Radio galaxies and black-hole demographics

Elaine M. Sadler

- Black holes in massive galaxies
- Demographics of radio galaxies nearby and at z~0.55
- Are radio galaxies signposts to black-hole mergers?

Work done with Russell Cannon, Scott Croom, Helen Johnston, Tom Mauch, Paul Hancock & the 6dFGS, 2dFGRS , 2SLAQ and AT20G teams

The problem:

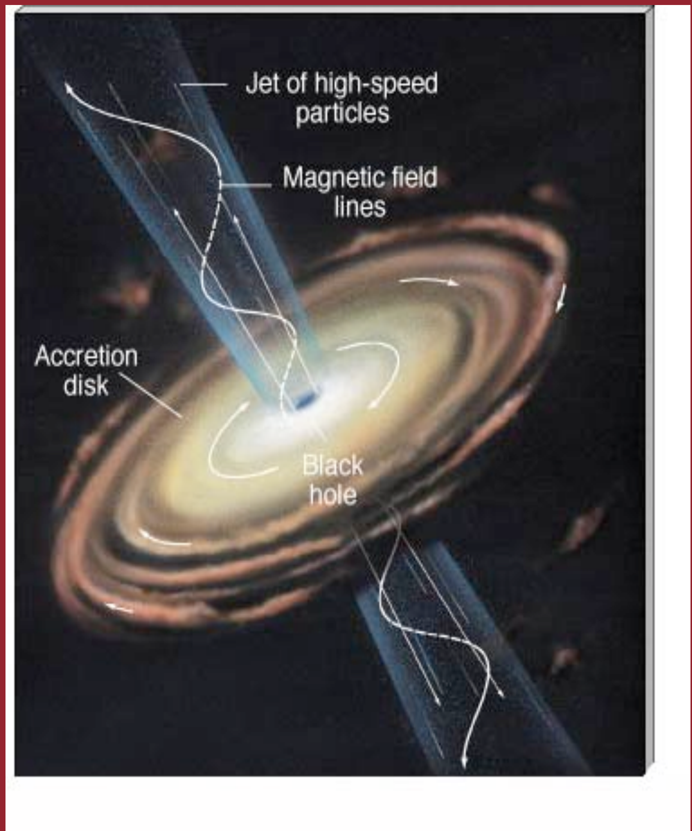
How can we map out the demographics of black holes in galaxies…

…and especially *binary and merging* black holes…

over a wide range in cosmic time?

Easier if the black hole is *doing something* which makes it easier to see!

Active Galactic Nuclei (AGN)



Standard model:

- Black hole
- Accretion disk
- Collimated jets

Typical black hole masses in powerful radio galaxies and QSOs : 10^7 - 10^{10} solar masses

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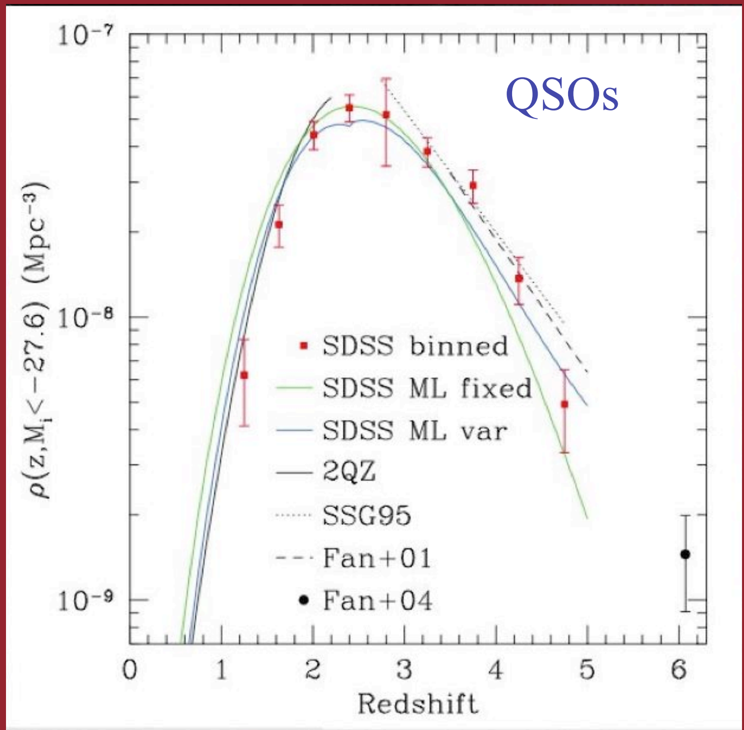
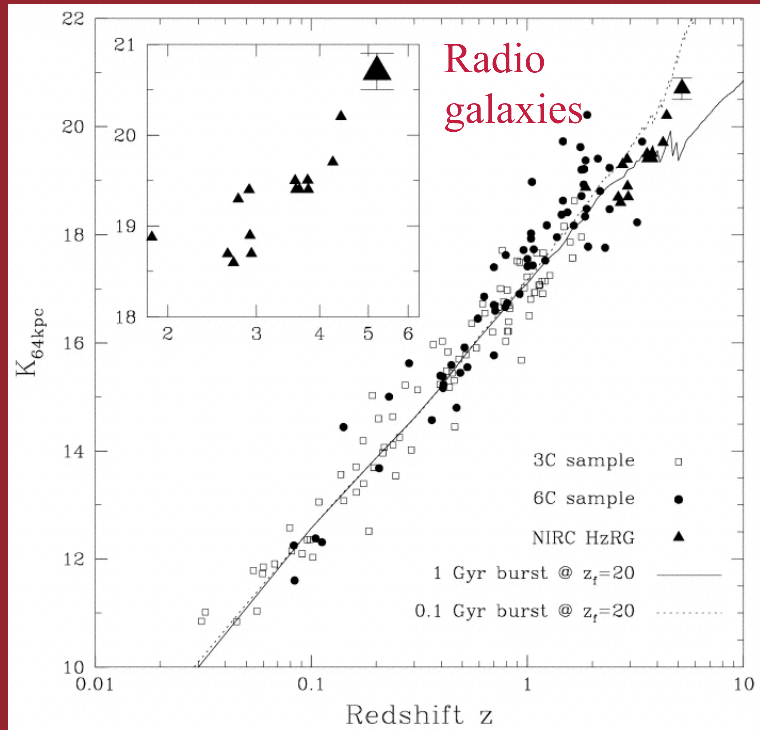
QSOs and radio galaxies can be observed out to redshift z > 5-6, so already probe >90% of cosmic time



(Richards et al. 2005)



(van Breugel et al. 1999)

Black-hole mass estimates

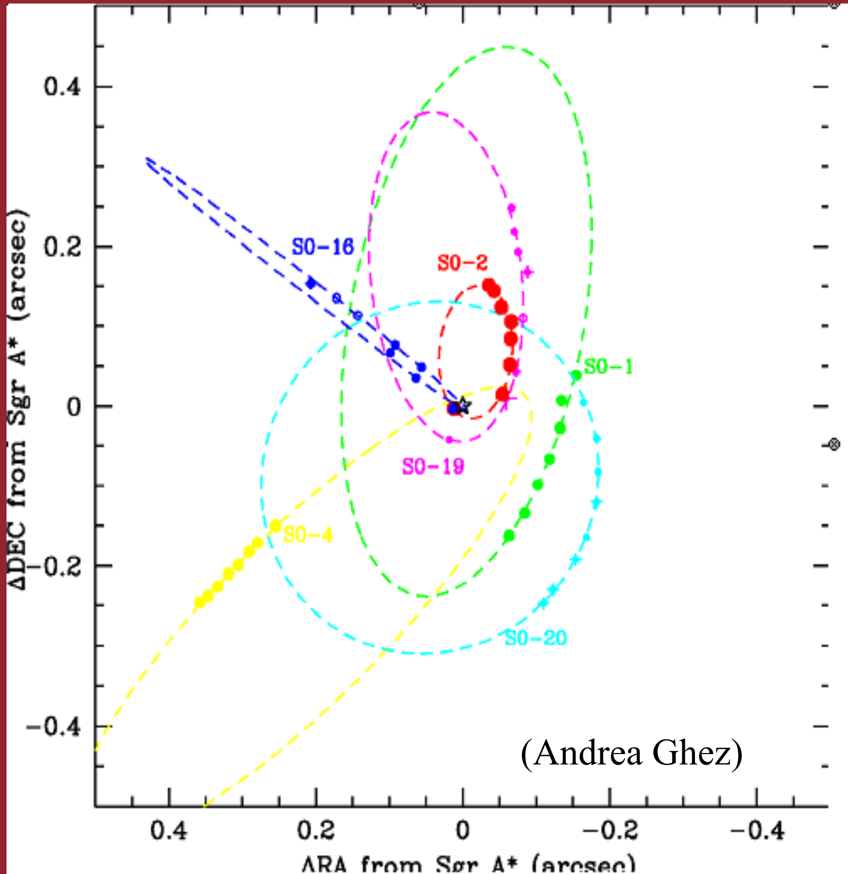
Galactic centre: Orbits of individual stars - becoming increasingly accurate over time. MW BH mass ~ $3x10^6$ $M_\odot$

Nearby galaxies: (i) *Stellar motions* deduced from integrated light. Needs velocity dispersion profile at high spatial resolution (HST) plus mass model. BH masses accurate to typically ~30%. (ii) Rotation curve of central *emission-line gas* at high spatial resolution . Accuracy harder to estimate - gas may not be on circular orbits.

Distant galaxies/QSOs: BH mass estimates from emission line widths/reverberation mapping

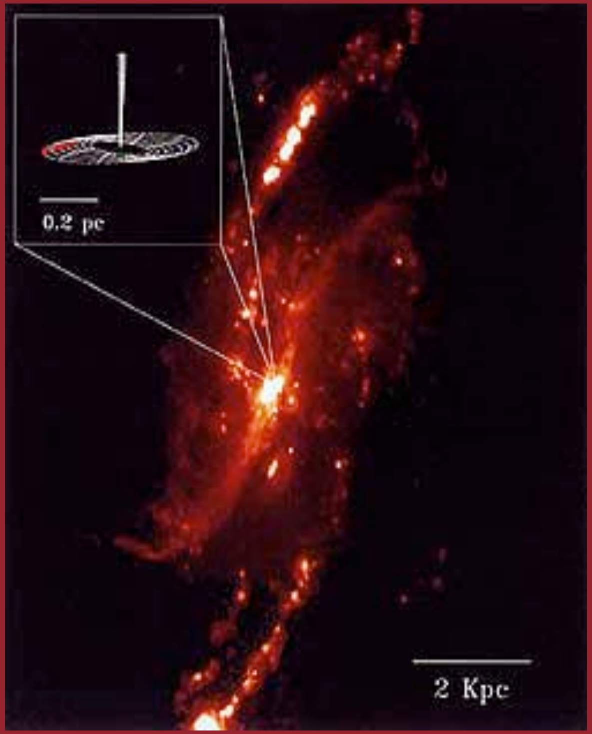
The Galactic Centre Black Hole

- Nearest supermassive black hole: $2.6 \times 10^6 \, M_\odot$
- Black hole mass can be measured accurately from the 3D orbits of stars which pass close to the centre:
  - Proper motions & radial velocities (Ghez/Genzel)
  - Measurements in IR because of dust

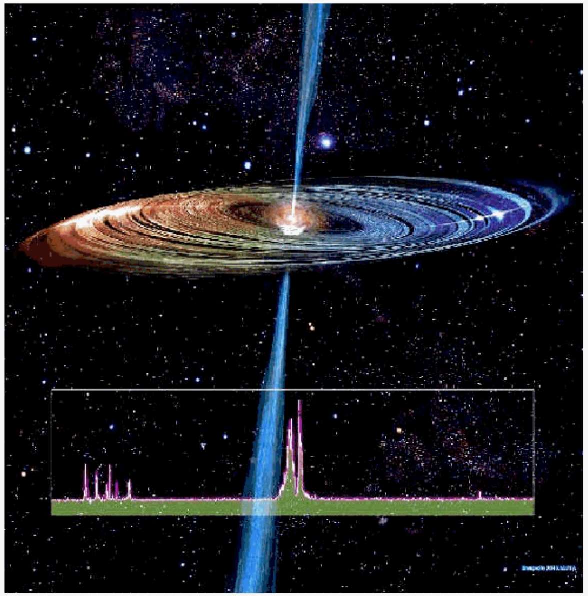


Nearby galaxy NGC 4258

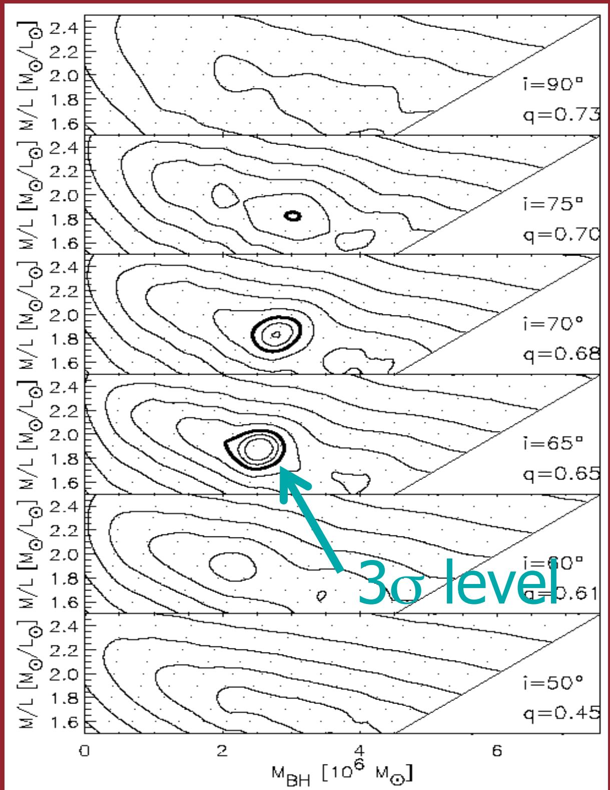
Black hole mass measured as $3 \times 10^7\ M_{sun}$



Model of H_2O maser emission around NGC4258



Stellar dynamical BH masses

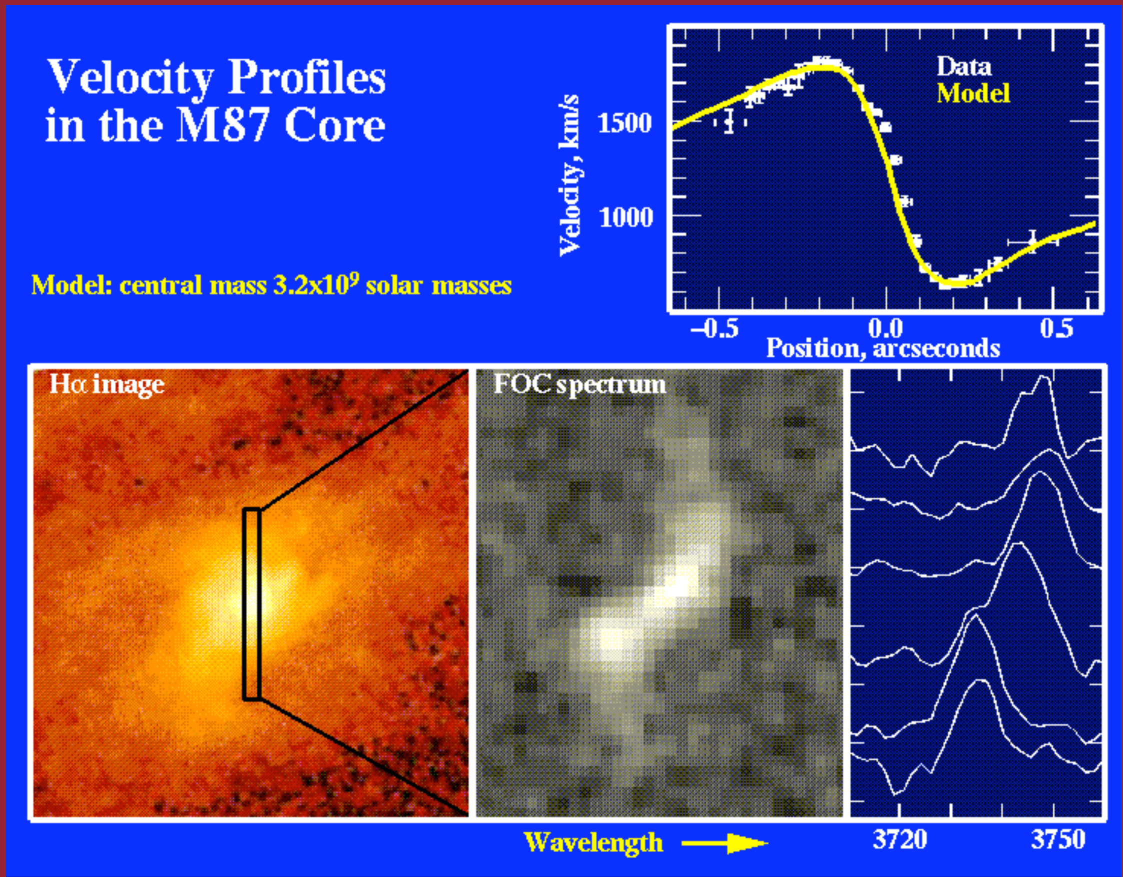


(Verolme et al. 2002)

e.g. Nearby E3 galaxy M32

- Ideal case for stellar-dynamical BH mass estimate
  - Nearby, high surface brightness galaxy
  - Velocity field from HST +ground-based data
  - Tight constraints on M/L, inclination & M_{BH}
  - $M_{BH} = 2.5 \times 10^6 M_\odot$

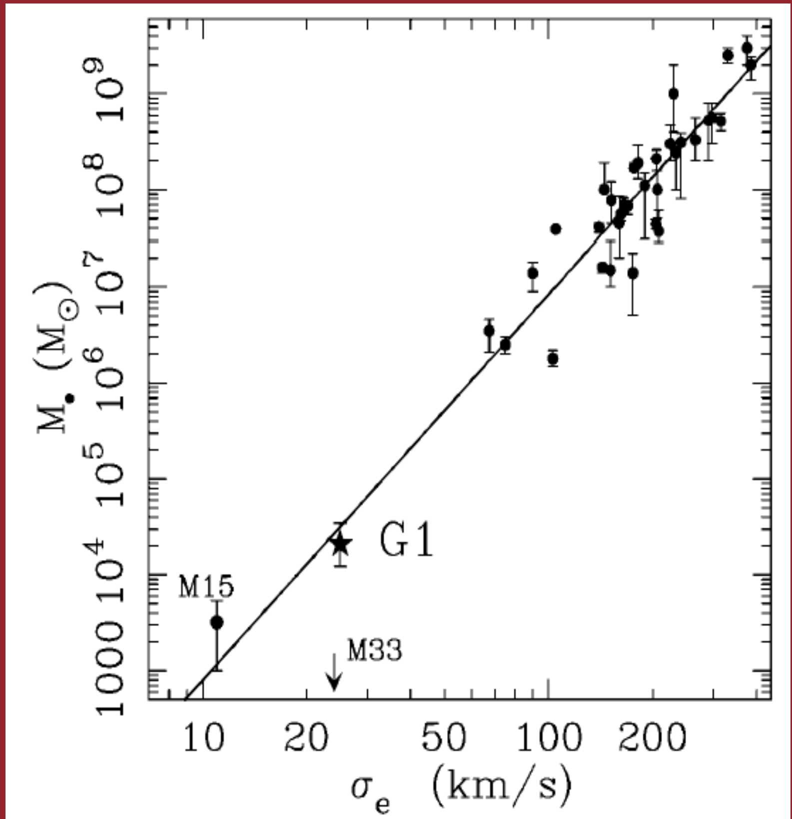
BH masses from gas dynamics



Elliptical galaxy M87: Black-hole mass estimated from velocity field of gas in central region - $M_{BH} = 3.2 \times 10^9$ solar masses

(Harms et al. 1994)

Local Black Hole Demographics



Several recent studies: correlation between masses of galaxies and their central black holes appears well-established, at least for $>10^6$ $M_\odot$ BHs.

M_{BH} ~0.006 M_{bulge}

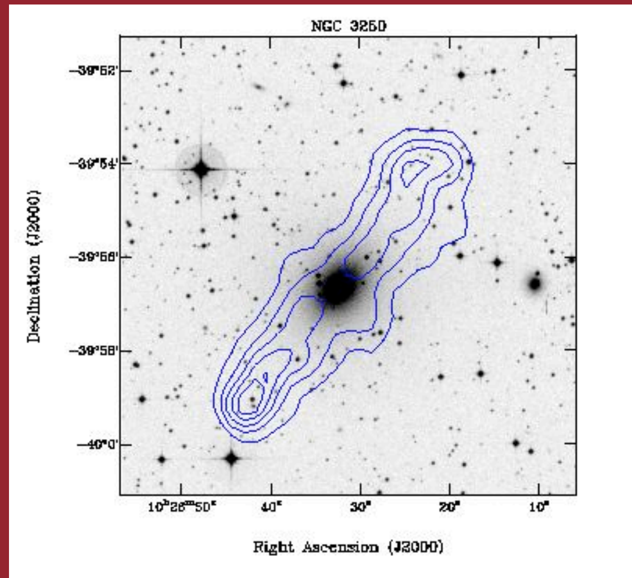
(Magorrian et al. 1998)

The local radio galaxy population

Radio galaxies (radio-loud AGN) in the local universe - associated with massive elliptical galaxies and powered by central black holes.

- How common are they?
- What triggers them?
- What is the radio-source lifetime/BH duty cycle?

Local benchmark for measuring cosmic evolution and understanding high -redshift galaxies.



Radio AGN and galaxy evolution

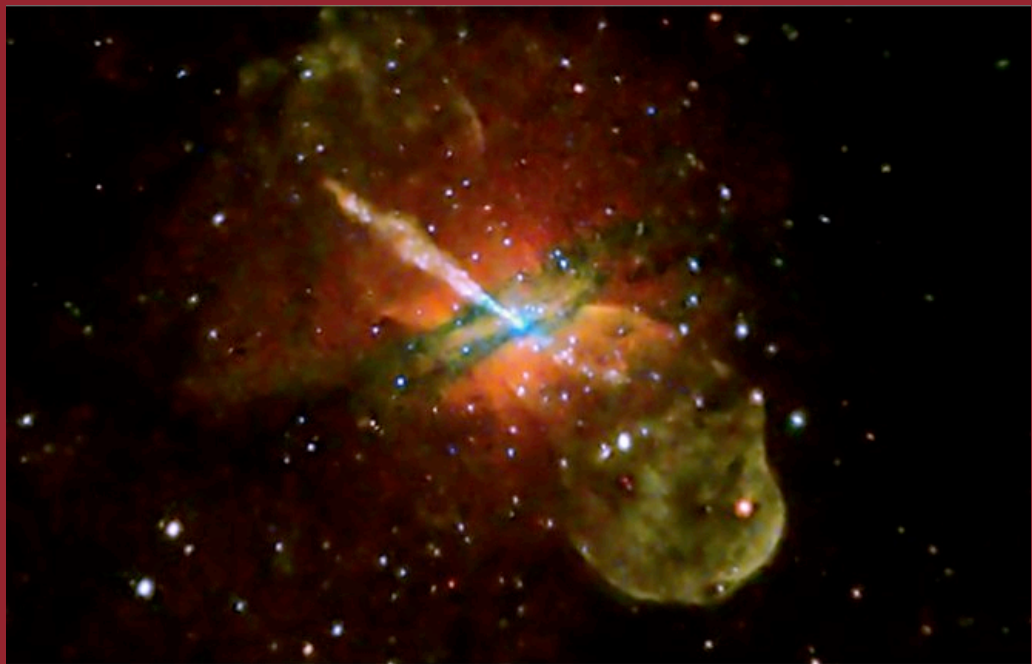


Image credit: X-ray: NASA/CXC/CfA/R.Kraft et al Radio: NSF/VLA/ Univ. of Hertfordshire/M.Hardcastle et al. Optical: ESO/VLT/ISAAC/ M.Rejkuba et al.

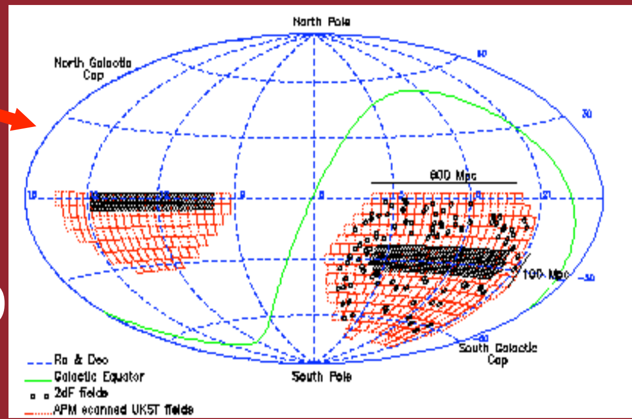
Mechanical energy input from radio jets is now believed to have a profound effect on the evolution of massive galaxies.

"AGN heating" now incorporated into semi-analytic models (Croton et al. 2006)

Spectroscopic redshift surveys

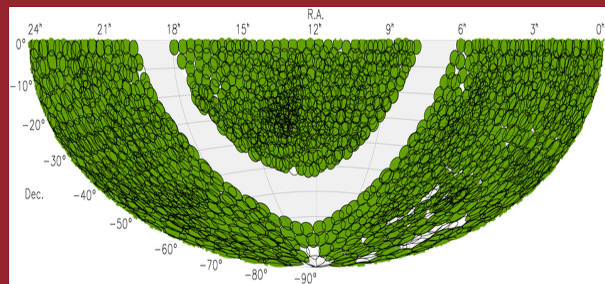
2dFGRS (AAT): ~220,000 galaxies to z~0.3, 1500 deg^2.

[~10^8 Mpc^3]



6dFGS (AAO Schmidt): ~150,000 galaxies to z~0.15, dec < 0^o.

[~ 4 x 10^8 Mpc^3]



2dF-SDSS LRG (AAT): ~15,000 luminous Es at z~0.4 to 0.8, 150 deg^2.

[~10^8 Mpc^3]

Radio imaging surveys

NVSS (VLA):

ν=1.4 GHz, north of -40^o

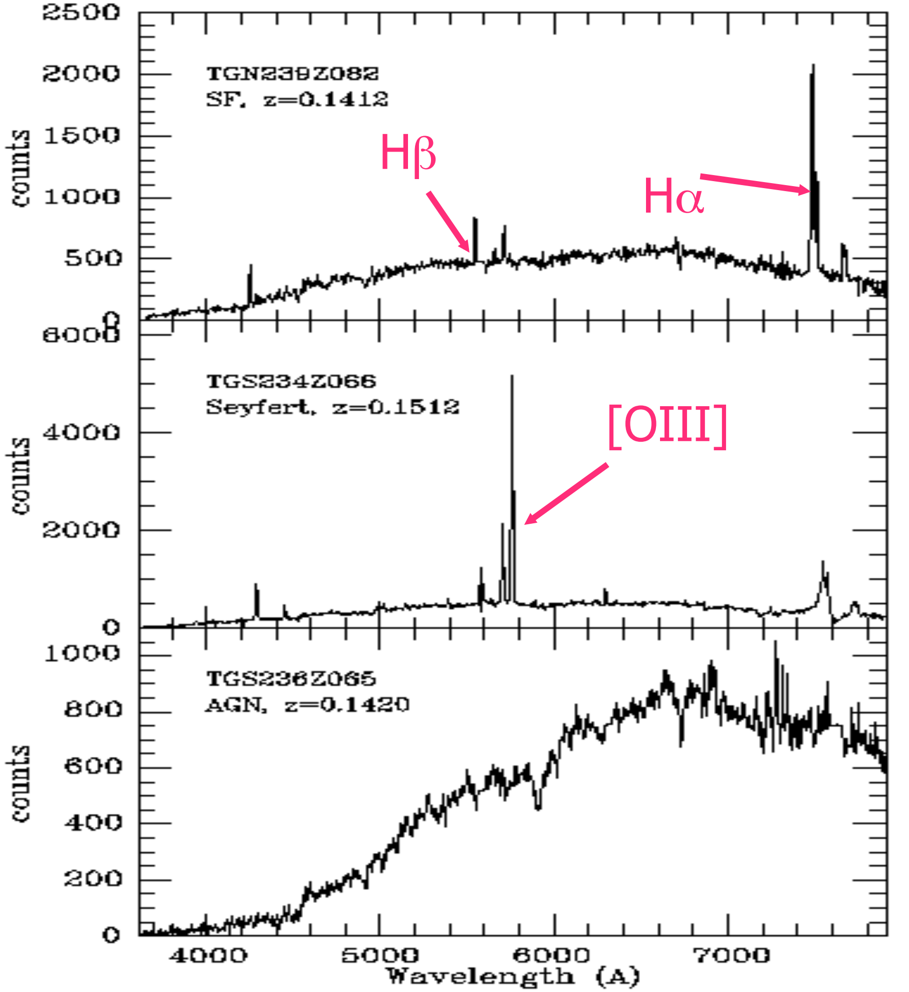
Data: www.cv.nrao.edu/nvss

+ **FIRST (VLA):** 1.4 GHz, subset of NVSS area

SUMSS (Molonglo):

ν=843 MHz, south of -30^o.

Data:www.astrop.physics.usyd.edu.au/SUMSS

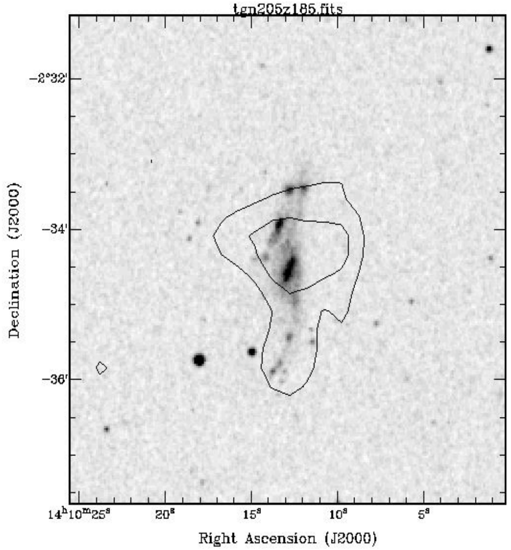


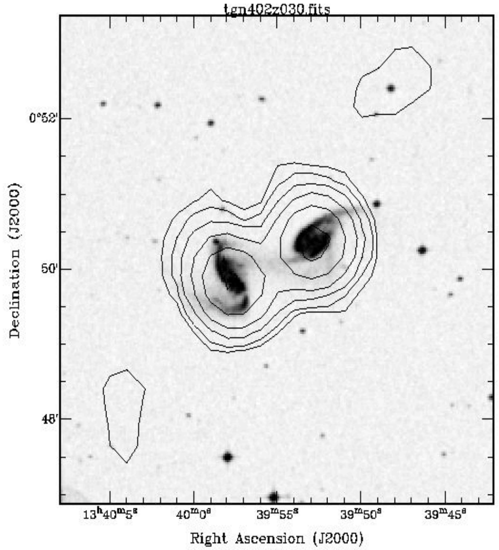
(Sadler et al. 1999)

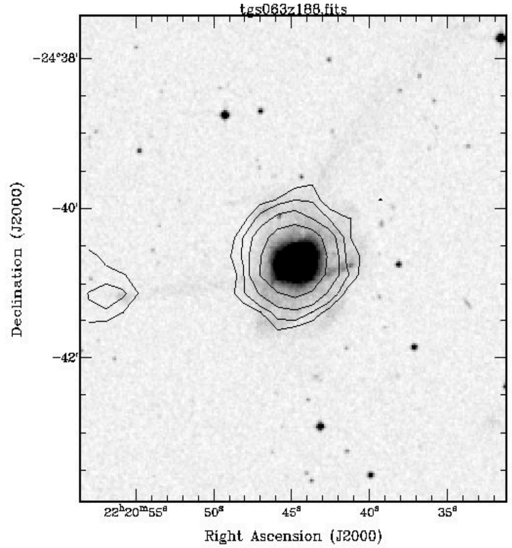
- Star-forming galaxy, z =0.14 (40%) "Starburst"
- Emission-line AGN, z =0.15 (10%) "Seyfert"
- Absorption-line AGN, z =0.14 (50%) "Radio galaxy"

Good-quality spectra now available for ~20,000 local radio-emitting galaxies!

2dFGRS star-forming galaxies





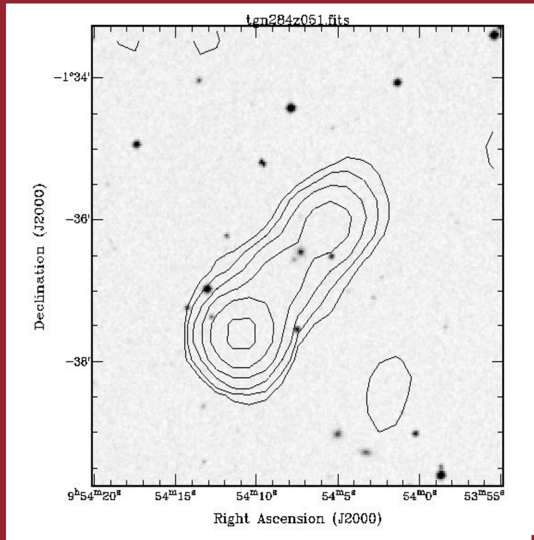


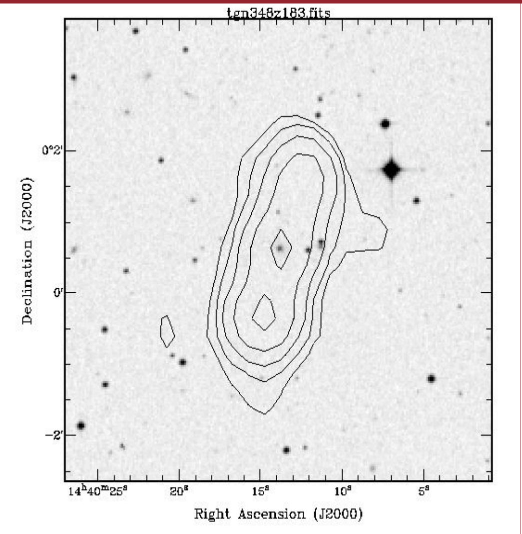
UGC 09057	NGC 5257/5258	NGC 7252
z=0.0054	z=0.0223	z=0.0161

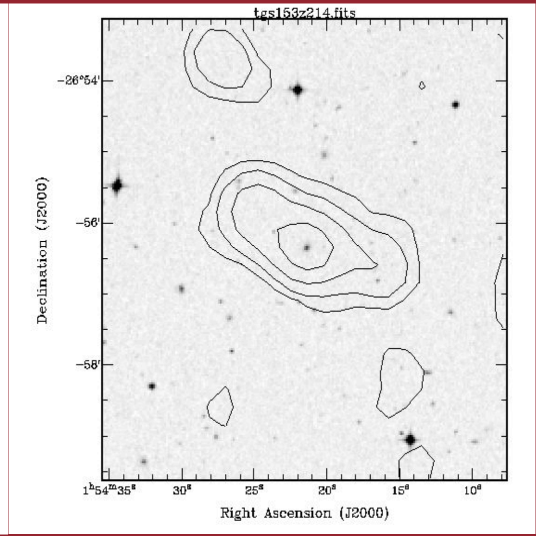
Derived SFR (from radio luminosity):

1.8 M_{sun}/yr	120 M_{sun}/yr	32 M_{sun}/yr

2dFGRS radio galaxies



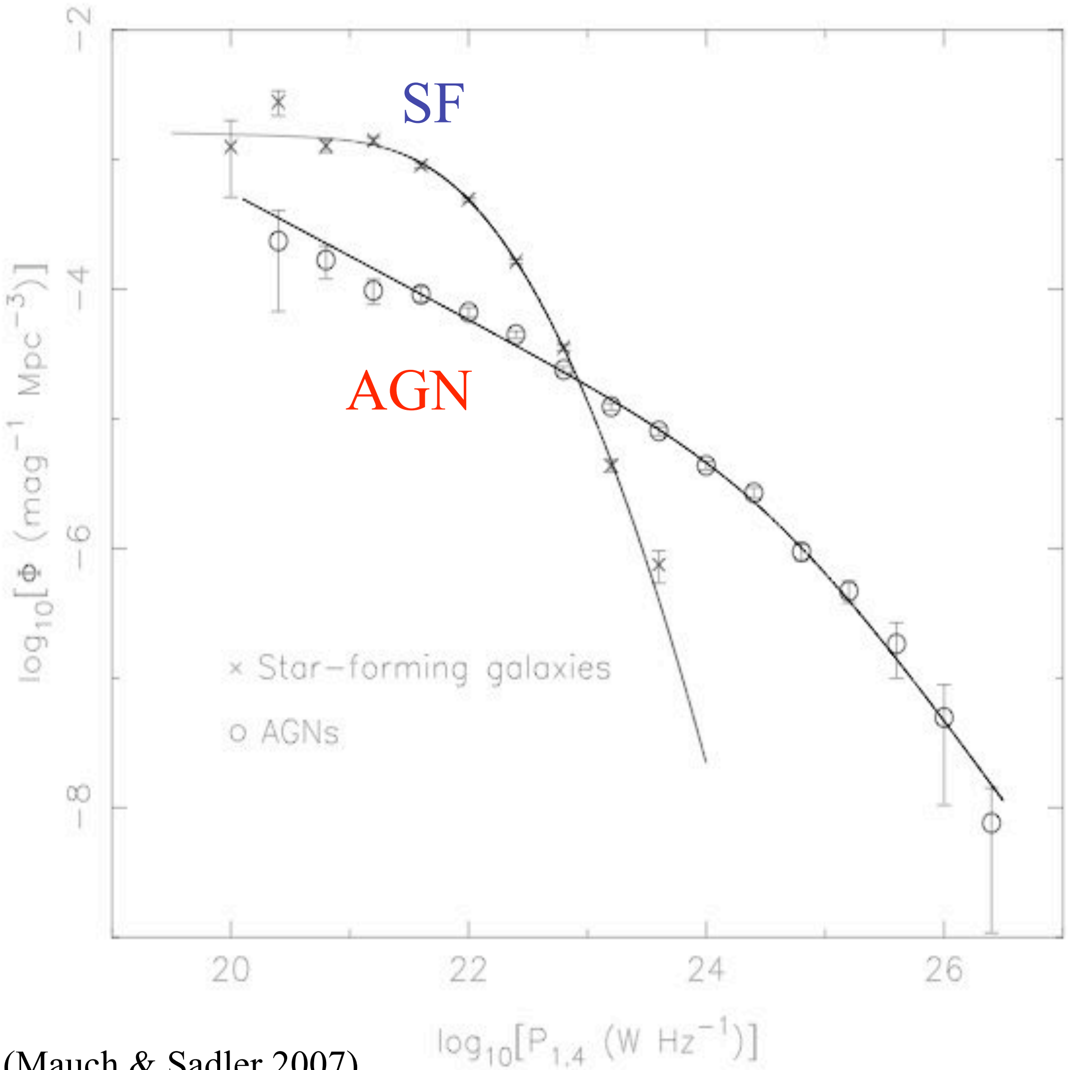




TGN284Z051	TGN348Z183	TGS153Z214
z=0.1065	z=0.1790	z=0.2079

1.4 GHz radio power and projected linear size:

$10^{24.3}$ W/Hz	$10^{25.0}$ W/Hz	$10^{24.8}$ W/Hz
327 kpc	475 kpc	471 kpc



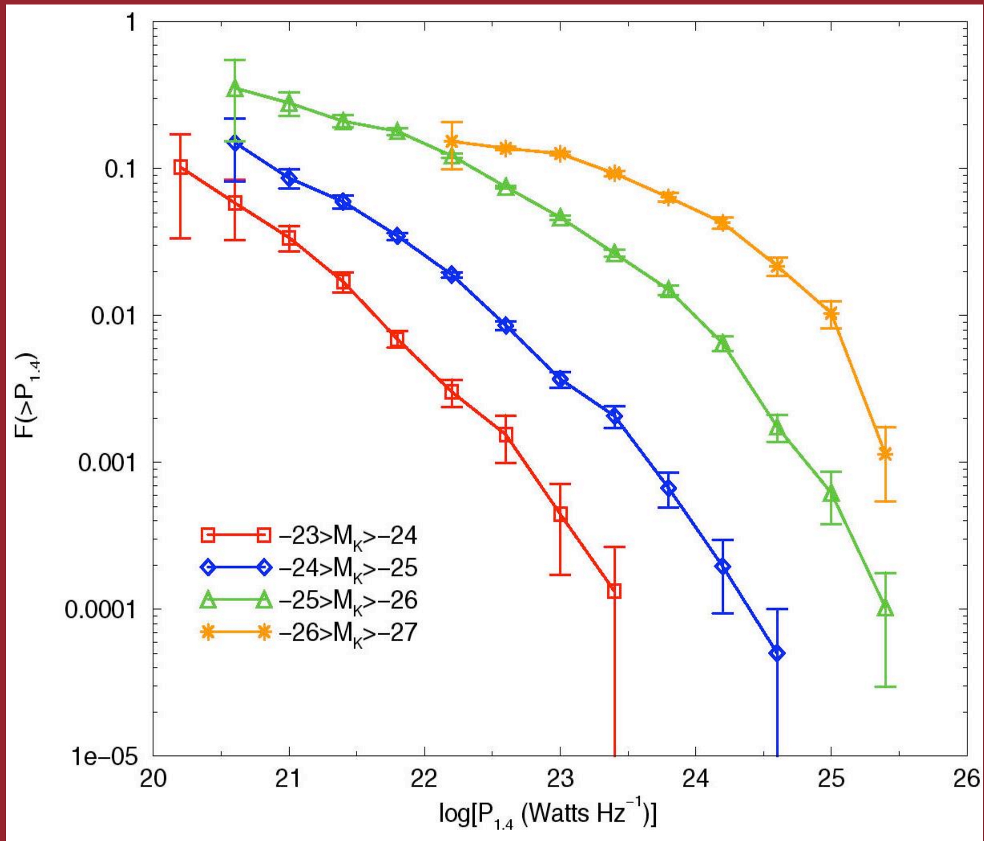
(Mauch & Sadler 2007)

6dFGS Radio Luminosity Functions:

Local (z~0) radio LFs for AGN and star-forming galaxies now accurately measured over six orders of magnitude.

Sample is large enough to split by M_K

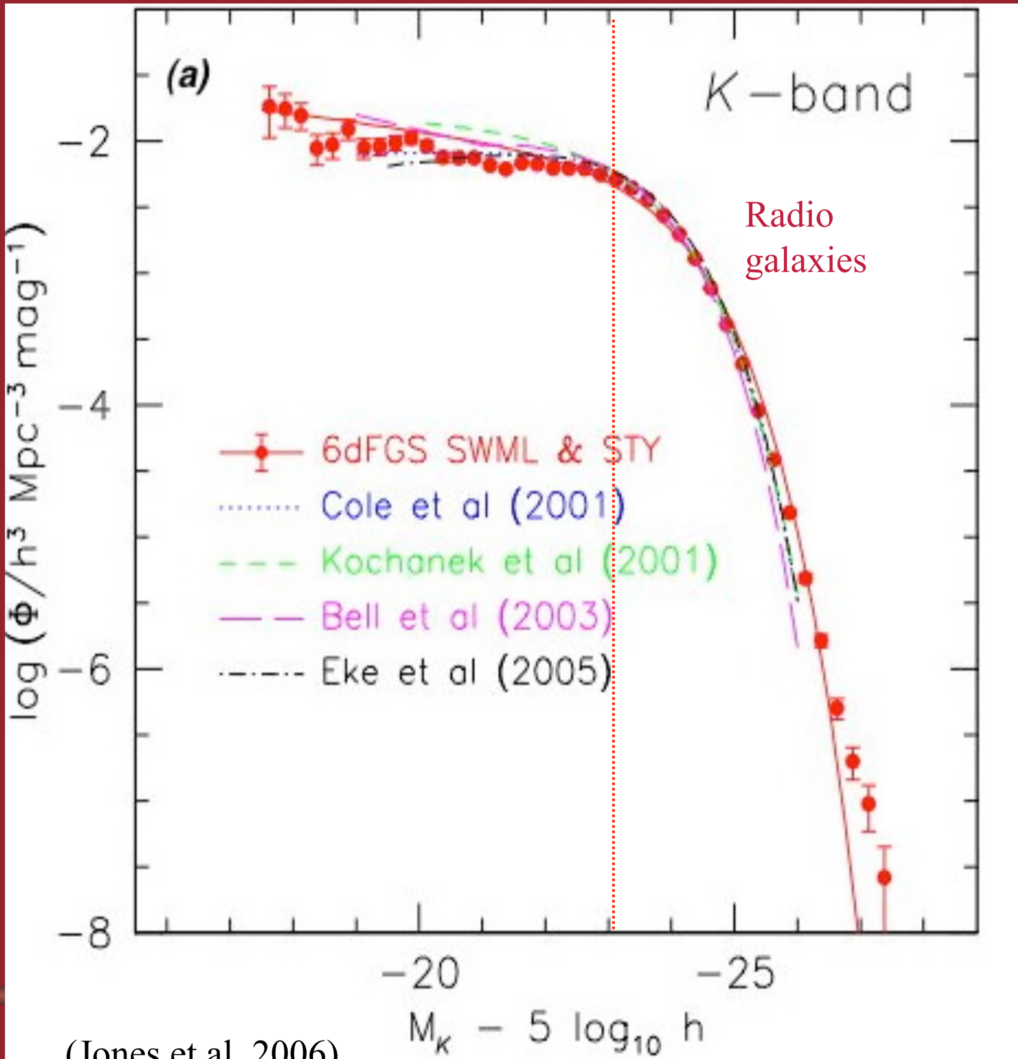
Bivariate fractional radio LF



Gives the fraction of galaxies of luminosity M_K which have radio power >P.

Fraction of galaxies hosting radio-loud AGN increases with stellar mass.

BH duty cycle *high* in local massive galaxies



(Jones et al. 2006)

6dFGS galaxy luminosity function:
Almost all radio galaxies are brighter than M_K~-23 mag.

Fits with a picture in which local radio galaxies all have massive BHs (> ~$6x10^8$ M_{sun}).

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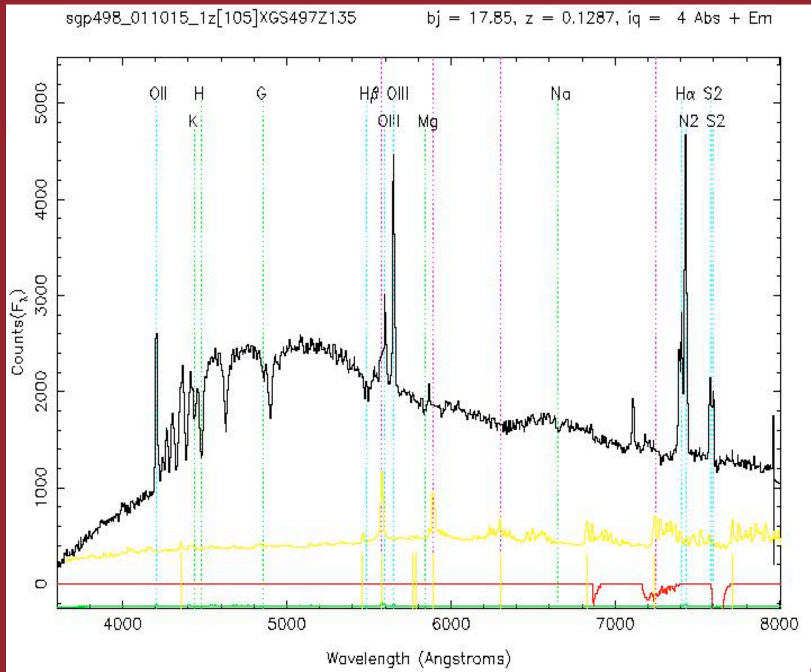
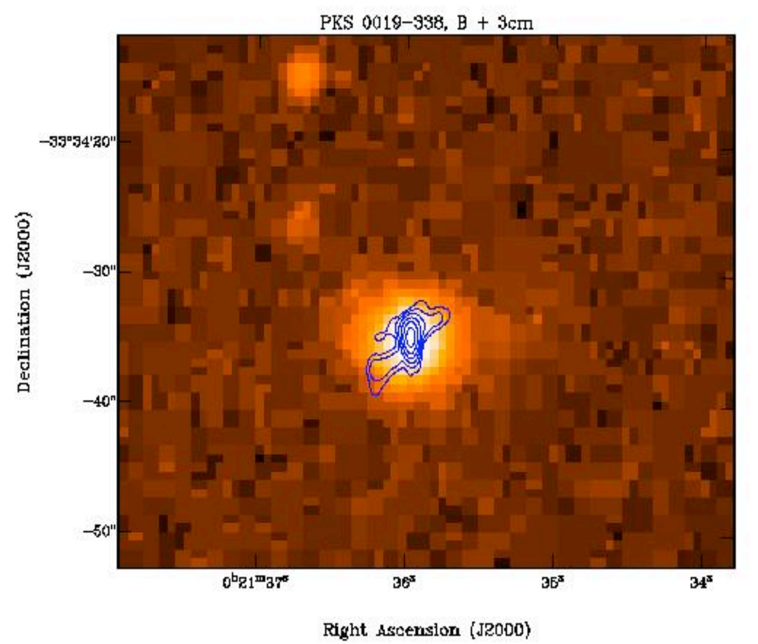
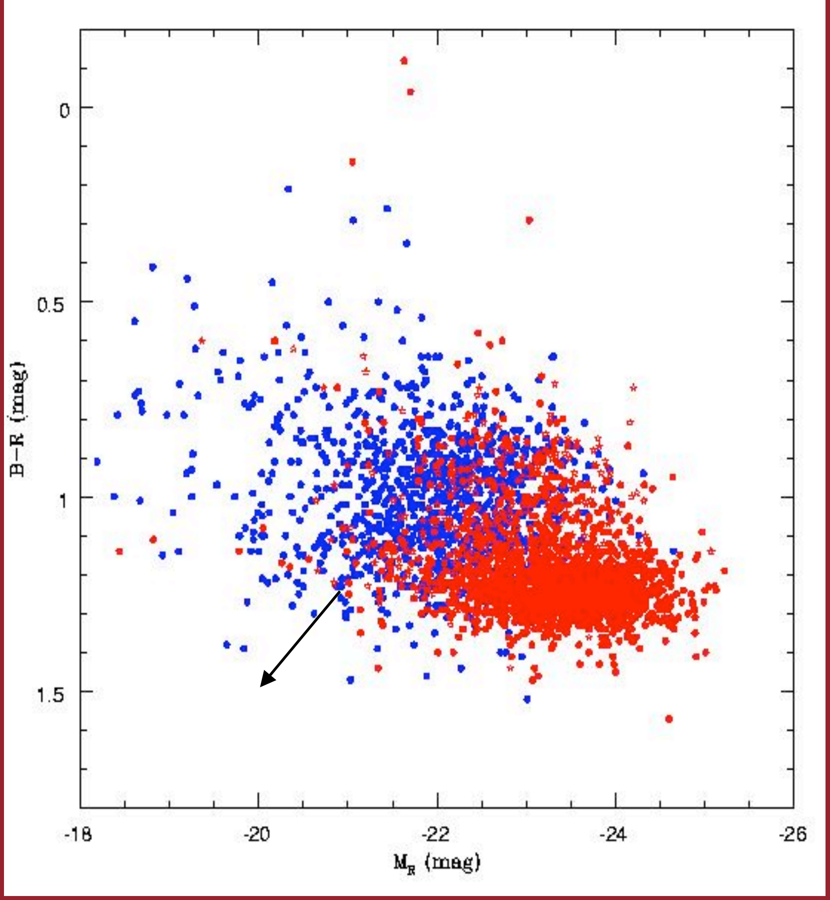
Do mergers trigger radio galaxies?





2dFGRS radio galaxy: Balmer abs. lines imply a massive (~10^{10} M_{sun}) starburst occurred ~0.15 Gyr ago. Compact, steep-spectrum radio source has $P_{1.4}$ ~ 10^{25} W/Hz. BUT extremely rare locally!



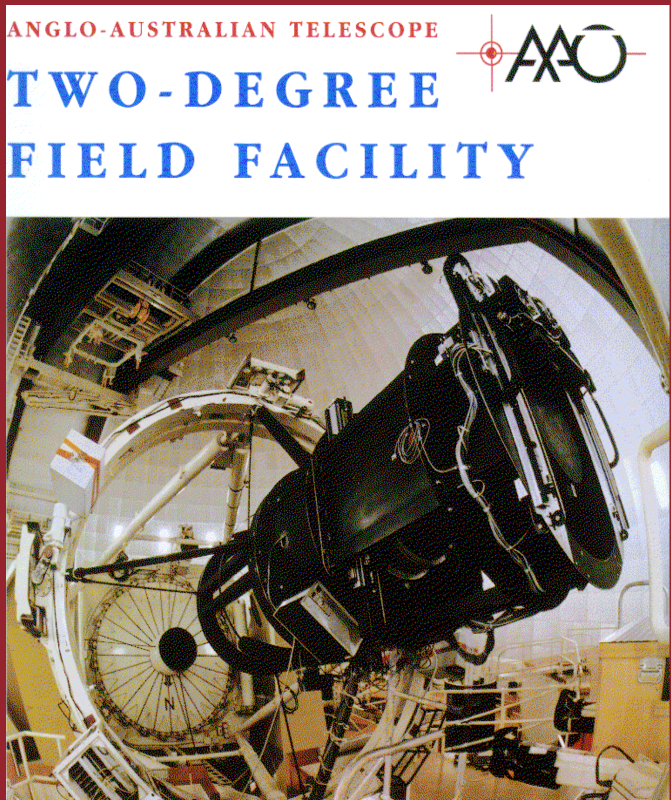
CMD for 3256 2dFGRS galaxies detected at 1.4 GHz (Red: AGN, Blue: Star-forming galaxies)

In general, star-forming galaxies and radio-loud AGN are almost disjoint in a 2dFGRS colour -magnitude diagram.

Evolution from one class to another (e.g. starburst followed by a radio-loud AGN) must therefore be *rare* in the local universe.

Things may be different at higher redshift.

AAT 2SLAQ survey (2dF-SDSS LRG And QSO)



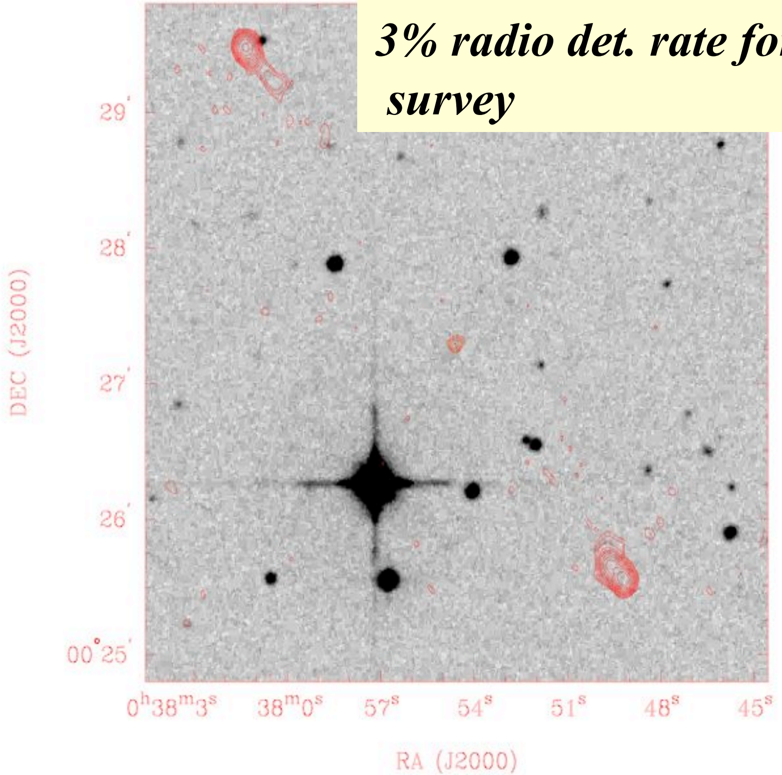
Survey completed late 2005:

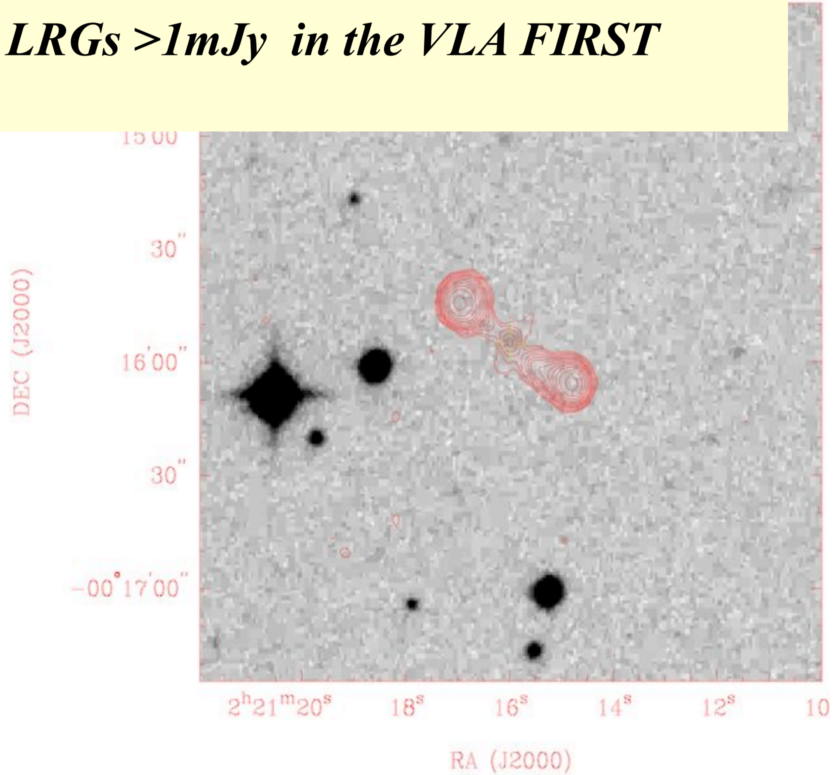
- Photometric selection from SDSS , sky area ~150 deg^2
- Optical spectra and redshifts from AAT/2dF
- 15,000 spectra, of massive red galaxies at 0.4<z<0.8,
- 10,000+ faint QSO spectra

Survey paper: Cannon et al. (2006) MNRAS 372, 425

2SLAQ radio galaxies

3% radio det. rate for LRGs >1mJy in the VLA FIRST survey

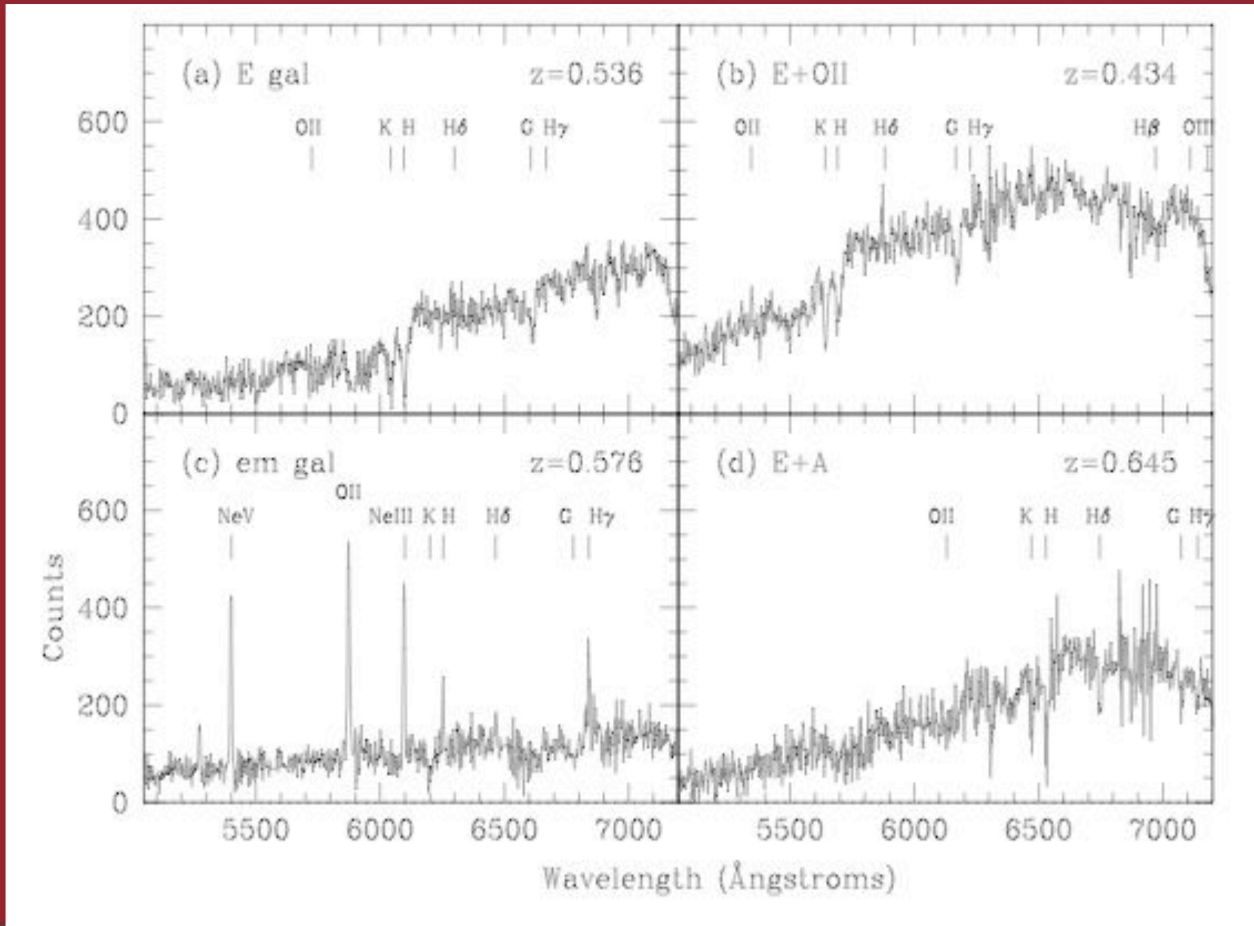




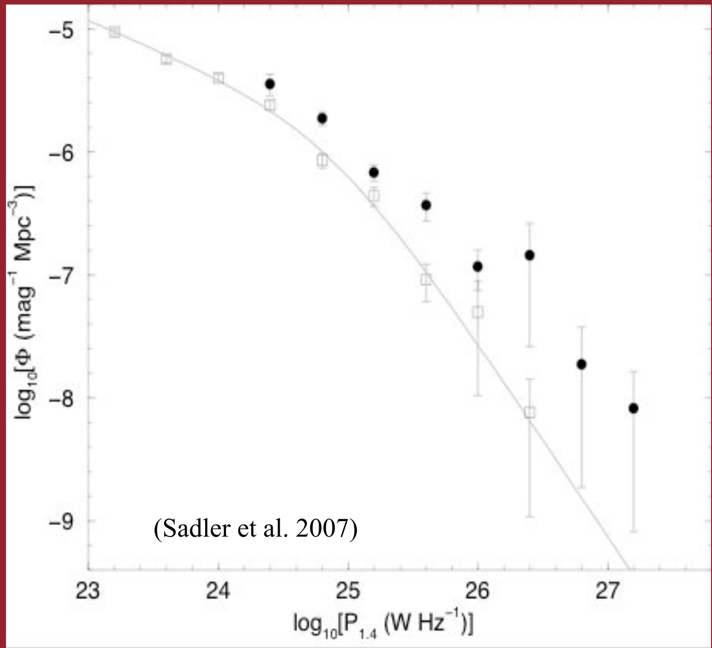
J003754+002717: z=0.59, a giant radio galaxy with proj. linear size ~2.0 Mpc!

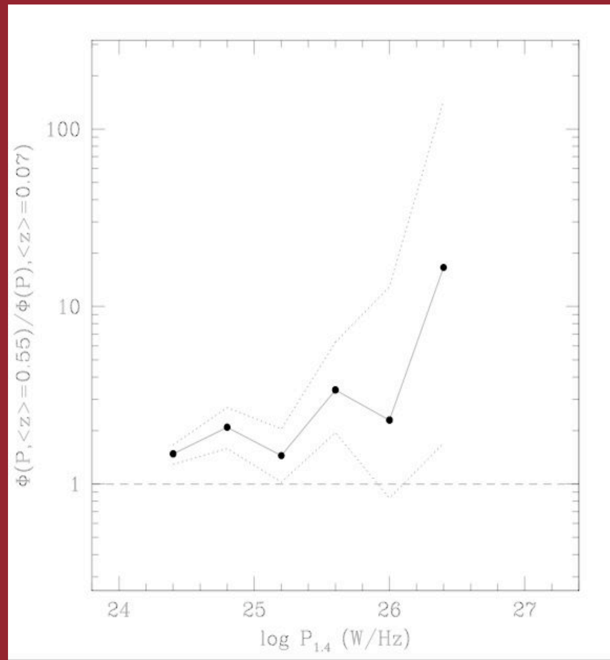
J022115-001554: z=0.54

Spectra of radio-detected LRGs at z~0.5



Cosmic evolution of low-power radio galaxies





First measurement of cosmic evolution for low-power radio galaxies. Low-power ($<10^{26}$ W/Hz) radio galaxy population well-fitted by luminosity evolution of the form $(1+z)^n$ where n~2.0. Non-evolving models ruled out at 7σ level. More rapid evolution seen for very powerful sources.

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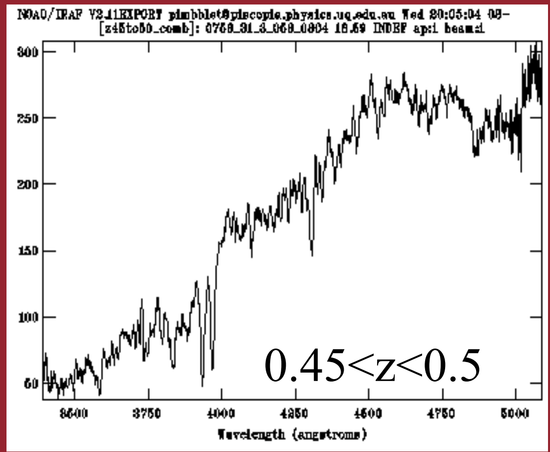
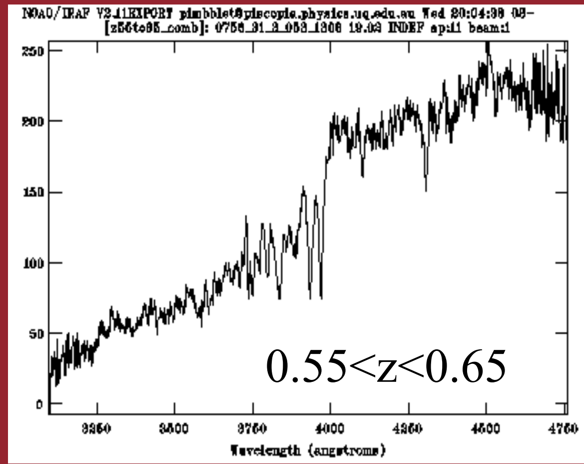
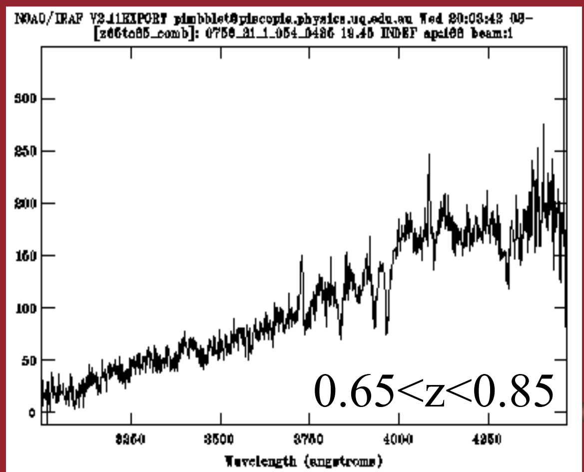
Composite LRG optical spectra

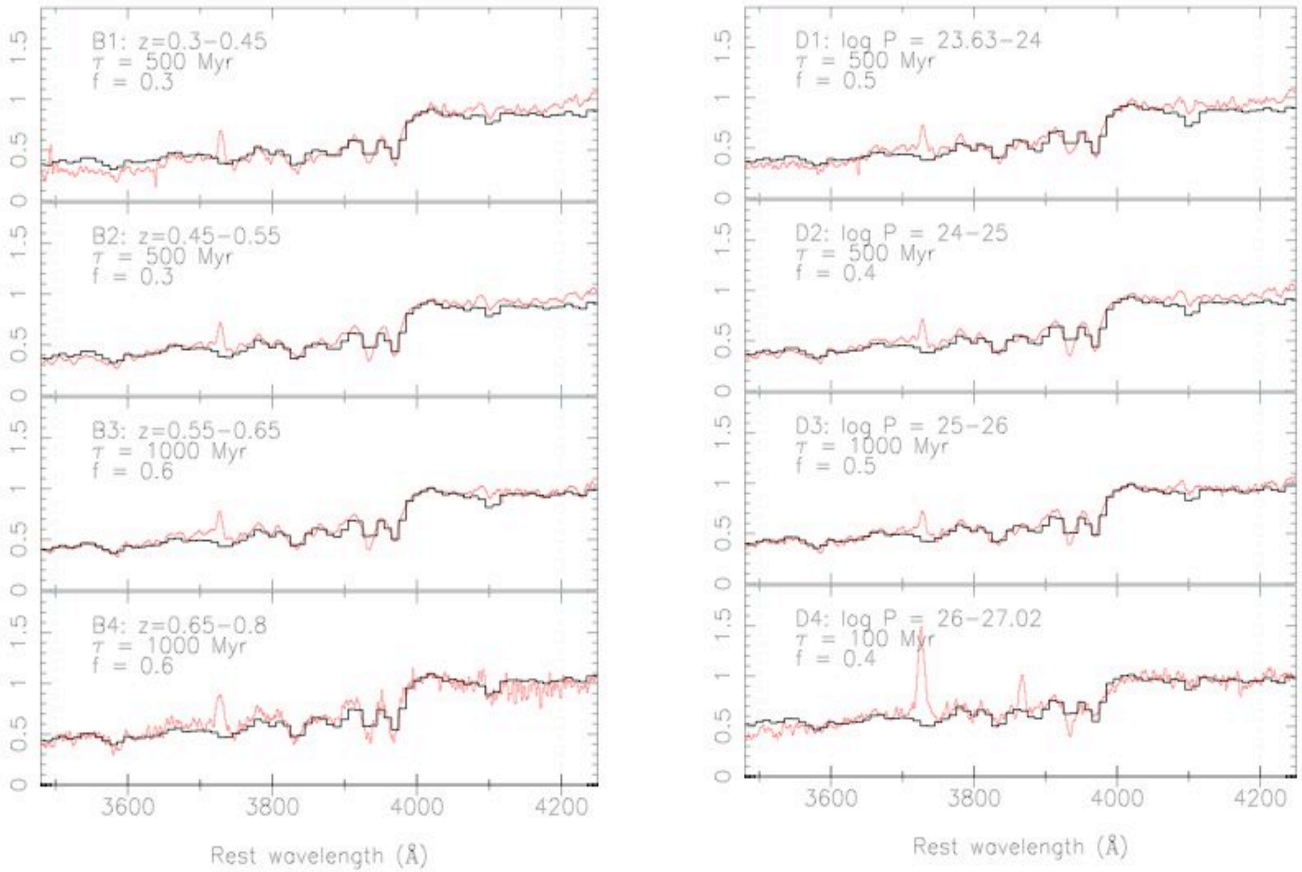




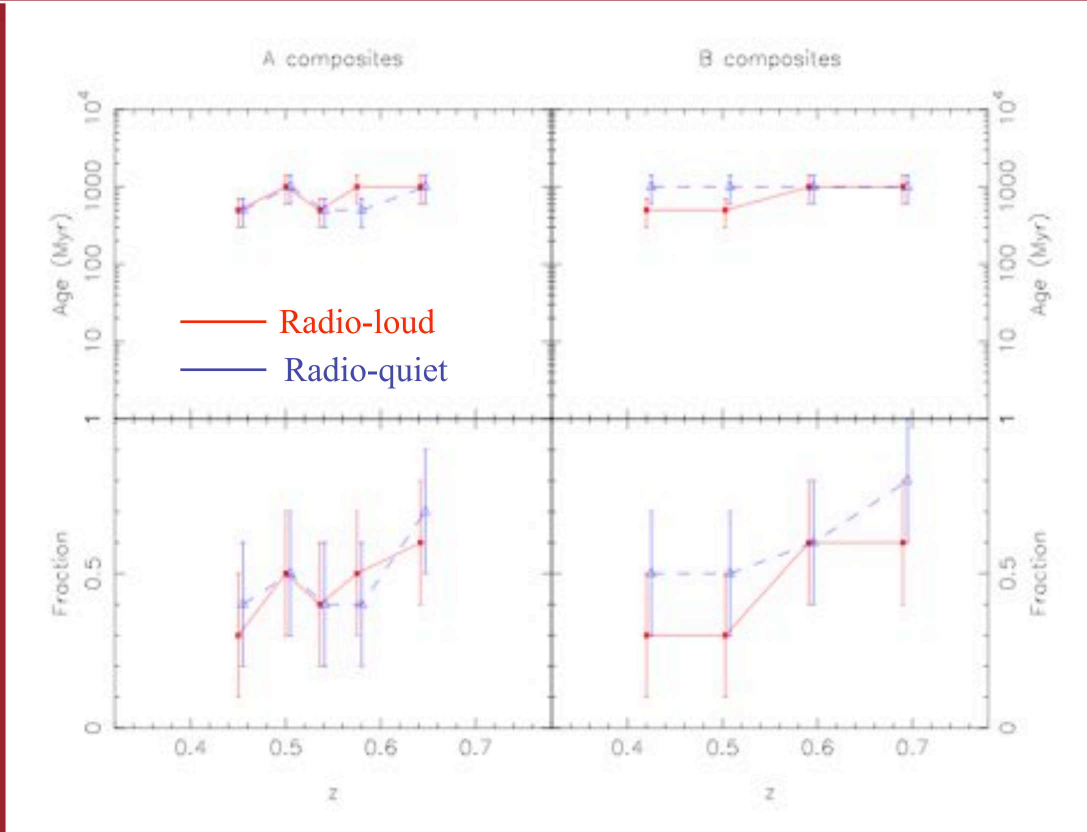


Analysed matched composite spectra to test for differences between the stellar populations of radio-loud and radio-quiet galaxies in general (Johnston et al. 2008)

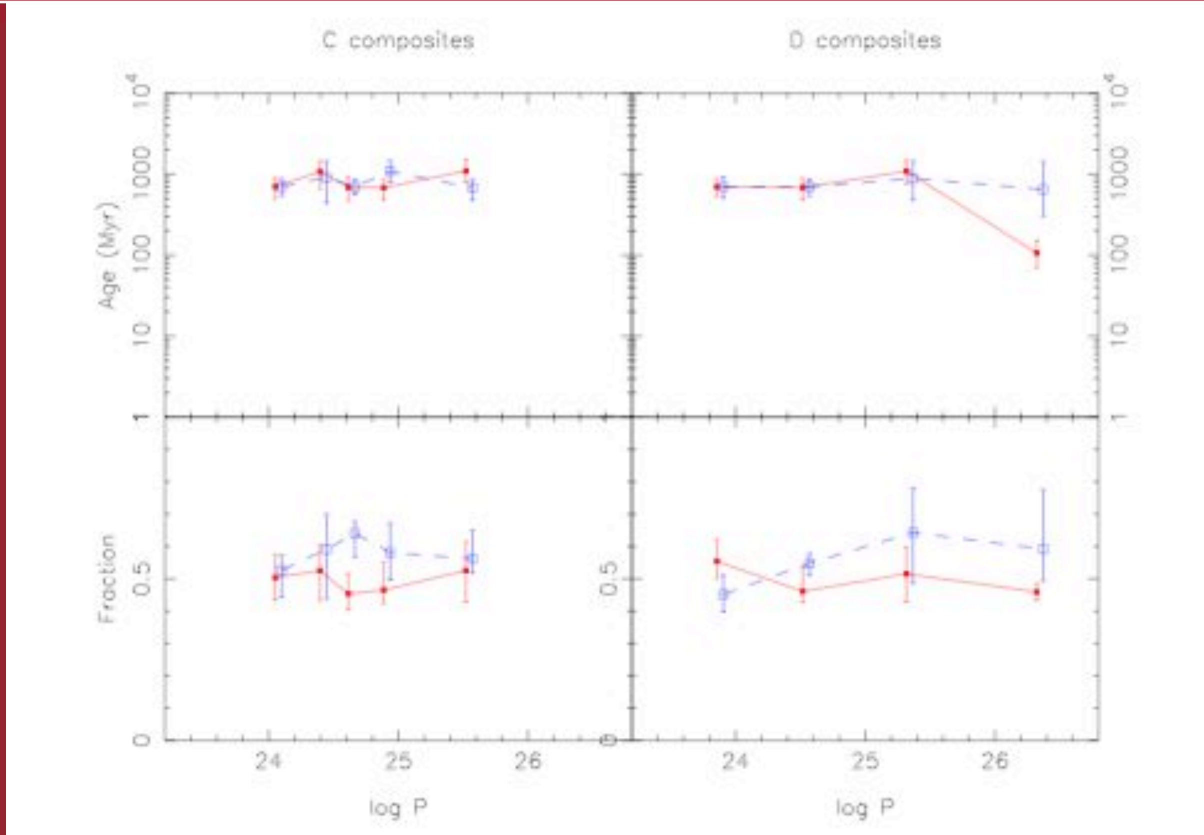
i.e. is there a merger/starburst trigger in most low-power radio galaxies at z~0.6?



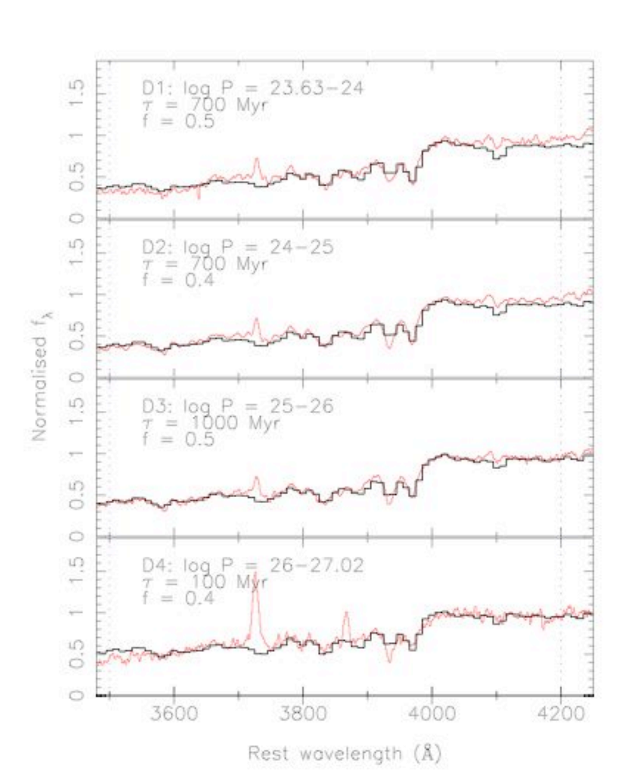
Fit composite spectra with *two* single-age stellar populations, old (~7 Gyr) plus younger (10 Myr to 5 Gyr).



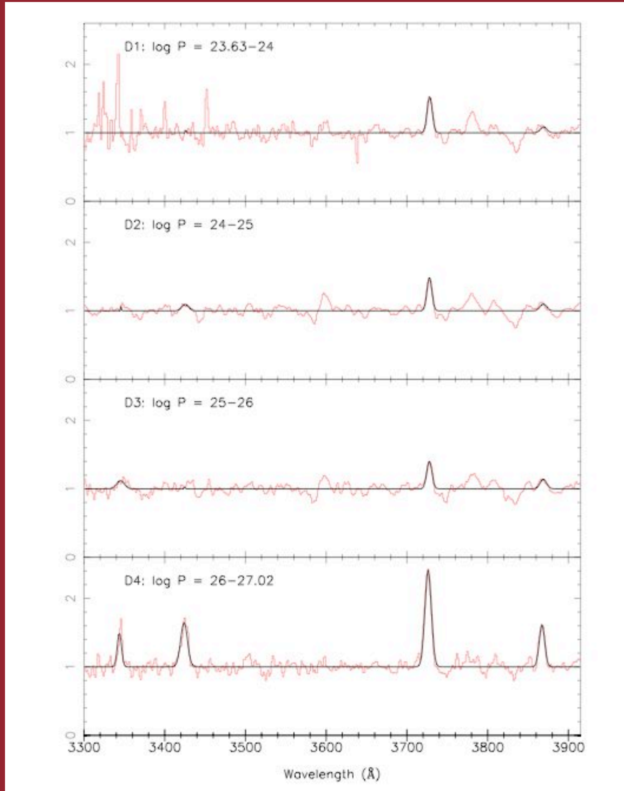
When binned in redshift, *no significant difference* between radio-detected galaxies and full 2SLAQ sample. Around 30-40% of the light at 4000A appears to come from intermediate-age stars (<1% by mass, ~1 Gyr old).



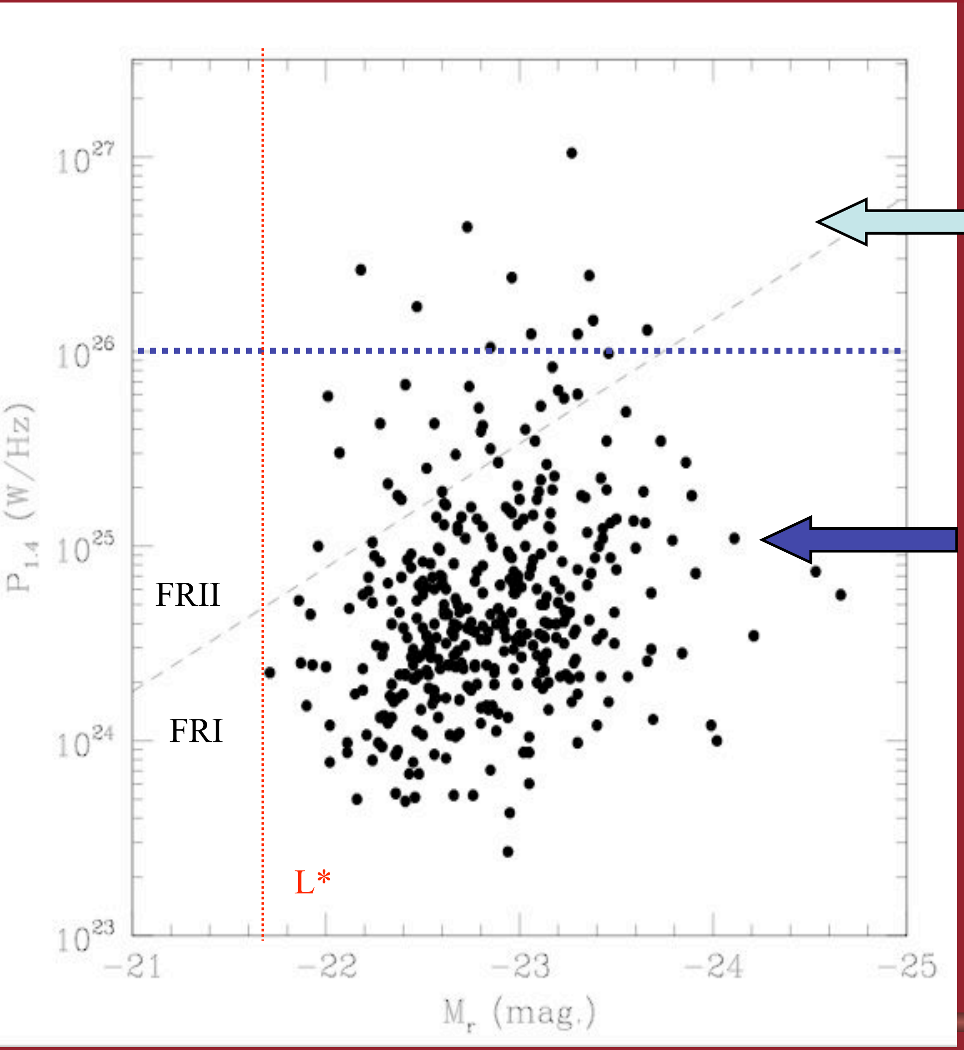
But binning in *radio power*, we find that the most powerful radio galaxies (>10^{26} W/Hz) have a significantly *younger* (~100 Myr) intermediate-age stellar population.



(Johnston et al. 2007)



The most powerful radio galaxies (>10^{26} W/Hz) have strong emission lines, AND a young (100 Myr) stellar population.



Recent mergers?

Rapid evolution like ULIRGS, QSOs.

Represent ~ 0.5% of massive galaxies at z~0.6

'Passive' radio galaxies?

Evolution as $(1+z)^2$, similar to cosmic SF density.

Not yet observed beyond z~0.7.

Summary

- Demographics of massive galaxies and black-hole activity now mapped in detail to z~0.7 (lookback time 6-7 Gyr). No clear evidence that most of these radio galaxies are triggered by mergers.
- We *can* use these data to estimate BH merger rates! And we have some candidates for binary/merging BH systems - i.e. rare (<1% of massive galaxies at z~0.5), powerful radio galaxies which show evidence of a young (~100 Myr) stellar population.
- If you want to actually *detect and study* candidate BH mergers in significant numbers out to z~2, maybe better to use AT20G! And locally, perhaps eVLBI studies of extreme starburst/merger systems (lower BH masses?)