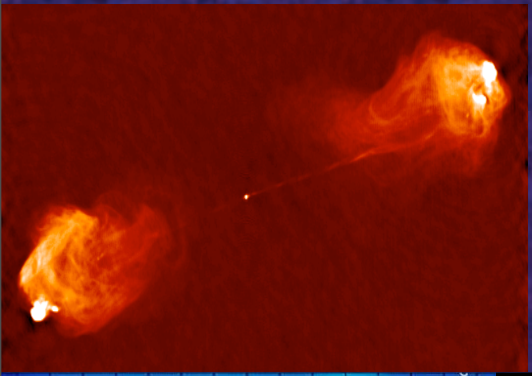
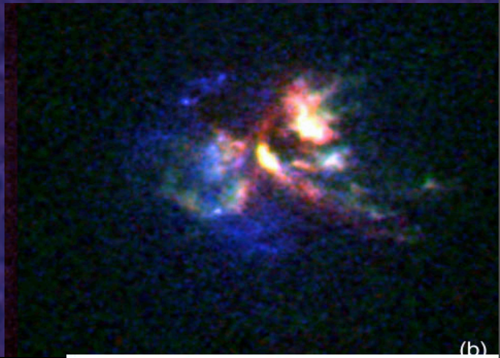
Obscured AGN across cosmic time:

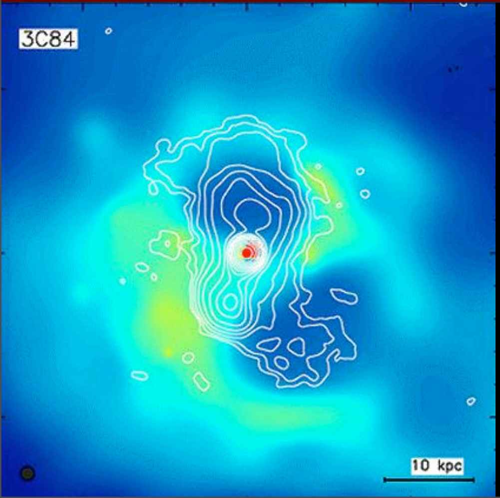
Identification of AGN in radio surveys

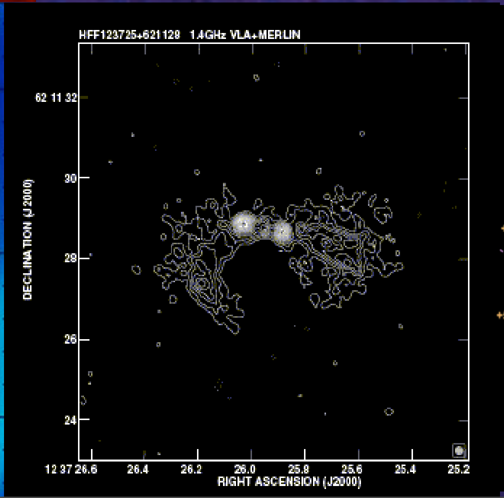


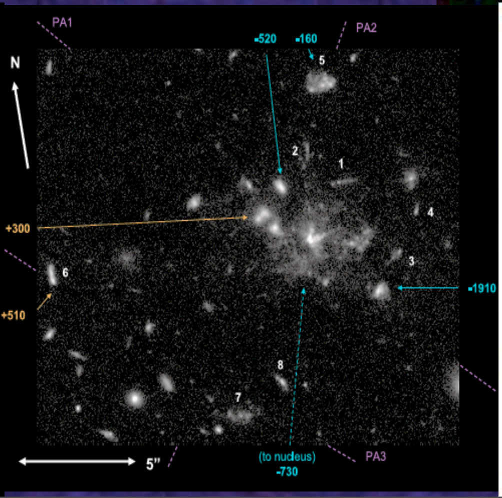


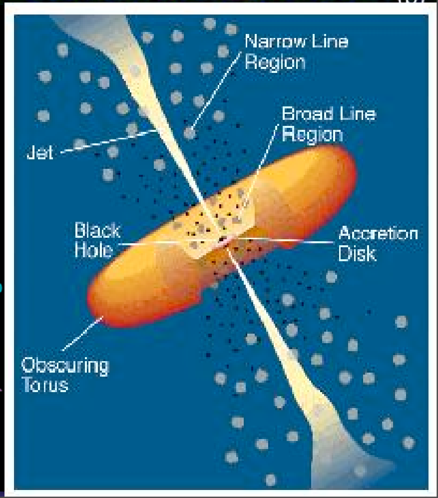
Philip Best

IfA, Edinburgh





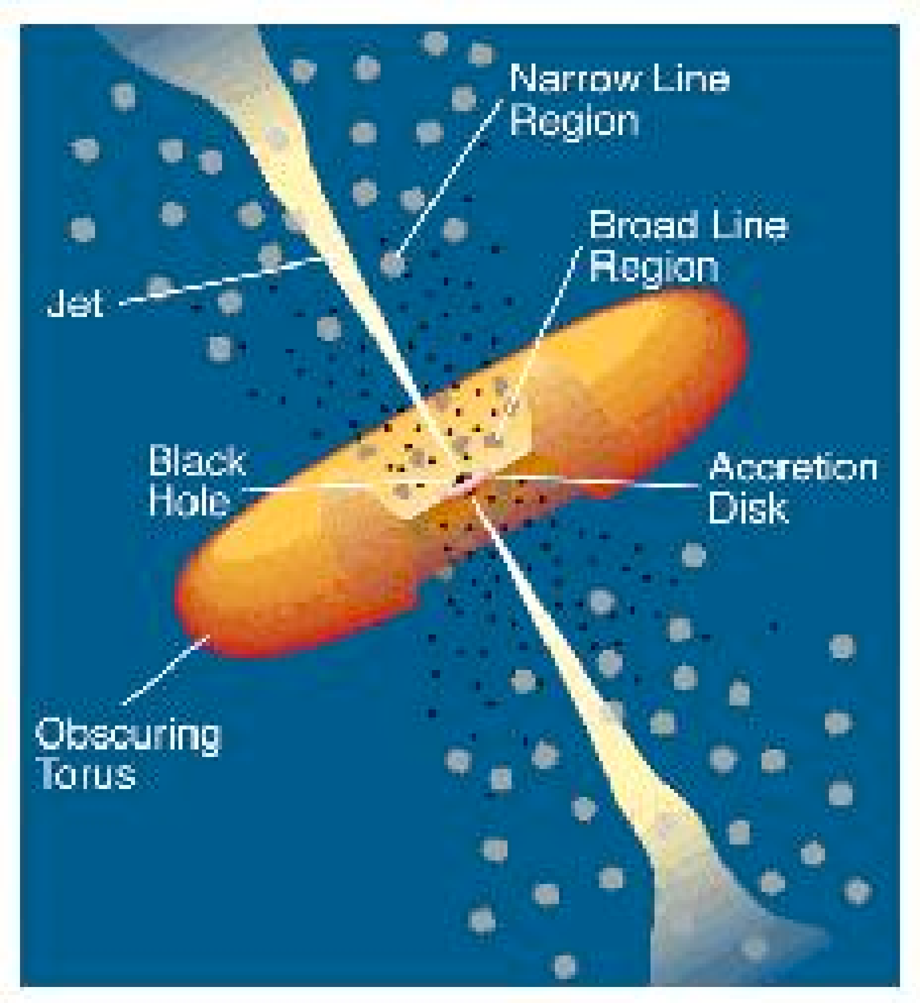




Overview

- Radio source properties
  - Fanaroff & Riley radio morphology divide
  - Properties, ages, duty cycles, etc of activity
- Unification schemes for radio-loud AGN
  - Evidence for Unification
  - Complications: low-excitation sources; receding torus?
- Cosmic evolution of radio-loud AGN
  - Luminosity-dependent evolution
  - High redshift cut-off?
- Host galaxies & environments of radio-loud AGN
- Role of low luminosity radio-AGN in galaxy

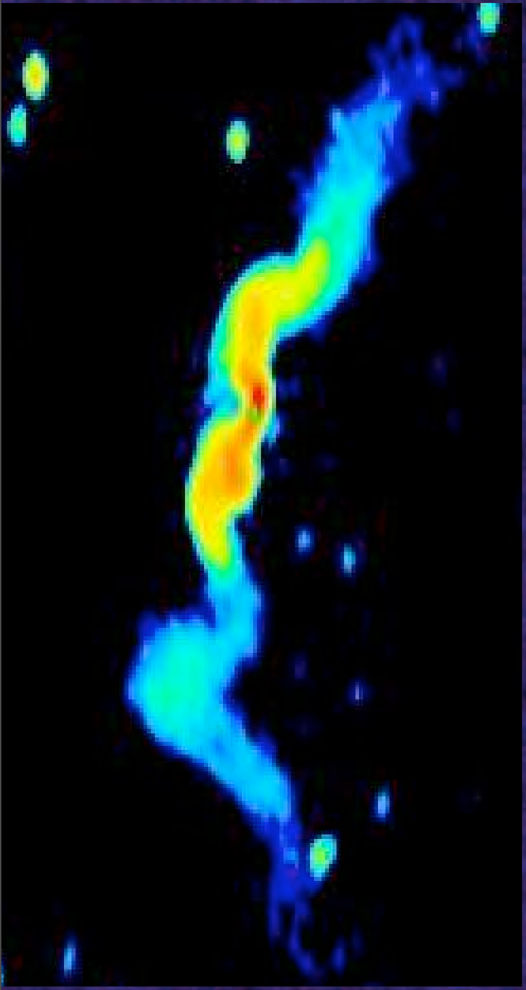
Active Galactic Nuclei (AGN)



Schematic illustration of AGN activity

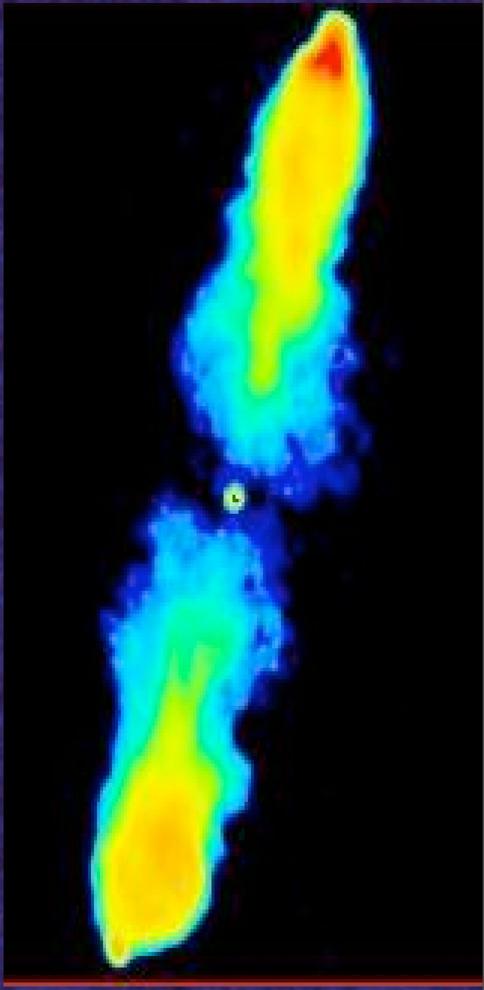
- AGN fuelled by accretion onto supermassive (> million solar masses) black holes.
- Type-1 AGN are directly visible. Typical properties:
  - bright continuum emission
  - broad emission lines
  - variability
- Type-2 AGN are obscured.
  - narrow emission lines only
  - dust obscures nucleus
  - nucleus seen in scattered light, hard X-ray, mid-IR etc

Radio source properties

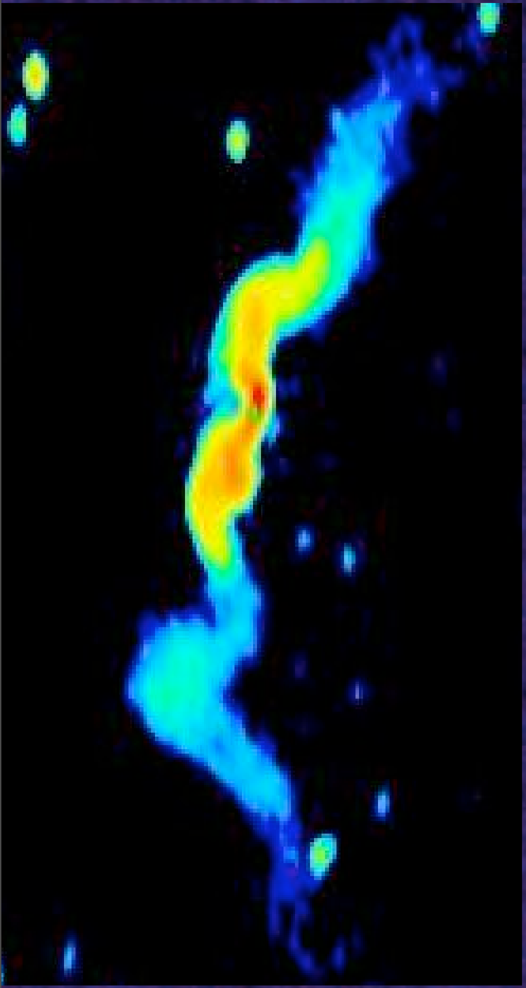

The FR1 radio source 3C31

Fanaroff & Riley Class 1 (FR1)

- "edge darkened"
- low radio luminosity (below ~10^{25} W Hz^{-1} at 1.4GHz)
- jets decelerate rapidly, and entrain material
- generally no obvious optical AGN activity (visible or obscured)
- generally only weak and low-excitation emission lines


The FR2 radio source 3C223

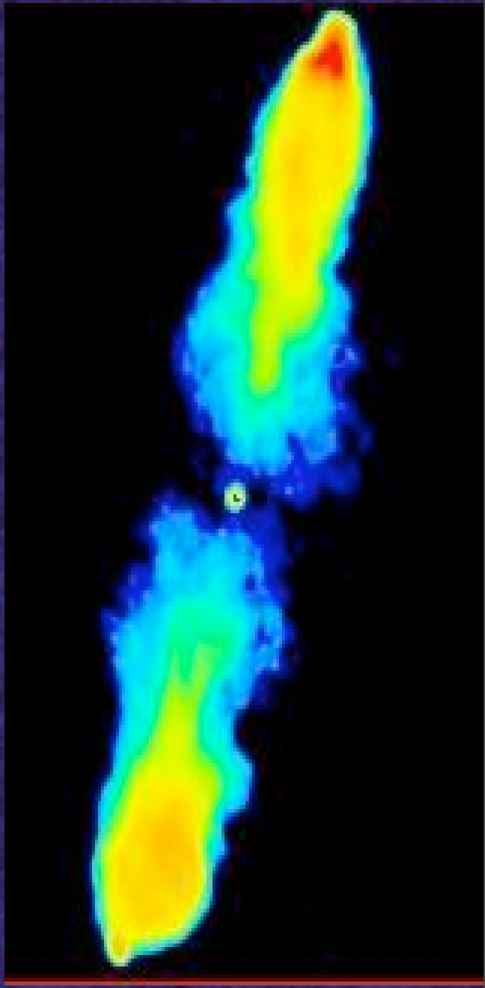
Radio source properties



The FR1 radio source 3C31

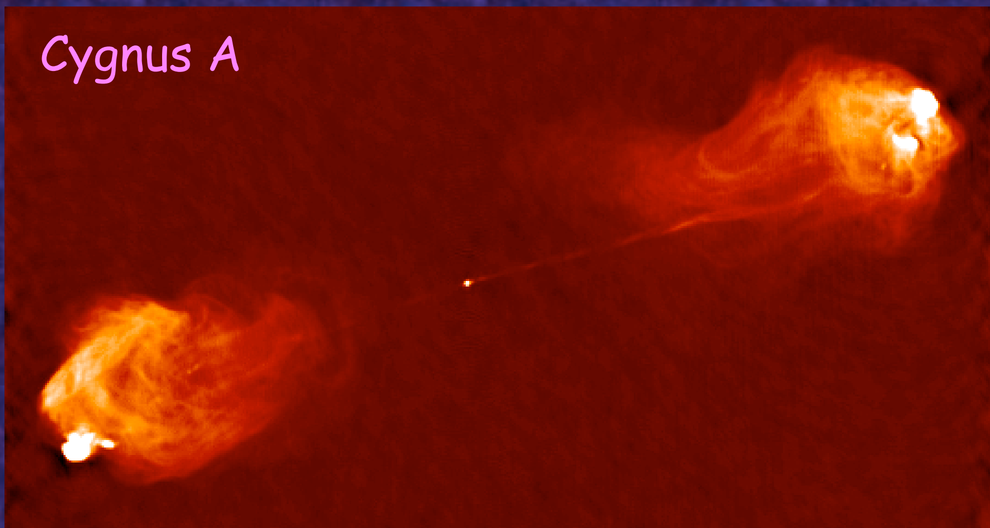
Fanaroff & Riley Class 2 (FR2)

- "edge brightened"
- high radio luminosity (above ~10^{25} W Hz^{-1} at 1.4 GHz)
- jets remain well-collimated, ending in bright hotspots.
- optical host can be quasar or galaxy
- galaxy hosts often have evidence for hidden type-1 AGN



The FR2 radio source 3C223

Properties of FR2 radio sources



- Synchrotron emission
- Core & jets have a fairly flat spectrum and are Doppler-boosted in quasars
- Lobes are steep spectrum and emit isotropically

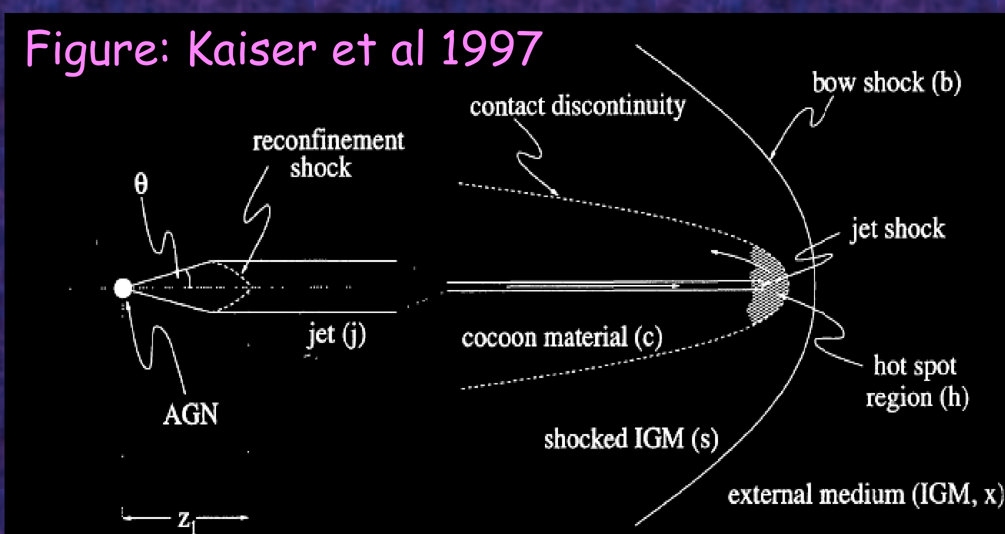
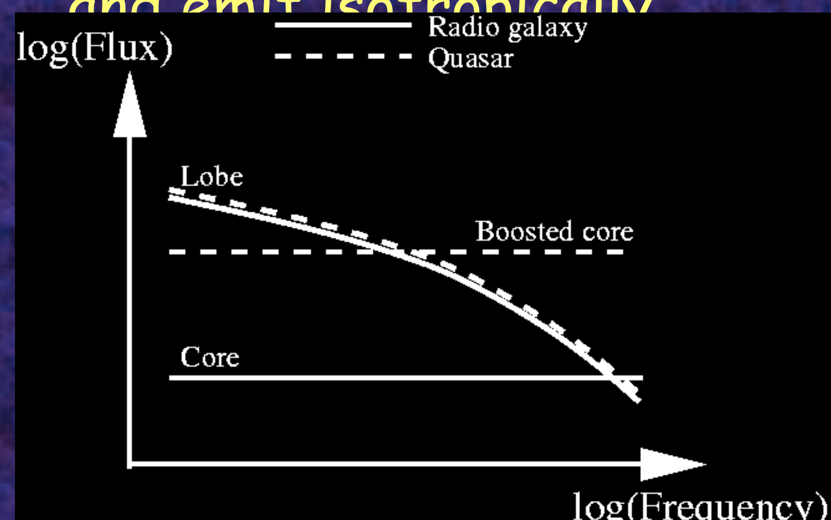


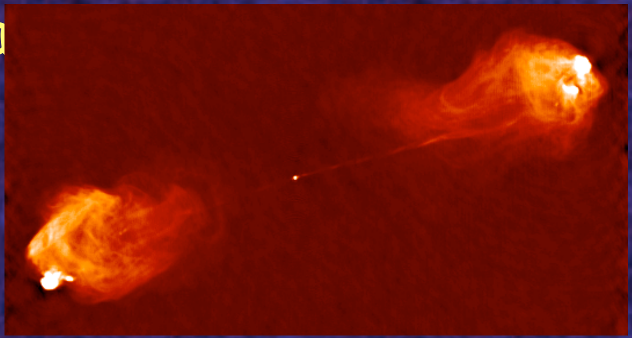
Figure: Kaiser et al 1997



Advantages of radio samples

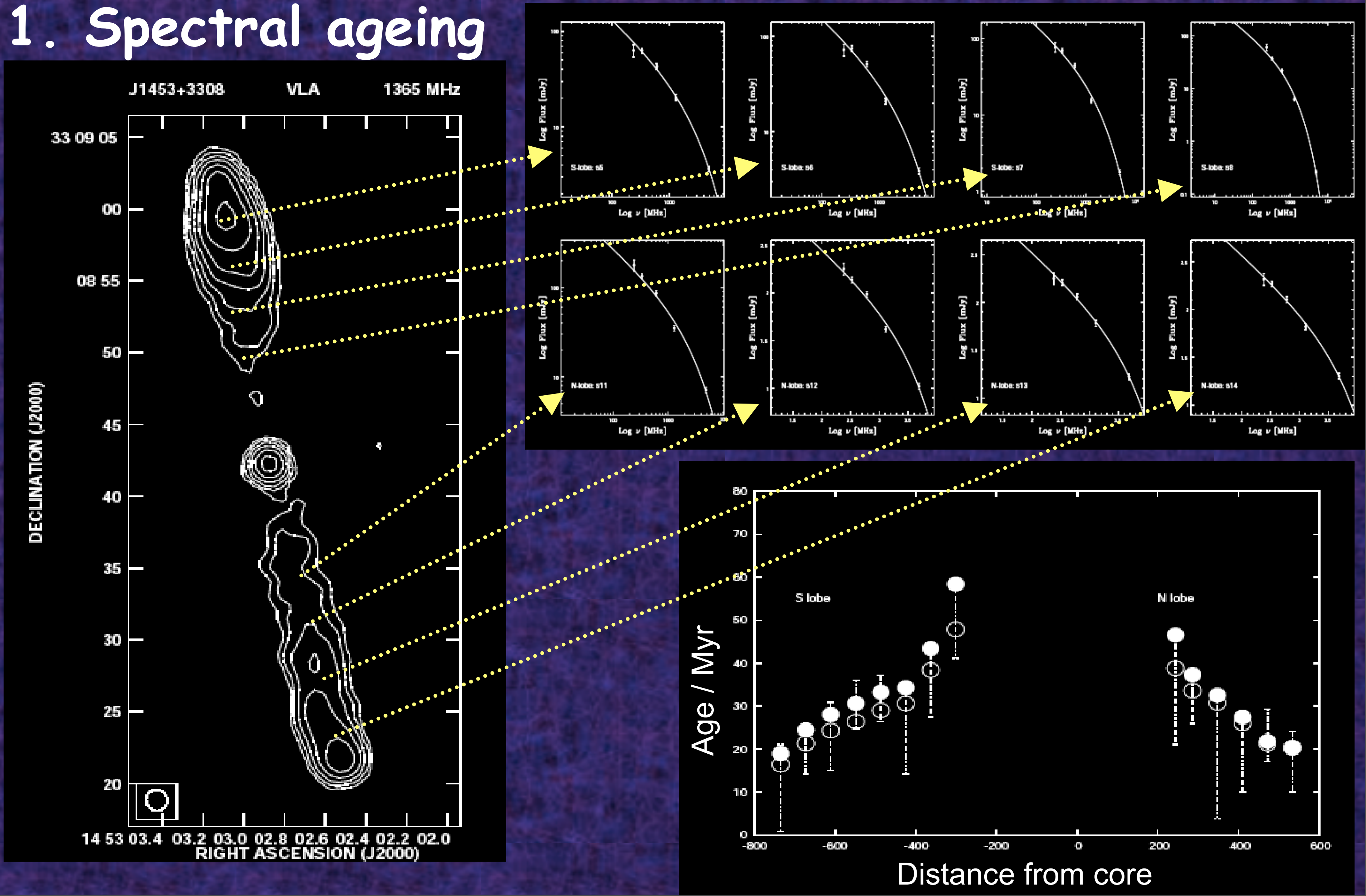
Radio sources have a number of advantages for studying obscured AGN activity:

- Low frequency samples selected isotropically
- Easy to locate and study Type-2 objects, out to the highest redshifts
- Radio source activity gives informa obtain by other means) on:
  - jet axis (accretion) stability
  - AGN lifetime
  - AGN duty cycle



Age-dating radio source activity:

1. Spectral ageing



Age-dating radio source activity:

2. Direct measurement of hotspot advance

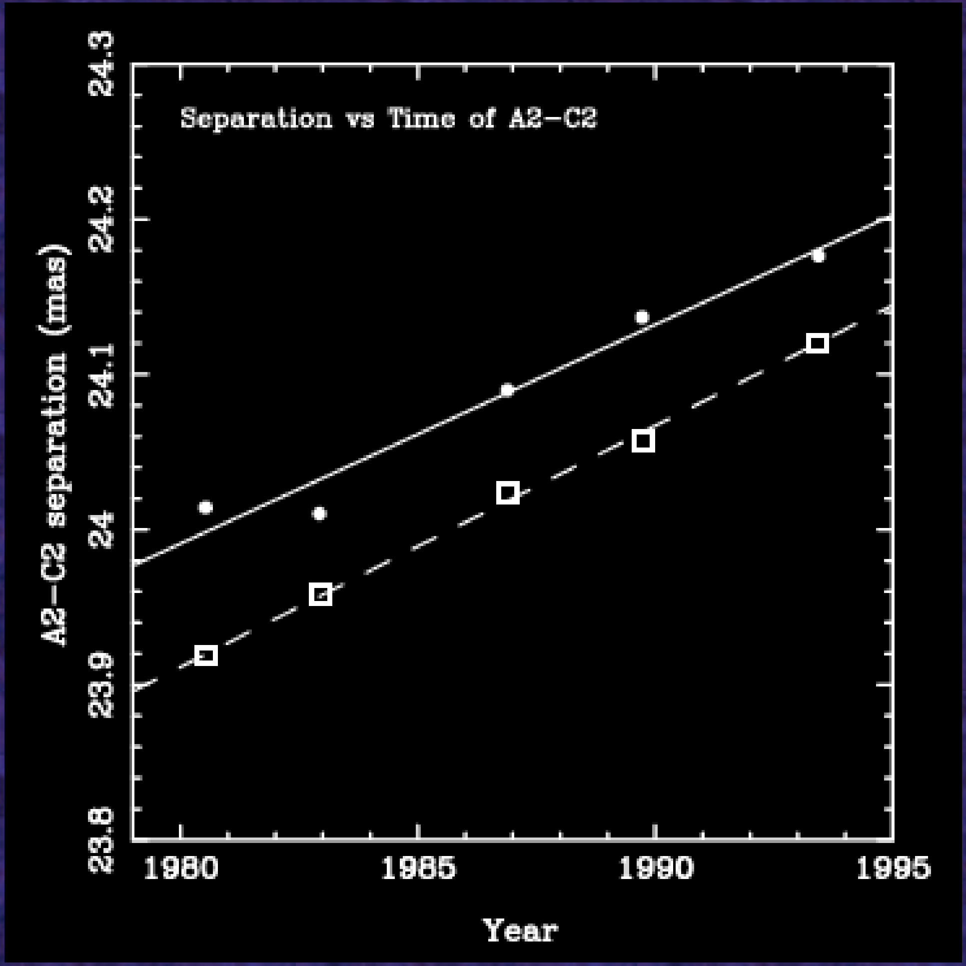


Figure: Owsianik & Conway (1998)

- Use VLBI techniques to get sub-milliarcsec resolution
- Measure directly the expansion of the smallest radio sources over time

⇒ Hotspot advance speeds of ~0.2c. Ages of some sources < 10^3yr

⇒ AGN lifetime 10^7-10^8 yr.

AGN duty cycle

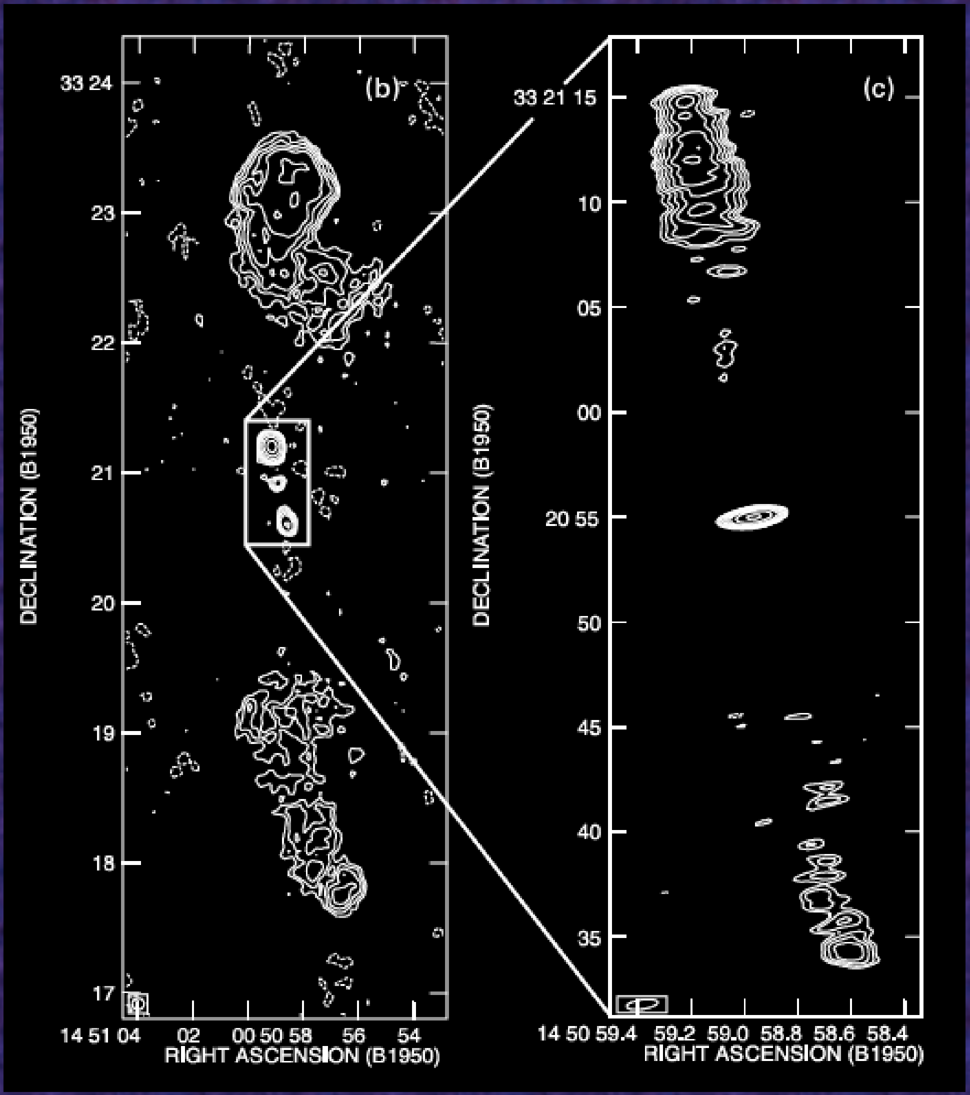


Figure: Schoenmakers et al. (1998)

- "Double-double" radio sources:
  - giant (10^8 yr) radio sources
  - 2^{nd} outburst age few Myr.
  - jet axis unchanged

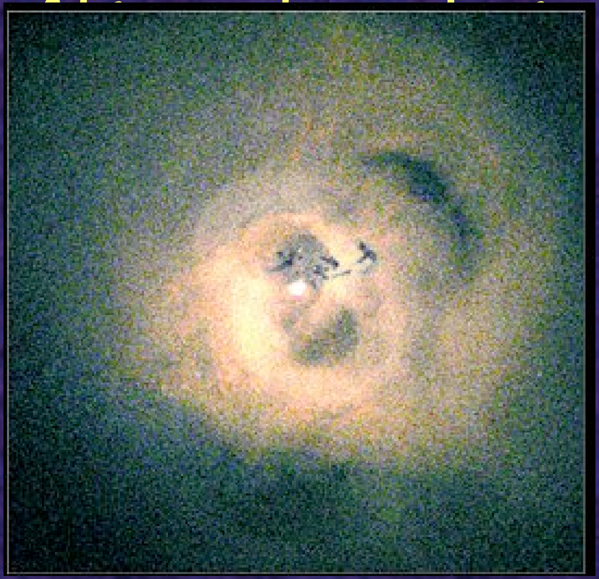
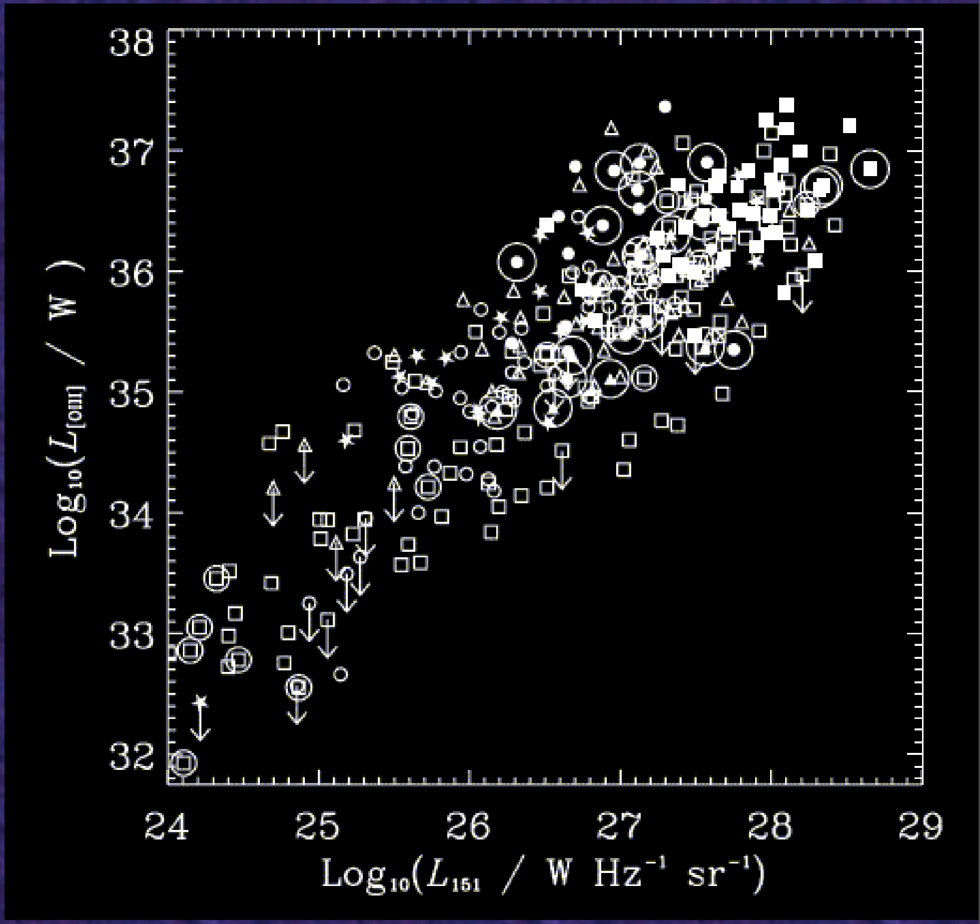


Figure: Perseus Cluster (Fabian et al 2003)

Unified schemes & radio sources

Much evidence for unification of FR2 radio gals & quasars

- Common ionising source
  (e.g. Rawlings & Saunders 1991)
- Relative numbers and radio size distributions
  (e.g. Barthel 1989)
- Depolarisation asymmetry
  (Laing-Garrington effect)
- Core boosting, arm-length asymmetries, jet sidedness
- Ionisation cones
  (Cygnus A; Fosbury et al. 3C265;



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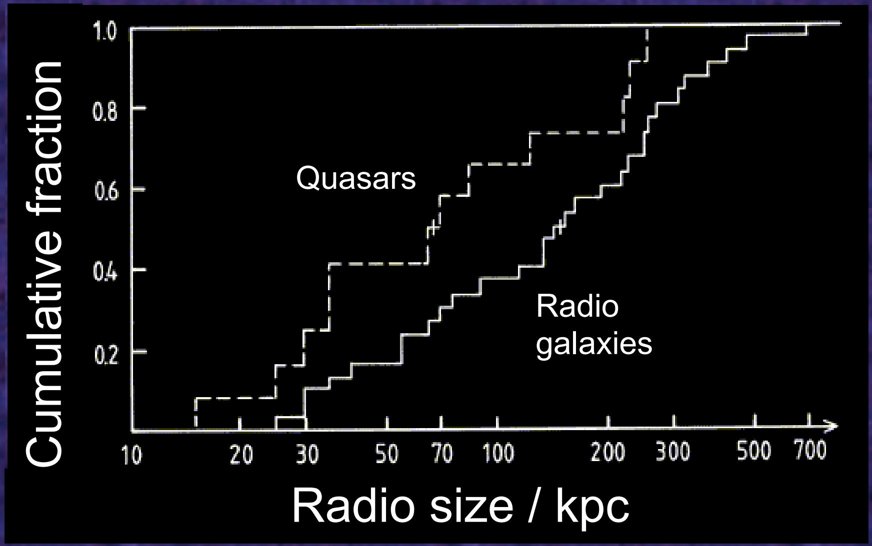

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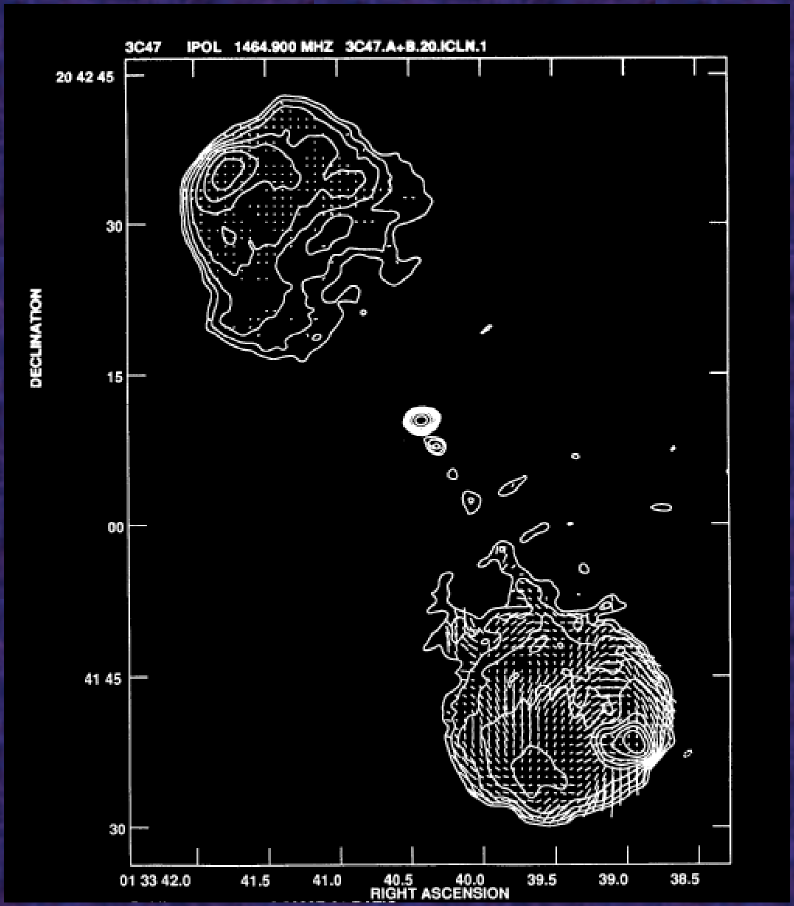

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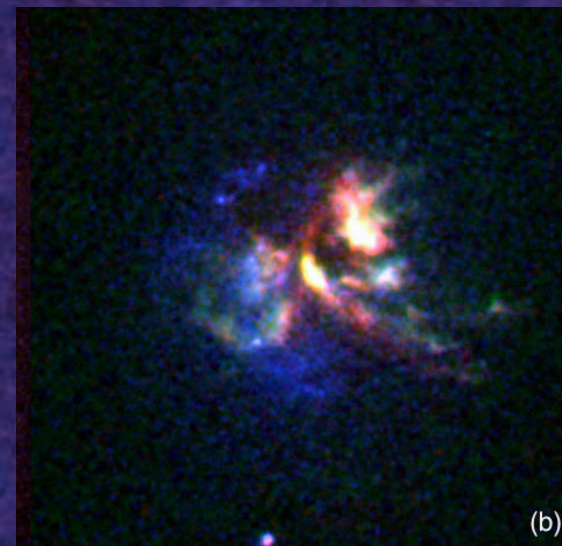

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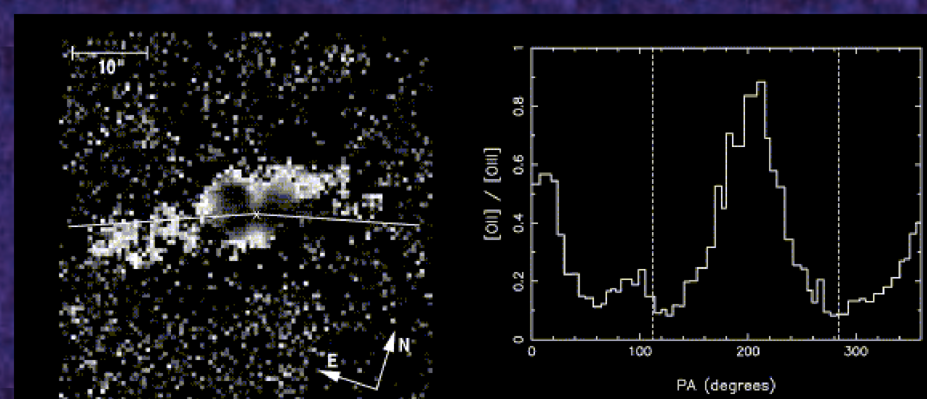

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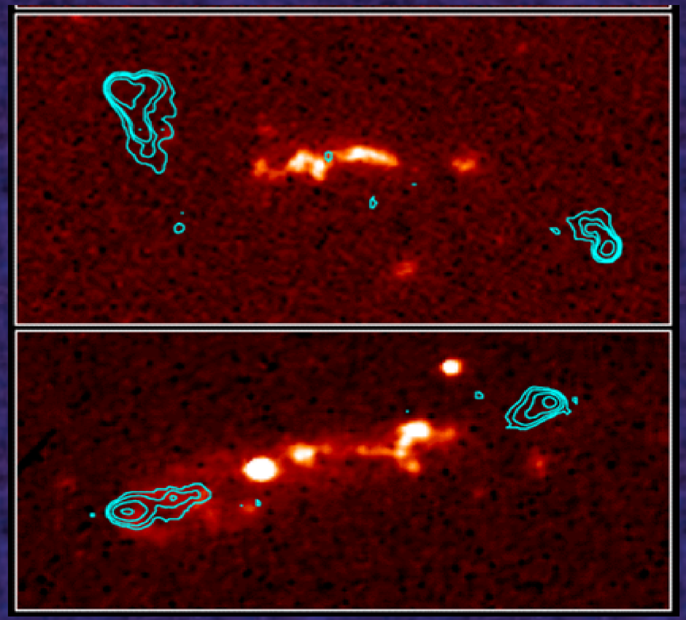
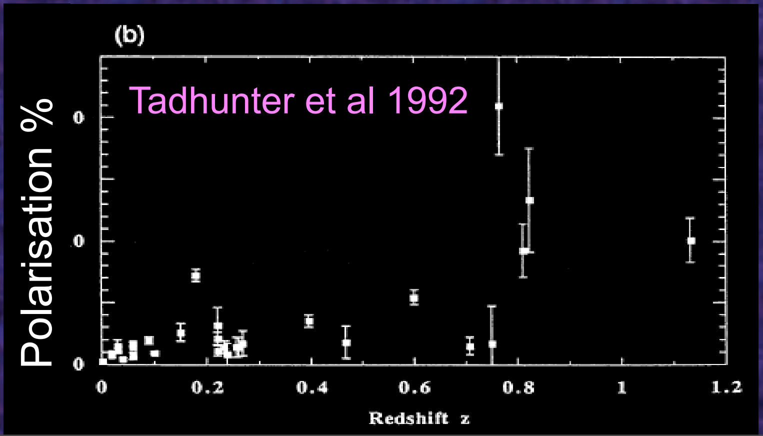


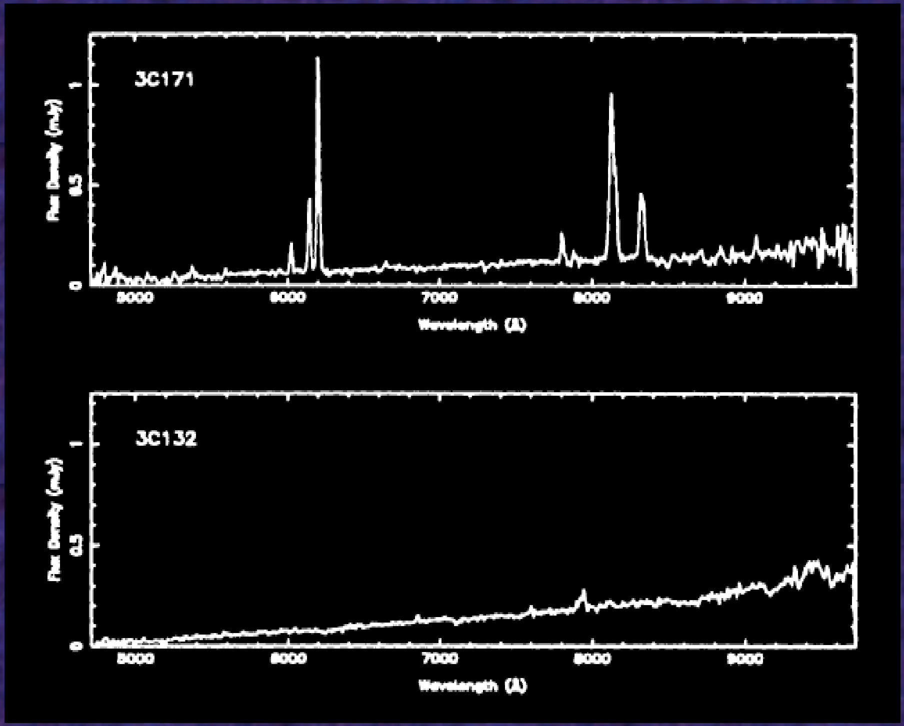


Low excitation FR2 radio sources

A proportion of FR2 radio sources were found to have very different emission line properties:

- Very weak emission lines
- Low excitation spectrum

More like FR1s. Not part of unification scheme?



Spectrum of a low excitation FR2 radio source (Laing 1994)

Low excitation FR2 radio sources

A proportion of FR2 radio sources were found to have very different emission line properties:

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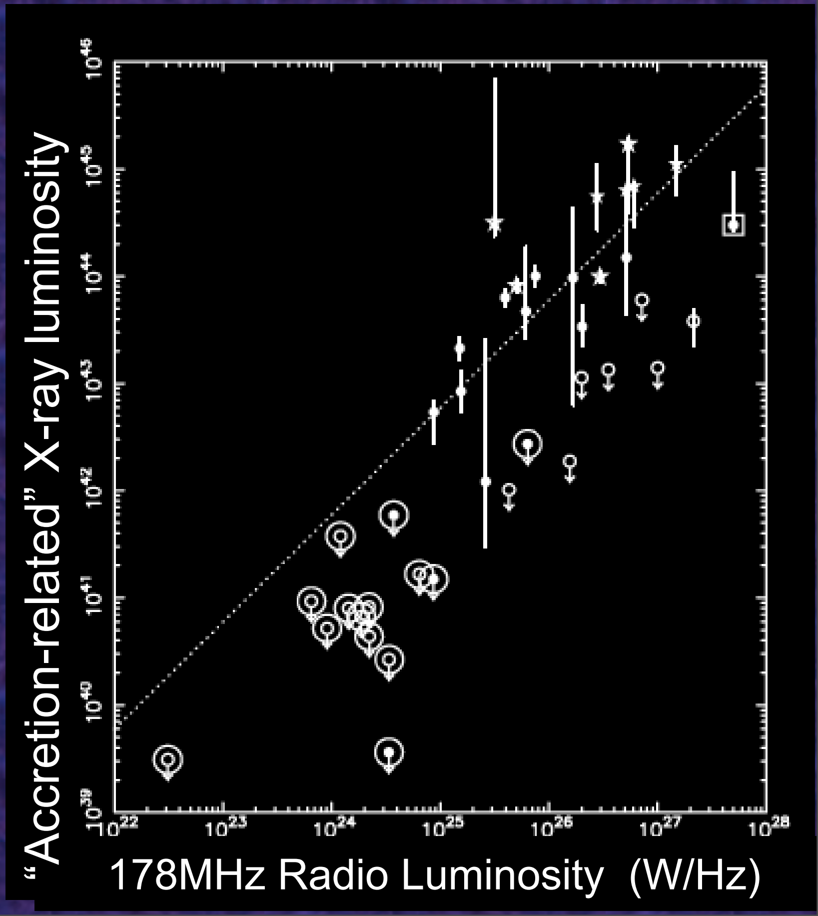
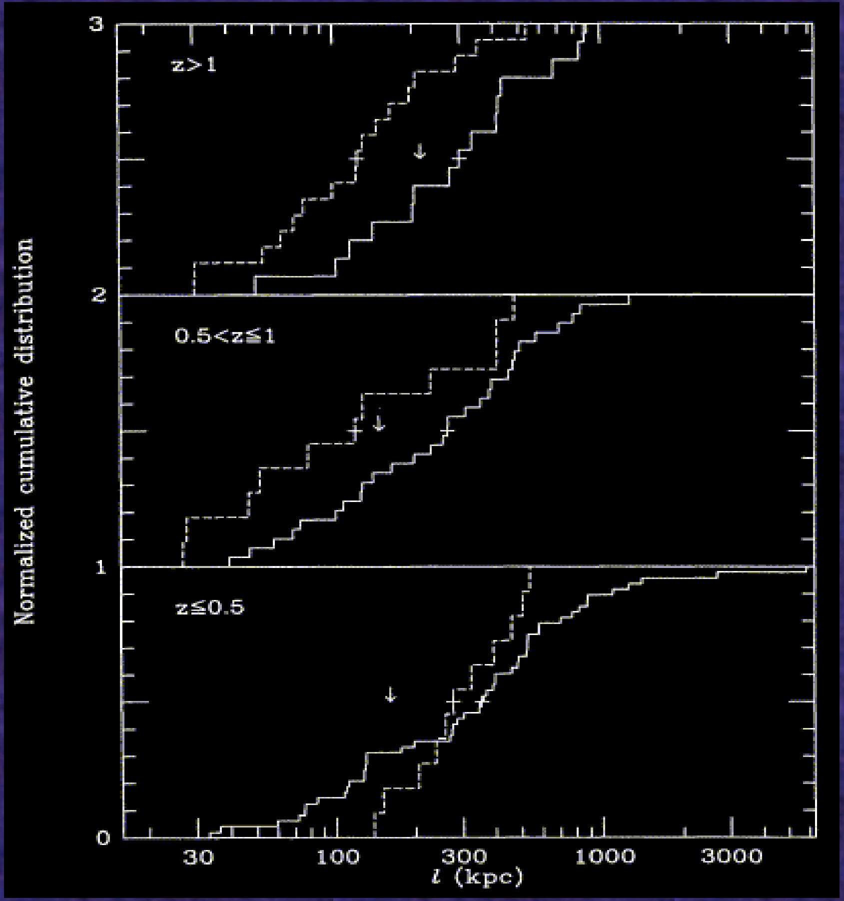
More like FR1s. Not part of unification scheme?

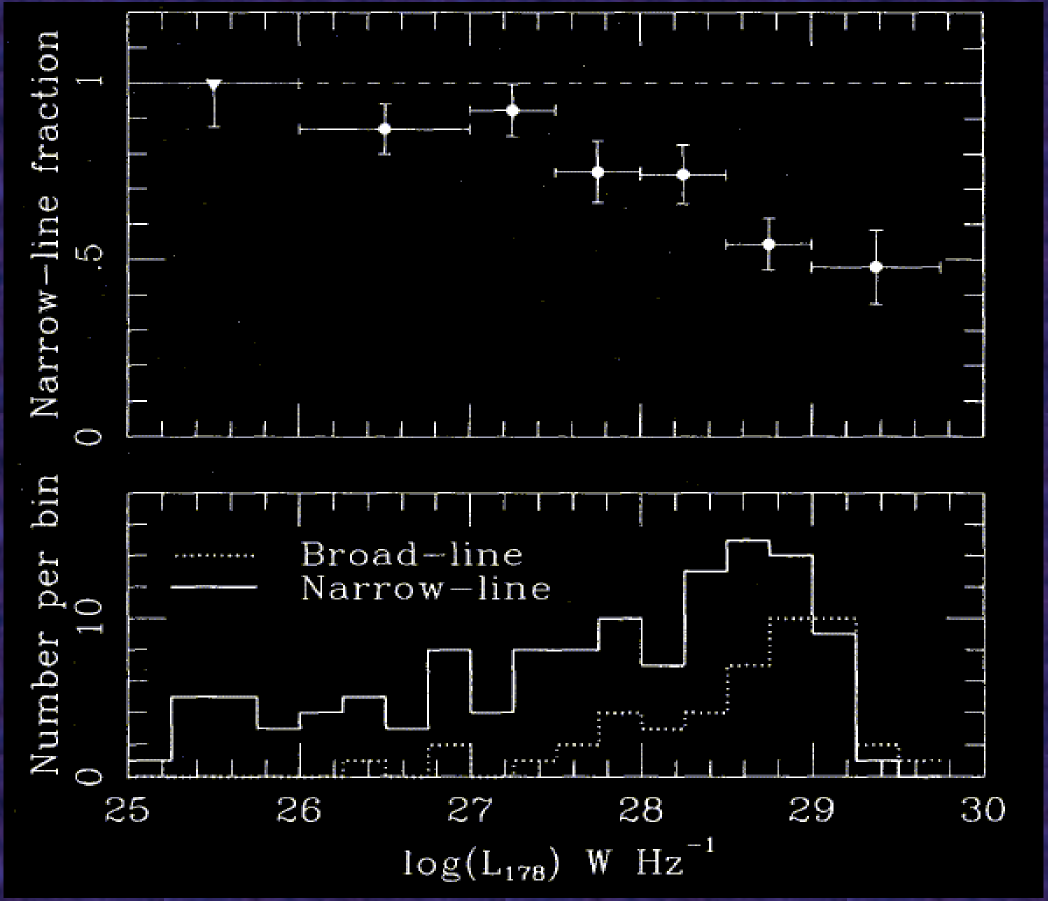
Also no evidence of quasar nucleus at X-ray wavelengths

e.g. Hardcastle et al 2006: figure is (corrected) L_x of the highly-obscured (accretion-related) component of X-ray nucleus vs L_{178}; solid = high-excitation;



Unification complications



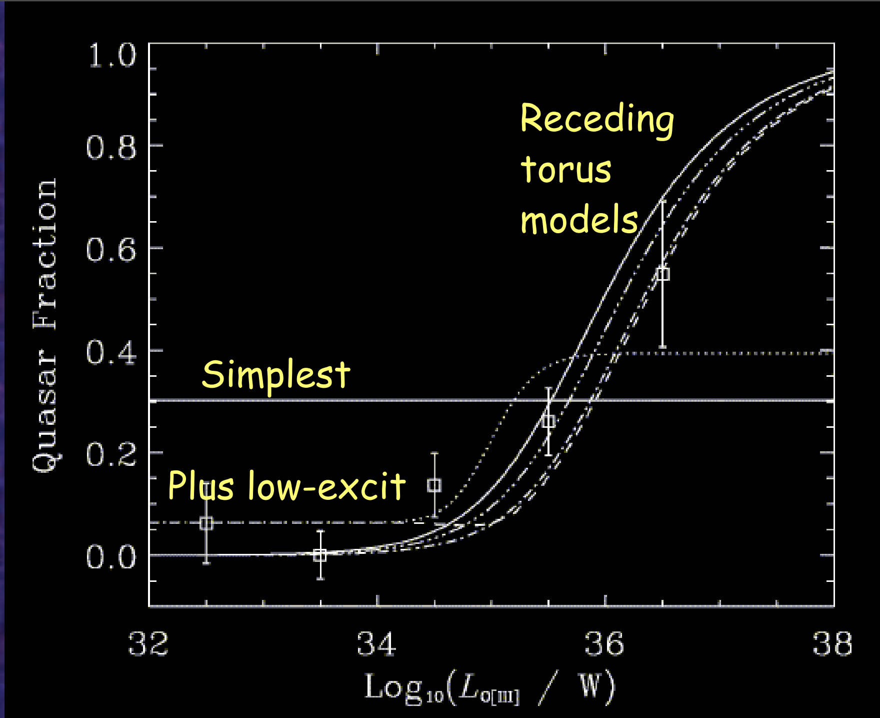


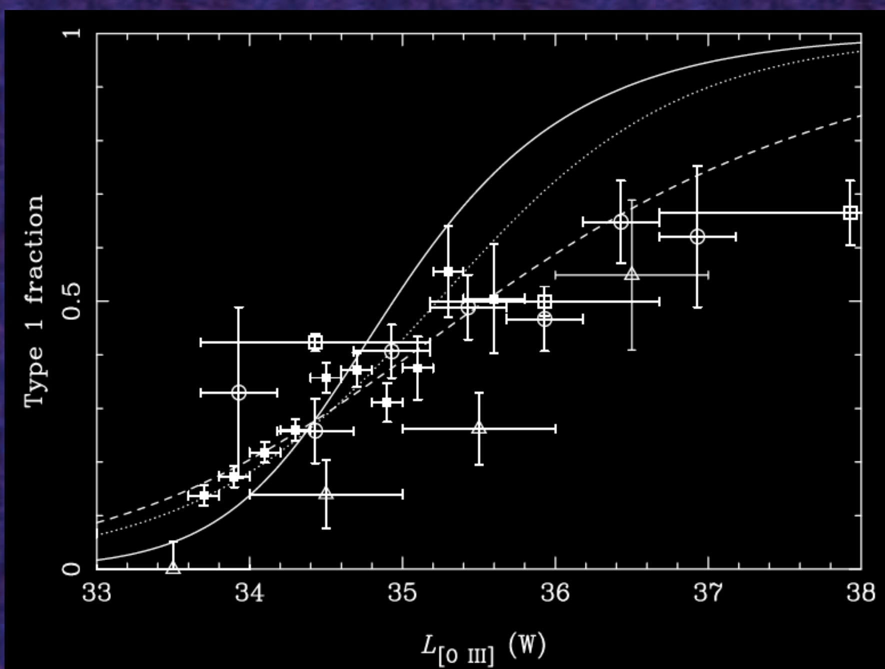
Relative radio size distribution varies with redshift (Singal 1993)

Type-2 fraction varies with radio luminosity (Lawrence 1991).

⇒ Receding torus model? [$\theta_{div} \propto \tan^{-1}(h/r_{in})$ where $r_{in} \propto L^{0.5}$]

Simple unification without low-





- Quasar fractions from current radio samples are consistent with either receding torus models or simple unification after removing low-excitation sources, with f_Q ~ 0.4.
  (e.g. Grimes et al 2004; top figure)
- Optically selected AGN also suggest simplest receding torus models don't work but more advanced models can work
  (e.g. Simpson 2005; lower figure)

Cosmic evolution of radio sources

1. The local radio luminosity function

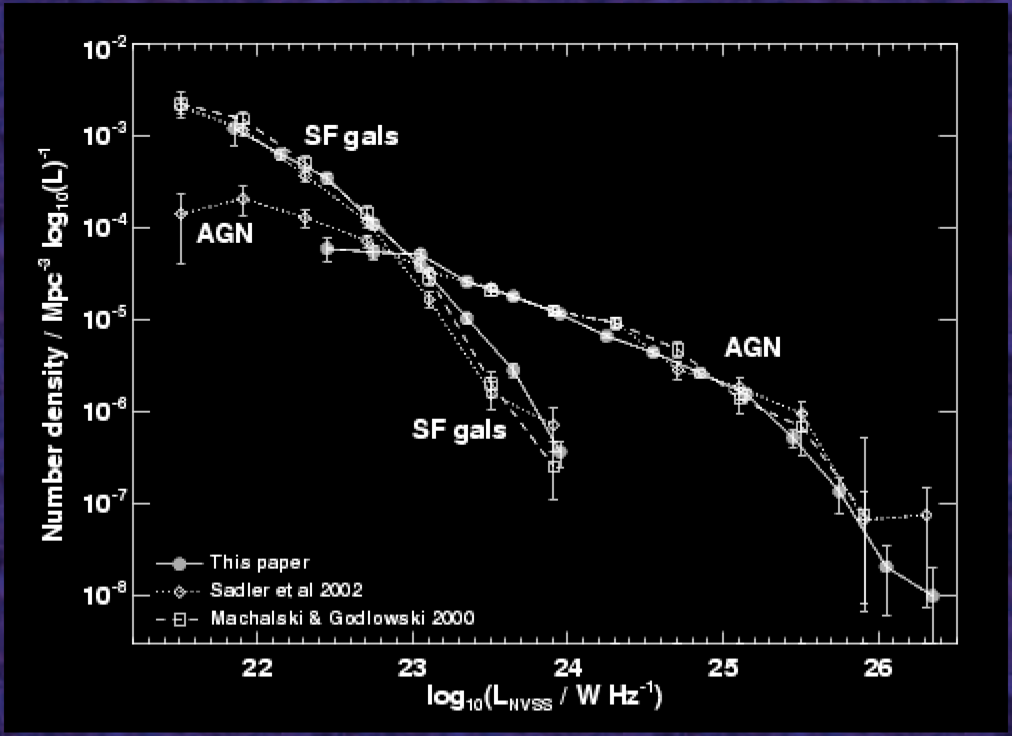
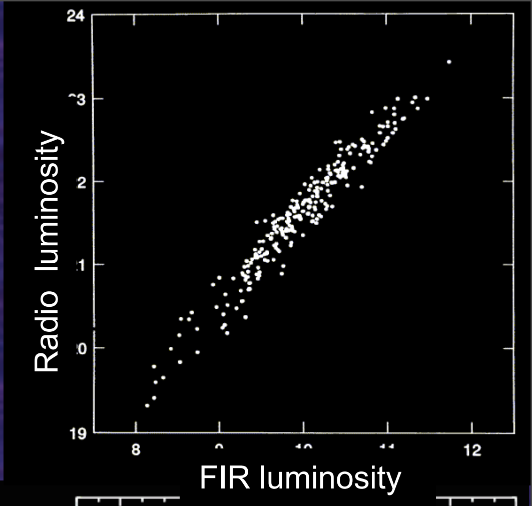


Figure: local radio luminosity function of star-forming galaxies and AGN; from SDSS (Best et al 2005).

- Local radio population comprises AGN and star-forming galaxies
- AGN dominate above $L_{1.4GHz} \sim 10^{23}$ W/Hz
- Luminosity function of AGN generally fit with broken power-law:

$$\rho = \rho_0 \left\{(L/L_*)^{\alpha} + (L/L_*)^{\beta}\right\}^{-1}$$

AGN-SF separation



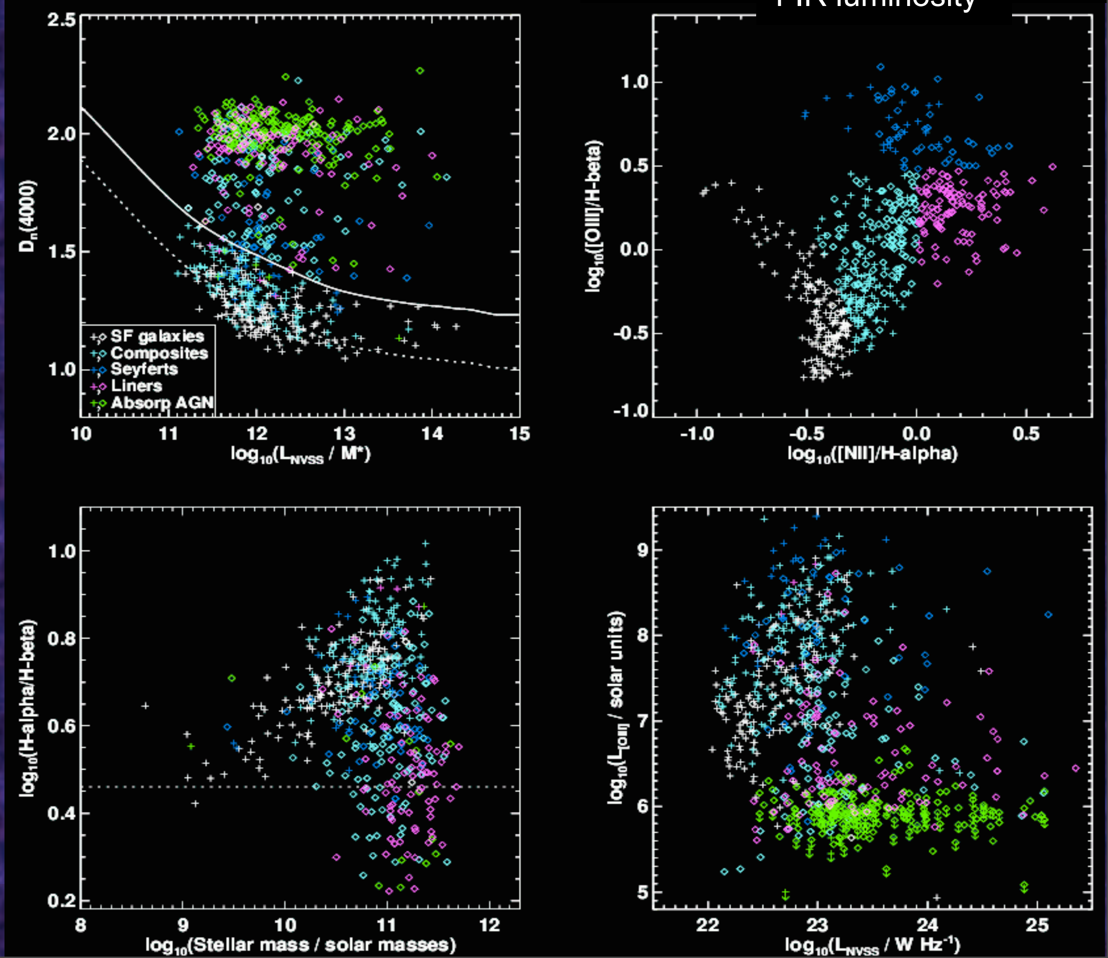
Ideally, identify AGN as being offset from the radio-FIR correlation.

(Top figure: Condon 1992)

However, normally FIR data too shallow.

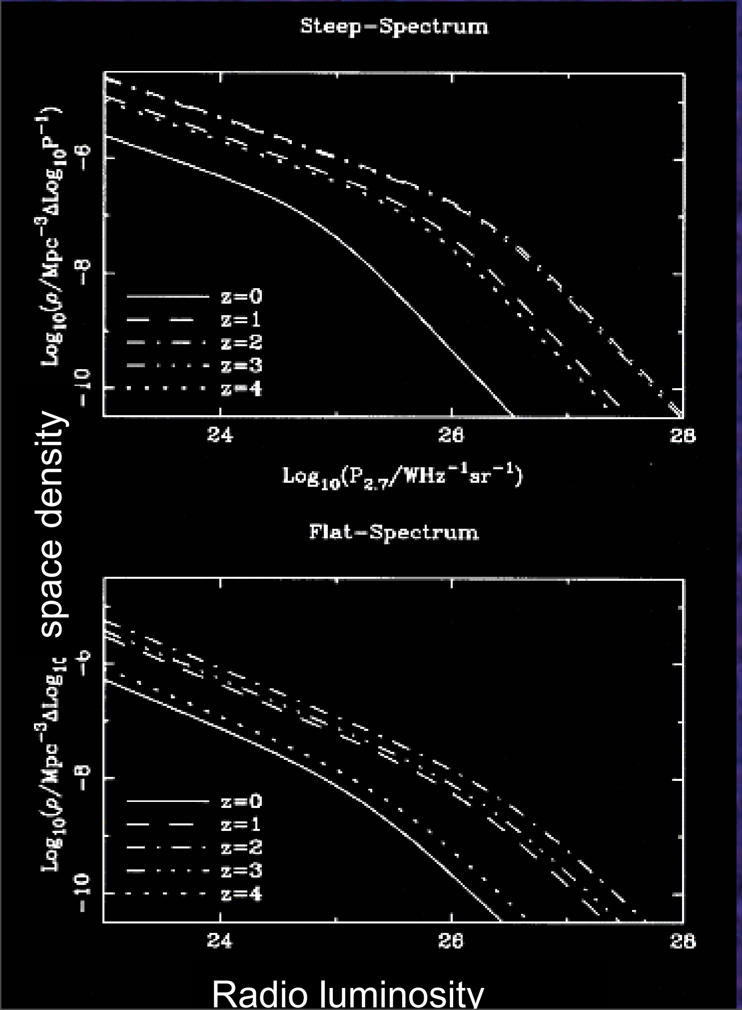
Alternatively:

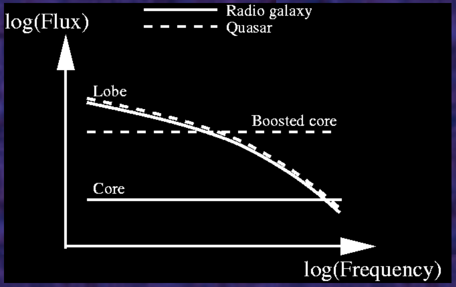
- optical/radio flux ratio
- emission line strength
- emission line diagnostics
- stellar mass & 4000Å break strength



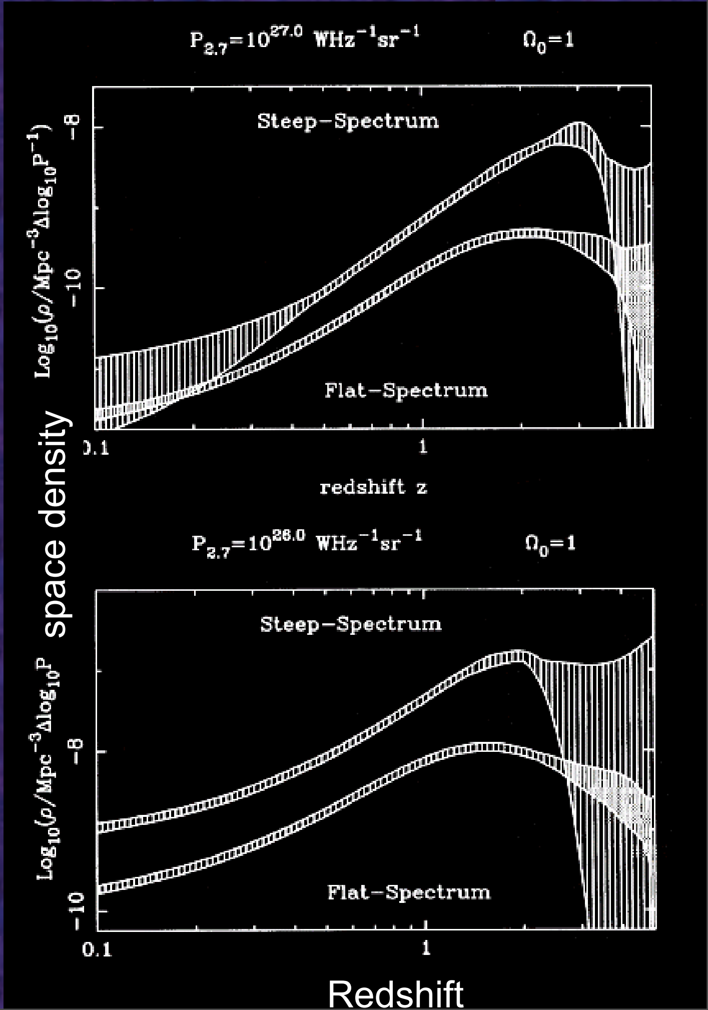
Radio luminosity function evolution

Strong evolution of RLF out to z~2. Cut-off at higher z?





Figures from work of Dunlop & Peacock (1990)



Luminosity-dependent low-z evolution

Radio source number counts indicated in the 1960's that high luminosity sources evolve strongly but low luminosity sources less so or not at all.

More detailed studies confirm this (e.g. see right).

Often assumed that FR2s are an evolving population and

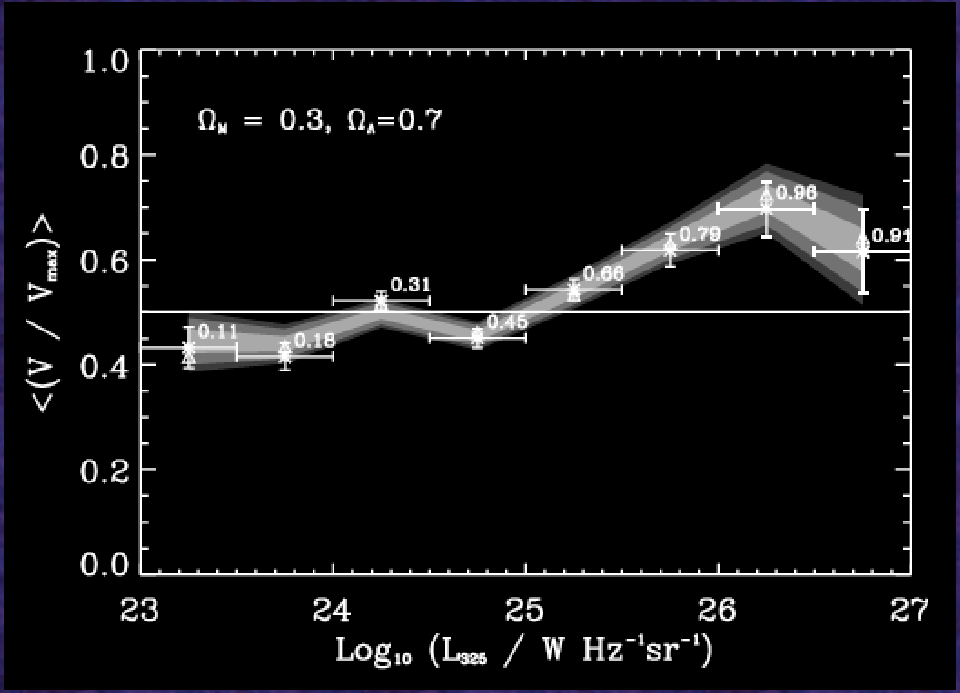


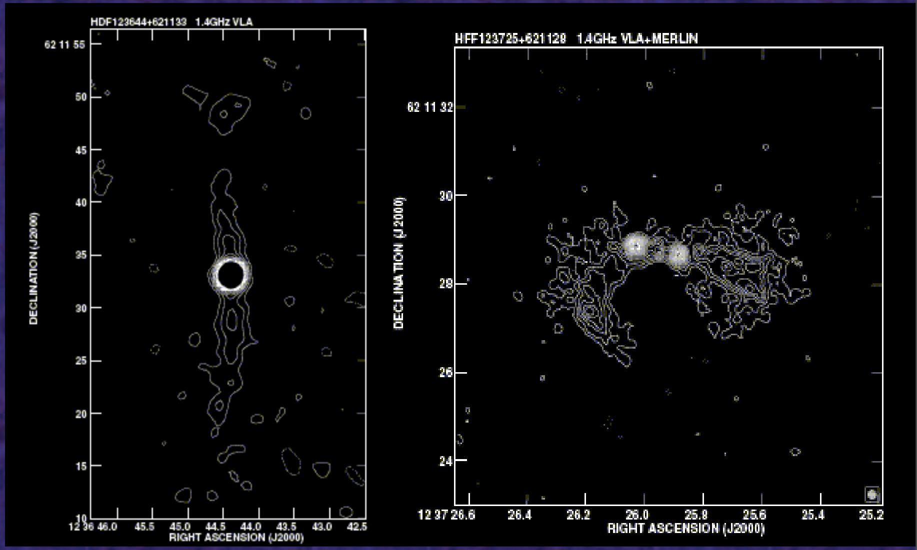
Figure: V/V_{max} test for radio sources selected from SDSS (from Clewley & Jarvis 2004).

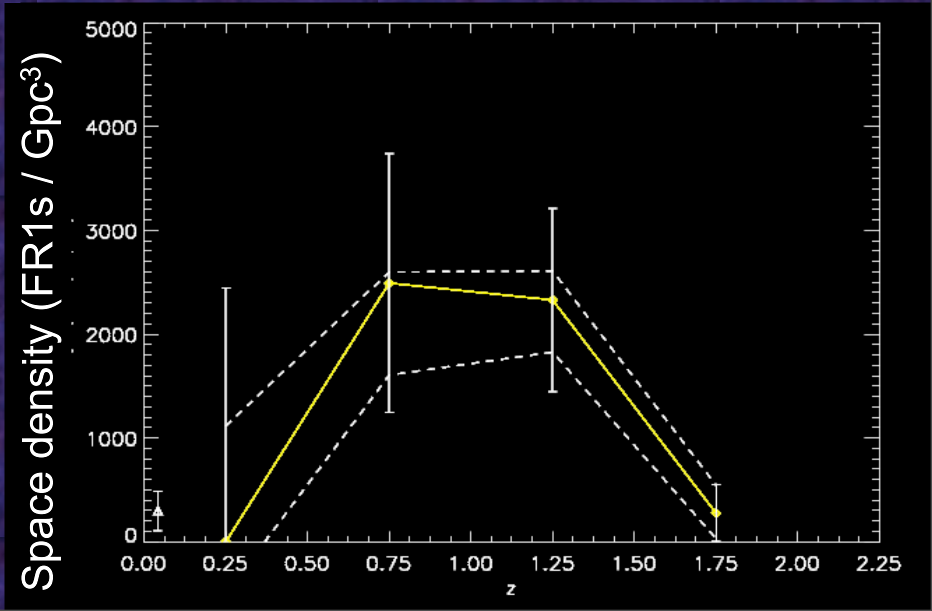
$\langle V/V_{max} \rangle = 0.5$ means no evolution;

Cosmic evolution of FR1s

- Snellen & Best (2001) identified 2 z>1 FR1s in the Hubble deep & flanking fields (upper figures) rejecting no evolution at the >99% level.

- Rigby et al (in preparation) have extended this study by factor ~20, and measure a factor 3-10 increase in the space density of luminous FR1s to z~1 (lower figure).





High redshift evolution:
P-z coverage and spectral index issues

Problems with determining

the high-z evolution are:

- Flux-limited samples don't sample same luminosities at all redshifts (L-z correlation).
- Calculating rest-frame radio luminosity means correcting for spectral variations
- Calculating space density needs accessible volume for each source, hence need to know

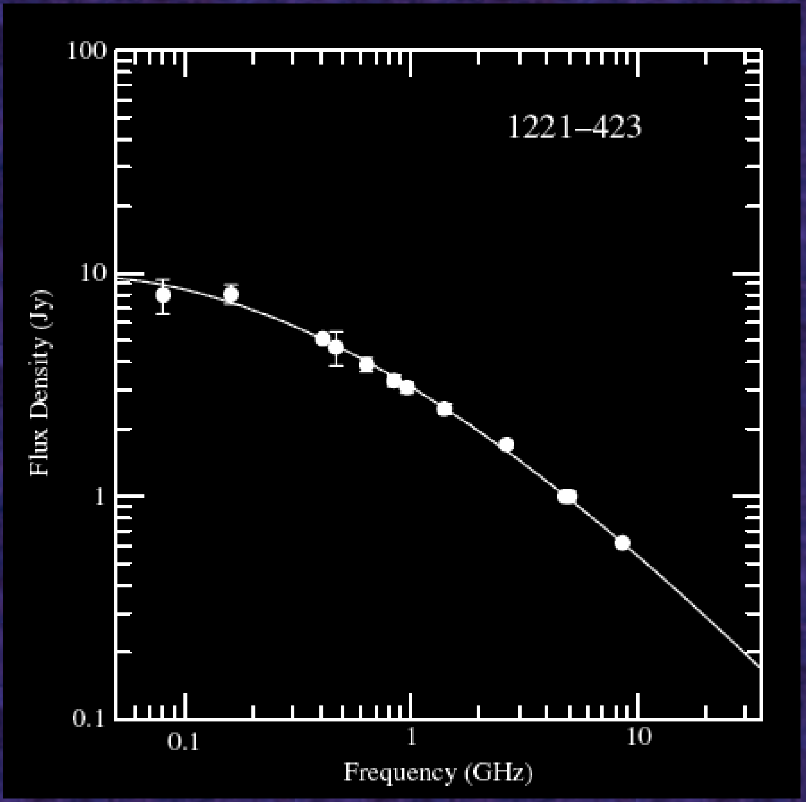
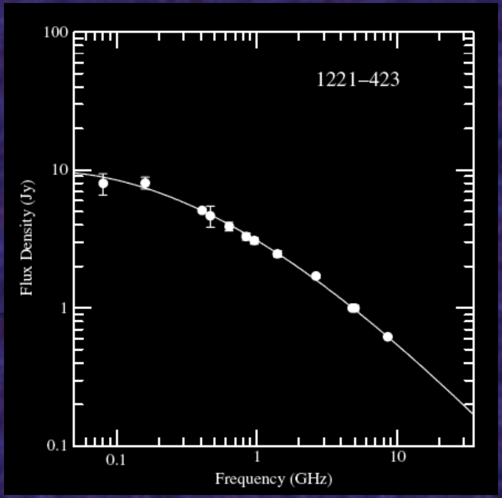


Figure: radio source spectra are typically curved.

Aside: Taking advantage of spectral curvature



- Spectral curvature is not all bad: it can help to pinpoint the highest redshift radio galaxies
  - select from large radio surveys those sources with the steepest spectral index.
- Not complete samples for luminosity function work, but great for host galaxy

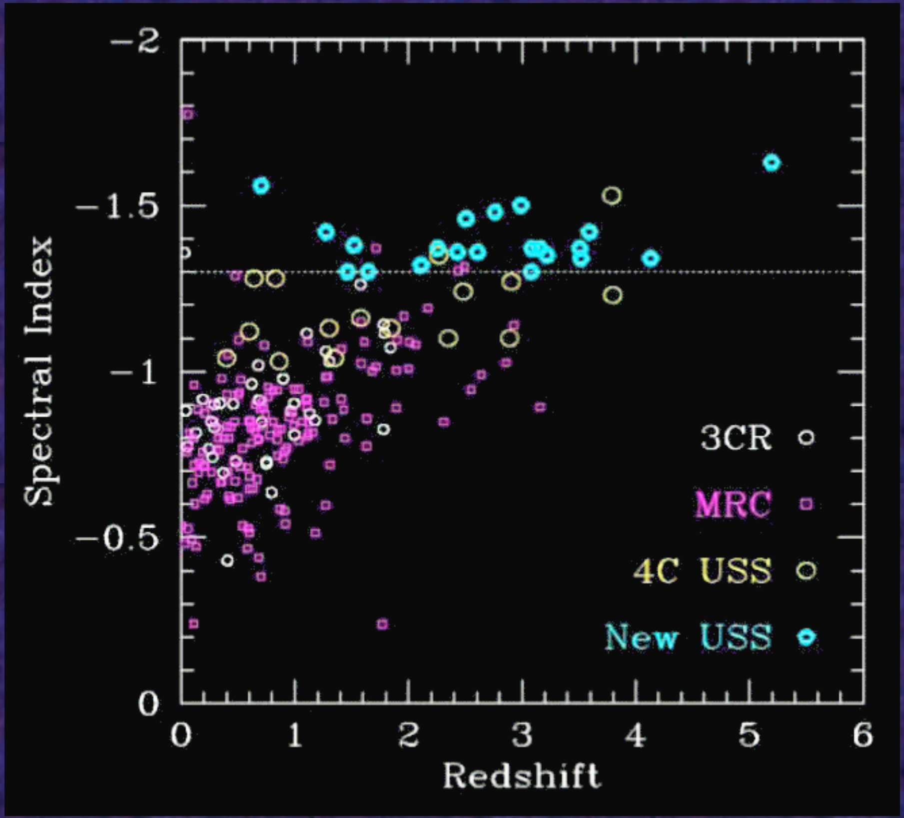
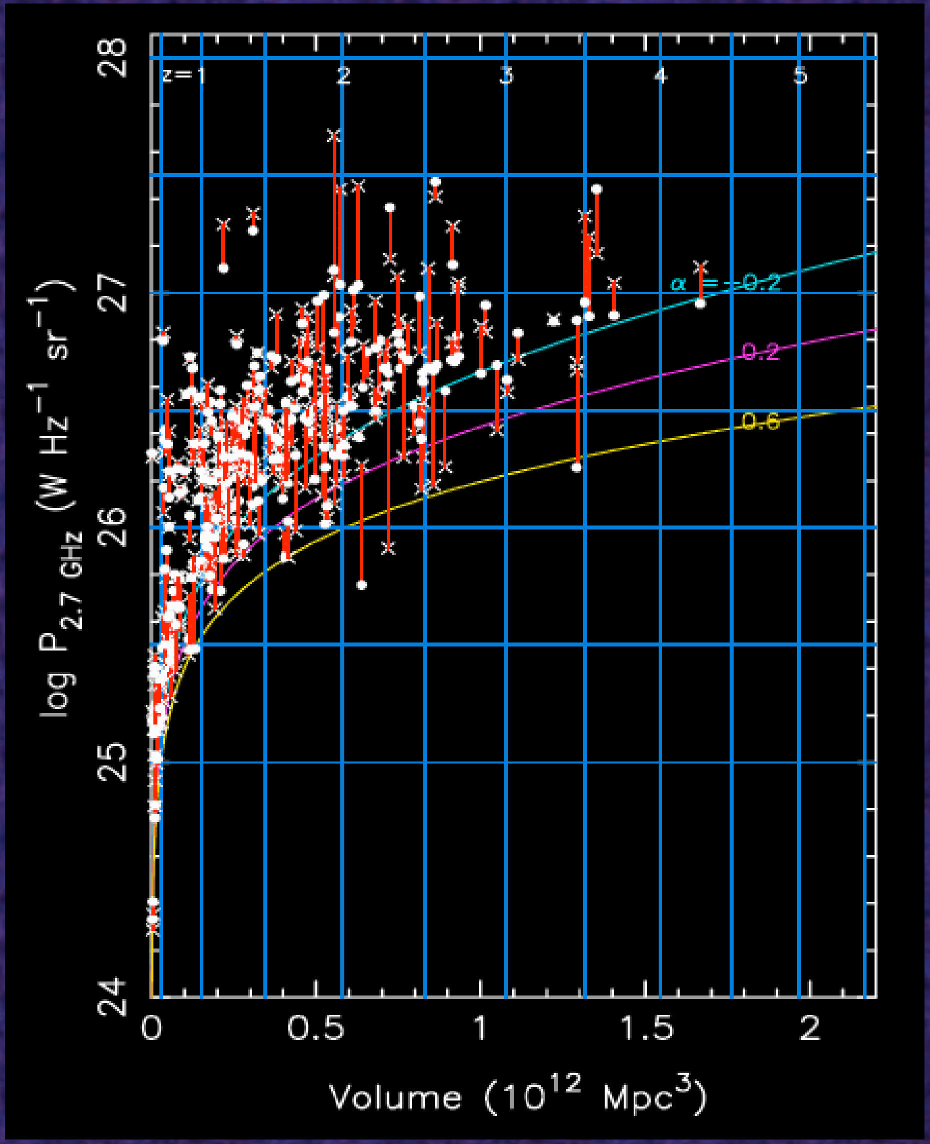


Figure: de Breuck et al 1998

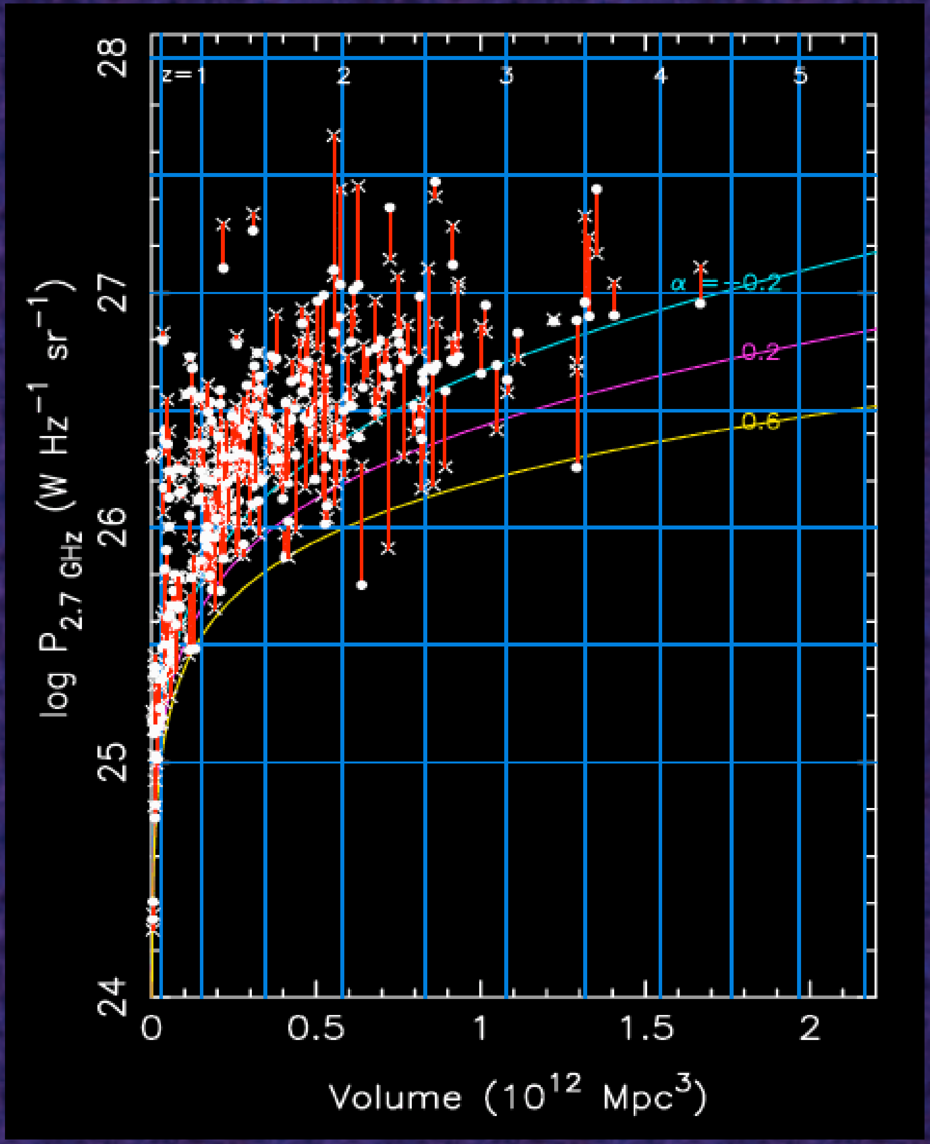
Evolution of flat spectrum sources

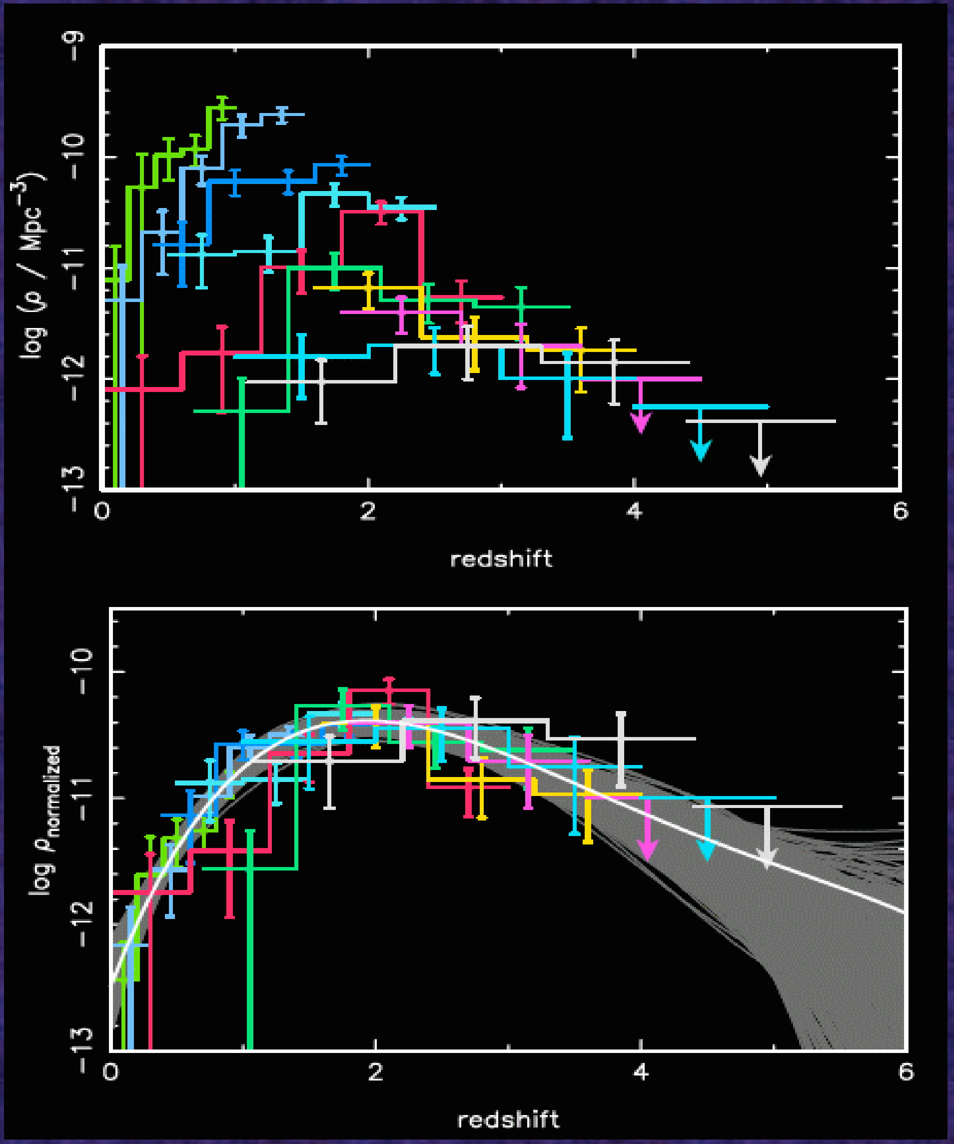


(From Wall et al 2005)

- Crosses are radio luminosity -estimates using standard (fixed) mean spectral index
- Filled circles are true radio luminosities calculated using observations at many frequencies
- To analyse, Wall et al ran Monte-Carlo simulations for other variables……

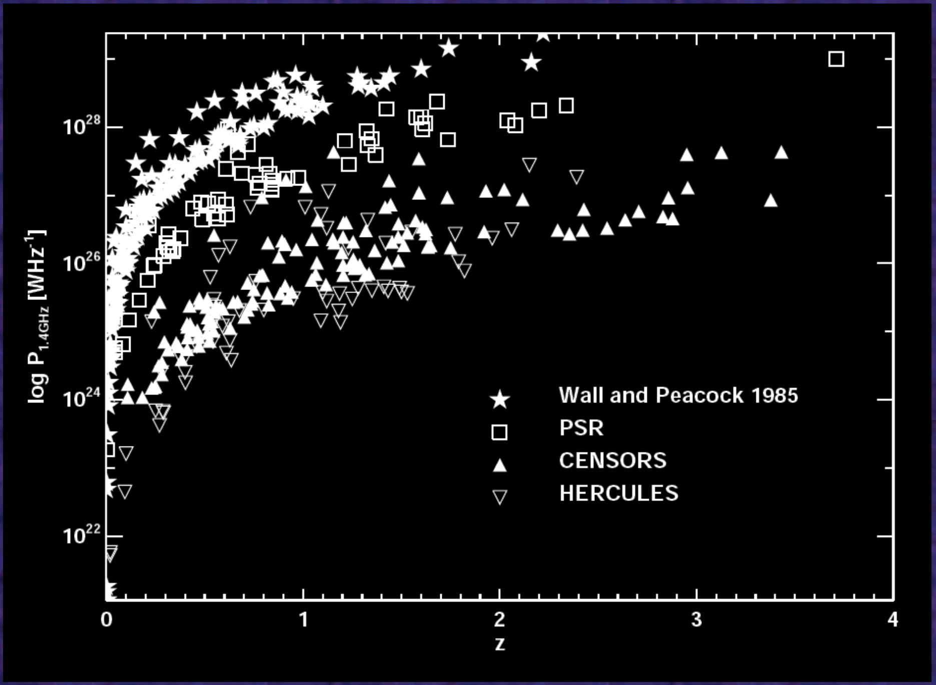
Evolution of flat spectrum sources

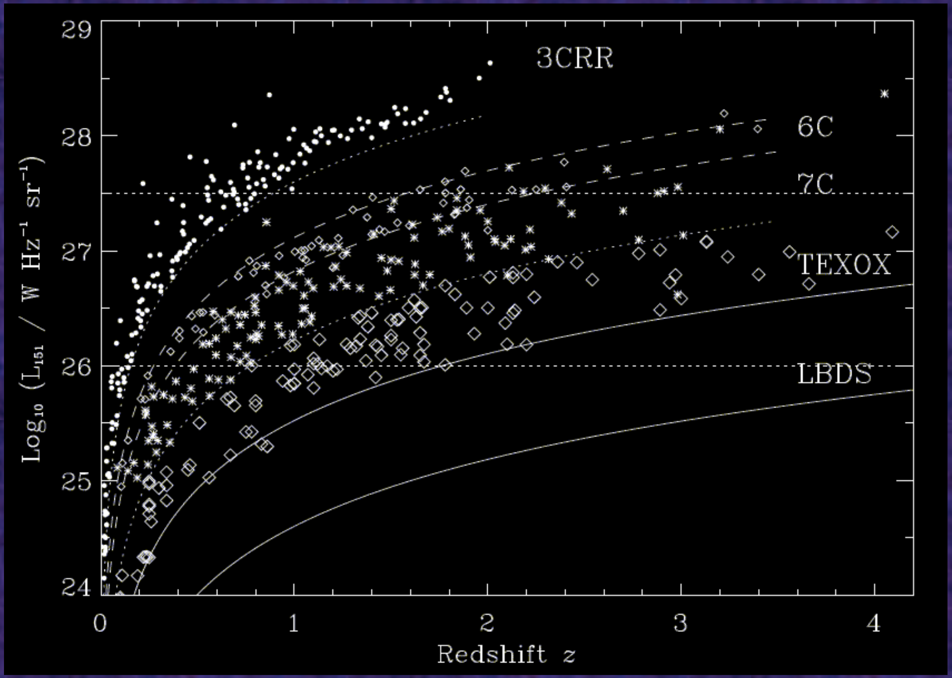




Evolution of steep-spectrum sources

Favoured approach is to combine multiple radio-source surveys to obtain more complete coverage of P-z plane. Different groups are progressively improving this.

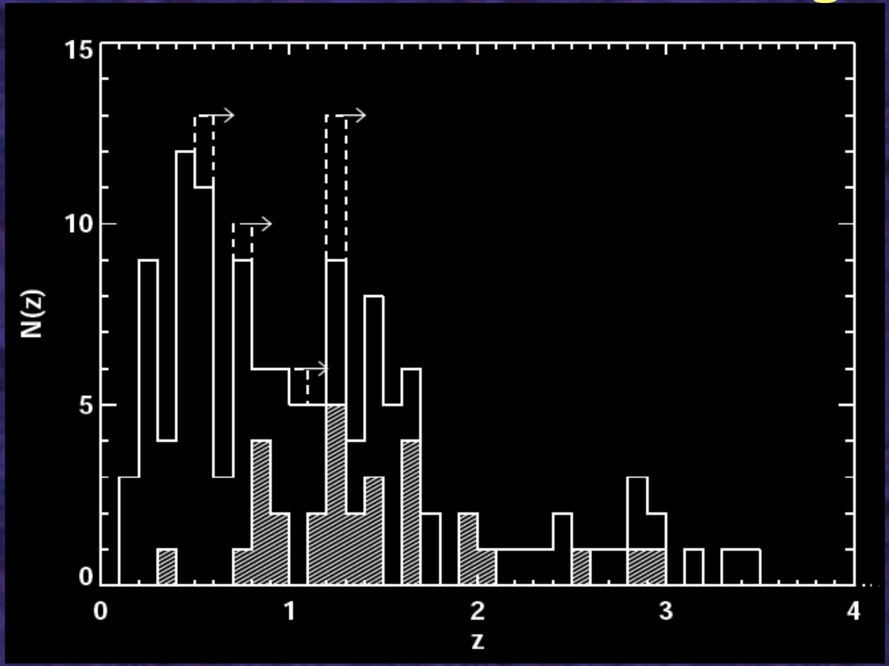


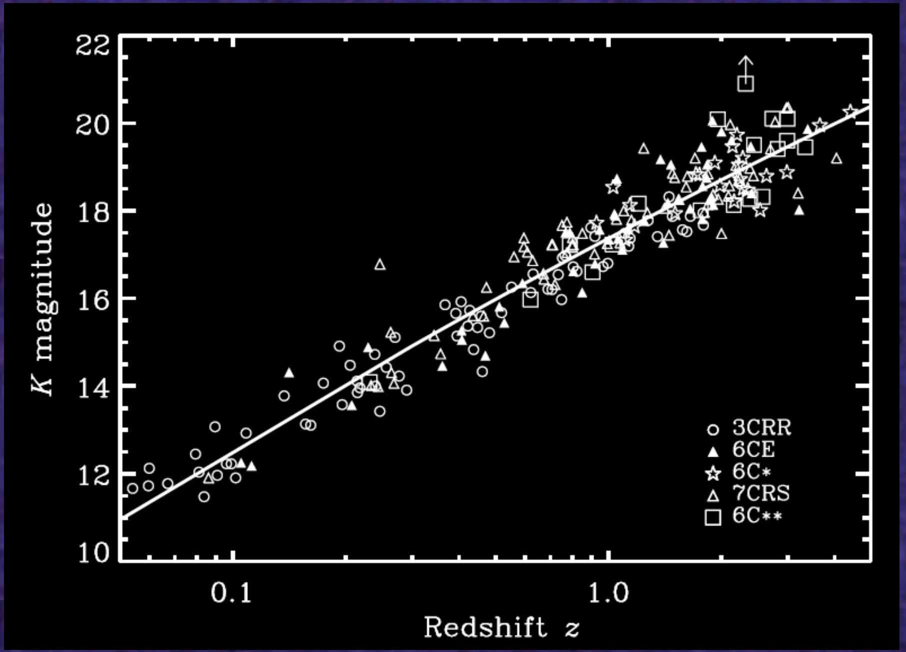


Figures: more complete P-z coverage produced by combining various radio source surveys. Left: CENSORS/WP85/PSR. Right: 3C/6C/7C/TOOT

CENSORS

- 150 radio sources, 6 sq deg, to 7.8mJy @ 1.4GHz
- Overlap of EIS Patch D and NVSS
- Work largely done by Jasper Arts (radio) and Mairi Brookes (IR imaging, spectroscopy, modelling)





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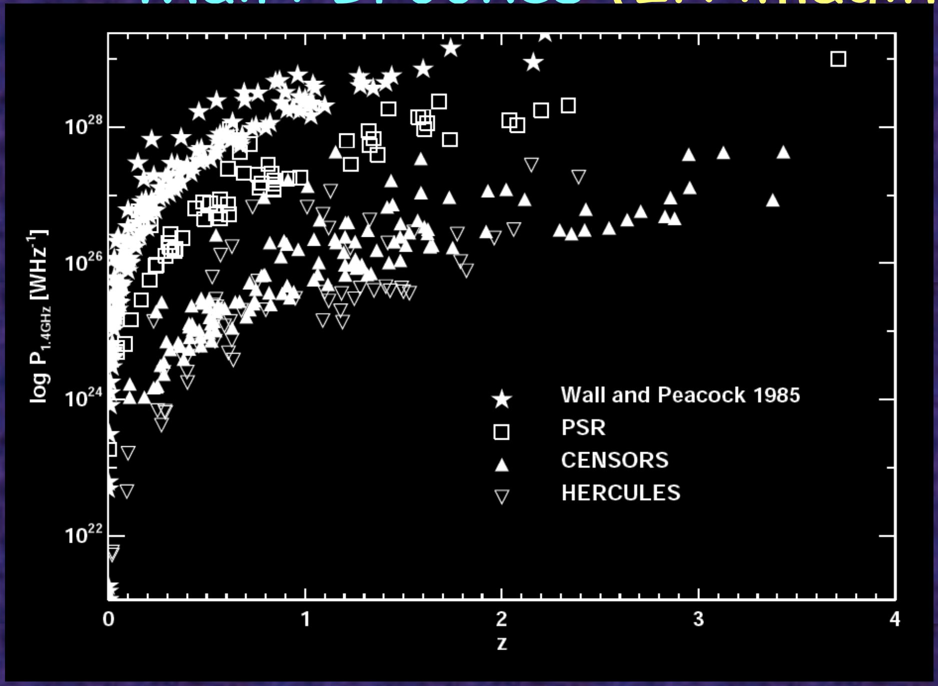
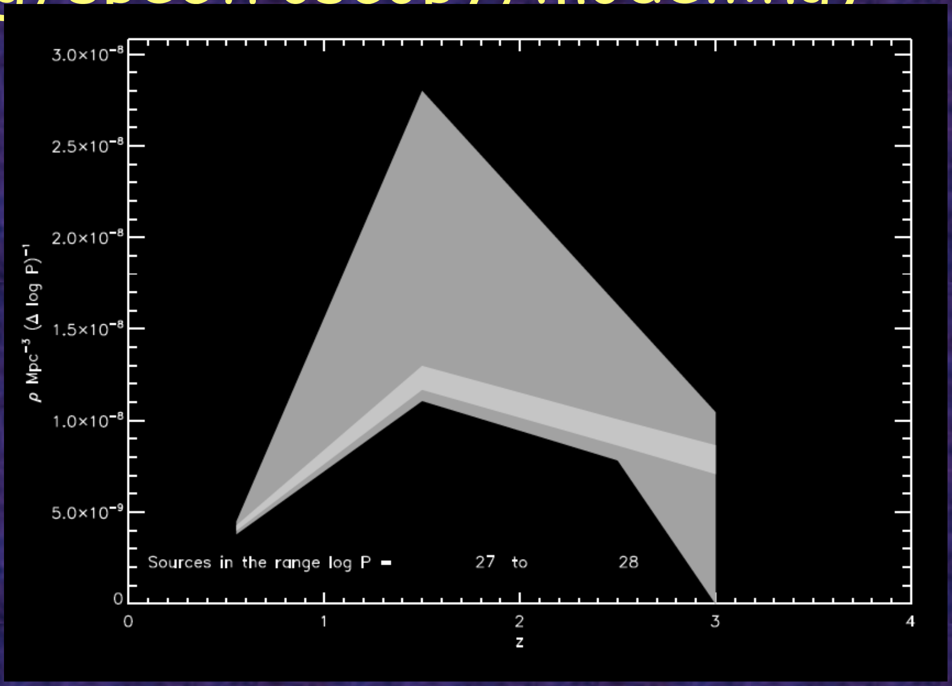
- Work largely done by Jasper Arts (radio) and Mairi Brookes (IR imaging, spectroscopy, modelling)

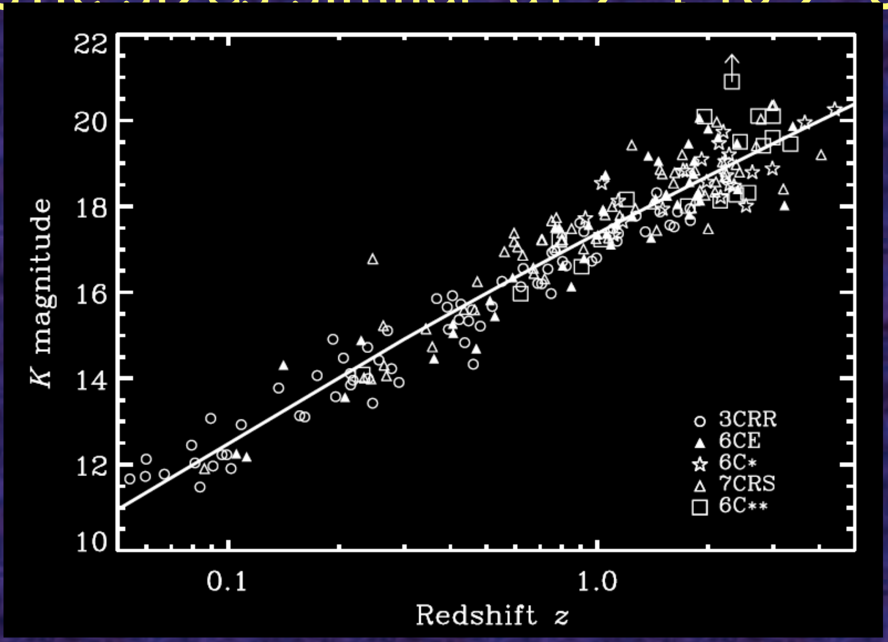




Host galaxies of radio sources

Massive ellipticals: already well-formed by z~1

- K-z relation consistent with "passive evolution" of stellar population formed at high redshift
- Near-IR light profiles well-fitted by de Vaucouleur's law
- Characteristic sizes similar at z~1 to z~0.2



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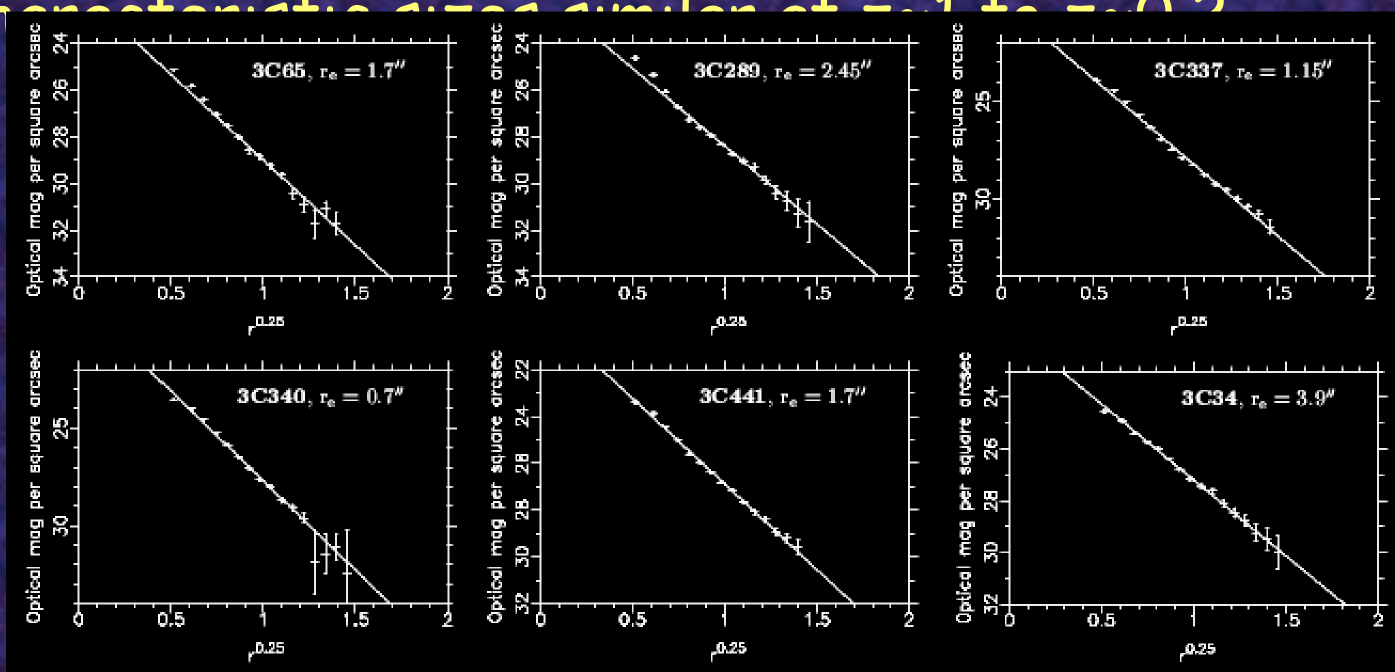

From Best et al (1998)

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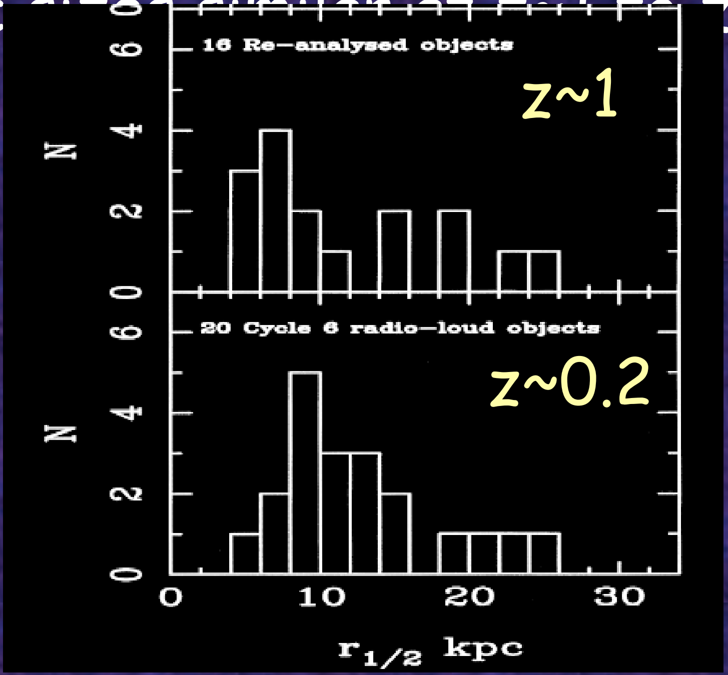
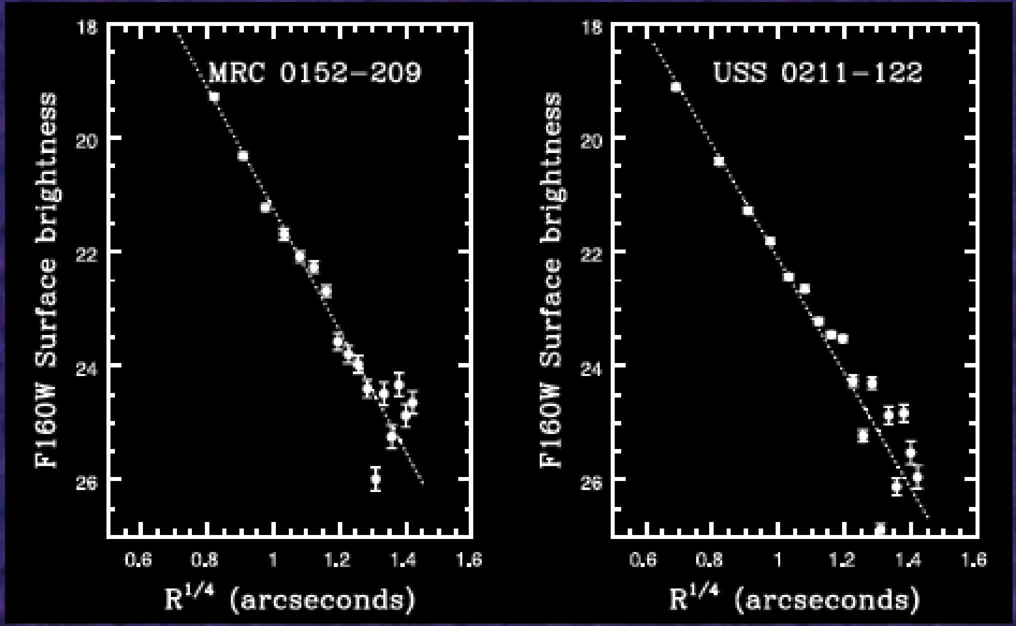
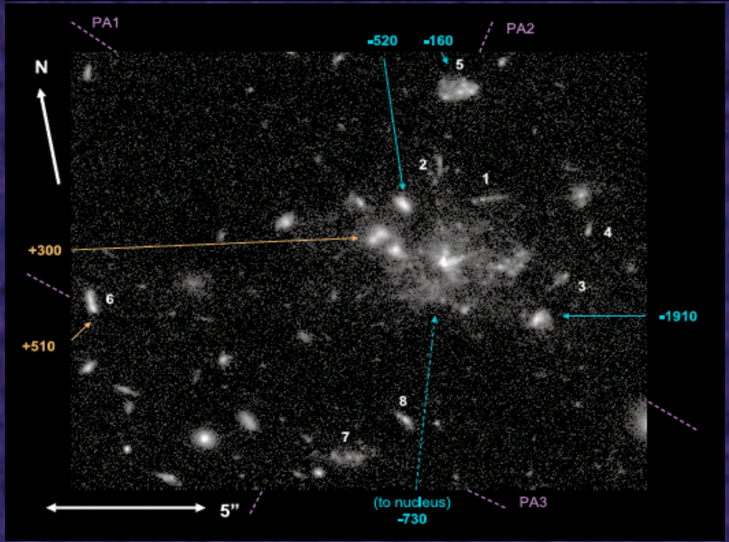


From McLure & Dunlop (2000)

Radio source hosts at higher-z



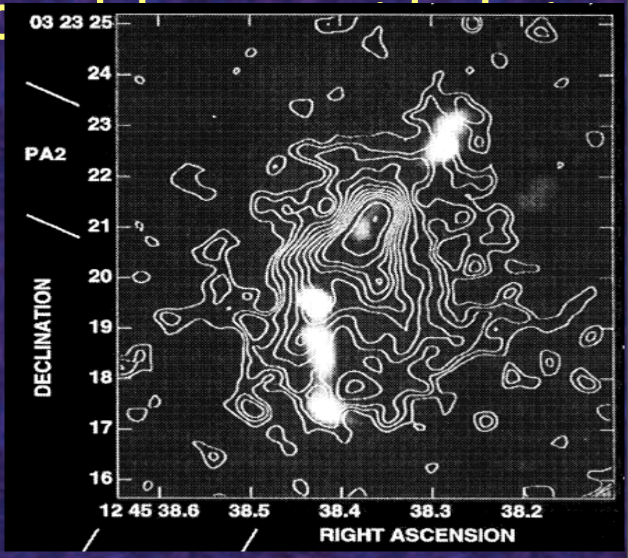
- At z~2, radio source hosts still have a de Vaucouleur's core, but smaller sizes and much disturbed structure.
- Many contain extended quiesc



Top: Radial profiles of z~2 radio galaxies. (Pentericci et al 2000)

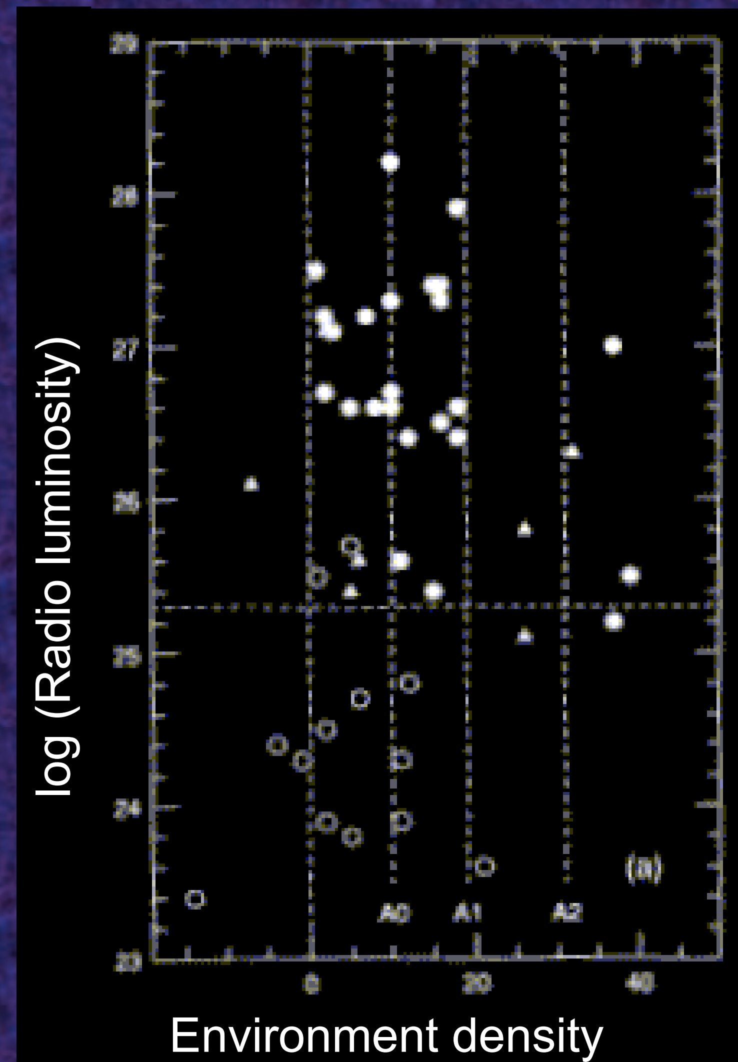
Left: "Spiderweb" (Miley et al 2007)

Right: Ly-α halo (van



Environments of radio sources

- Nearby powerful radio galaxies preferentially lie in moderately rich environments (e.g. Prestage & Peacock 1988; Hill & Lilly 1991)
- Environment richness may increase with L_{rad} & redshift (e.g. Wold et al 2000)
- Range of environments at z~1-2, but some well-formed clusters with red ellipticals (e.g. Best et al 2003)
- Most powerful radio galaxies



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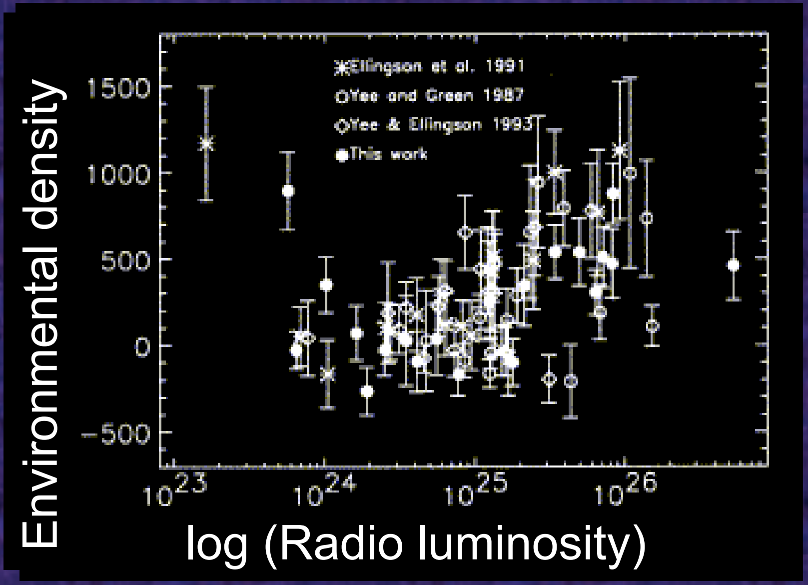

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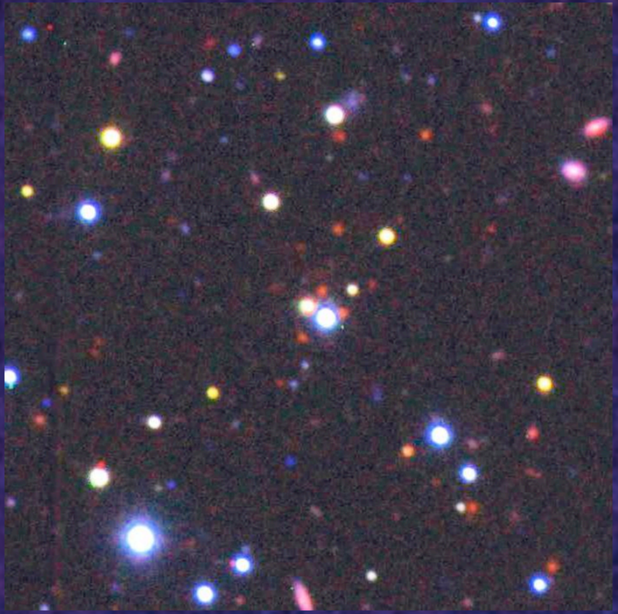

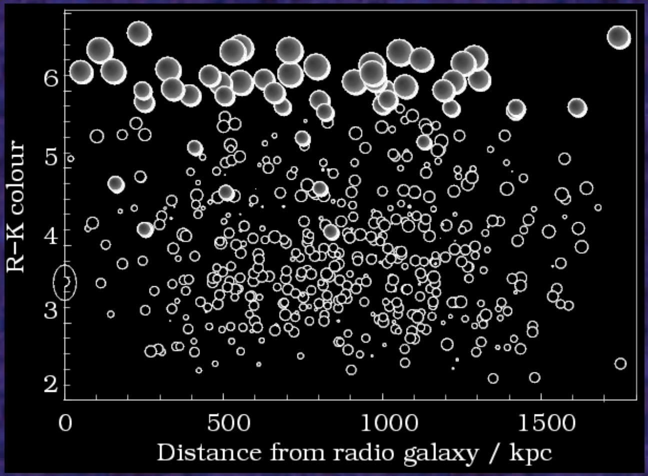

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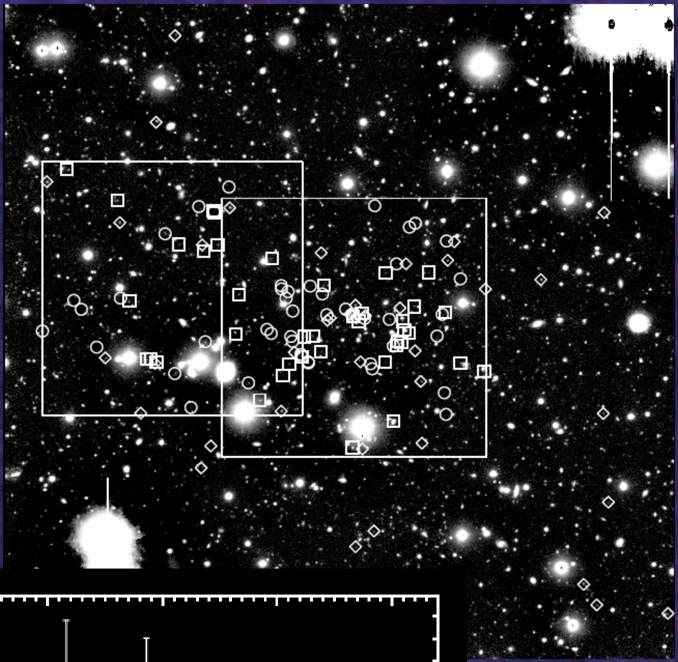
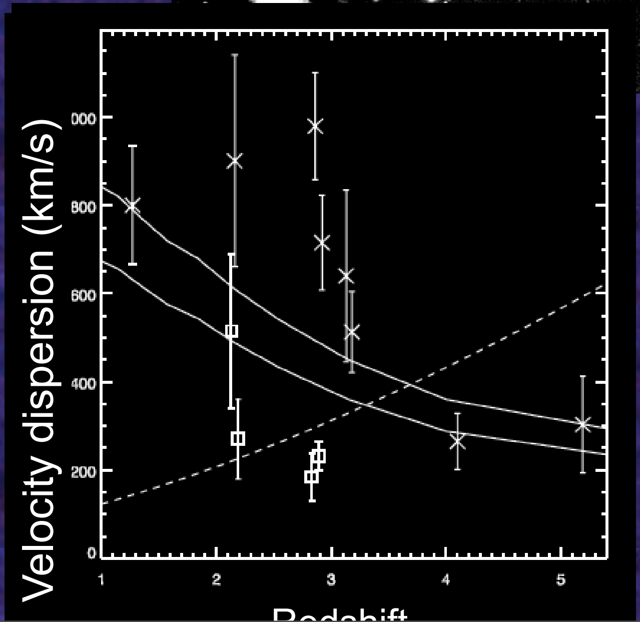




Top: 1138-262 cluster (Kurk et al 2004).

Left: Clust. velocity disp. vs z

Low-excitation radio sources and their role in galaxy formation

- No obvious optical/X-ray AGN
  - most of energy in jet
  - different triggering / fuelling?
  - radiatively ineffecent accretion?
- Strong dependence of activity on galaxy/black hole mass:

$$f_{radio\text{-}loud} \propto {M_{BH}}^{1.6}$$

- Scaling is same as that at which hot gas cools and accretes

⇒ Low-luminosity radio-loud AGN

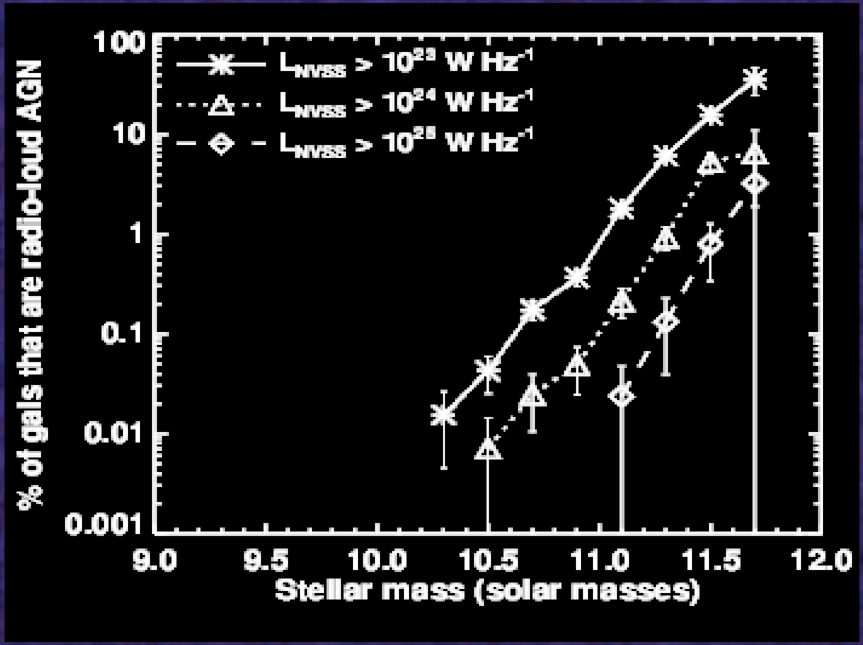
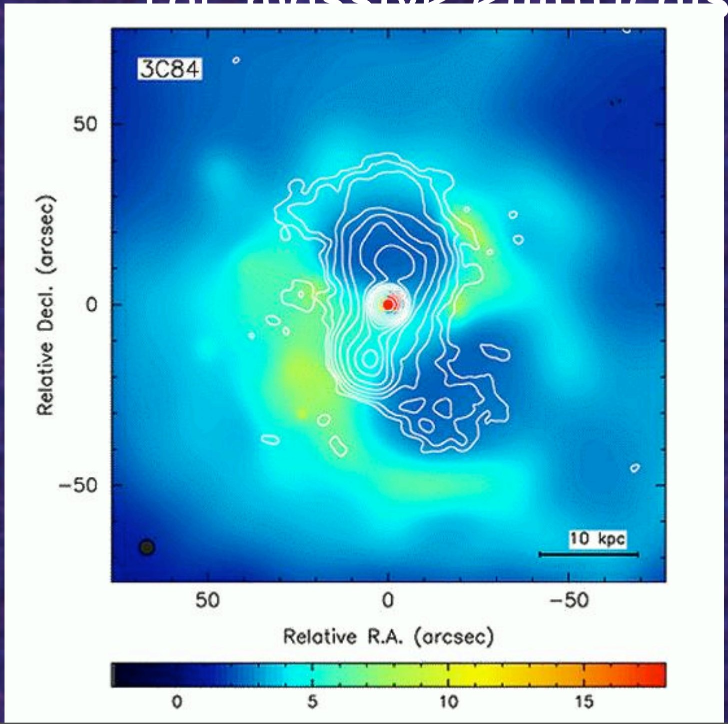


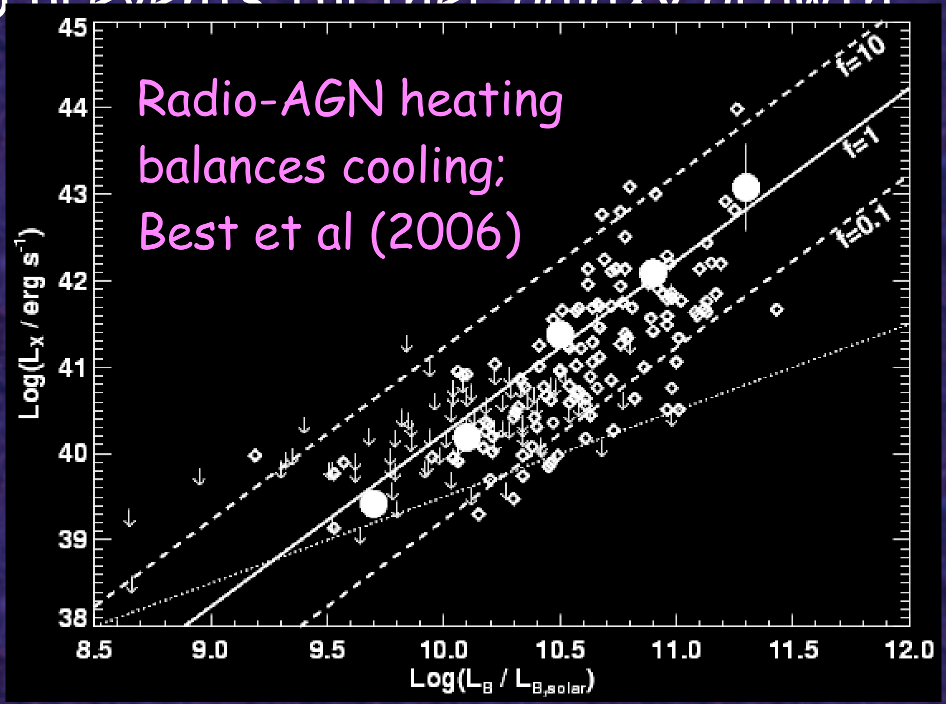
Figure: fraction of galaxies in the SDSS main sample that host radio-loud AGN, as a function of their mass; from Best et al (2005)

Low-excitation radio sources and their role in galaxy formation

- Use radio-driven cavities to estimate L_{rad} to L_{mech} conversion
- Integrate mass-dependent radio-LF to get heating rate

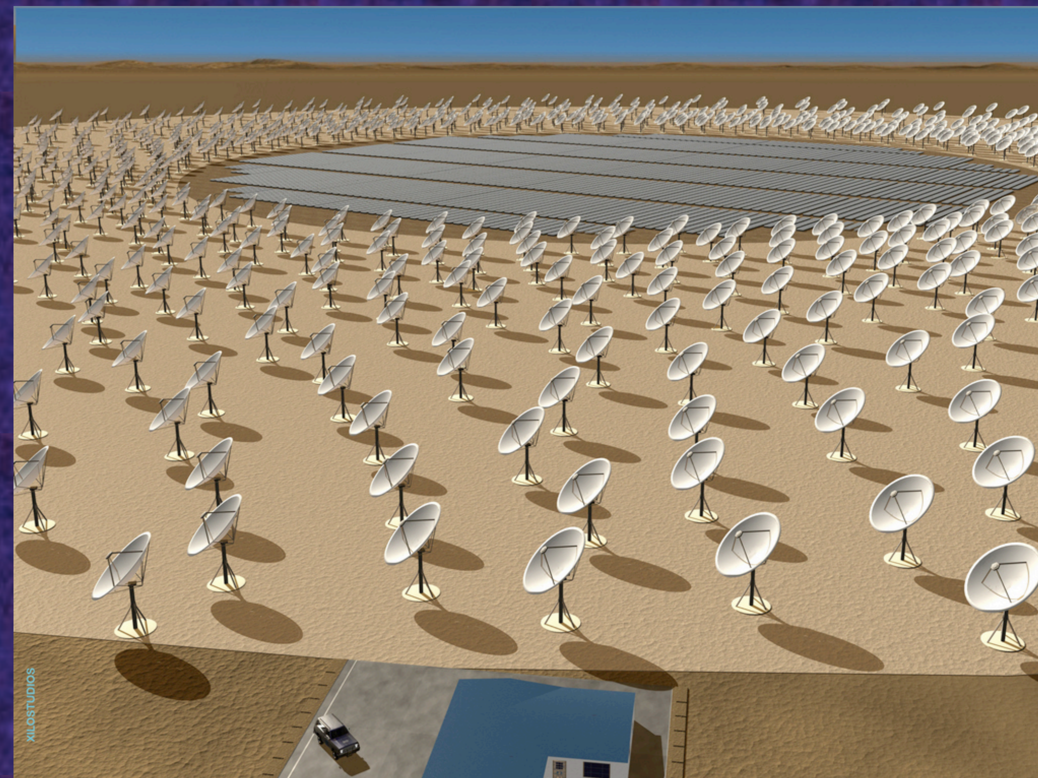
⇒ Radio-AGN heating able to offset radiative cooling losses for massive ellipticals, so prevents further galaxy growth





A look to the future

- Square kilometre array (2018ish?)
- Low Frequency Array (LOFAR; early 2009)
  - high sensitivity
  - large field of view



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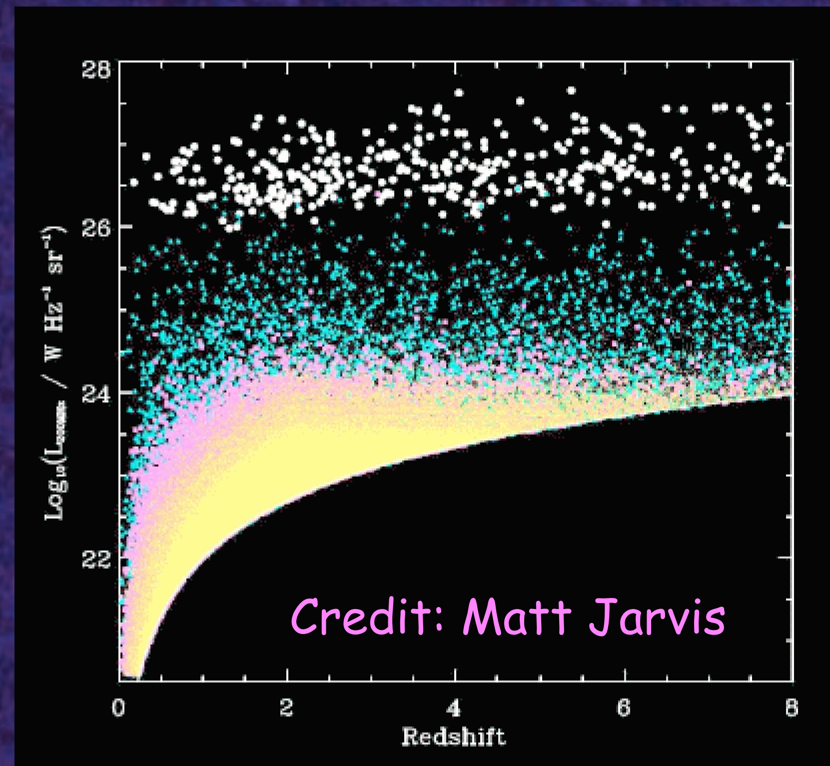

White: FR2

Blue: FR1

Pink: RQQs

Yellow: SF gals

LOFAR should detect all radio-loud AGN to the highest redshifts and the majority of "radio-quiet" AGN as well!

“The ‘second golden age’ of radio astronomy is coming”