X-ray accretion versus radio ejection in local AGN

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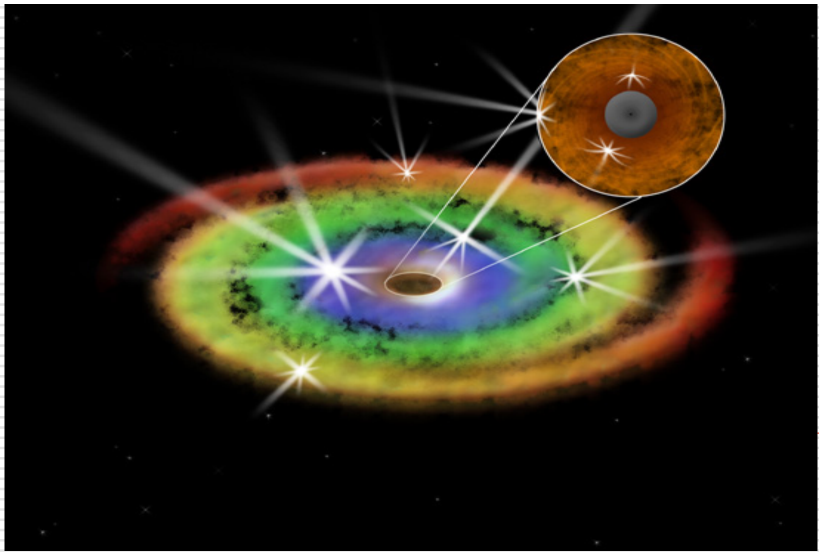
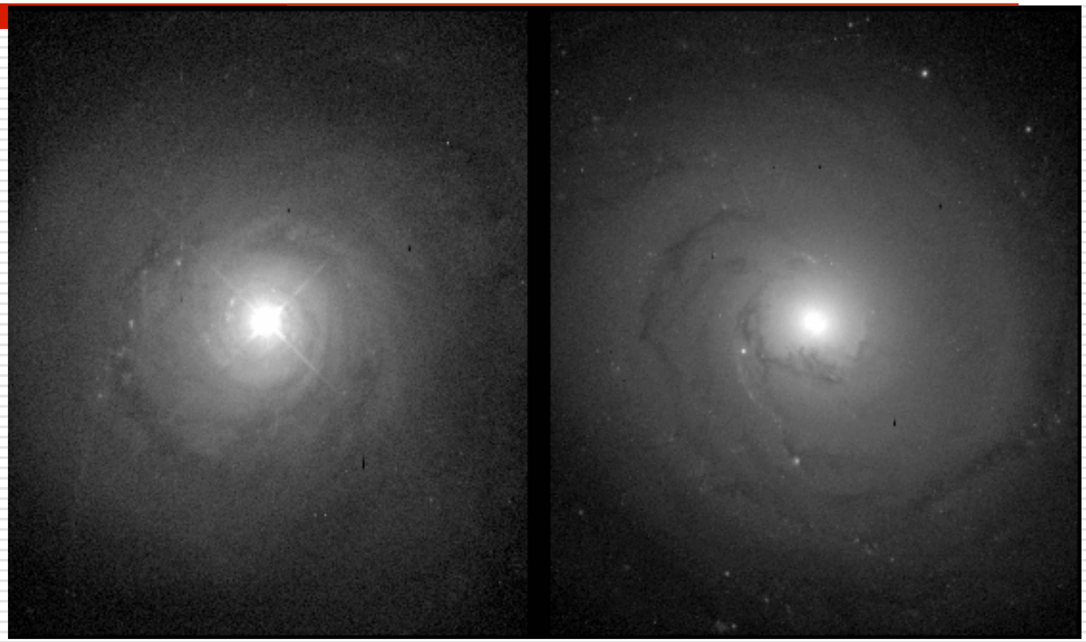
Active Galactic Nuclei (AGN)

BASIC PARADIGM:

Copious energy output from AGN (10^9 - 10^{13} $L_\odot$)

from accretion of material onto a Supermassive Black Hole SMBH (10^6 - 10^9 $M_\odot$).

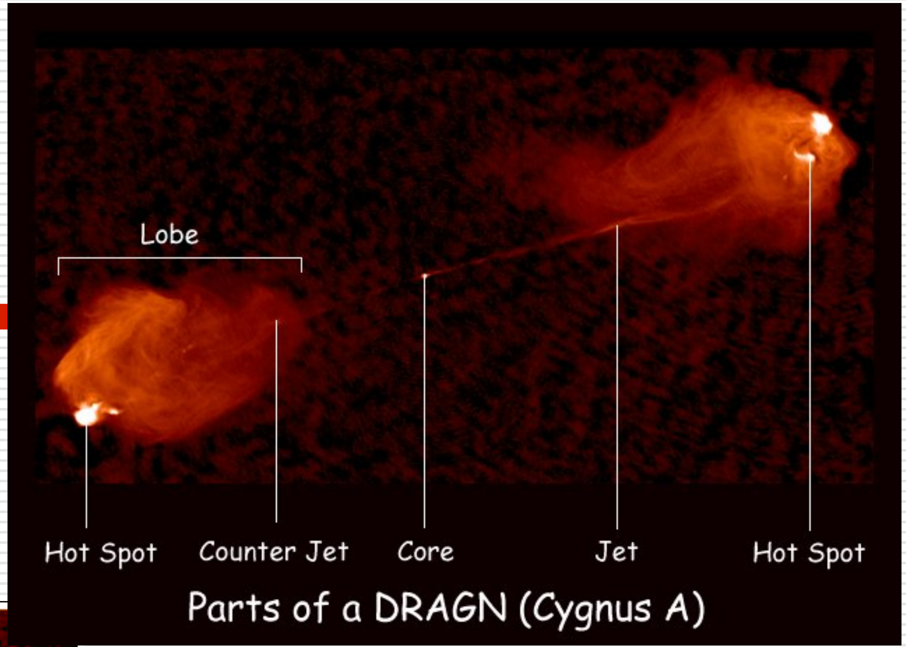


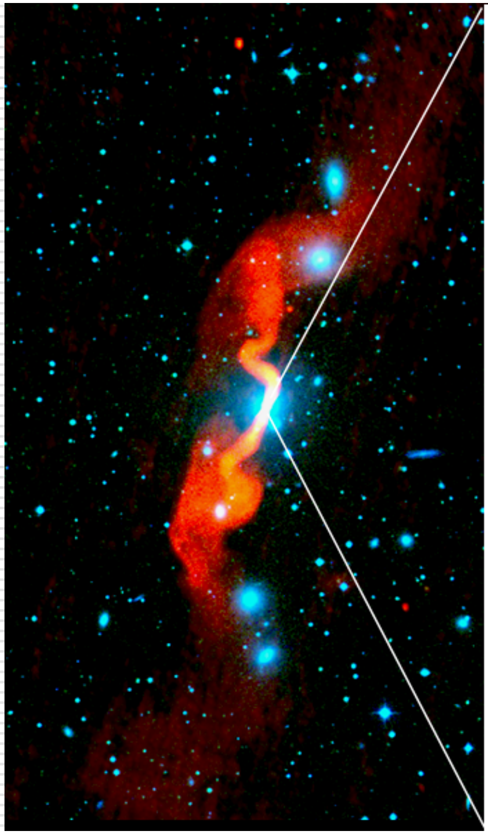


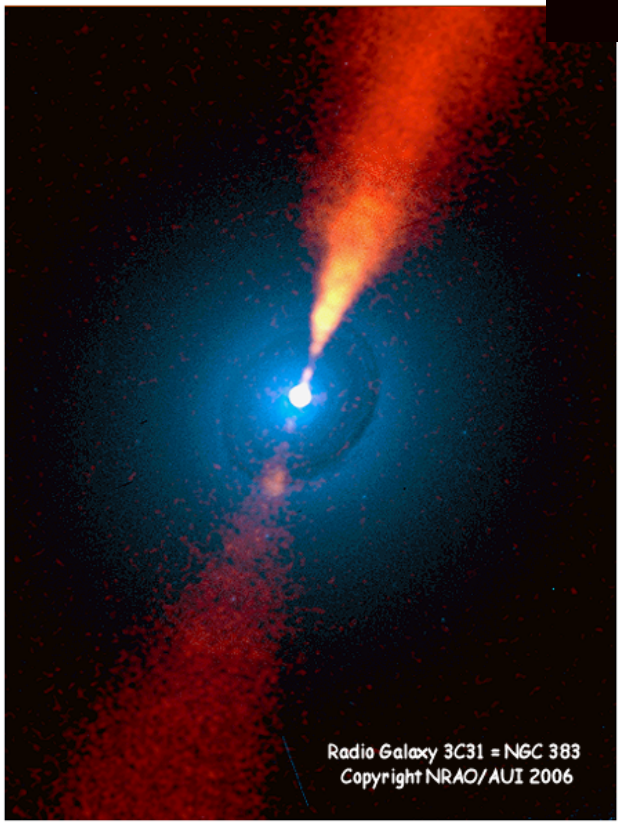
AGN

Normal Galaxy

Radio Galaxies







Single or double radio components

Compact cores (also in AGN lacking the extended emission)

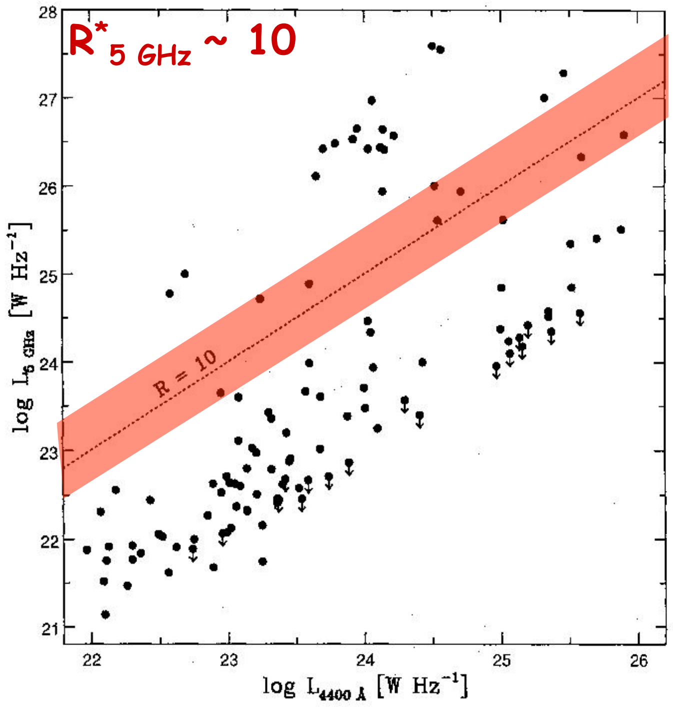
High brightness Temperature T_B (10^{9-12} K)

Steep Spectral indeces (Synchrotron emission)

Flat Spectral indeces (Sef-absorbed Synchrotron emission)

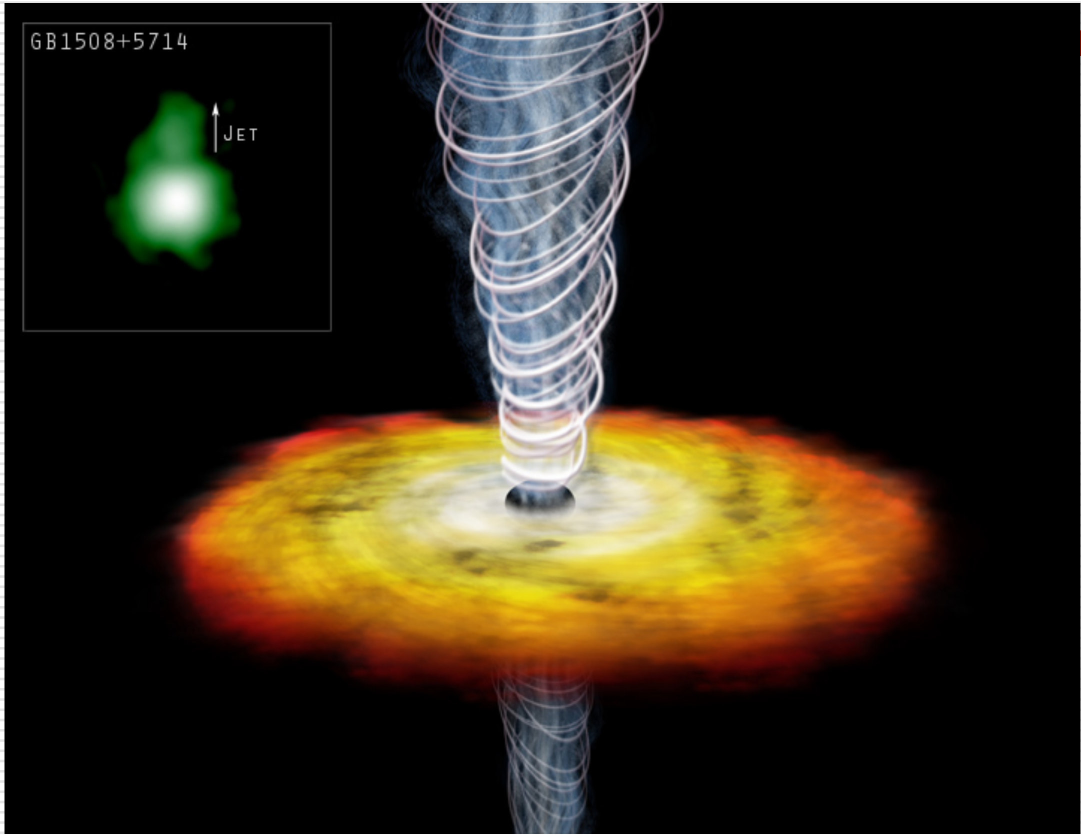
Radio Loud vs Radio Quiet AGN

Padovani_1993



R = L(5 GHz) / L(B) --> Log R = 1   RADIO LOUDNESS

Radio Loud AGN



Mechanism responsible for triggering RADIO emission

↓

Relativistic Jet

Non thermal radiation
(Synchrotron and Inverse Compton)
emitting at RADIO, OPTICAL and X-RAY

RQ AGN?

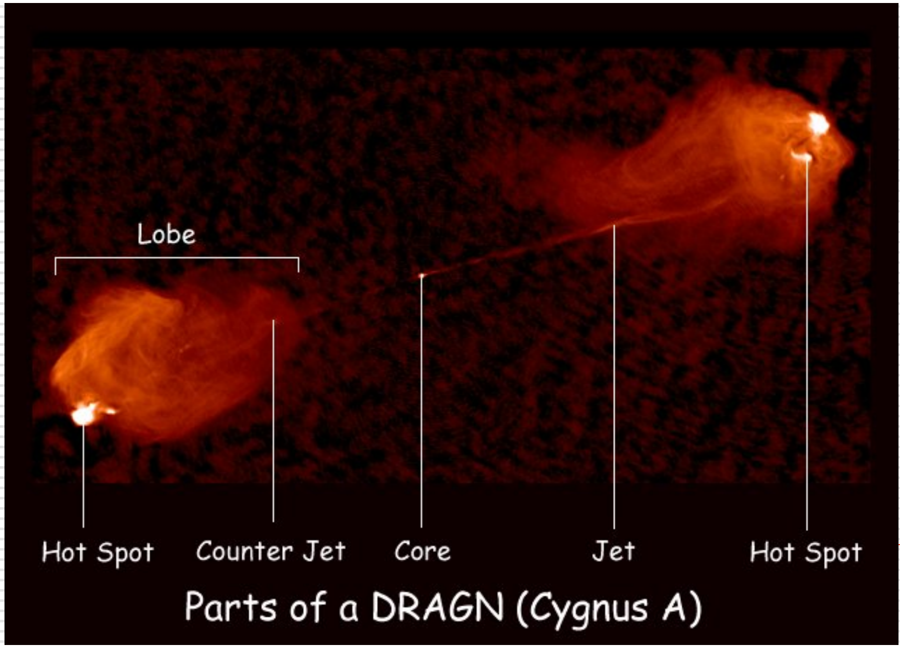
Radio observations with
Very Large Array & Very Long Baseline Array show that ALL AGN are radio sources at some level
(Ho&Ulvestad 2001; Nagar et al. 2002, 2005)

Radio Loud vs Radio Quiet AGN

Radio Loud RL:

✓ Large scale radio lobes

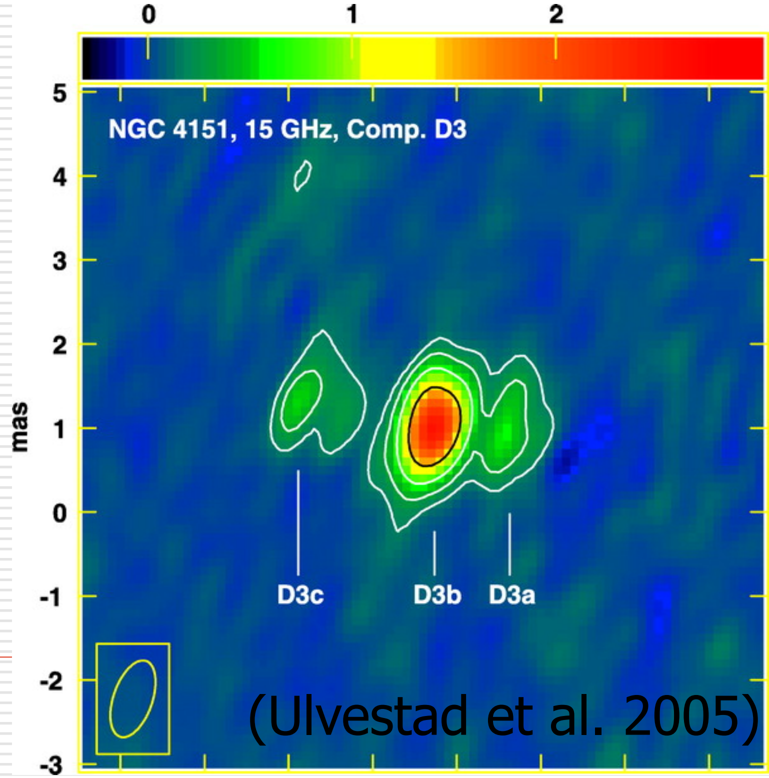
✓ Compact luminous cores often with apparent luminal motions



Radio Quiet RQ:

✓ Faint radio sources

✓ Emission confined to sub-kpc scale



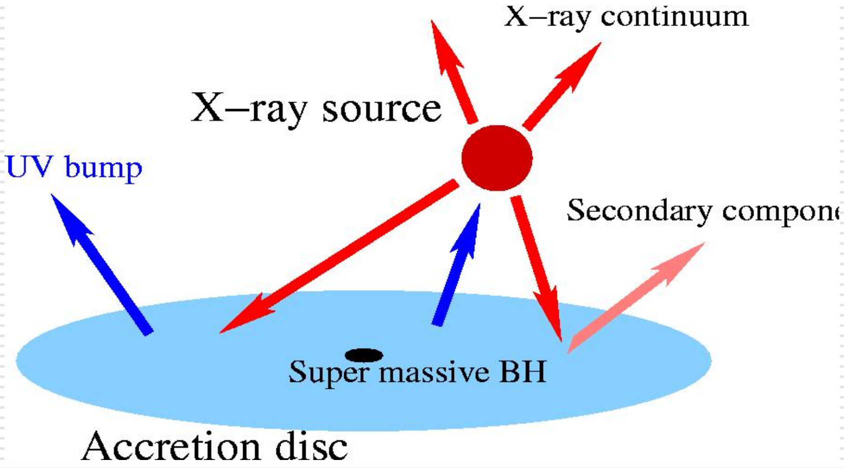
Radio Quiet vs Radio Loud

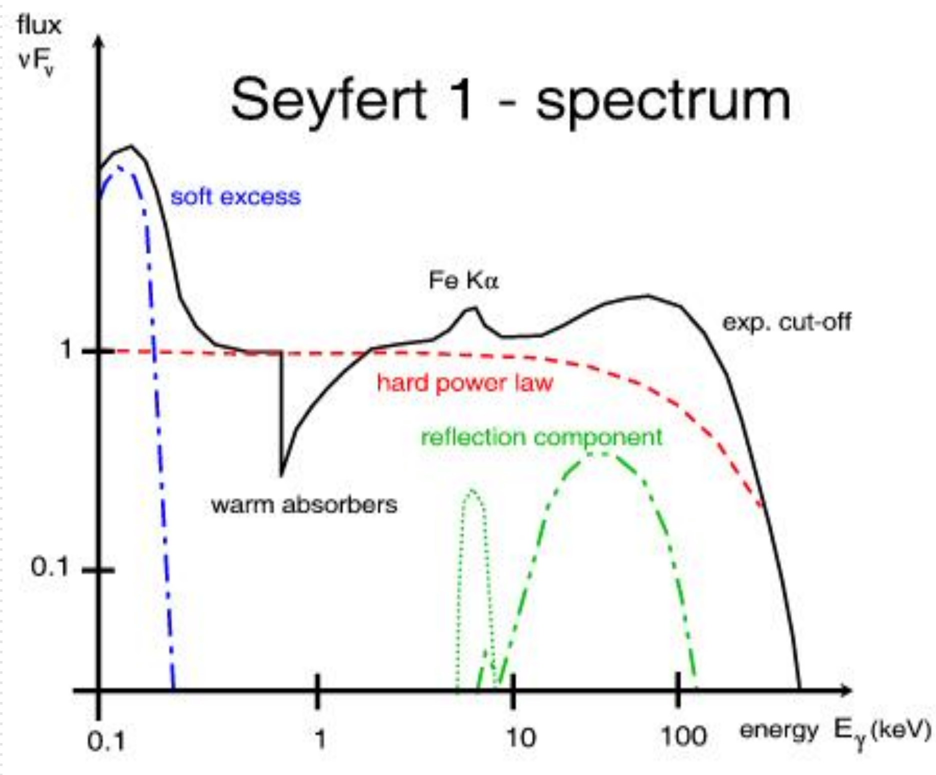
- **What triggers the formation of a powerful jet in RL AGN?**
- **Is there a real DICHOTOMY between Radio-Quiet vs Radio-Loud?**

--> Sample selection effects?
--> Different jet/disk physics?

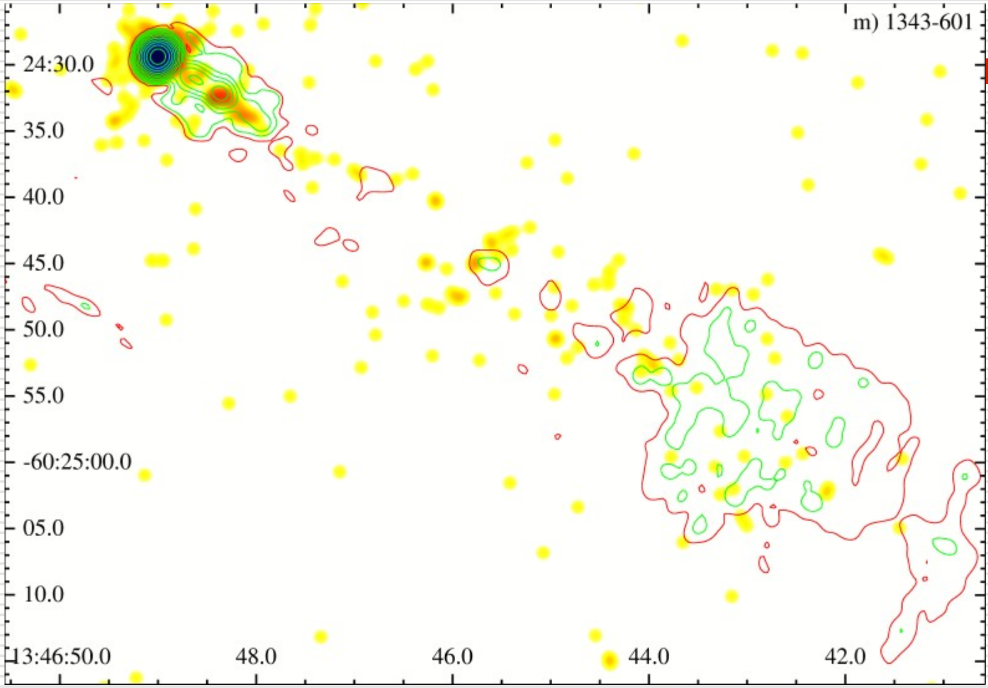
RQ AGN in X-rays

X-ray emission from ACCRETION DISK/CORONA System around a SUPER MASSIVE BLACK HOLE

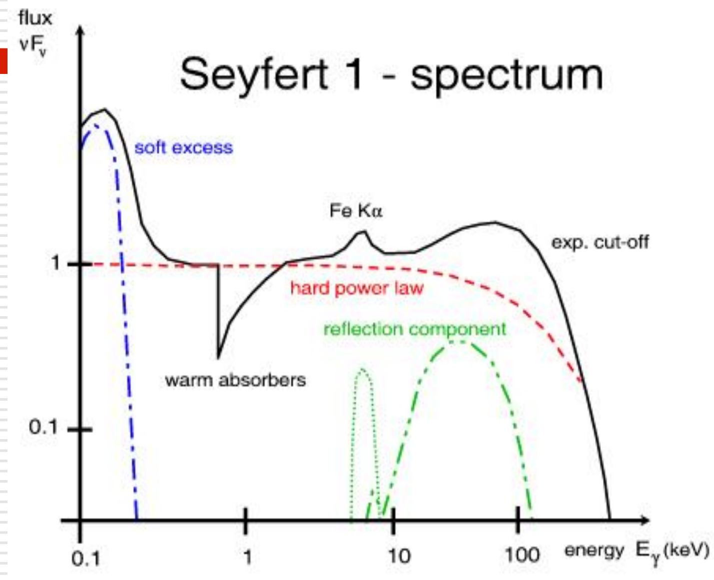




RL AGN in X-rays



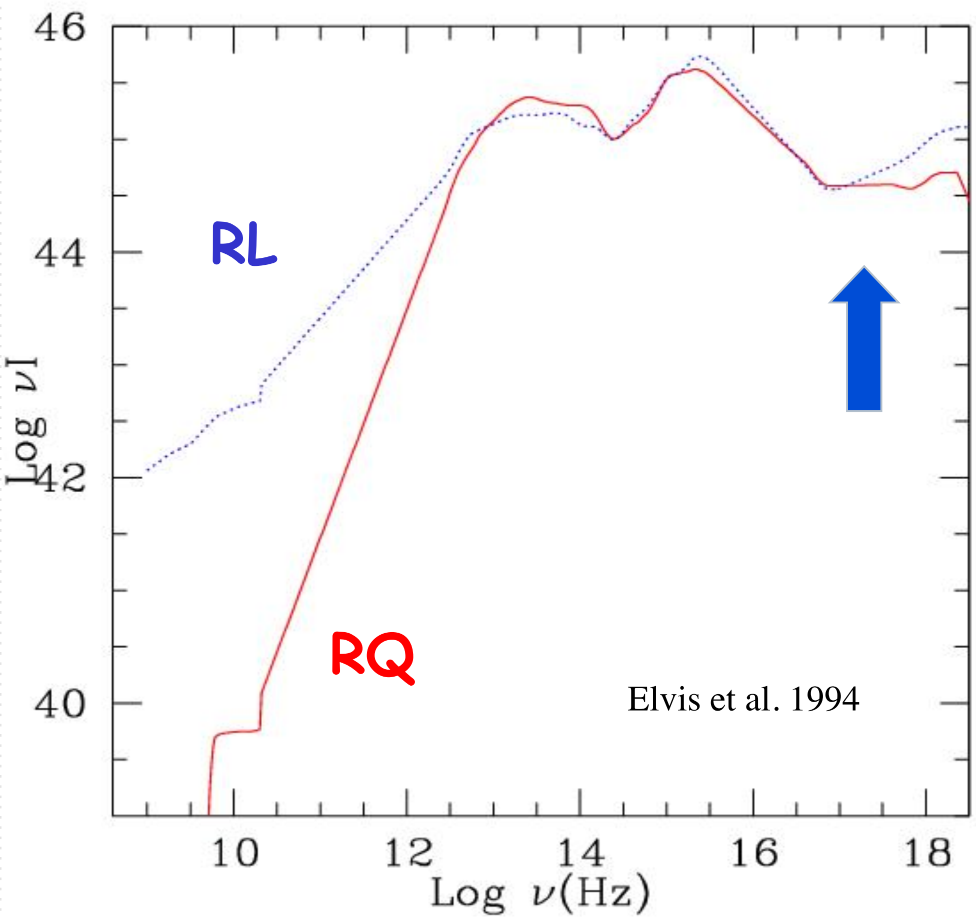
X-ray (color), Radio (contours)
From: Marshall et al. (2005)



Flatter power-law slopes
Weaker Reprocessing features

- Different geometry and/or accretion efficiency
- Jet and beaming effects contaminate/dilute the accretion component
- Ionized reflection

SPECTRAL ENERGY DISTRIBUTION



RADIO LOUD

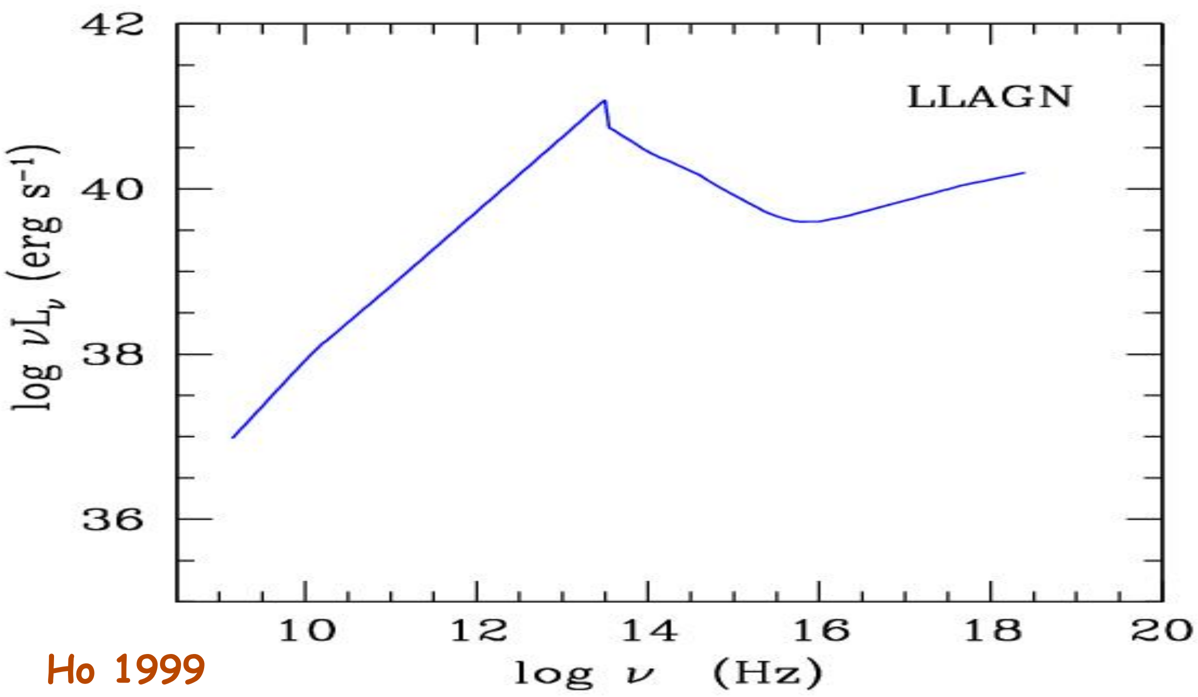
-- SED dominated by the relativistic jet emission from radio to X-ray/Gamma ray

RADIO QUIET

-- Jets absent or very weak. High energy emission softer than RL AGN. X-ray emission from Corona/ Disk system.

SED of Low Luminosity AGN

- Lack of the 'big blue bump' feature
- Radio emission higher than luminous RQ AGN



Ho 1999

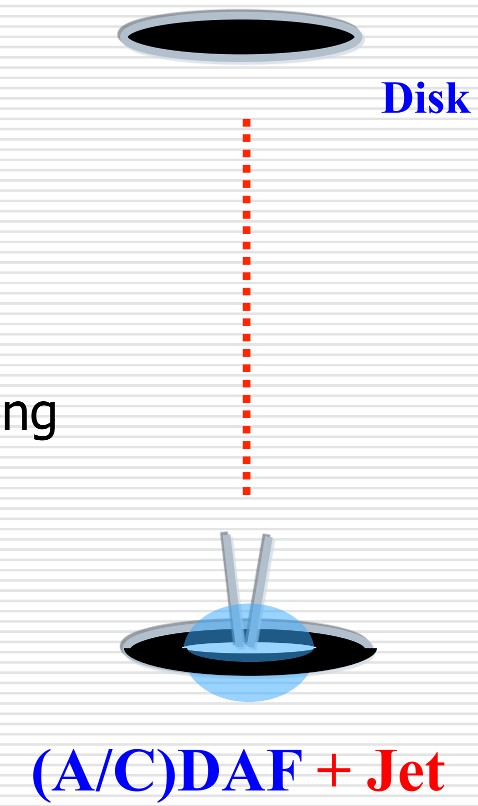
Is there an evolution of the SED?

→ Below a critical accretion rate
disks become **radiatively inefficient**
e.g., advection dominated: ADAFs, CDAFs, RIAFs

-> At lower accretion rates
disks become less and less prominent, jets remain strong

-> Radio Loud - Radio Quiet dichotomy caused by
a switch of accretion mode - RQ appear only at
high accretion rates

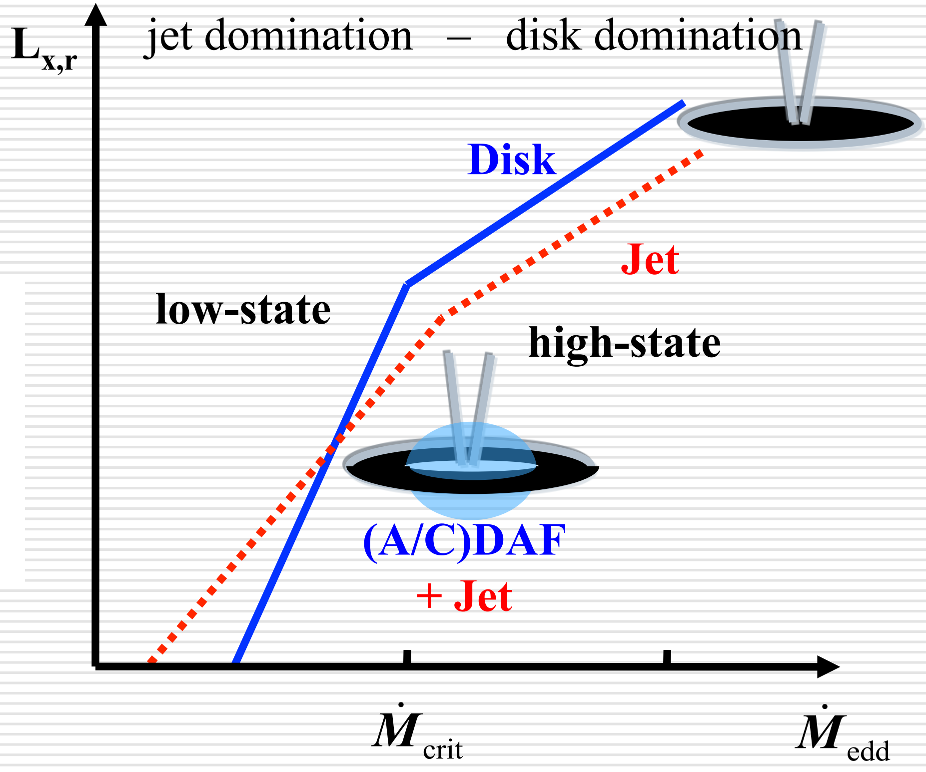
At low luminosity no dichotomy is expected
(Nagar et al. 2002)



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?

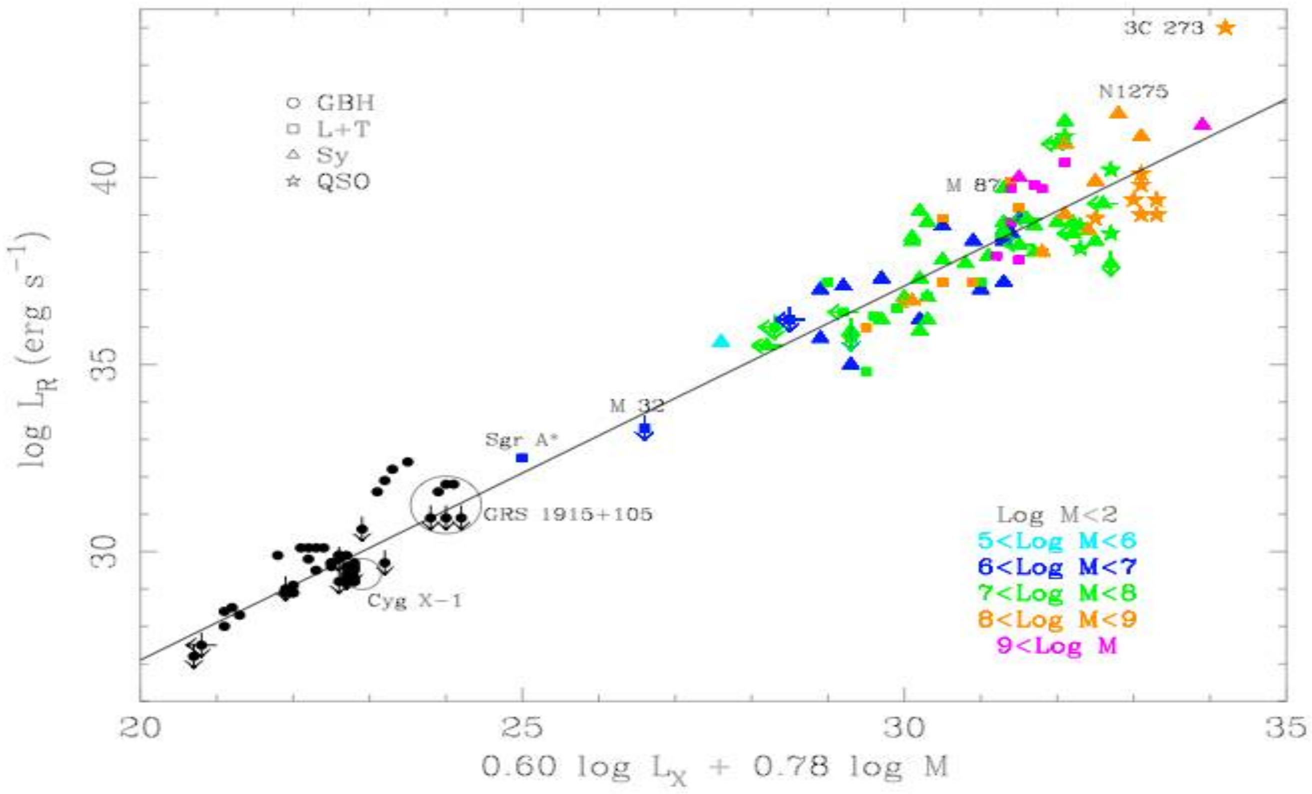


Körding, Falcke, & Markoff (2002);
see also Fender, Gallo, & Jonker (2003)

Analogy with black hole X-ray binaries

Fundamental plane for BH activity

Merloni et al. 2004



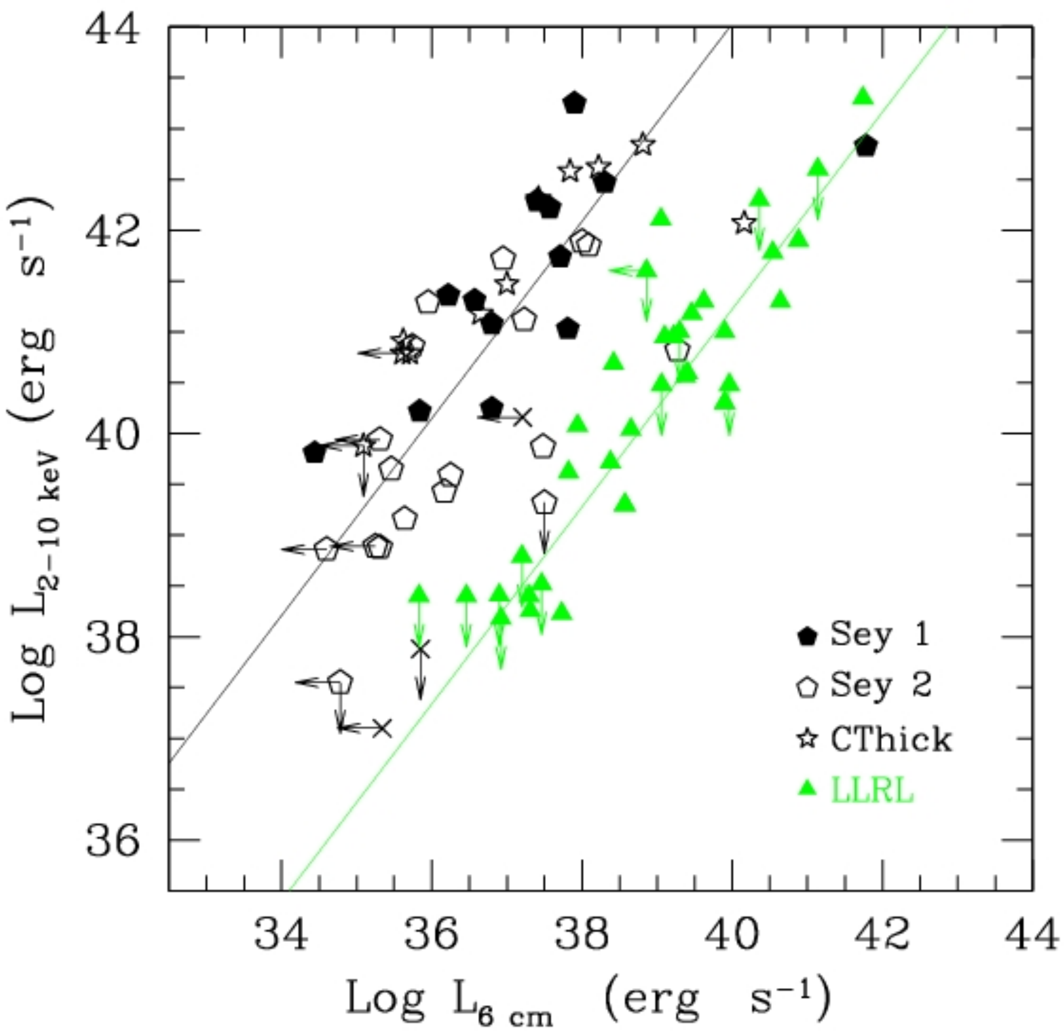
- X-ray marginally consistent with optically thin synchrotron emission from a jet
- Radiatively inefficient accretion flows

Low-Luminosity AGN: the Palomar Seyfert Complete Sample

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

- ✓ Accurate optical classification (Ho et al. 1997)
- ✓ XMM-Newton & Chandra X-ray images and spectra (Cappi et al. 2006, Panessa 2004, Ph.D. thesis)
- ✓ 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}



Low Luminosity Radio Galaxies
(Balmaverde&Capetti 2005)
VLA + Chandra

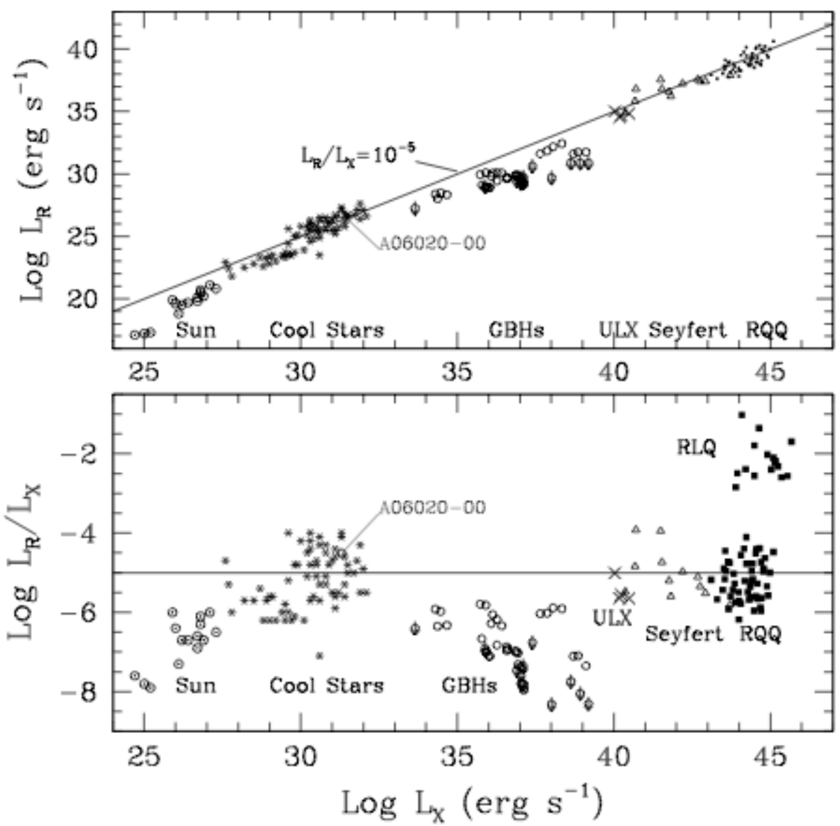
Low Luminosity RQ AGN (Palomar)
(Panessa et al. 2007 A&A)
VLA + Chandra/XMM

-> X-ray and radio from the same component?
-> Jet/outflow are disk related
(jet, disc-corona)

(Merloni et al. 2003, Ghisellini et al. 2004)

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

(Laor & Behar 2008)

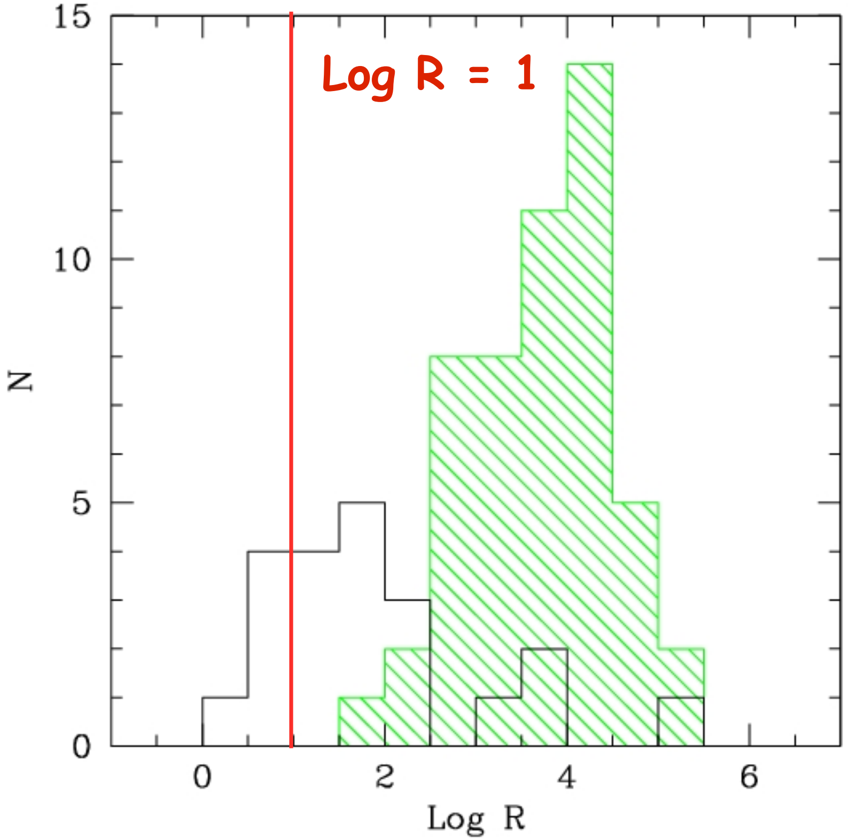


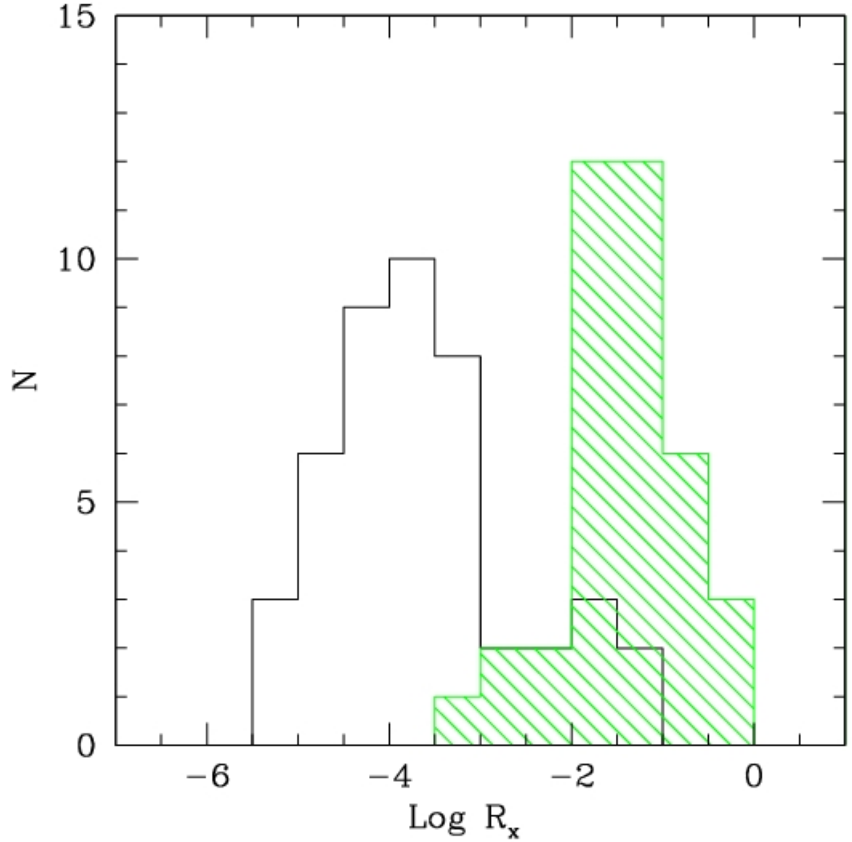
Correlation extended to bright AGN (PG QSOs)

Hypothesis: RQ AGN lie on the same relation as Coronally Active stars and radio emission originates from coronal mass ejections

Radio Loudness

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

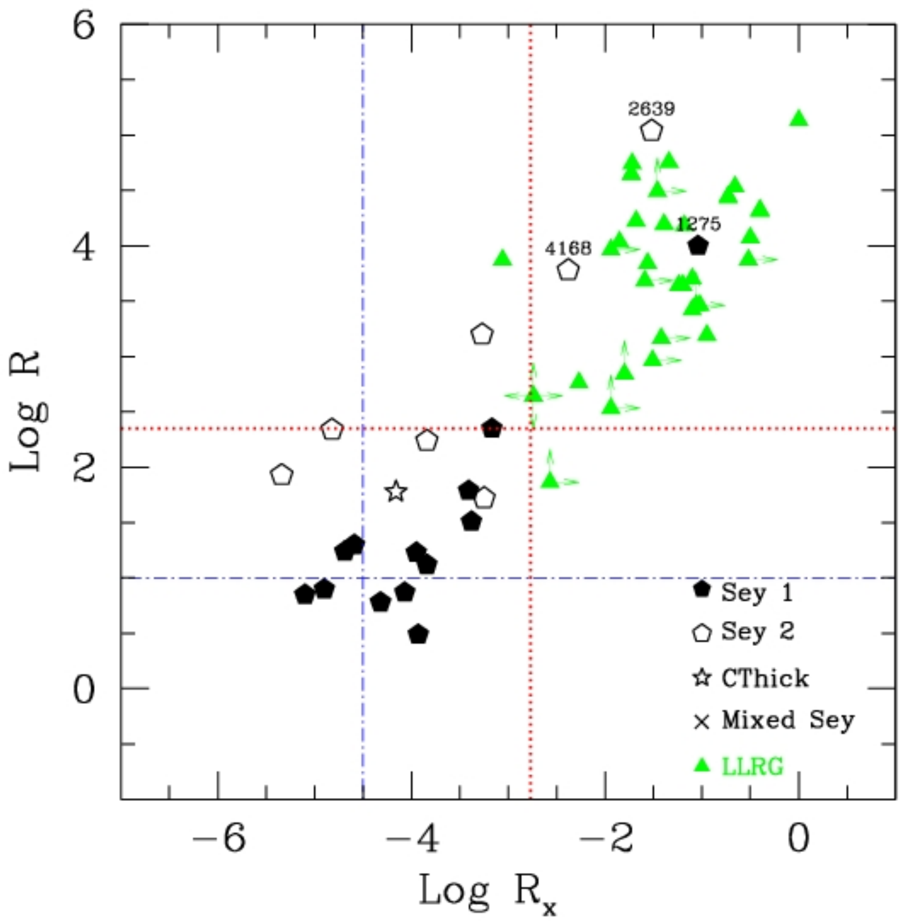




R = L(5 GHz) / L(B)

R_X = L(5 GHz) / L(2-10 keV)

Radio Loudness



Maximum separation between the two distributions:

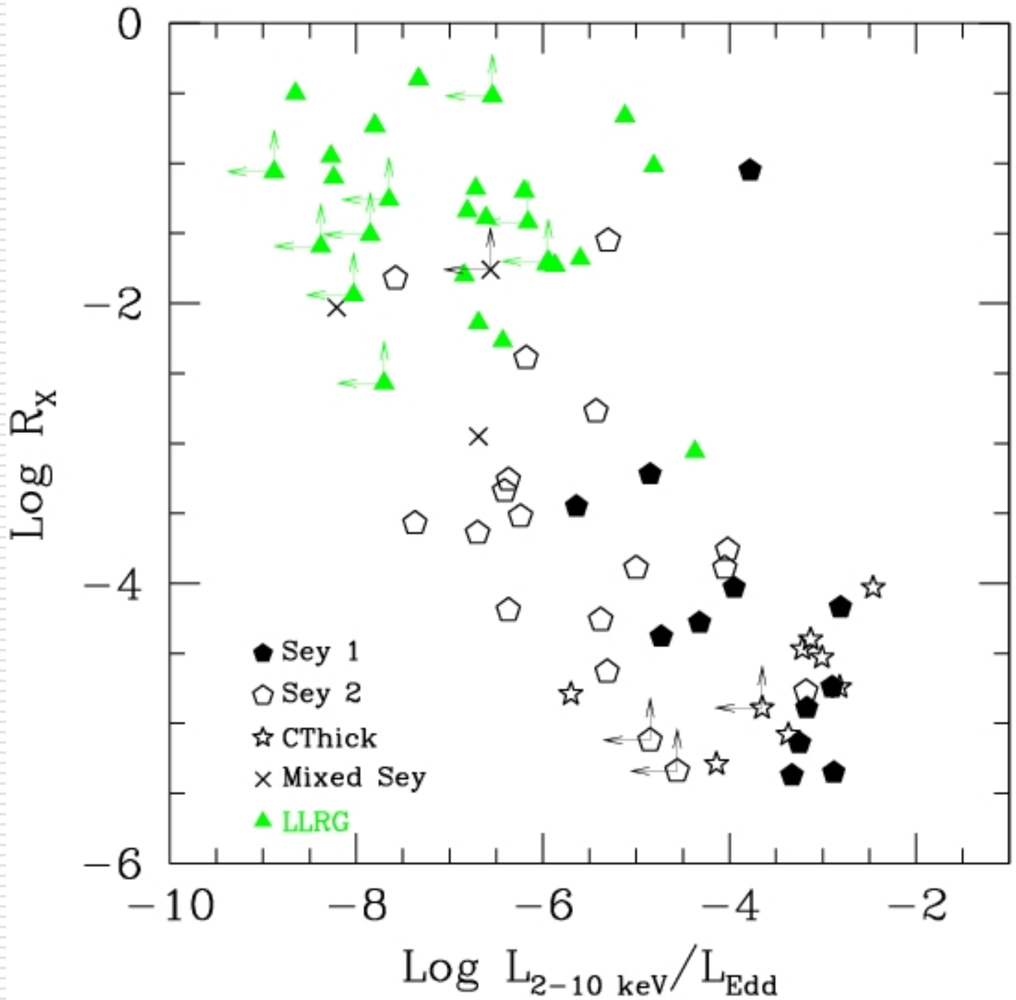
New boundaries at low luminosities?

Log R = 2.40 ± 0.05

Log R_X = -2.76 ± 0.02

Radio Loudness

Panessa et al. 2007, A&A

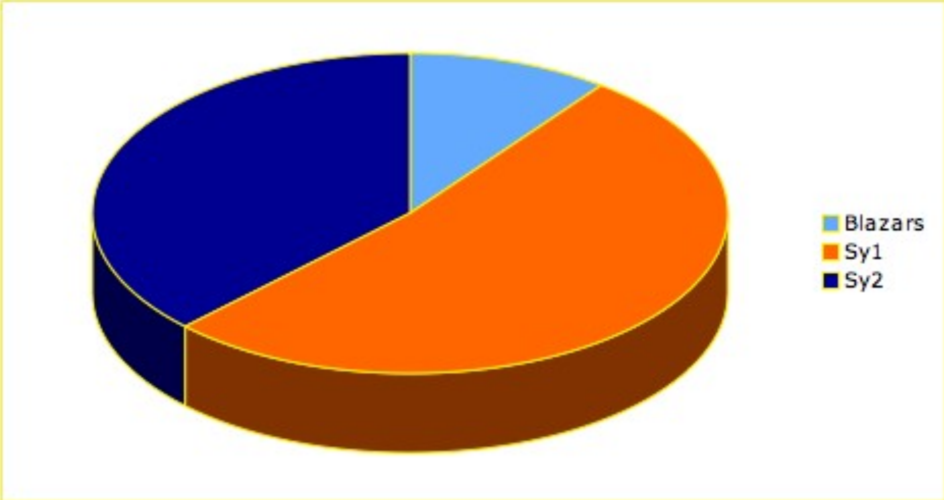


- ✓ Increasing radio-loudness with decreasing Eddington ratio? (Ho et al. 2002, Sikora et al. 2006)

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!

Hard X-ray selected INTEGRAL AGN Complete sample

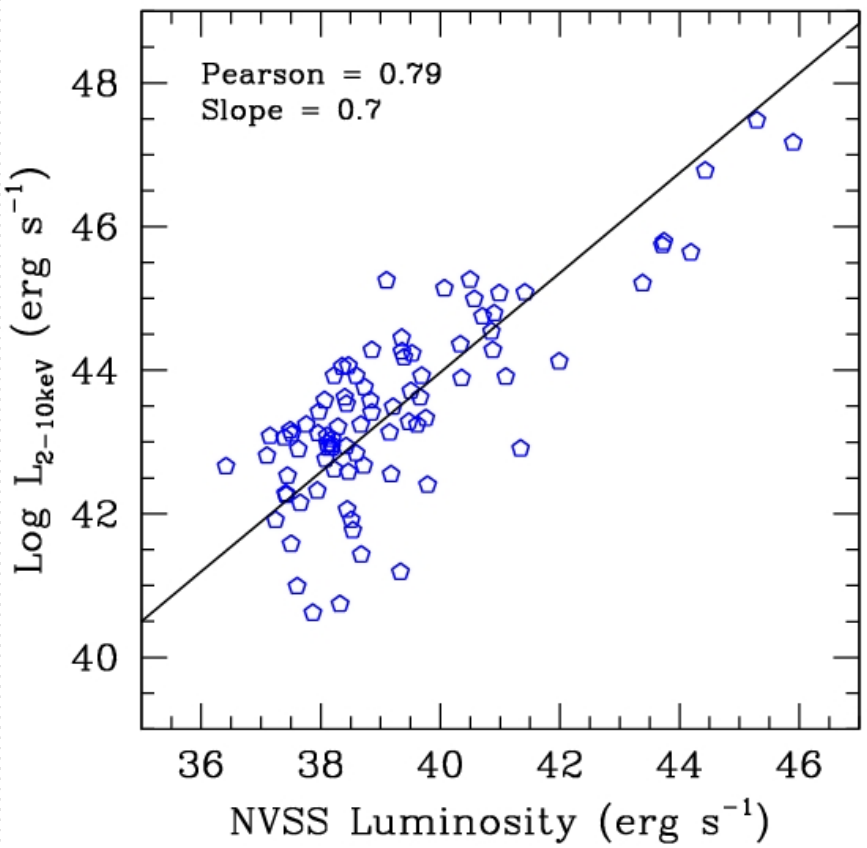


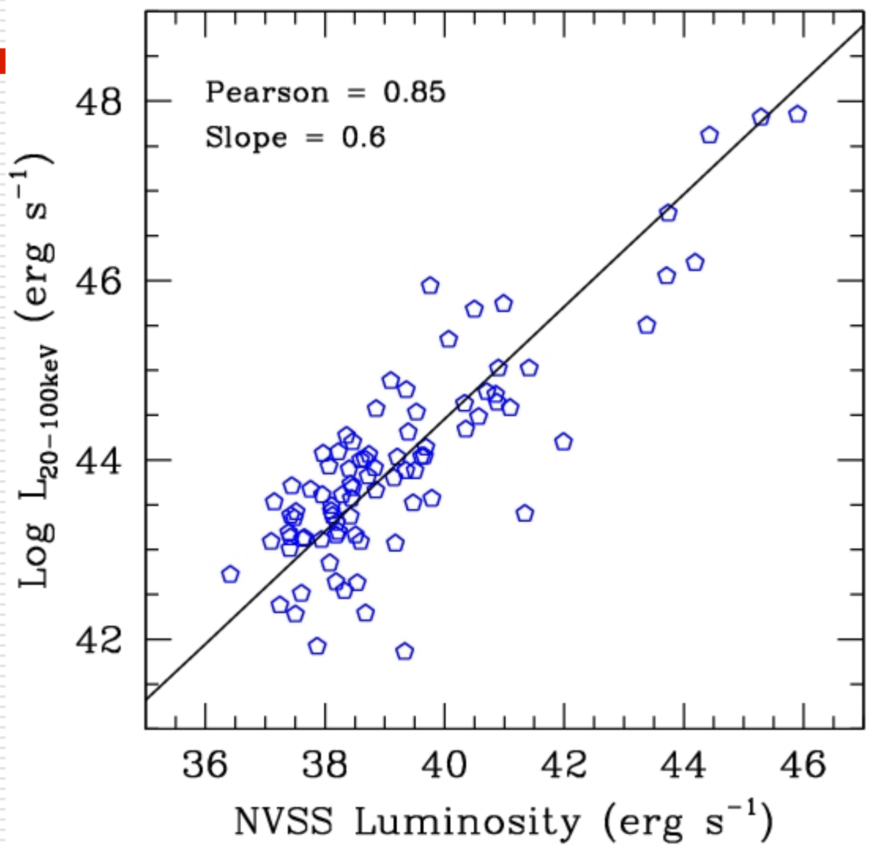
~ 88 Seyfert galaxy
complete sample
between 20-40 keV
(Malizia et al. 2009 MNRAS)

- ✓ Hard X-ray selected sample of luminous AGN:

-> INTEGRAL 20-100 keV (Malizia et al 2009)
-> 2-10 keV X-ray data (Malizia et al. + literature)
-> NVSS radio data (Maiorano et al. in prep)

INTEGRAL AGN Complete sample

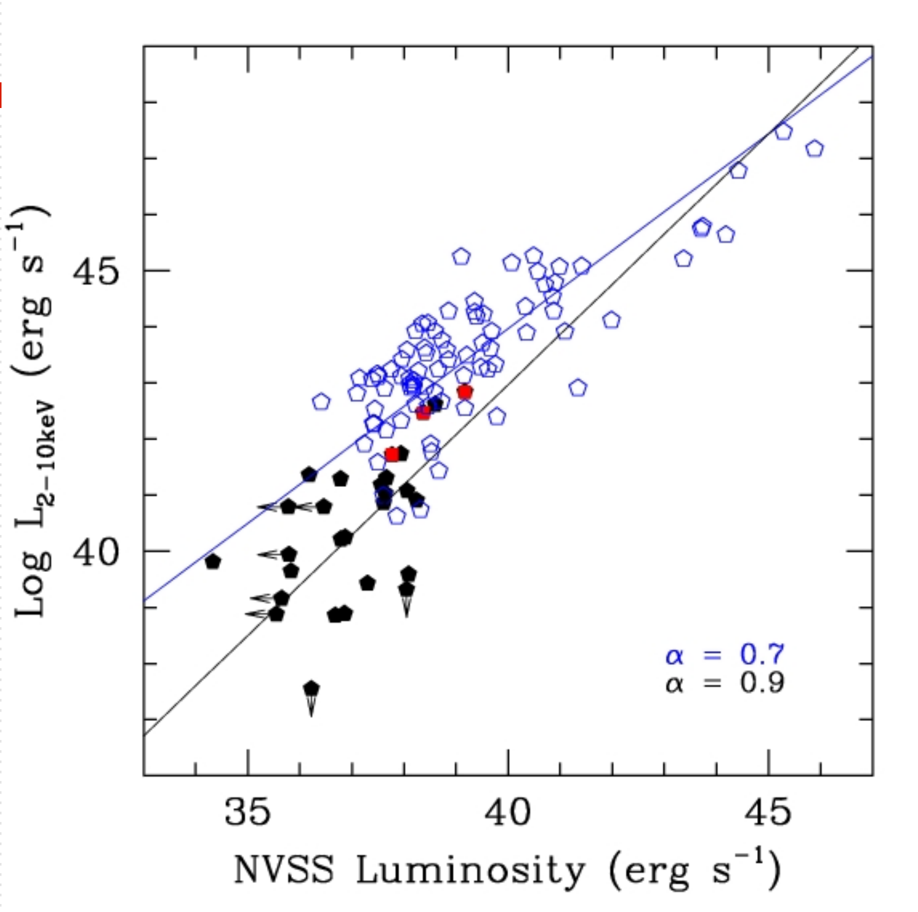




- ✓ Correlation between 2-10 keV, 20-100 keV vs 20 cm NVSS

Maiorano et al. in preparation

The X-ray versus NVSS correlation

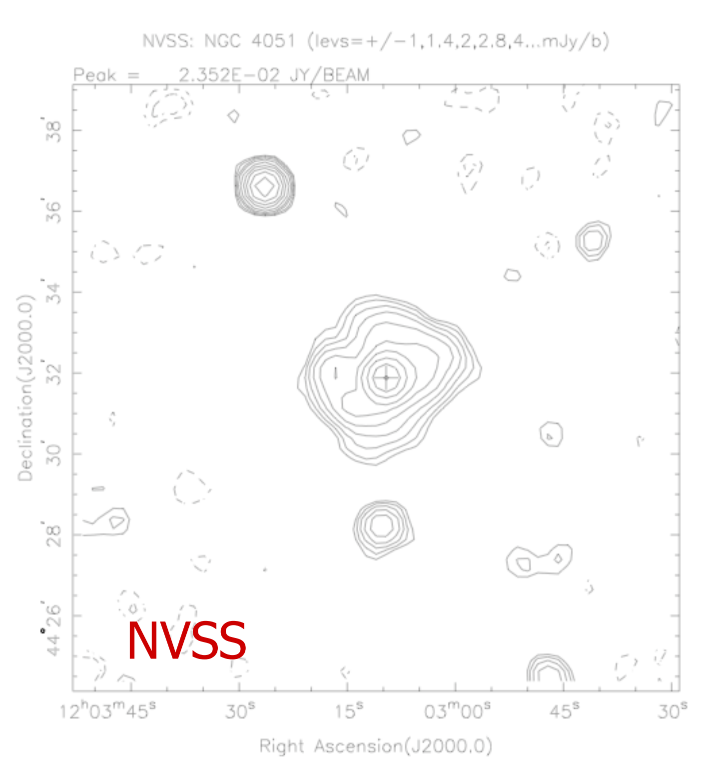


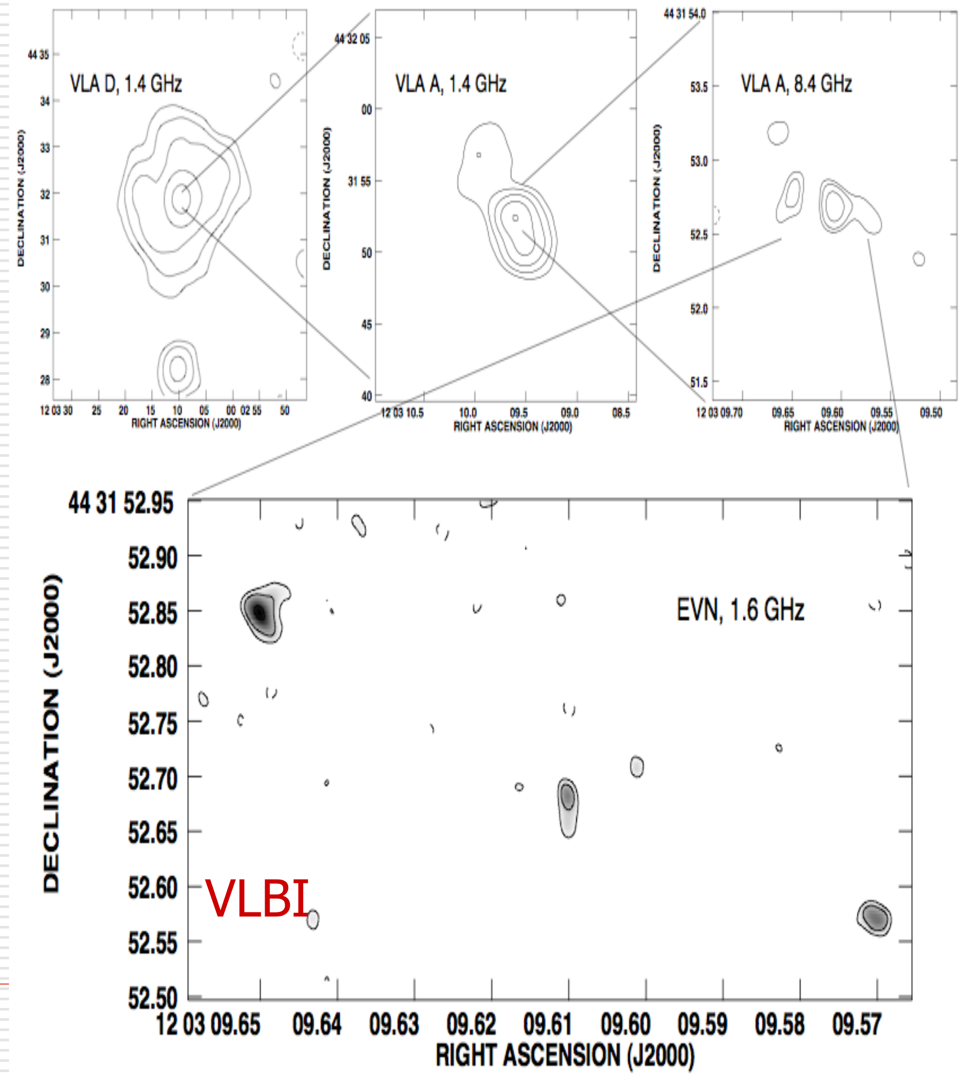
-> INTEGRAL sample

-> Optical Palomar sample

✓ Correlation changes slope at low luminosities

Radio emission scales





NVSS --> up to tens of kpc

VLA -->Tens of pc up to kpc scales

VLBI < 1 pc

VLA & VLBI observations of RQ AGN

- ✓ On arcsec scale (VLA):
  - ✓ Cores with collimated jets and extended emission (SB) confined to a few kpc or sub-kpc scales
- ✓ On milli-arcsec scale (VLBI):
  - ✓ Compact radio cores (mostly flat spectra)
  - ✓ High brightness temperatures ($T_B > 10^8$ K)
  - ✓ Extended jet-like features

(Wrobel&Ho06, Gallimore+04, Nagar+02, Mundell+00, Ulvestad+05, etc,etc)

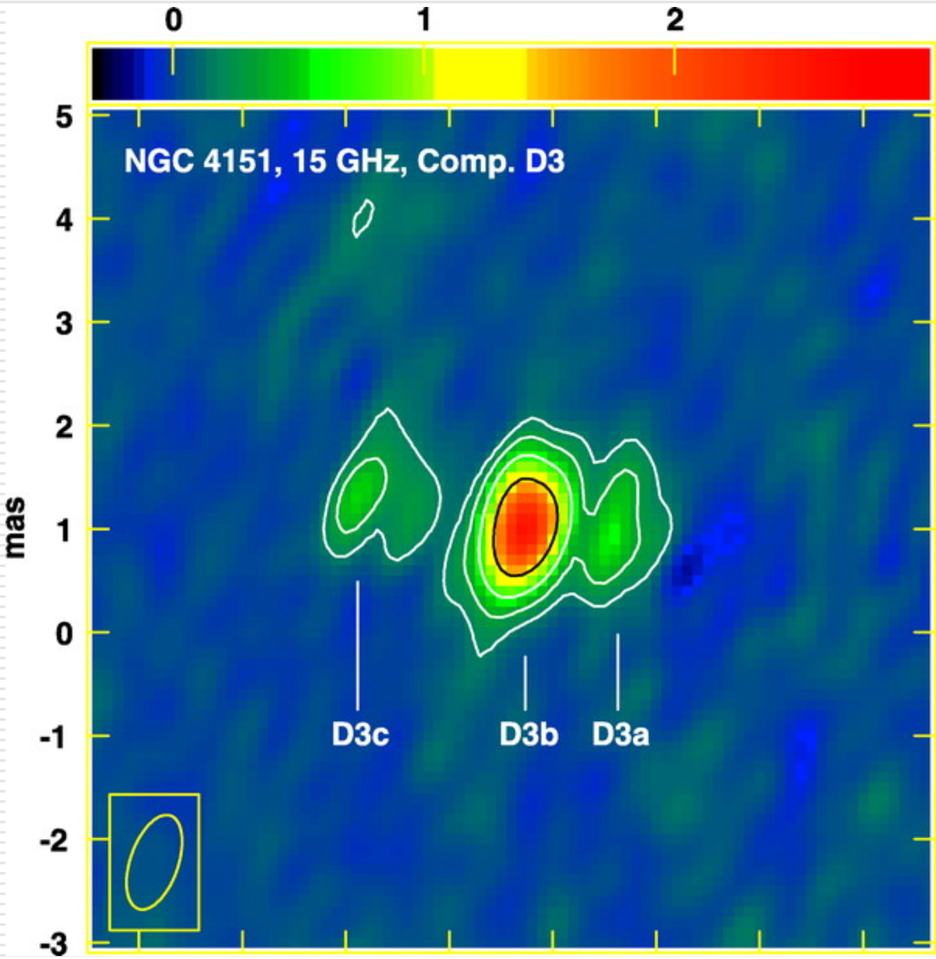
VLBI Observations of Radio Quiet Nuclei

Discriminate between jet synchrontron, SSA, ADAF, free-free emission?

Physical constraints:

- ✓ Compactness of the source (ADAF < 10^4 R_S)
- ✓ Brightness temperature limits (high T_B -> non thermal emission)
- ✓ Spectral indeces (steep, flat or inverted --> Synch, ADAF or SSA)
- ✓ Motions (relativistic/sub-relativistic)

VLBI Observations of Radio-Quiet Nuclei

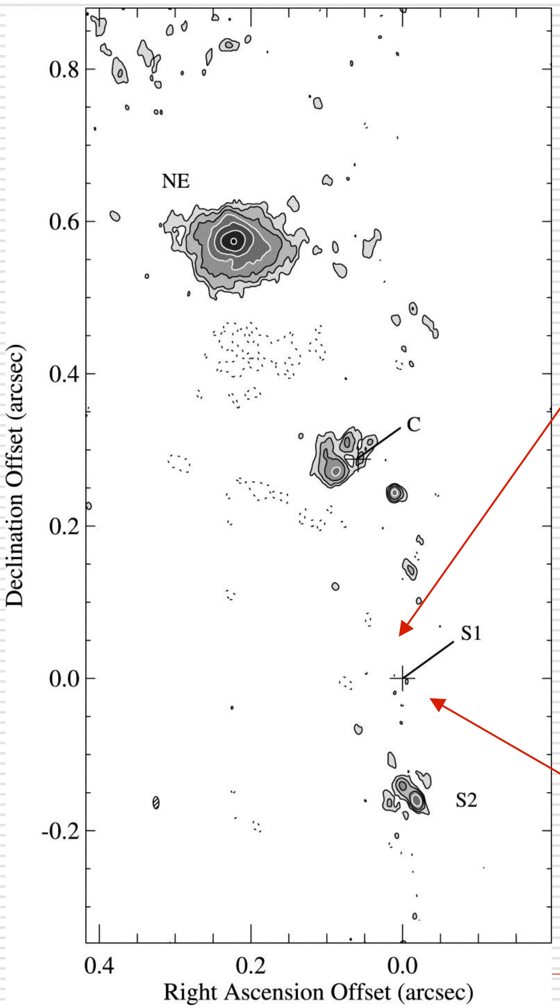


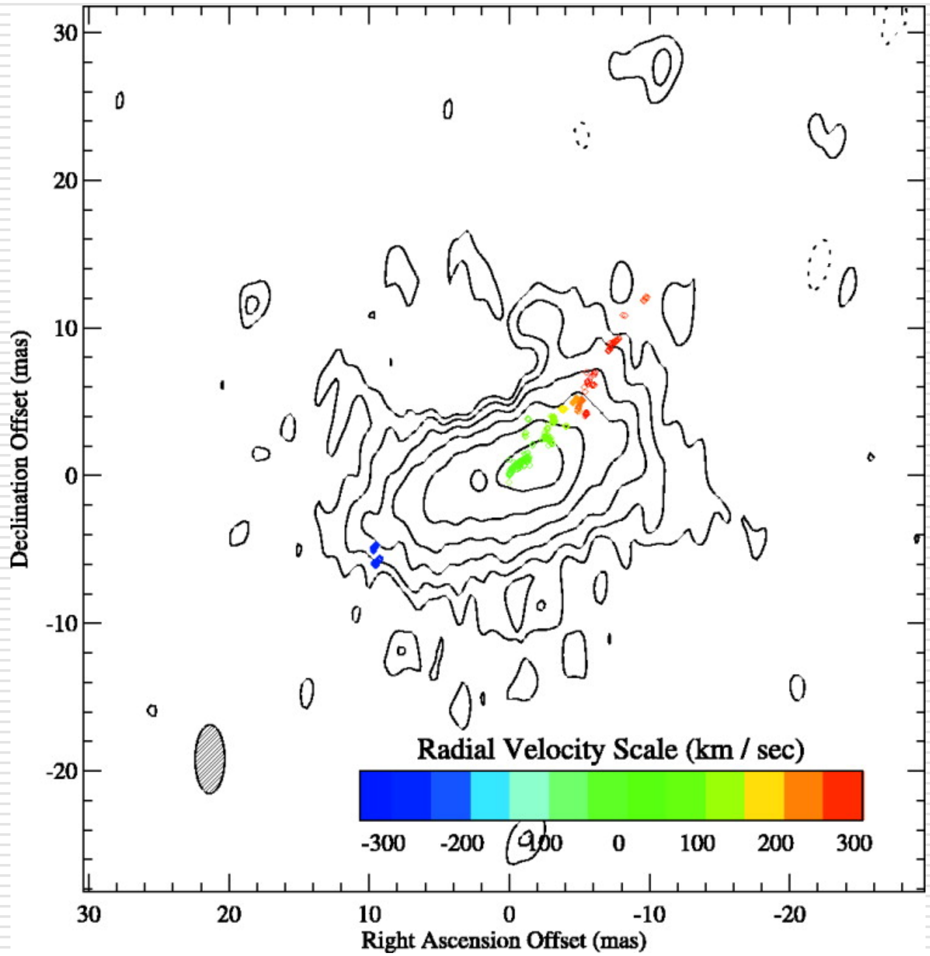
- NGC 4151: radio-quiet Sey 1.5 nucleus
- Radio source size < 0.035 pc, BLR scales
- VLBI compact flat-spectrum radio component with Tb > 2.1 * 10^8 K (non-thermal)
- A weak 0.2 pc two-sided base to the well-known arcsecond radio jet
- Sub-relativistic motions

VLBI at 15 GHz   Ulvestad et al. 2005

✓ 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 a molecular disk

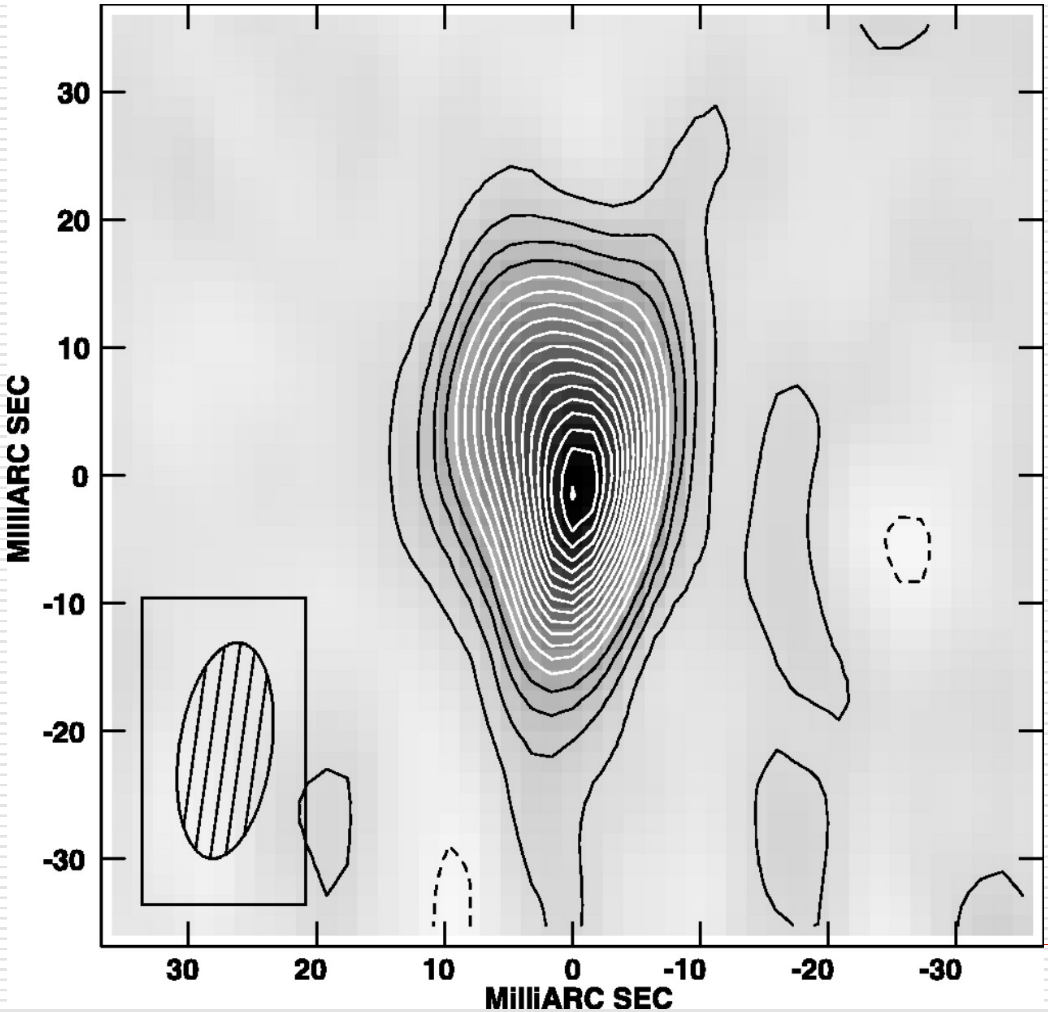




VLBA + phased-VLA 1.4 GHz contour image
Gallimore et al. (2004) + H_2O Maser

Low $T_b = 2.5 \times 10^6$ K and flat-inverted spectrum

VLBI Observations of Radio Quiet Nuclei



- NGC 4395: radio-quiet type 1 nucleus with L_X/L_{Edd} = 0.004
- Brightness temperature > 2 * 10^6 K
- VLBI elongated structure which suggests radio outflow on sub-pc scales

VLBA HSA at 1.4 GHz
(SCALE of 0.021 pc/mas)
Wrobel & Ho (2006)

VLBI Observations of a distance limited Complete Sample of Seyferts

- ✓ Optically selected sample of 28 nearby Seyfert galaxies (Cappi et al. 2006, D < 27 Mpc)

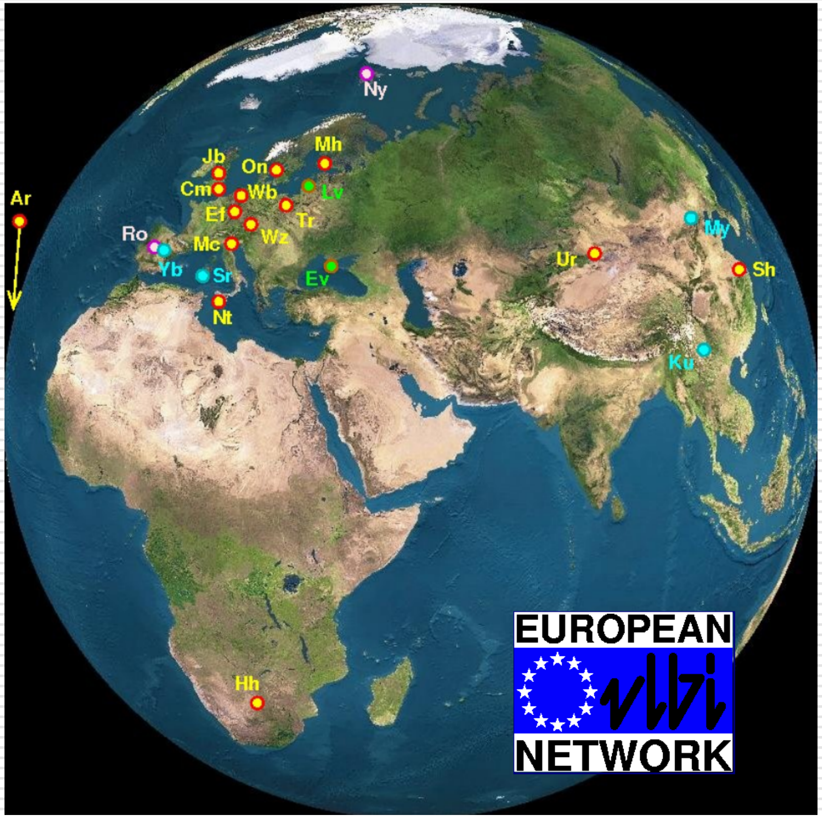
- ✓ For the first time sources with S < 1 mJy (VLA cores)

- ✓ European VLBI Network new observations to complete the sample at mas scales

-> 2-10 keV X-ray data (Cappi et al. 2006)
-> NVSS (Panessa&Giroletti in prep)
-> VLA 6 cm (Ho&Ulvestad 2000)
-> VLBI 6 cm (Giroletti&Panessa 2009+ Bontempi et al. in prep + liter.)

The European VLBI Network (EVN)

- The European VLBI Network (EVN) is an interferometric array
- unique, high resolution, radio astronomical observations
- the most sensitive VLBI array in the world, thanks to the collection of extremely large telescopes.



- Eight of the FAINTEST nearby Seyfert galaxies with the EVN at 1.6 and 5 GHz
- Unprecedented sensitivity of about a few hundreds μJy (rms)
- Size of the order of 10 mas --> linear resolution around <0.1 pc

LLAGN Radio Detection rates

- NVSS detection rate of 26/28 (**93%**) at 1.4 GHz
- VLA detection rate of 18/28 (**64%**) at 1.4 GHz

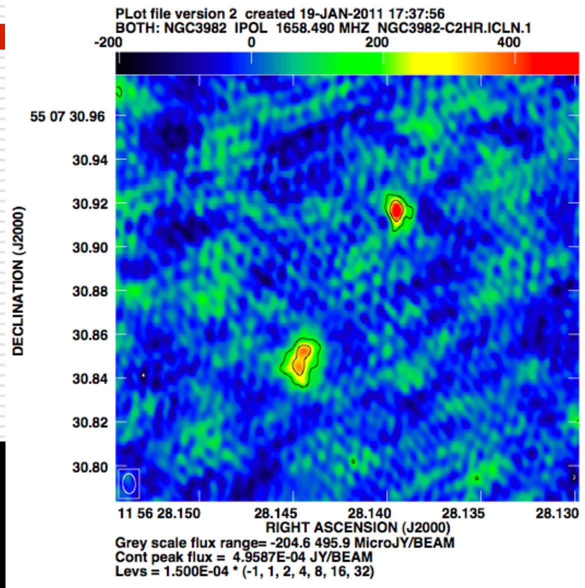
- VLA detection rate of 23/28 (**82%**) at 5 GHz
- VLBI detection rate of 15/28 (**54%**) at 5 GHz

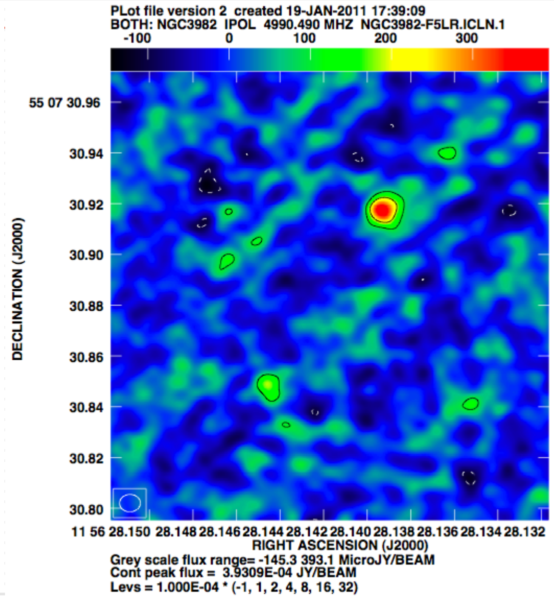
Very low detection rate

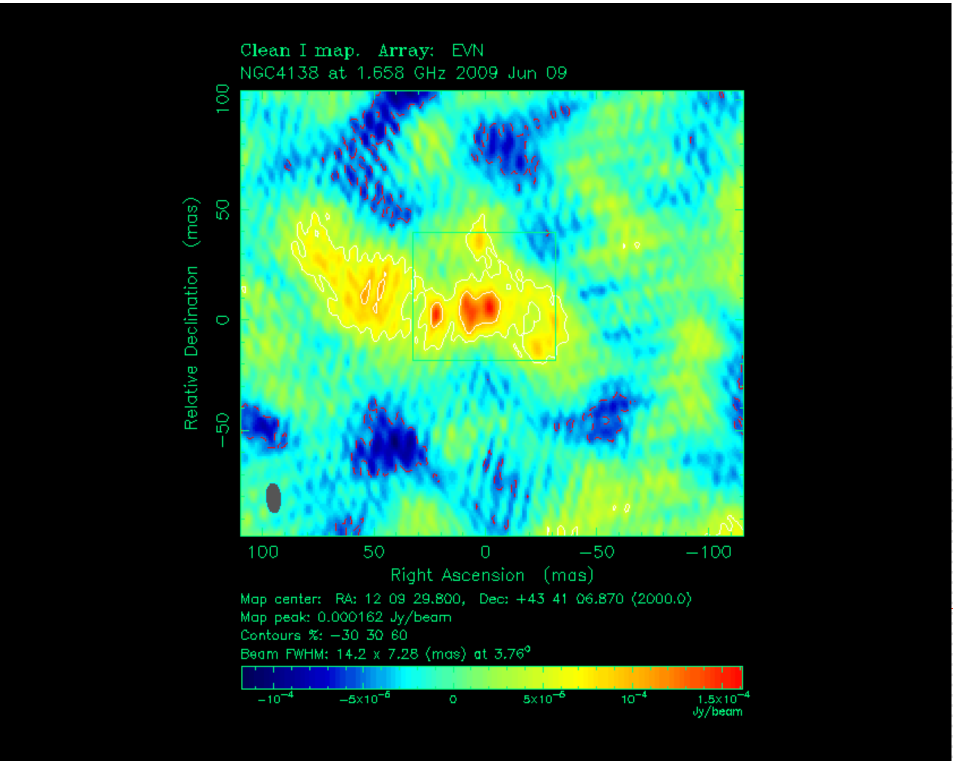
Radio Quiet nuclei are not ubiquitous at VLBI spatial scale resolution

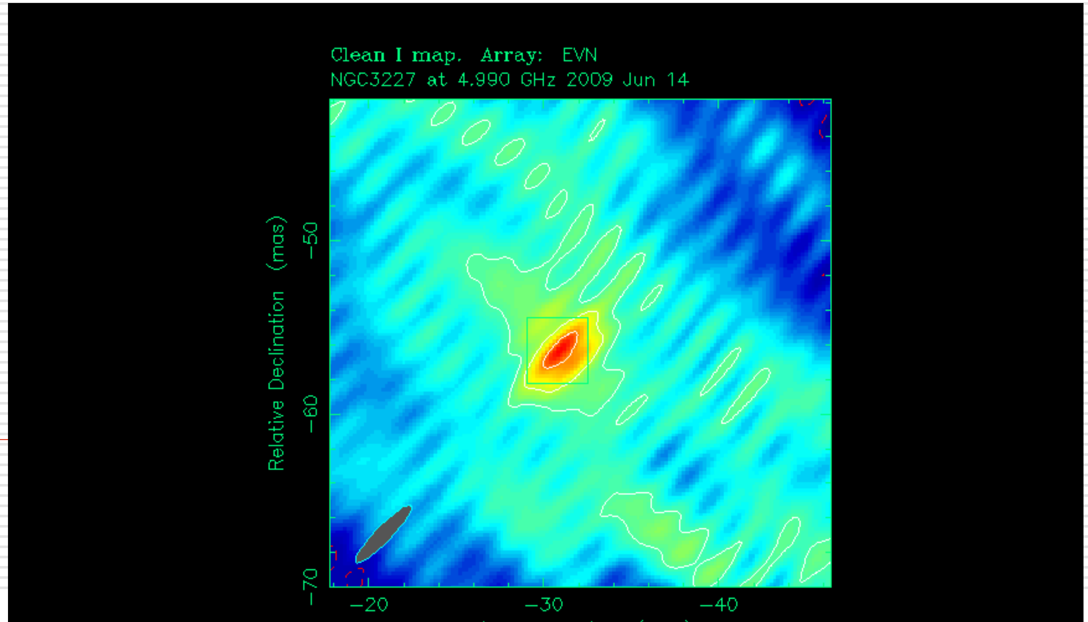
VLBI Observations of a distance limited Complete Sample of Seyferts : morphology

- Single compact
- Double at one freq.
- Double at both freq.
- Jet like structure







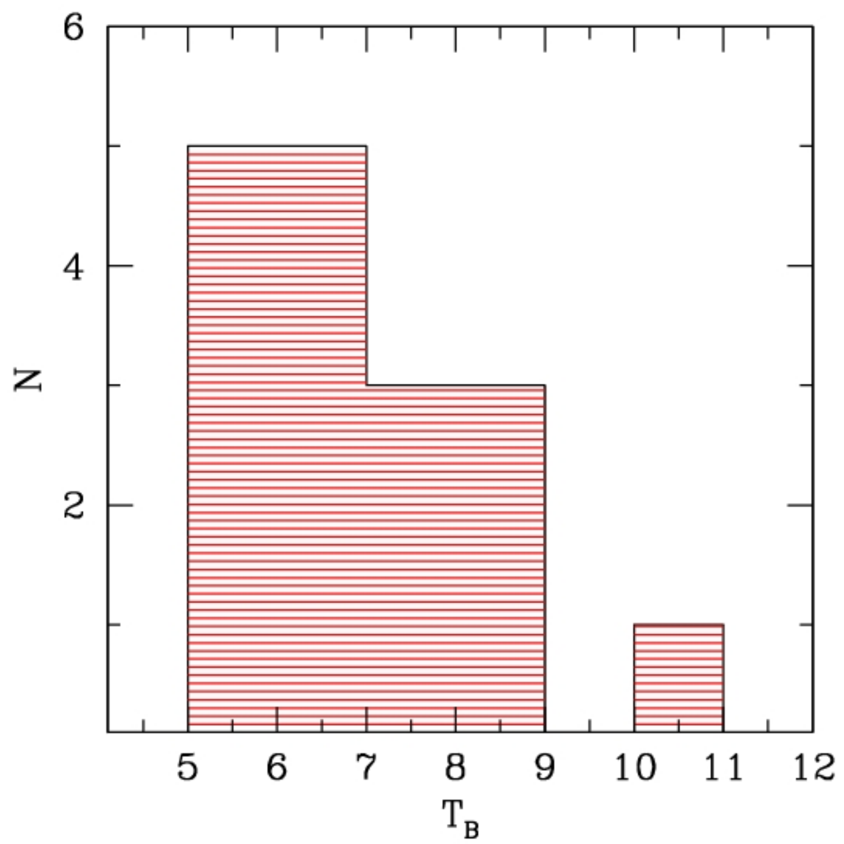


VLBI Observations of a distance limited Complete Sample of Seyferts

✓ Peak at low brightness temperature

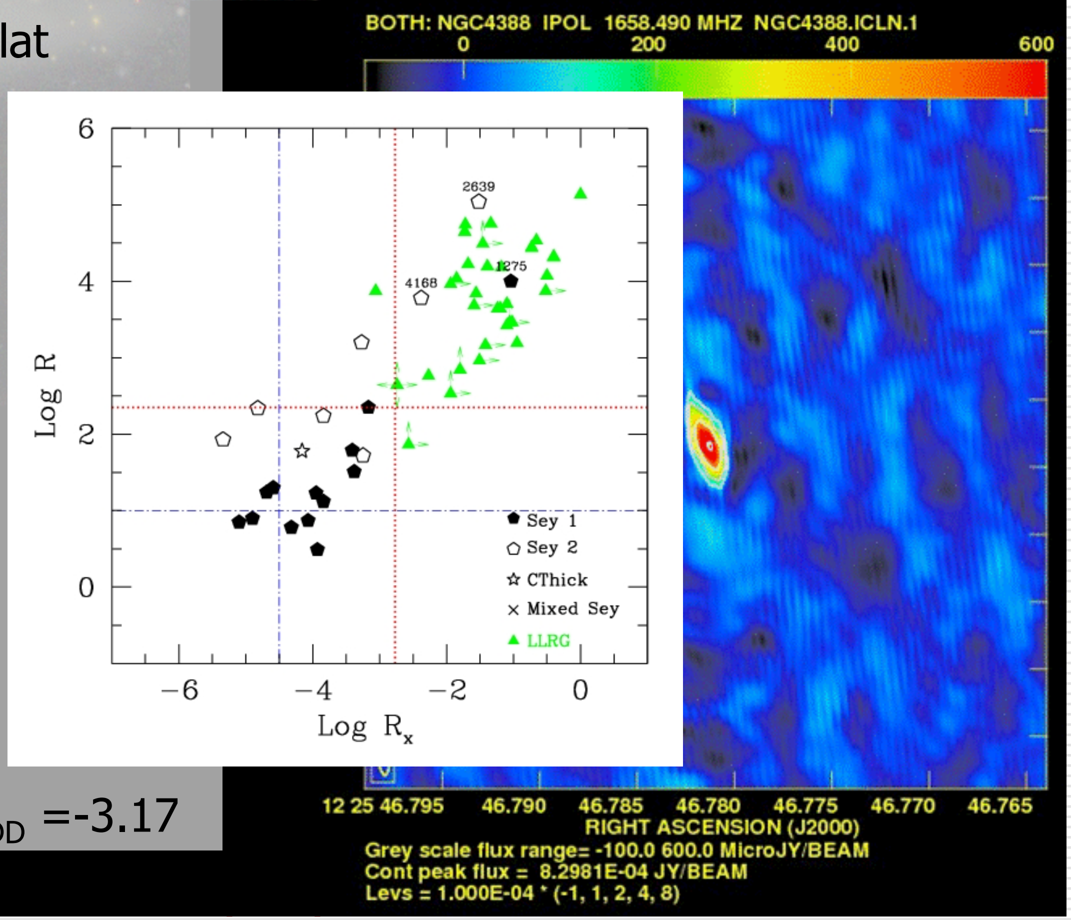
-> Consistent with free-free emission

✓ Flat-inverted spectra mainly associated with a type 1 Seyfert classification



EVN Observations: NGC 4388

- ✓ Type 1.9 Seyfert galaxy
- ✓ Several VLA detections up to 15 GHz, flat spectrum (Falcke et al. 1998)
- ✓ Detected at 1.6 GHz (not at 5 GHz) -> very steep $\alpha > 1.3$
- ✓ Compact radio emission at 1.3 mJy
- ✓ Extension of 6 mas (0.48 pc)
- ✓ $T_B = 1.3 \times 10^6$ K
- ✓ H_2O Maser emission
- ✓ $\text{Log } L_{5\text{ GHz}}/L_{2\text{-}10\text{ keV}} < -6.1$ & $\text{Log } L_X/L_{EDD} = -3.17$

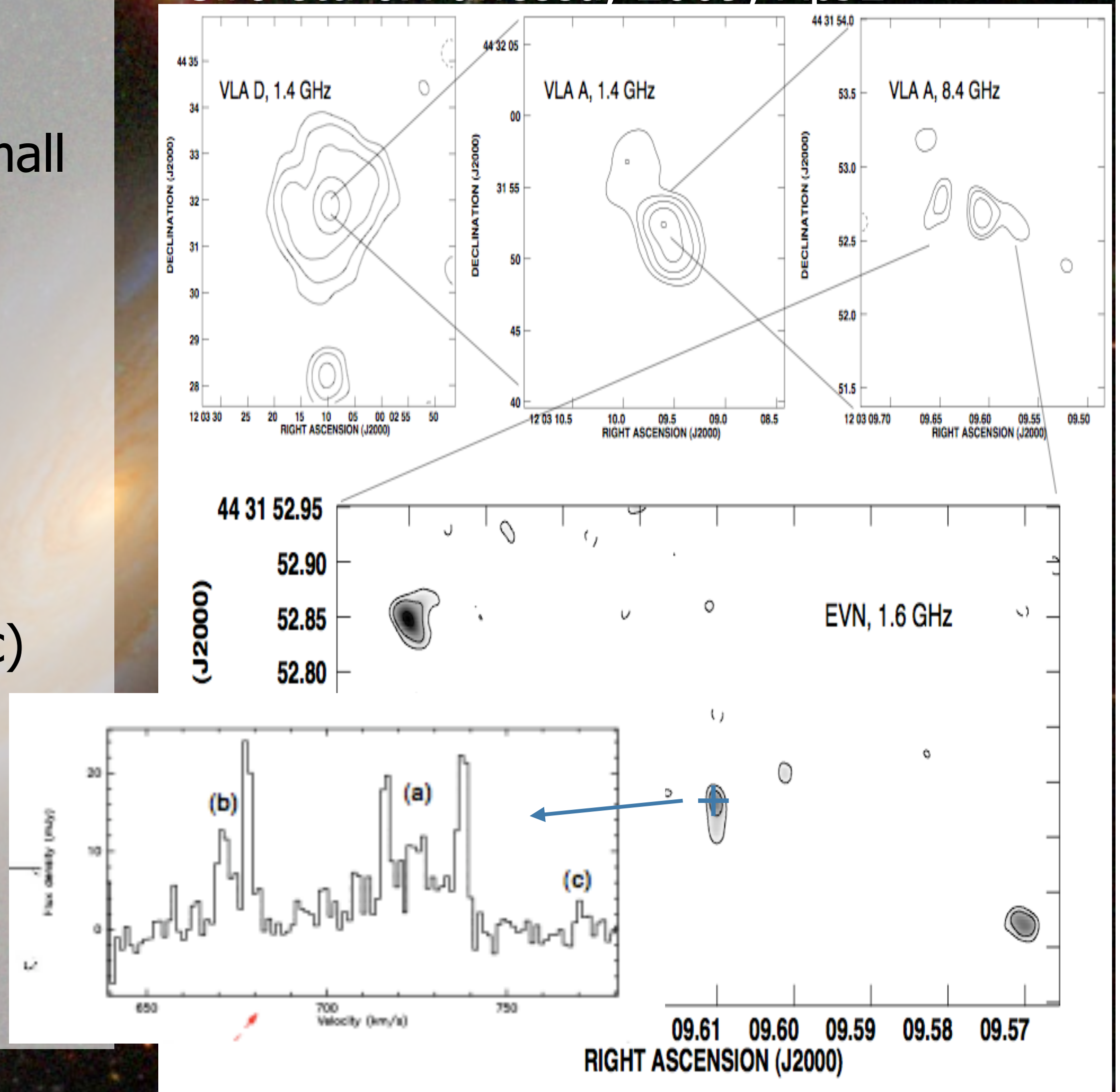


No ADAF (steep α, $10^6 R_S$) --> Free-free emission from the torus?

The Narrow Line Seyfert 1 NGC4051

- ✓ At 1.6 GHz 3 sub-mJy components:
  - ✓ Two associated with the VLA small scale double structure
  - ✓ Third is symmetric to the easternmost one
- ✓ Steep spectral index (α = 0.7)
- ✓ $T_B = 10^5$ K - linear size < 0.31 pc (compared to the BLR size 0.006 pc)
- ✓ Log $L_{5\ GHz}/L_{2\text{-}10\ keV}$ < -5.8
- ✓ Log L_X/L_{EDD} =-3.4
- ✓ H_2O Maser coincident with core

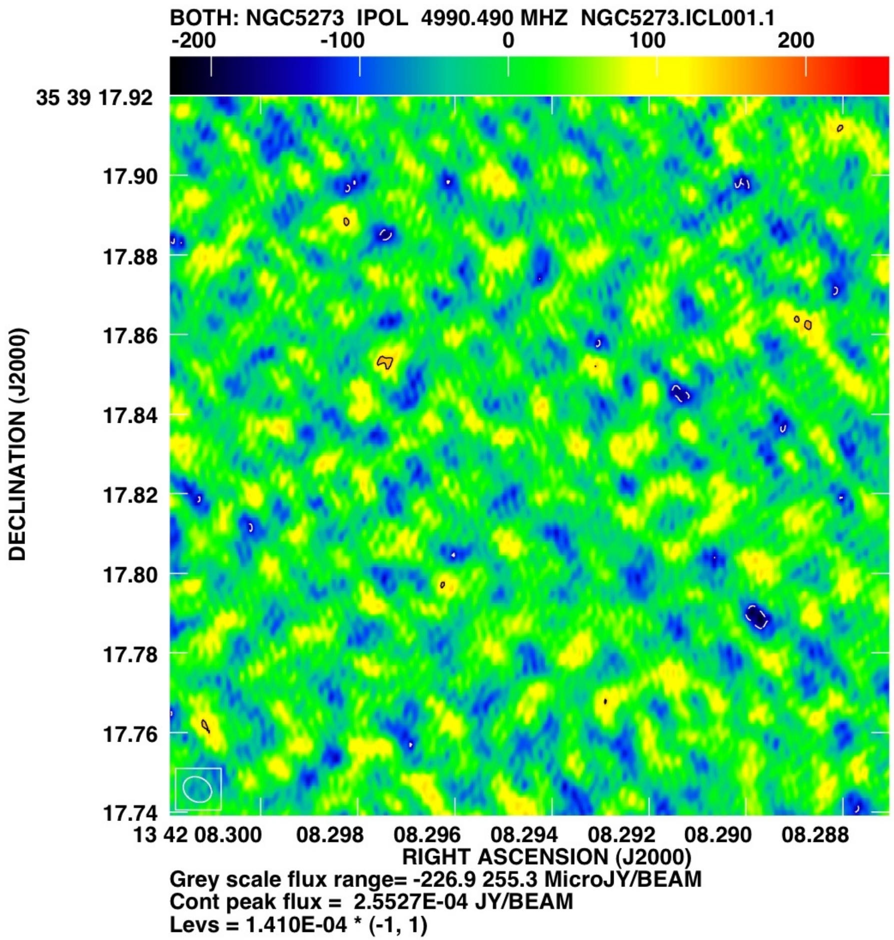
Giroletti & Panessa, 2009, ApJL



Jet base? thermal emission from an outflow/molecular disk/nuclear wind

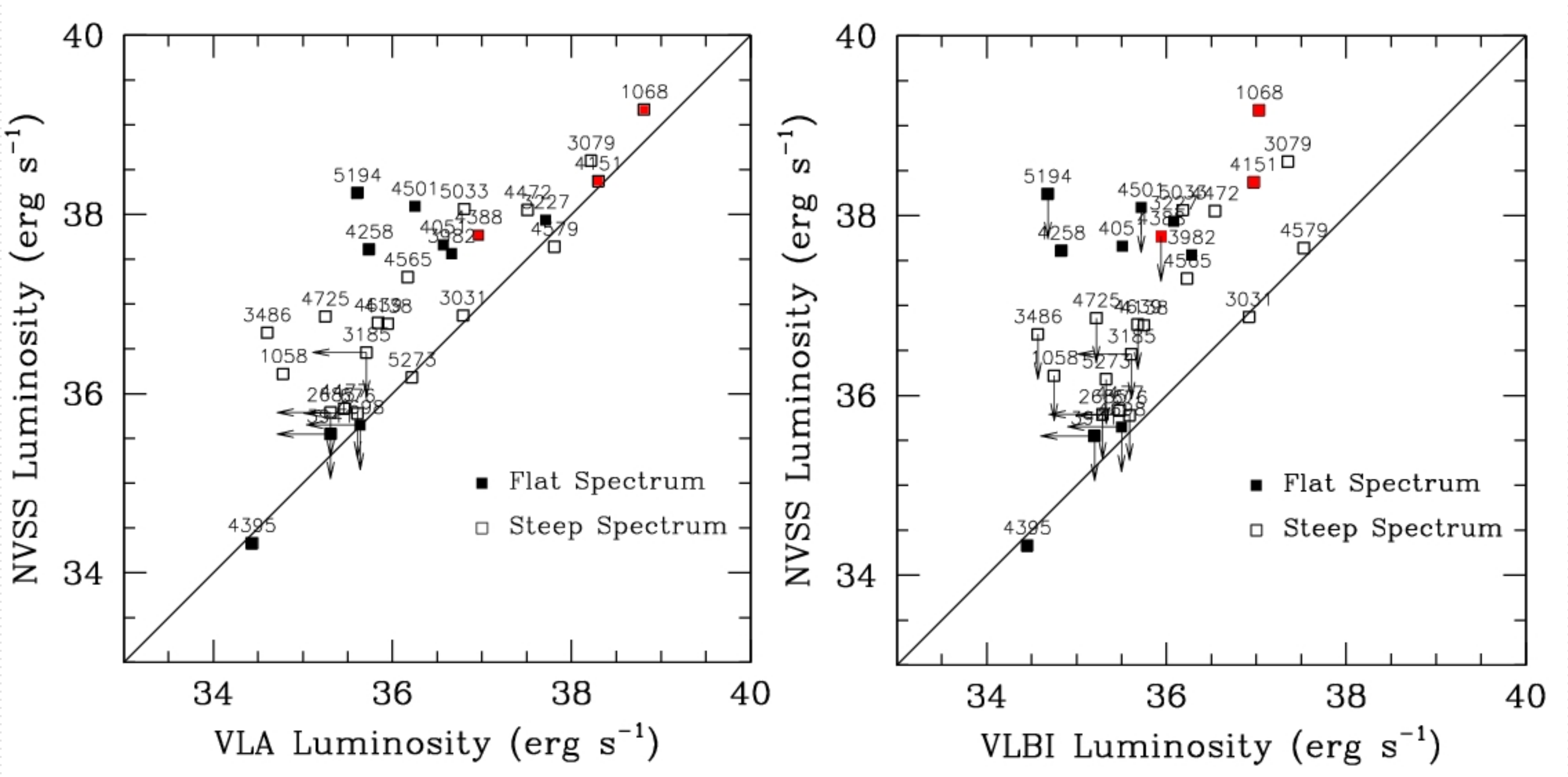
EVN Observations NGC 5273

- ✓ Sy 1.5 VLA detection (S= 0.6 mJy, Nagar+99) at 8 GHz, an unresolved flat component
- ✓ EVN non detection!!!
  (3 σ peak < 90 microJy at 1.6 GHz)
  - 95 % of the VLA flux resolved at 20-300 mas scale
  - significant variability
- ✓ Log $L_{5\ GHz}/L_{2\text{-}10\ keV}$ < -6
- ✓ Log L_X/L_{EDD} =-3.2



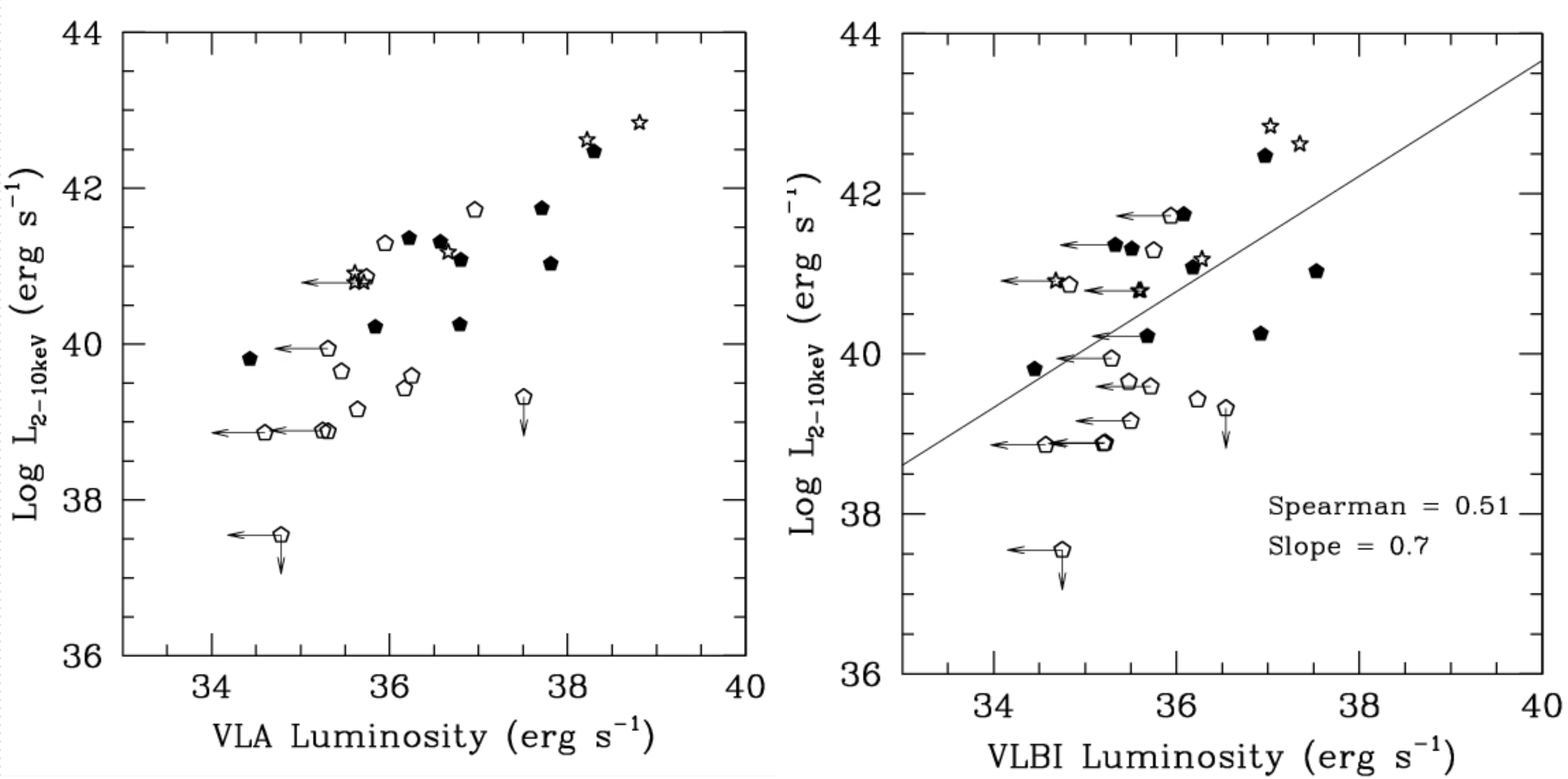
Resolved radio emission or variable radio source?

Resolved Radio emission



✓ At higher resolution most of the radio flux is resolved

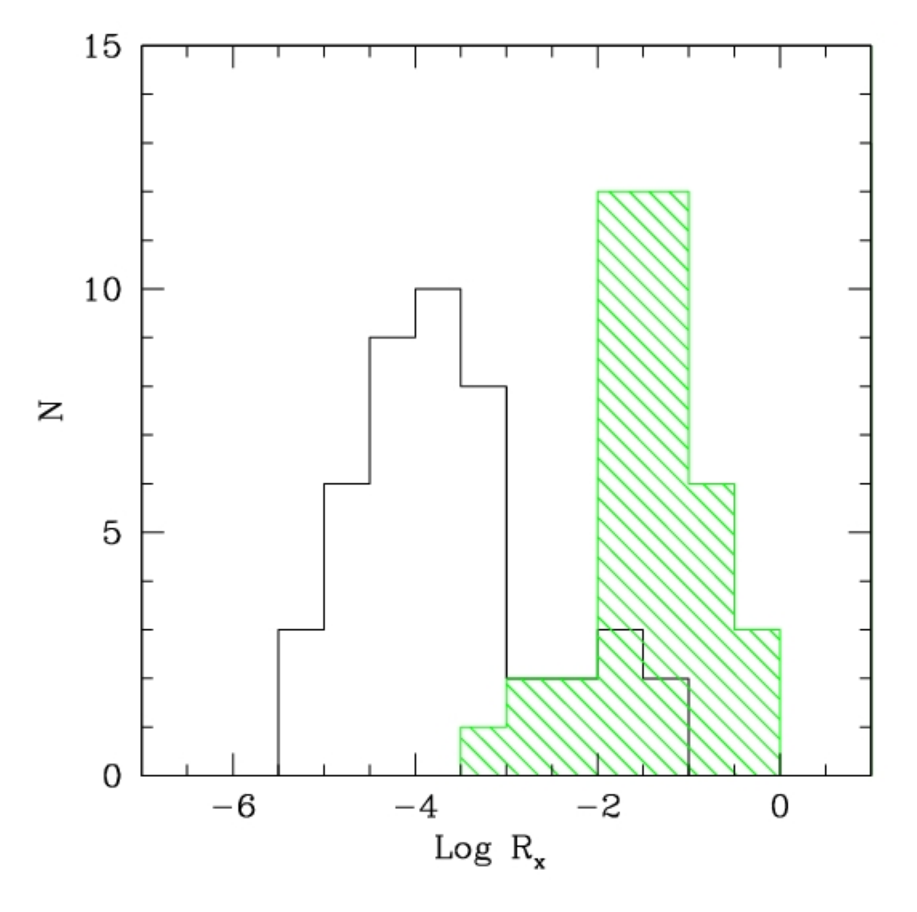
X-ray versus Radio correlation



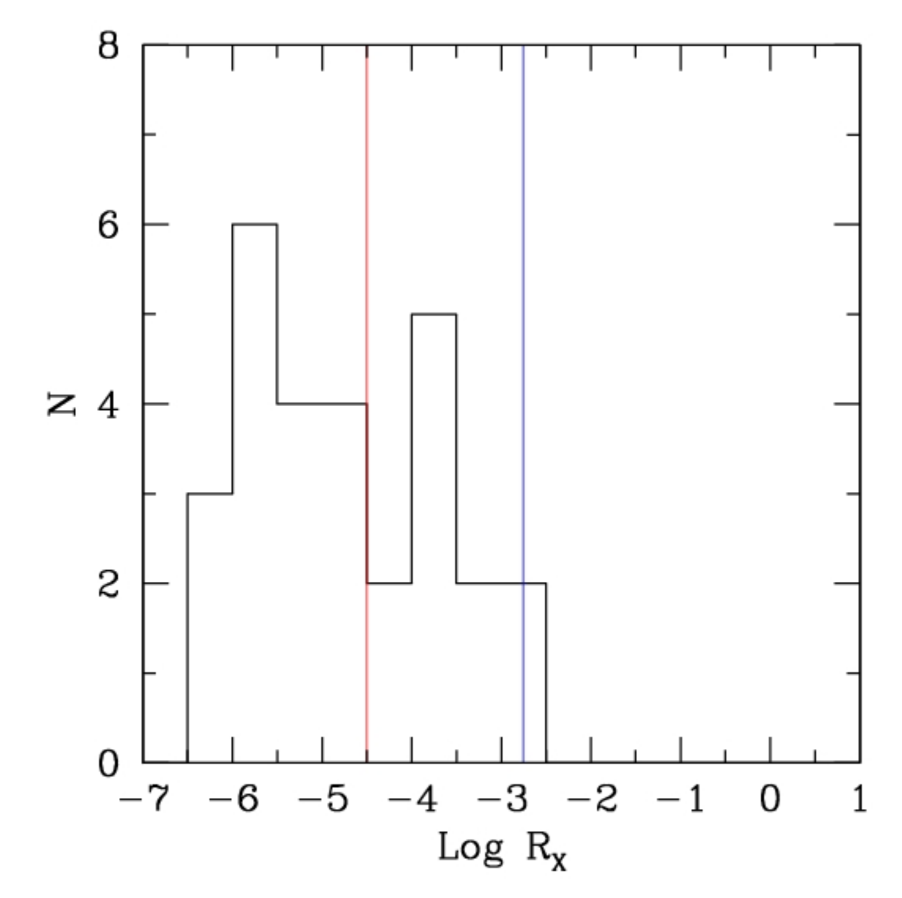
✓ Correlation is lost at VLBI resolution

X-ray radio loudness

R_X = L(5 GHz) / L(2-10 keV)



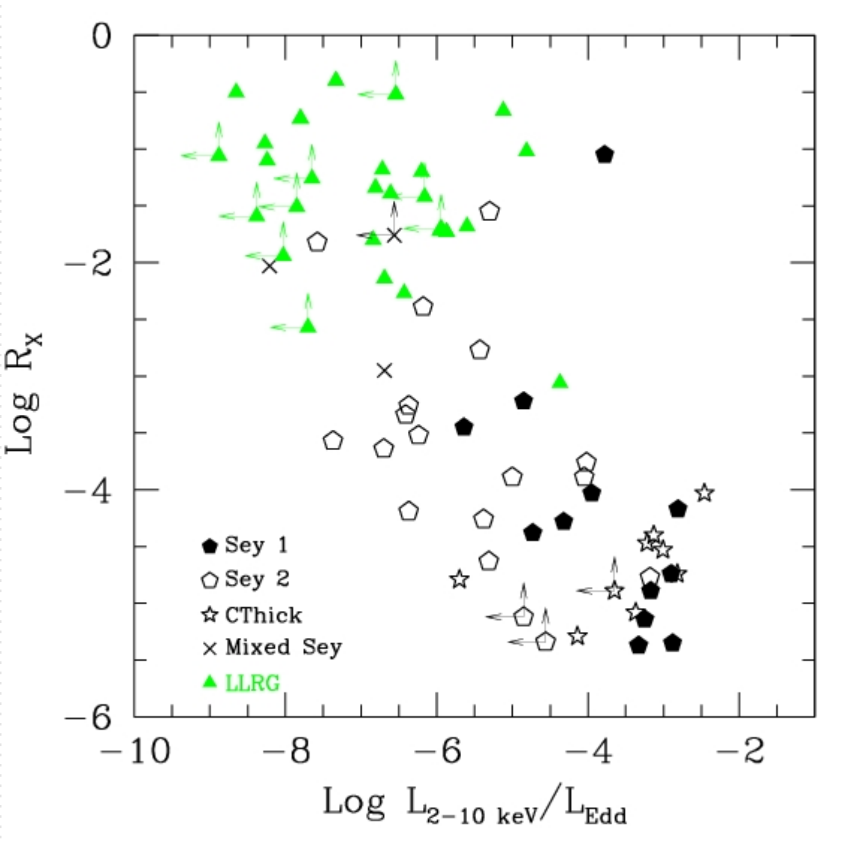
VLA radio data

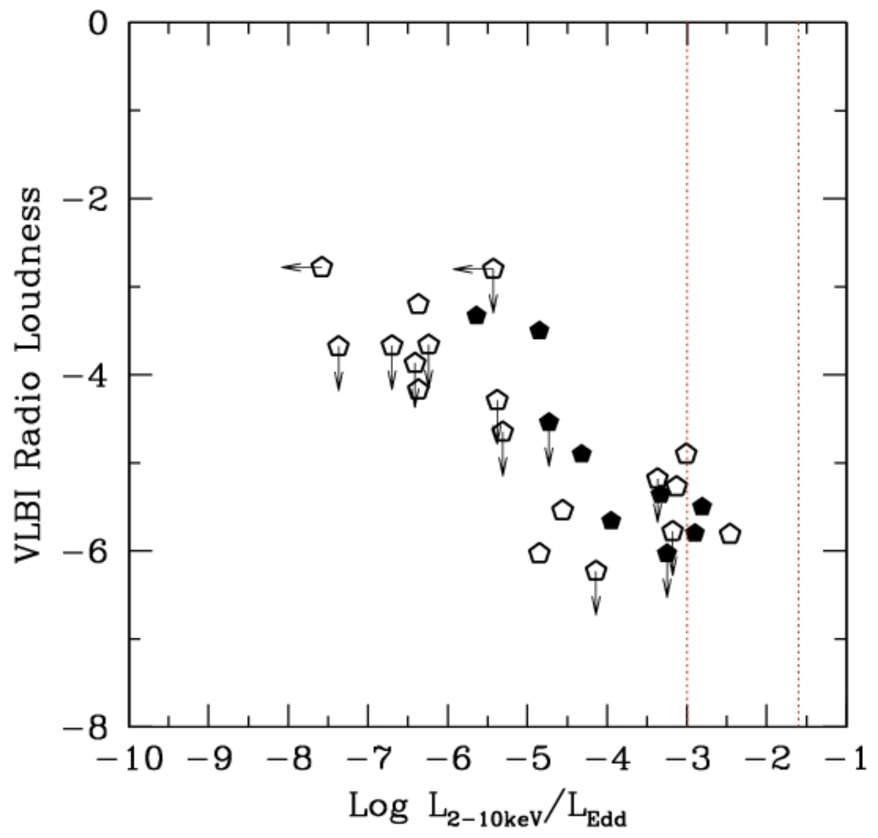


VLBI radio data

✓At higher angular resolution sources are more RQ

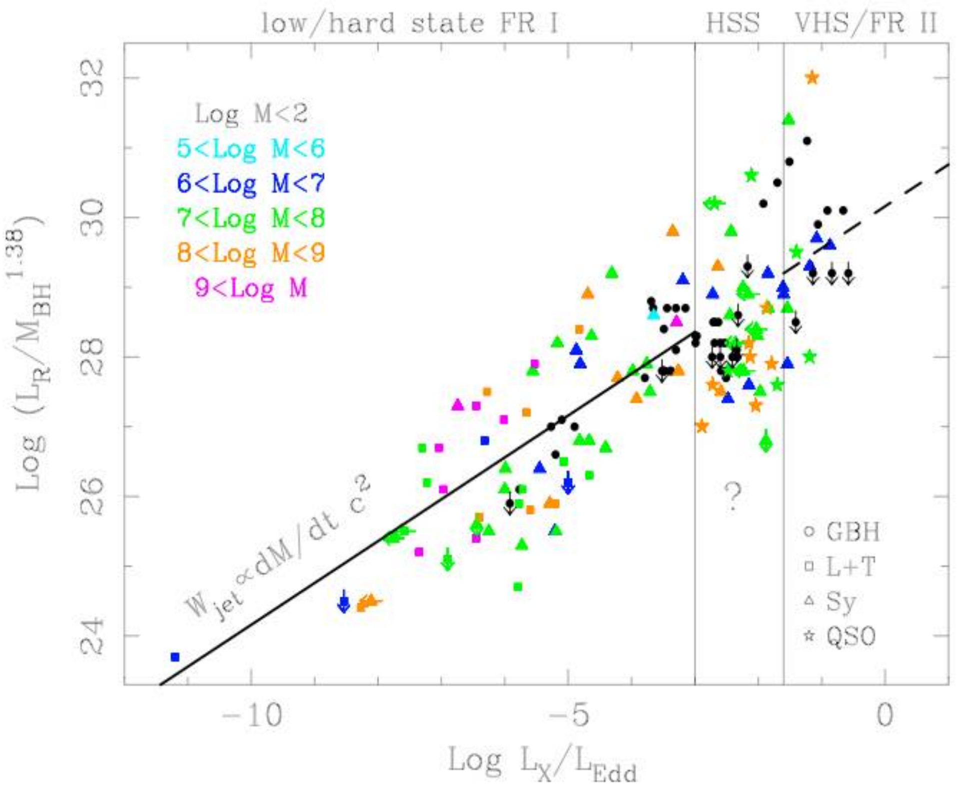
VLBI Radio Loudness

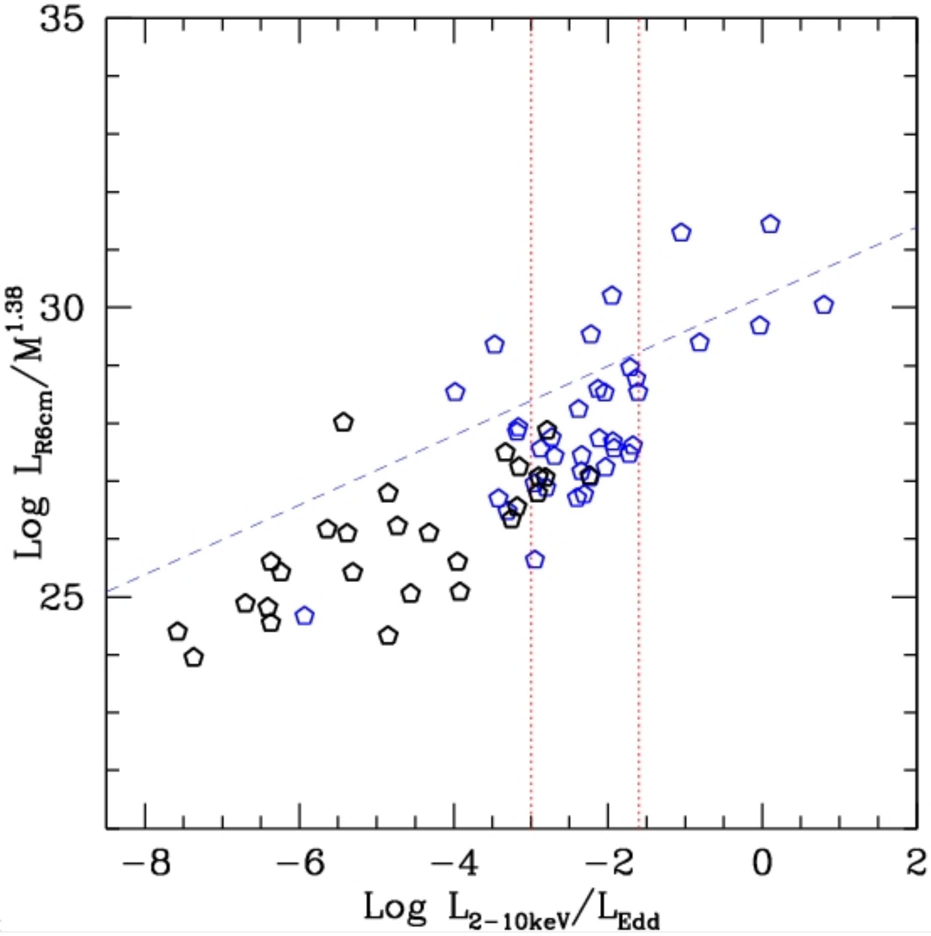




✓Accreting at low Eddington ratios

VLBI Fundamental plane





✓ Systematically below the FP equation

Conclusions:

- Large scale NVSS radio correlates with Hard X-ray and X-ray luminosity both at high and low luminosities with different slopes

  -> the galaxy knows about the BH activity?

- 54% detection rate: very low rate at the microJy flux level
  - VLBI cores are not ubiquitous

- At high angular resolution --> 5-100% of emission is resolved

  -> the sub-pc cores are extremely RADIO QUIET

- Very heterogeneous physical properties:
  - Steep, flat or inverted spectra
  - Compact or extended
  - With or without jet-like feature

- No X-ray vs Radio correlation at VLBI resolution

  -> different mechanisms involved depending on the source

Giroletti & Panessa, 2009, ApJL + Bontempi et al. in preparation + Panessa & Giroletti, in preparation