The Connection Between Stellar Coronae and Accretion Disk Coronae

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collaborators
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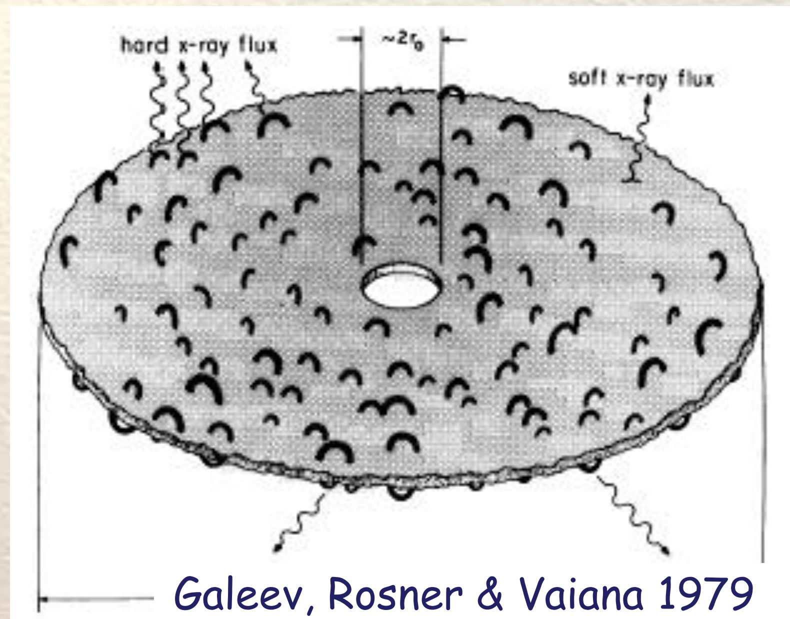
Technion

Modest Goals of This Talk

- to convince the audience that radio emission from accretion disks might not be solely due to jets, but also to a coronae akin to stellar (Laor & Behar 2008)
- to interest capable radio astronomers to monitor radio quiet AGNs at high frequencies (~ 100 GHz)
- to promote simultaneous radio and X-ray monitoring to test the coronal hypothesis

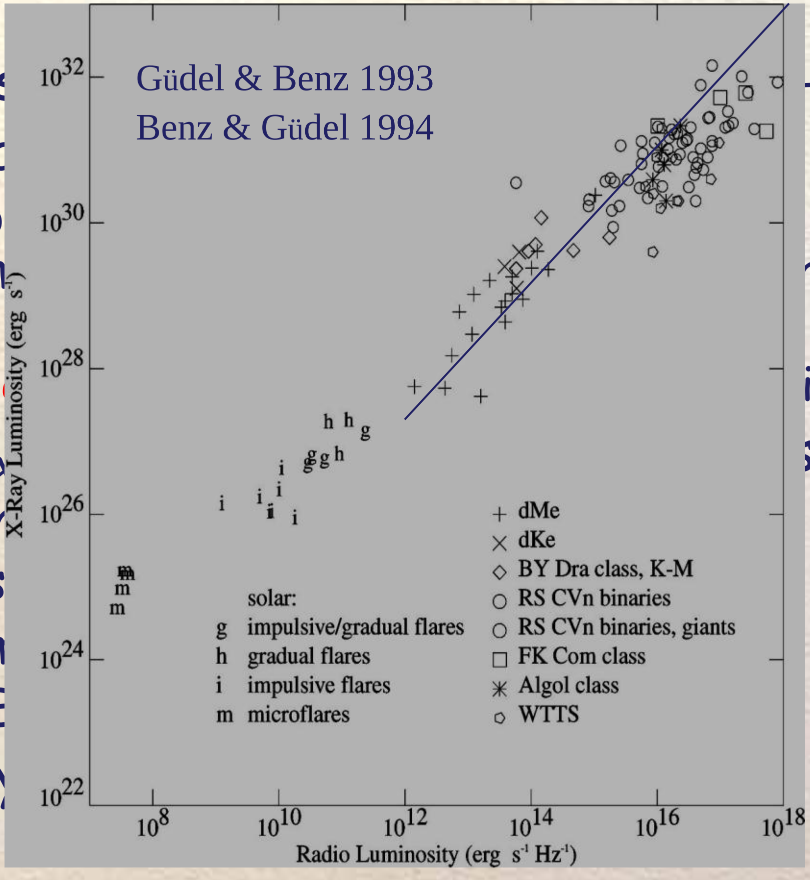
The Analogy



Galeev, Rosner & Vaiana 1979

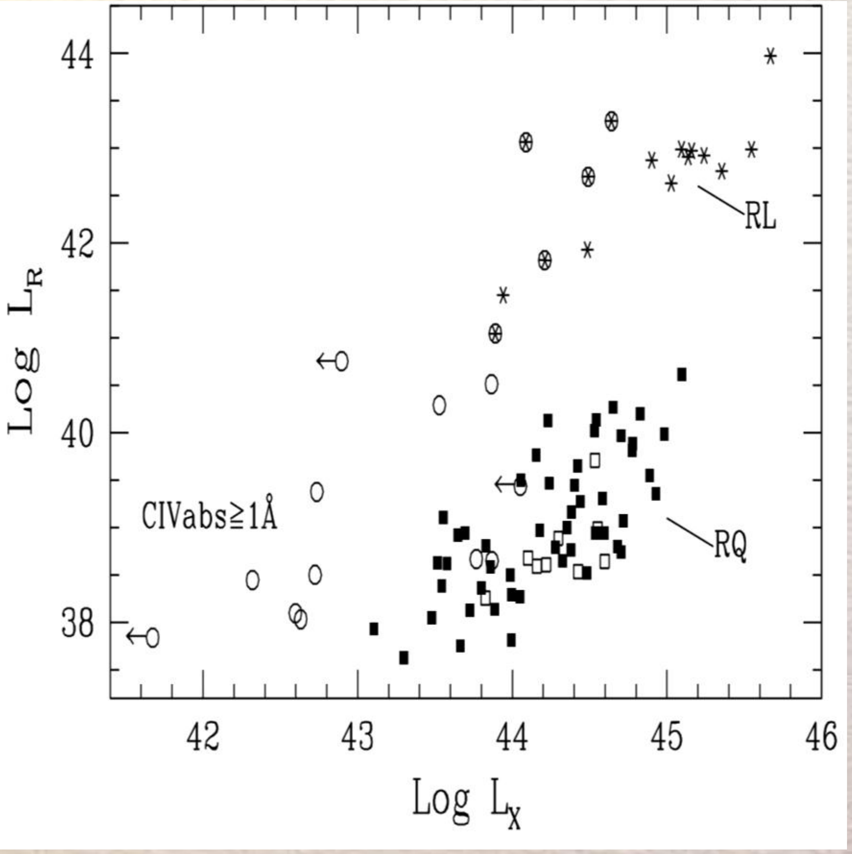
A Few Things We Know about Stellar Coronae

- Radio:
  High T_B , flat s ... -3, $p \approx 2$ - 4
- Radio and X-ra
  - Total lumino
    $L_R \approx 10^{-5} L_X$ n ... r types
  - Variability
    X-radio flar ... izing the corona
  - $L_R \approx 10^{-5}$ L_X ... sts:
  - Magnetic er
  - Radio emiss
  - X-rays fron
  - Outflows: E
- See reviews by ... '09 (X-ray)

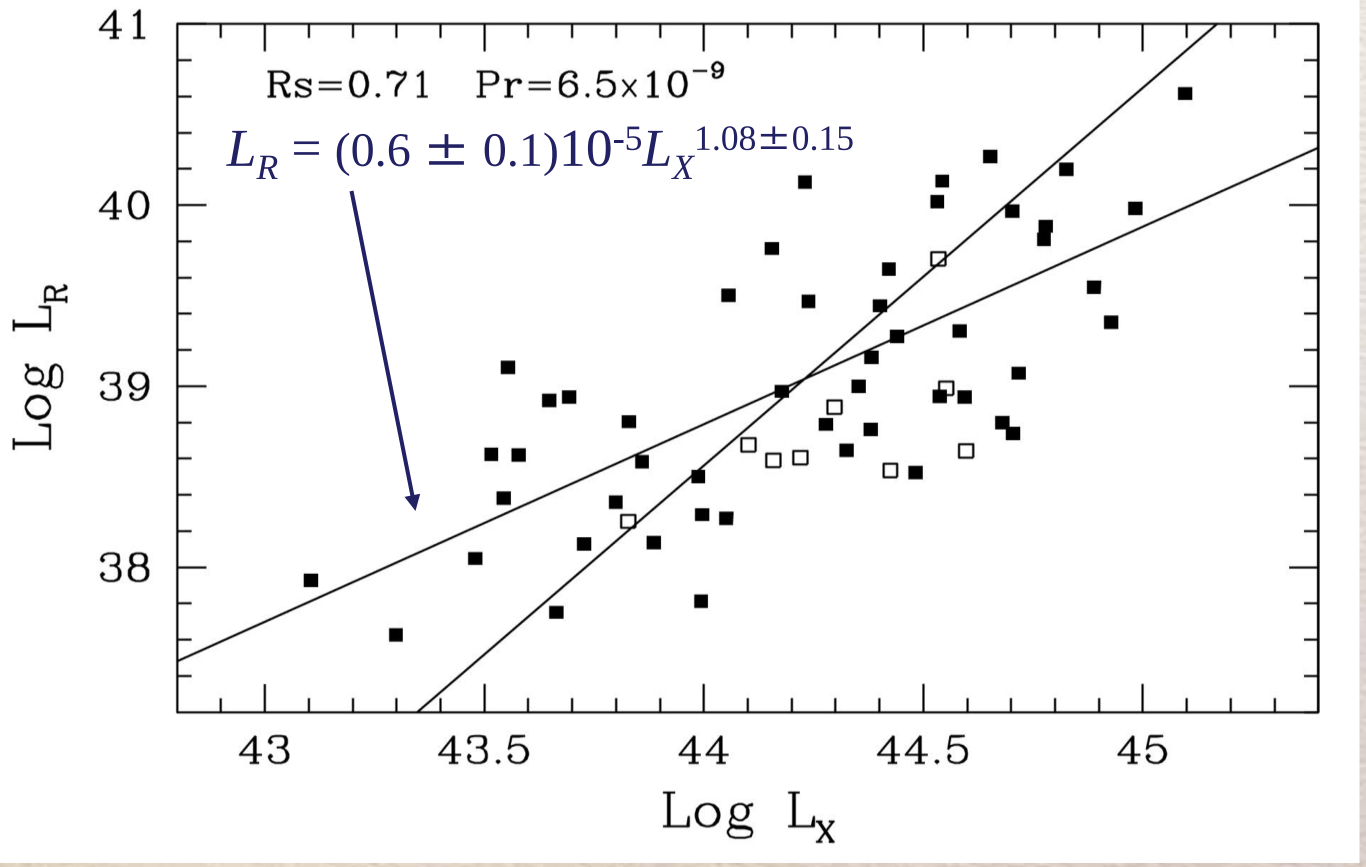


Optically selected PG quasars
(Boroson & Green 1992)

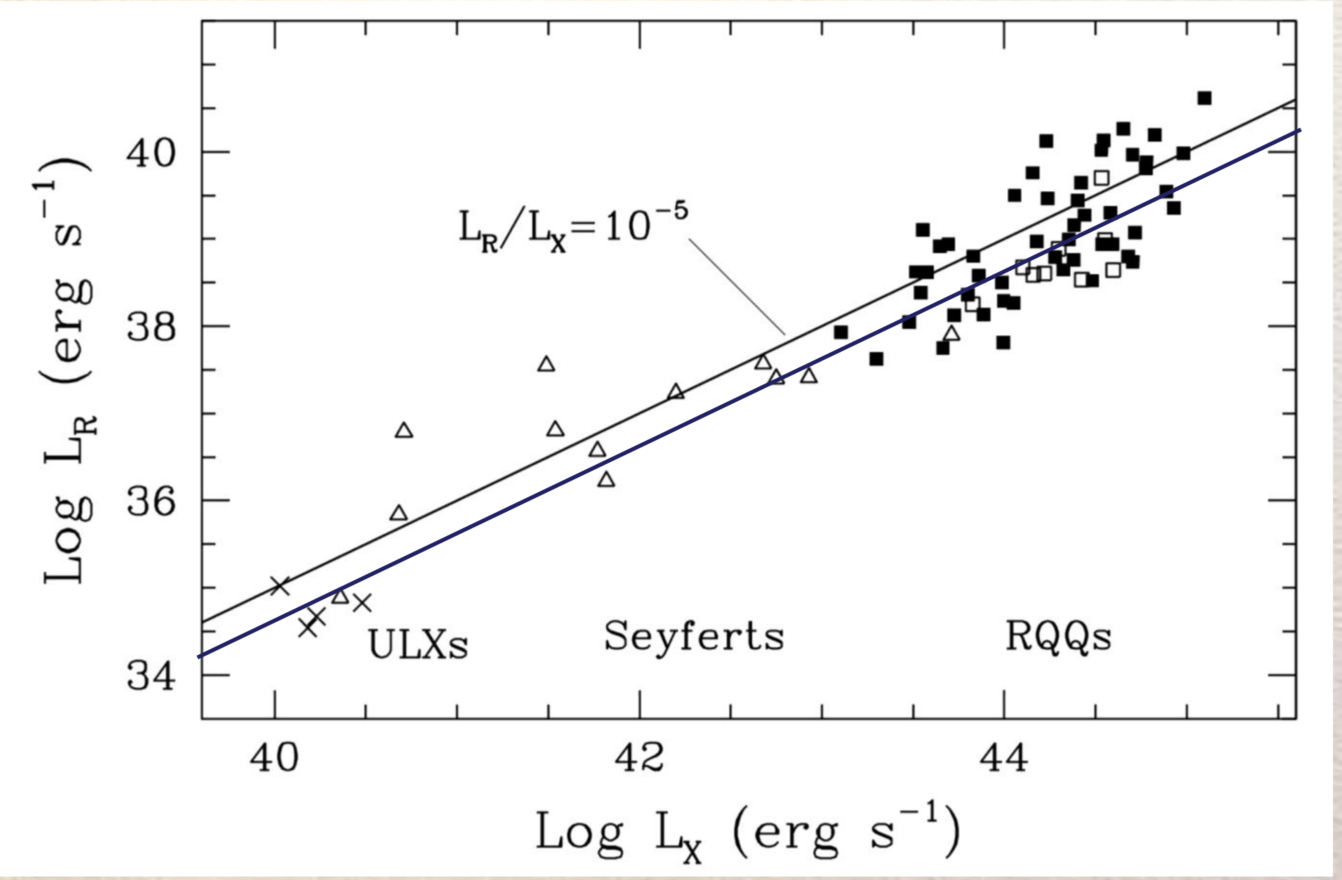
- 87 Low-z (<0.5)
- **$L_R = \nu L_\nu$ at 5 GHz**
  78/87 detected by VLA,
  (Kellerman et al. 1989, 1994)
  vs. non-simultaneous
  L_X from 0.2 to 20 keV
  84/87 ROSAT detections
  (Brandt et al. 2000,
  Laor & Wills 2000)
- Remove RLQs and absorbed quasars (Laor & Brandt 2002) leaves 59 RQQs



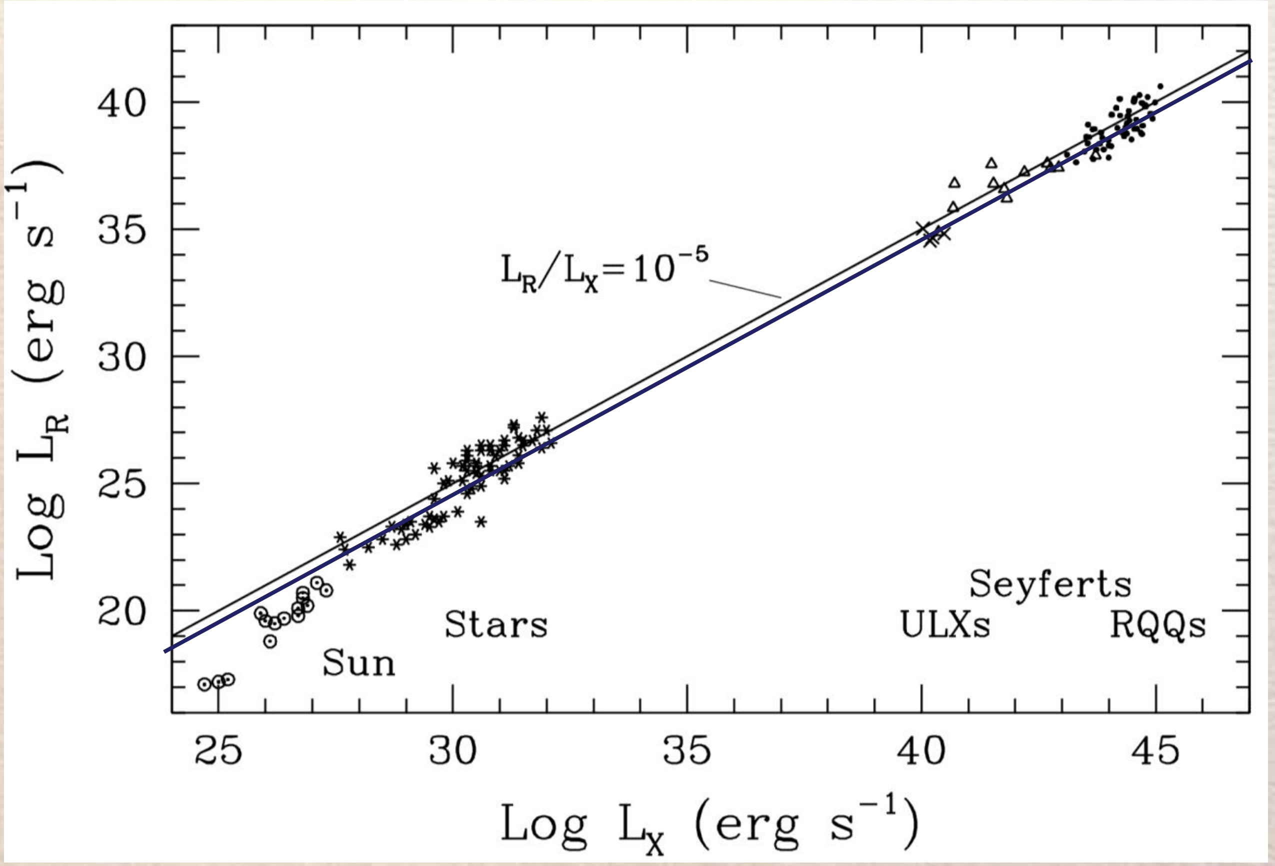
L_R-L_X Correlation for Radio-Quiet PG Quasars



Extending to Lower Luminosities
(VLA & XMM)

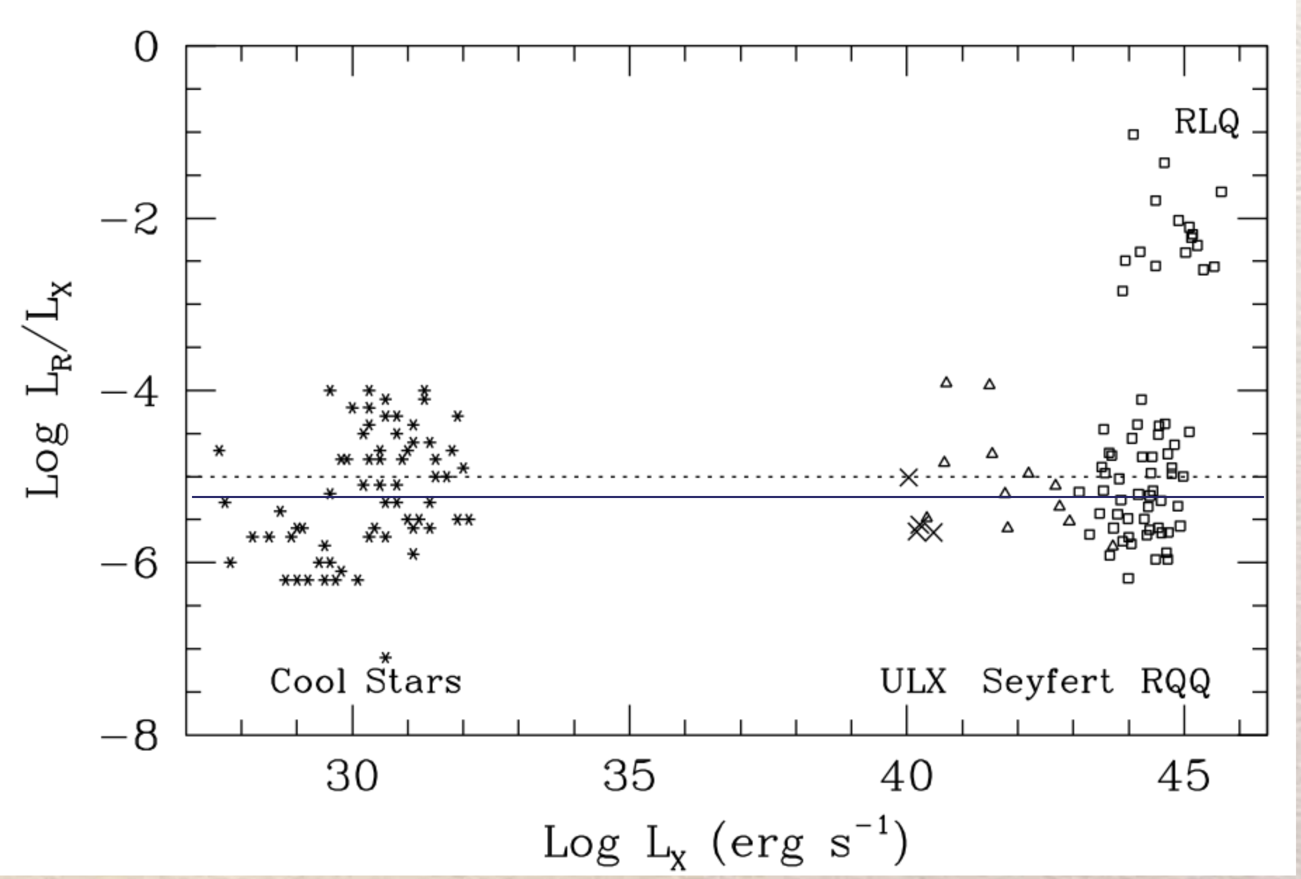


The Big News



Log L_R (erg s^{-1})
Log L_X (erg s^{-1})
$L_R/L_X=10^{-5}$
Sun
Stars
ULXs
Seyferts
RQQs
20
25
30
35
40
45

Or



Log L_R/L_X
Log L_X (erg s^{-1})
0
−2
−4
−6
−8
30
35
40
45
RLQ
Cool Stars
ULX
Seyfert
RQQ

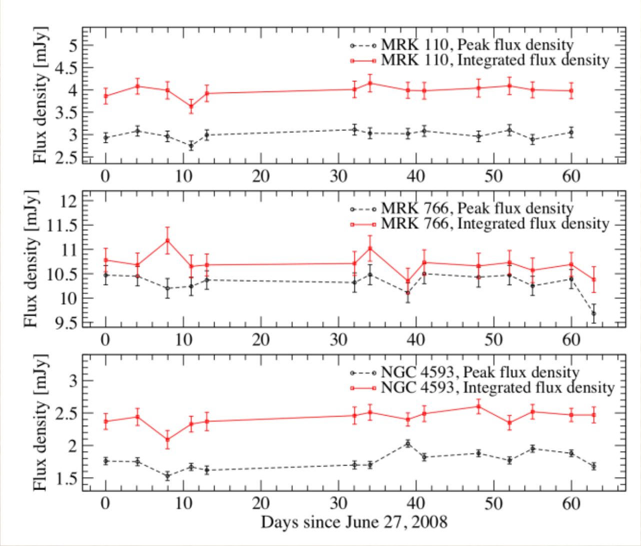
Coronal Conjecture for Radio-Quiet AGNs

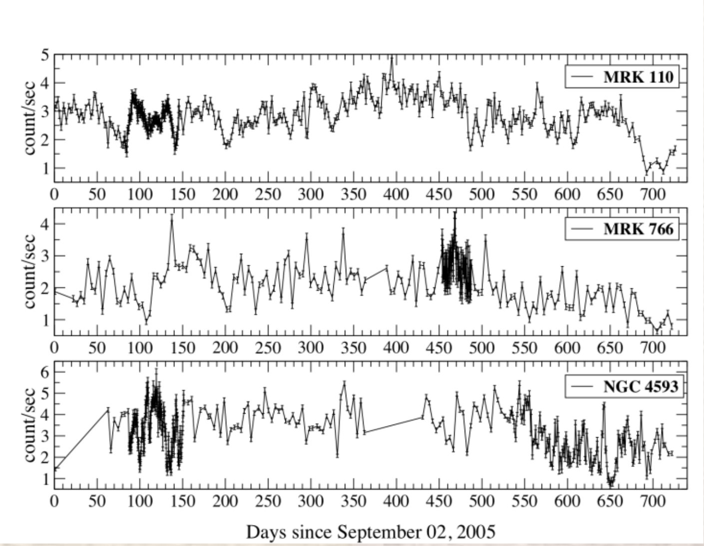
- Magnetic activity above the disk produces relativistic electrons that emit radio
- Main cooling mechanism is Coulomb collisions
- Thermalized electrons IC scatter disk photons to produce the X-rays (sparse covering factor)
- Mass ejections create outflows
- Differs from jet in lack of
  - collimation
  - relativistic ordered motion (global magnetic field lines)

Challenges to Analogy

- Variability
  - Stellar: Radio+X flares, e.g., Neupert effect
  - RQ AGNs: Rapid X-ray variability with very little radio variability
- X-Ray Spectra
  - Stellar: thermal
  - RQ AGNs: non-thermal (IC scattering)
- Extended Emission
  - Stellar: coronal mass ejections
  - RQ AGNs: unresolved

(high) X-Ray vs. (low) Radio Variability in Seyferts





- See also Anderson & Ulvestad '05, Bell et al '11, Jones et al. '11, King et al. '11
- Barvainis et al. '05 for quasars

The Radio-Sphere

- Synchrotron self absorption (from $L_\nu/4\pi d^2 = S_\nu \pi R^2/d^2$)

$$R_{ssa} = 0.1 \left(\frac{\nu L_\nu}{10^{40}\,\mathrm{erg\ s^{-1}}}\right)^{1/2} \left(\frac{B_\perp}{\mathrm{Gauss}}\right)^{1/4} \left(\frac{\nu}{5\mathrm{GHz}}\right)^{-7/4} \mathrm{pc}$$

- RQQ $\{$ $L_\nu \sim 10^{40}$ erg/s $R_{ssa} \sim 0.1$ pc ~ 4 light mon.

  LLAGN $\{$ $L_\nu \sim 10^{36}$ erg/s $R_{ssa} \sim 10^{-3}$ pc ~ light day
- Perhaps a tad less than observed variability time scales
- More than 10 times the corresponding nuclear X-ray variability time scales

Easily Refutable Prediction

- Sync. absorption decreases with frequency $\langle_{\nu} \propto \nu^{-(p+4)/2}$

$$R_{ssa} = 0.1 \left(\frac{\nu L_{\nu}}{10^{40} \, \mathrm{erg\ s^{-1}}} \right)^{1/2} \left(\frac{B_{\perp}}{\mathrm{Gauss}} \right)^{1/4} \left(\frac{\nu}{5\mathrm{GHz}} \right)^{-7/4} \mathrm{pc}$$

- For B ∝ 1/*R* $R_{ssa} \propto L^{1/2} / \nu$
- <u>Higher Frequencies will Vary on Shorter Time Scales</u>
- For flat spectrum, X-ray sizes expected at > 100 GHz
  - FIR dominated by dust emission at $T \geq 30$ K (Hass et al. '00), that drops by five orders of magnitude from 0.1 - 1 mm (Polleta et al. '00), so no dust emission by 300 GHz

Current Radio Telescopes

- Improved sensitivity enables *simultaneous* L_R L_X measurements of all PG quasars and perhaps extension of luminosity range (higher and lower – see Ashley King's talk from Saturday)
- Improved resolution enables better characterization of core and extended emission
- Most importantly, high-frequency capability enables for the first time to probe the inner synchrotron-self-absorbed region and perhaps to start approaching the size of the X-ray source

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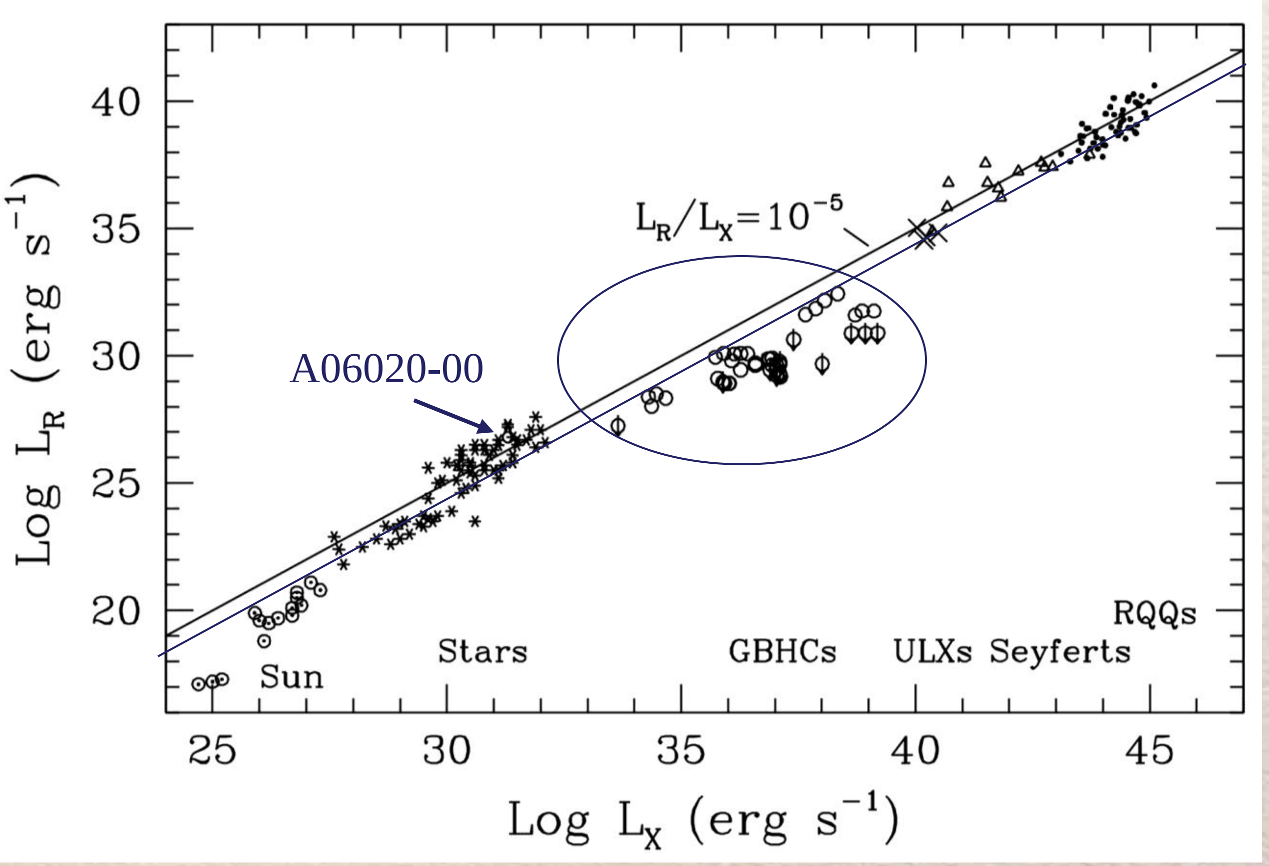
THANK YOU
FOR YOUR ATTENTION

What About Galactic Black Holes?



Fundamental Plane for GBH & AGN

- Merloni et al. (2003)
  also Flacke et al. (2004)
- Main difference is M_{BH} and disk temp T_{GBH}~10-100 T_{AGN}
- In a thin disk
  (Shakura & Sunyaev 1973)
- Using the bolometric relation (Just et al. 2007)
- The dependence on M_{BH} replaced by T
- Indeed, L_R/L_X differ by factor 10 - 100

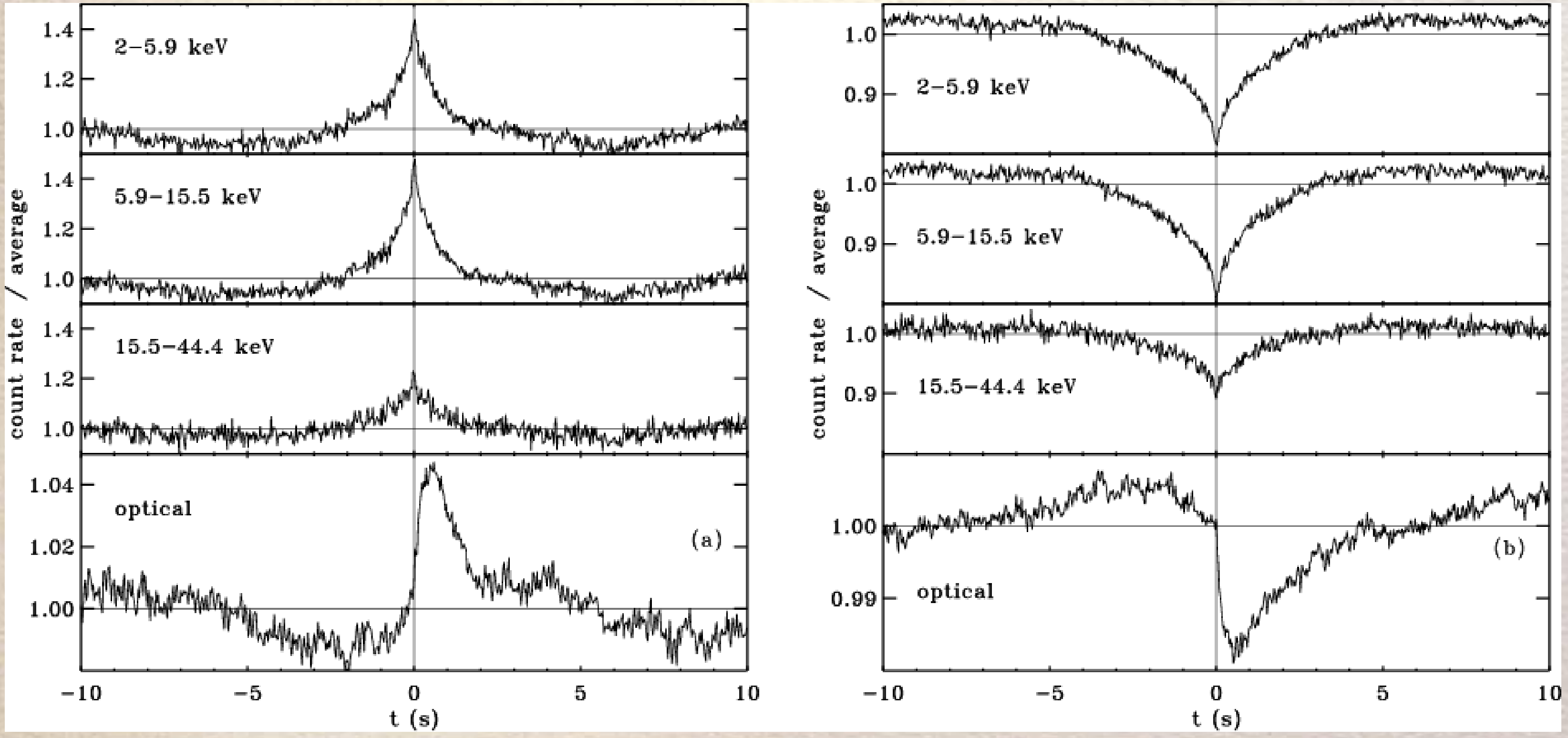
$$\frac{L_R}{L_X} \propto L_X^{-0.46\pm0.14}\left(\frac{M_{BH}}{M_{Sun}}\right)^{0.78\pm0.13}$$

$$\frac{L_{bol}}{L_{Edd}} \mu \; T^4\left(R/R_g\right)^3 \frac{M_{BH}}{M_{Sun}} \quad \text{or} \quad L_{bol} \mu \; M_{BH}^2 T^4$$

$$L_X \mu \; L_{2500A}^{-0.71\pm0.01} \mu \; L_{bol}^{-0.71\pm0.01}$$

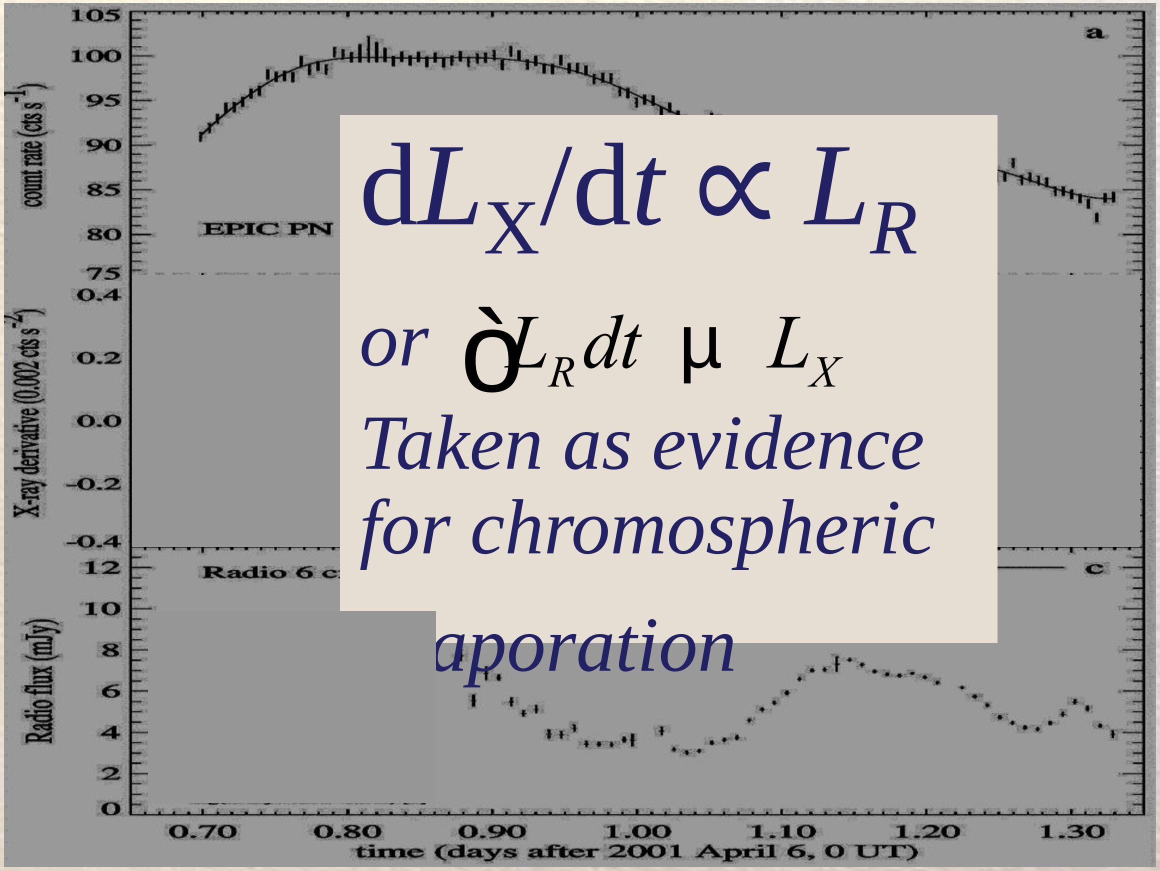
$$\frac{L_R}{L_X} \mu \; L_{bol}^{-0.33\pm0.10} M_{BH}^{0.78\pm0.13} \mu \; T^{-1.32\pm0.4} M_{BH}^{0.12\pm0.24}$$

Inverse-Neupert Effect in XRBs?



XTE J1118+480, Malzac et al. 2003

Large Stellar Coronal Flares
The Neupert Effect



$$dL_X/dt \propto L_R$$

or $\int L_R \, dt \propto L_X$

Taken as evidence for chromospheric

aporation

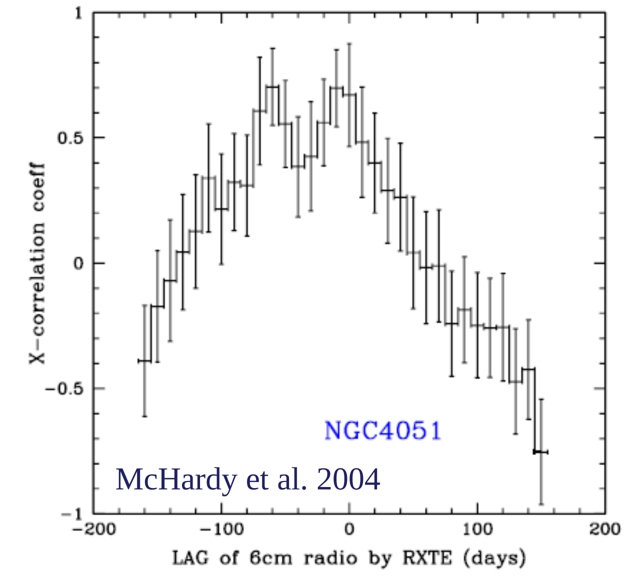
Cooling of The Radio Electrons

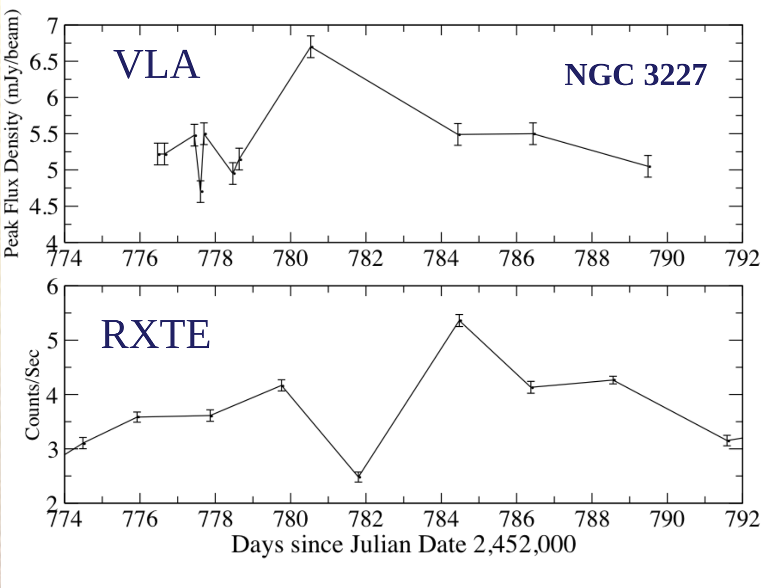
- Radio synchrotron is likely *not* the main coolant
- Compton cooling in radio-sphere is comparable or faster $$\frac{t_{comp}}{t_{synch}} = \frac{U_B}{U_{ph}} = \frac{B^2/8\pi}{L_{bol}/4\pi R^2 c} \approx 0.1 B_{\perp}^{1/2} B^2 \nu_{5GHz}^{-7/2}$$
- In analogy with stellar coronae, radio electrons may cool through elastic Coulomb collisions $$\frac{t_{coll}}{t_{synch}} = \frac{2 \times 10^{12}\gamma/n}{5 \times 10^{8}/\gamma B^2} = 4000\frac{\gamma^2 B^2}{n}$$

  provided that *n* is large enough > 10^5 cm^{-3}
- If coll. dominate var. $t_{coll} < t_{var} \approx 10^4 - 10^7$ s (≈ Rc) => $n > 2\times10^5$© cm^{-3} (RQQ) ; $n > 2\times10^8$© cm^{-3} (LLAGN)

Preliminary Results & Prospects

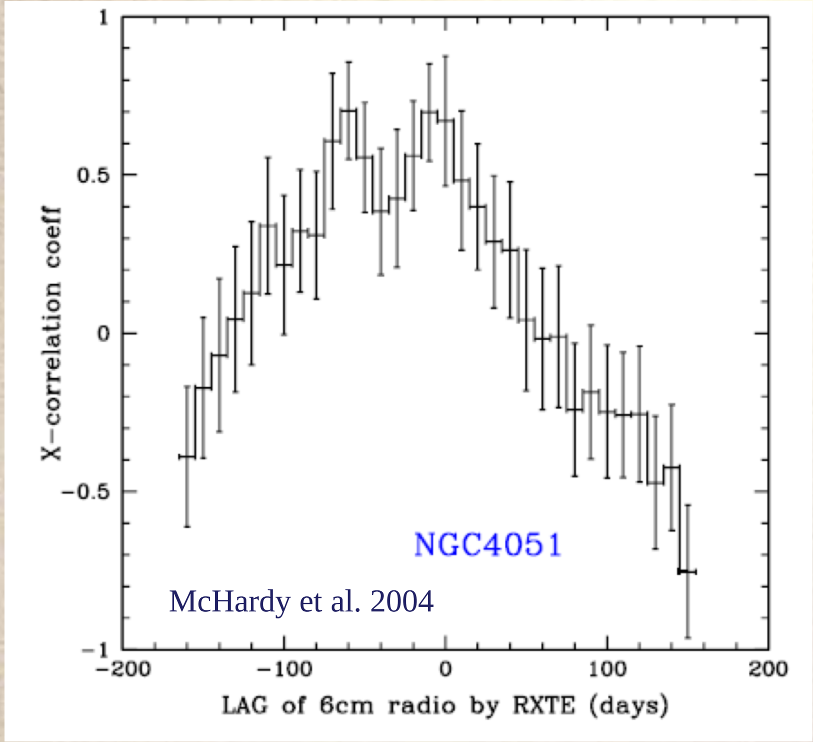
- X-ray-radio correlated variability
  - VLA with RXTE





- Clearly, more monitoring is needed

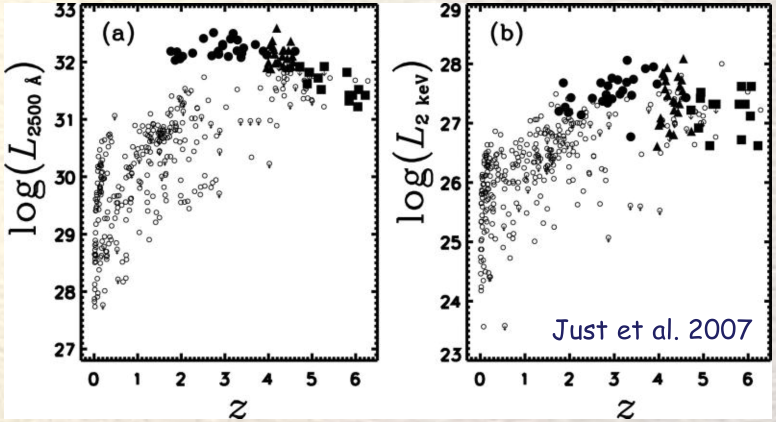
L_R and L_X in NGC 4051

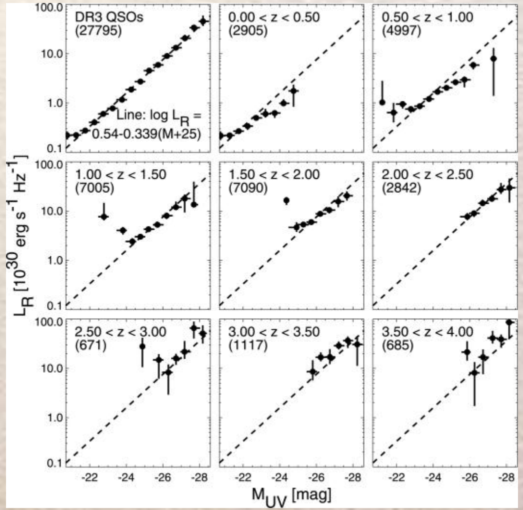


- Jones et al. '11 ~consistent with $L_R \propto 10^{-5} L_X$
- Jones et al. '11, Ashley et al. '11 find no significant radio variability with X-ray variability

Does $L_R \propto L_X$ Hold at Higher Luminosities (L_X > 10^{47}erg/s)?

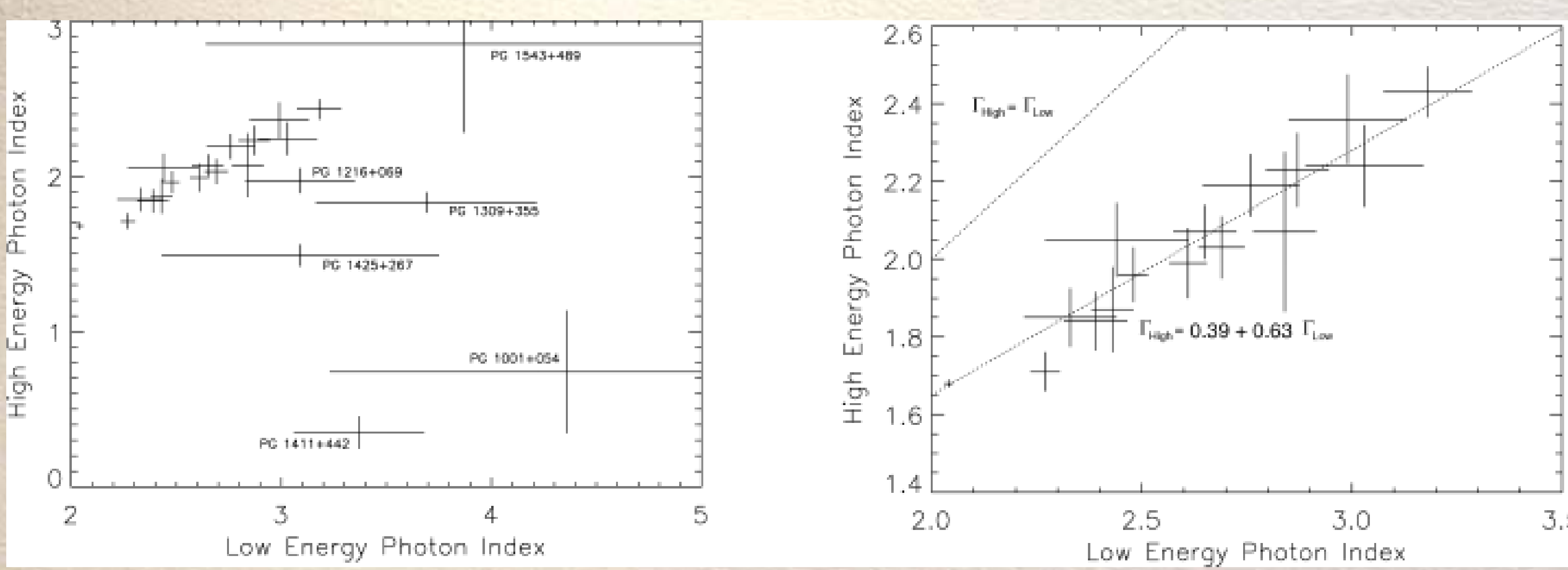
- $L_{2keV} \propto L_{2500Å}^{0.72\pm0.08}$ mostly SDSS, independent of z (up to z ≈ 5)
- FIRST survey for similarly high-L sources: L_R **(5 GHz)** $\propto L_{2500Å}^{0.85\pm?}$ again with no significant z dependence
- Lack of z-dependence suggests again: Microphysics of electron heating and cooling determines L_R / L_X not the source specifics





White et al. 2007

Brocksopp et al. (2006)



Radio Observations of Stellar Corona
(review by Güdel 2002)

- Resolved, extended coronal structures (mas) constrain a combination of B-n_e, through $F \sim I_{\{} R^2 \sim n_e B^{\langle (p)} R^2$,
  but not B or n_e separately
- Turnover frequency v_{peak} at a few GHz (if identified)
  => B through $B \sim \{_{peak}^{5} (F/\theta^2)^{-2} \approx 100$ Gauss
- Flares lasting minutes to hours; if synchrotron cooling dominates (with $\{_{peak}$): B ≥ 100 G ; © ≈ 7 (e.g., Benz et al. 1998).