The radio source - host galaxy connection

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With thanks to:
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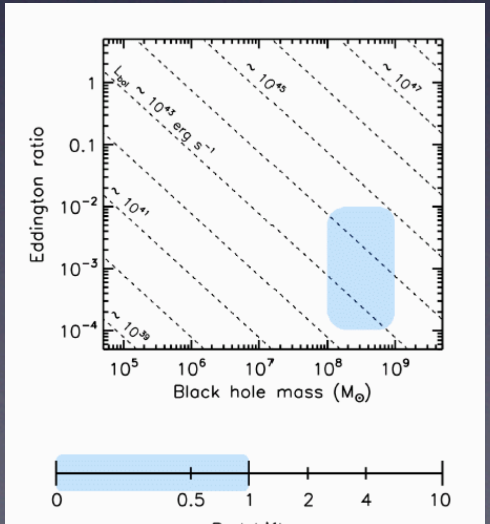
Overview of talk

- Part 1: Radio-source energetics and feedback
  - Galaxy formation models & AGN feedback
  - Energetics of radio sources & the global AGN energy budget
  - Why radio-loud AGN?
  - Radio-AGN duty cycle and time-averaged energetics

- Part 2: Radio-source modes, triggering & cosmic evolution
  - Radio source populations
  - High vs low excitation sources
  - A triggering / feedback loop with hot gas halos
  - Cosmic evolution of the low-excitation population



Part 1:

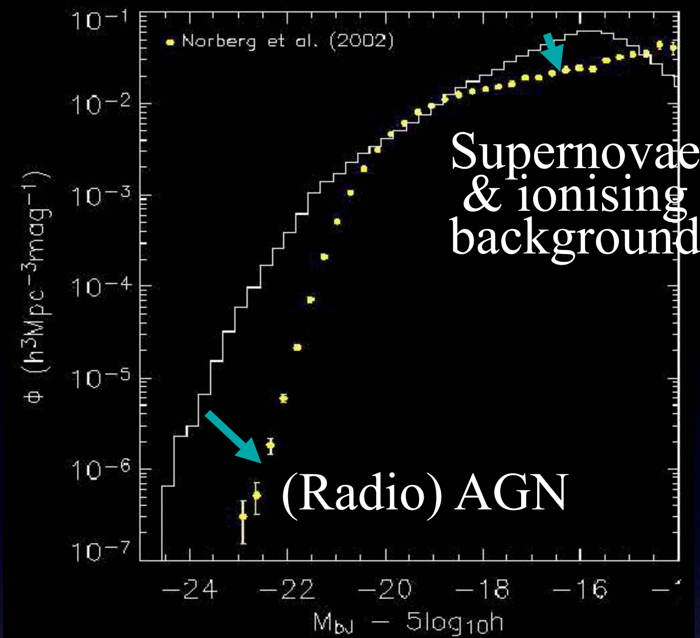
Radio source energetics and feedback

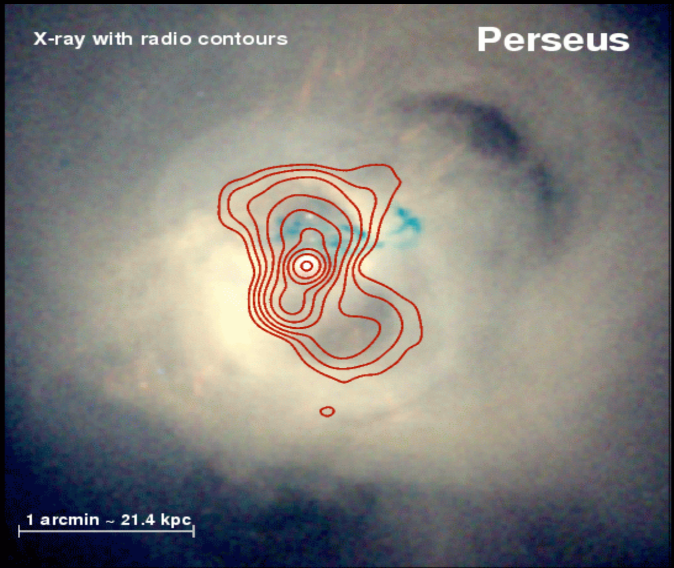
AGN feedback

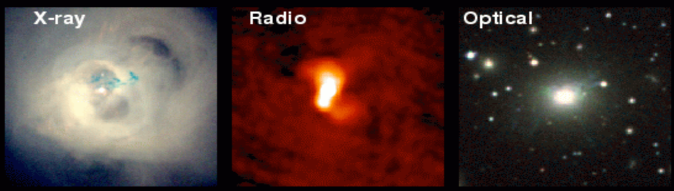
"AGN feedback" is currently postulated to explain many issues in galaxy evolution:

- Black-hole - bulge mass relation
- Avoidance of over-production of massive galaxies
- "Old, red and dead" appearance of massive ellipticals

I will argue the case that recurrent radio-loud AGN activity is responsible for the latter two.







Energetics of radio sources

It is difficult to estimate the total energetics of radio sources as most of the energy is in mechanical (jet) form rather than radiative. [Simple arguments suggest $L_{mech} \approx 100\text{-}1000\ \nu L_\nu$]

- One estimate uses cavities blown in hot X-ray gas by radio sources, $E_{cav} = f\ pV$ (where best estimate is f~4)

$$L_{mech} = (3.0 \pm 0.2) \times 10^{36}\ f\ (L_{1.4GHz} / 10^{25} \mathrm{W\ Hz^{-1}})^{0.40 \pm 0.12}\ \mathrm{W}$$

- Alternative uses minimum energy condition for radio synchrotron

$$L_{mech} = 1.4 \times 10^{36}\ f_W\ (L_{1.4GHz} / 10^{25} \mathrm{W\ Hz^{-1}})^{0.85}\ \mathrm{W}$$

where $f_W \sim 10$ incorporates the uncertainty factors (nature of jet plasma; low energy synchrotron cutoff)

Jets & the cosmic energy budget

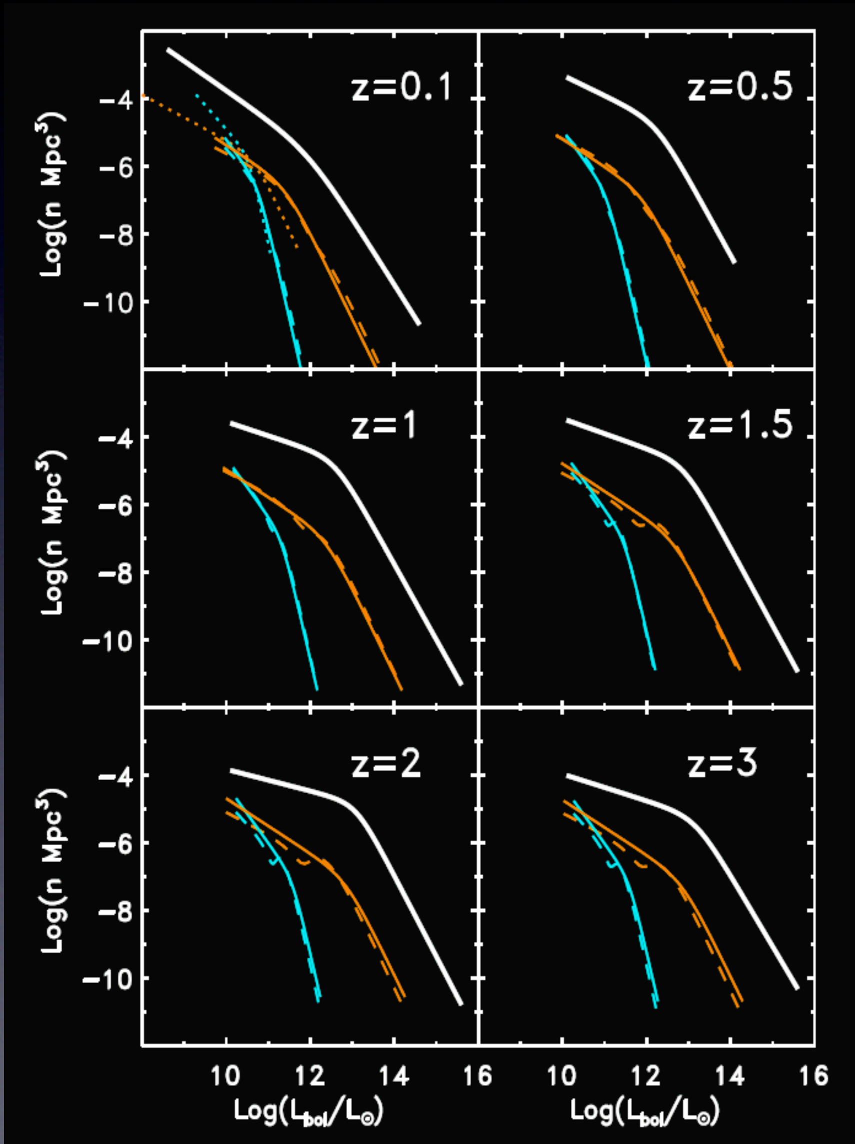
(Cattaneo & Best 2009)

Convolving these relations with the radio LF gives the total bolometric heating rate of AGN in a kinematic mode, as a function of redshift

This can be compared with estimates of the radiated AGN bolometric luminosity.

Radio-AGN produce 2-10% of the total AGN energy budget, and are dominated by AGN radiation at all z.

[Figure: white line = QSO BLF; blue,red = kinetic LF from cavities, min energy]



Radio-AGN & massive galaxies

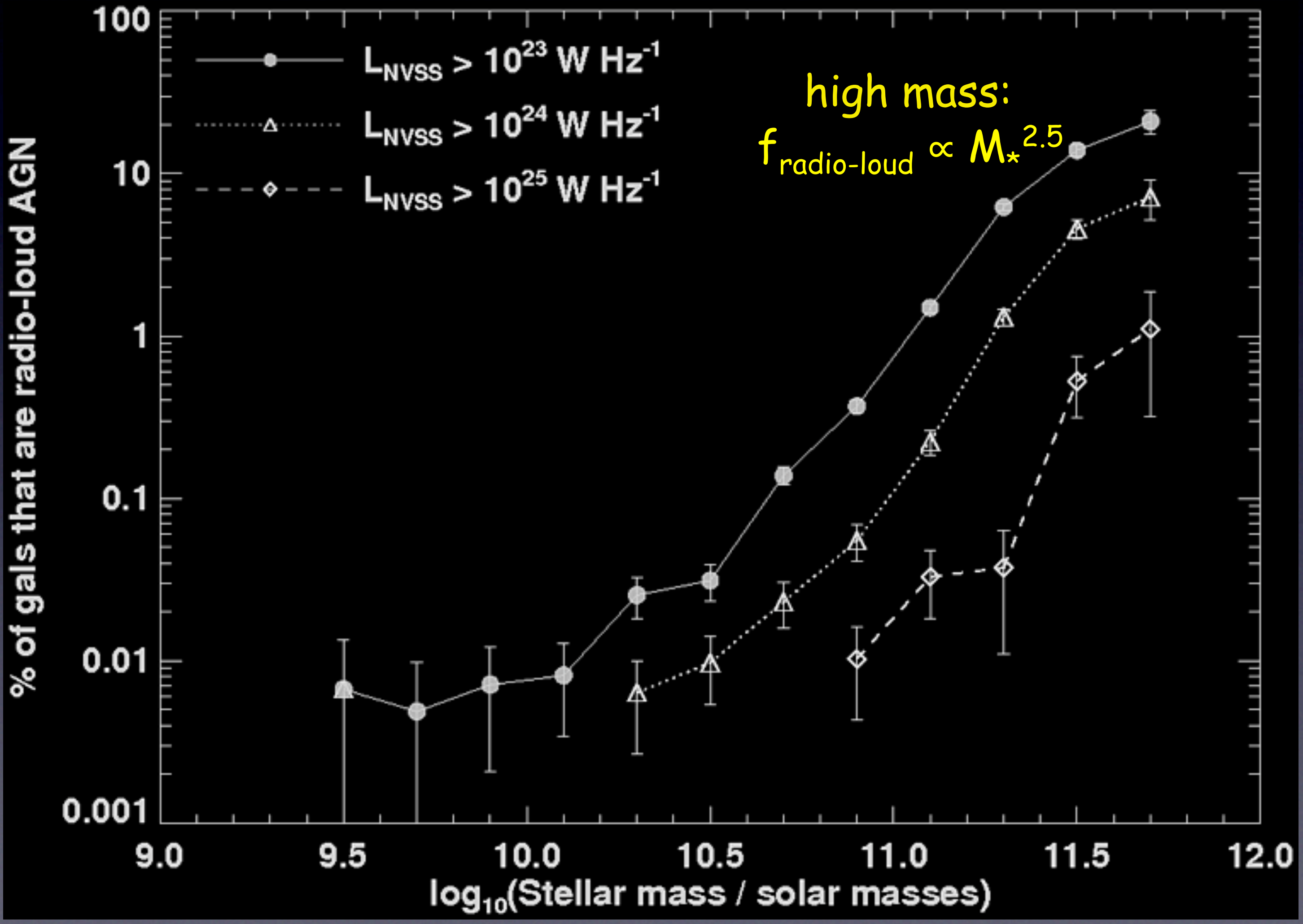
Radio-jet energetics cosmically unimportant compared to radiative output, but the energy is all deposited locally.

- Radio-AGN therefore provide the dominant AGN source for inputting energy locally to a host galaxy

Use a statistical study of SDSS galaxies to investigate:

- What fraction of galaxies are radio-loud AGN, as a function of galaxy (black-hole) mass?
- What is the radio LF, and hence the mechanical LF
- How does the time-averaged radio-AGN heating rate compare with the cooling rate of the hot gas halo? - do they provide enough energy to control galaxy growth?

Mass fraction of radio-loud AGN



Mass-dependent radio luminosity function

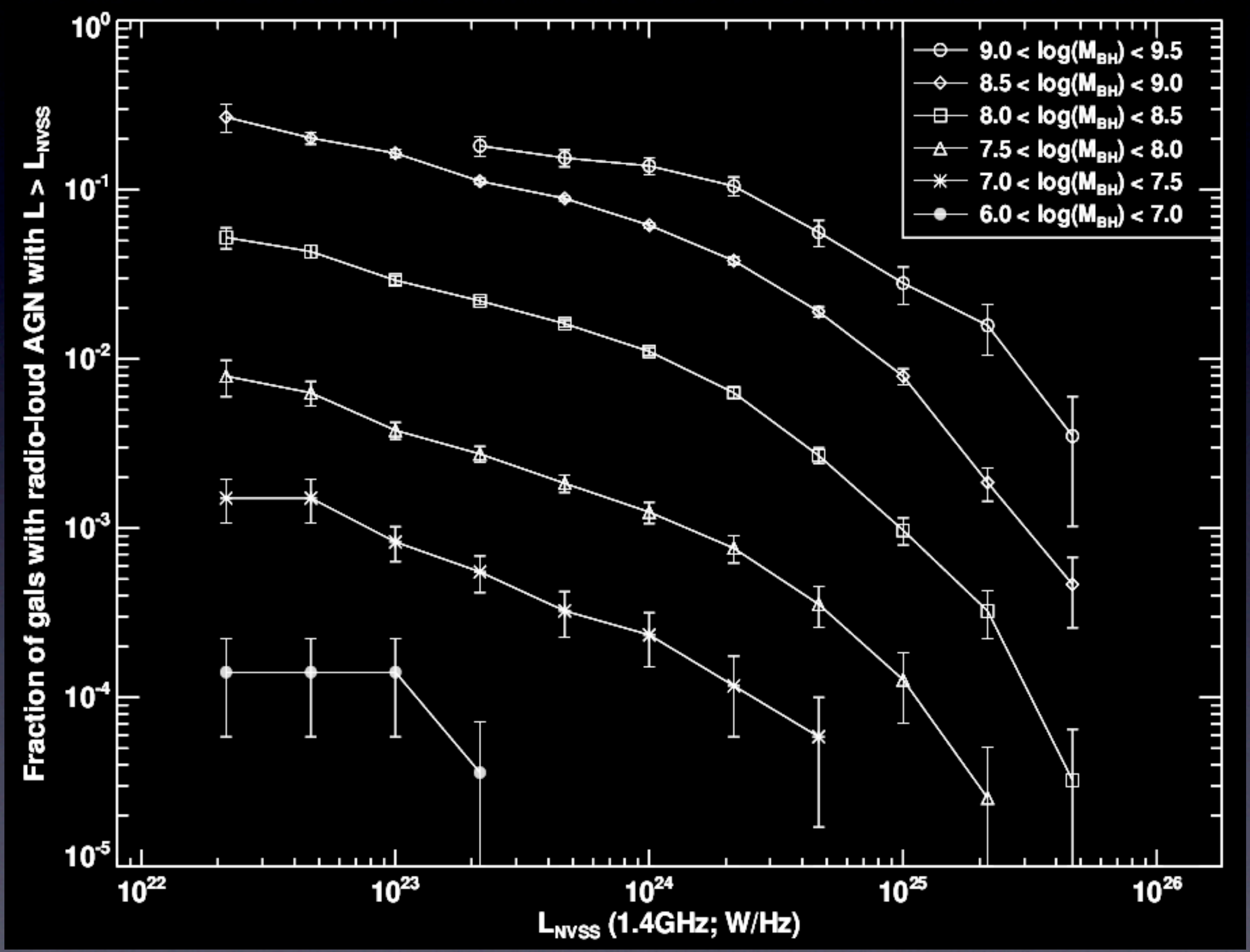


Figure: the fraction of galaxies that host radio-loud AGN as a function of both black hole mass and radio luminosity.

Large size of SDSS sample of radio-loud AGN allows the luminosity function to be derived as a function of mass.

Luminosity function has a similar shape (and characteristic break luminosity) at all masses.

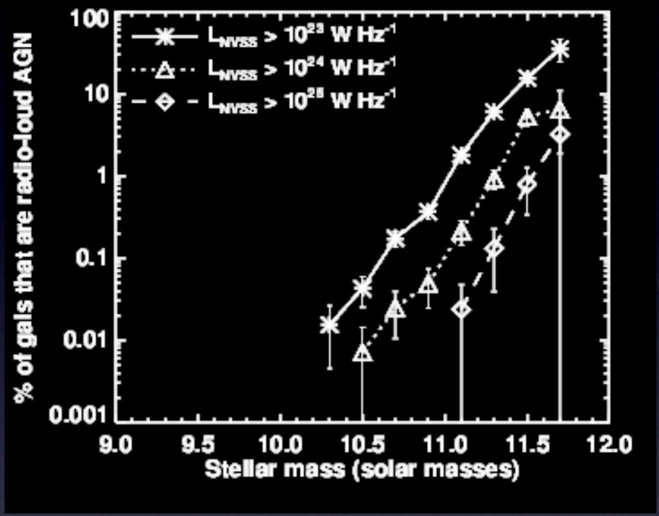
Recurrent radio activity, and energetics

Best et al 2006, MNRAS, 368, L67

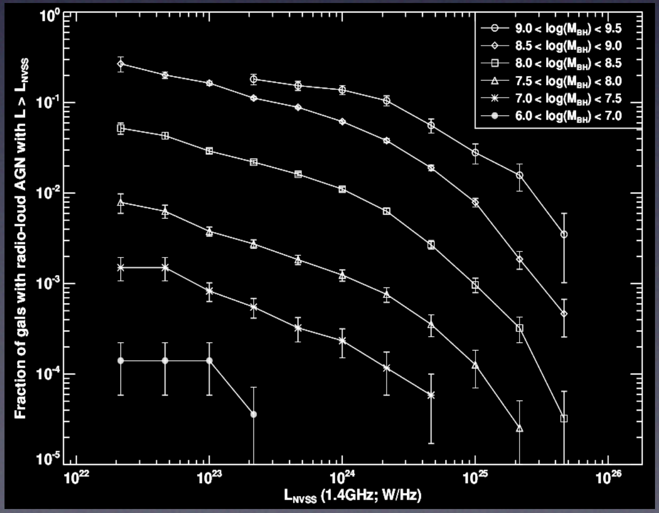
Radio sources live for only 10^7-10^8 yrs.

Nevertheless, the previous results suggest that at least 25% of the most massive galaxies are radio-loud.

⇒ Radio sources must be constantly re-triggered



We can then interpret the "fraction of gals of given mass that are radio-loud at a given luminosity" probabilistically as "the fraction of time that a galaxy of given mass spends emitting at a given radio luminosity"



Time-averaged radio AGN heating

Combining the L_{mech} vs L_{rad} relation with the mass-dependent radio luminosity function gives the time-averaged heating rate due to radio sources, as a function of black hole mass:

$$H = 10^{21.4}\, f\, (M_{BH} / M_{sun})^{1.6} \;\; W$$

Normalisation comes from radio LF and L_{mech}-L_{rad} conversion

Mass dependence comes from mass-dependence of radio-loud fraction

Uncertainties in L_{mech} vs L_{rad} relation only lead to a change in the normalisation of the relation (accounted for in "f" factor)

Heating versus Cooling

Compare:

- Bolometric X-ray luminosity (rate at which energy is radiated from the host haloes)
- Derived radio-AGN heating rate for ellipticals, as a function of galaxy mass (luminosity)

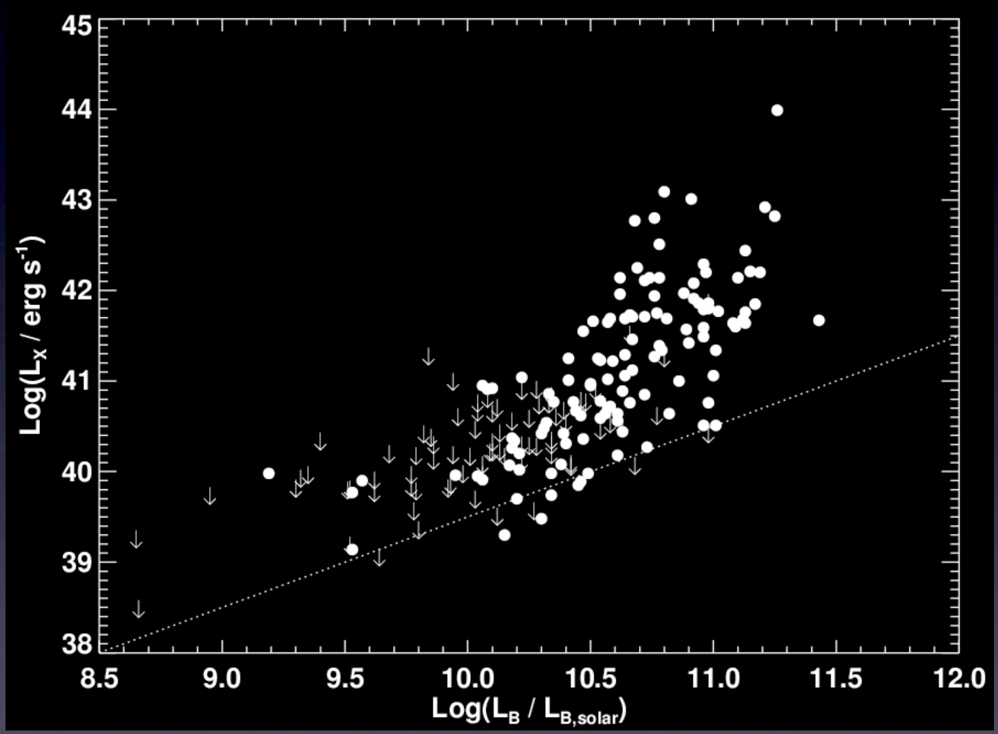


Figure: Bolometric X-ray luminosity vs optical luminosity of elliptical galaxies (from O'Sullivan et al 2001).

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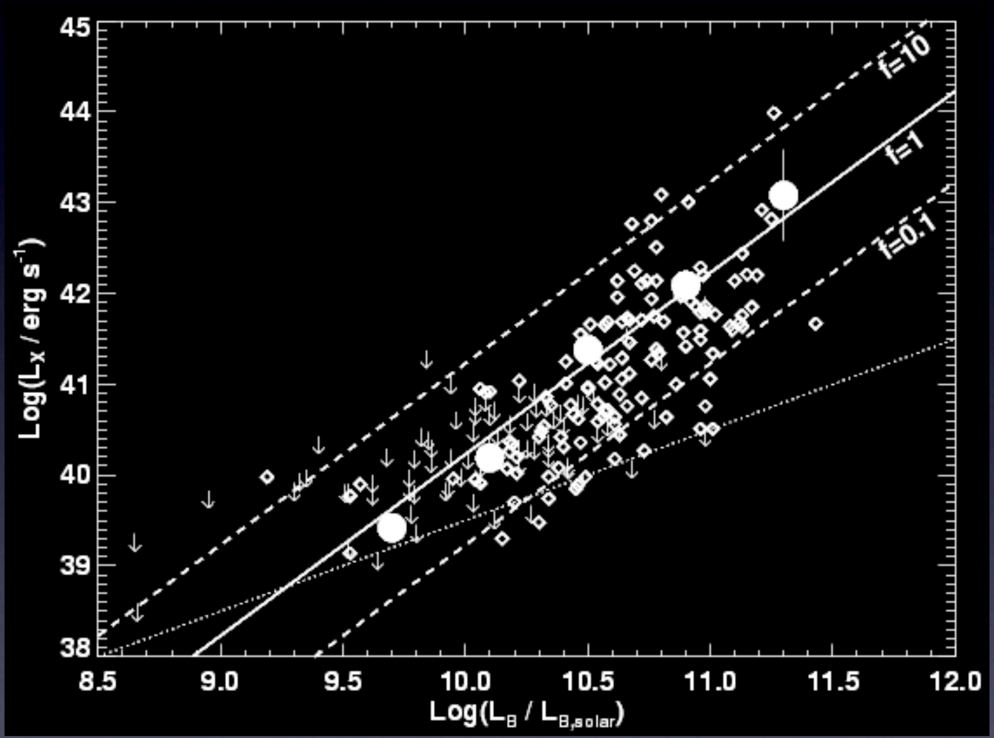


Heating from radio-loud AGN (over-?) balances gas cooling for elliptical galaxies of all masses

Interpretation: part 1

- For all ellipticals, the time-averaged heating due to radio sources balances the radiation losses from the hot gas
- Therefore the radio source may prevent gas cooling, and control the rate of growth of the galaxies.

⇒ Energetically this can solve problems of semi-analytic models of galaxy formation.

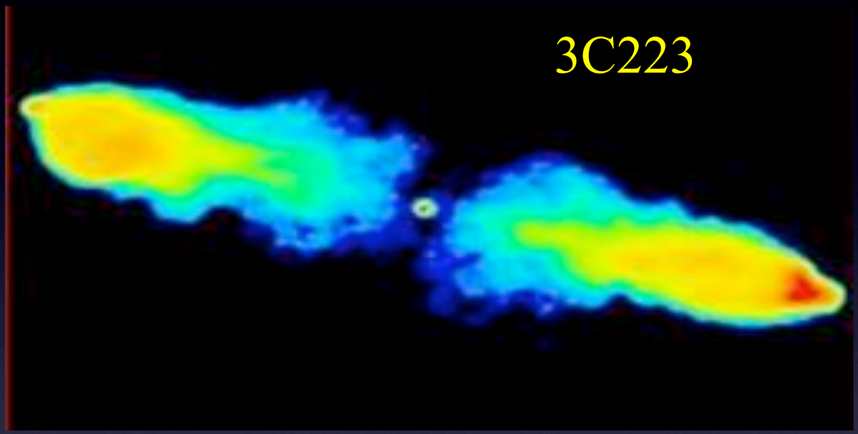
⇒ To understand this physically (e.g. a feedback cycle) we still needs to understand which radio source populations are involved and how they are triggered......

Part 2:

Radio source modes, triggering and cosmic evolution

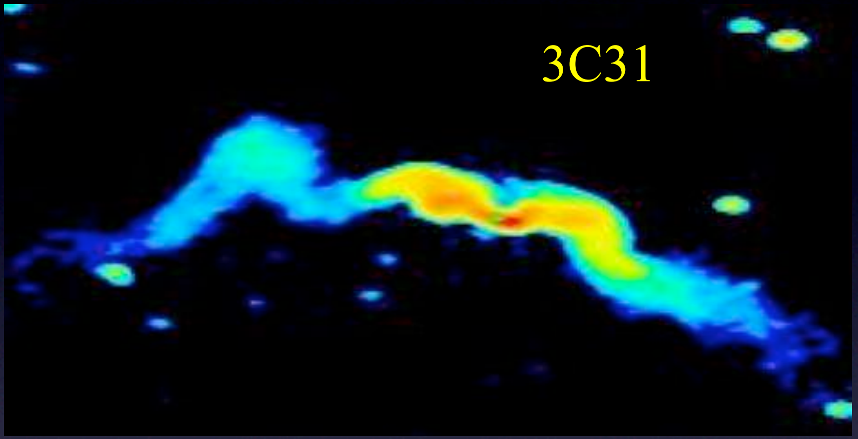
Radio source morphologies

Fanaroff & Riley Class 2 (FR2)



- "edge brightened"
- high L_{rad} ($P_{1.4GHz}$ >~ 10^{25} W/Hz)
- jets remain well-collimated
- optical host quasar or galaxy (gals often with hidden AGN)
- most have high-power high-excitation emission lines

Fanaroff & Riley Class 1 (FR1)



- "edge darkened"
- low L_{rad} ($P_{1.4GHz}$ <~ 10^{25} W/Hz)
- jets decelerate & entrain
- usually no optical / X-ray AGN (visible or obscured)
- generally only weak and low-excitation line emission

High / low excitation sources

Radiatively efficient / inefficient sources
"Quasar-mode" / "Radio-mode" sources

Most (but not all) FR1s, and a proportion of FR2 sources have very different properties to 'quasar-like' sources:

- Different emission line properties:
  - Very weak emission lines
  - Low excitation spectrum

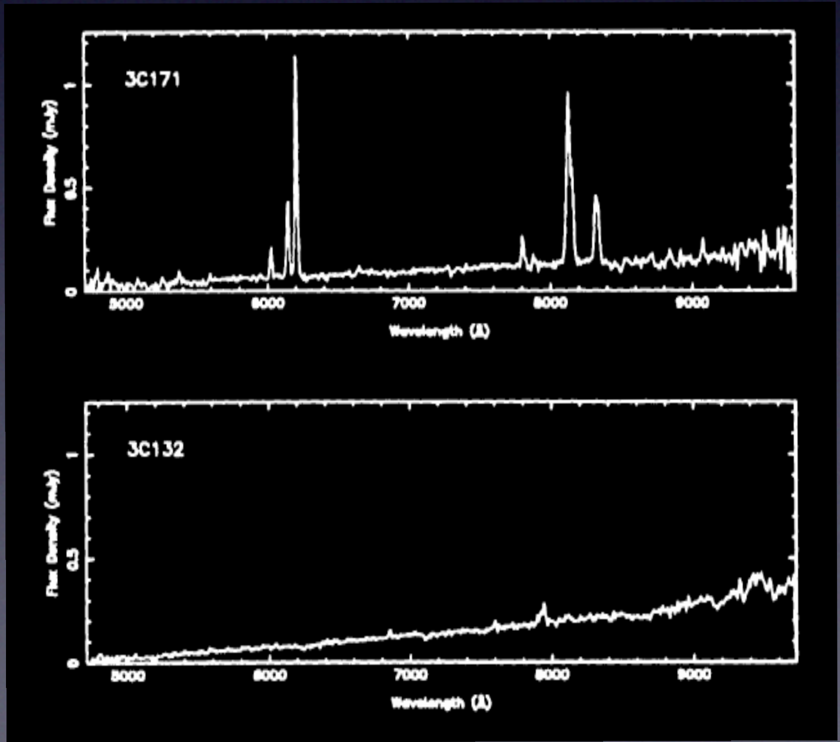


Figure: Spectrum of high and low-excitation FR2 radio source (from Laing et al 1994).

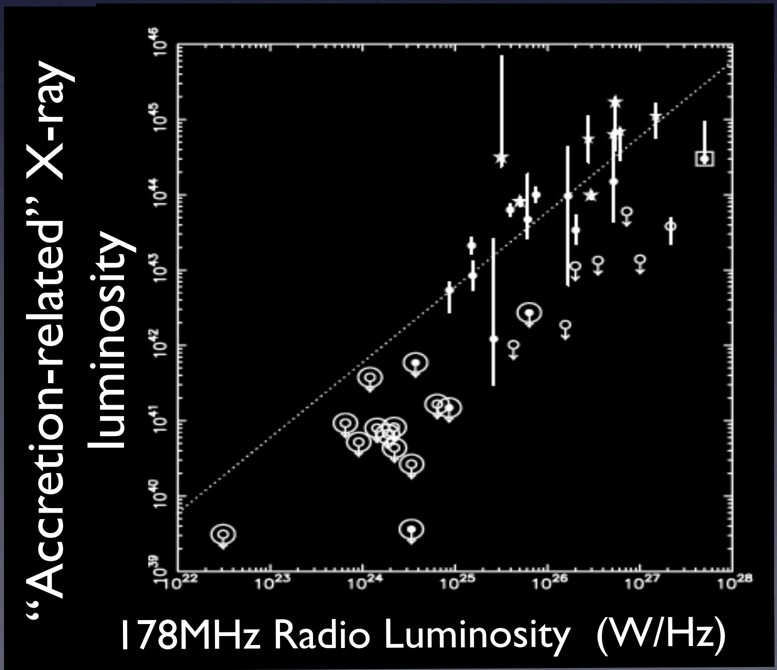
High / low excitation sources

Radiatively efficient / inefficient sources
"Quasar-mode" / "Radio-mode" sources

Most (but not all) FR1s, and a proportion of FR2 sources have very different properties to 'quasar-like' sources:

- Different infrared and X-ray properties
  - No evidence in IR for dusty torus
  - No accretion-related X-ray component.

Figure: X-ray luminosity of the highly-obscured (accretion-related) component of AGN vs radio luminosity: solid - high-excitation; open – low-excitation; circled – FR1. (From Hardcastle et al 2007).



Low excitation vs FR class?

The high / low excitation state of radio galaxies is a fundamental property of the active nucleus

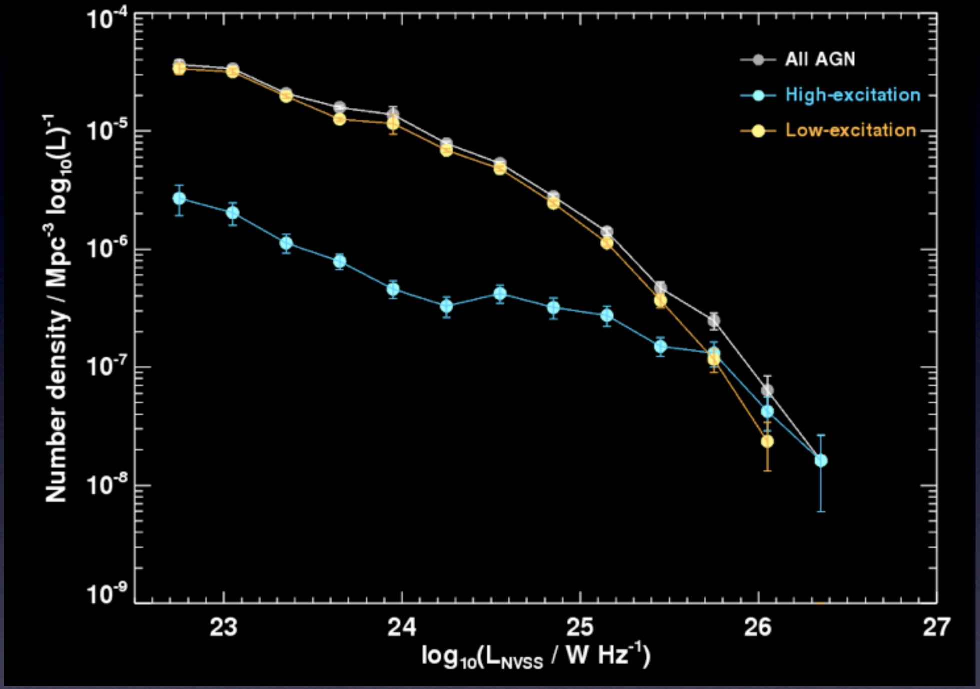
- radiatively efficient vs radiatively inefficient
- triggering mechanism?
- accretion rate / mode?
- black hole spin?

The FR1/2 classification is something entirely different

- large scale environmental effects?
  - "hybrid sources"
  - host galaxy dependences
- all sources begin as FR2s, but jet disrupts to FR1 in dense environments? (cf. Kaiser & Best 2008)

High vs low-excitation sources

- Population switch from low to high-excitation at ~$10^{25.5}$ W/Hz

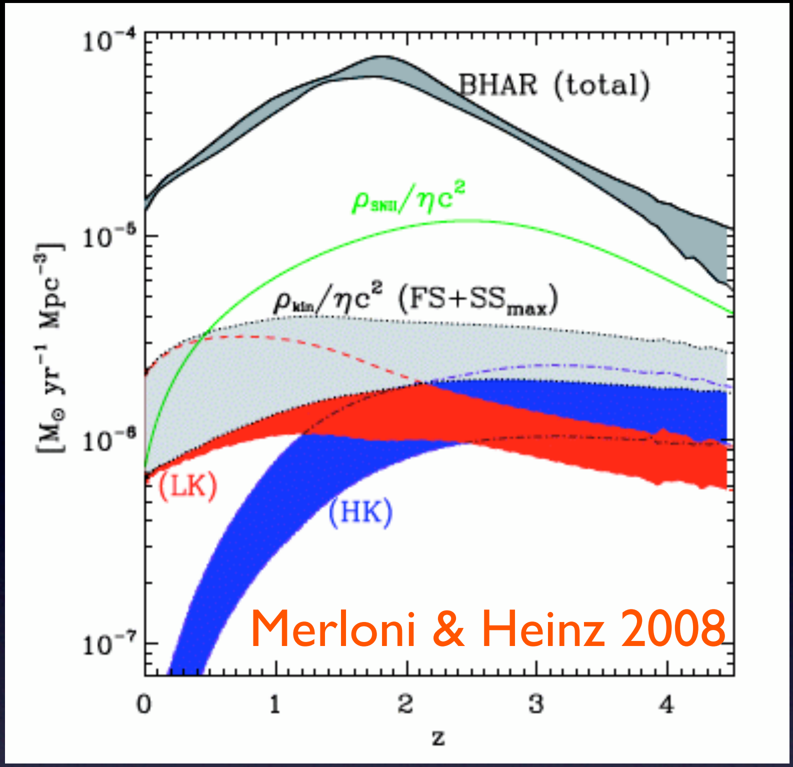


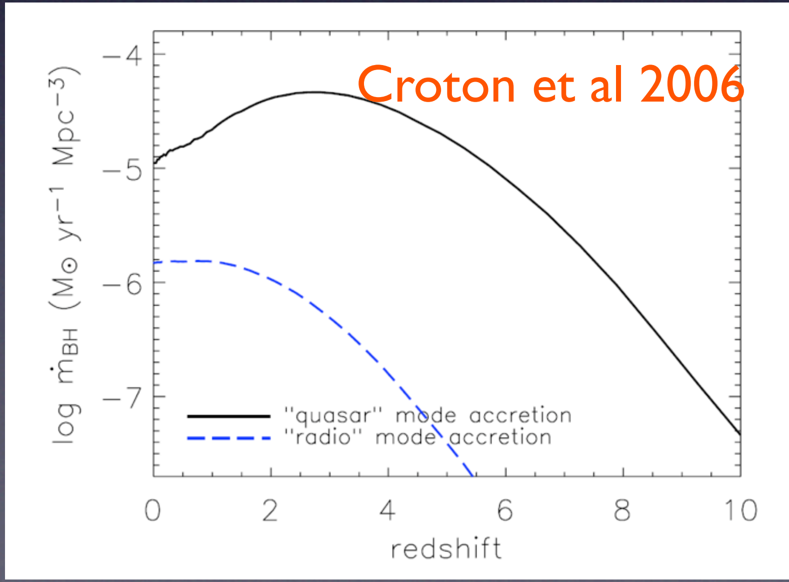
- But switch not sharp: high-excitation sources seen down to lowest luminosities
- Low-excitation sources dominate energetic output (low lum. events), and hence are those involved in feedback
- These require low accretion rates, as provided by Bondi accretion or by low cooling rates from hot gas halo
  - offers possibility of a feedback cycle

Cosmic evolution of the low-excitation radio population

A key observational requirement is determine the evolution of radio-AGN feedback (cf. models)

This requires us to determine the cosmic evolution of the low-excitation radio source population





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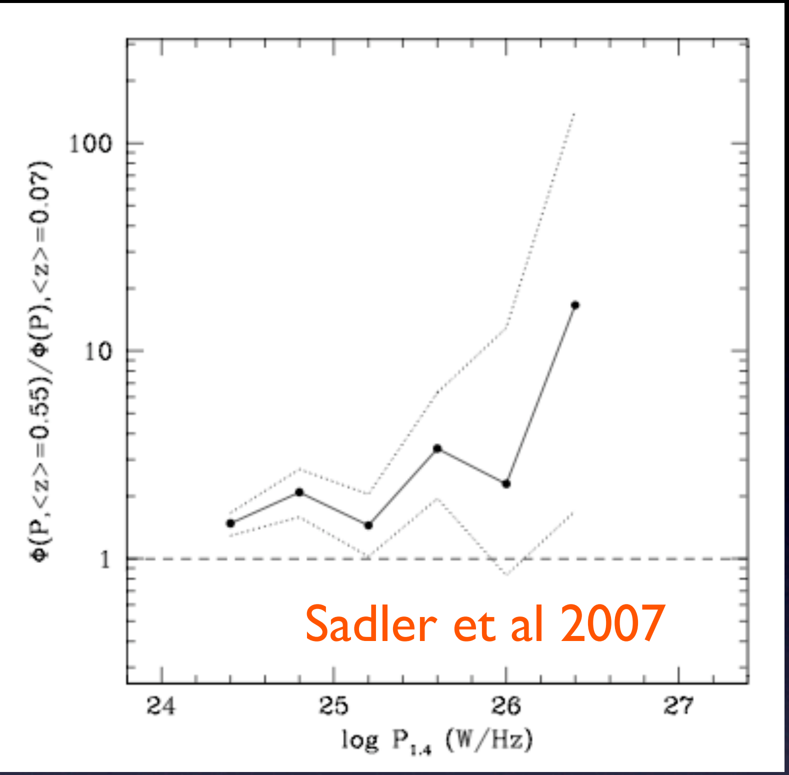
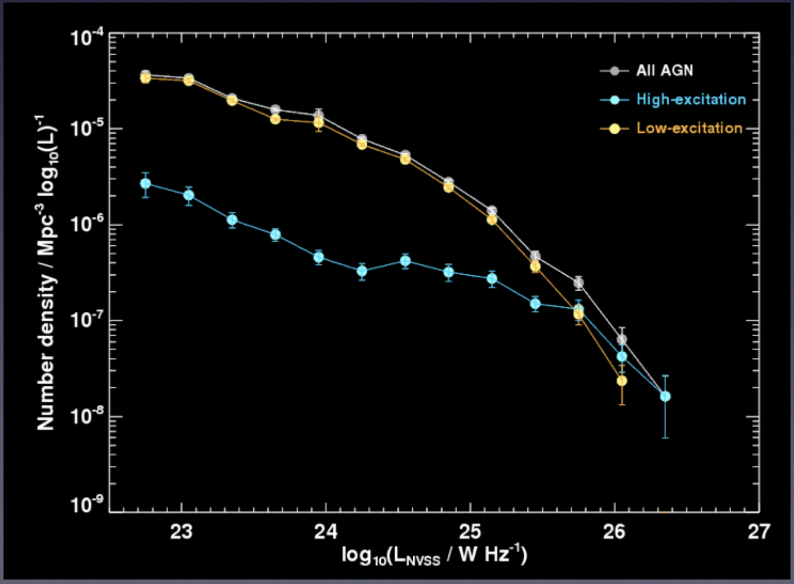
RLF does evolve positively (albeit weakly) at low power, but this is a mix of high & low excit. sources

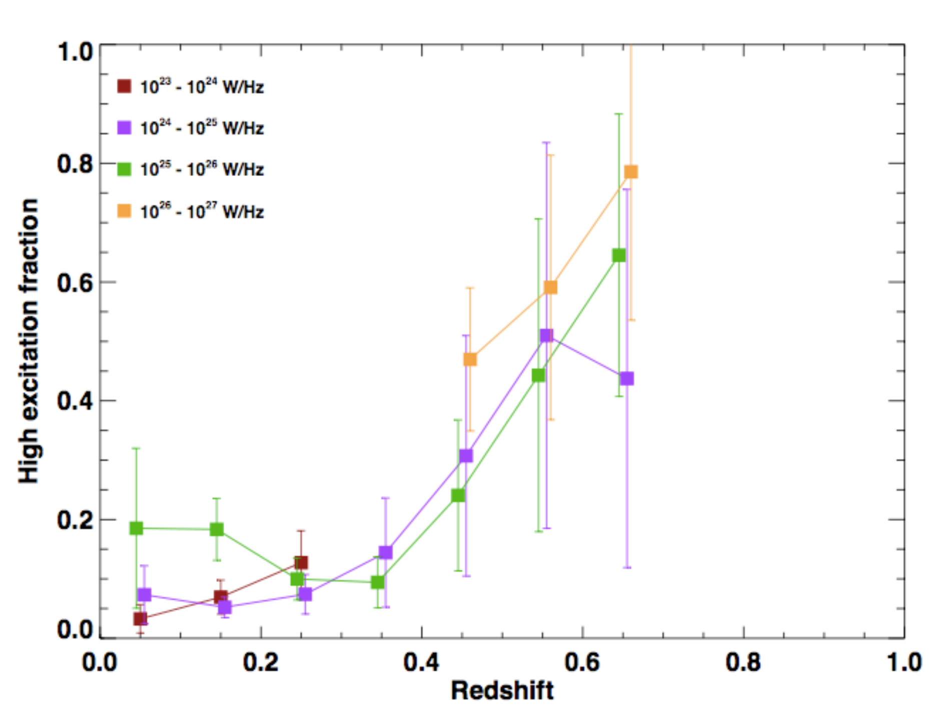




The high/low excitation ratio

If there's differential evolution of the high and low radio source populations, the ratio of high/low excitation sources should change with redshift.

Using the SDSS sample (with spectroscopic data) a trend is seen, but S/N is low because at high-z a growing fraction of sources can't be classified with SDSS data.



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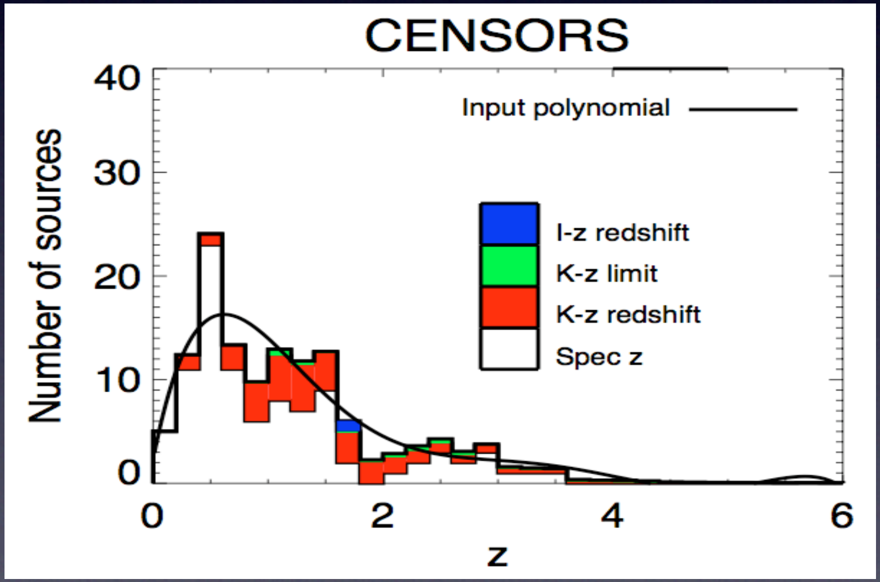
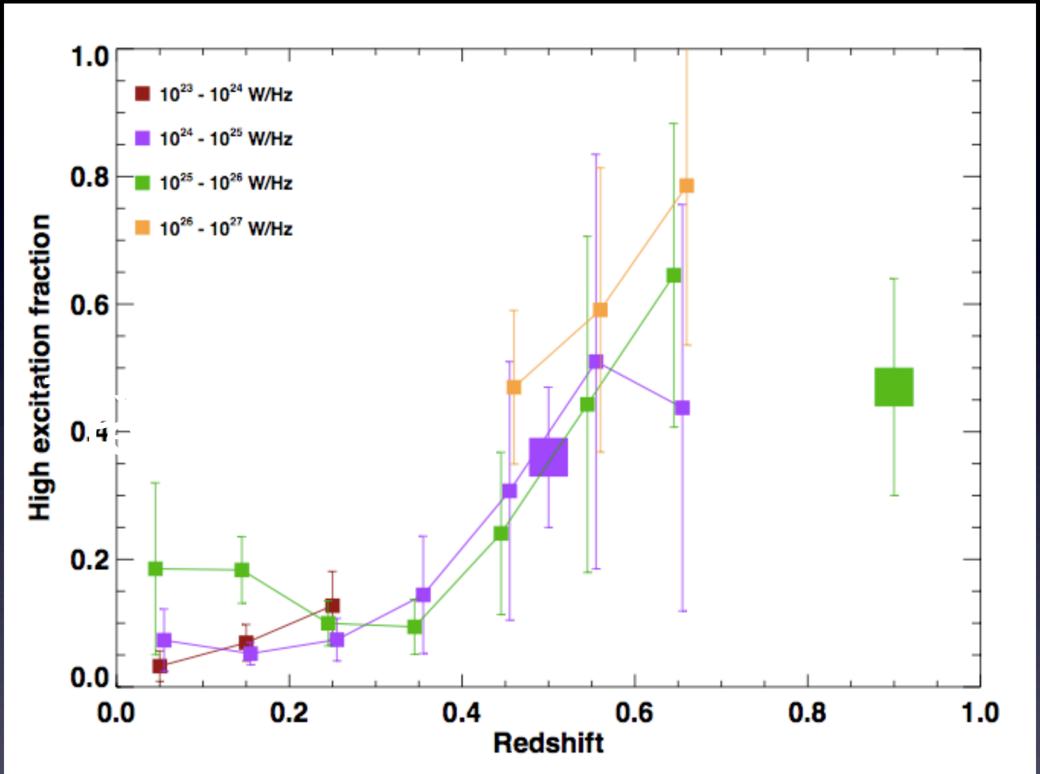


Compare with data from our CENSORS low-luminosity radio sample (150 sources to 7mJy, with deep spectroscopy)

The high/low excitation ratio

Clear increase in the high-excitation fraction at low luminosity, from 10-20% at z=0 to 40-50% at z~0.5-1.0.

(Weak) evolution of faint low-luminosity end of the RLF does not directly translate to evolution of "radio-mode" feedback.



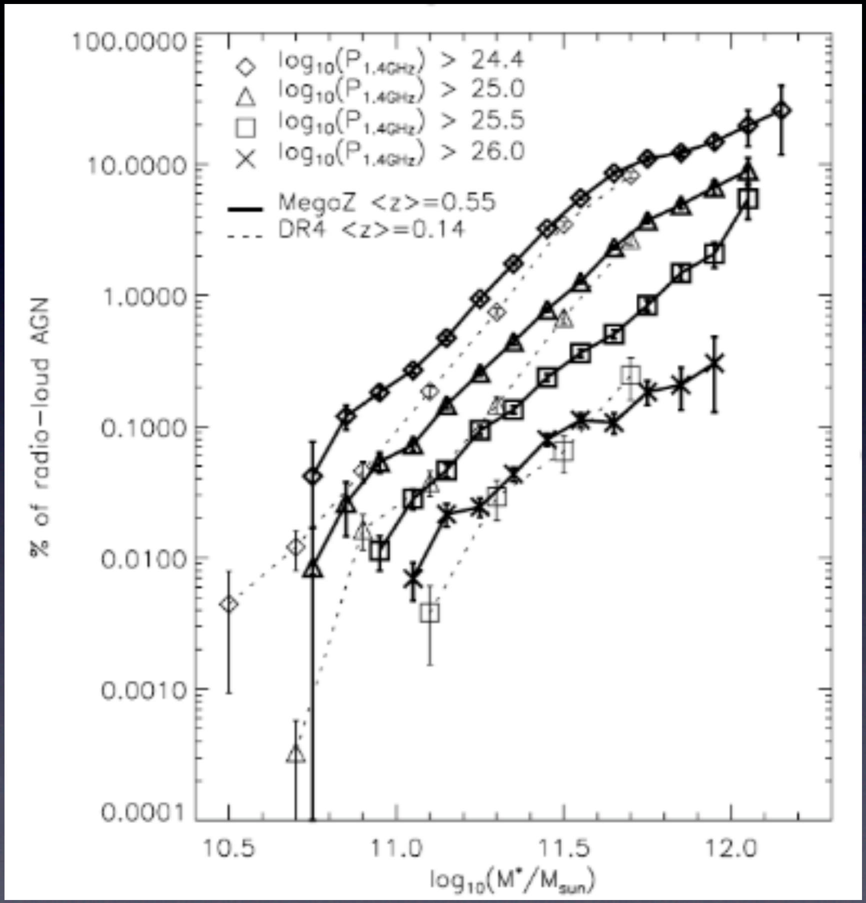
We are working to use CENSORS and complementary surveys to measure the evolution of the RLF of low excitation sources (= "radiatively inefficient mode" feedback). Results soon...

Evolution of the mass fraction

Look at how the fraction of galaxies hosting radio-loud AGN as a function of mass evolves with redshift:

- Using large SDSS Mega-Z LRG sample (Donoso et al 2009)
- Using deeper radio sample in XMM-LSS (Tasse et al 2009)

At high masses essentially the same relation is found out to z~1 as in the local Universe



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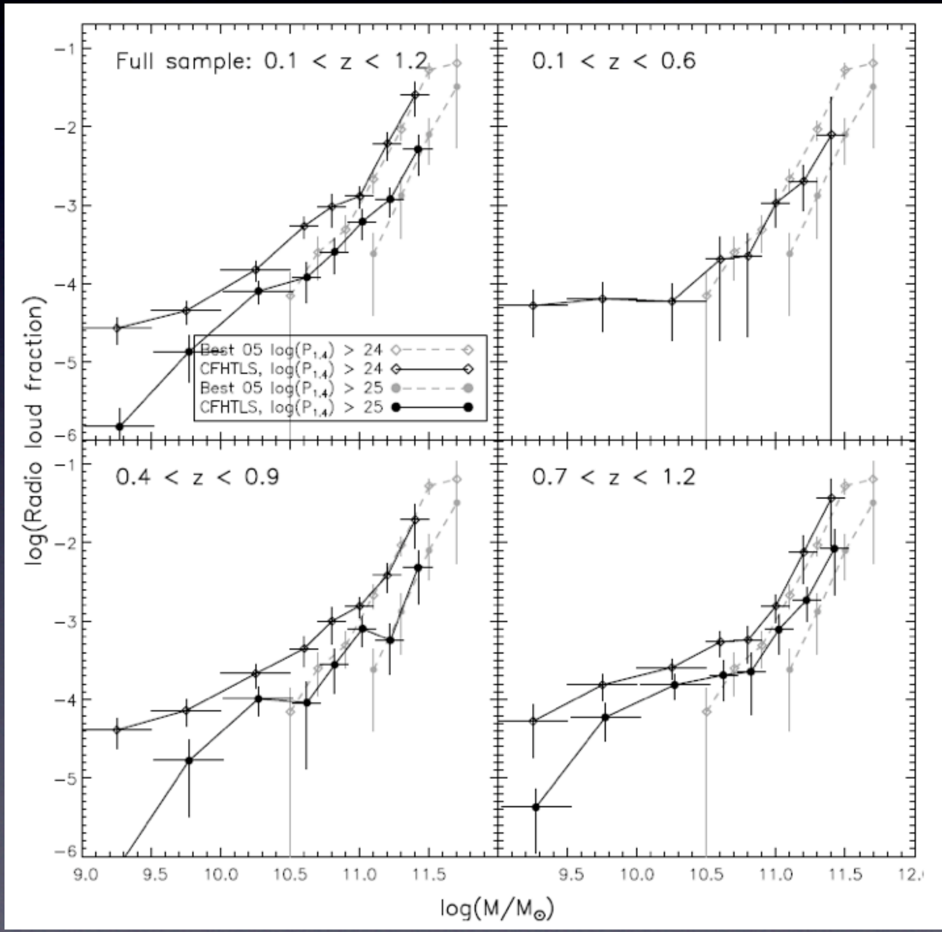

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Turn-up in relation at low mass due to high-excitation pop

Summary

- Low luminosity radio source activity is highly-recurrent with a fast duty cycle, especially in the most massive gals
- "Radio-mode" AGN feedback is associated with a population of low-excitation radio sources, which dominate the low-luminosity end of RLF (and are distinct from FR1/FR2 split!) Better name: "radiatively ineffecent mode"
- These are fuelled at low accretion rates, probably directly or indirectly from the hot gas halo. Energetic output (over-?) balances cooling rates, leading to feedback cycle.
- Radio-AGN vs mass relation doesn't evolve much to z~1. RLF of low-excitation sources also evolves little, but no precise measurements have yet been made.