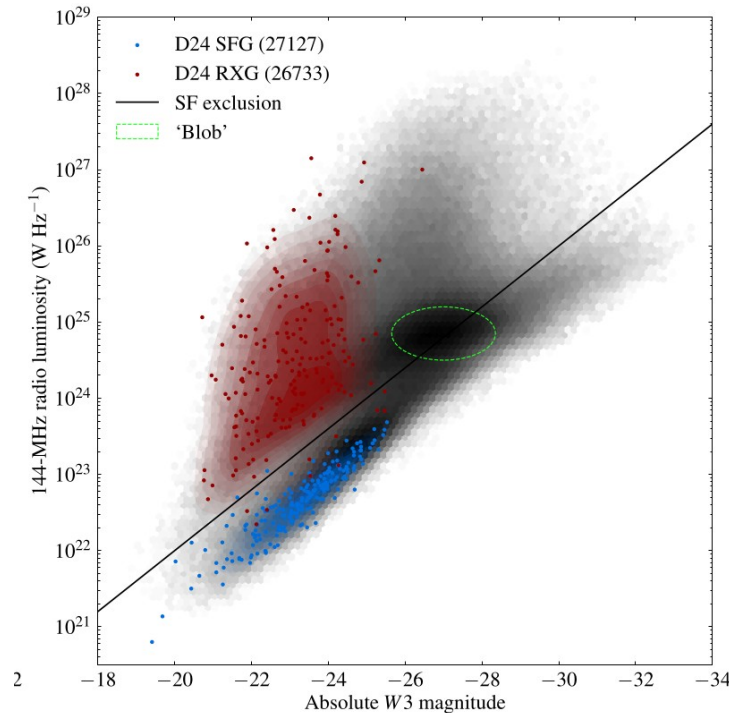
(a) COSMOS



(b) XMM-LSS

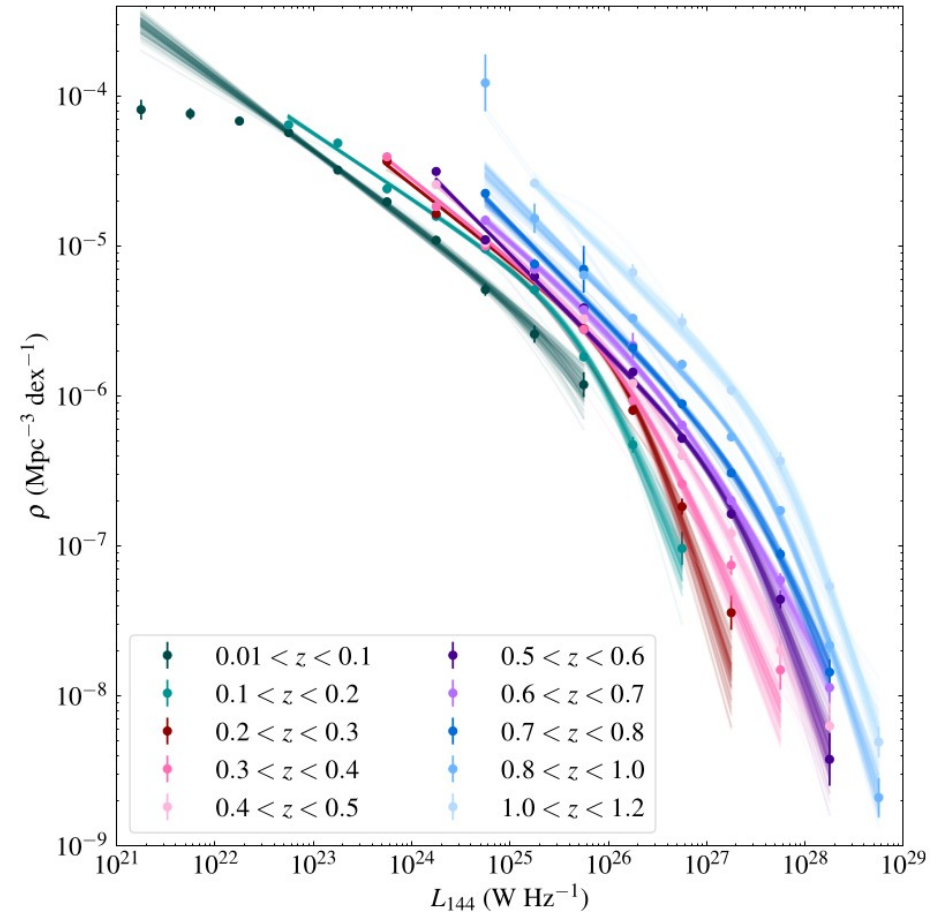
Radio AGN selection effects

- Flux limit
- Surface brightness limit
- Optical identifications
- Redshifts
- Star formation cut
- All of these affect our ability to model radio source evolution



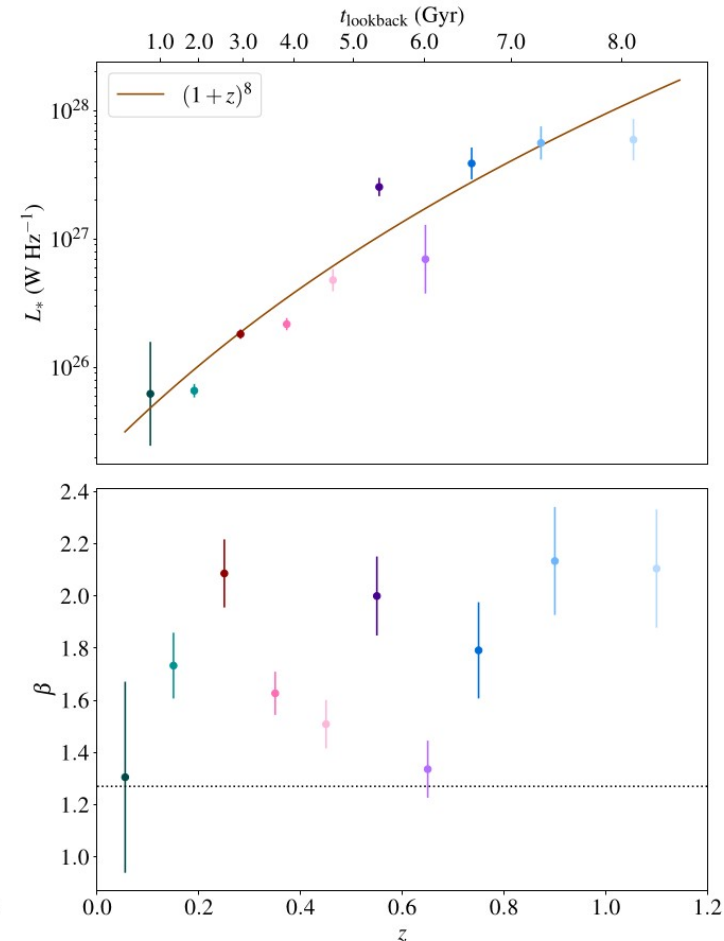
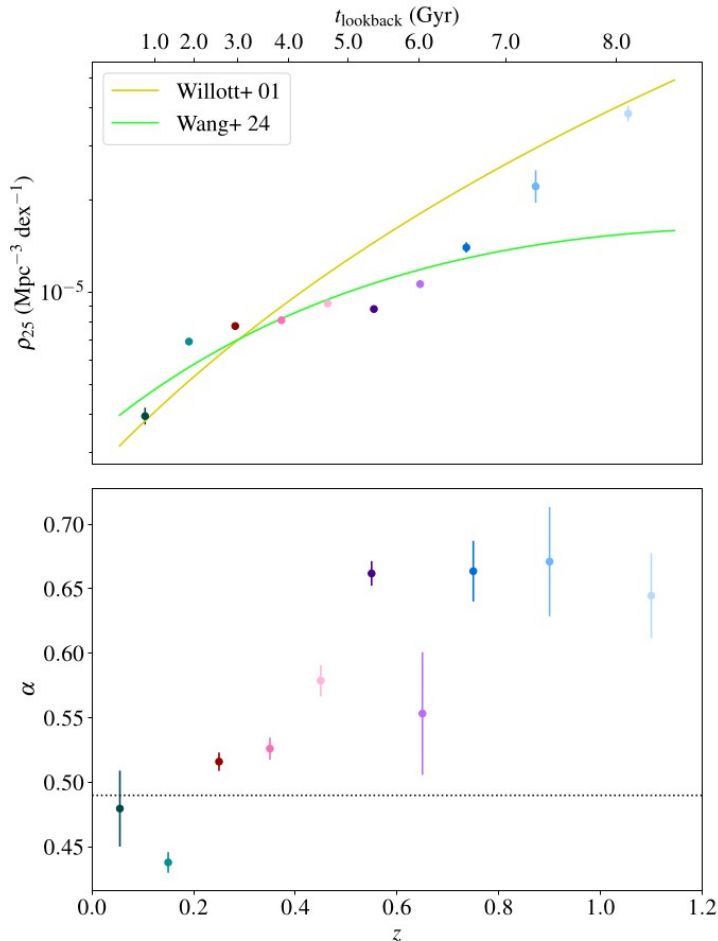
Cosmological evolution

- Traditional to derive the 'radio luminosity function' which expresses the comoving number density of sources with a particular radio luminosity and redshift
- This luminosity function evolves positively with time (more sources at earlier times) and also changes shape (larger numbers of bright sources).
- Carries on evolving positively out to 'cosmic noon' ($z = 2-3$) though hard to constrain well with existing data.



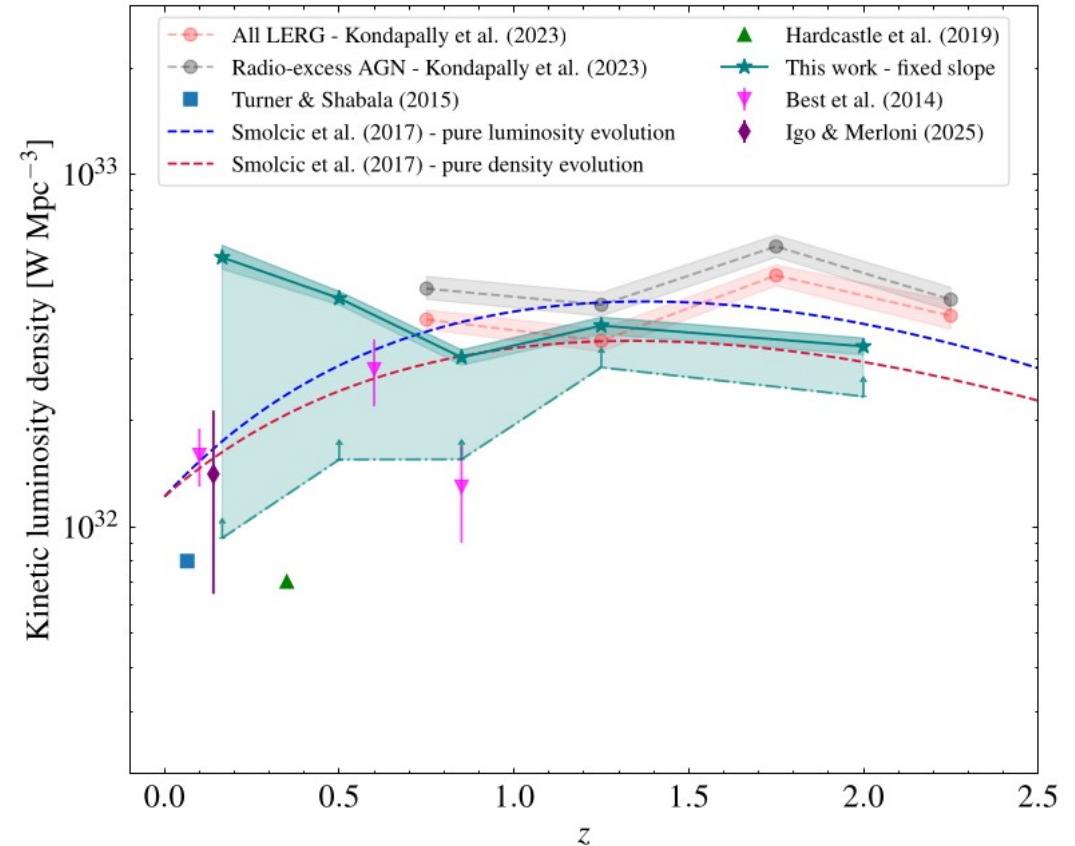
Cosmological evolution

- Traditional to derive the 'radio luminosity function' which expresses number density of source radio luminosity and reds
- This luminosity function evolves with time (more sources at high redshift) and also changes shape (larger bright sources).
- Carries on evolving post 'reionisation' ($z = 2-3$) though has been constrained with existing data.



Cosmological evolution

- We can also look at the cosmological evolution of the *kinetic* luminosity function (in terms of estimated Q – see caveats earlier)
- Current state of this summarized by Pierce+ 26
- Only modest positive evolution detected, but data are uncertain as this has so far been done in deep fields with small numbers of objects
- Wide fields with deep optical data would let us model the full population and should give better answers...



Open questions and future work

- How does the radio source population really evolve to high z ?
 - What is the nature of the large population of faint, compact sources? Are they normal jetted sources that are dying young or are they something else?
 - What are the real integrated feedback effects of the population on their host galaxies and environments? (related to particle content question in the previous section)
 - How do actual observations of AGN compare in detail to cosmological models?
-
- SKA (+ LSST, Euclid etc) will give wide, deep data over large areas of the sky very quickly
 - Some of the issues with resolution and optical identification will remain the same
 - LOFAR 2.0 surveys like ILoTSS will remain competitive because of their high resolution
 - Overall expect big progress in the next decade

Section 5 summary

- Selection of radio AGN in bulk is still complicated
- Populations we do select are heavily influenced by selection effects
- Clear evidence that the radio AGN population evolves positively to high z , but quantitative effects are not so clear
- SKA and LOFAR 2.0 (plus LSST, Euclid) will provide a big step forward in our capabilities but much work still to be done

Synthesis (take-home messages)

- Whereas the last session was mostly about the physics, this session has been about what we can infer from observations on kpc scales
- Morphology gives us important insights into the physics as described by analytic models of source evolution as well as the interactions with the external medium
- Jet power and age are perhaps the key observables for an active source but are hard to compute
- It is clear that the radio source population evolves cosmologically but less clear what effect that has on the overall evolution of host galaxies and environments.
- Overall these two sessions should have given you an overview of the basic physics of radio AGN and their evolution, and Marisa will tell you more about the environmental interactions this afternoon!