The host galaxies of AGN and radio-AGN feedback

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With thanks to:
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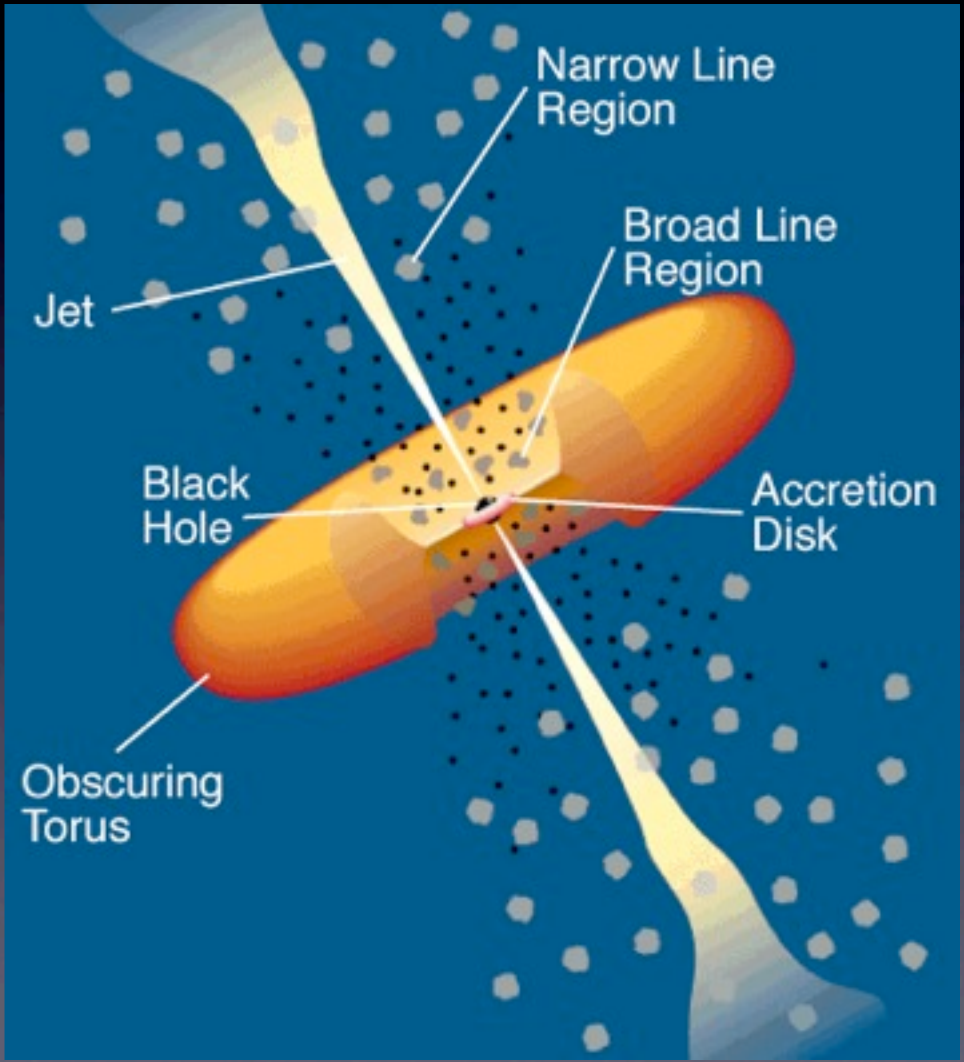
Overview of talk

- Part 1: AGN accretion modes
  - Two observed types of AGN
  - Evidence for radiatively inefficient accretion
  - Relative importance of the two accretion modes
- Part 2: AGN host galaxies
  - Differences in host galaxies of different AGN classes
  - Implications for triggering and fuelling of AGN
- Part 3: Radio-AGN feedback
  - Energetics of radio sources
  - Controlling the growth of massive elliptical galaxies
  - Evolution of radio-AGN feedback

Part 1:
AGN accretion modes

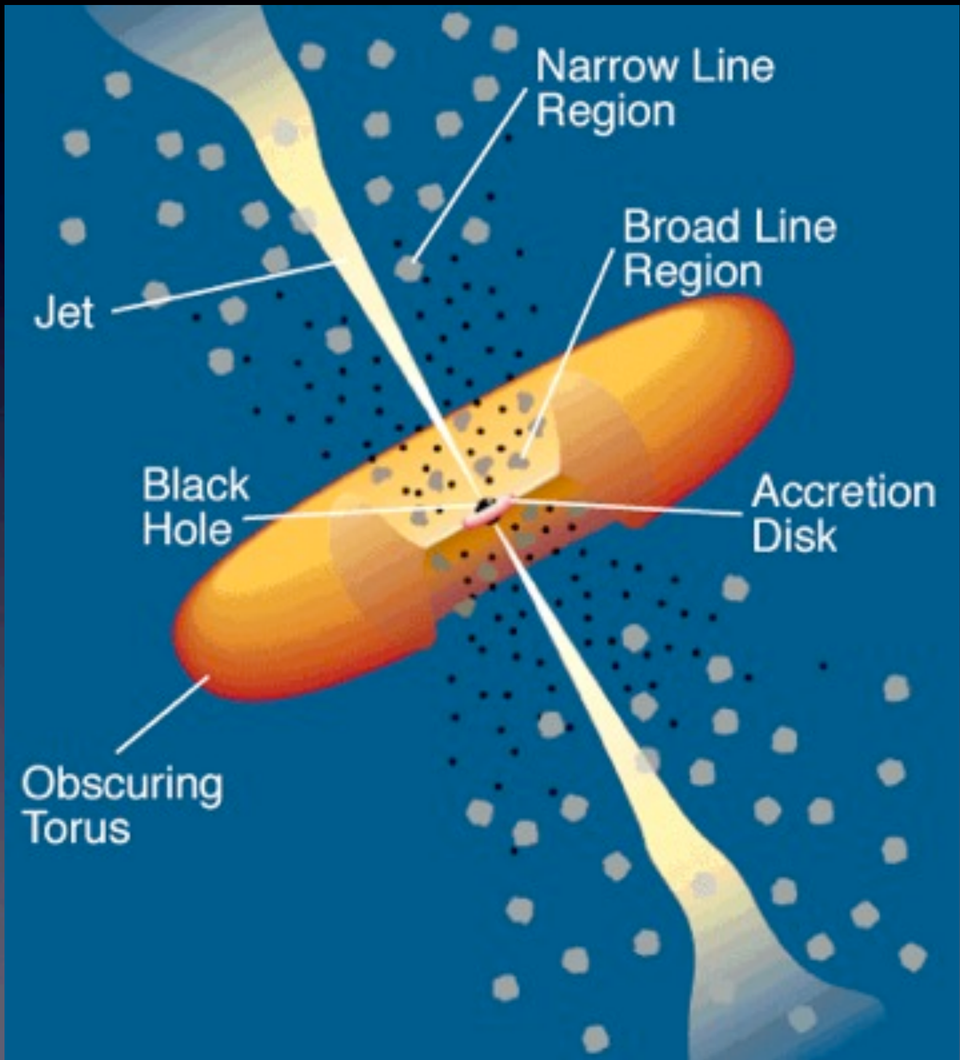
"Standard" picture of AGN



"Standard" AGN have:

- Luminous accretion disk (with X-ray corona)
- Bright line emission (ionised by disk)
- Dusty obscuring torus (emits in IR/sub-mm)
- Orientation-dependent observed properties
- Sometimes, extended radio jets

Another class of AGN



Other AGN, exemplified by weak radio sources, don't fit this scheme:

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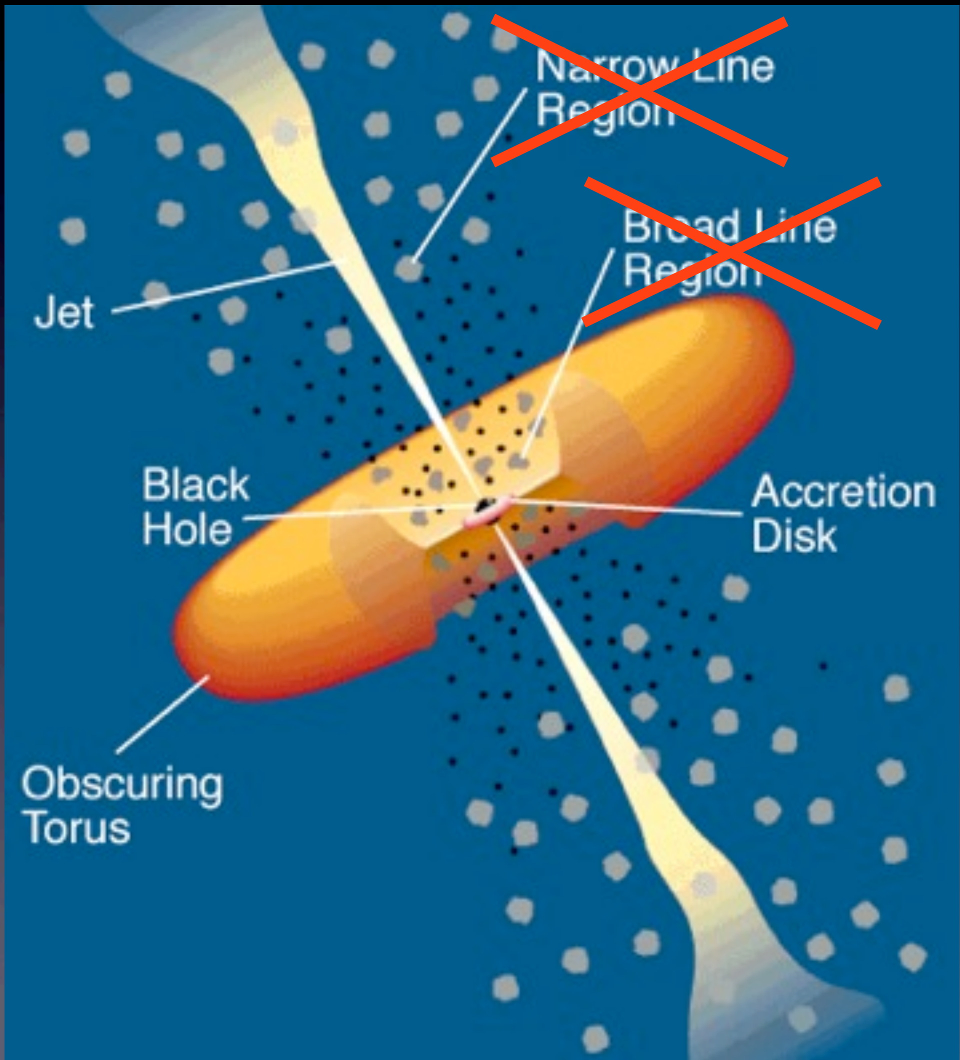

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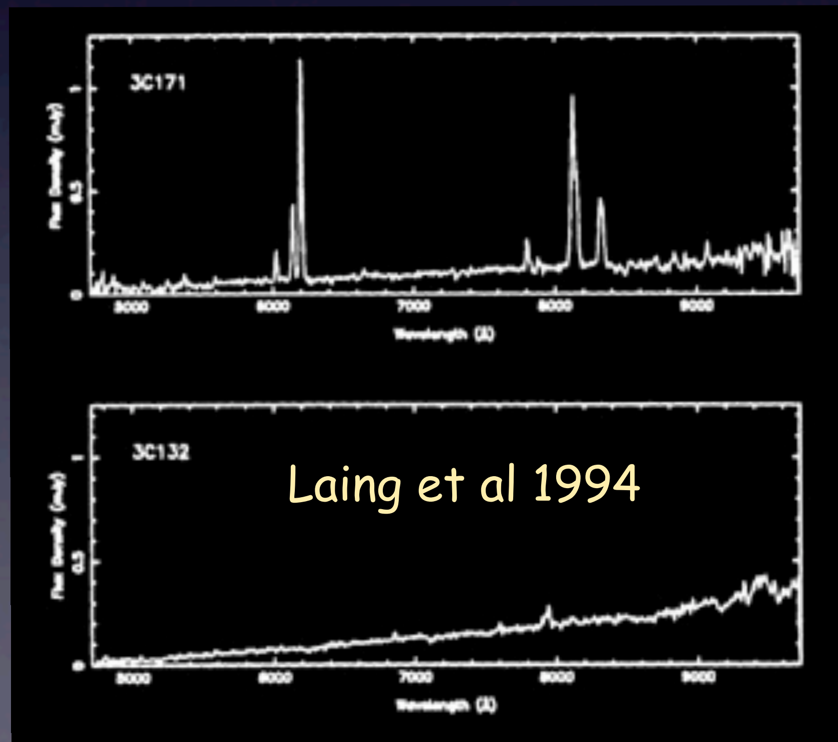
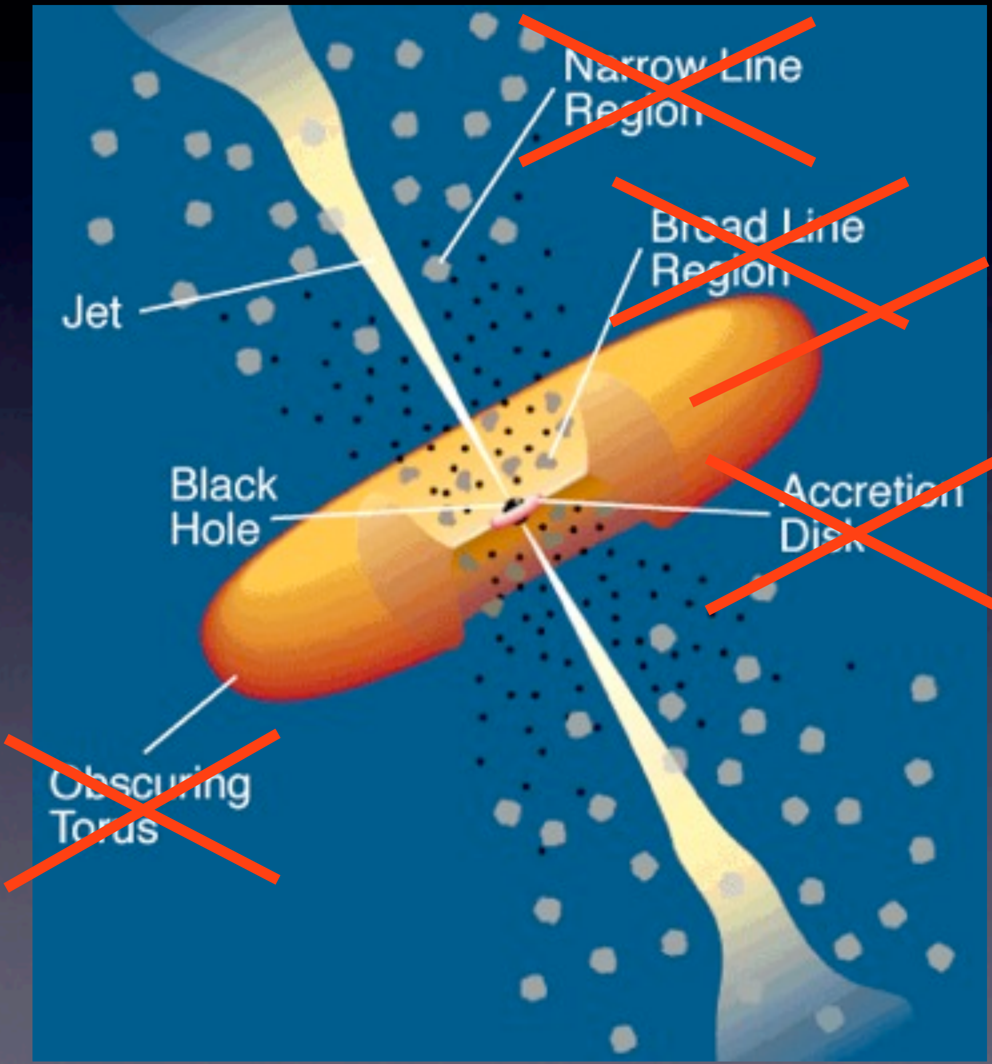


Another class of AGN



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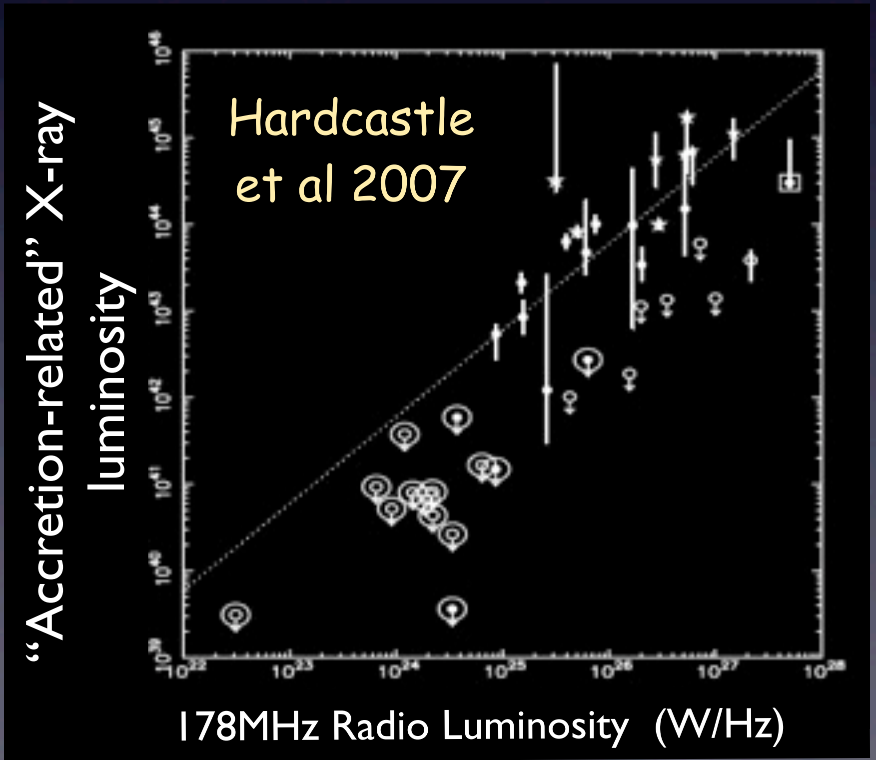
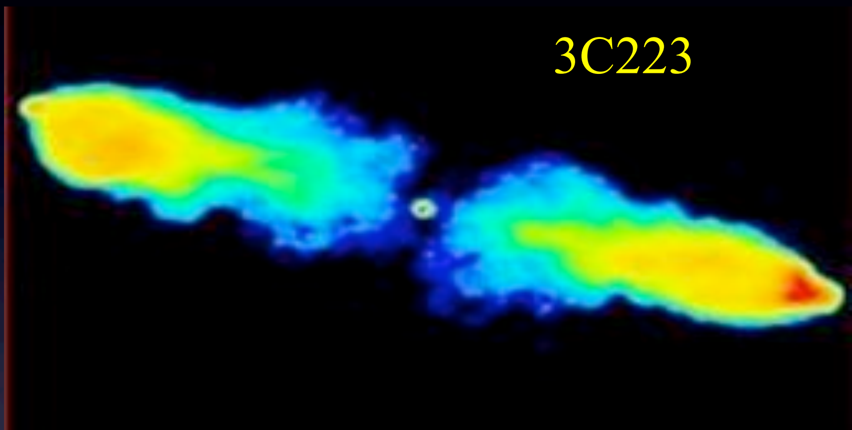


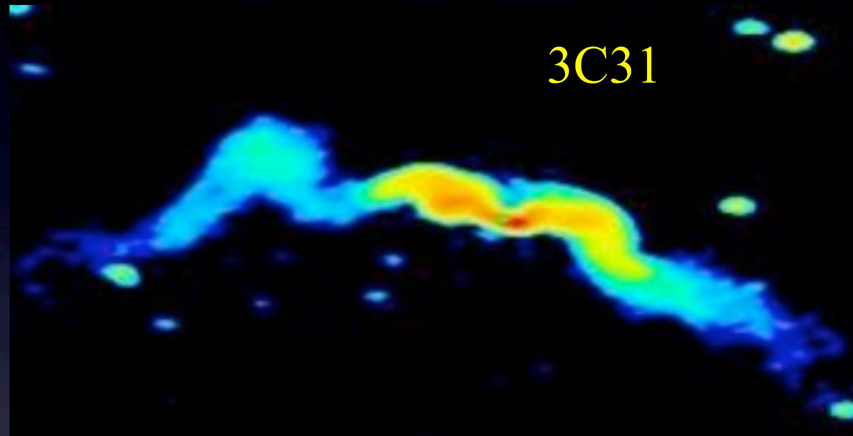
Aside: not same as FR-split

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
- mostly, but not always, strong-lined, quasar-like sources

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
- mostly, but not always, weak-lined, inefficient sources

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

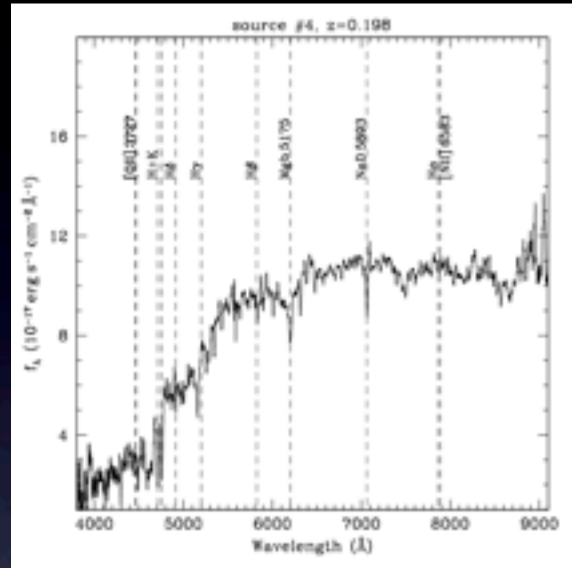
- large scale environmental effects?
  - "hybrid sources"
  - host galaxy dependences
- all sources begin as FR2s, but jet disrupts to FR1 in dense environments? (cf. Kaiser & Best 2008)

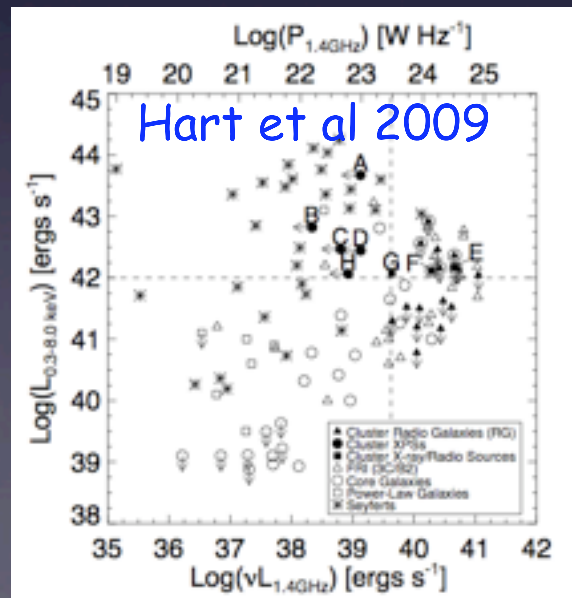
More jet-dominated AGN?

Deep X-ray surveys have discovered a population of X-ray bright but optically normal galaxies ("XBONGs")

- Powered by AGN
- No or very weak emission lines
- No evidence for X-ray absorption (so unlikely to be heavily absorbed)
- X-ray to radio ratios a factor ~100 higher than weak radio sources

AGN with jet only, Doppler-boosted X-rays, but not radio-boosted BLLacs?

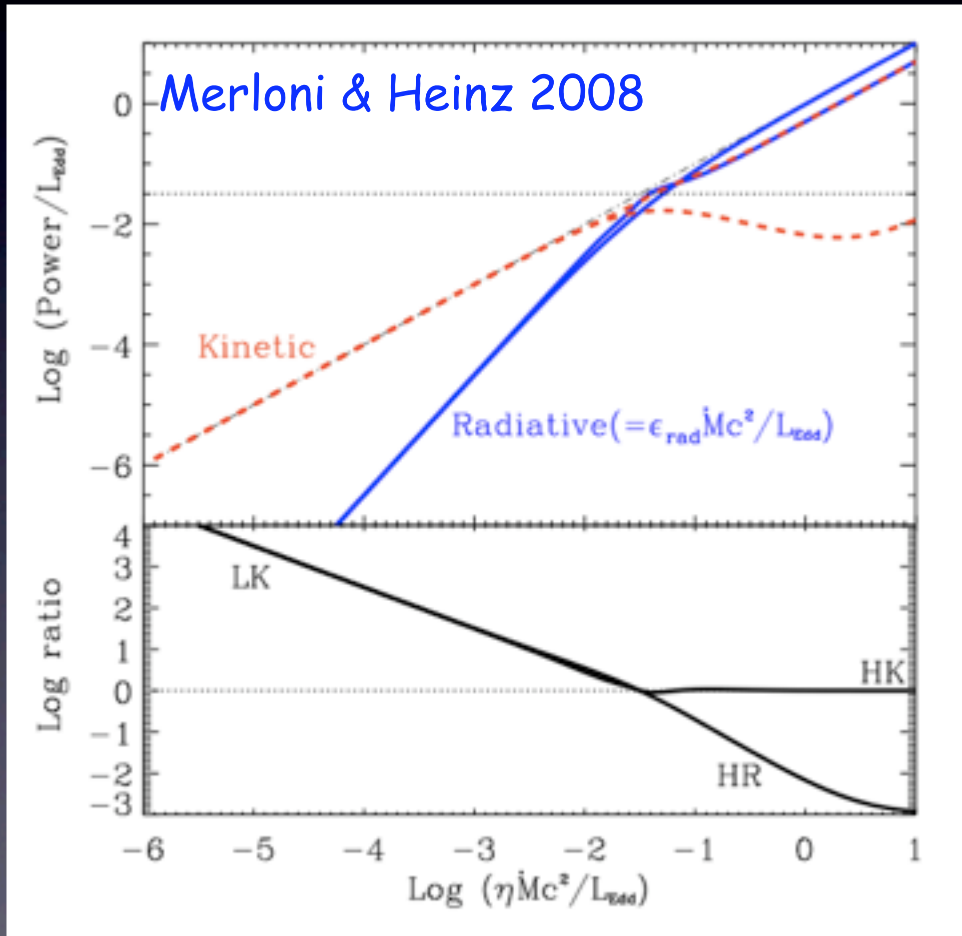




Why different AGN?

Accretion models predict a change in the nature of the accretion flow at low fractions of Eddington:

- low accretion - most energy comes out as jets in "kinetic mode"
- high accretion - strong radiative emission, sometimes also with radio jets



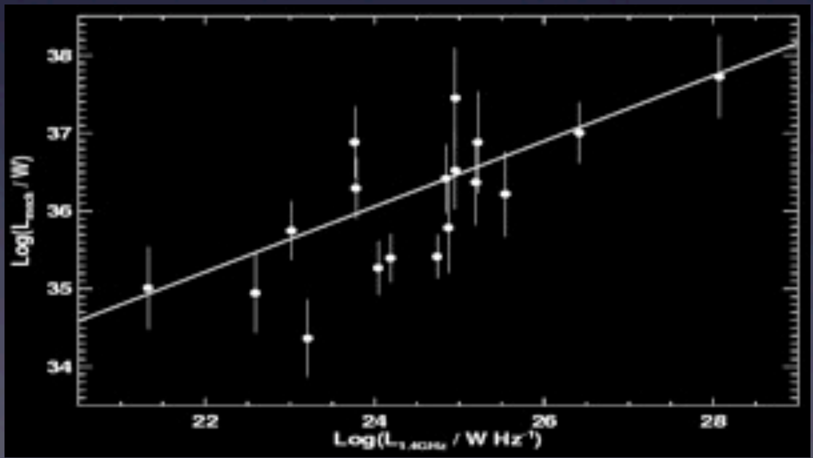
Testing accretion models

- Cross-matched SDSS DR7 with radio catalogues
  - sample of >18,000 radio sources
- Classify all radio galaxies as high- or low excitation
  - use SDSS emission line ratios (where possible)
  - use [OIII] 5007 line equivalent width
- Estimate black hole masses from velocity dispersions
- Calculated radiative luminosity, scaling from [OIII] 5007
  - corrected for reddening using Hα/Hβ line ratio
  - calibrated using quasars (cf. Heckman et al 2004)
- Estimated mechanical (jet) luminosity from radio luminosity......

Energetics of radio sources

Most of the energy of radio sources is in mechanical (jet) form. Simple arguments suggest $L_{mech} \approx$ 100-1000 νL_ν

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



$L_{mech} = 8 \times 10^{37}\ f\ (L_{1.4GHz}\ /\ 10^{25} \mathrm{W\ Hz^{-1}})^{0.70}\ \mathrm{W}$ (Cavagnolo et al 2010)

Energetics of radio sources

An alternative estimate uses minimum energy condition for radio synchrotron (cf Willott et al 1999)

$$L_{mech} = 1.4 \times 10^{36}\ f_W^{3/2}\ (L_{1.4GHz}\ /\ 10^{25} W\ Hz^{-1})^{0.85}\ \ W$$

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

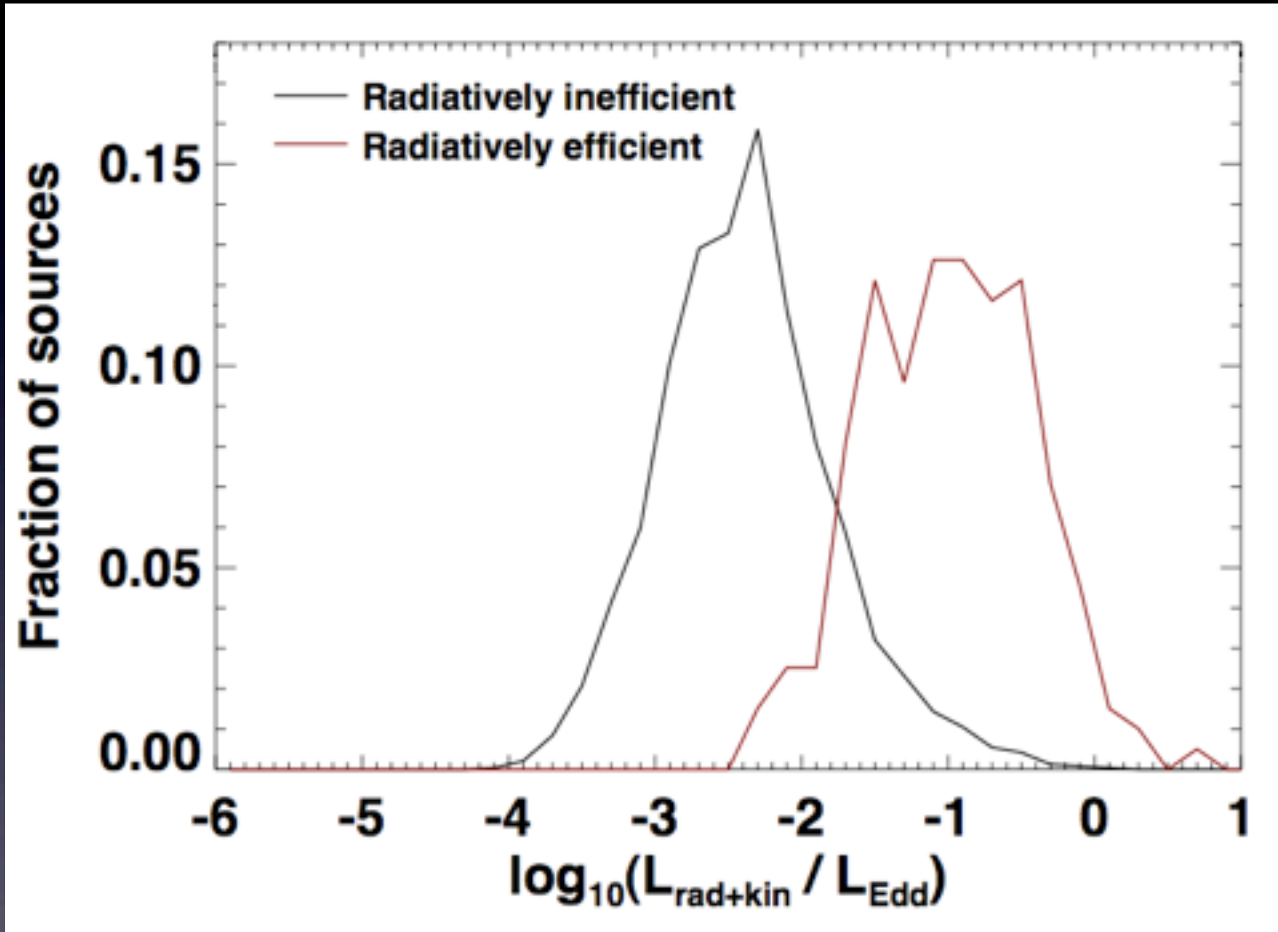
Comparing the two, for best-estimate values:

$$L_{mech,sync} \sim 4 \times 10^{37}\ (L_{1.4GHz}\ /\ 10^{25} W\ Hz^{-1})^{0.85}\ W$$

$$L_{mech,cav} \sim 3 \times 10^{37}\ (L_{1.4GHz}\ /\ 10^{25} W\ Hz^{-1})^{0.70}\ W$$

Agreement between two estimates is well within scatter.

Accretion modes of low-z RGs



Given all uncertainties on estimates, the agreement with a dichotomy at accretion rate $\log(L/L_{edd}) \sim -1.5$ is quite good

A word on nomenclature

"Standard" AGN:

- High-excitation
- Strong-lined
- Quasar-mode
- Cold-mode
- Radiative mode

=> Radiatively efficient

(standard accretion disk)

"Non-standard" AGN:

- Low-excitation
- Weak-lined
- Radio-mode
- Hot-mode
- Kinetic mode

=> Radiatively inefficient

(ADAF/RIAF/ADIOS)

Jets & the cosmic energy budget

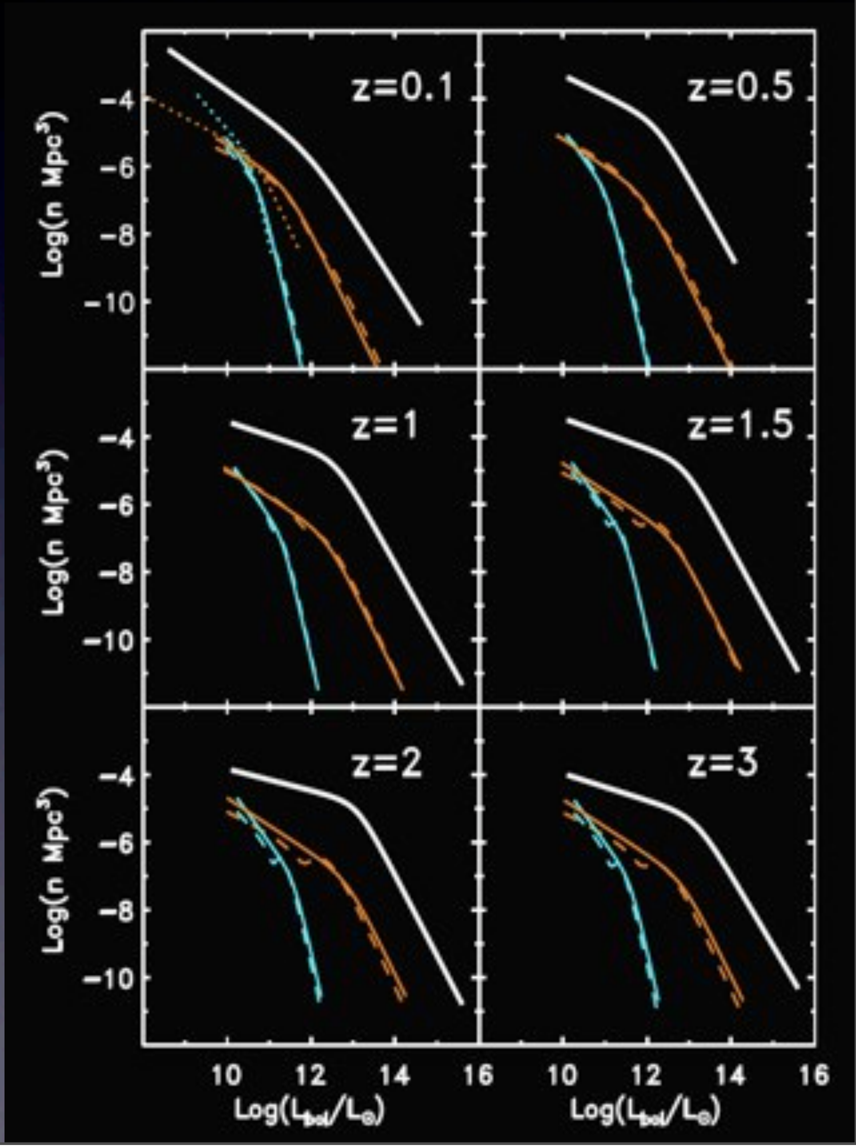
(Cattaneo & Best 2009)

Convolving the relations between radio and mechanical luminosity with the radio LF gives 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.

Typically at least an order of magnitude lower.....

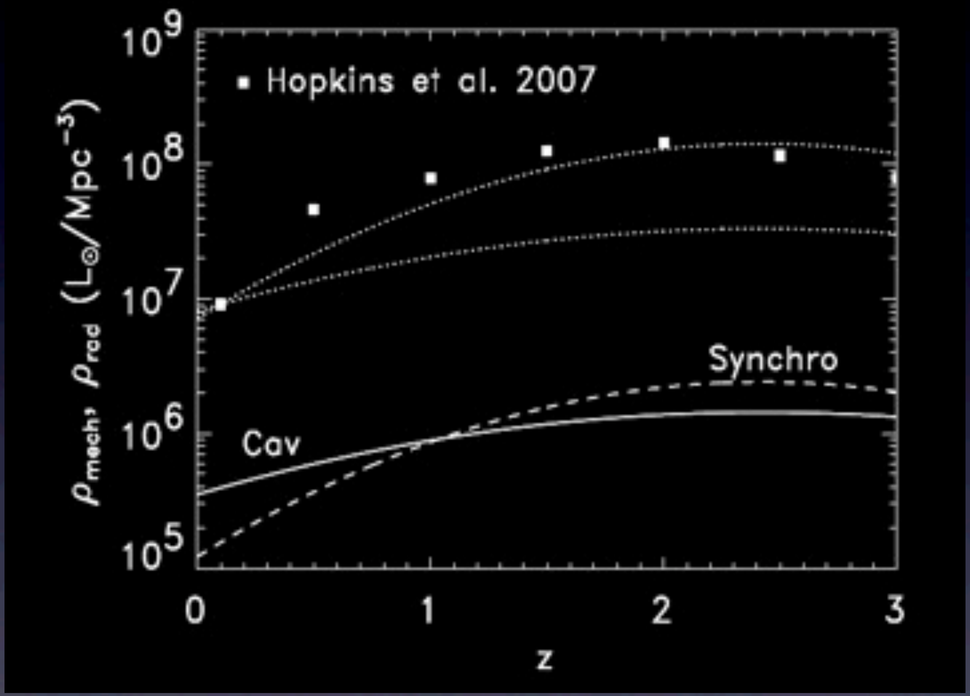
[Figure: white line = QSO BLF; blue,red = kinetic LF from cavities, min energy]



Jets & the cosmic energy budget

Integrating over L gives total energetic output.

Jets produce 2-5% of local AGN energetic output, and their importance decreases further at higher-z (as in galaxy formation models)



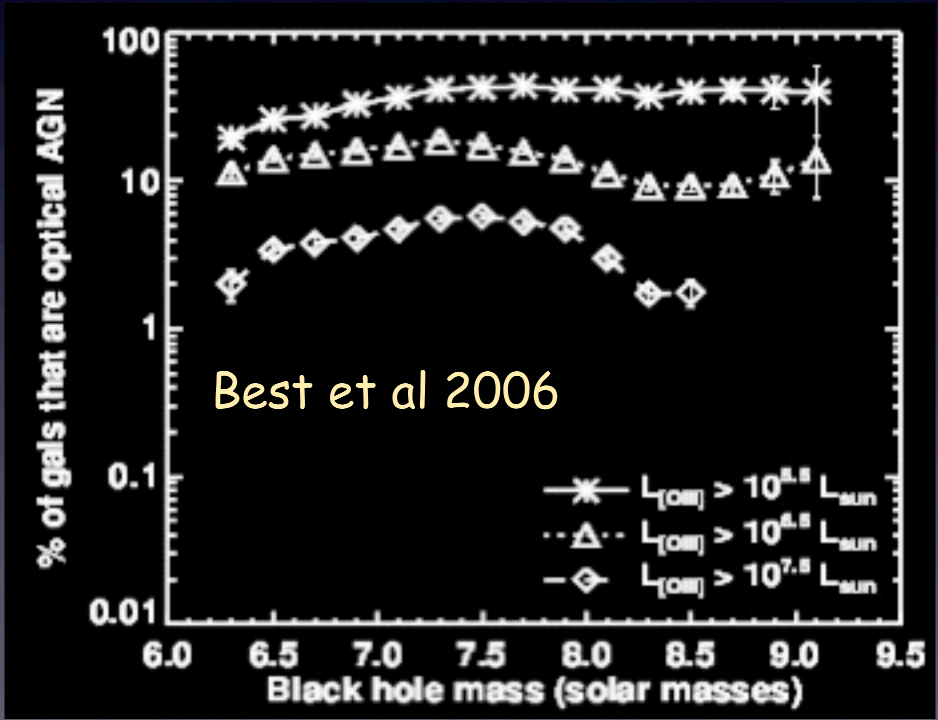
Radio-jet energetics are therefore cosmically unimportant, but all jet energy is deposited locally and may go into feedback, whereas most radiated energy passes through nearby ellipticals.

Part 2:
AGN host galaxies

"Optical AGN" hosts

The host galaxies of optically-selected (ie. radiatively efficient) AGN:

- are found at all BH masses



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The host galaxies of optically-selected (ie. radiatively efficient) AGN:

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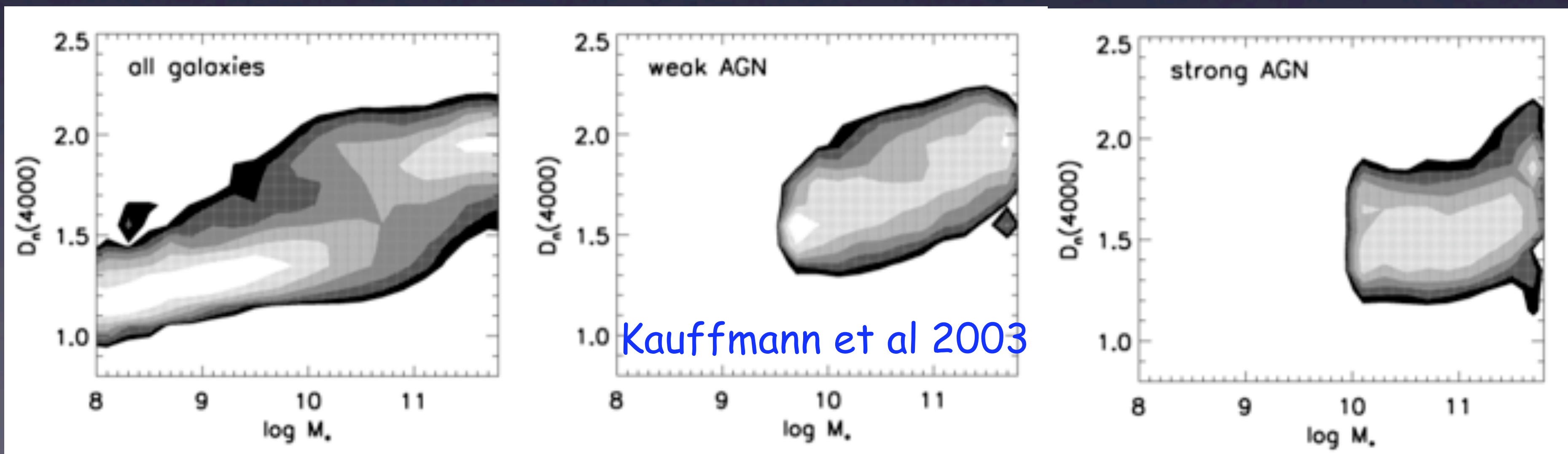
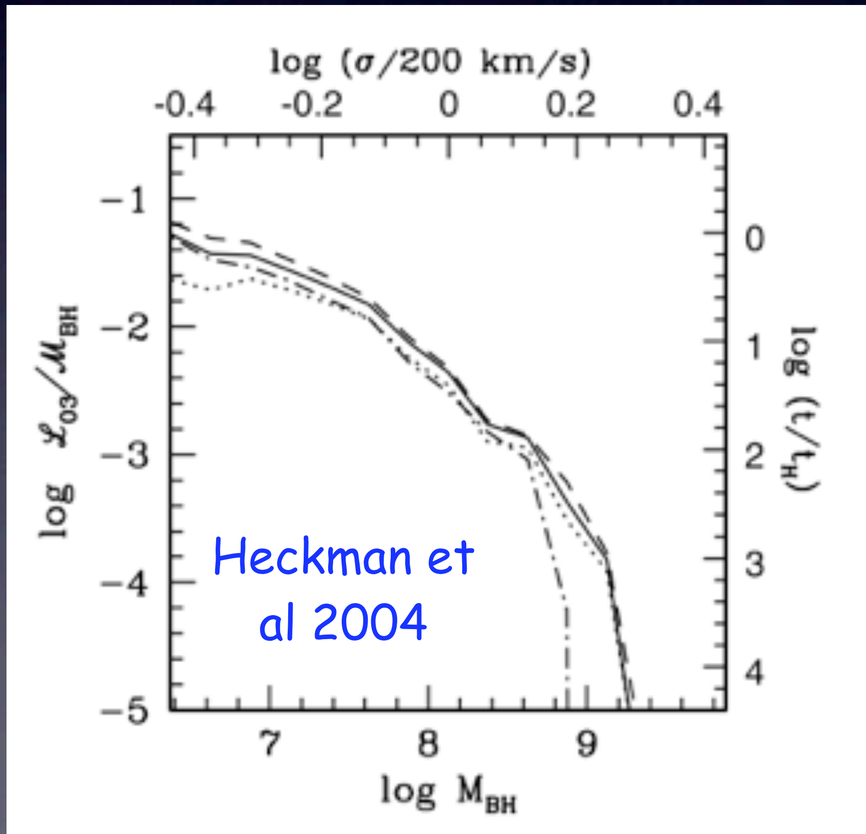


Kauffmann et al 2003

“Optical AGN” hosts

The host galaxies of optically-selected (ie. radiatively efficient) AGN:

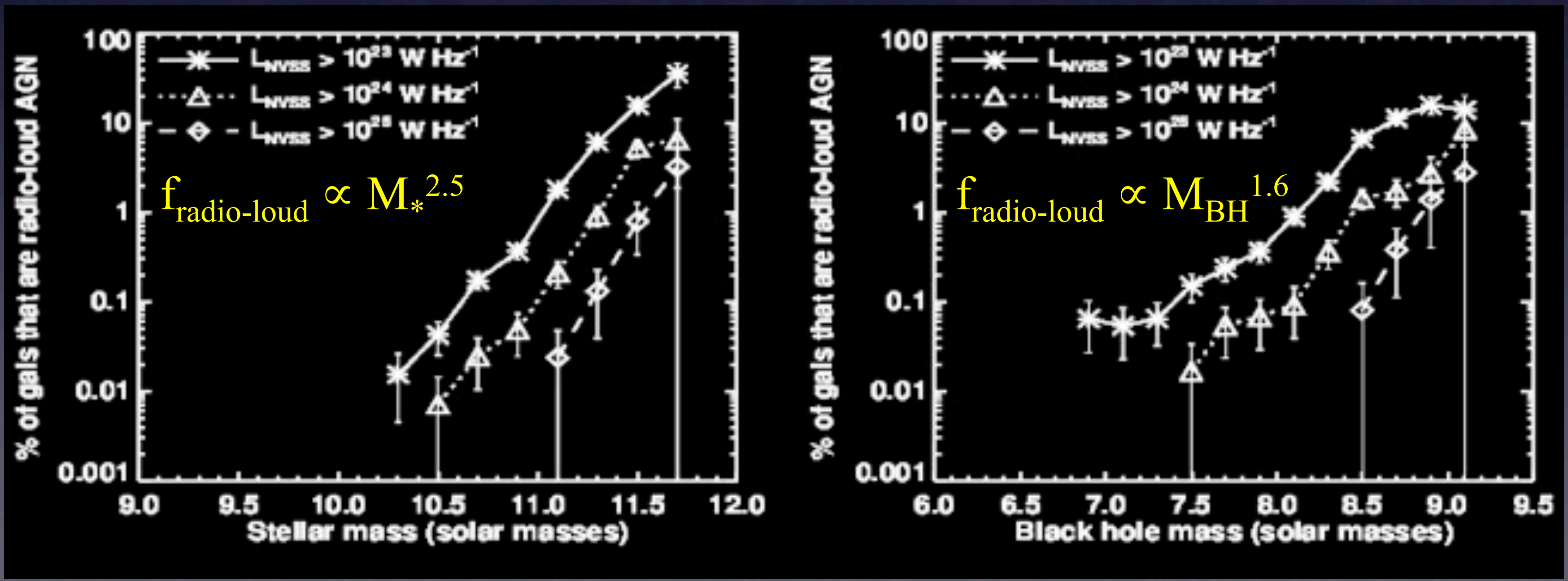
- are found at all BH masses
- are often star-forming
- have ‘down-sized’: low-mass black holes are still rapidly growing but high-mass BHs are typically switched off.



“Radio-AGN” hosts

In contrast, low-luminosity radio-AGN:

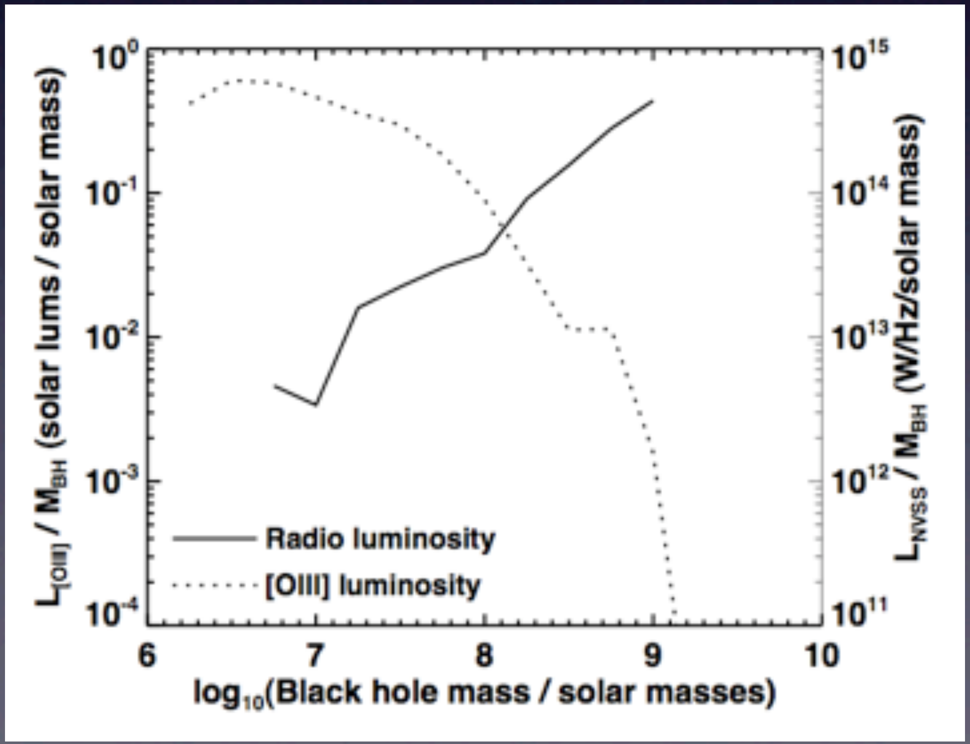
- are hosted by old, passive early-type galaxies, with a strong preference for the most massive systems.



“Radio-AGN” hosts

In contrast, low-luminosity radio-AGN:

- are hosted by old, passive early-type galaxies, with a strong preference for the most massive systems.
- show completely the reverse of down-sizing



Interpretation

Radiatively efficient AGN activity:

- Generally galaxies with relatively low mass black holes
- Fuelled by cold gas in standard thin accretion disk
- Gas source may be secular, or from interaction/merger
- Associated star formation - from same cold gas supply
- Significant mass growth during accretion

• Important phase of black hole and galaxy growth

Radiatively inefficient (low-luminosity radio) AGN activity:

- Predominantly in massive black holes
- BH growing slowly at low accretion rate
- Gas supply is likely to be the hot halo of gas surrounding gal.

• Re-fuelling of already well-formed massive black holes.

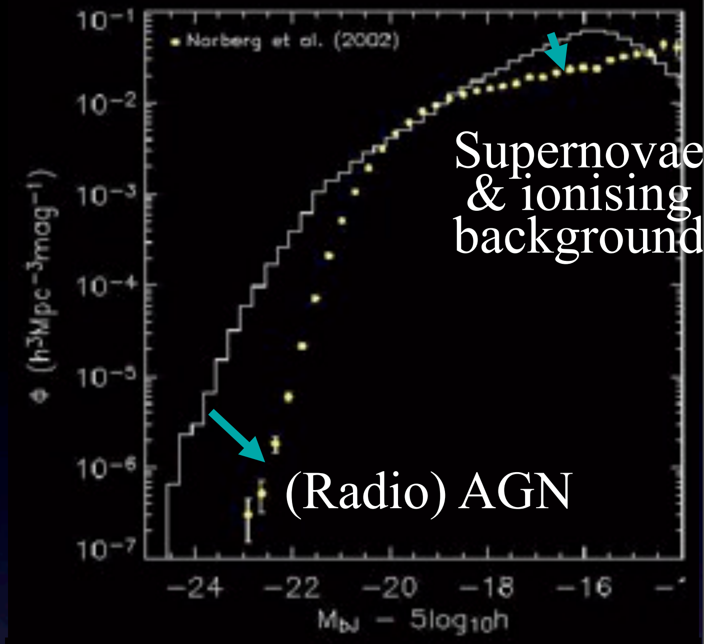
Part 3:
Radio-AGN feedback

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.



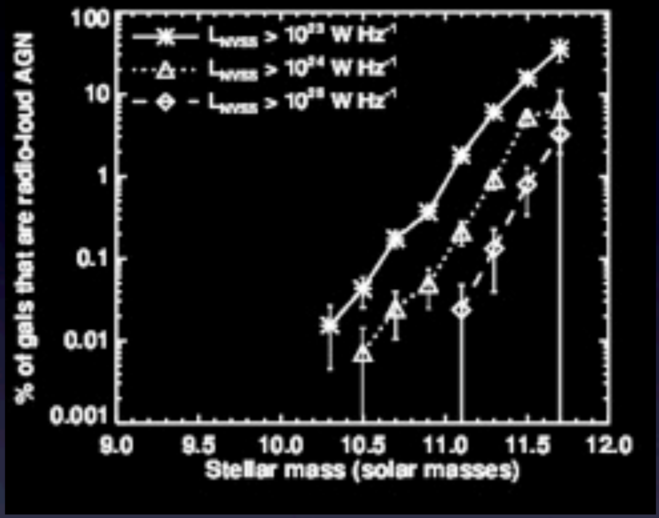
Recurrent radio activity, and energetics

Best et al 2006, MNRAS, 368, L67

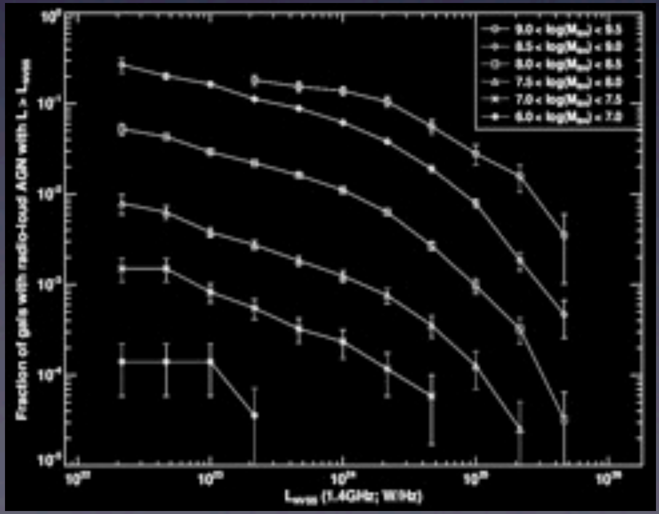
Radio sources live for only 10^7-10^8 yrs.

Nevertheless, the radio-loud fraction suggests 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"



Monday, 27 September 2010

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)

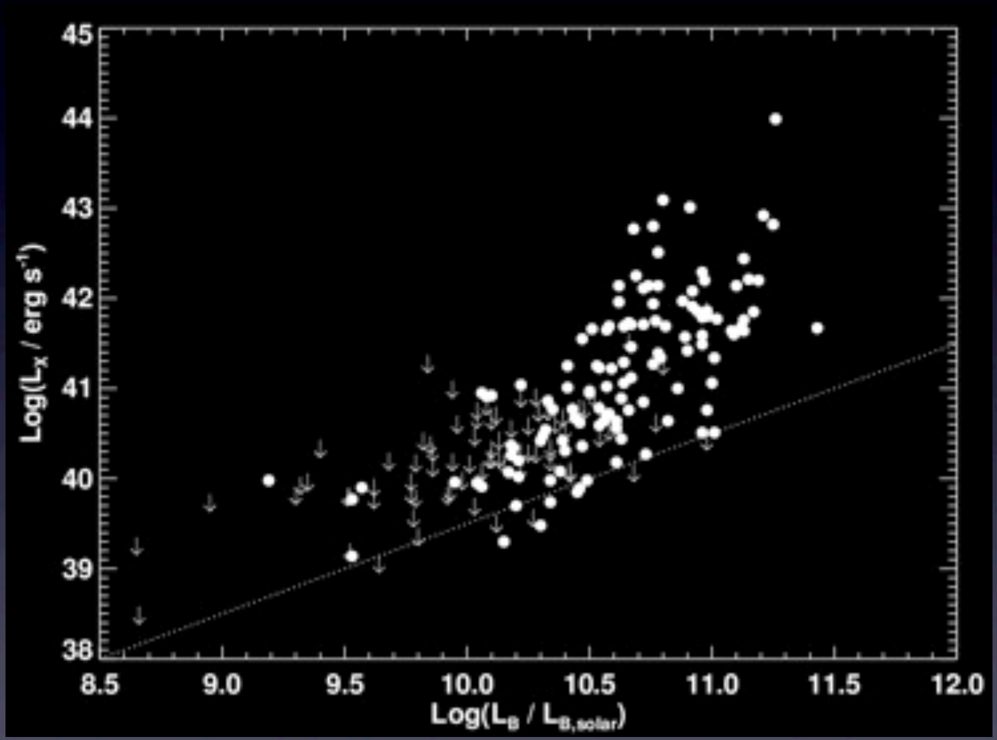


Figure: Bolometric X-ray luminosity vs optical luminosity of elliptical galaxies (from O'Sullivan et al 2001).

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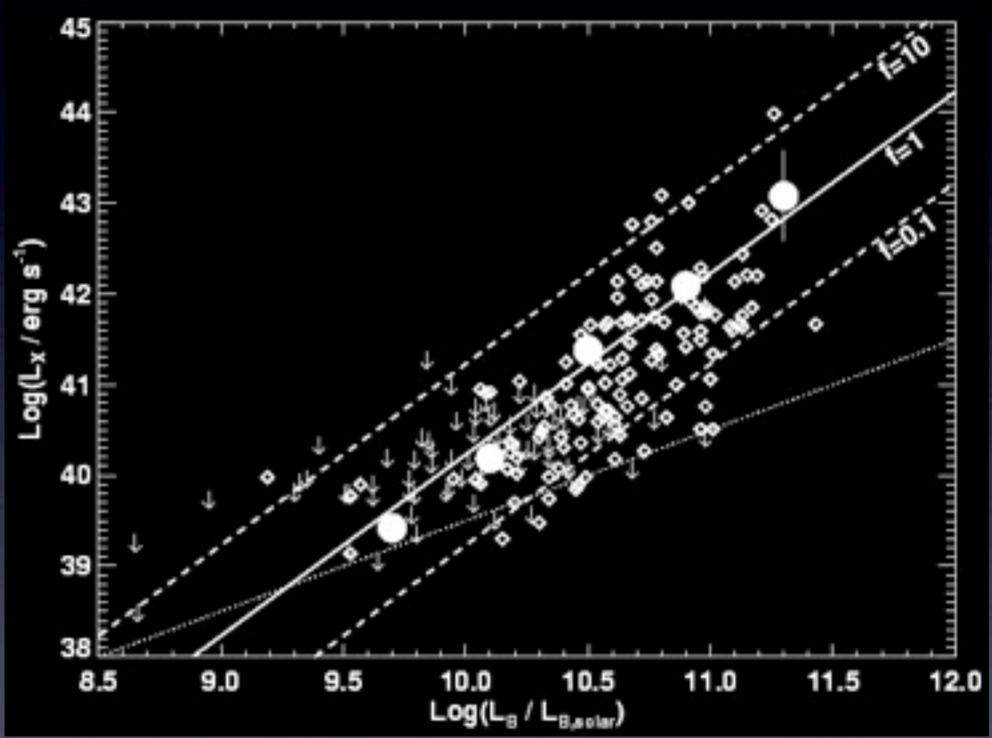


Heating from radio-loud AGN (over-?) balances gas cooling for elliptical galaxies of all masses

Interpretation

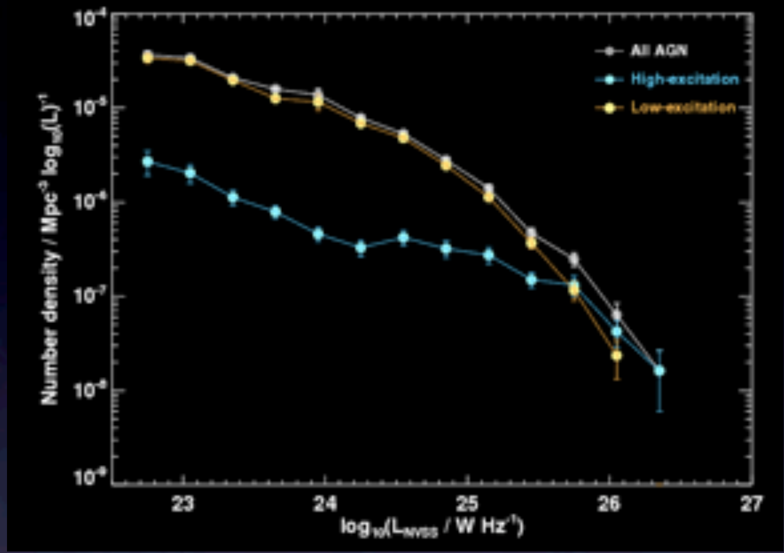
- For all ellipticals, the time-averaged heating due to radio sources balances the radiation losses from the hot gas
- Therefore the radio source may prevent gas cooling, and control the rate of growth of the galaxies.

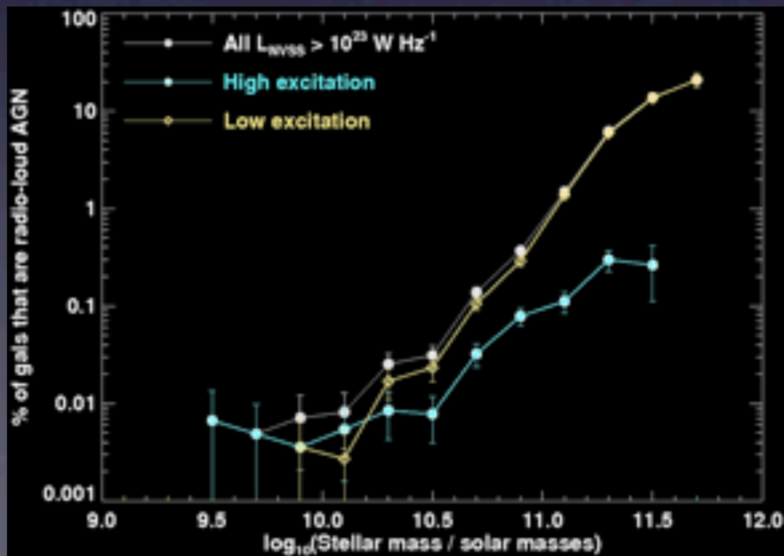
⇒ Energetically this can solve problems of semi-analytic models of galaxy formation.

⇒ 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.....

High vs low-excitation sources

- Low-luminosity radio source population (below ~$10^{25.5}$ W/Hz), which dominate energetic output, is predominantly low-excitation.
- Radio-loud fraction vs mass relation (high masses) also dominated by low-excitation RGs.
- Hence, it's low-excitation sources that are involved in feedback
- These require low accretion rates, as provided by Bondi accretion or low cooling rates from hot halos
- => possibility of feedback cycle

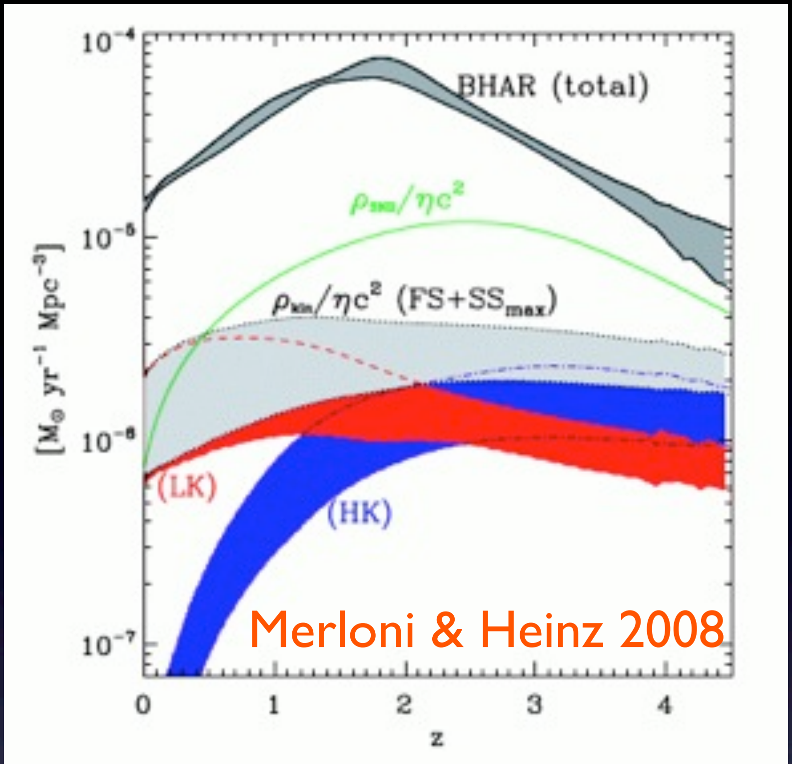


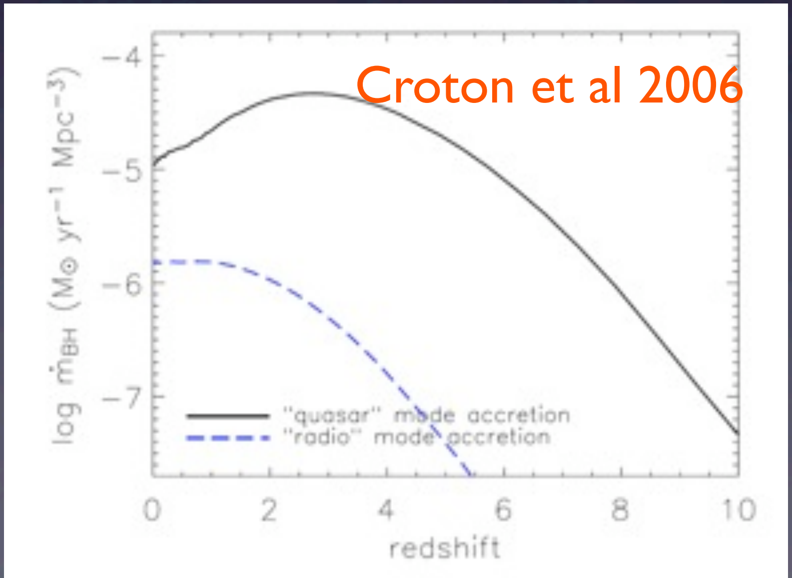


Cosmic evolution of the low-excitation radio population

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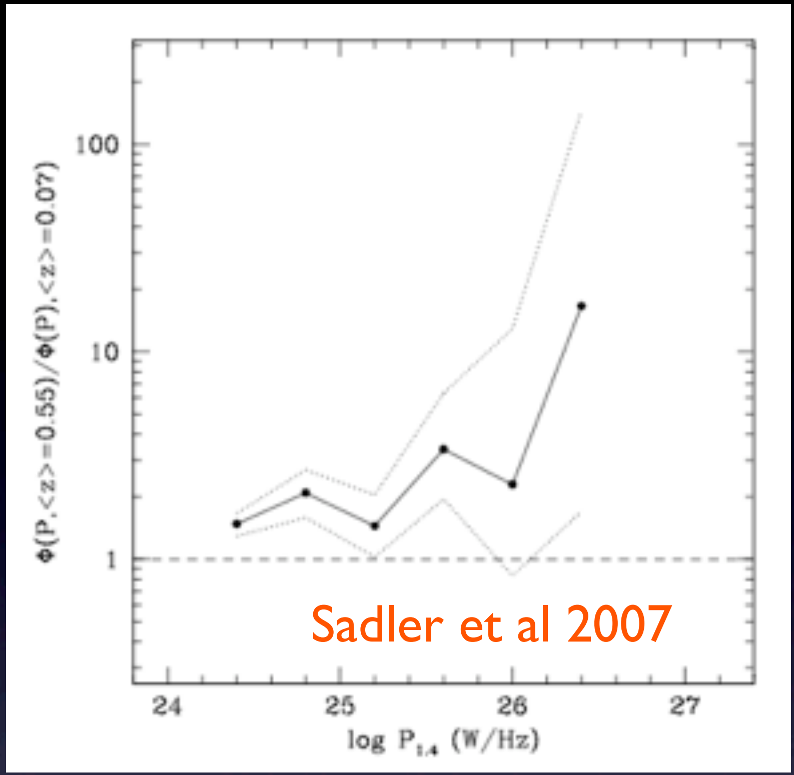
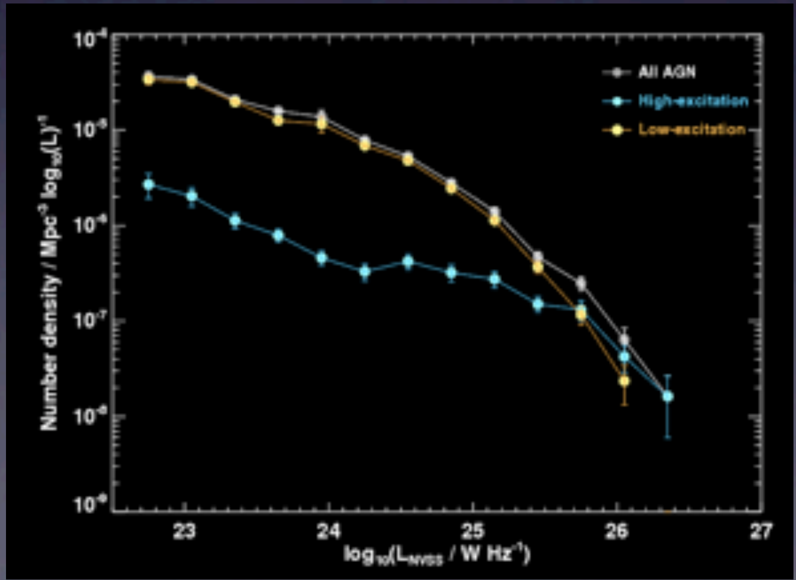
RLF does evolve positively (albeit weakly) at low power, but this is a mix of high & low excit. sources

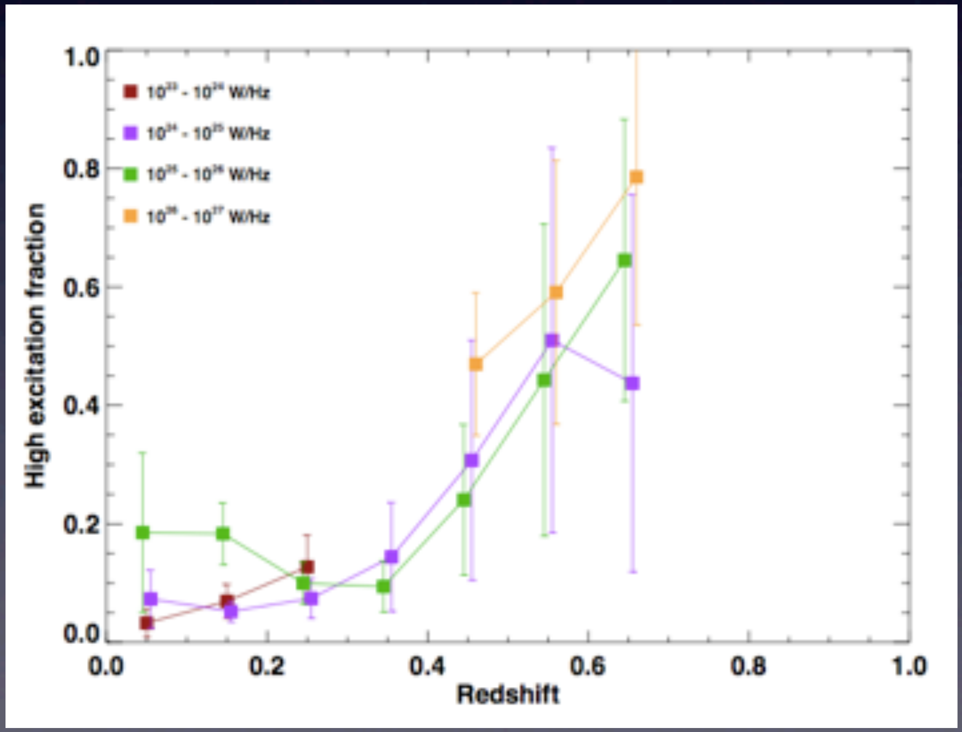




The high/low excitation ratio

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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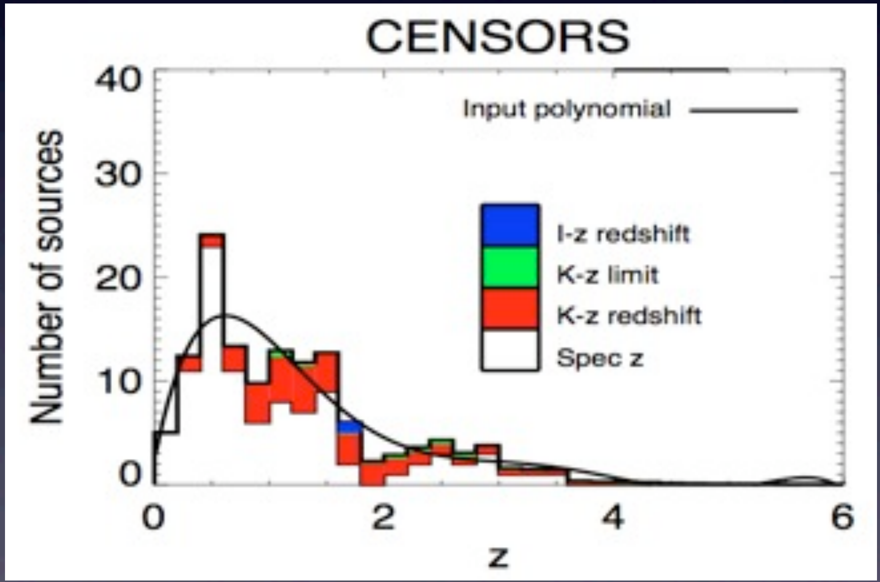
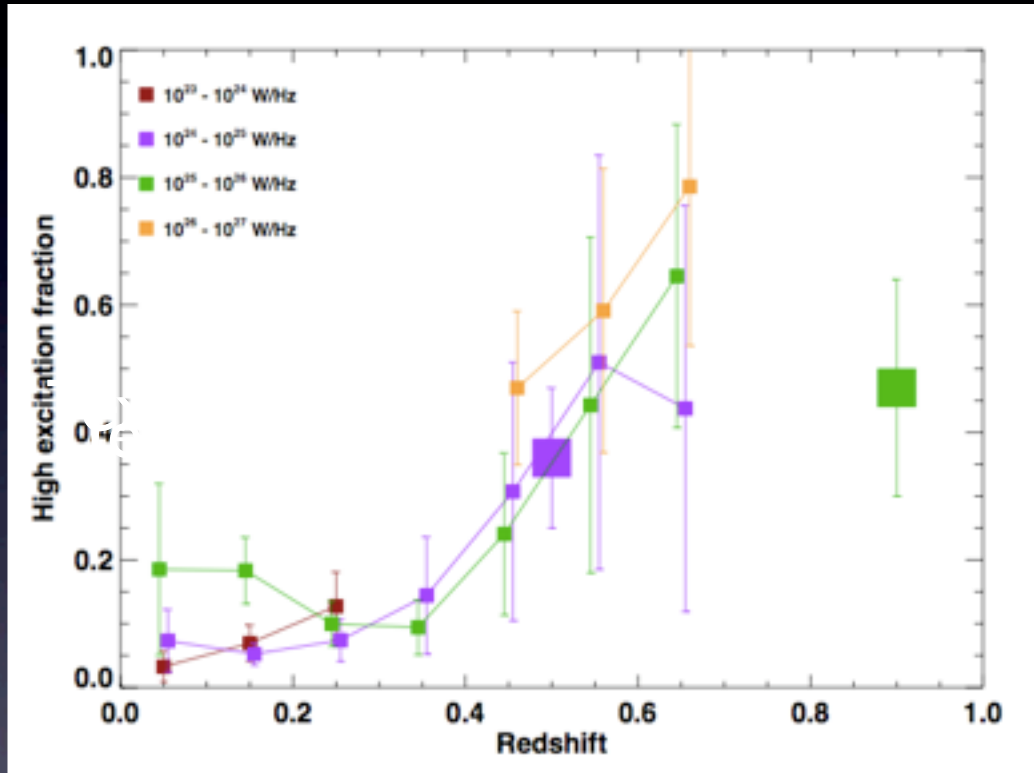


Compare with data from our CENSORS low-luminosity radio sample (150 sources to 7mJy, with deep spectroscopy)

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.



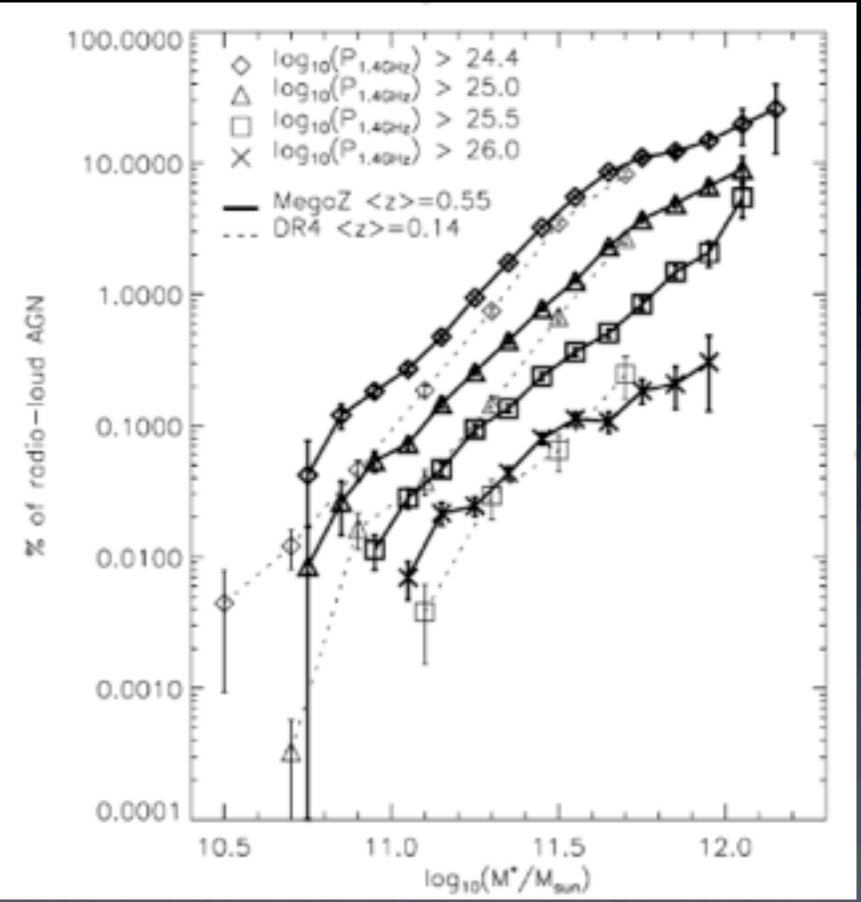
Louise Ker is working to use CENSORS and complementary surveys to measure the evolution of the RLF of low excitation sources (= “radiatively inefficient” feedback). Results soon...

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



Summary

- Not all AGN follow the "standard" accretion disk picture.
- A population of low accretion rate, radiatively inefficient, radio sources, dominates the low-luminosity end of RLF
- This is not the same as the FR1/FR2 split!
- These sources are in massive galaxies, and are probably fuelled directly or indirectly from the hot gas halo.
- Low luminosity radio source activity is highly-recurrent with a fast duty cycle, especially in the most massive gals
- Energetic output (over-?) balances cooling rates, leading to feedback cycle.
- Radio-AGN vs mass relation doesn't evolve much to z~1. RLF of these sources also evolves little (better measure needed)