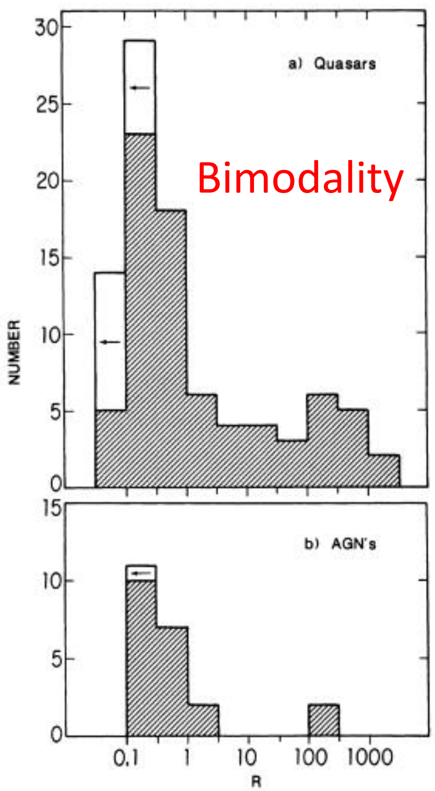
Is there really a dichotomy in AGN jet power?

Jess Broderick
(University of Southampton)

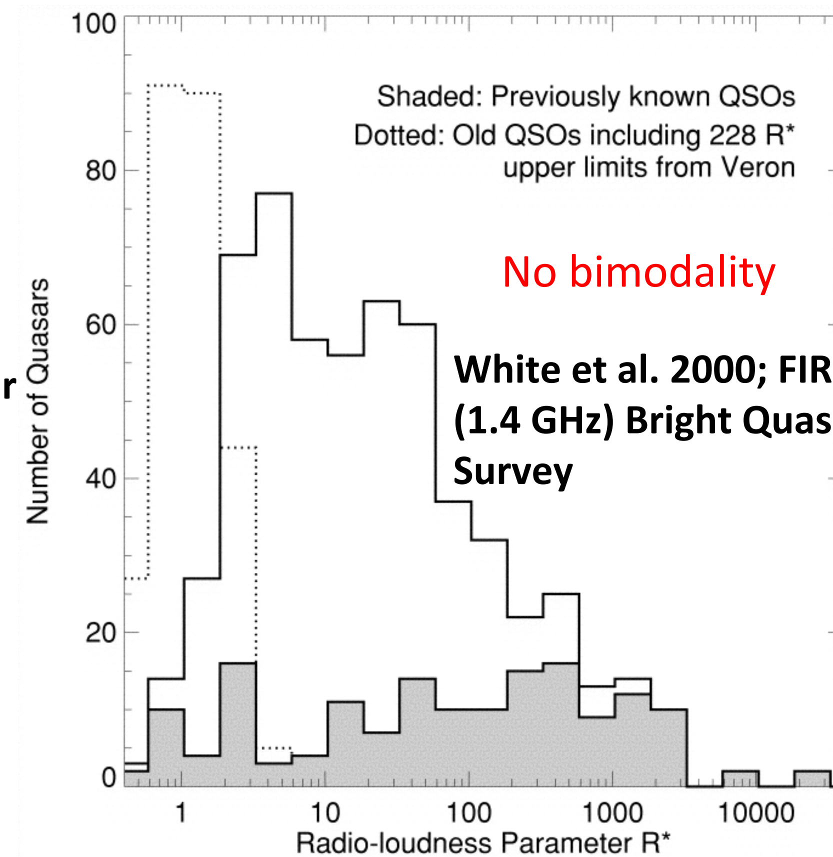
Rob Fender
(University of Southampton)

Radio loud and radio quiet AGN

* Early radio surveys appeared to show two separate populations of **'radio loud'** and **'radio quiet'** AGN. This dichotomy becomes part of the received wisdom for AGN, and is stated without many caveats in textbooks, etc. This in turn drives much study into the origin of this difference, usually tying it to the evolution of black hole spin via the merger history etc. **Big business.**



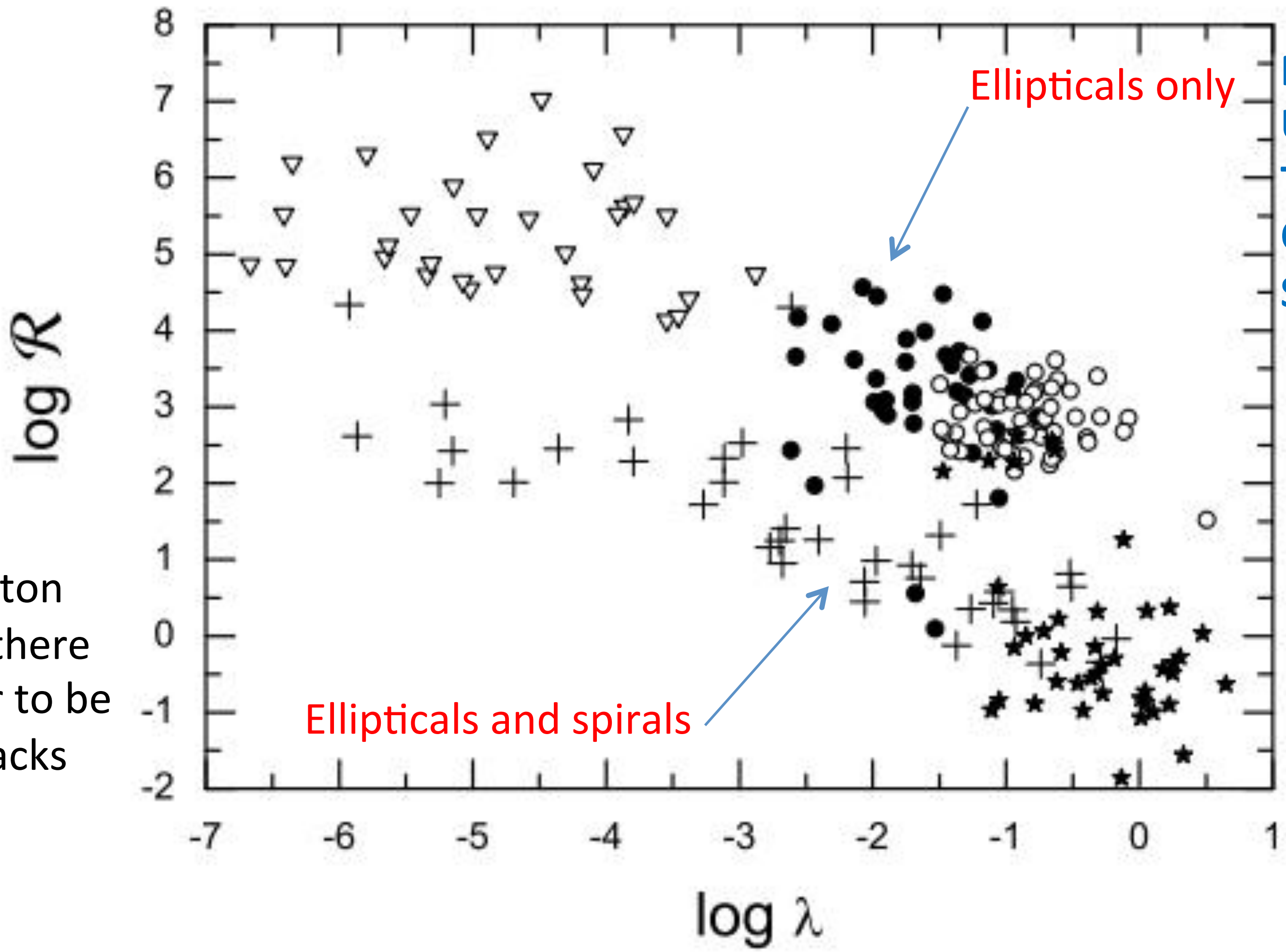
Kellermann et al. 1989; 5 GHz VLA observations of objects in the Palomar Bright Quasar Survey.



White et al. 2000; FIRST (1.4 GHz) Bright Quasar Survey

But the existence of the RL/RQ dichotomy is still a somewhat contentious issue…

At low Eddington ratios there appear to be two tracks

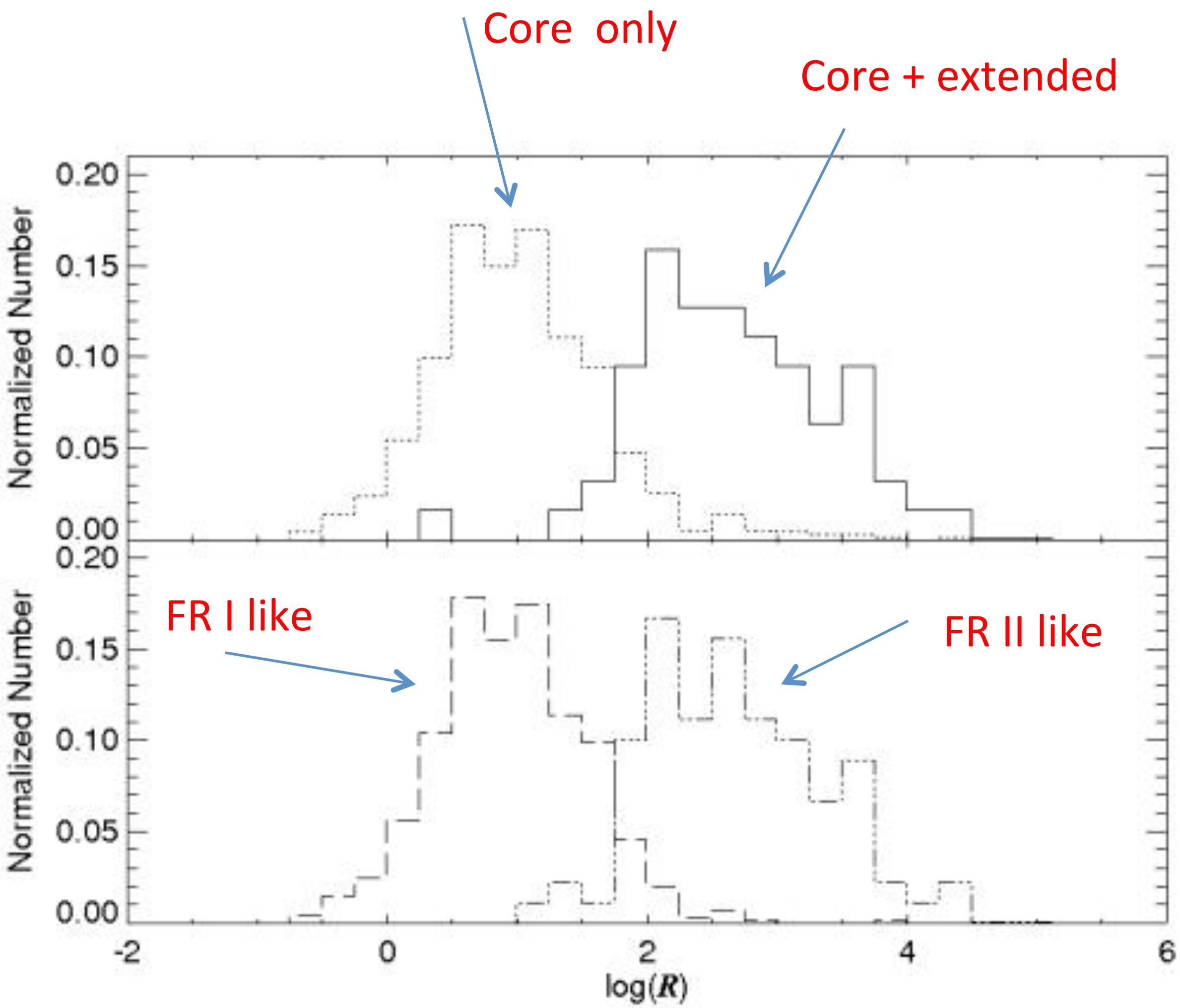


Filled circles - BLRGs
Unfilled circles -RLQs
Triangles - FR I RGs
Crosses - SGs/LINERS
Stars - PGQs

At high Eddington ratios there is some mixing

* Sikora, Stawarz & Lasota (2007; henceforth SSL07) revived the discussion using recently estimated black hole masses to plot radio loudness as a function of Eddington ratio, **using total (core + extended) radio emission**. The interpretation presented is that **black hole spin affects the radio loudness** – higher spin = more powerful jets, but at high Eddington ratios there are also state changes (like for black hole X-ray binaries).

* How does the presence of extended radio emission affect the RL/RQ dichotomy?



Rafter et al. 2011; sample of low-*z* broad-line AGN from SDSS. Radio data from FIRST.

(also see e.g. Xu et al. 1999, Terashima & Wilson 2003, Laor 2003)

Revisiting the SSL07 study

*** Do the two tracks merge if *core* radio luminosities are used instead of total radio luminosities, and if so, are the results consistent with the predictions of BH spin models?**

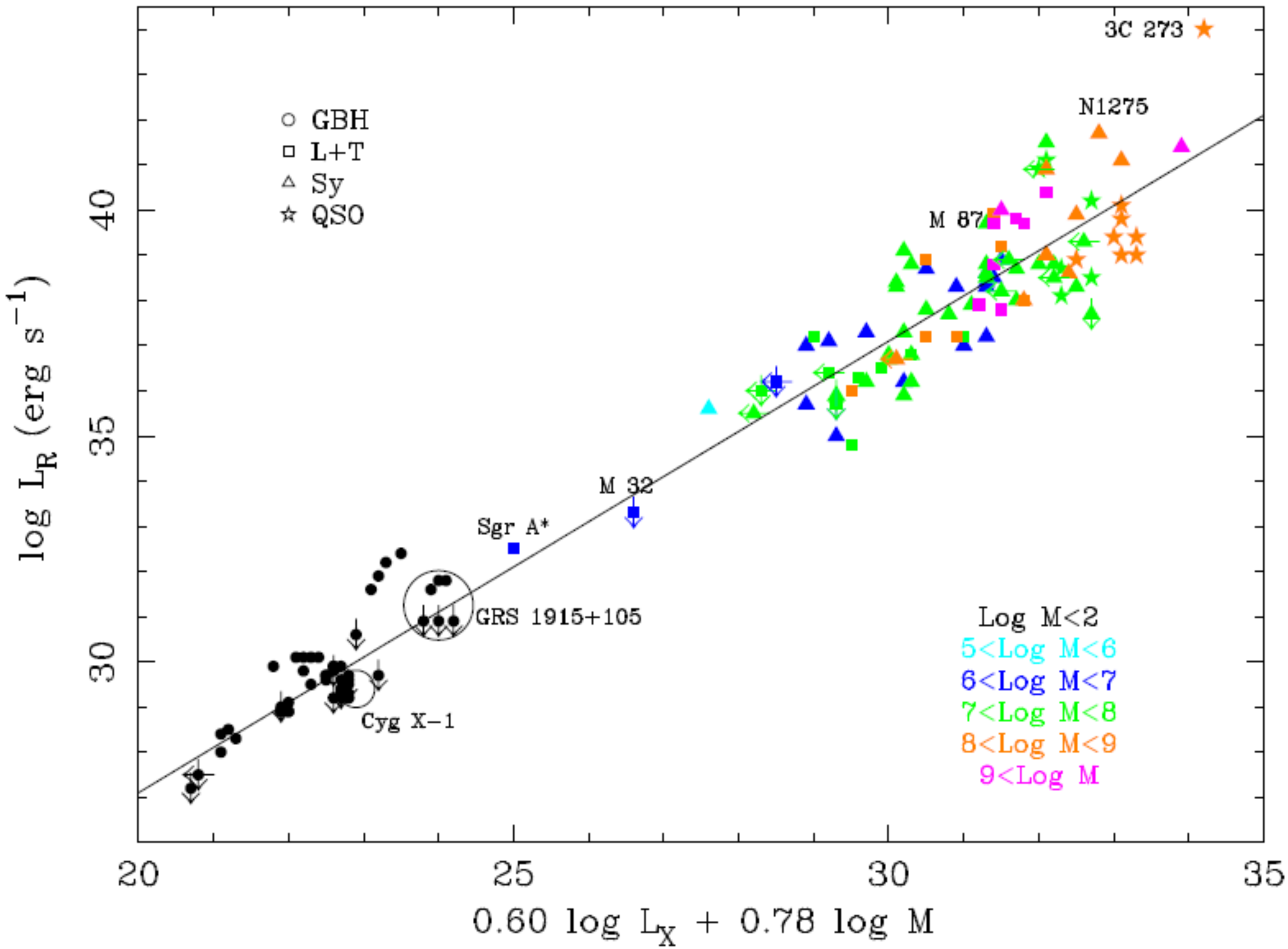
*** Broderick & Fender (MNRAS, in press; arXiv:1105.3769).**

* 199 AGN spread across five different populations:
* Broad-line radio galaxies (37 sources)
* Radio-loud quasars (50 sources)
* Seyfert galaxies and LINERS (38 sources)
* FR I radio galaxies (31 sources)
* Palomar-Green Quasars (43 sources)
* Median redshift 0.138

Typically low-res. measurements compiled by SSL07.

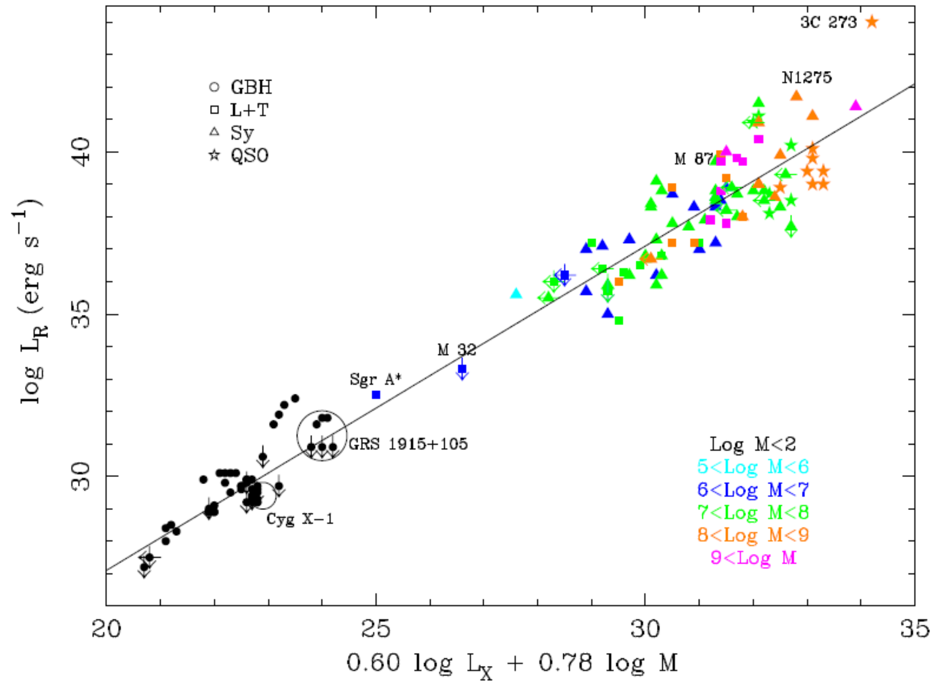
High-res. measurements obtained from variety of references

Subsample	N	$<z>$	$<\log(L_B)>$ (erg s^{-1})	$<\log(L_{5,\,\mathrm{total}})>$ (erg s^{-1})	$<\log(L_{5,\,\mathrm{core}})>$ (erg s^{-1})	$<\log(\lambda)>$	$<\log(M)>$ ($M_\odot$)
BLRGs	37	0.157	44.1	42.3	~41.1	−1.6	8.4
RLQs	50	0.325	45.1	42.8	~42.3	−0.8	8.8
SGs and LINERS	38	0.009	42.3	38.4	~37.7	−2.1	7.6
FR I RGs	31	0.0251	~41.2	41.1	39.8	−4.8	8.6
PGQs	43	0.144	45.0	39.4	~39.1	−0.3	8.2



The 'fundamental plane' (L_x, L_5, *M*) relations of Merloni et al. (2003) and Falcke et al. (2004) use core luminosities.

$$L_{5,\mathrm{core}} \propto L_X^{0.6} M^{0.8}$$

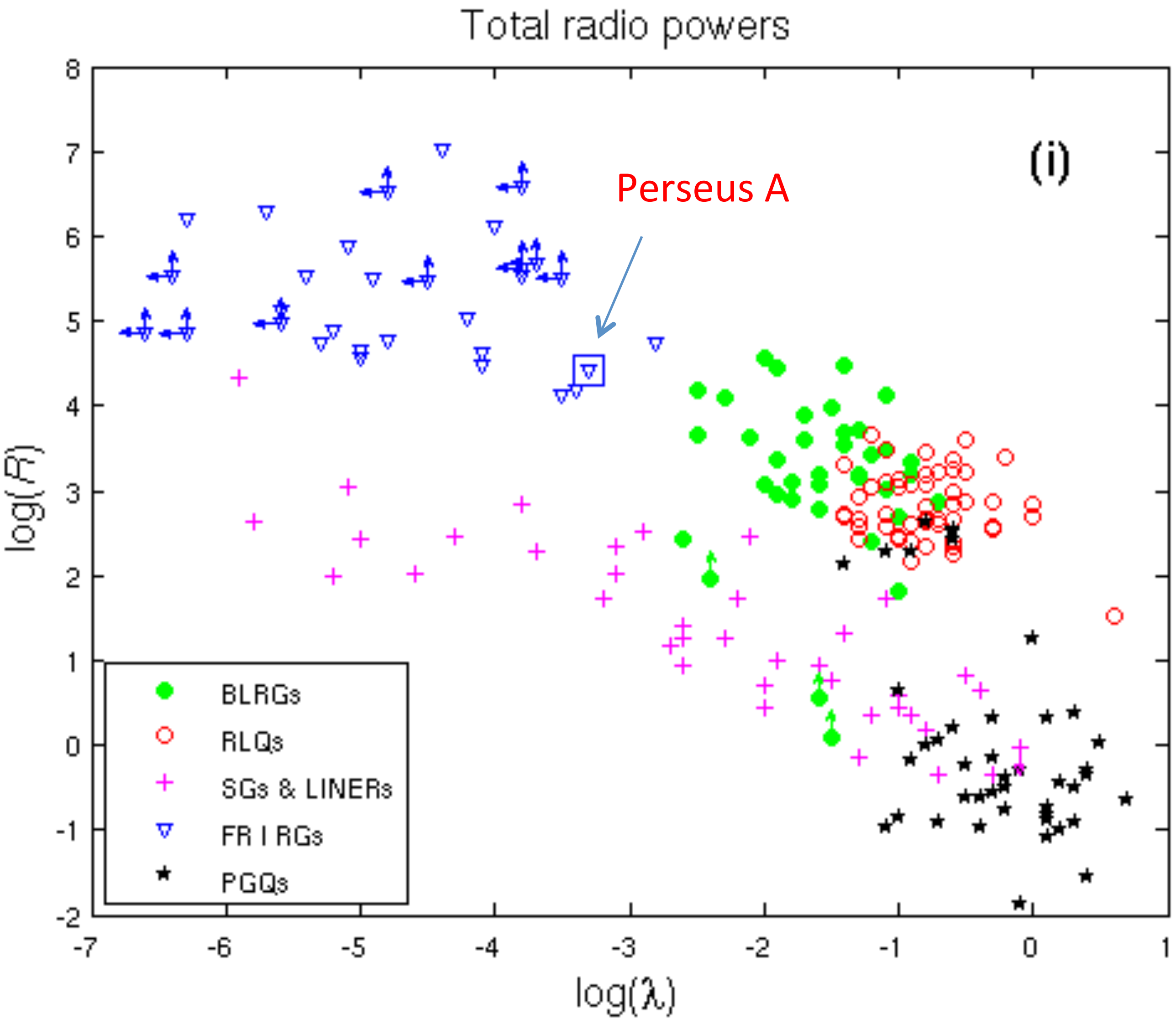


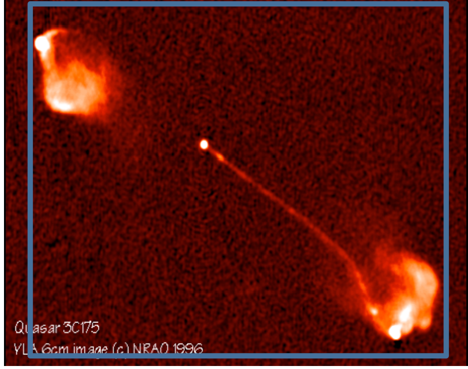
$$\log(R) = -0.4\log(\lambda) + 0.4\log(M) + \mathrm{constant}$$

($R \equiv L_{\nu 5}/L_{\nu B}$ and assume $L_{\mathrm{bol}} = 10L_B$)

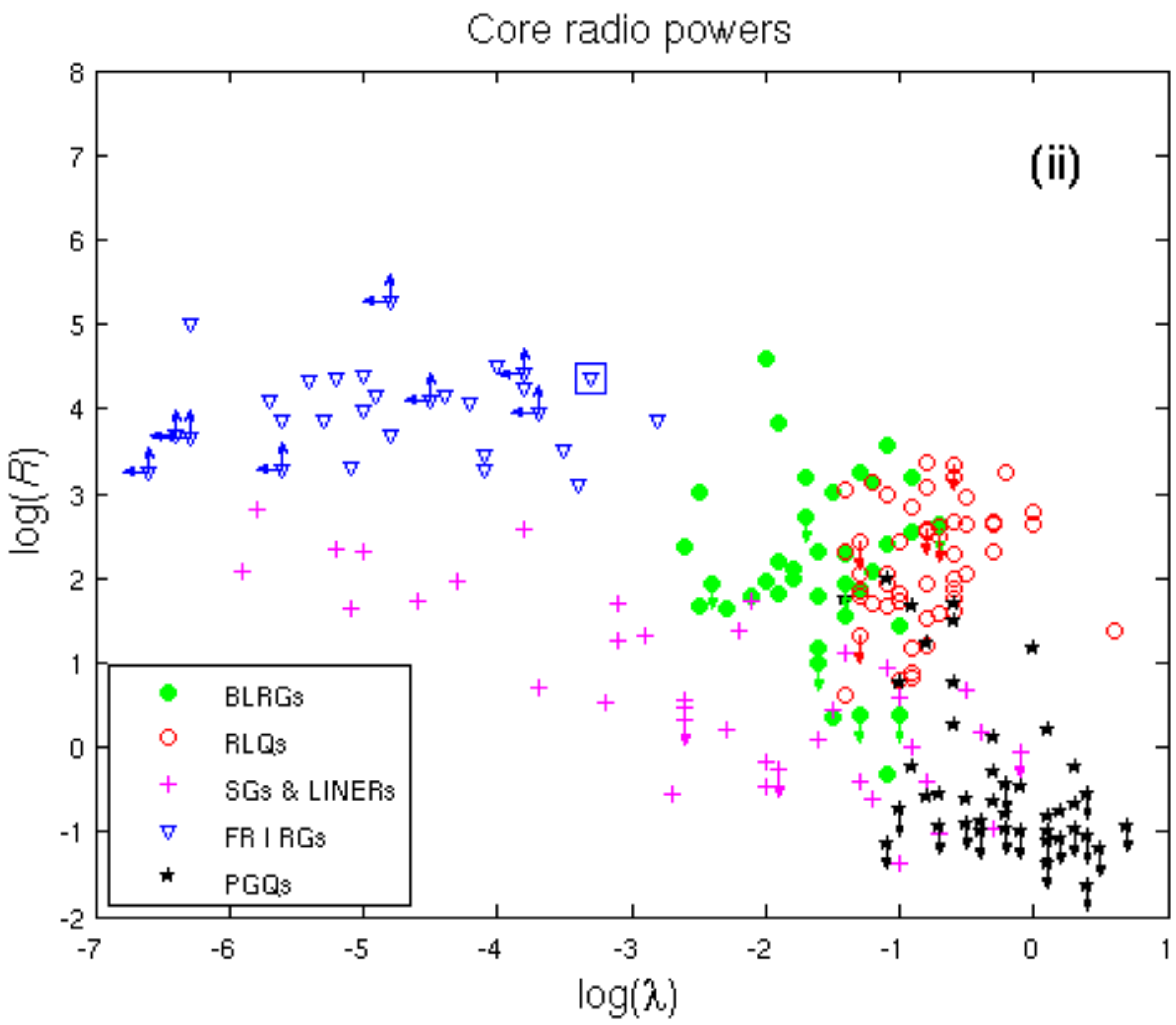
Therefore, subtract $0.4\log(M)$ to obtain mass-corrected radio loudnesses.

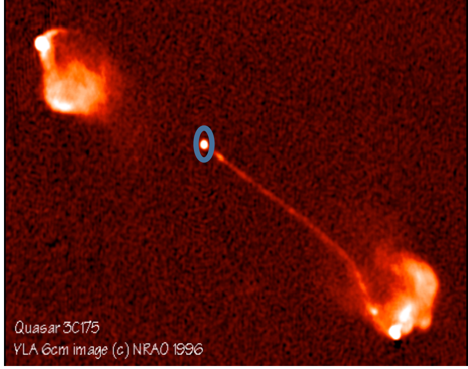
Caveat! X-ray to optical conversion



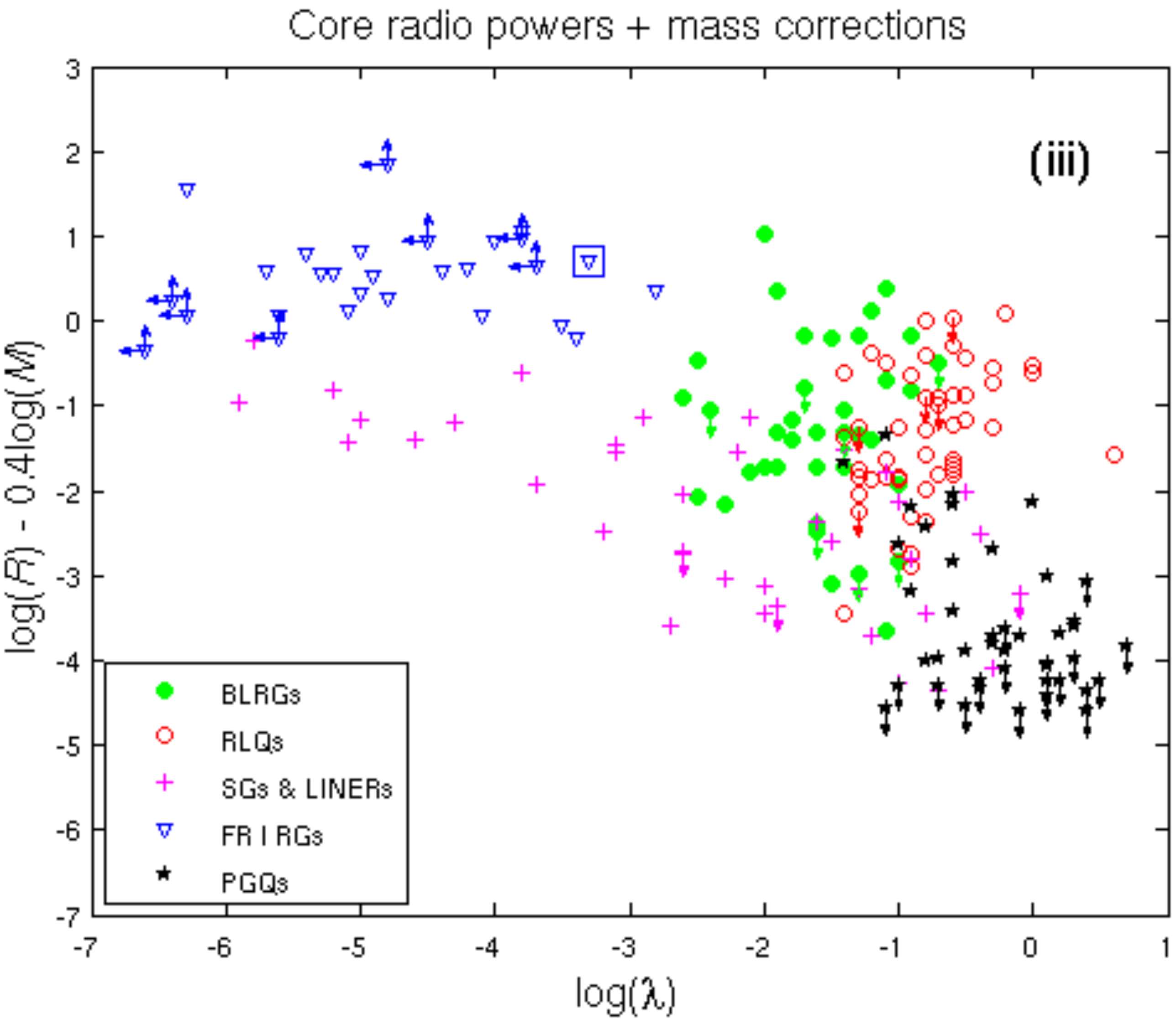


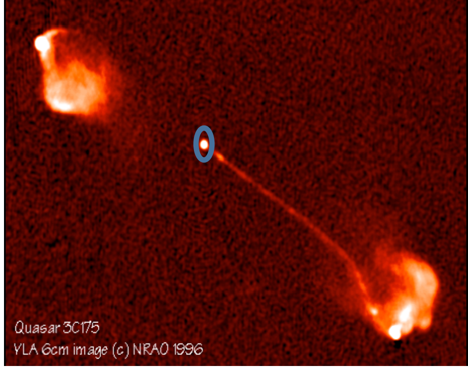
Reproduction of original plot from SSL07



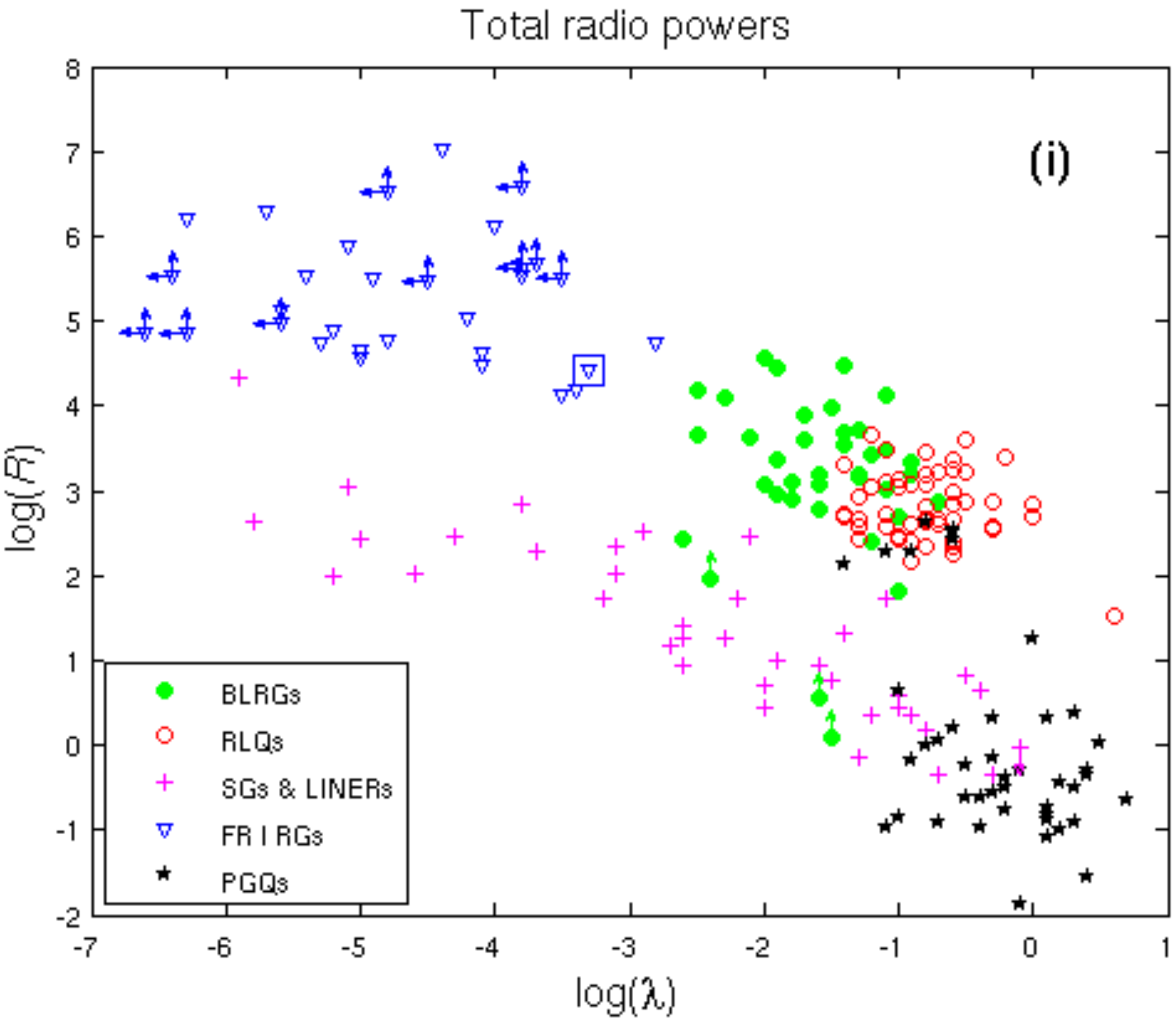


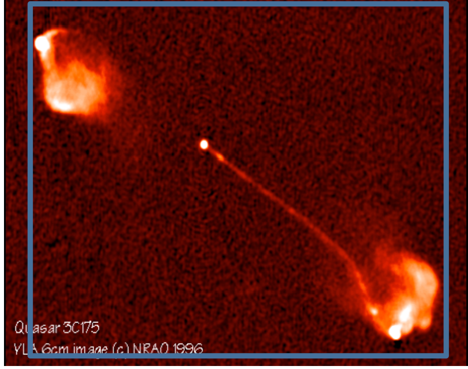
Gap between tracks closes





Further merging of tracks after mass correction





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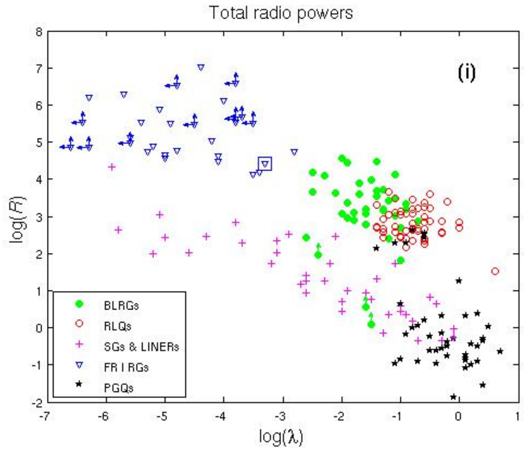
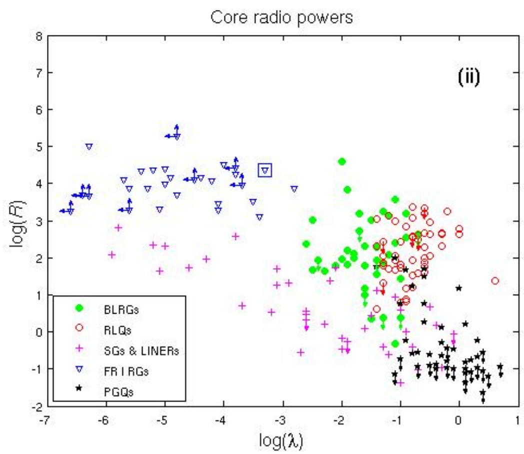
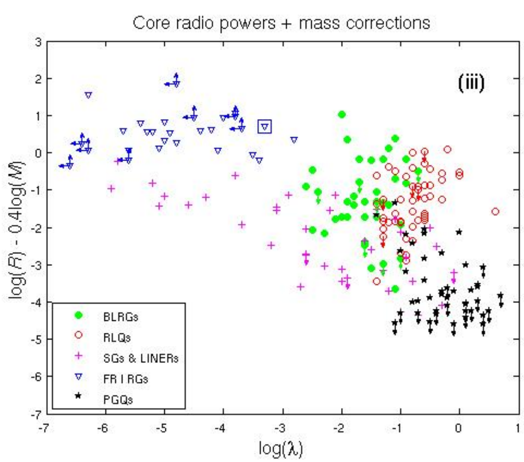




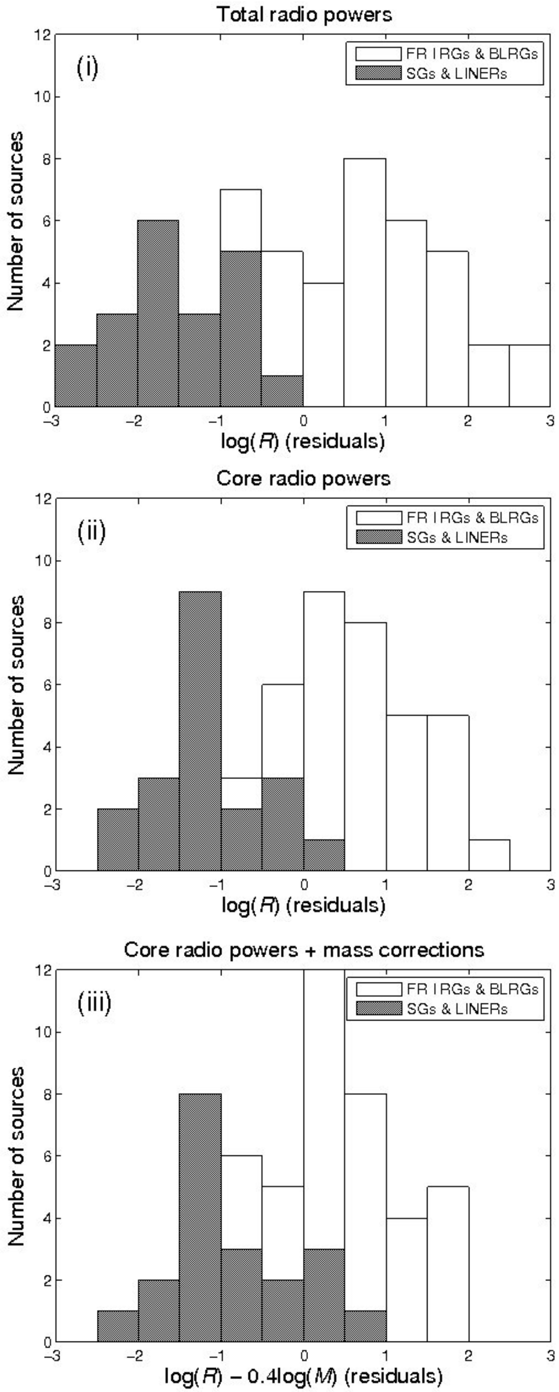


* Restrict range to -6 < log(λ) < -2; upper sequence RGs (mainly FR Is), lower sequence SGs + LINERS (mainly SGs).

* 2D KS tests (RGs vs SGs/LINERS): highly-significant P-values in all three cases (10^{-6}-10^{-8}) . Small *P*-values mainly due to differences in log(*R*).

* Fit linear functions to each RG and SG/LINER subset: average vertical offsets between the lines are 2.6 dex (panel i), 2.1 dex (panel ii) and 1.5 dex (panel iii).

<u>* Tracks have not merged completely</u>



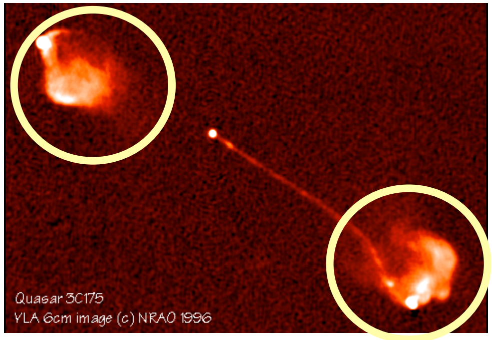
* Fit a linear function to both tracks combined for -6 < log(λ) < -2 and then look at the vertical residuals about this fit.

* For the unbinned data, difference between median residual of each group
= 2.5 dex (case i), 2.0 dex (case ii), and 1.7 dex (case iii).

* Replacing total radio luminosities with core radio luminosities, and applying a mass correction results in a narrower gap between the radio loud and radio quiet sequences in the log(*R*)-log(λ) plane (about 1.6 dex on average for -6 < log(λ) < -2).

* This corresponds to about a 1 dex difference in total jet power ($L_{radio} \propto P_{jet}^{1.4}$).

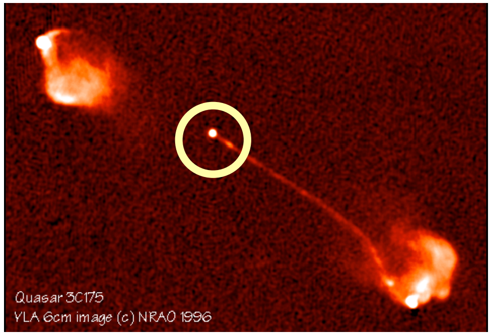
Should we use core or extended emission ?



Extended emission (=bimodality)

- **Pros:** unbeamed

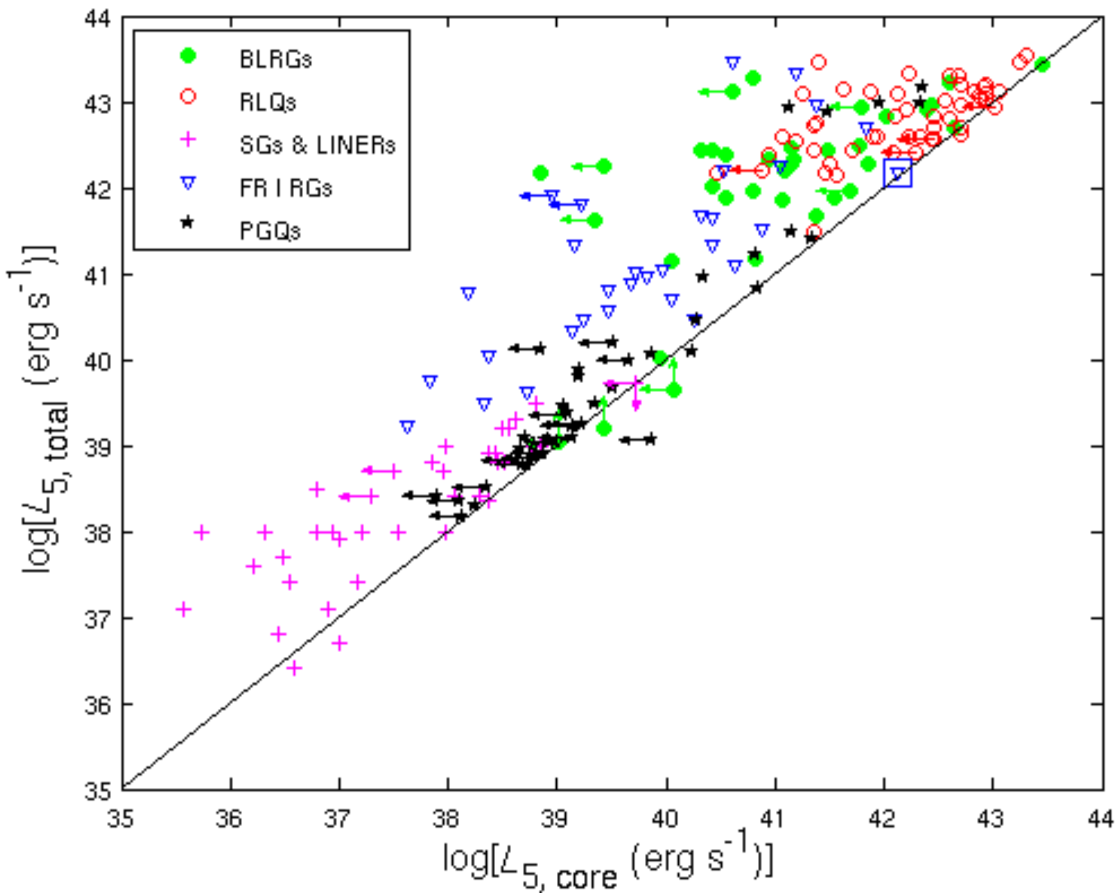
- **Cons:** <u>must</u> be affected by environment (jets in a dense environment are brighter than jets in a vacuum). Time-averaged, but compared with instantaneous core optical, X-ray etc measurements.



Core emission (=weaker bimodality)

- **Pros**: Instantaneous measurement – good for comparing to X-ray, optical, etc. Not affected by large-scale environment. The only relevant measurement for comparison to X-ray binaries.

- **Cons:** could be beamed (but seems unlikely that beaming alone could remove and collapse a real intrinsic bimodality).



Median core fractions (approx):

- **BLRGs (7%)**
- **RLQs (25%)**
- **FR I RGs (6%)**
- **SGs/LINERS (20%)**
- **PGQs (possibly > 20-30%)**

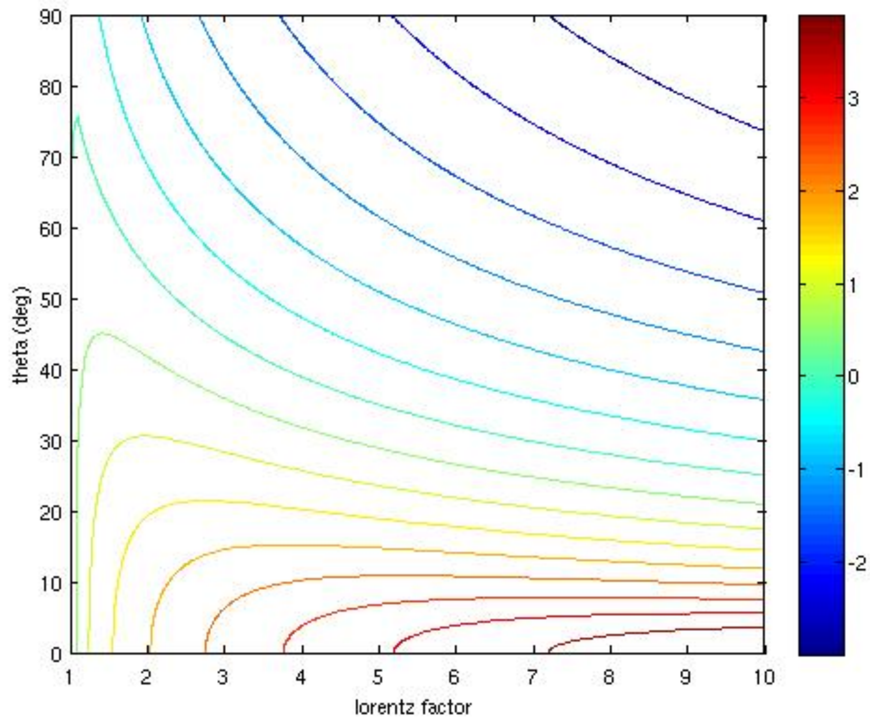
*** For log(λ) < -2, essentially comparing FR I RGs and SGs with a dominant extended component, though possibly less so in latter case given that there could be significant contributions from starbursts (typical spatial scale of extended emission related to the AGN also different).**

Relativistic beaming

* Ratio of core to extended radio luminosity (or flux density) is often used as an orientation indicator (e.g. Orr & Browne 1982).

* $S_{obs} = S_{rest} \times D^{3-\alpha}$
$(S_\nu \propto \nu^\alpha)$

* $D = [\gamma(1-\beta\cos\theta)]^{-1}$



log(D^3)

*** Beaming/debeaming might not be important for SGs (e.g. Bicknell 2002, Lal et al. 2011) but definitely cannot be ruled out for FR I RGs, BLRGs and RLQs on upper track.**

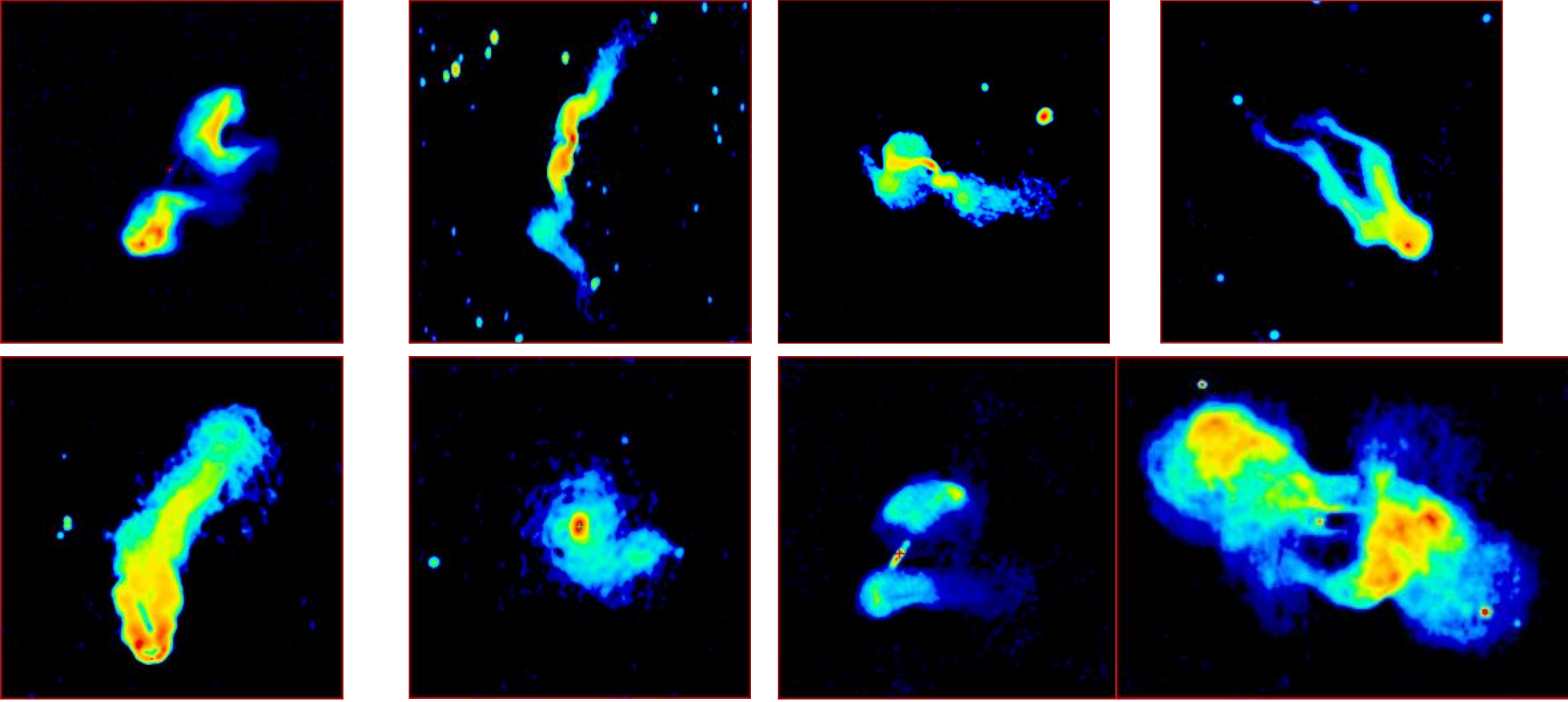
Black hole spin – how significant?

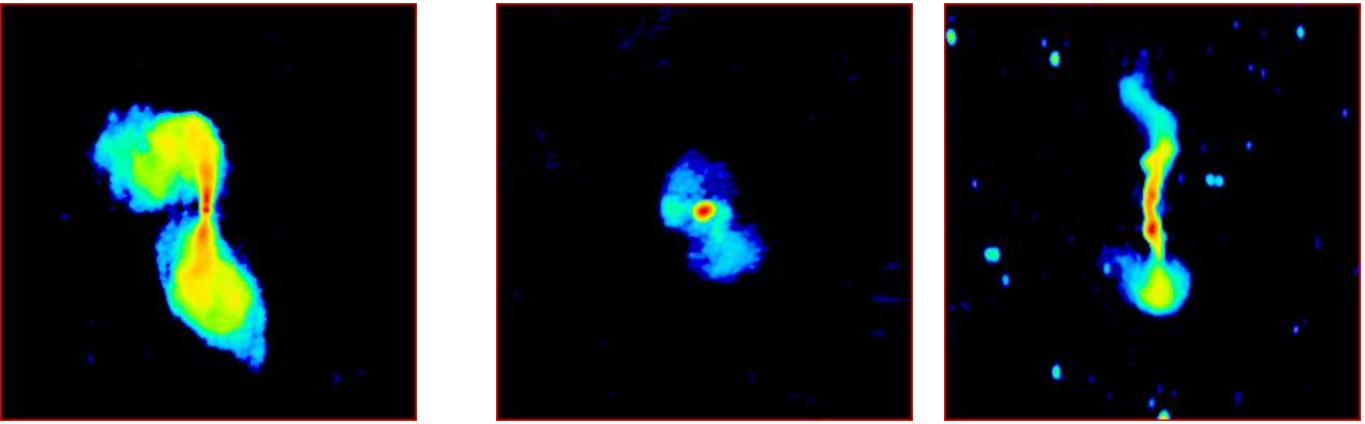
* Recent studies (e.g. Daly et al. 2011, Martínez-Sansigre & Rawlings 2011) use extended radio luminosities to suggest that jet power is directly related to black hole spin; bimodality in spin distribution.

* But for the SSL07 sample, there appears to be a link between the radio loudness bimodality and the level of extended emission. Is this consistent with the spin paradigm? Why would the extended emission be affected more by BH spin than the emission from the core?

Black hole spin – how significant?

* Radio luminosity of extended emission scales with black hole mass, external density and the age of the jet (e.g. Heinz 2002). RGs appear to reside in denser large-scale environments than SGs/LINERS (e.g. Prestage & Peacock 1988; De Robertis et al. 1998). ISM also different for ellipticals/spirals.



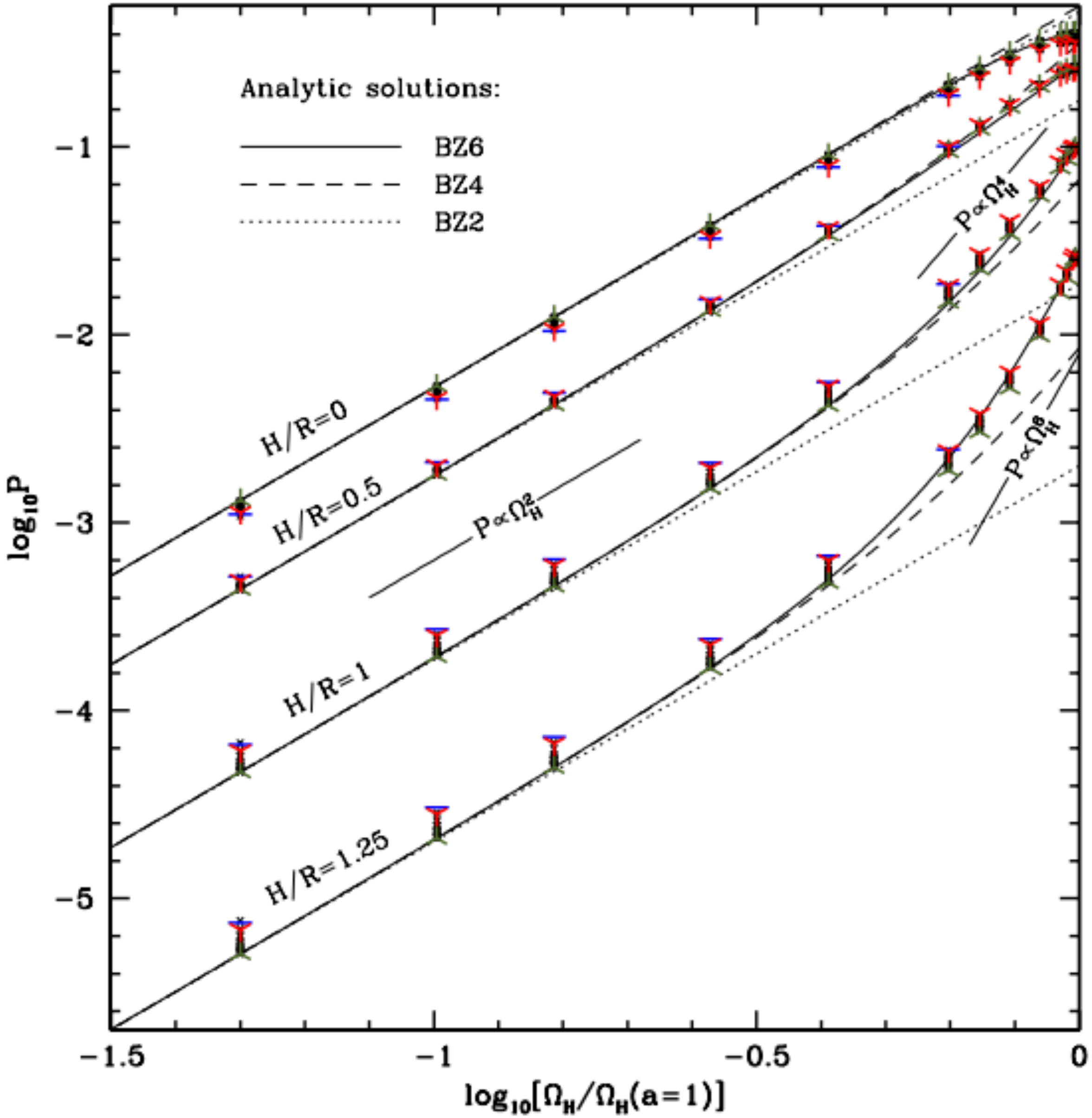


3CRR online atlas

A significant number of FR I RGs in the SSL07 sample are known to reside in clusters.

Black hole spin – how significant?

* Perhaps the characteristics of the ambient environment and/or the radio source age could be equally as important as BH spin in producing a radio-loud/radio-quiet dichotomy seen in total radio luminosity.



Jet power output resulting from BH spin

(Tchekhovskoy et al. 2010)

Difference in jet power depends on geometry of accretion disk. Spin could still affect core emission in our plots at some level, but it seems to have less impact than suggested here (and in other previous studies).

Other sources of uncertainty

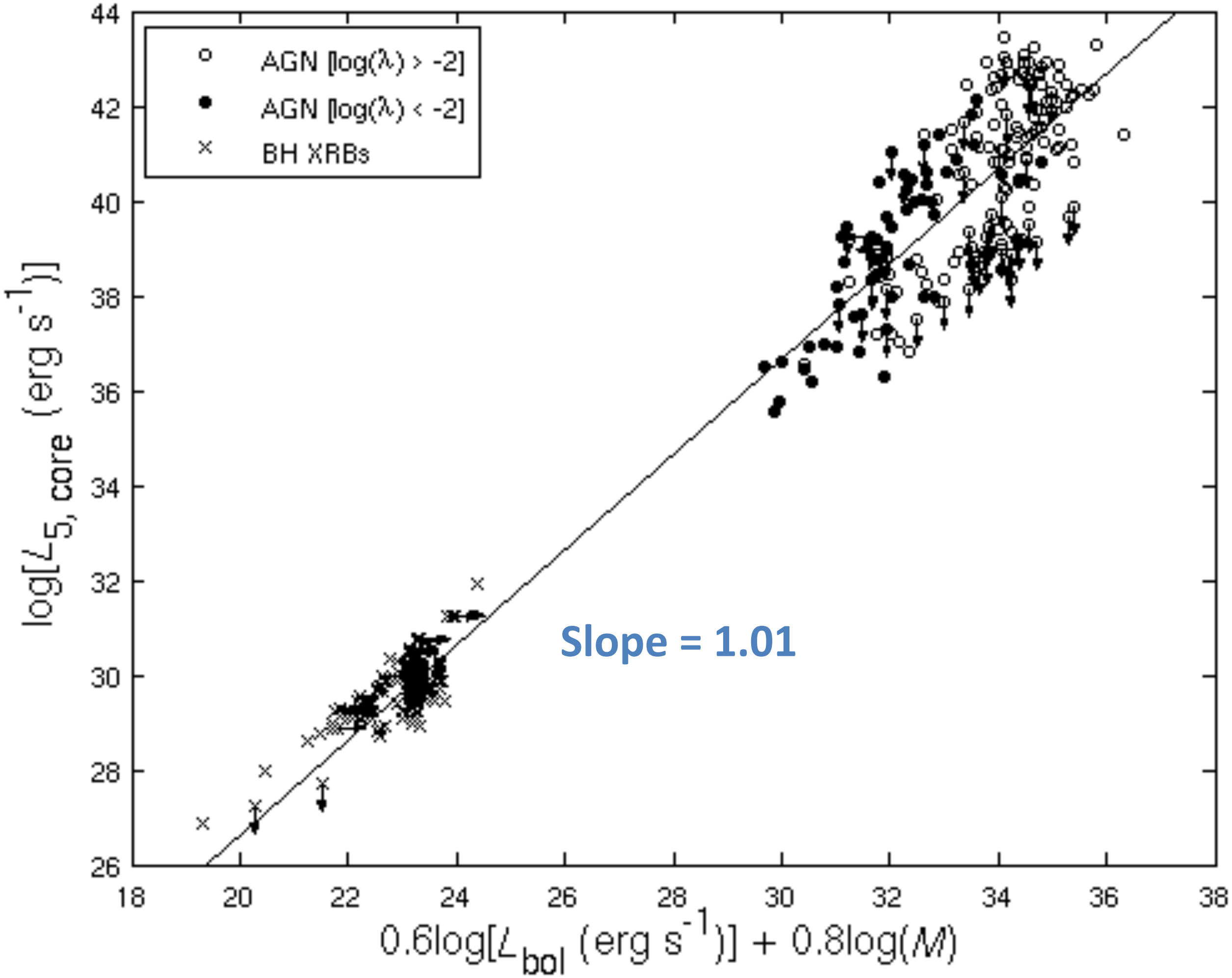
* Deviations about mass correction term.

* Uncertainties in BH mass estimates.

* Uncertainties in radio and optical measurements, which (i) could be or are known to be variable, and (ii) were not conducted simultaneously.

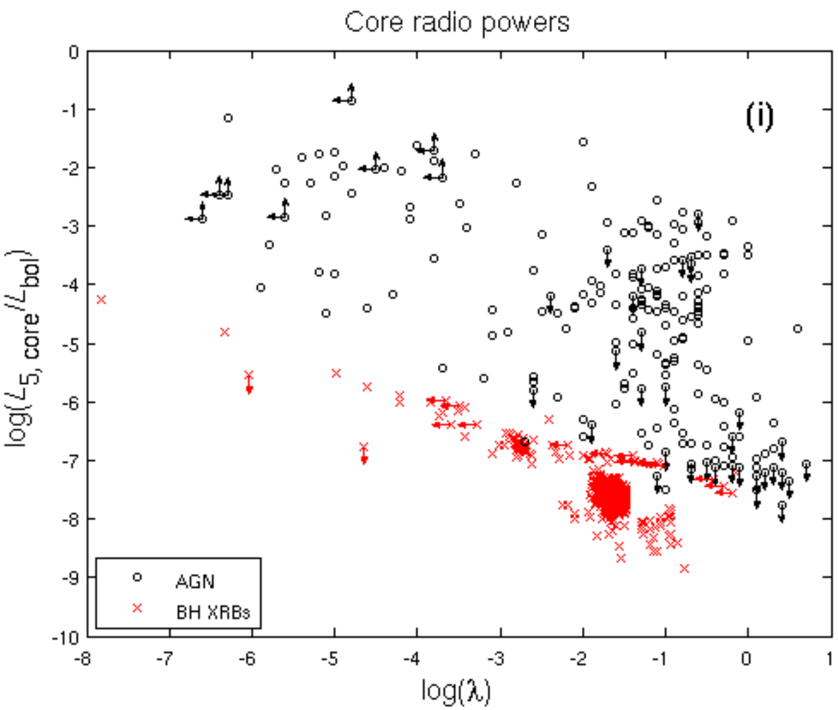
* Angular resolution may not be sufficient to isolate true radio core.

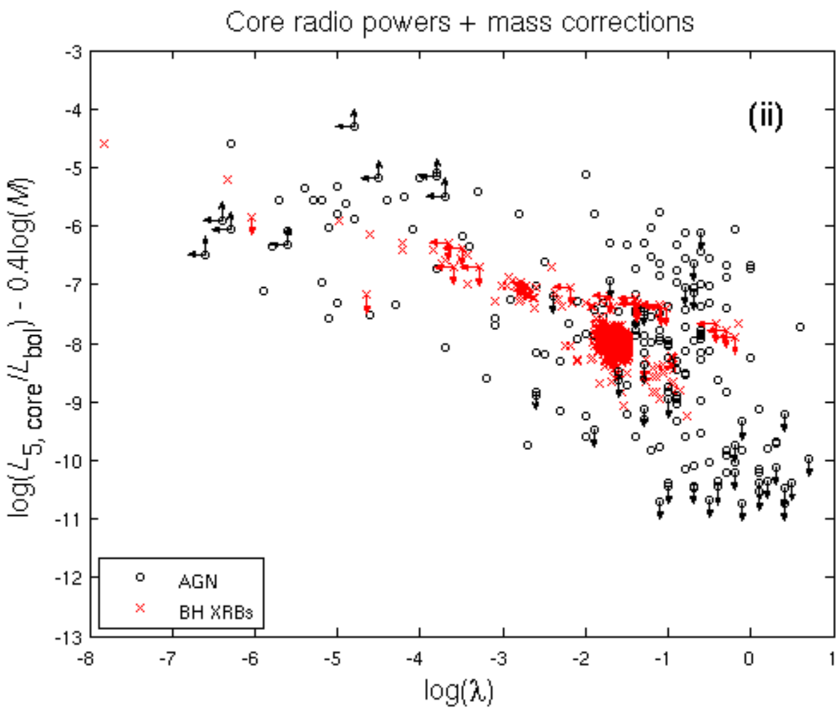
* Possibly complex relationship between optical and X-ray nuclear luminosity (e.g. dust extinction).



BH XRBs (Fender et al. 2010) - $L_{\rm bol} = 5L_X$

AGN (SSL07) - $L_{\rm bol} = 10L_B$





Mass correction important!

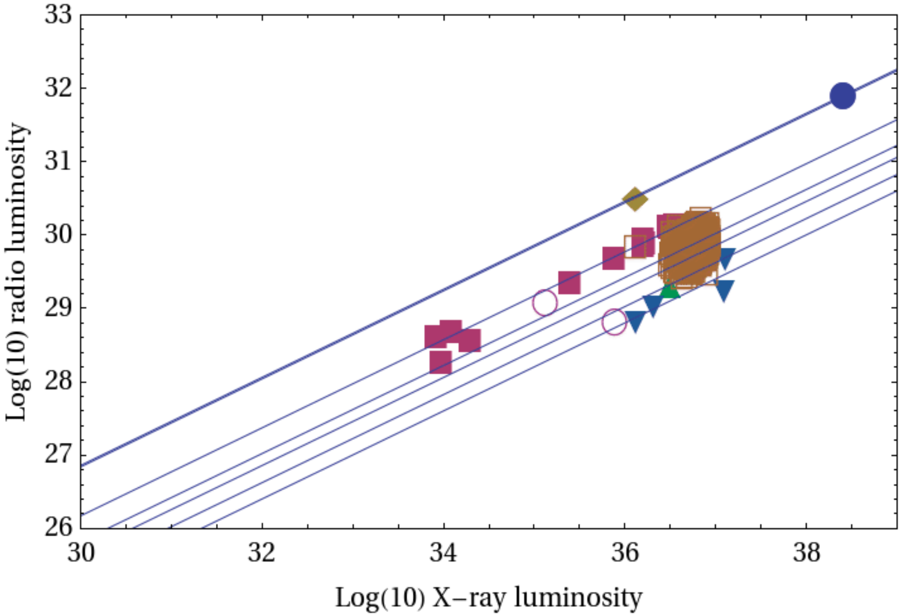
For XRBs, there is no correlation of any of the jet parameters (radio power, speed) with

- Reported spin measurements

- Any other known binary parameter (binary separation, inclination, disc size)

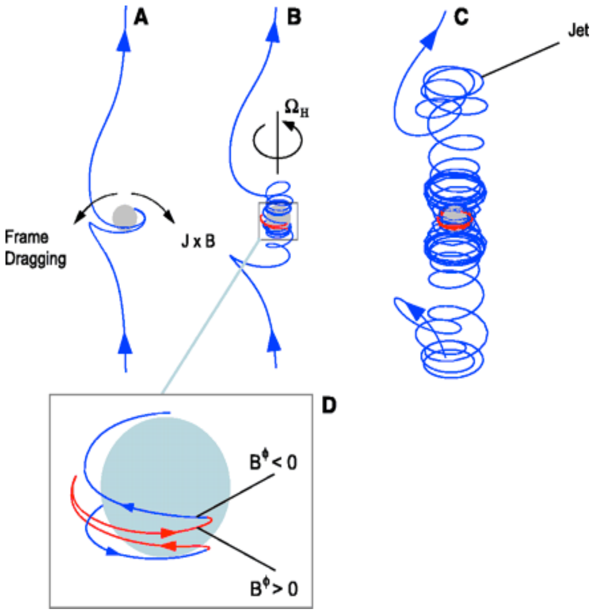
- Furthermore, the radio-quiet BH are not really distinguishable from neutron star systems in the radio:X-ray plane

Fender, Gallo & Russell (2010)
Soleri & Fender (2011)



So one or more of these statements is true for black hole binaries

- The jet power estimates are wrong
- The spin measurements are wrong
- Spin is not important for jet power (i.e. Blandford-Znajek not important)



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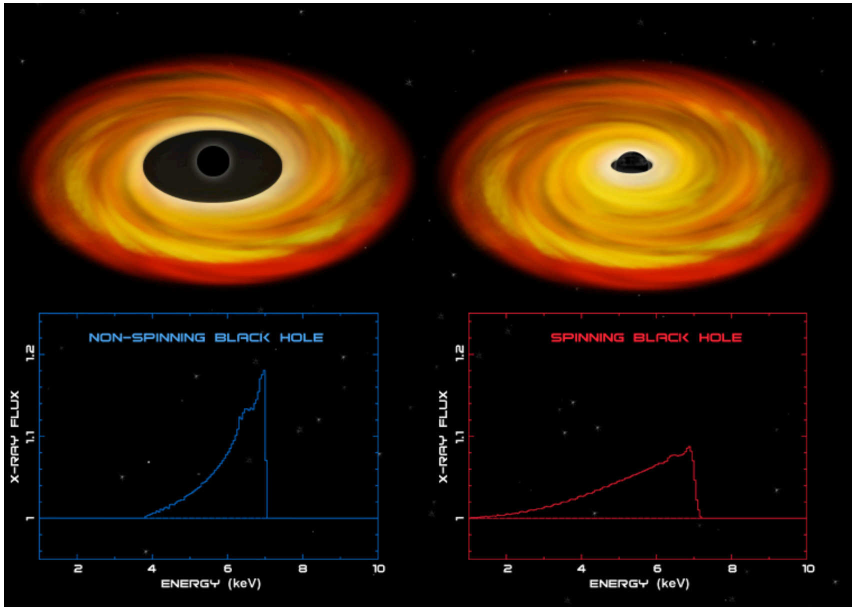
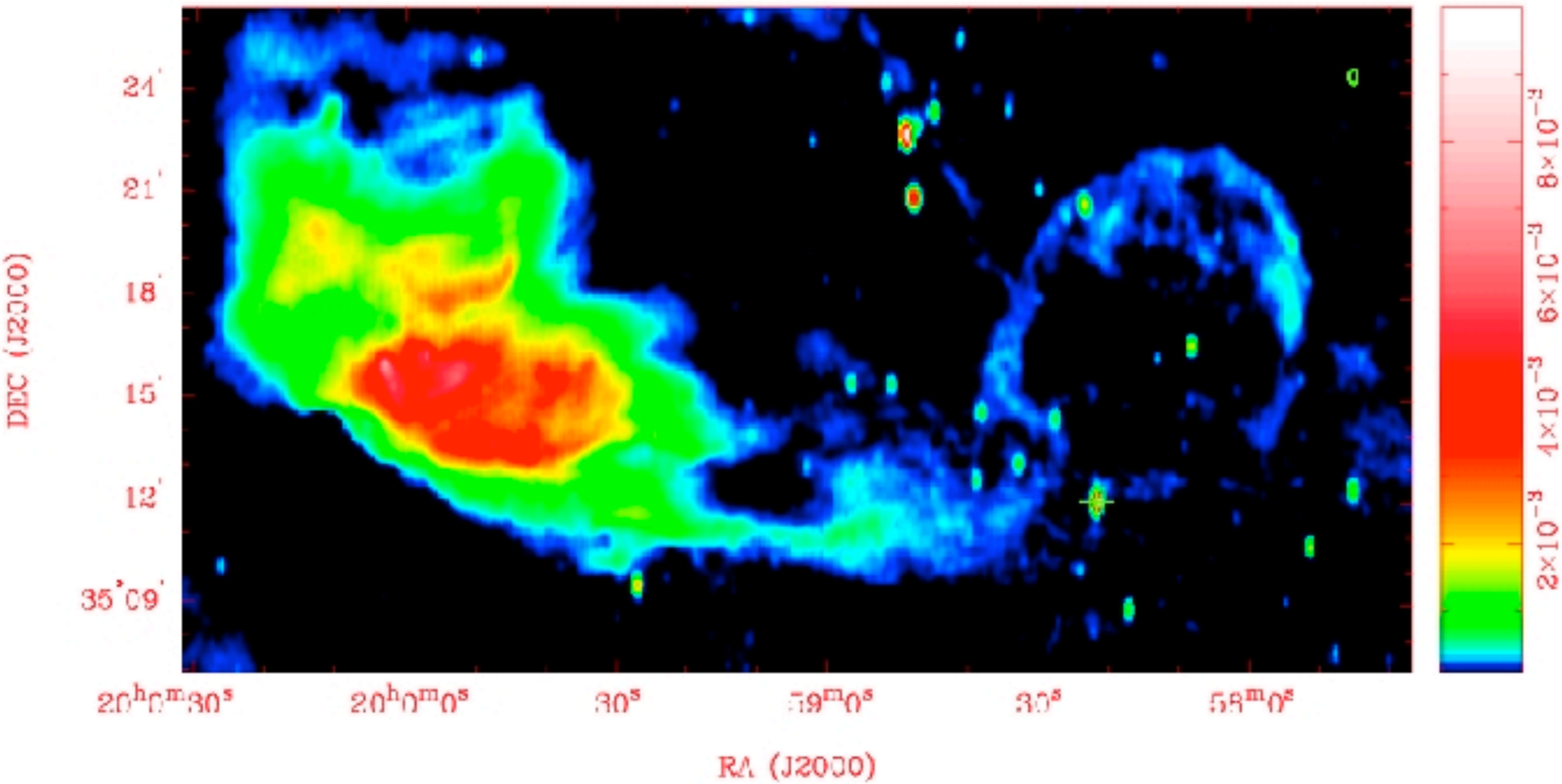


The lowest reported spin could be associated with a well-measured jet



For Cyg X-1 **(a=0.05+/-0.01)** we have strong lower limits on jet power which are already comparable to the X-ray luminosity **and to the (mass normalized) jet power of (LL)AGN** (see also Heinz 2006; Malzac et al. 2009 .. lots of work on this jet)

[though recent work (e.g. Gou et al. 2011) suggests that the spin is much higher!]

Conclusions

*** For AGN, the distribution of points in the log(R)-log(λ) plane is strongly dependent on the measure of radio power used. Using core-only radio luminosities and applying a mass correction narrows the gap between the radio loud and radio quiet sequences by about an order of magnitude for -6 < log(λ) < -2.**

*** After the corrections are applied, RGs are more radio-loud than SGs/LINERS by about 1.6 dex; a mild dichotomy is therefore still present (about an order of magnitude in jet power). Thus, spin appears to have considerably less impact on jet power than previously reported (also keep in mind the lack of evidence for spin-powering of jets in BH XRBs).**

*** The characteristics of the ambient environment and/or the radio source age could at least be equally as important as spin in producing a radio-loud/radio-quiet dichotomy seen in total radio luminosity.**

*** A large sample of AGN is needed with (quasi)-simultaneous radio (VLBI) and optical/X-ray observations to shed further light on the radio-loud / radio-quiet dichotomy.**