Parsec scale radio nuclei in Local Seyfert Galaxies

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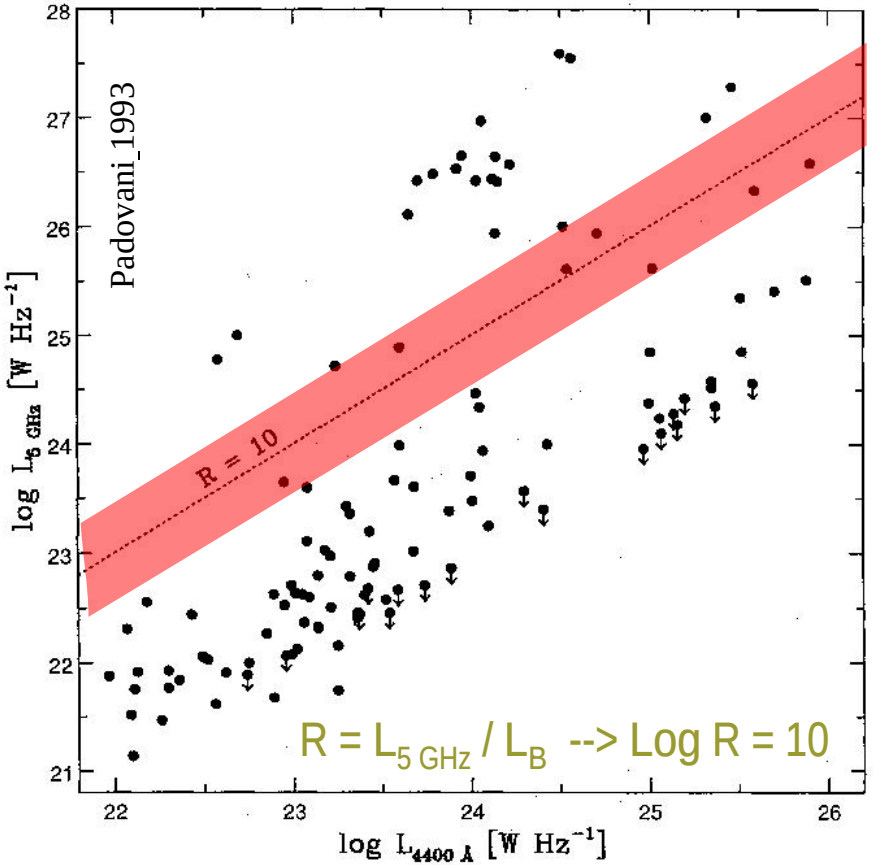
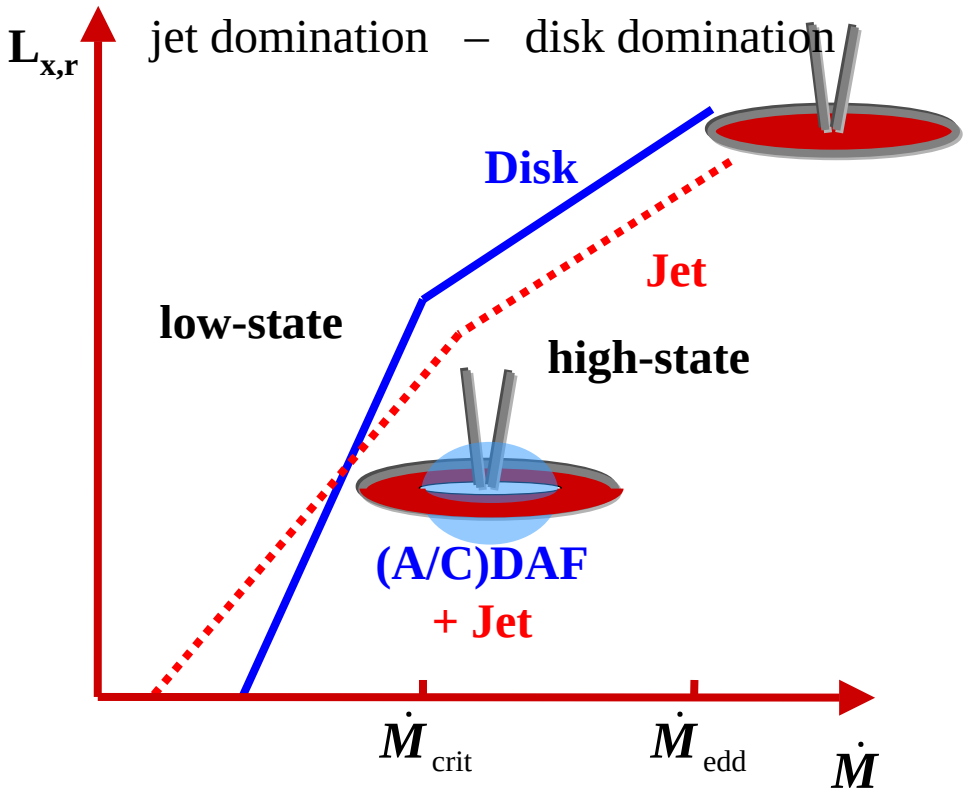
Radio Quiet vs Radio Loud

- Radio Loud objects
  - powerful radio sources $L>10^{22}$ W Hz^{-1}
  - large scale radio lobes
  - compact VLBI (bright) cores (with superluminal motions)
- Radio Quiet (Seyferts)
  - faint radio sources
  - emission confined to sub-kpc scale
- Recent VLA & VLBA surveys show that most AGN are radio sources at some level
  - Ho&Ulvestad 2001; Nagar et al. 2002, 2005



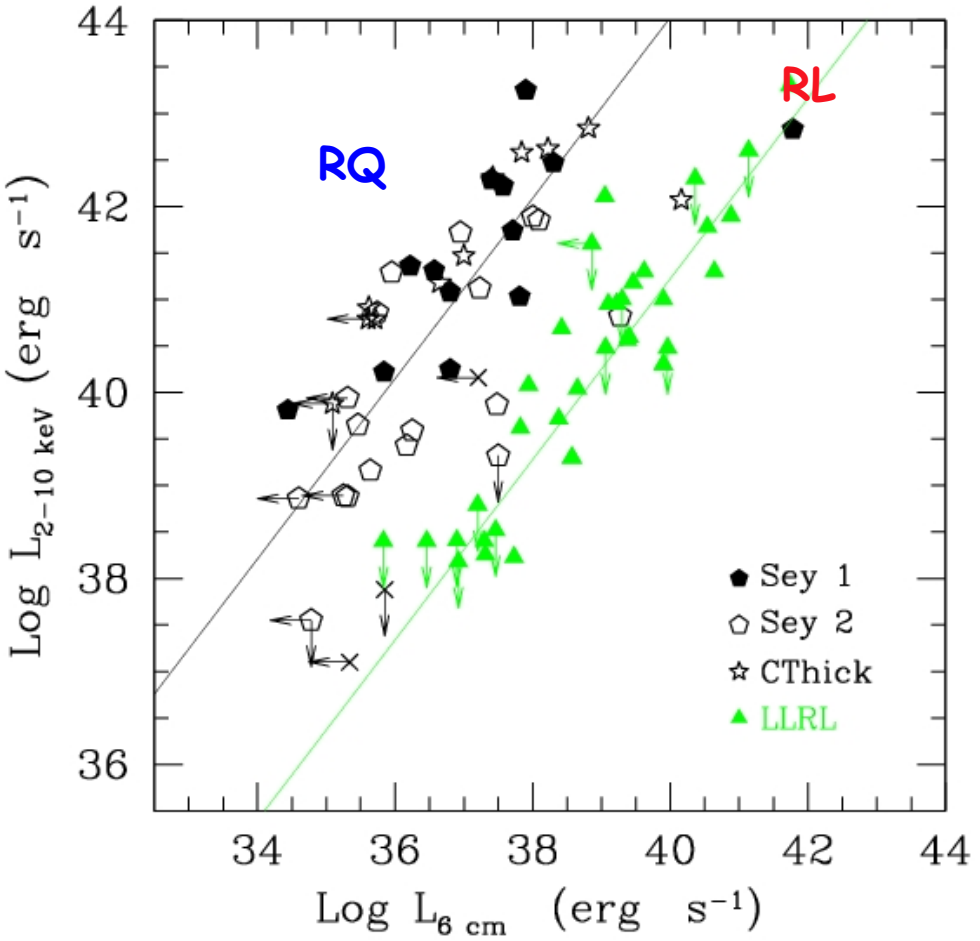
Origin of radio emission in Radio Quiet

- Which is the origin of radio emission in Seyfert galaxies?
- How it is related to the accretion flow? To the accretion rate?
- At lower accretion rates disks become less and less prominent, jets remain strong.
- Analogy with black hole X-ray binaries



Körding, Falcke, & Markoff (2002);
see also Fender, Gallo, & Jonker (2003)

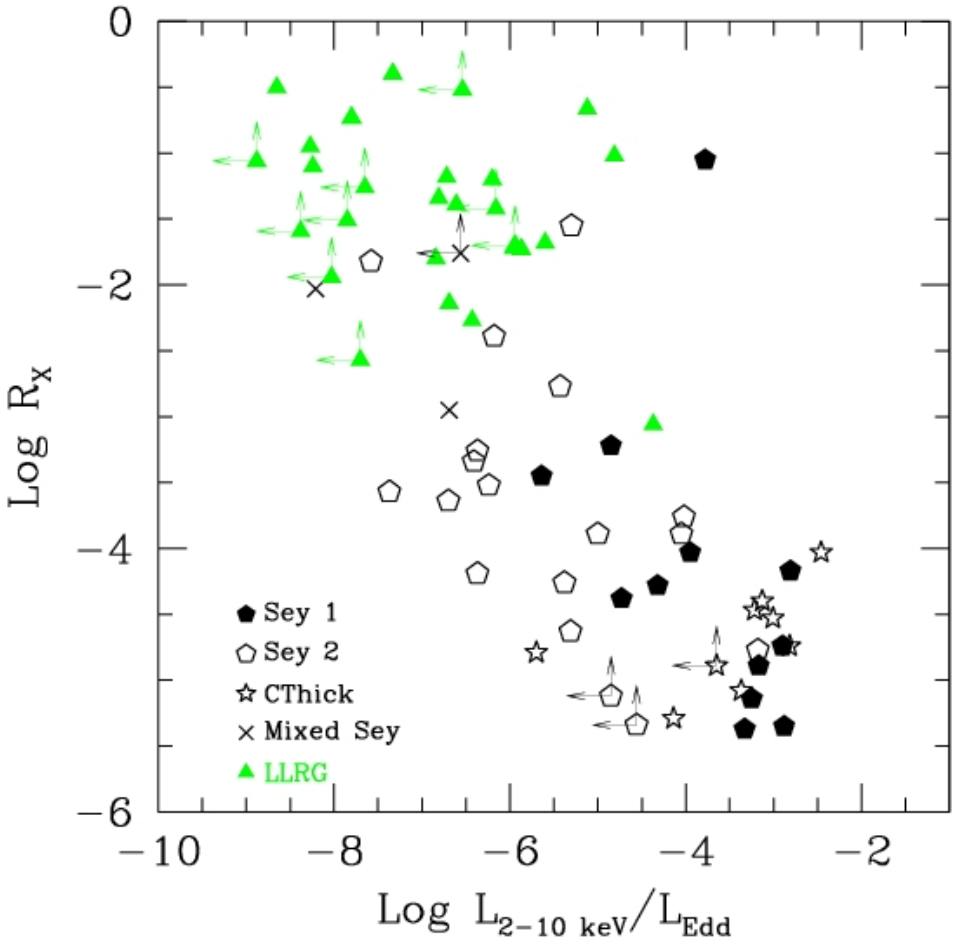
Scaling Relations: X-ray vs radio luminosity



RQ: Panessa et al. (2007)
RL: Low Luminosity Radio Galaxies (Balmaverde&Capetti 2005) from VLA surveys + HST + Chandra

- The two correlations extend for 8 orders of magnitude --> down to the regime of Low-Luminosity AGNs
- In Radio Quiet
  - Some physical parameter that links the jet related power to the corona emission (corona is at the base of the jet)
  - Radio and X-ray emission produced in outflows
    - Merloni et al. 2003, Ghisellini et al. 2004

Radio loudness

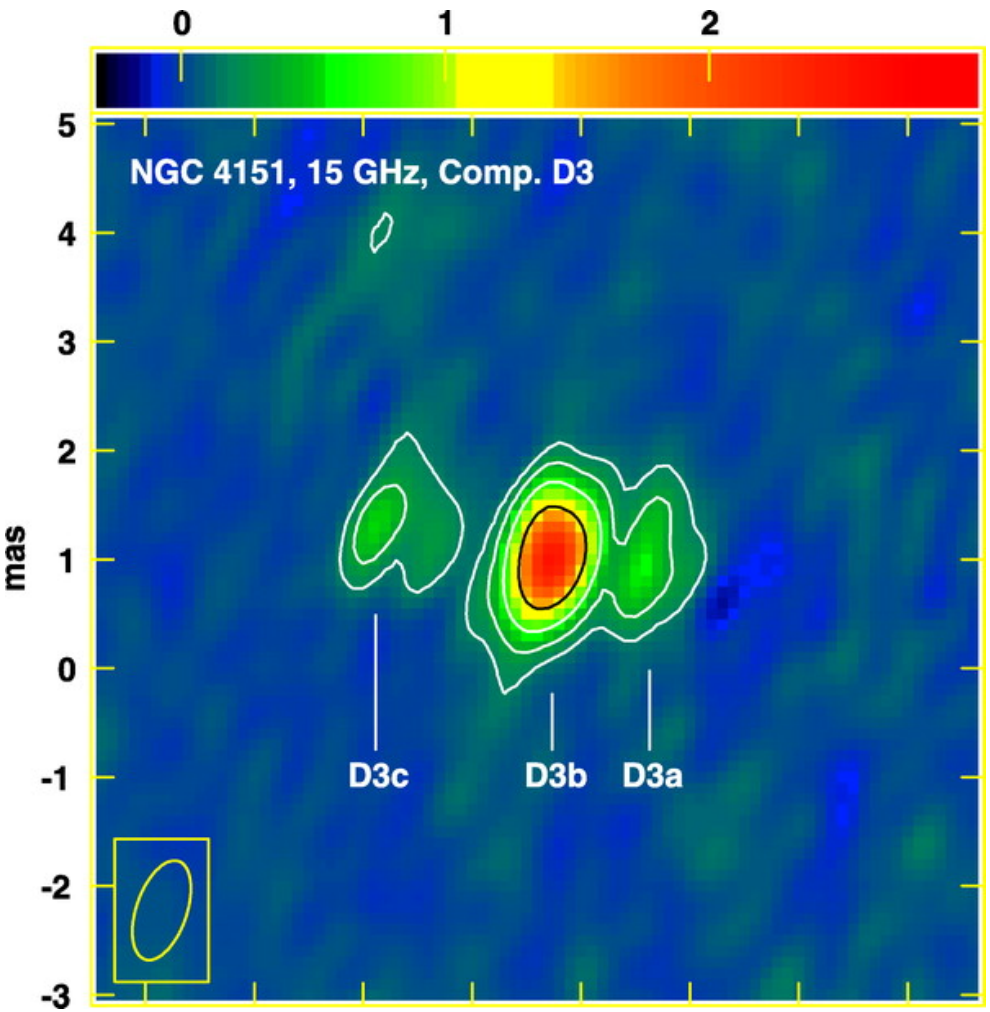


- Increasing radio-loudness with decreasing Eddington ratio?
  - (Ho et al. 2002, Sikora et al. 2006)
- The formation of a jet in LLAGN is related to the accretion rate as in XRBs?
- --> Need to look at the radio emission first to see if jets are there!

VLBI Observations of a Complete Sample of Seyferts

- A complete sample of 27 Seyfert nearby galaxies
  - D < 27 Mpc
  - XMM data in Cappi et al. (2006)
  - VLBI images available in the literature for a few bright objects (this are really nearby sources!)
  - For the first time sources with S < 1mJy (VLA cores)
- European VLBI Network new observations for 6 objects to complete the sample at mas scales

VLBI Obs. of RQ Nuclei: NGC 4151

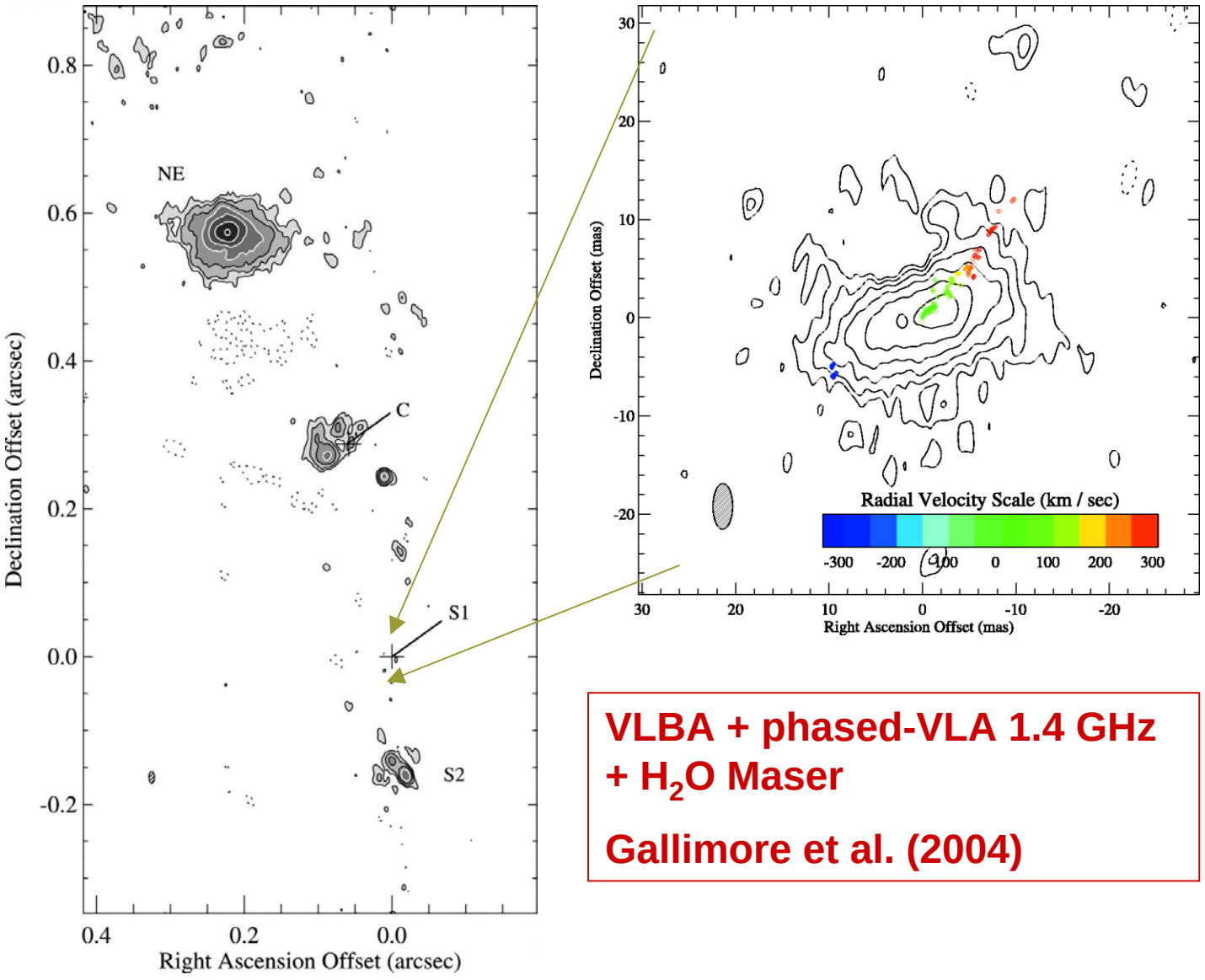


VLBA @15GHz

Ulvestad et al. 2005

- NGC 4151
  - a radio-quiet Sy1.5 nucleus
  - Radio source size < 0.035 pc, BLR scales
  - VLBI compact flat-spectrum radio component with $T_b > 2 \times 10^8$ K
  - A weak two sided beginning to the large scale radio jet
  - Sub-relativistic motions

VLBI Obs. of RQ Nuclei: NGC 1068



VLBA + phased-VLA 1.4 GHz + H_2O Maser

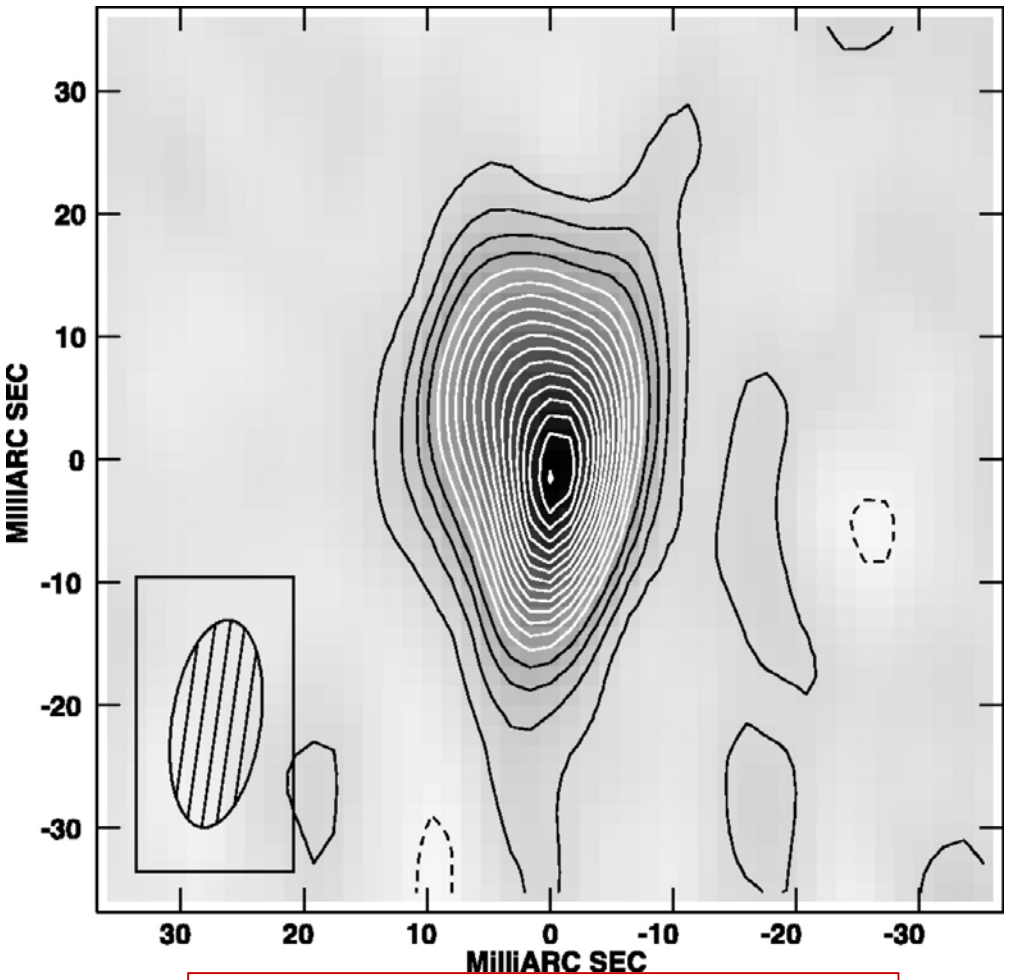
Gallimore et al. (2004)

NGC 1068: S1 component resolved into an extended 0.8 pc long structure oriented perpendicular to the jet and aligned to the maser disk

Thermal free-free emission from an X-ray-heated corona or wind arising from molecular disk

Low T_b: 2.5×10^6 K and flat-inverted spectrum

VLBI Obs. of RQ Nuclei: NGC 4395



HSA at 1.4 GHz

Wrobel & Ho (2006)

- NGC 4395: radio-quiet type 1 nucleus with $L_X/L_{Edd} = 0.004$
- $T_B > 2 \times 10^6$ K
- VLBI elongated structure which suggests radio outflow on sub-pc scales
  - (scale of 0.021 pc/mas)
- going to low flux densities

VLBI Obs. of RQ Nuclei: EVN is in!

- 1 Gbps is really needed
- large apertures also necessary: Effelsberg, Jodrell (Lovell), Westerbork
  - and looking forward to Yebes, SRT!
- six targets with VLA detection at 1.4, 5 GHz
  - some of them only about 1 mJy
- 9 hours per target at 1.6, 5 GHz with full EVN
  - NGC 4051, 4388, 4501, 5033, 5194, 5273

EVN Observations

- Observations performed on 2007 session 2, 2008 session 1
- What worked well:
  - scheduling, even pipeline! ☺
- What didn't work:
  - telescopes ☹ - we had various failures at large apertures
- some interesting stuff coming out, though!
  - sensitivity of about 20 microJy (rms)
  - a linear resolution around 0.1 pc

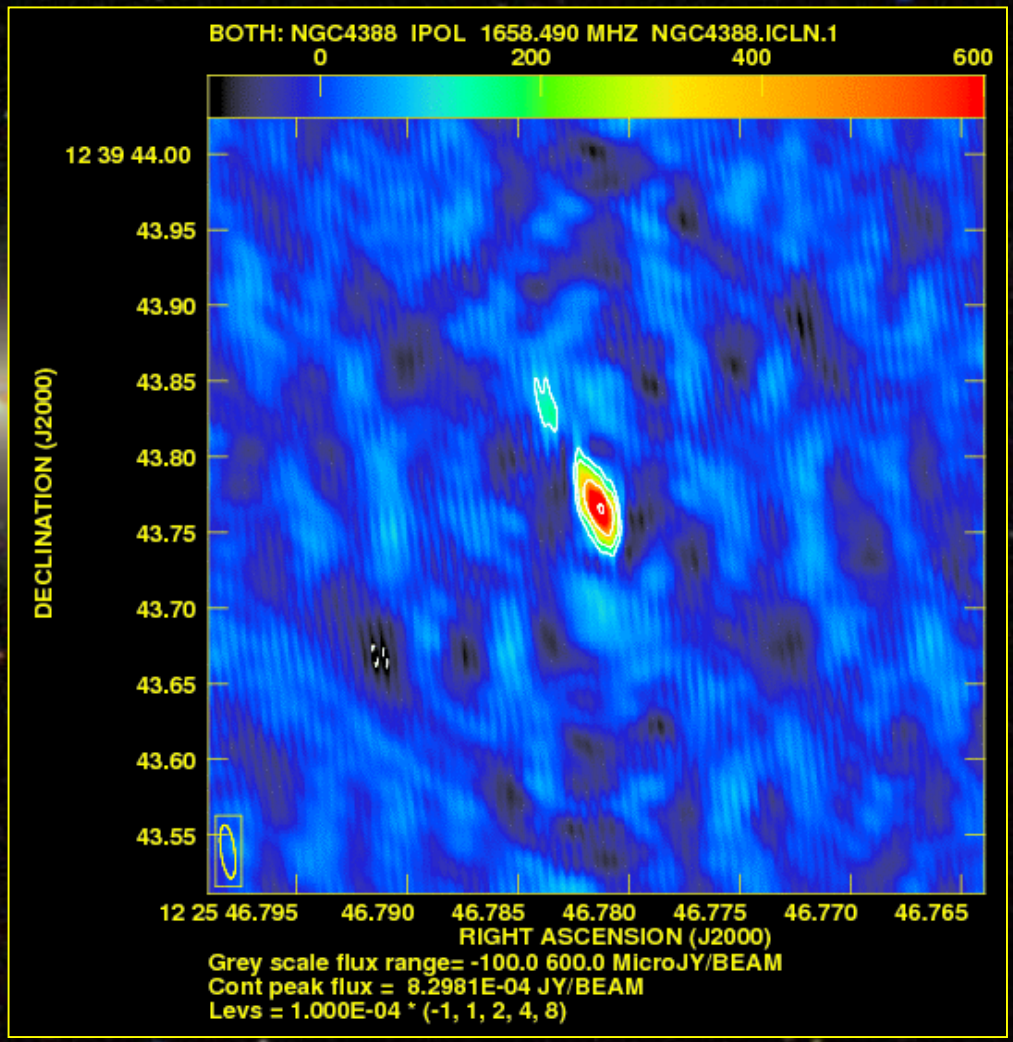
EVN NEW results: NGC 4051

- Sy1.5
- d=10.2 Mpc

- emission difficult to constrain but clearly present in the visibility data at 1.6 GHz

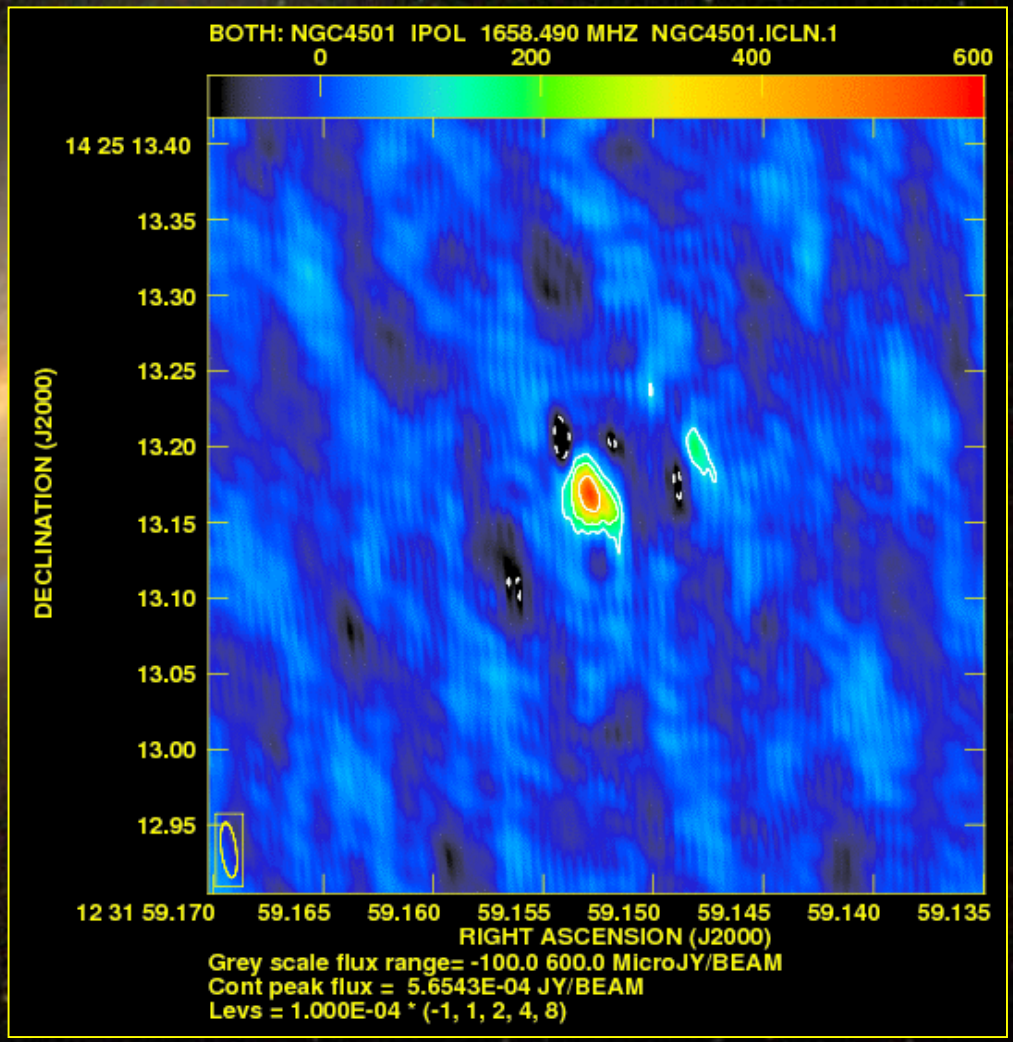
EVN NEW results: NGC 4388

- Sy2
- d=34 Mpc
- 1.6 GHz peak: 0.8 mJy
- tentative jet to NE



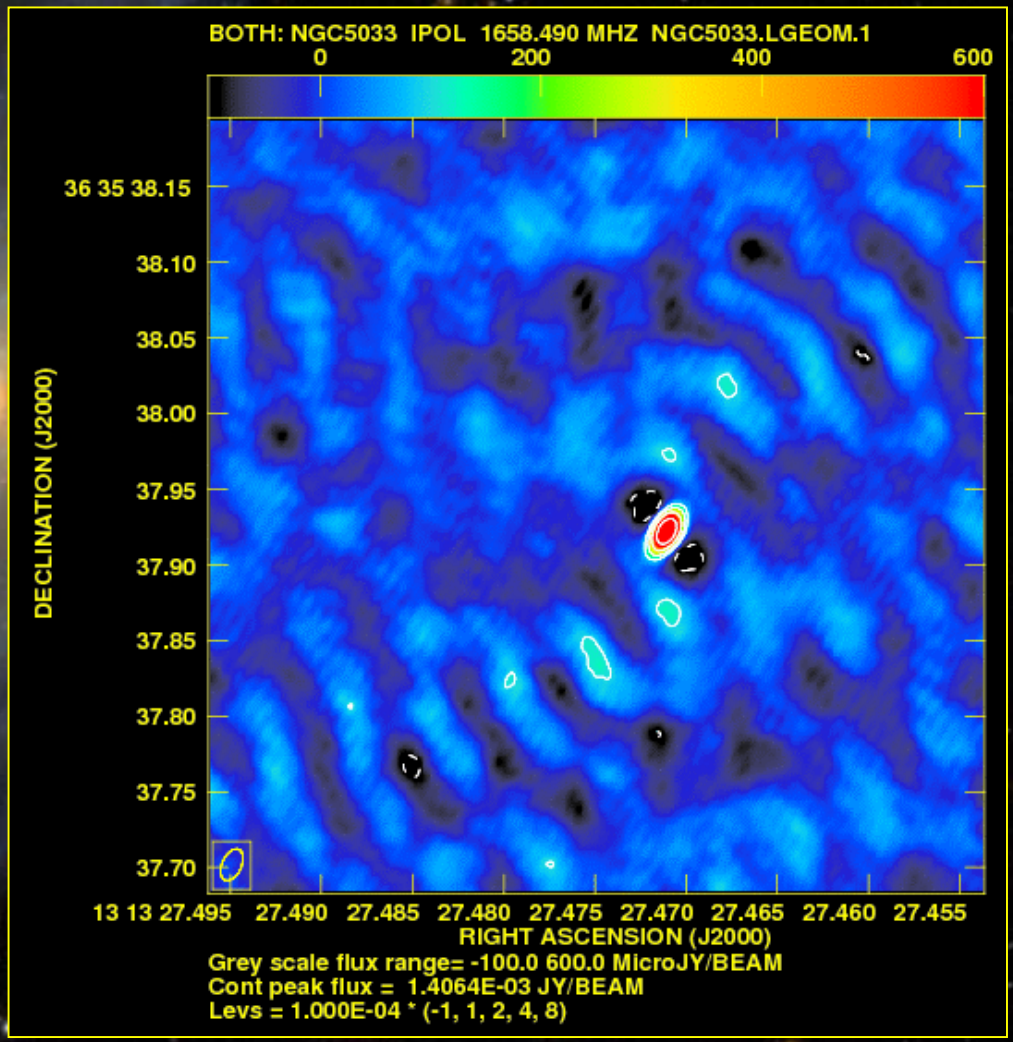
EVN NEW results: NGC 4501

- aka M88
- Sy2
- d=31 Mpc
- 1.6 GHz peak: 0.6 mJy



EVN NEW results: NGC 5033

- Sy1.9
- d=12.7 Mpc
- 1.6 GHz peak: 1.4 mJy
- detected also at 5 GHz, moderately flat spectrum

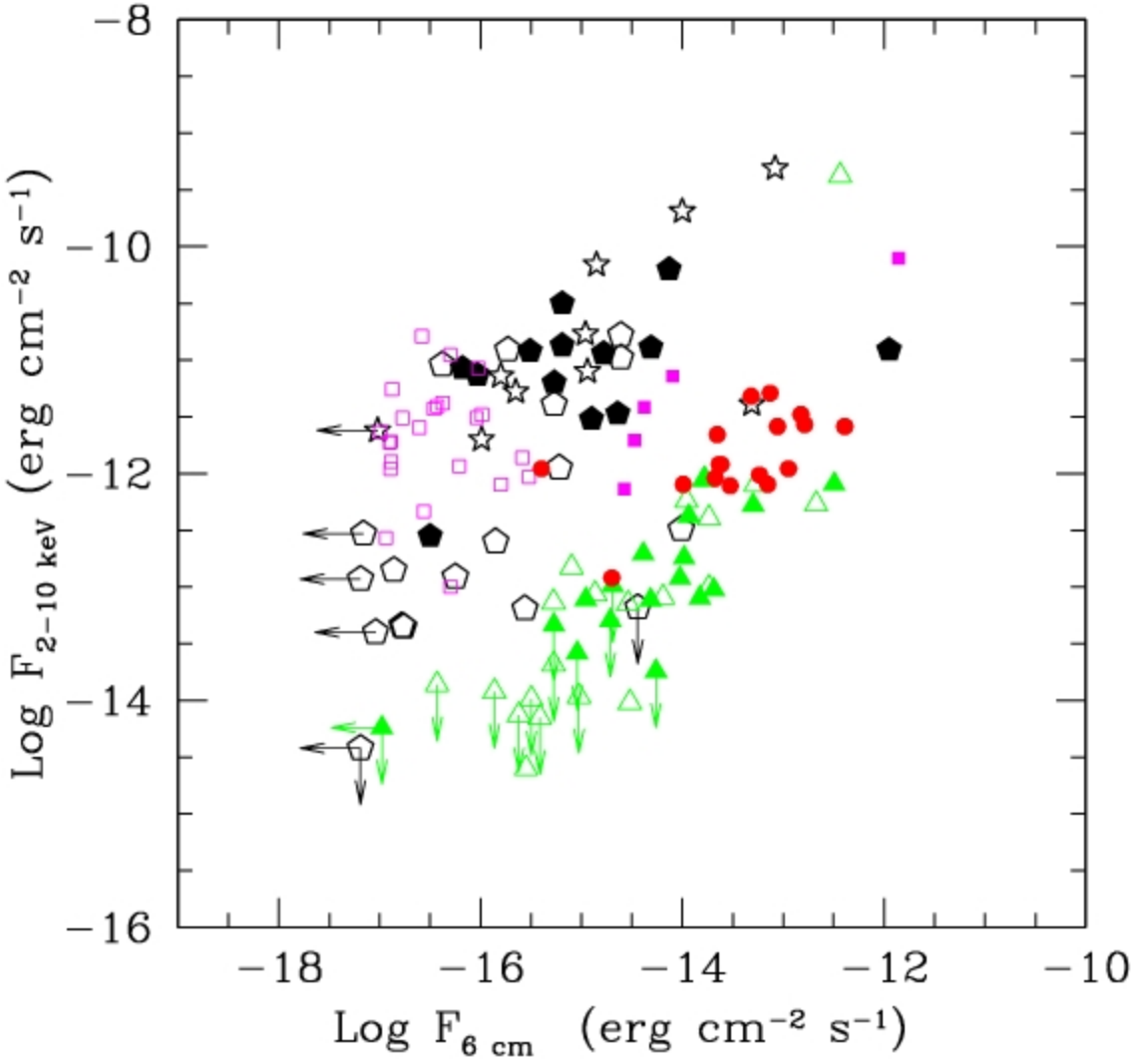


New EVN data: summary

- 6 sources observed
  - 4 detected at 1.6 GHz
  - one also at 5 GHz
    - is there a physical reason or just bad 5 GHz data?
  - two non detection (so far)
    - is there a physical reason or some error (eg position)?
  - more detailed analysis may be necessary
- For sure, measured brightness temperatures are in excess of 10^8 K, i.e. presumably non thermal
- Overall good, bearing results
  - may want to observe more targets soon

Conclusions

- Strong X-ray versus radio correlation --> coupling of the X-ray and radio source
- Systematic study for a complete sample of the VLBI radio properties
  - Seyfert nuclei display compact cores, jets and/or outflows
  - High T_b, flat α
  - Proper motions <0.25 c non-relativistic speeds
  - 40% of the sample show no detection with VLA


−8
−10
−12
−14
−16
−18
−16
−14
−12
−10
Log $F_{2-10\ keV}$ (erg cm^{-2} s^{-1})
Log $F_{6\ cm}$ (erg cm^{-2} s^{-1})

Multi-wavelength analysis of the Palomar Seyfert Complete Sample

60 Seyfert galaxies (13 type 1, 39 type 2, 8 “Mixed Seyferts”)

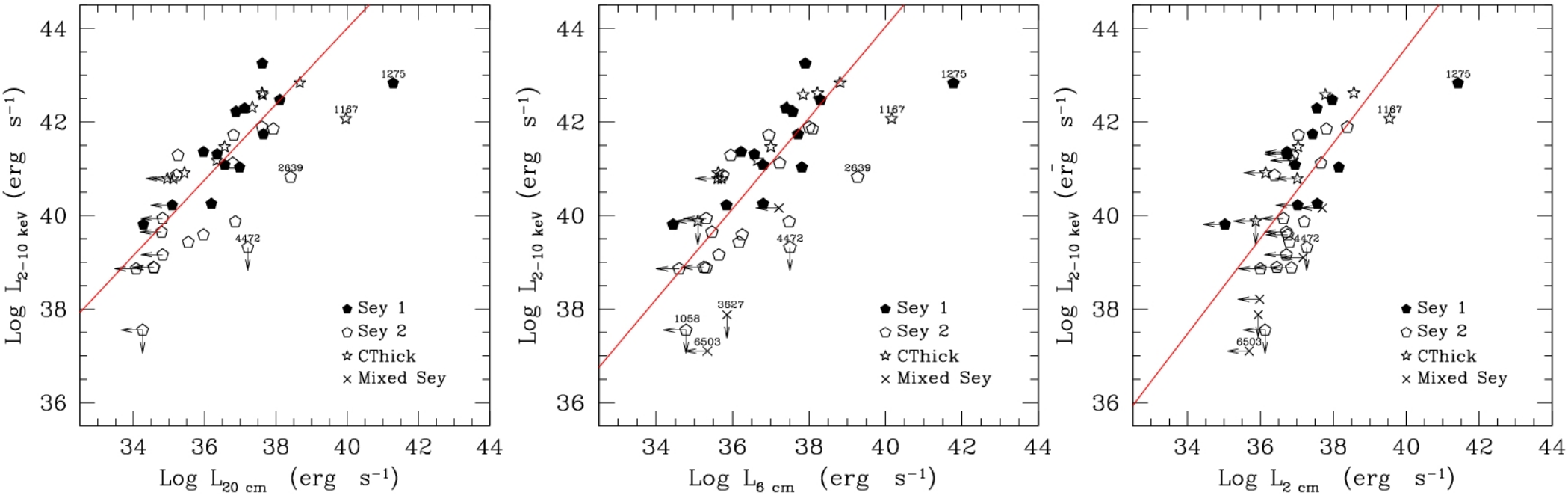
✓ XMM-Newton & Chandra X-ray images and spectra (Cappi et al. 2006, Panessa 2004, Ph.D. thesis)

✓ Accurate optical classification (Ho et al. 1997)

✓ Optical, X-ray, M_{BH} correlations (Panessa et al. 2007)

✓ VLA & VLBI observations (Ho&Ulvestad 2001, Nagar et al. 2002)

Scaling Relations: $L_{2\text{-}10\ keV}$ vs. L_{Radio}

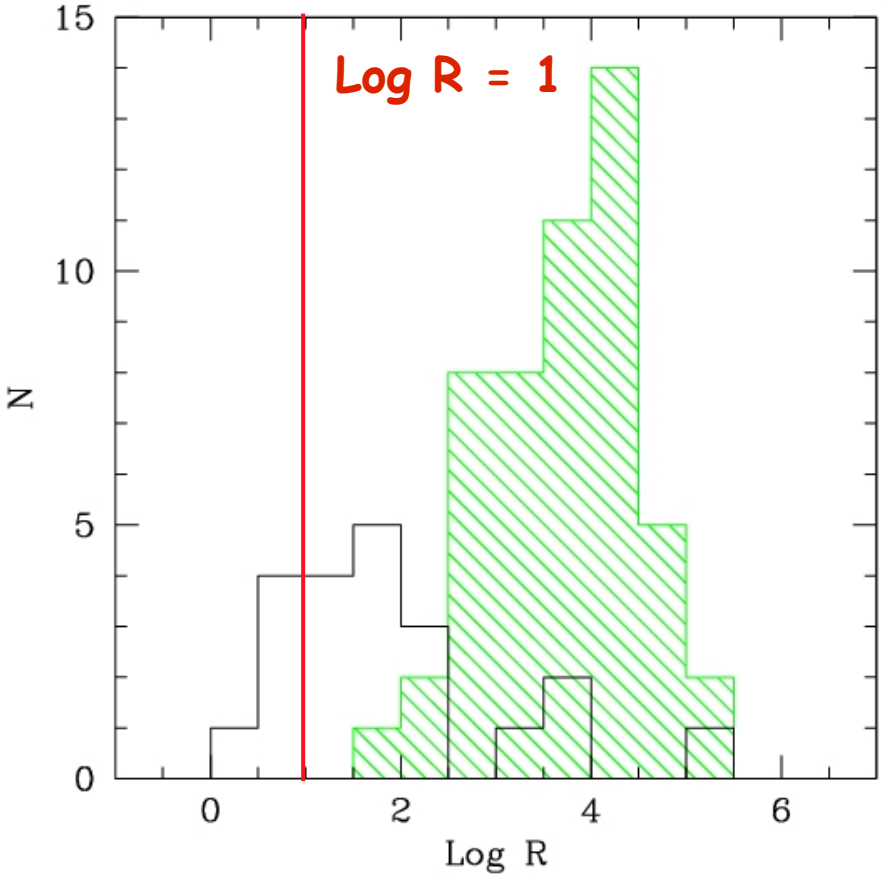


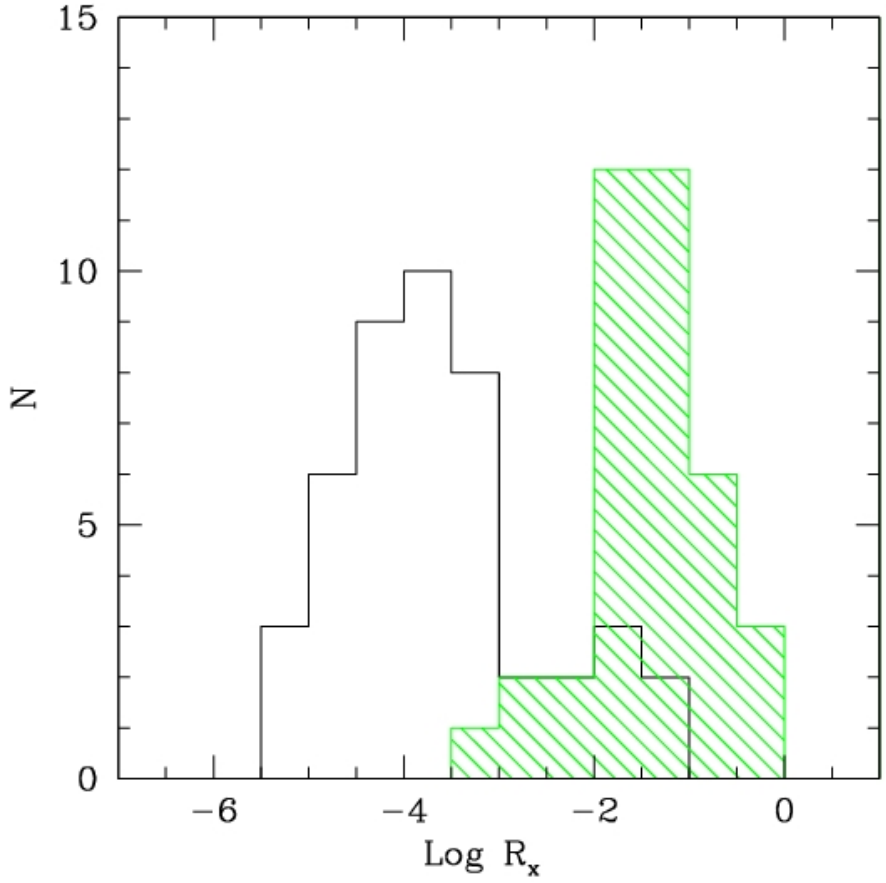
For a COMPLETE SAMPLE of local SEYFERT GALAXIES:

$\text{Log } L_{2\text{-}10keV} = (0.97 \pm 0.01) * \text{Log } L_{5GHz} + (5.23 \pm 0.28)$

Radio Loudness

Are all Sey galaxies Radio-Loud or need a redefinition of the Radio-loudness boundary at low luminosities?

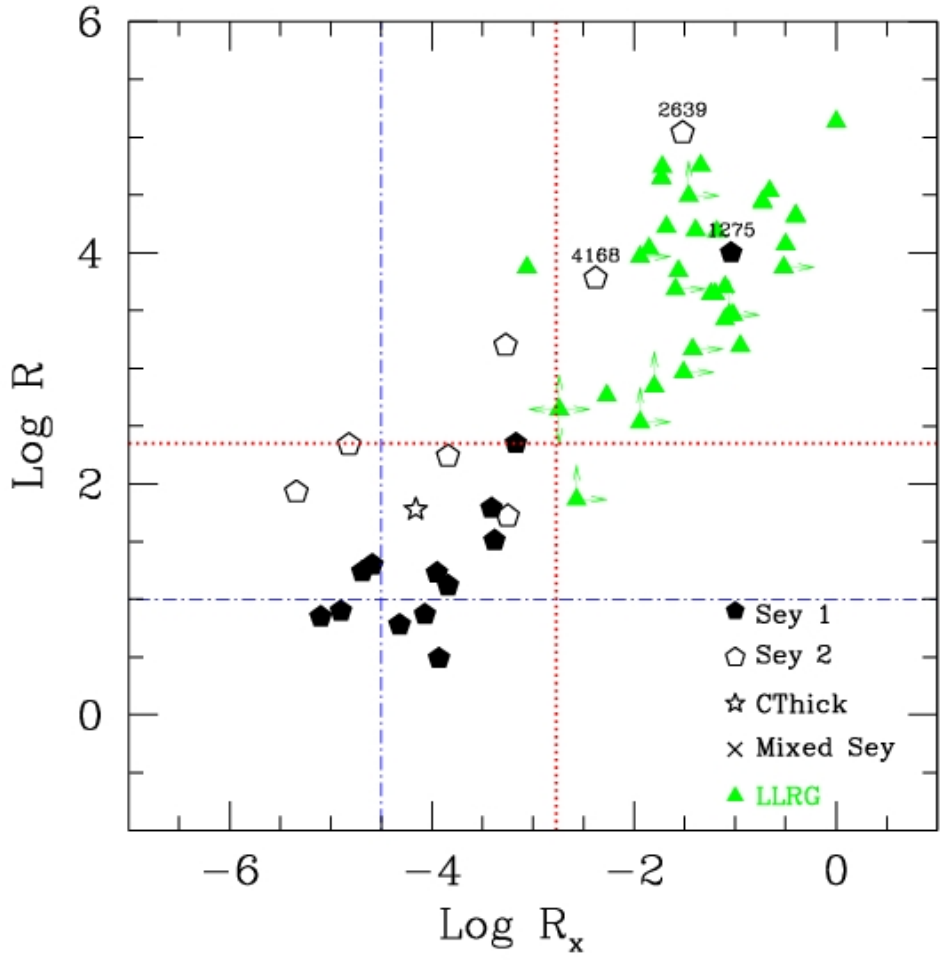




R = L(5 GHz) / L(B)

R(X) = L(5 GHz) / L(2-10 keV)

Radio Loudness



Maximum separation between the two distributions:

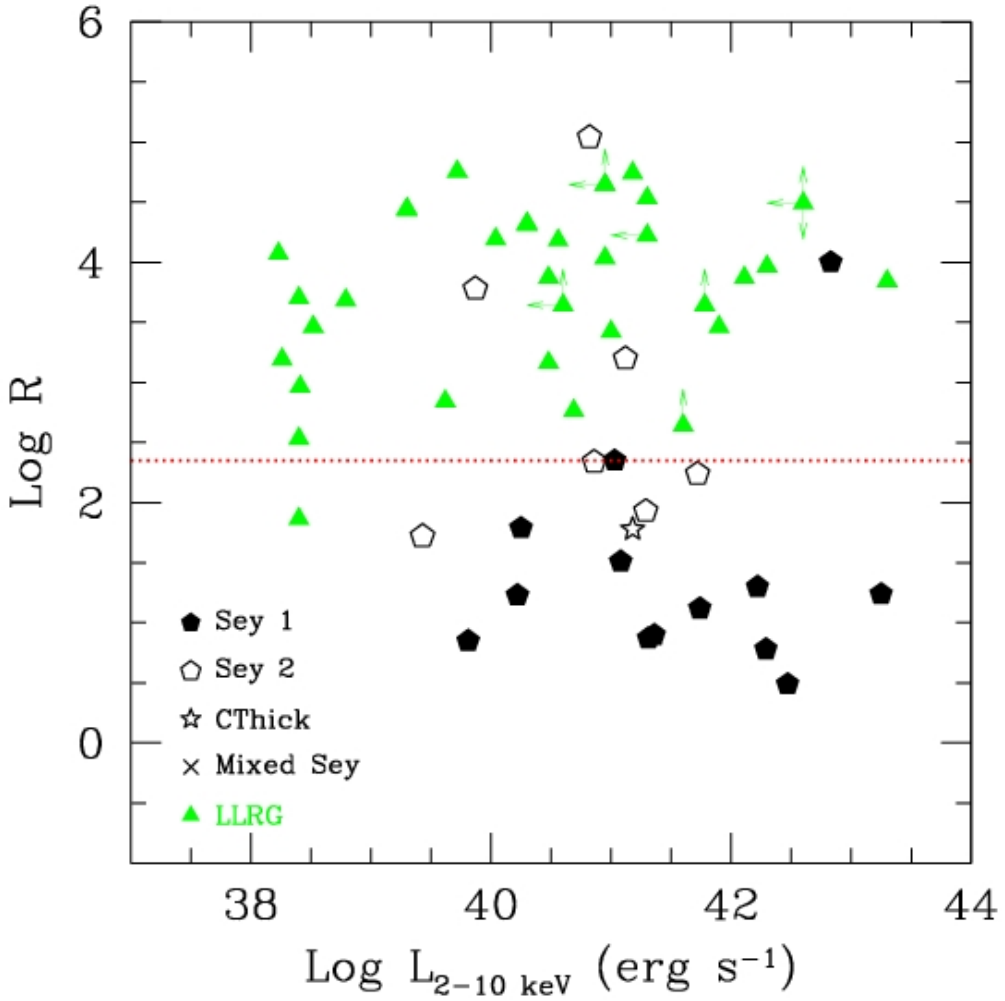
New boundaries at low luminosities?

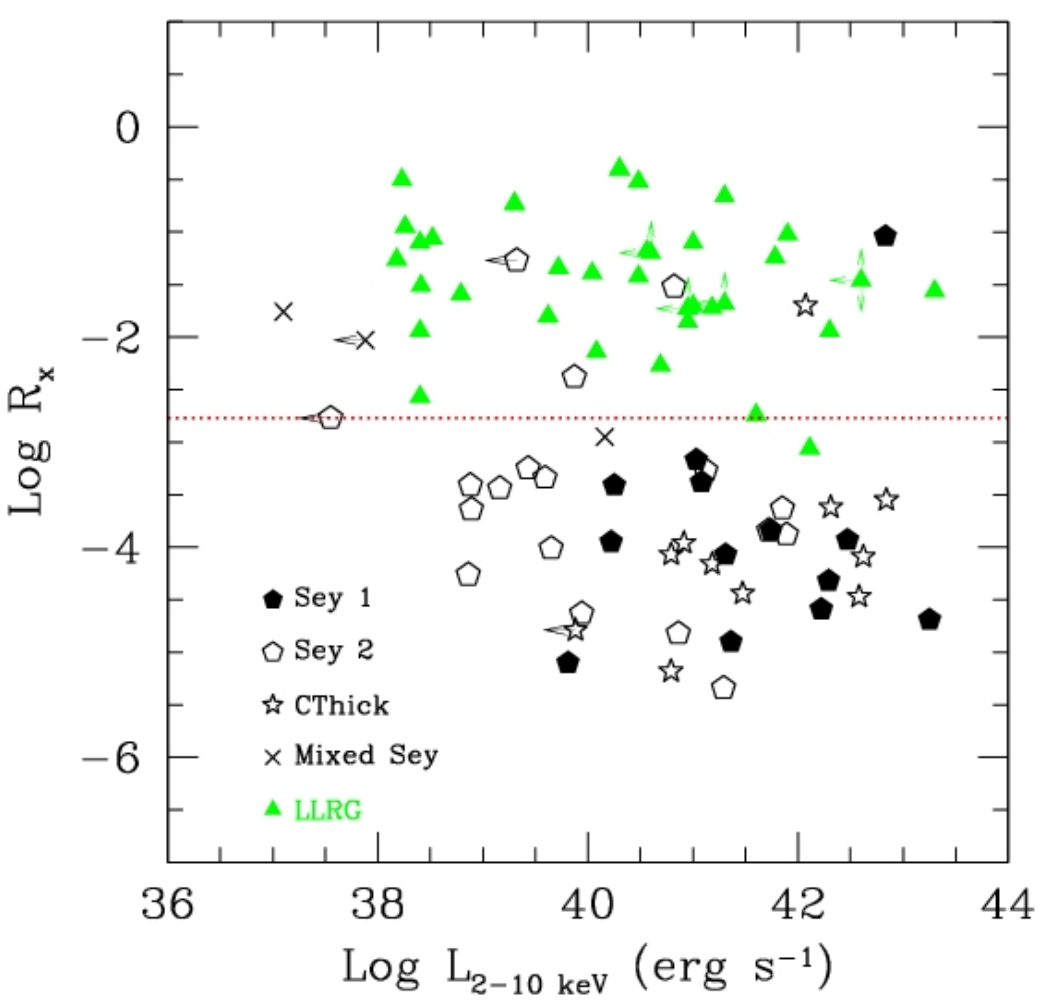
Log R = 2.40 ± 0.05

Log R_X = -2.76 ± 0.02

Radio Loudness

- However, no evidence of a dependence of R with luminosity





Radio Loudness

Radio-Loud AGN are associated with massive BHs