AGN X-ray Variability
and AGN/Binary Unification

Ian McHardy

University of
Southampton

Talk Outline

1. AGN / binary `states'

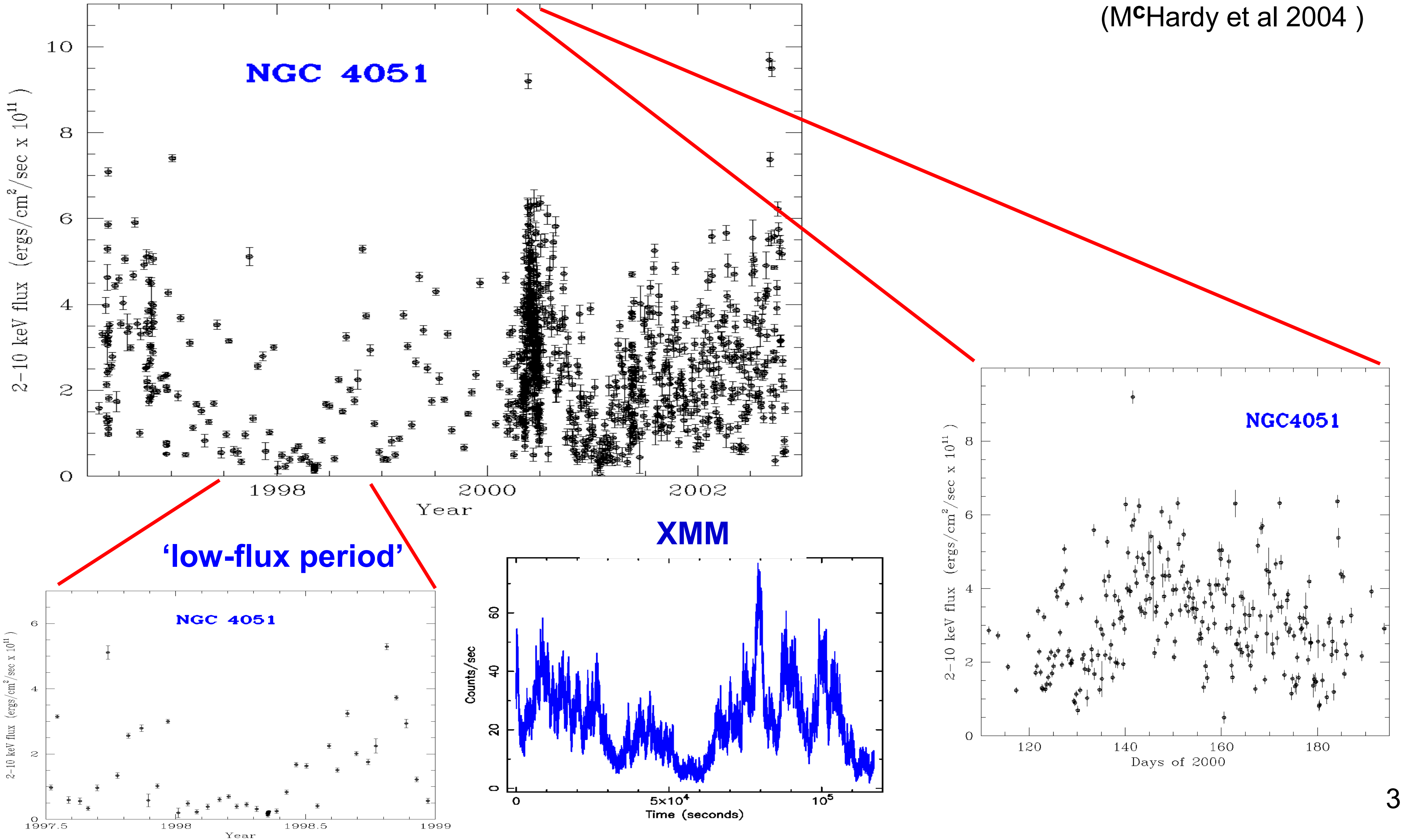
2. Black Hole Timing unification

3. Structure of the emission region
- origin of the variations

4. X-ray / optical & X-ray / radio variability

TYPICAL AGN X-RAY DATA….
Eg NGC4051 RXTE Long Timescale Observations

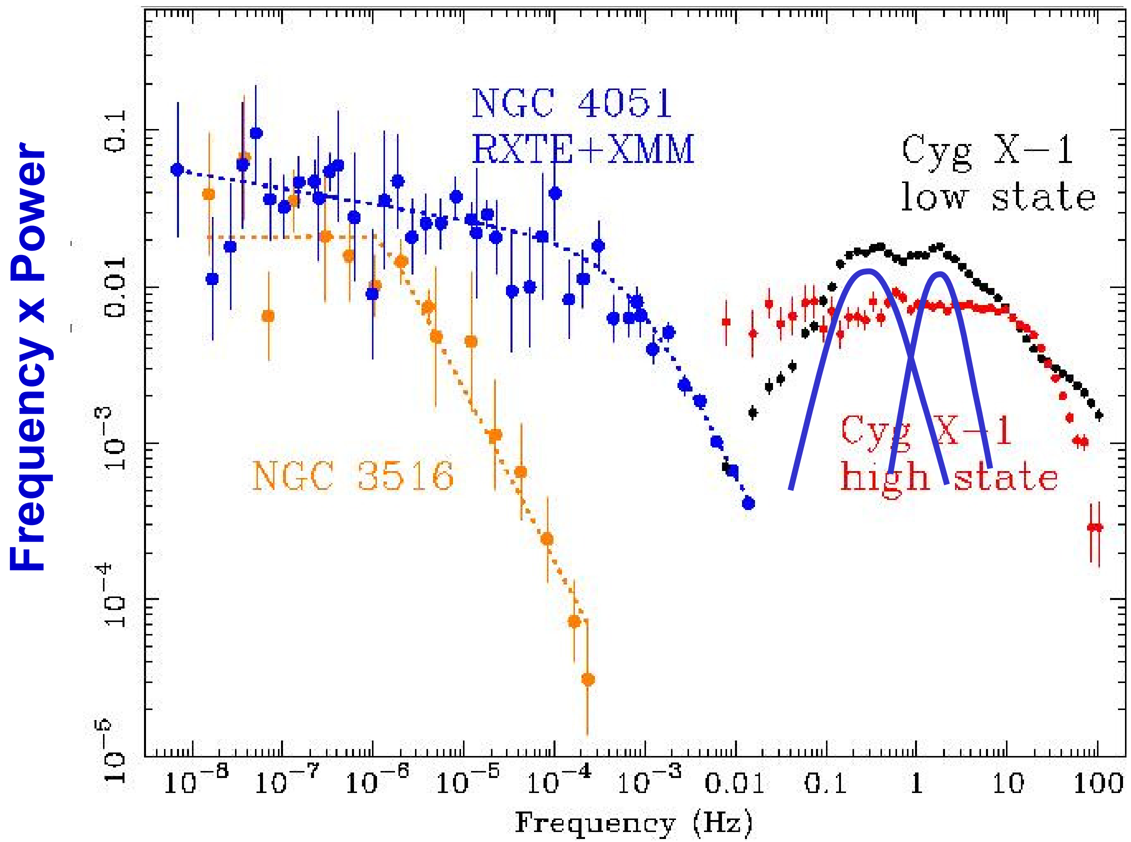
(M^c^Hardy et al 2004)



TIMING STATES

Frequency x Power

`Unfolded' Power Spectral Density (PSD)



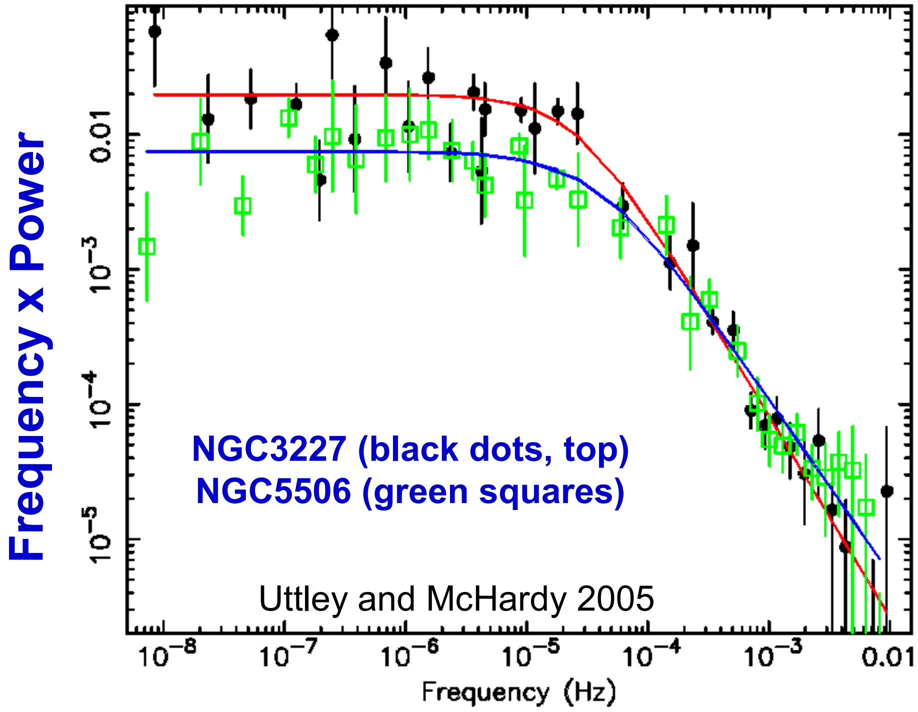
(McHardy et al., 2004)

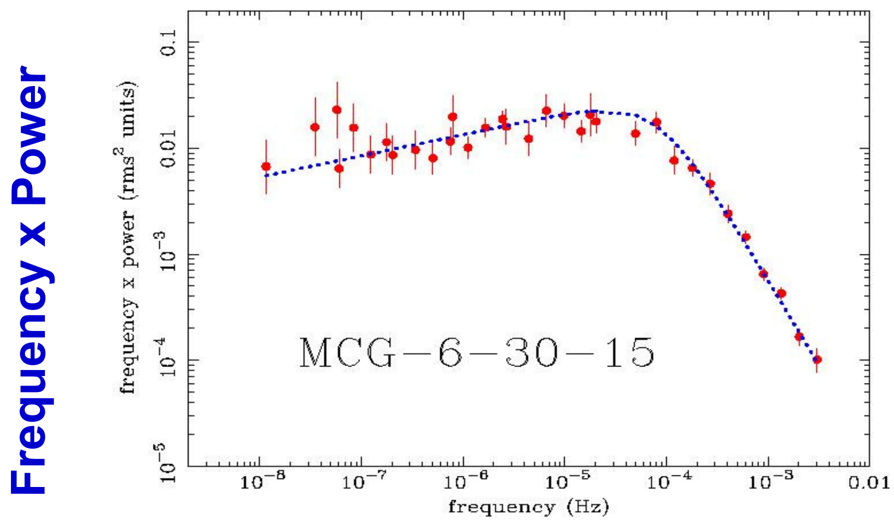
Cyg X-1 Low-hard state PSD:

Can be described either as powerlaw with two bends, or as sum of `Lorentzians'

- **NGC4051 partly like Cyg X-1 low-hard state, but no second break**
- **More like high-soft state of Cyg X-1**
- **High break timescale scales approximately linearly with mass**

PSDs of other AGN?





Vaughan et al 2003
McHardy et al 2005

No (timing) hard states confirmed yet.

NGC3227 has a hard spectrum (Γ=1.6)

Timing may be more fundamental than spectra

Lack of low state systems is probably a selection effect.
Present targets are X-ray bright - higher accretion rates

[Binary soft state systems are less variable as dominated by steady emission from disc.]

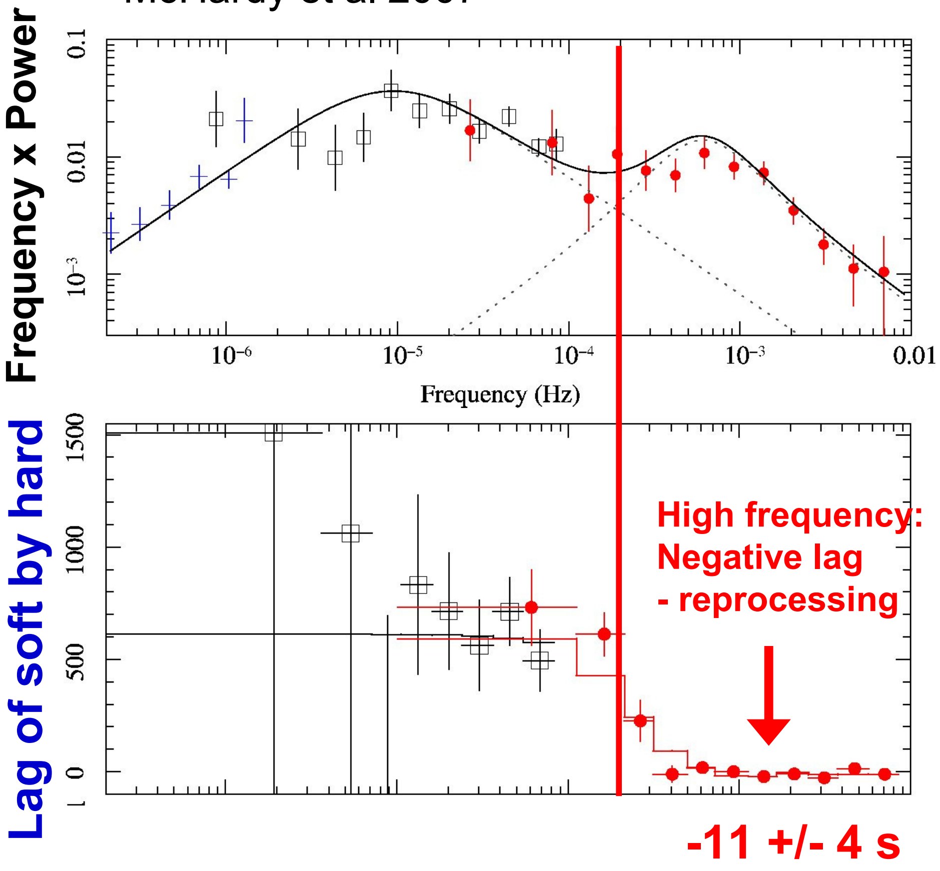
Another state diagnostic: Time Lags

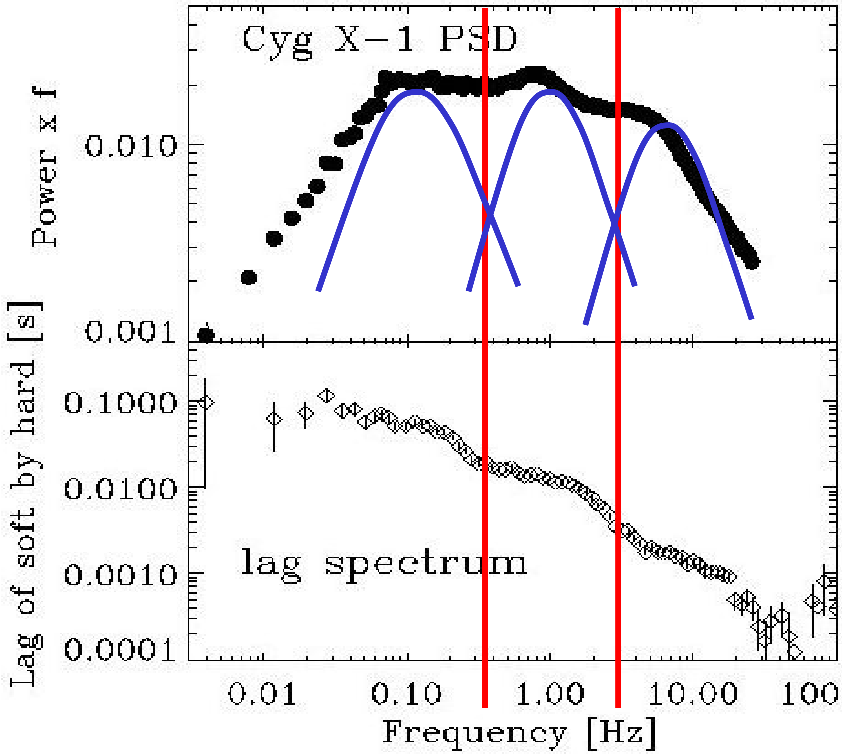
- **Take lightcurves in 2 different energy bands**
- **Split each lightcurve into separate Fourier components**
- **Measure time lag between the two energy bands as function of Fourier timescale.**
- (See Nowak and Vaughan 1996)

Southampton

Lorentzians and Time Lags: Akn564

McHardy et al 2007

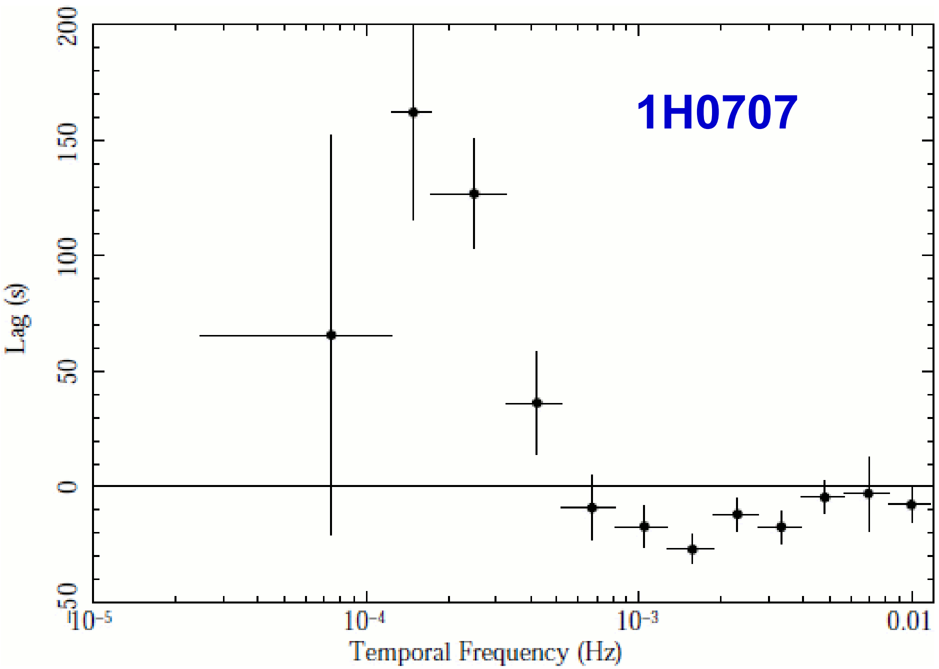


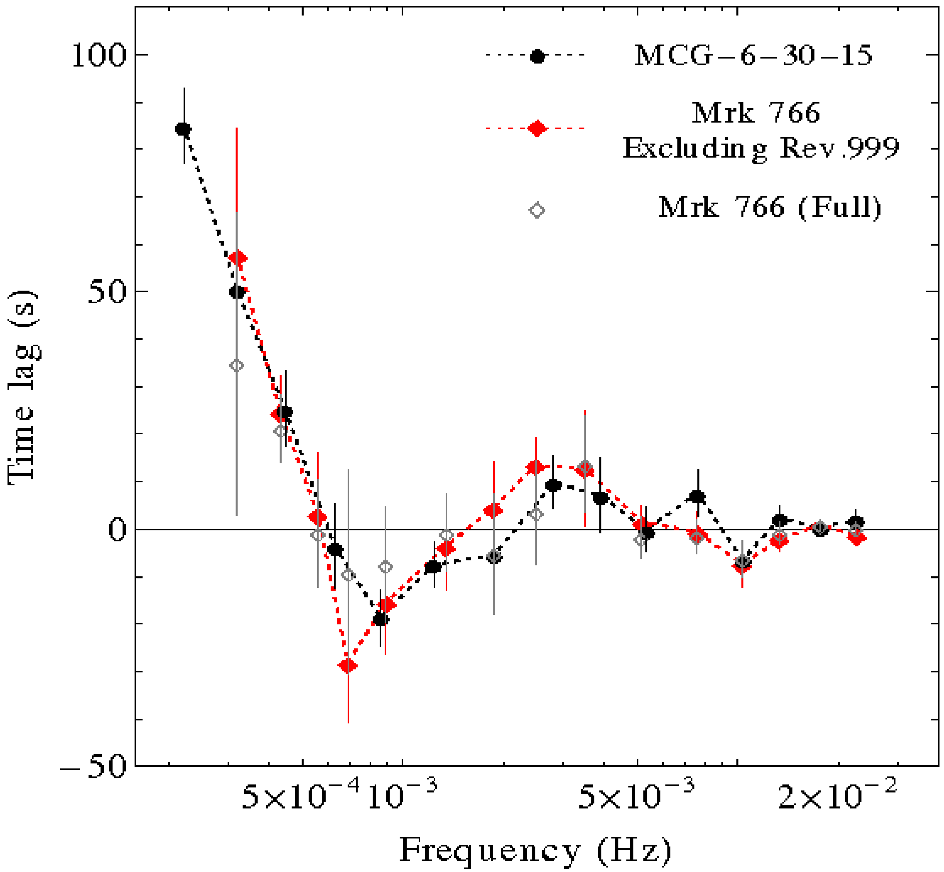


For binaries in hard or VHS state, lag is ~constant when one Lorentzian dominates

..same in Akn564 (As $\dot{m} \geq 1$ implies VHS, not `hard' state)

High Frequency AGN lags:
Diagnostic of reprocessing geometry





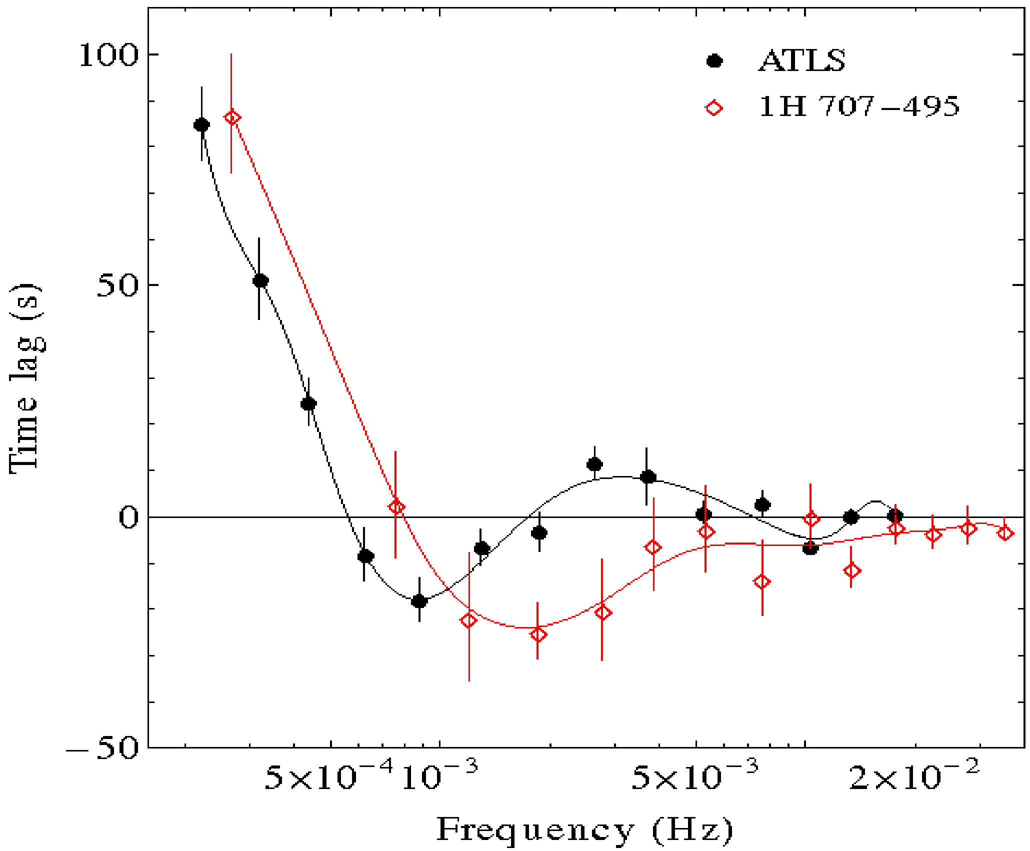
Fabian et al 2009

Fourier Transform of the response function.
[See Peterson 1993 for response functions.]

Emmanoulopoulos, McHardy and Papadakis 2011

MCG6 and Mrk766 almost identical

Lag Comparison

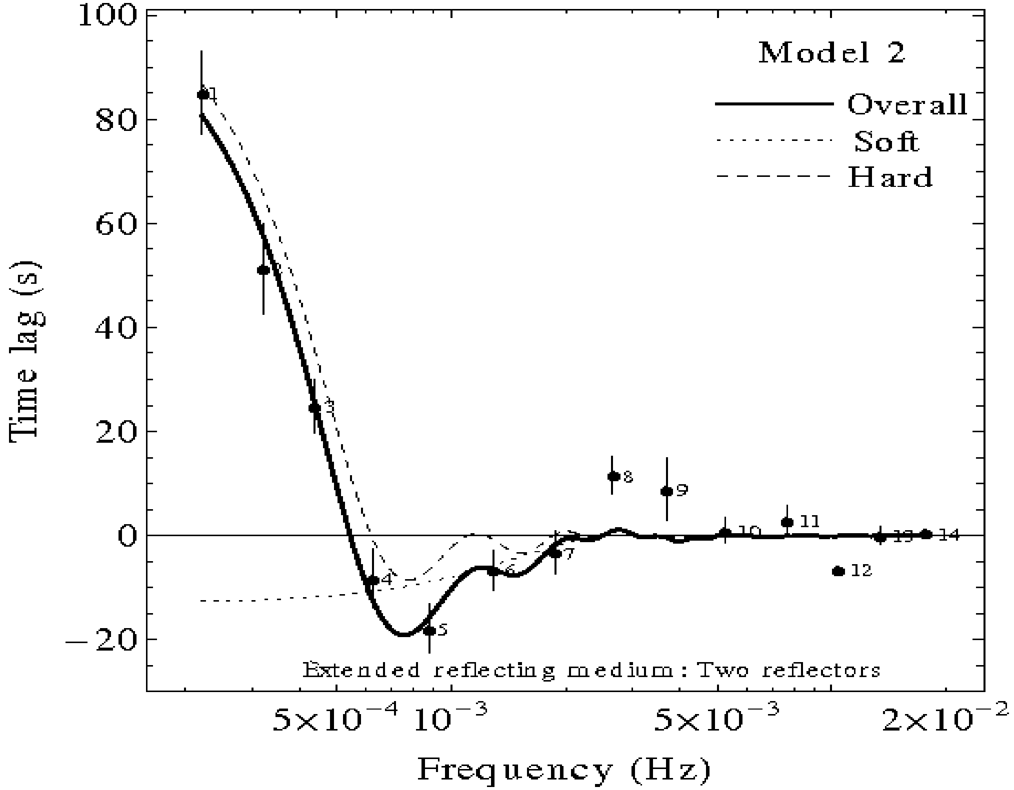


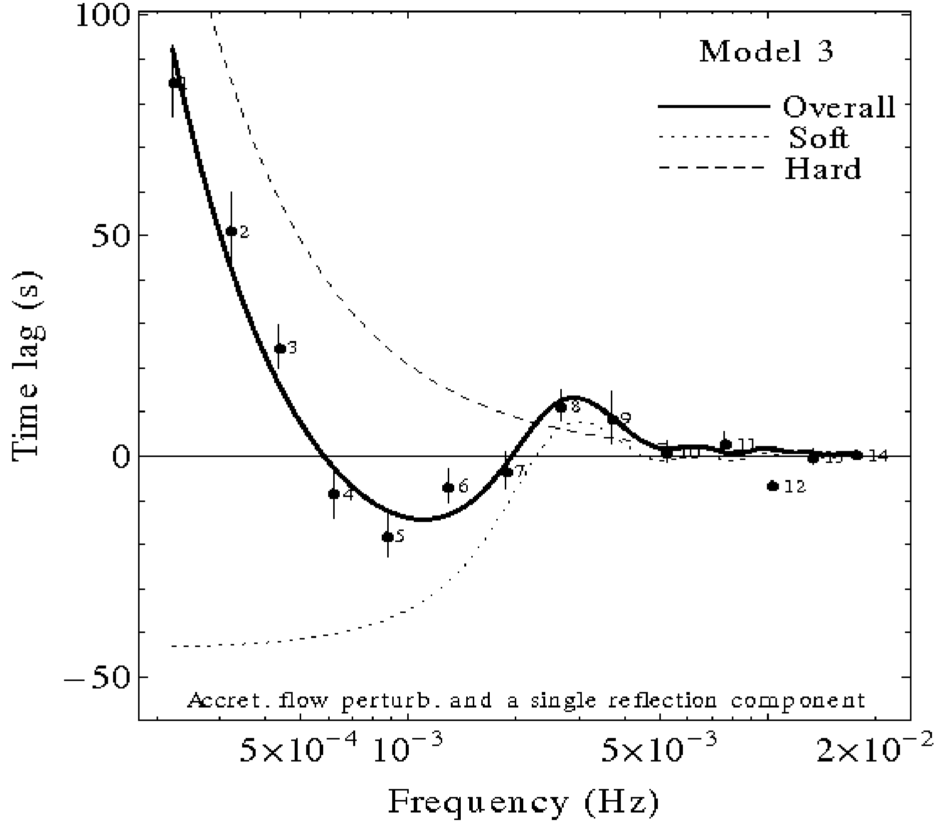
Average of MCG6 and Mrk766 – ATLS

No simple scaling with, eg,
PSD bend timescale, or estimated
black hole mass.

(Just splines, not physical fits)

Lags – Model fits to ATLS





Miller et al 2010 model

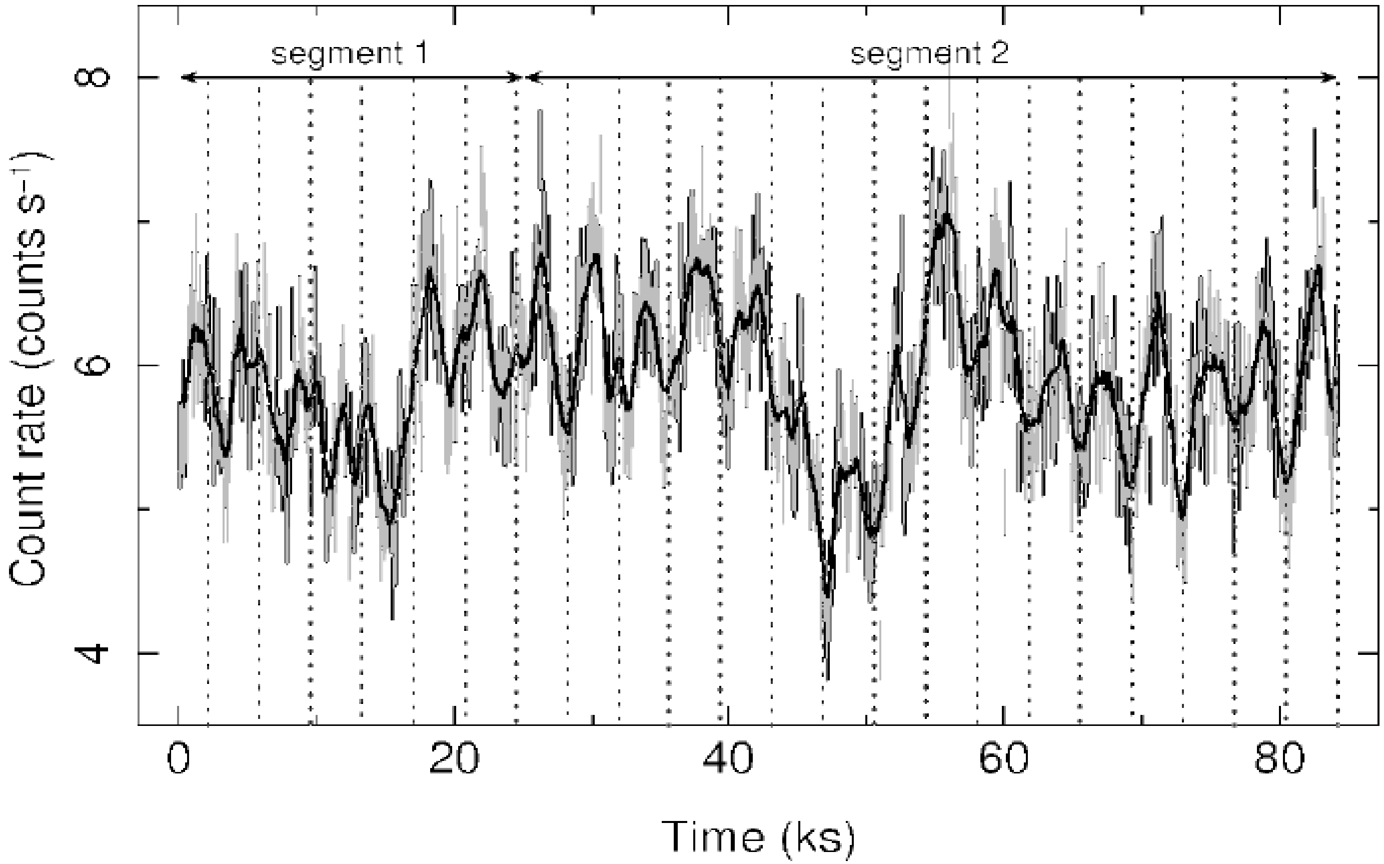
-reprocessing by wind

Zoghbi et al 2010 model

-Combination of reprocessing from disc and propagating accretion fluctuations.

Not perfect, but better fit

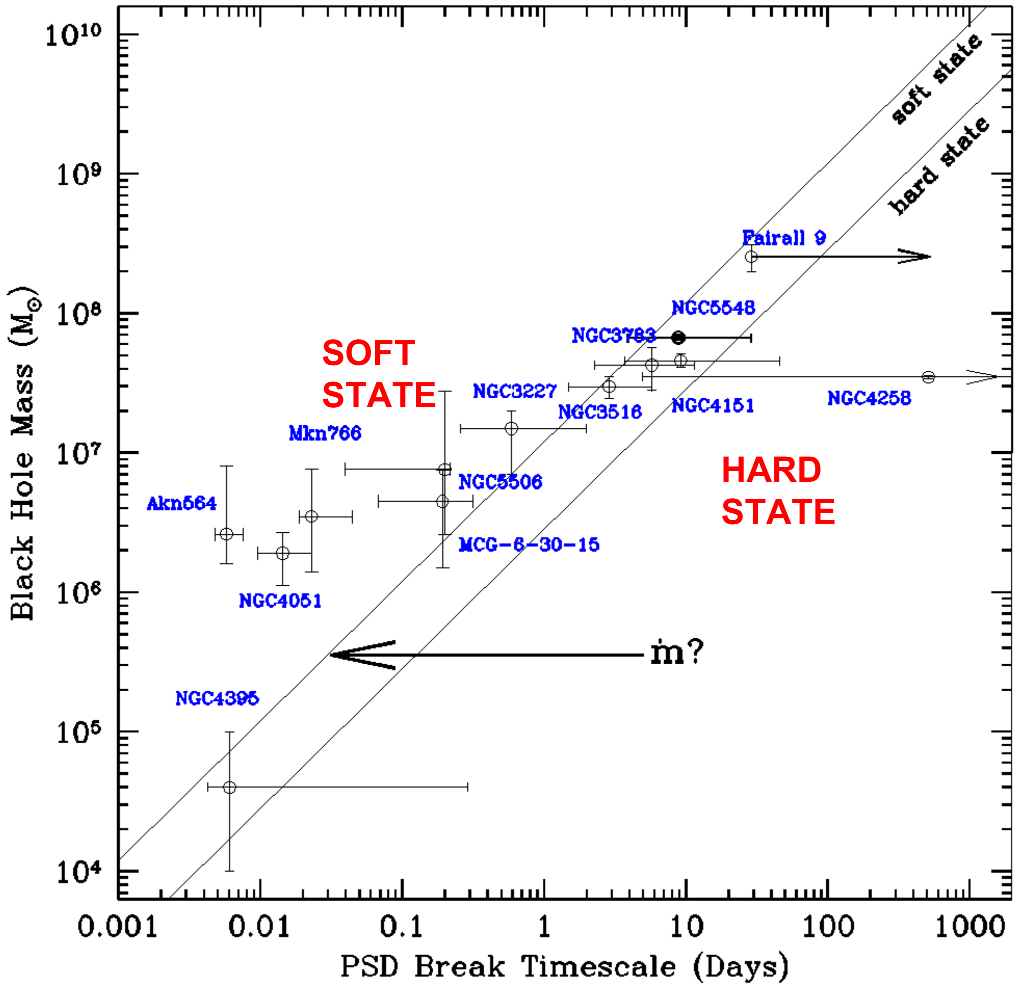
AGN QPO: REJ1034+396



Gierlinkski et al 2008; Middleton et al 2009, 2010

Similar to 67Hz QPO in GRS1915+105 with pure mass scaling

Scaling of Characteristic Timescales: Black Hole Mass vs. PSD Break Timescale (T_B)



AGN with narrower lines and higher accretion rates have shorter T_B.

T_B associated with inner edge of disc?

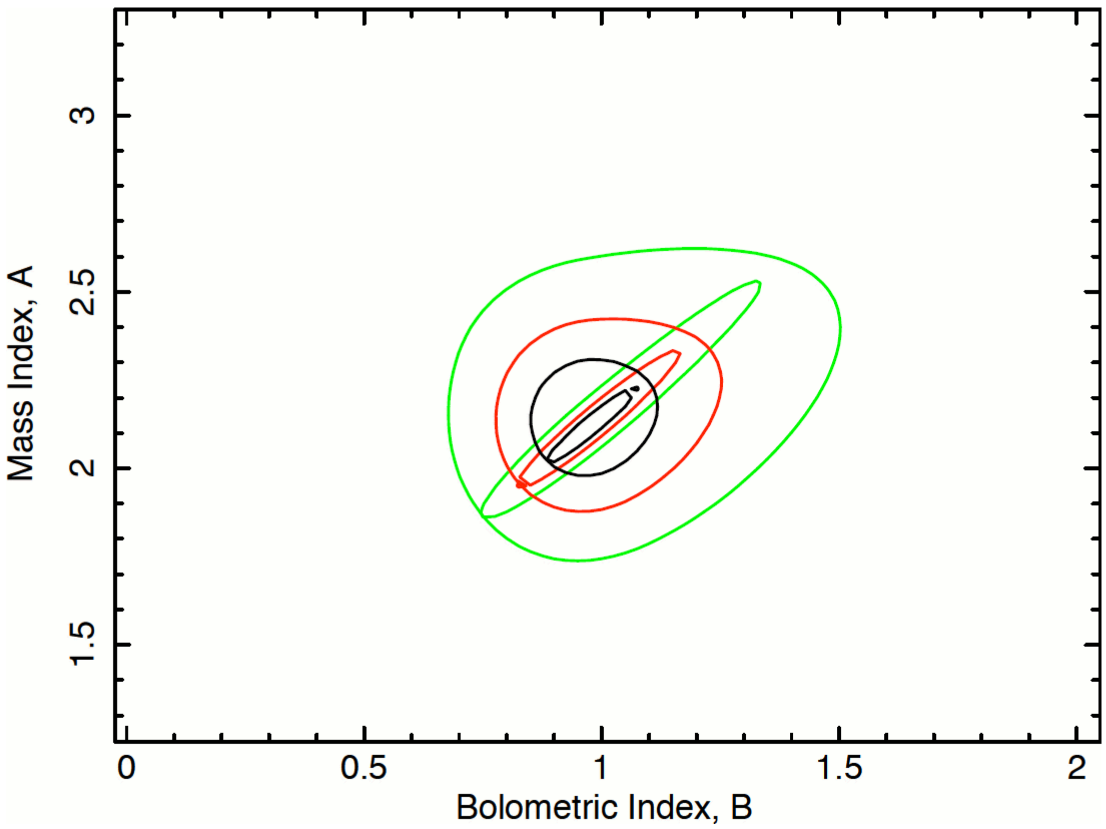
Higher accretion rate pushes in disc?

(McHardy et al 2004, 5)

(Note rough lines of linear scaling, not fits, from Cyg X-1 in its `low-hard' and `high-soft' states)

Proper 3D fit to T_b, M, $\dot{m}_E$

(**McHardy et al, 2006;** Summons et al in prep)



Large contours, just to AGN (20)
(mostly soft state)

As $\dot{m}_E = L_{Bol} / M$

we fit to $T_B \sim M^A L_{Bol}^{-B}$
-observables

Smaller contours include soft state binaries, GRS1915+105 and Cyg X-1

Good fit. Additional parameter (eg spin) not needed.

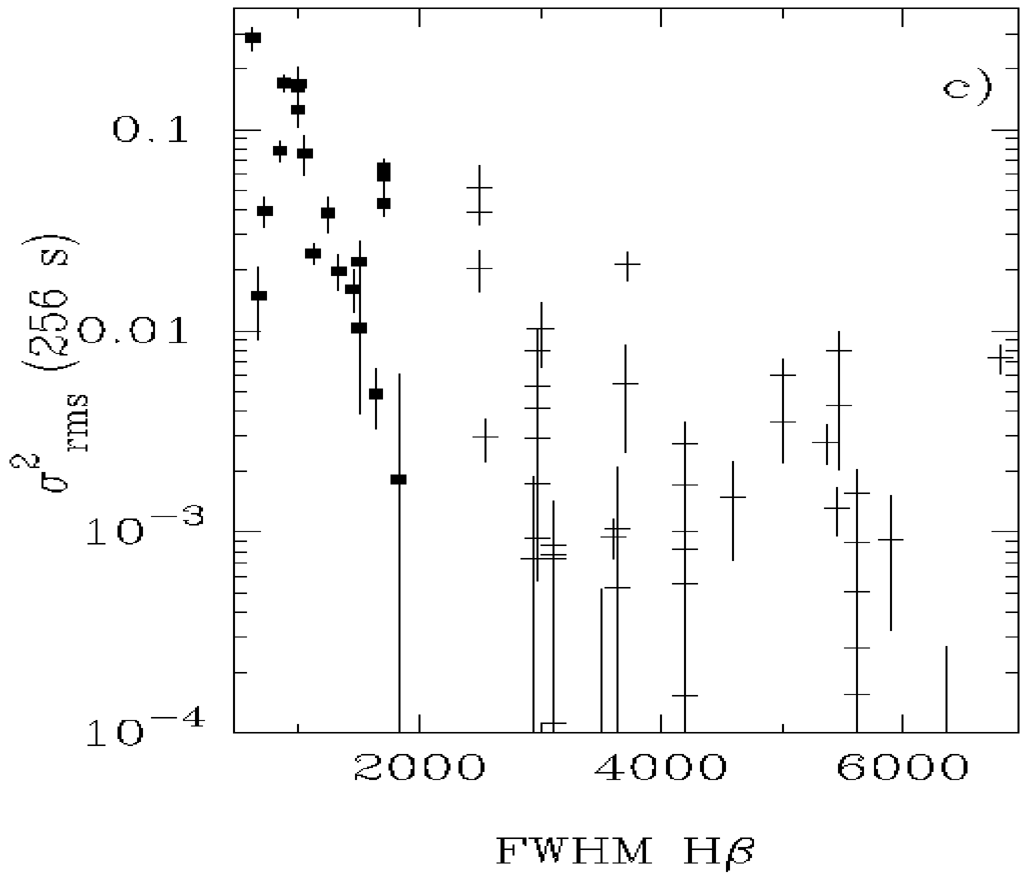
AGN $T_B \sim M^{1.28}\ \dot{m}_E^{-0.85}$

AGN+binaries $T_B \sim M^{1.12}\ \dot{m}_E^{-0.98}$

(eg, for $M=10^8 M_O$, mdot =0.1,T_B = 6d)

Koerding et al (2007) find same result for hard state sources.

AGN X-Ray Variability and Optical Linewidth



Optical linewidth correlates with X-ray variance

-but, physically, how?

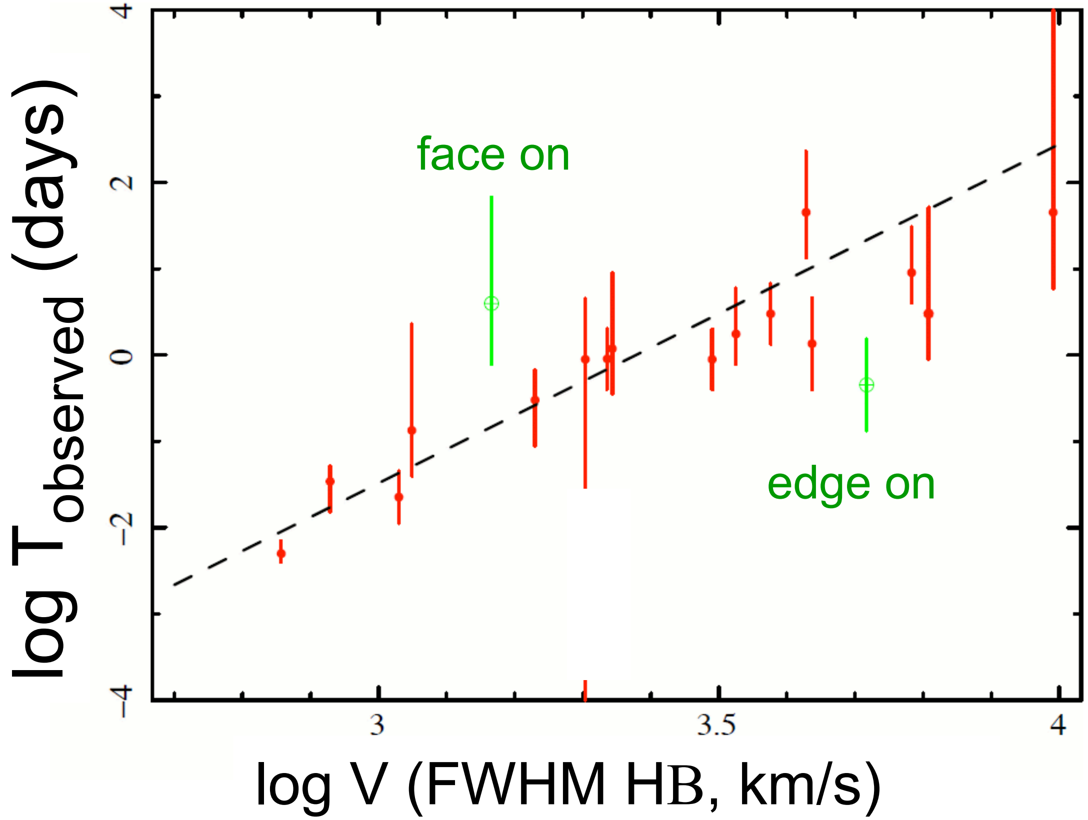
(Turner et al 1999)

NLS1s are the filled squares

Southampton

T_B and Linewidth, V

(McHardy et al, 2006; Summons et al in prep)



$T_B \sim V^{3.8 +/- 0.6}$

Simple scaling relationships:

1. $L \sim M \dot{m}_{Edd}$
2. $R_{BLR} \sim L^{0.5}$ **(LOC - Kaspi etal 1996)** Bentz etal 2006
3. $v^2 \sim GM/R_{BLR}$

Then expect

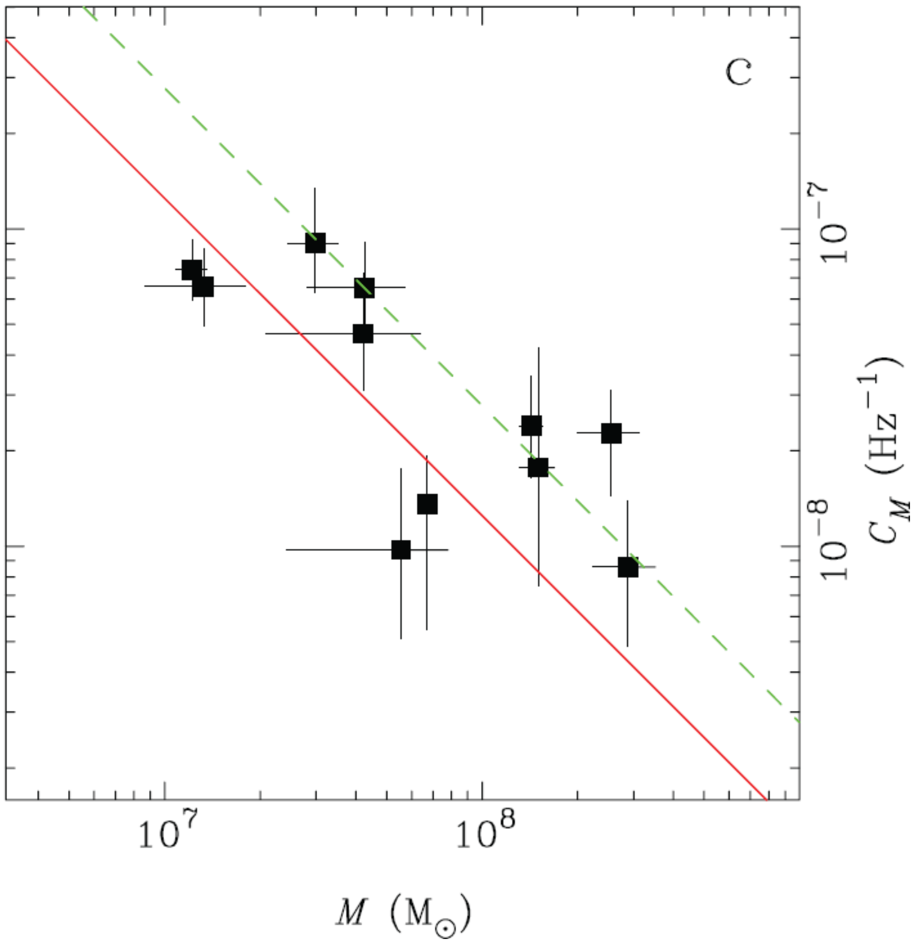
$$\text{Linewidth, } V^4 \sim \frac{M}{\dot{m}_{Edd}}$$

Consistent with $T_B \sim M / \dot{m}_E$

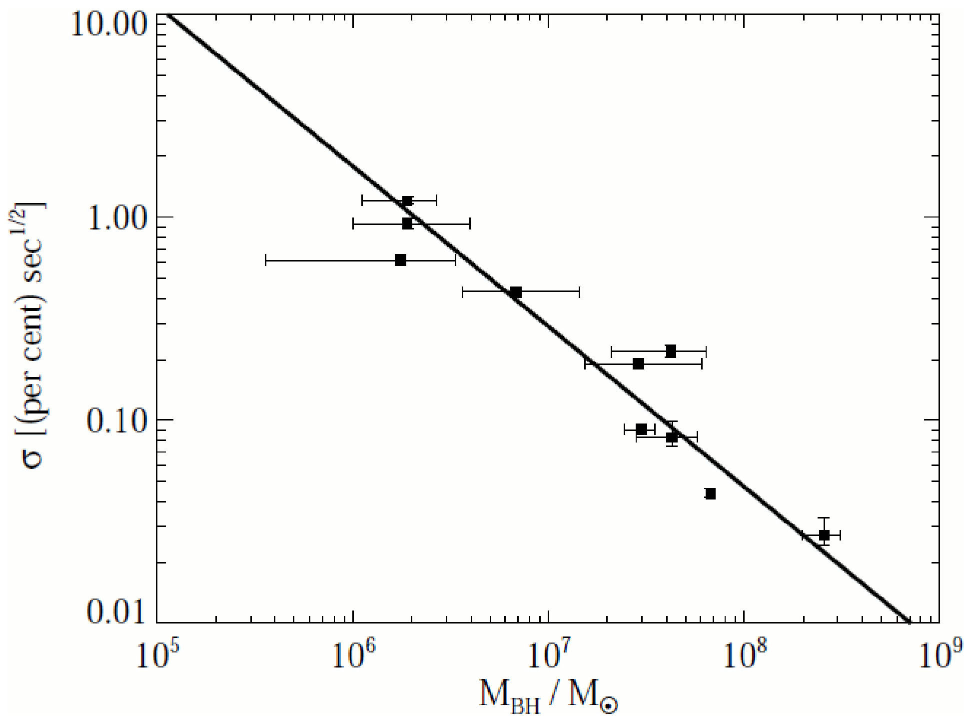
IMPLICATION: NLS1 same as other AGN but have smaller ratios of $M / \dot{m}_E$
Small masses are selection effect as $\dot{m}_E$ can't easily exceed unity

The high frequency PSD: Mass scaling

(eg McH 1988; Green et al 1993; Hayashida et al 1998; Gierlinski et al 2008; Kelly et al 2010)



Gierlinski et al 2008

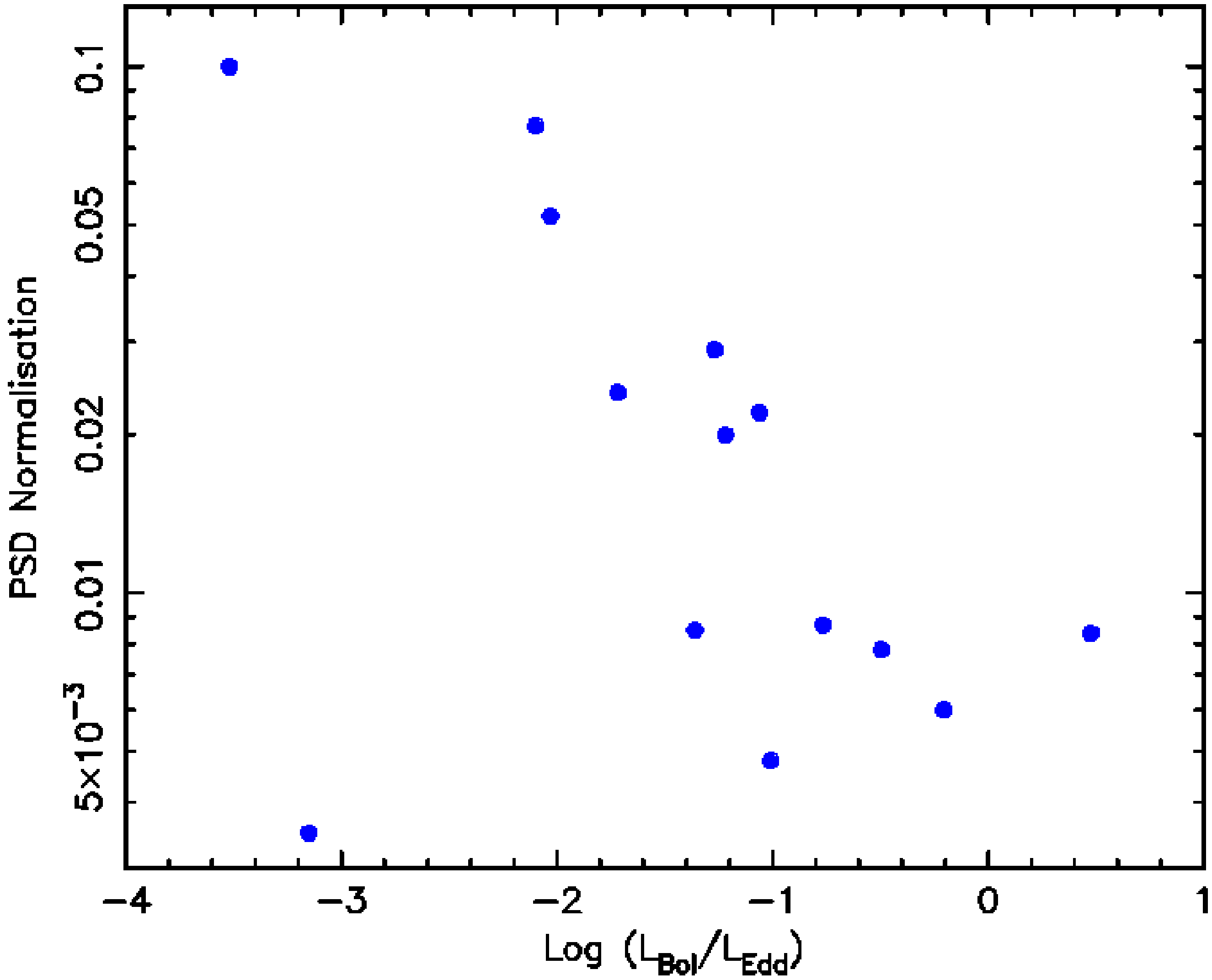


Kelly et al 2010

See also talk here by Gabriel Ponti.

Low frequency PSD Normalisation

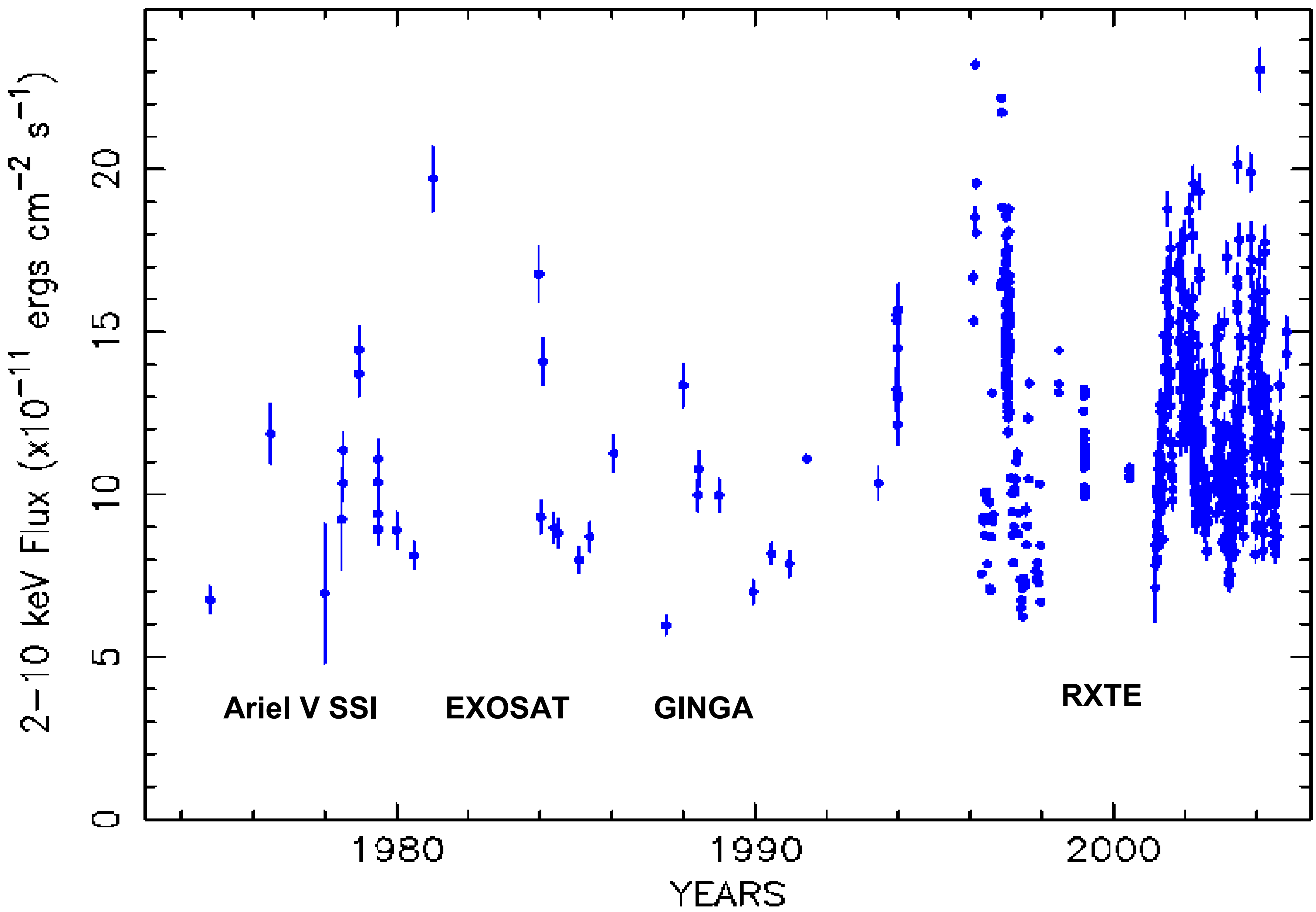
(Low frequency slope fixed at -1)



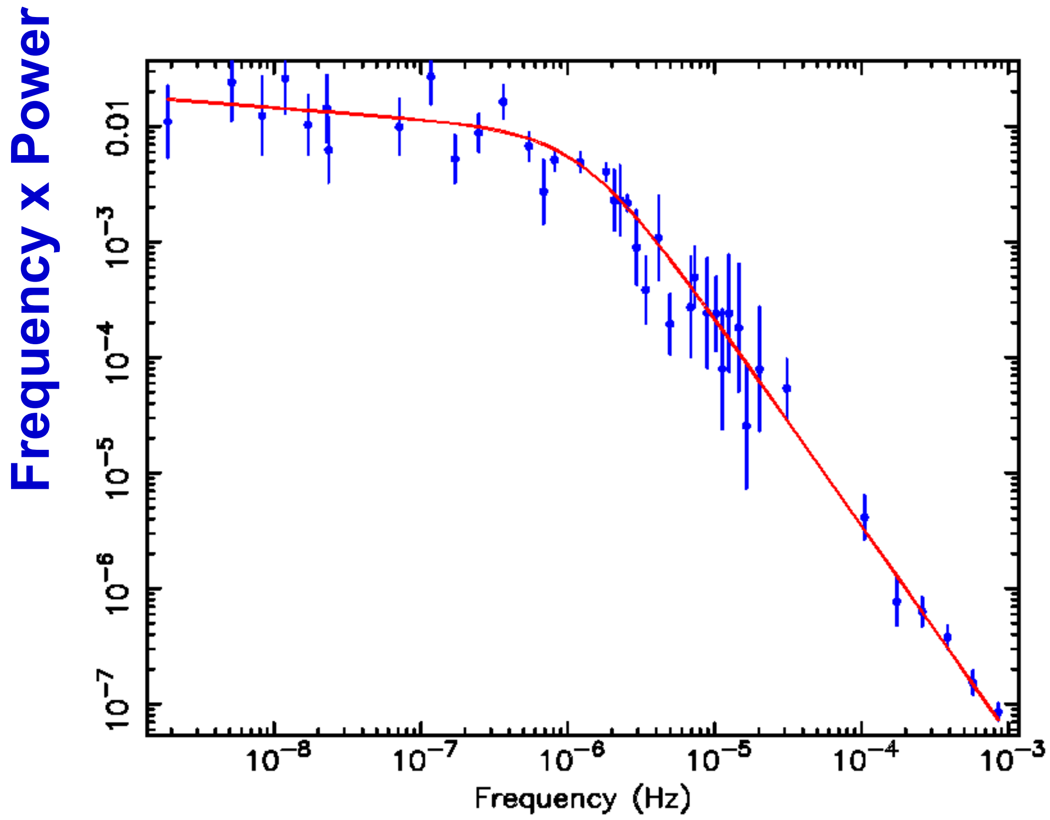
(Data from Summons et al, in prep)

Southampton

Jet-dominated sources: 3C273



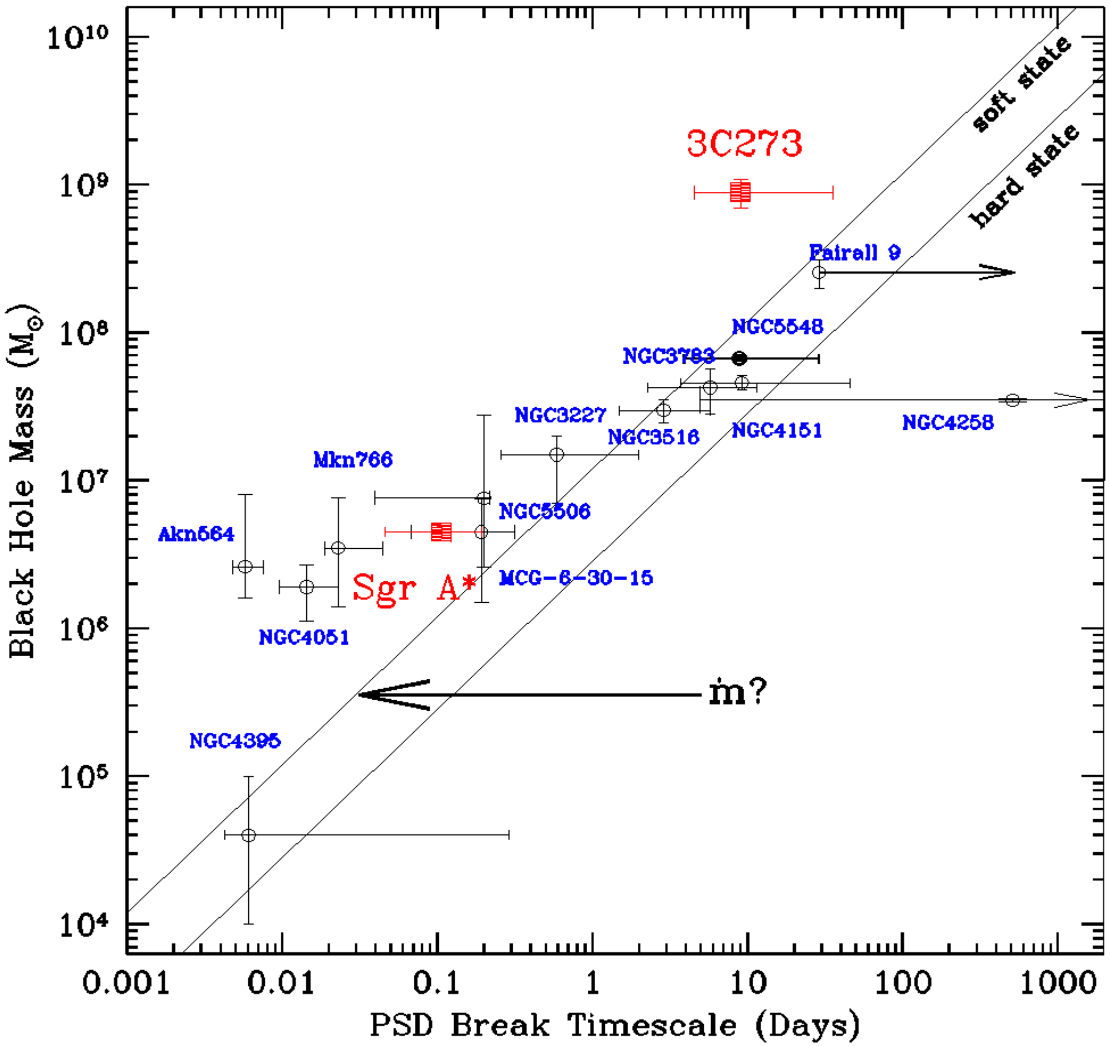
OVERALL PSD OF 3C273



Good fit to `soft' state model
Break timescale ~ 10 days

(McHardy et al, in prep)

Jets and timescales



3C273 fits M / $\dot{m}_E$ scaling

Different X-ray emission process from Seyferts but same source of variations?

But….

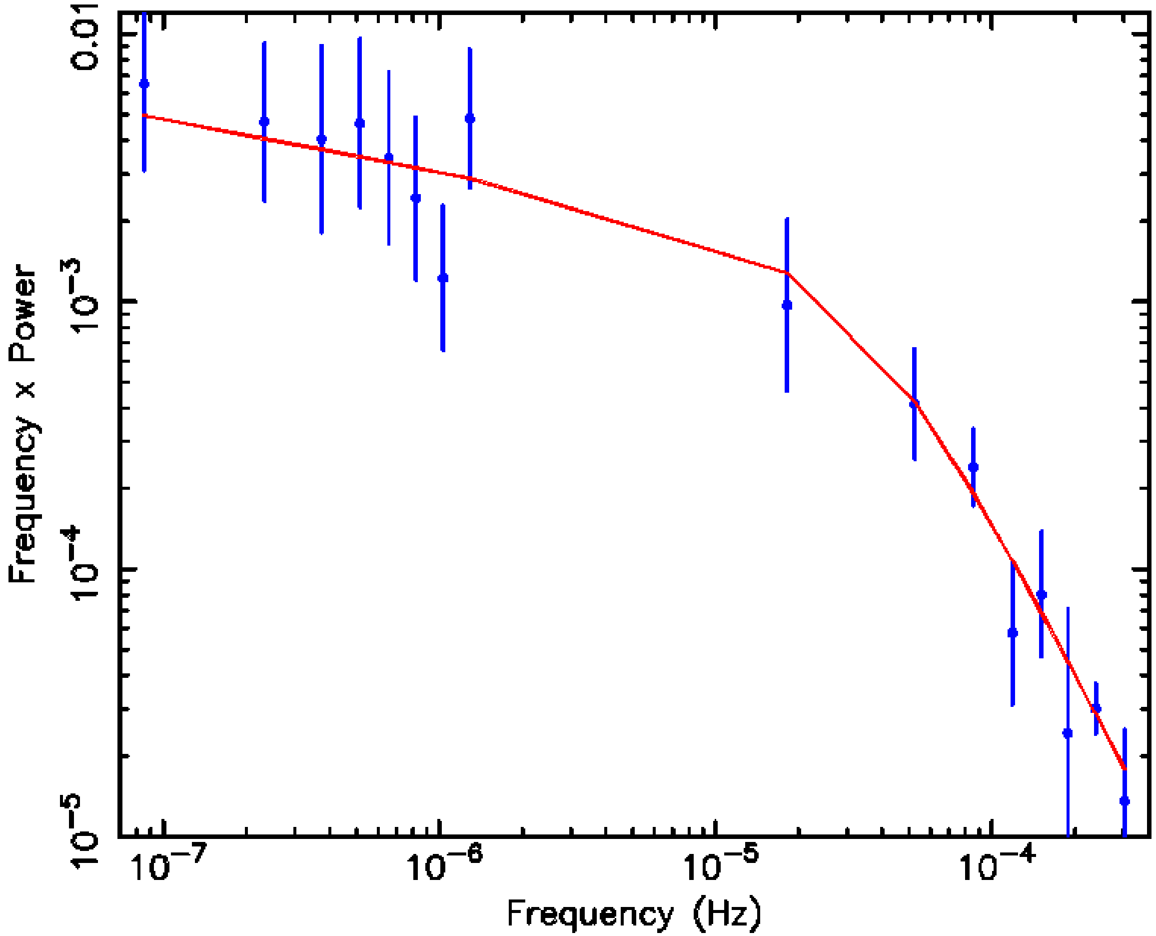
Sgr A* (in IR) (Meyer et al 2009) doesn't fit at all.

-VERY LOW ACCRETION RATE, COMPLETELY JET DOMINATED-

Do jets follow pure mass scaling?
X-rays from same distance from BH?

Southampton

M81 – radio loud, hard state



$\dot{m}_E$ ~10^{-5}

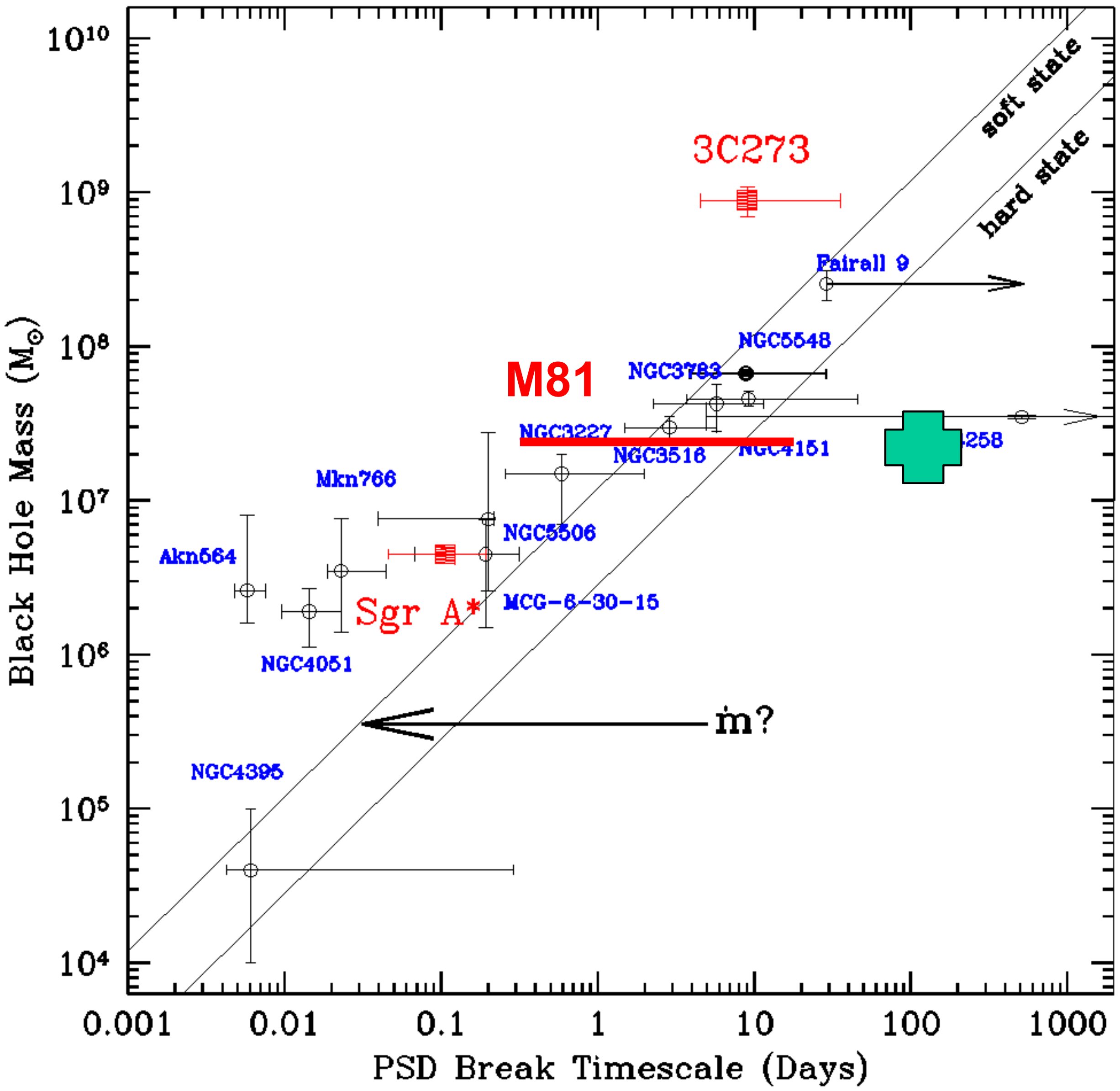
Work in progress ..

Combined Swift+XMM

Current unfolded PSD shows a bend around 1 day, but could be considerably longer within the errors.

Southampton

M81 Timescale scaling



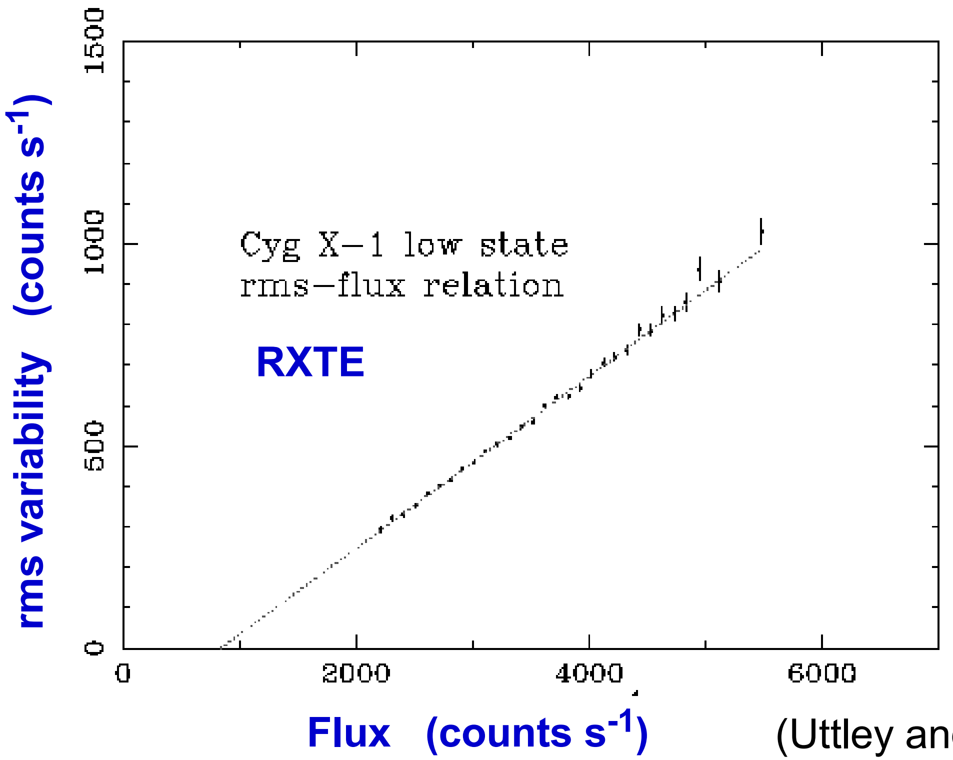
Green cross – expected position from Seyfert scaling

Red line – current estimate of timescale

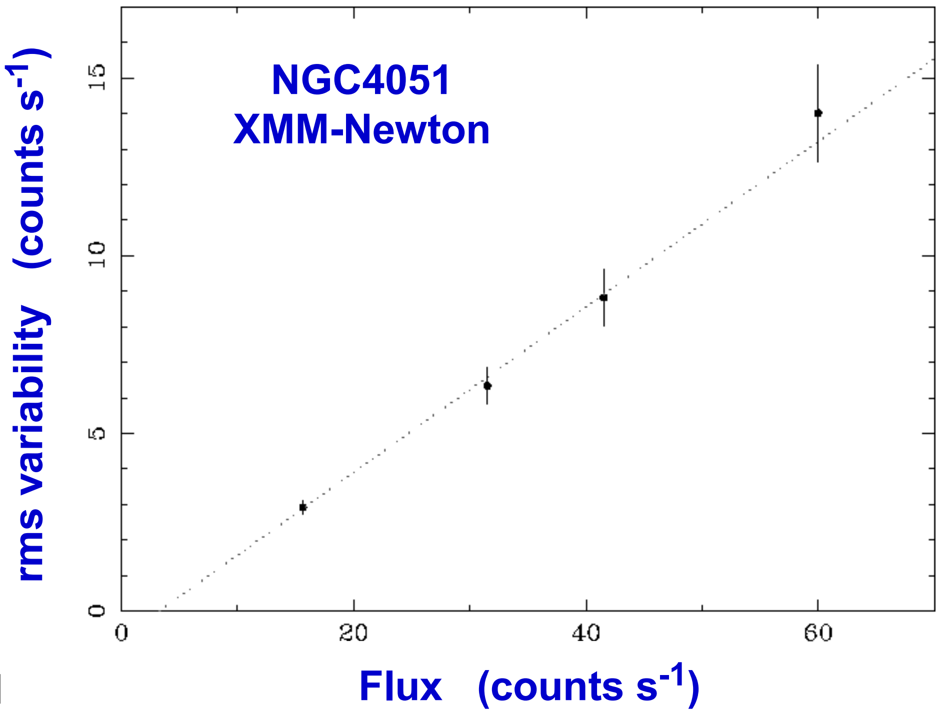
Radio-loud, hard-state, AGN scaling might be different

Origin of the Variability

Observations: RMS Variability (σ) vs. FLUX



(Uttley and McHardy 2001)

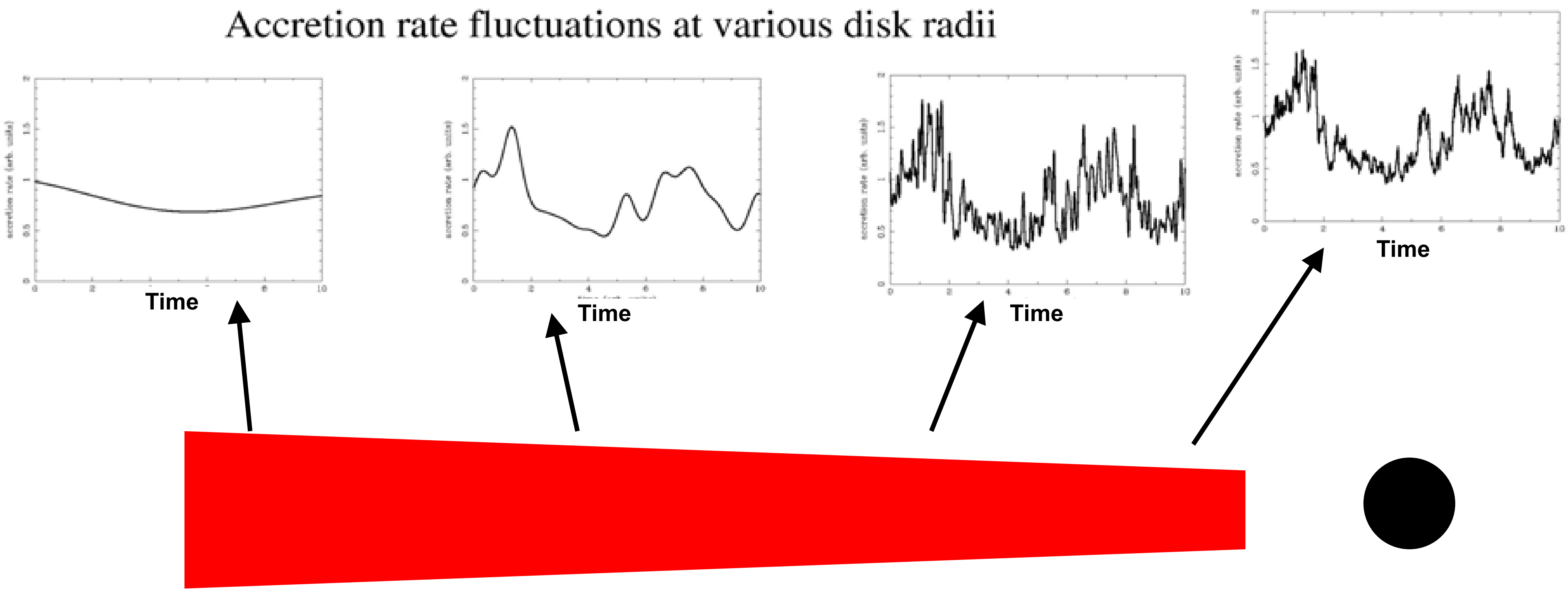


Amplitude of short timescale variations respond to long timescale average flux.

Same in NGC4051 as in GBHs.

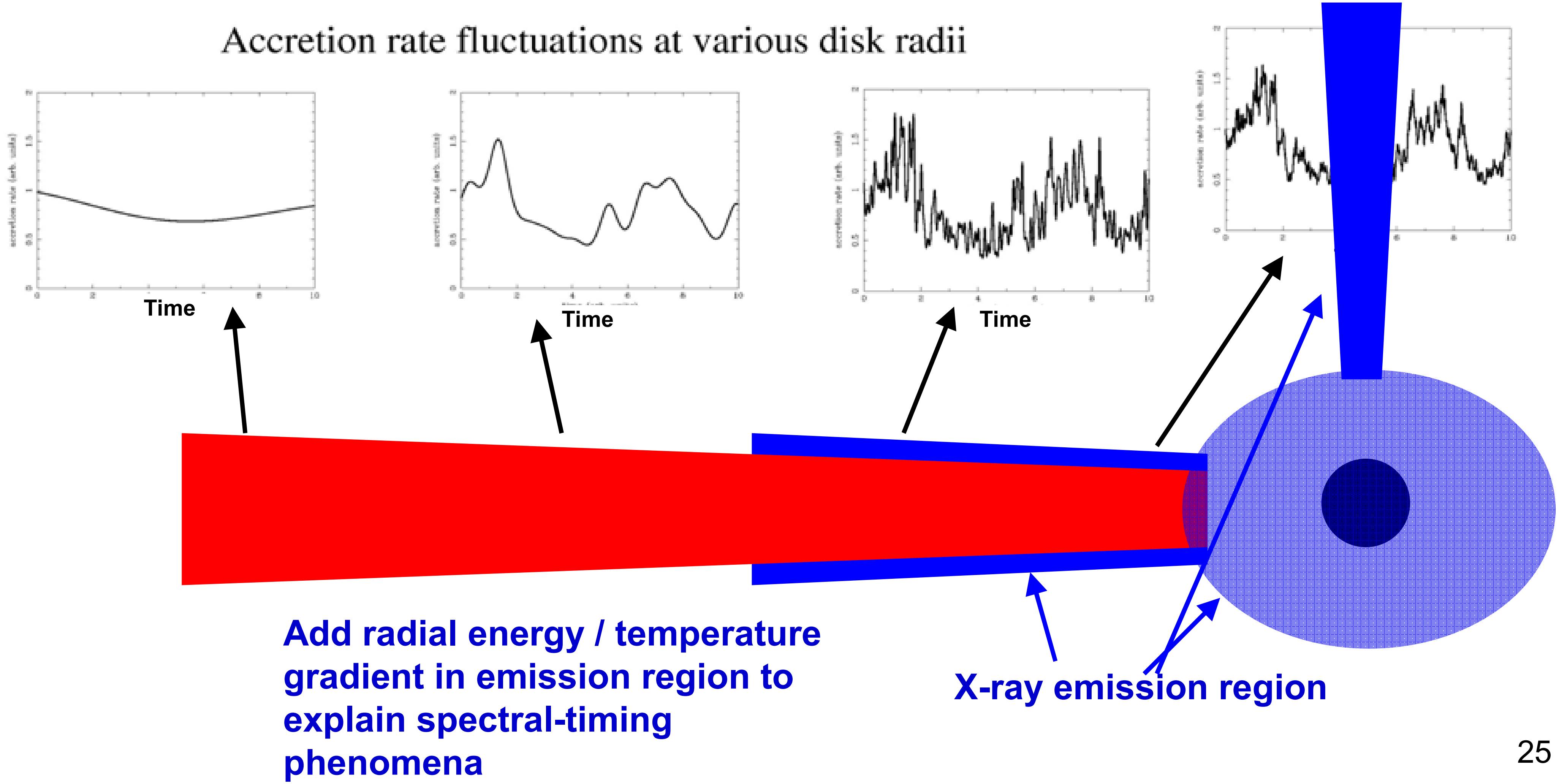
Theory: a fluctuating accretion flow drives the variability (e.g. Lyubarskii 1997)

Variations propogate inwards. Amplitude of fluctuation in each annulus is modulated by total amplitude of inward progating fluctuations.



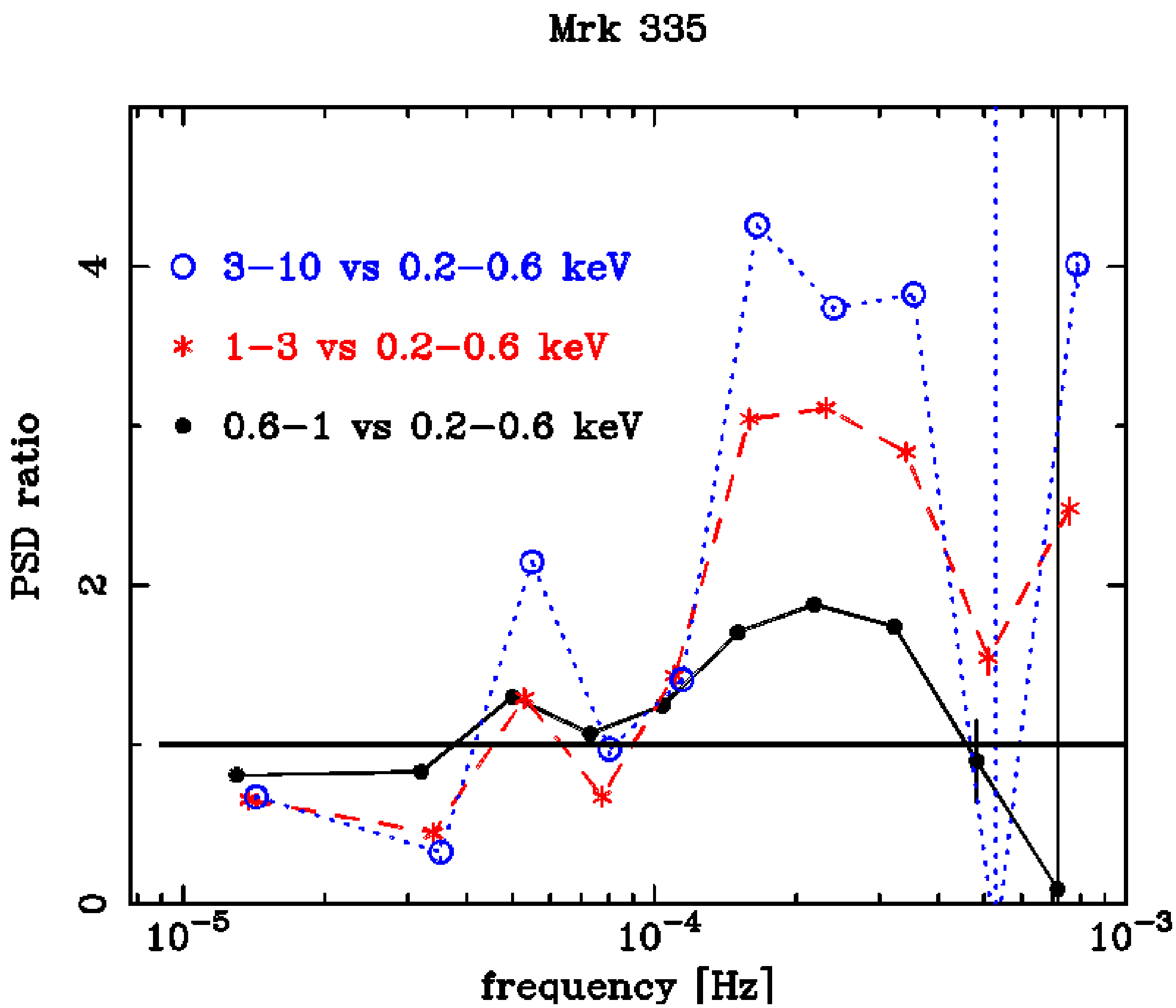
Separate source of variability and source of emission

Fluctuations eventually hit, and modulate, the X-ray emitting region
(Kotov et al 2001; Churazov et al 2001; Arevalo and Uttley 2006; Uttley et al 2011)



Southampton

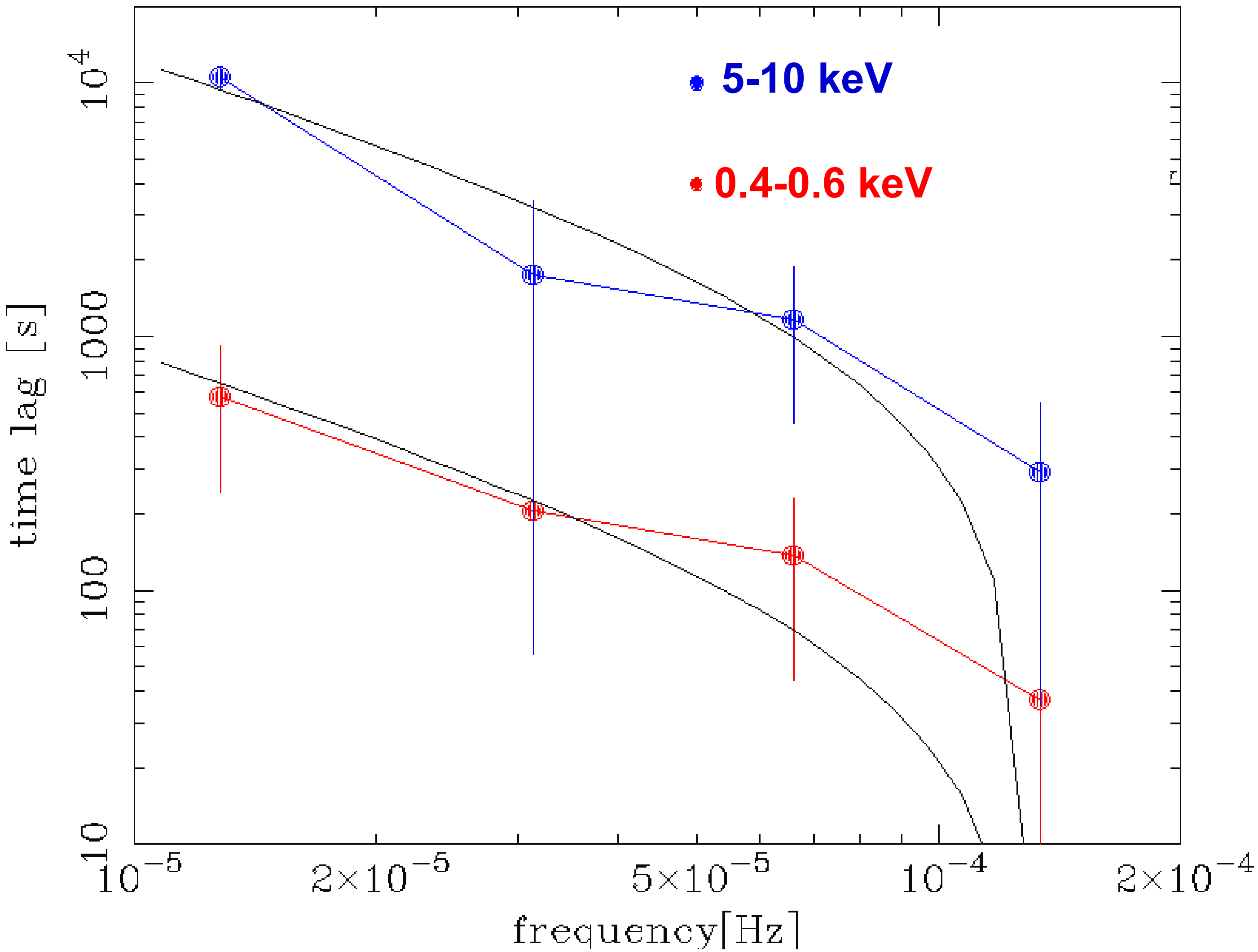
Mkn335: PSD ratios vs Frequency and Energy



More variability at high frequencies at high energies

MKN335 Low frequency Lags

Lag of higher energy relative to low energy (0.2-0.4 keV)



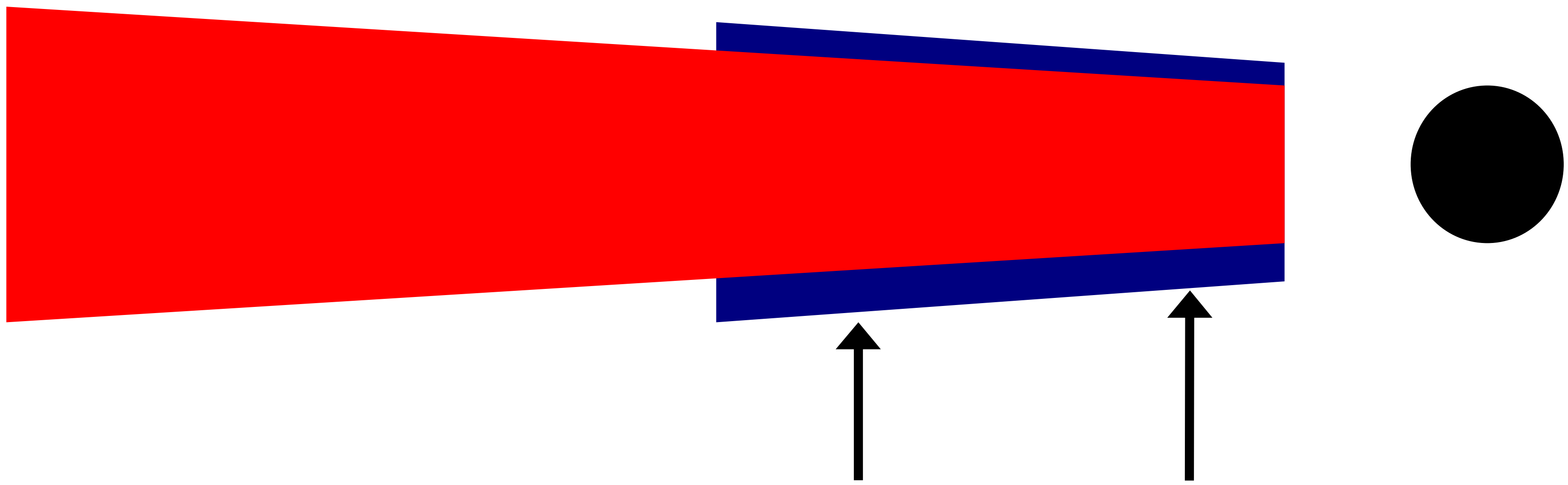
Lags increase as energy separation increases.

Lags decrease at higher Fourier frequencies

So emission region is harder at smaller radii.

Southampton

e.g., LAGS (low frequencies)



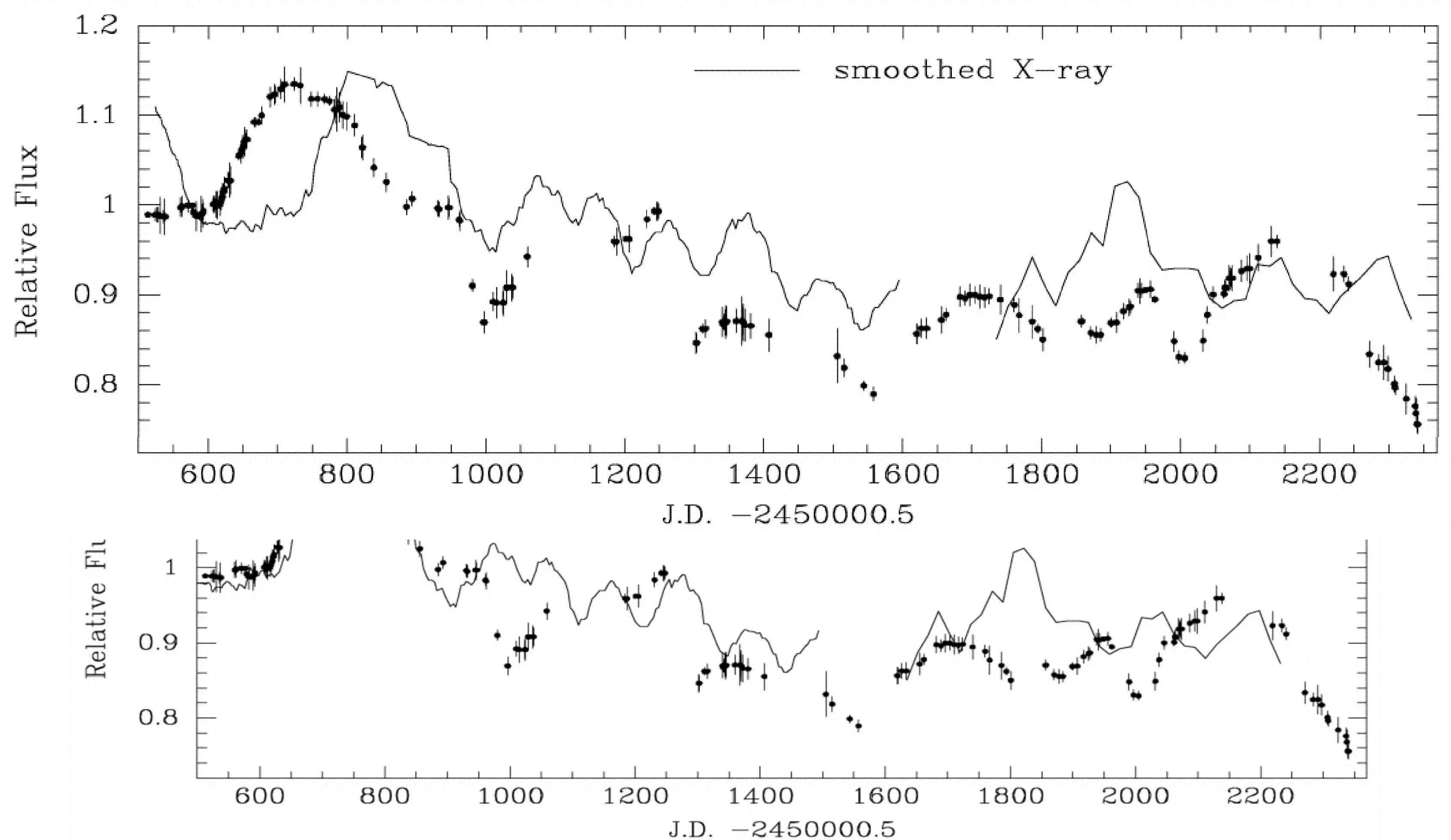
emission-weighted centroid of low energies

emission-weighted centroid of high energies

-as seen by fluctuation arising far out in disc

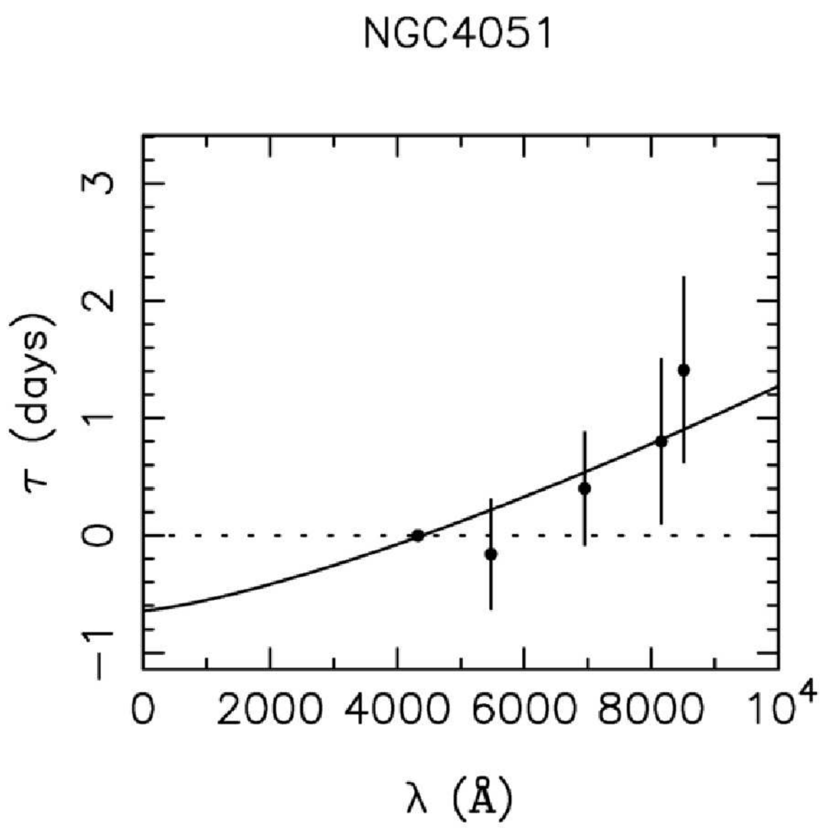
The lag is then the time for the fluctuation to travel between centroids.

Optical Variability in AGN:
Reprocessed X-rays or intrinsic disc variability?



NGC3516, intermediate mass (~2 x 10^7 M_0)   Maoz et al 2002

Is the optical band reprocessed X-rays?



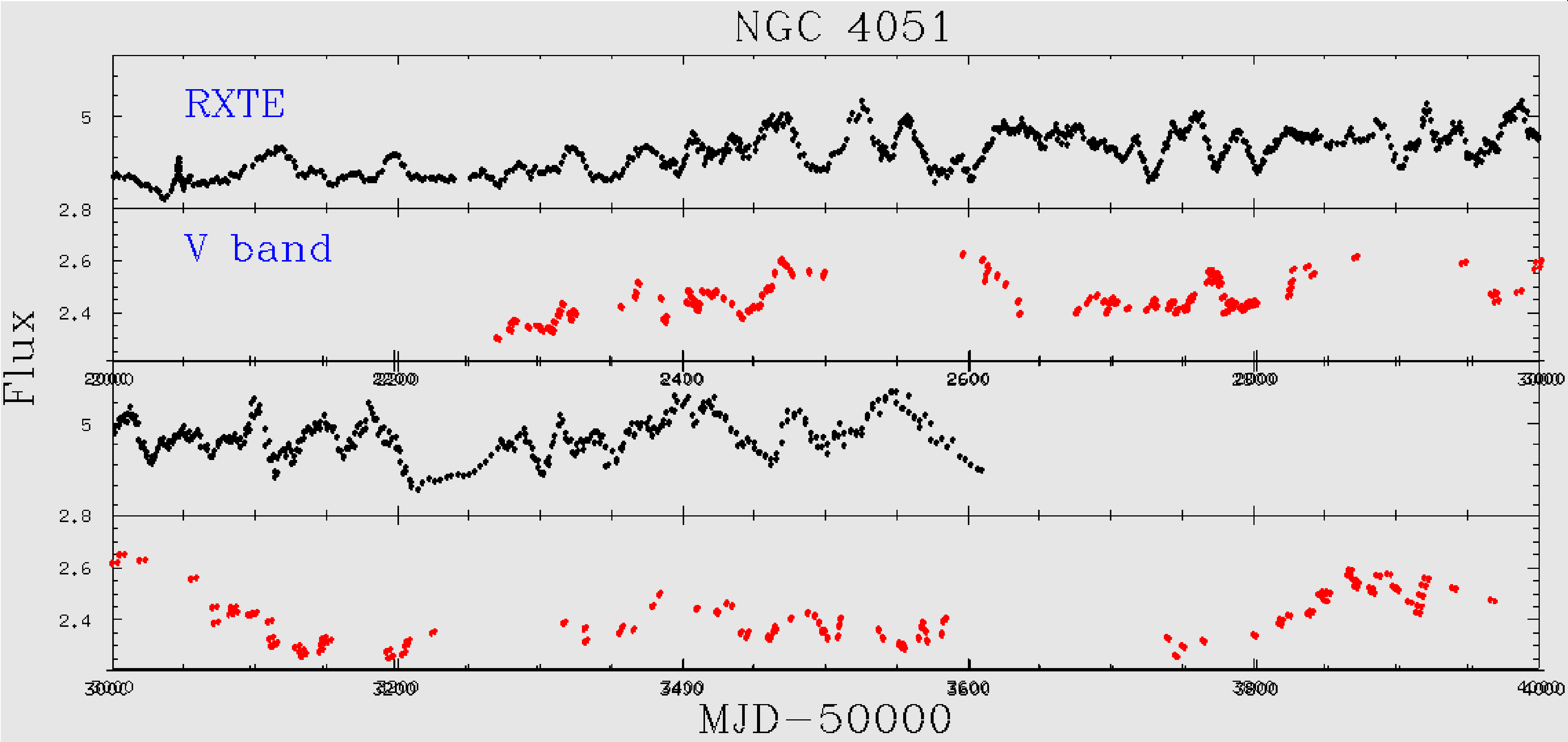
$$T \propto M_{BH}^{-1/4} \dot{M}^{1/4} R^{-3/4}$$

($\dot{M}$ in Eddington units and R in gravitational radii)

Solid line gives fit of lags between optical bands to reprocessing model

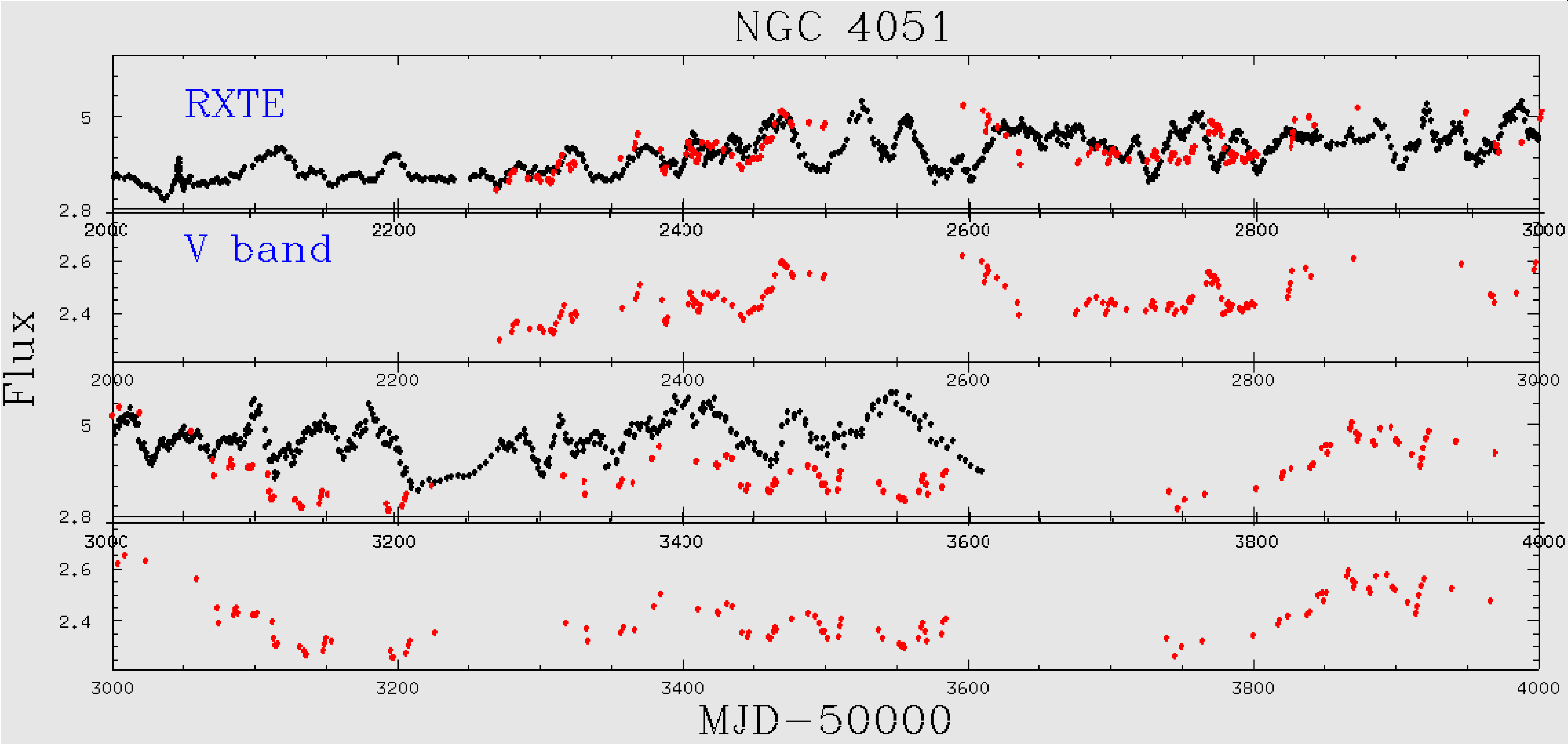
(Cackett et al, 2006; Sergeev et al 2005,6)

NGC 4051

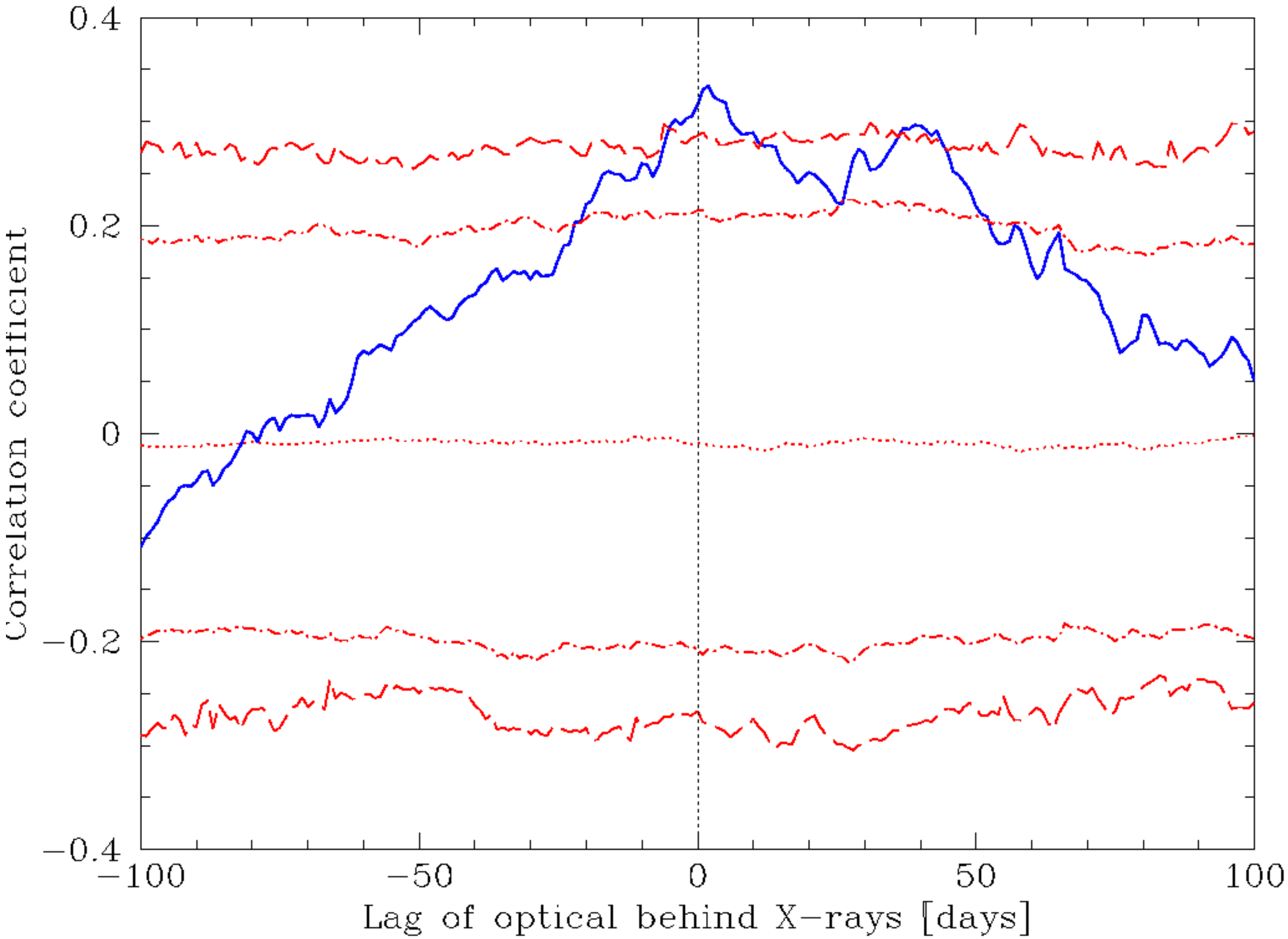

NGC 4051
RXTE
V band
Flux
5
2.8
2.6
2.4
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
MJD−50000

Southampton

NGC 4051



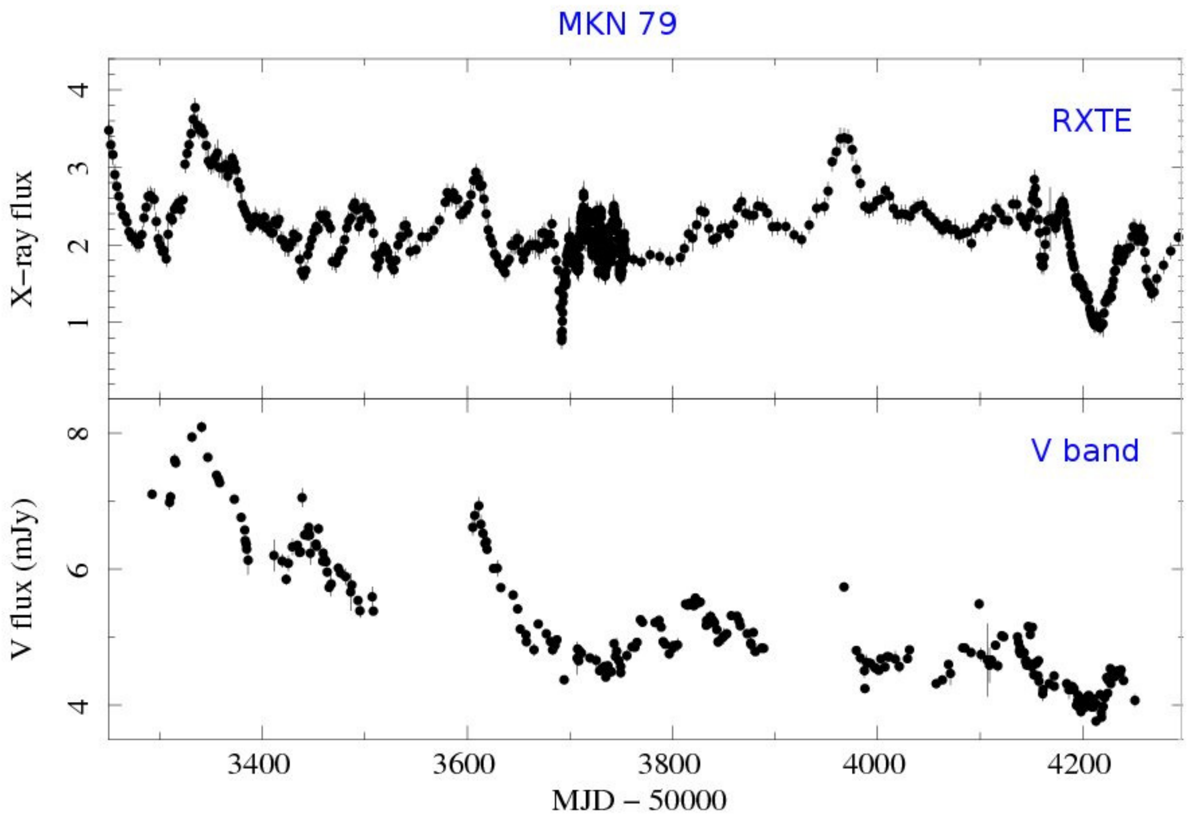
NGC4051

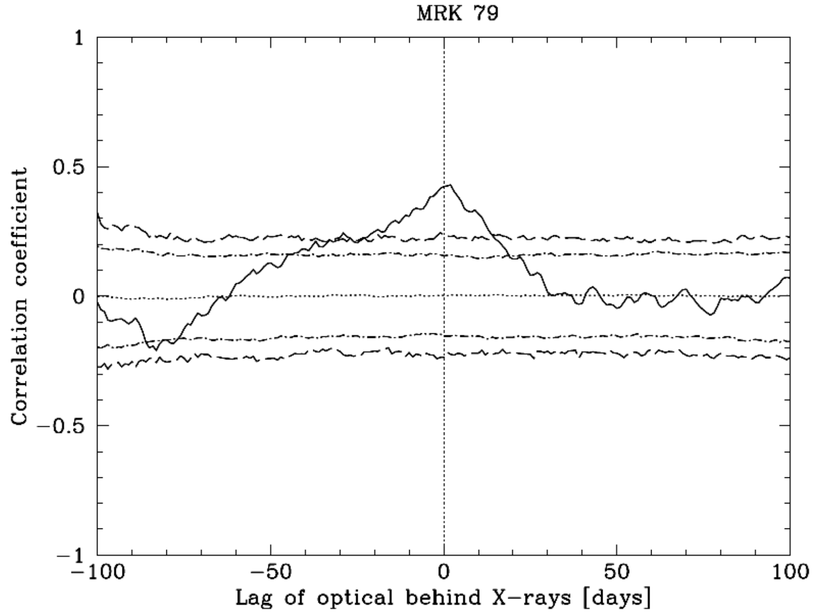


Optical lags by 1.5+/- 0.5 d (above 99% confidence)

Breedt et al 2010

MKN 79



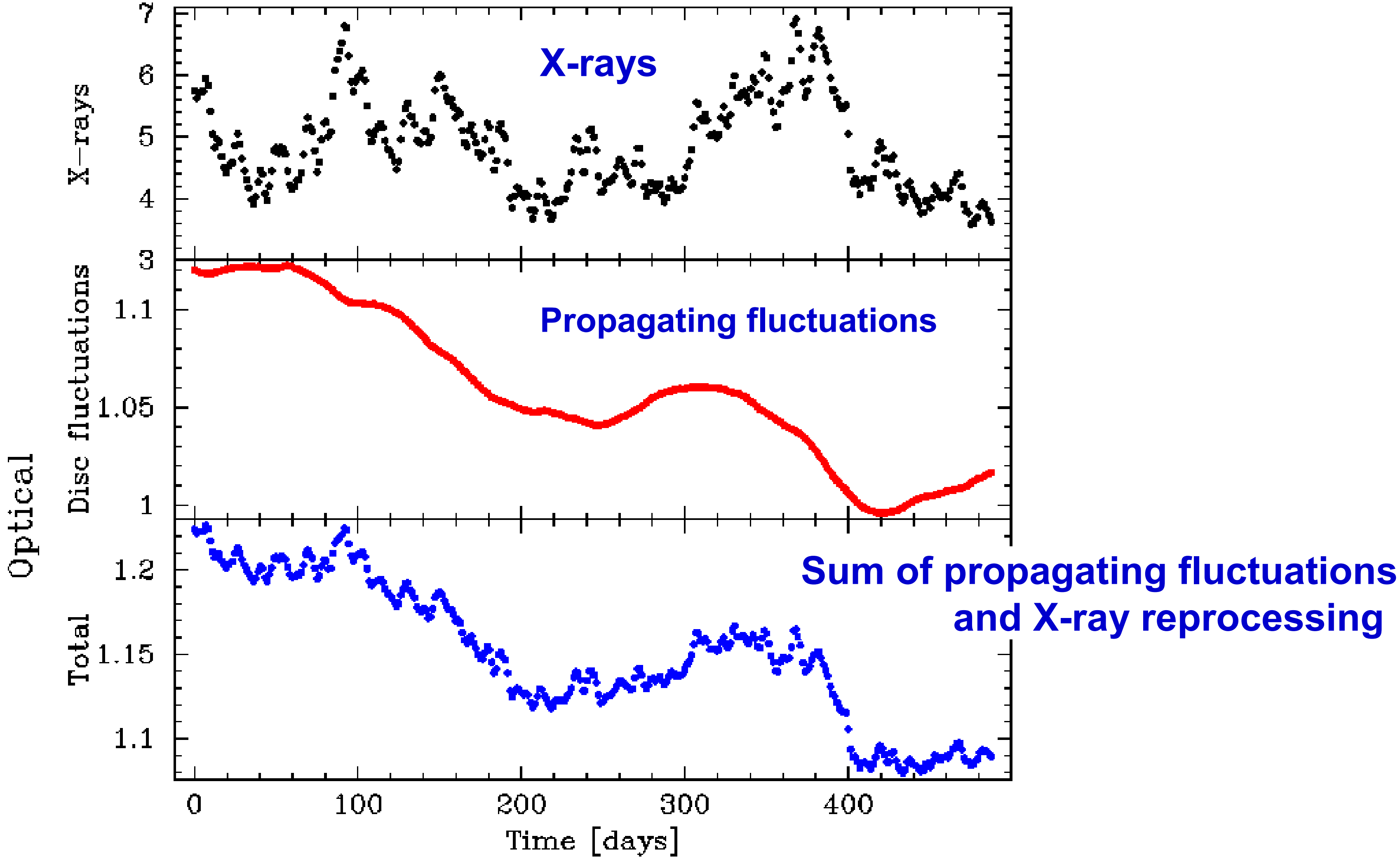


Short term correlation but different long term trends

Optical probably a combination of X-ray reprocessing and intrinsic disc variations (inwardly propagating fluctuations)

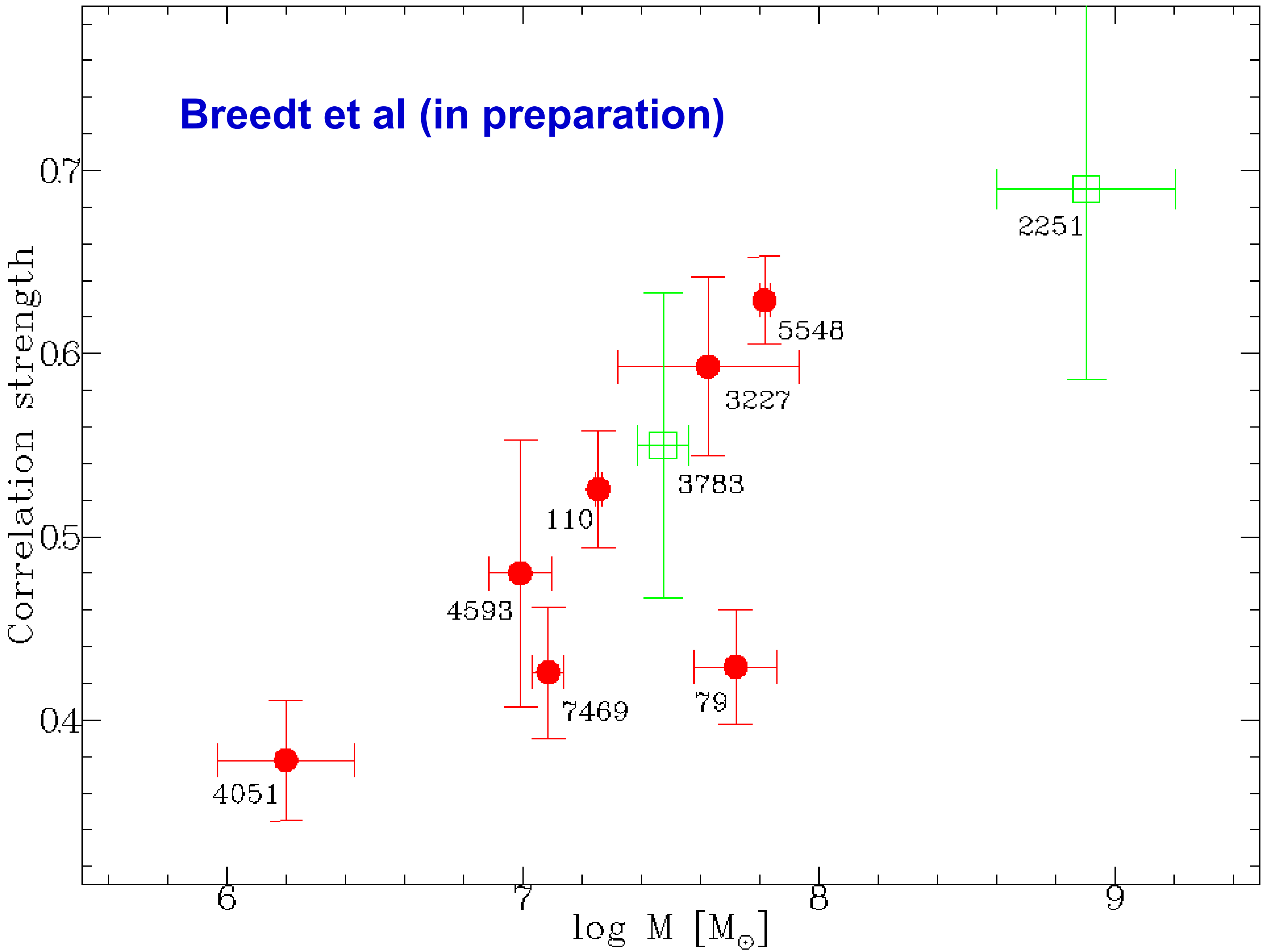
(Breedt et al, 2009, MNRAS)

Simulated Optical Lightcurves
Propagating fluctuations plus X-ray reprocessing



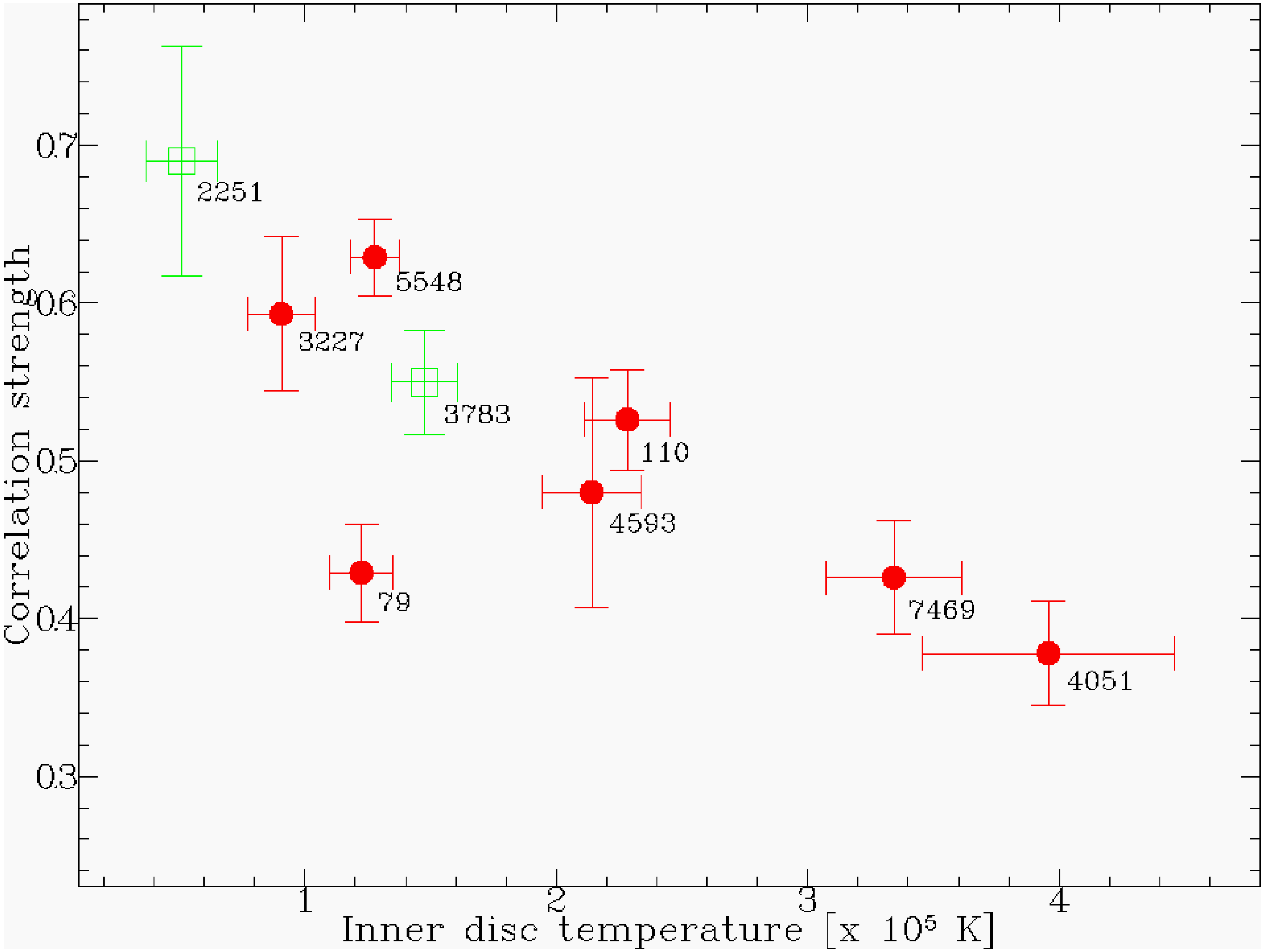
(from Arevalo et al 2008)

X-ray/optical peak correlation coefficient vs. black hole mass



X-ray/optical peak correlation coefficient vs. disc temperature

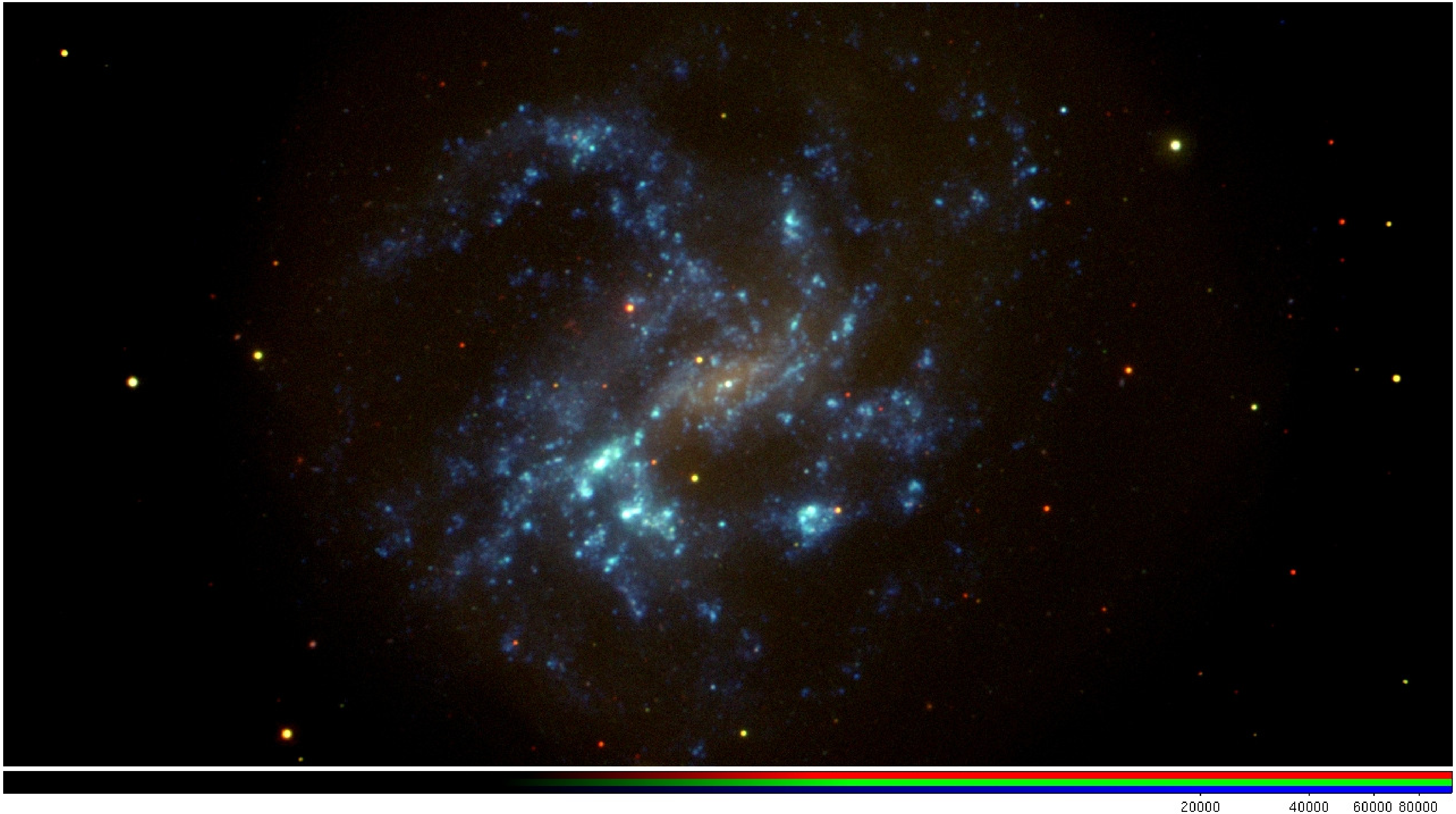
Southampton



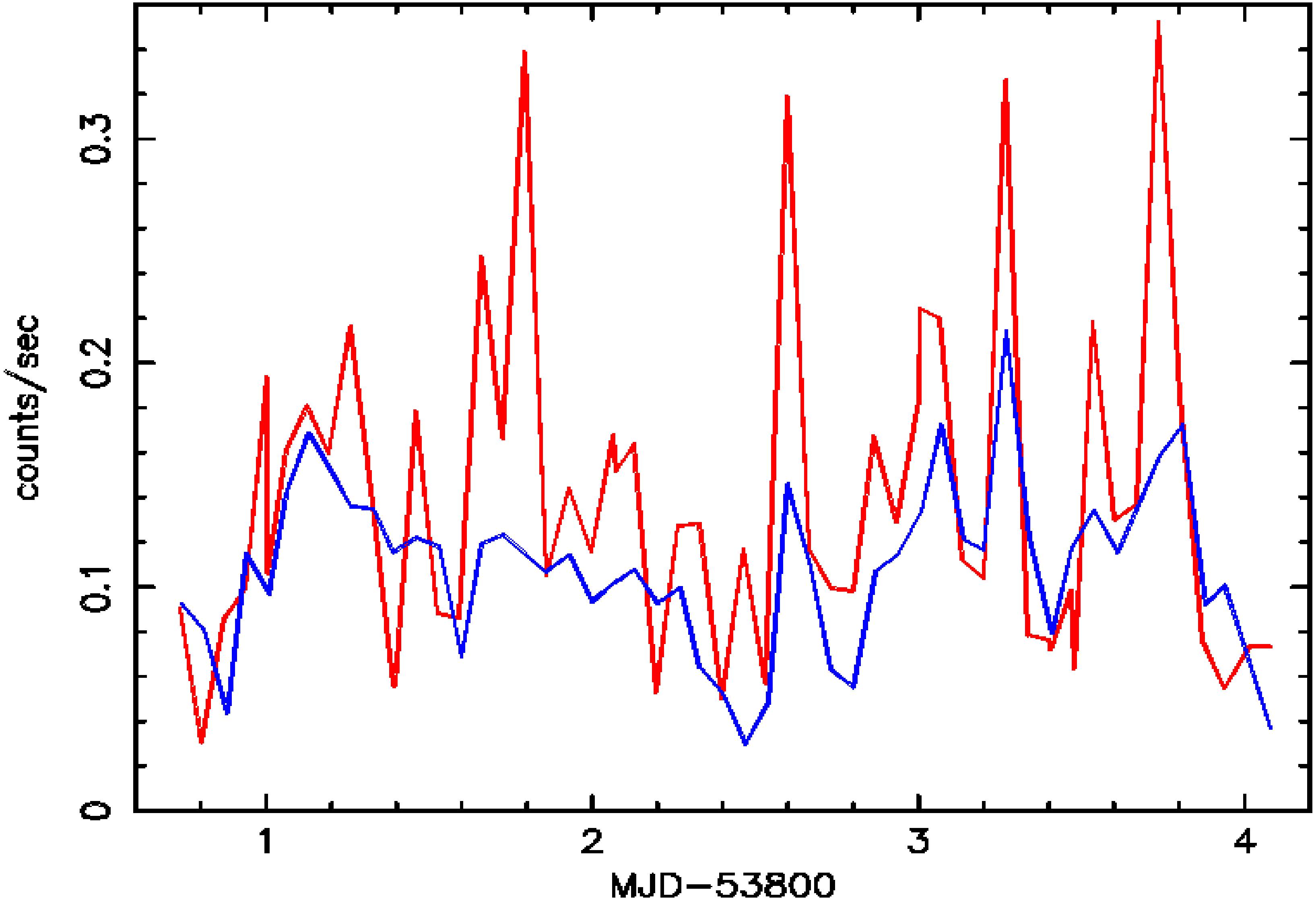
Correlation looks tighter than with mass, but is statistically very similar.

Temperature correlation explained by solid angle subtended by the optical emitting region at X-ray source

NGC4395 (~10^5 solar mass BH)- Swift



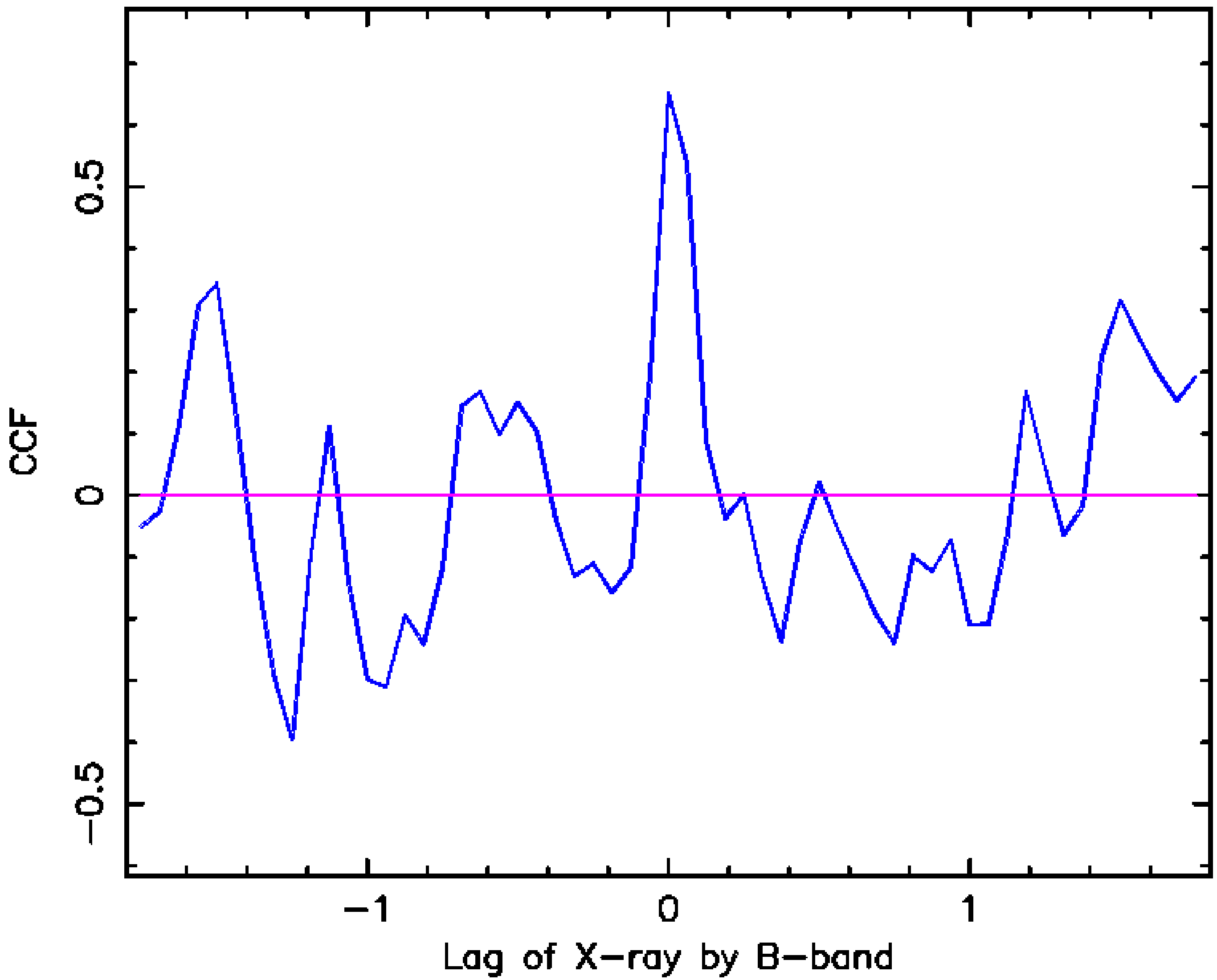
NGC4395: Shorter timescale (hours- days)



X-RAYS

B-BAND

NGC4395: Short timescale CCF



(days)

Very small lag
< 45min

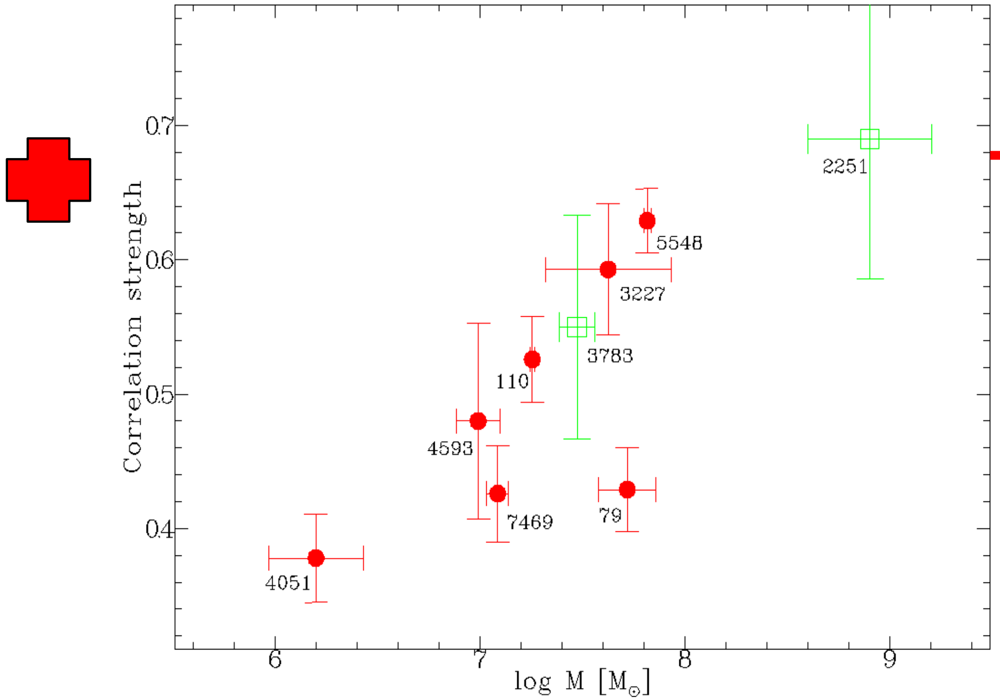
again indicating reprocessing

(Cameron et al, in prep)

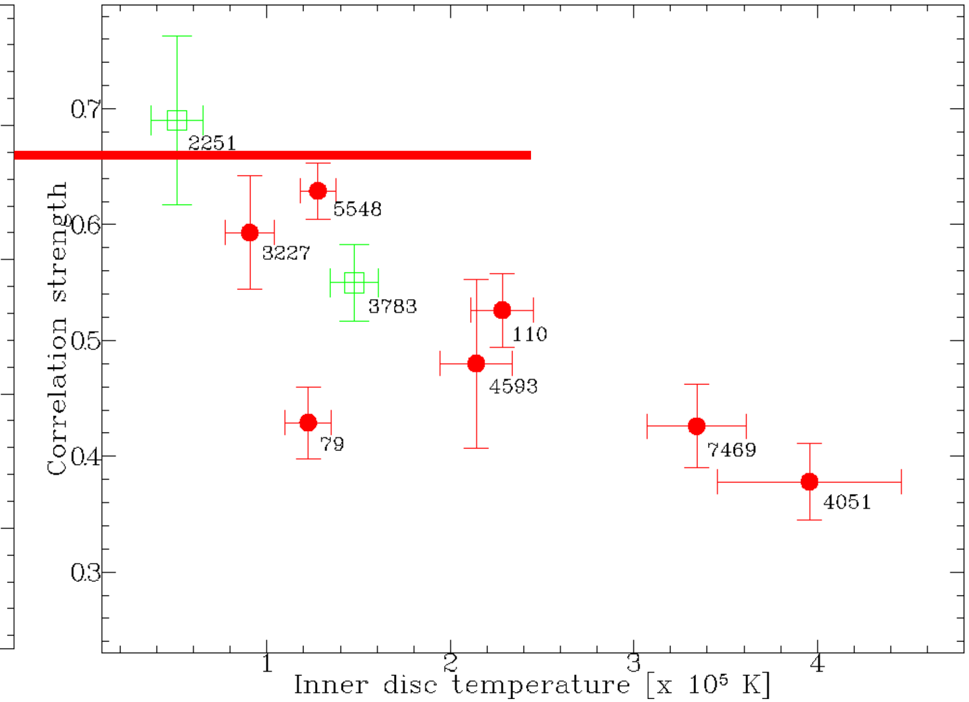
Southampton

How does NGC4395 fit the M, T correlations?

MASS

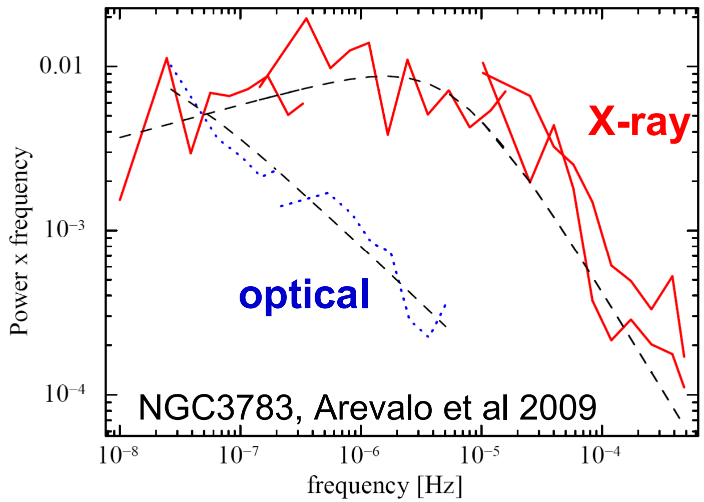


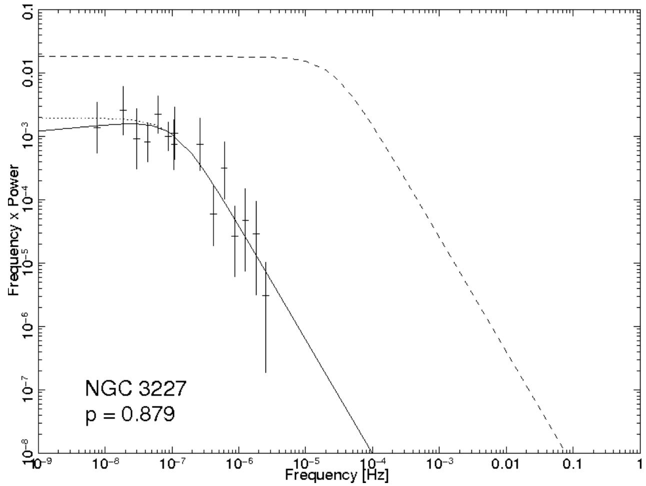
DISC TEMPERATURE

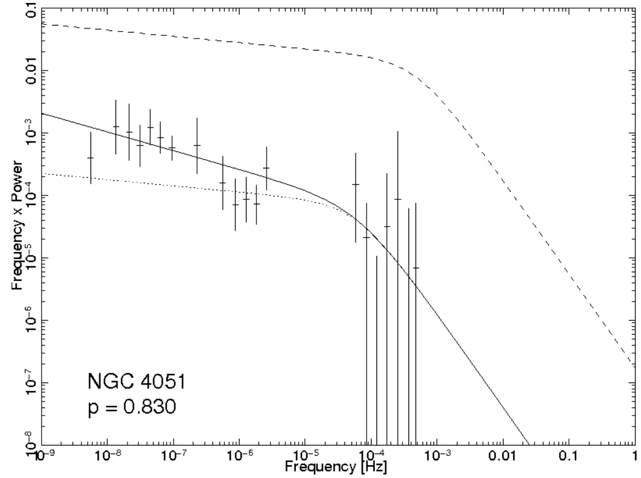


NGC4395 does not agree with pure mass scaling but is consistent with disc temperature scaling

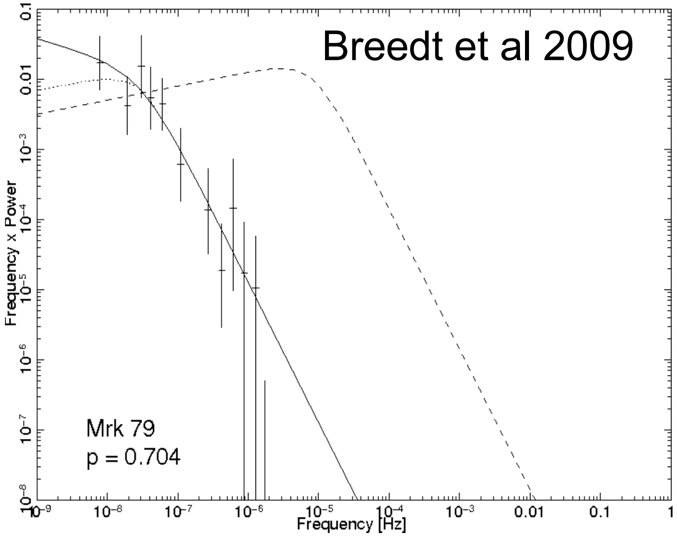
Optical and X-ray PSDs





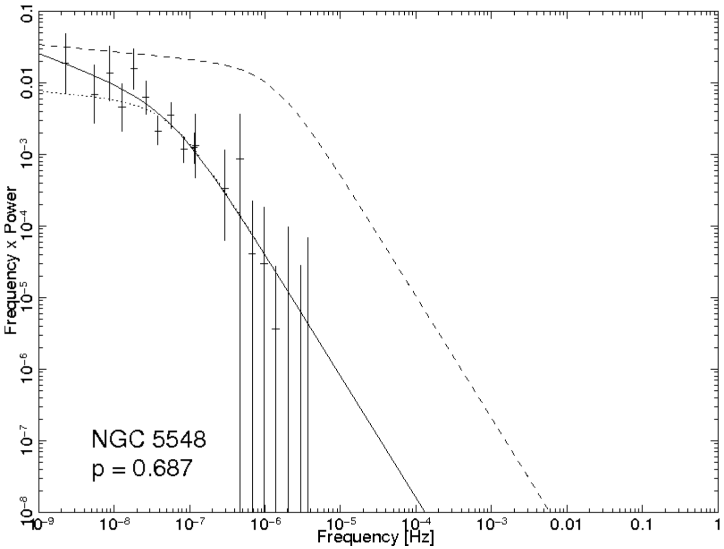


Breedt et al, in prep



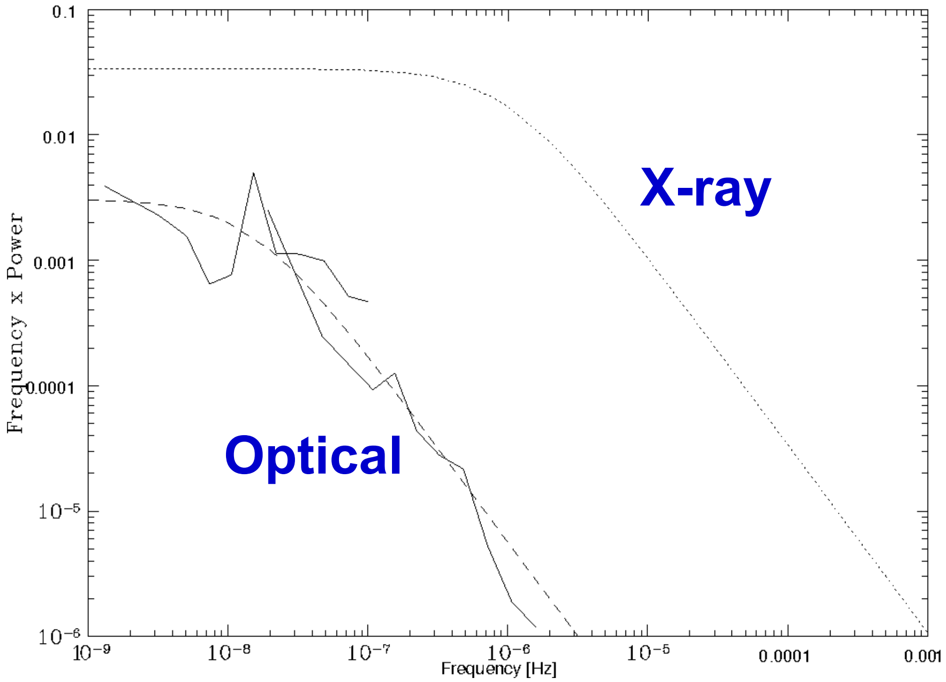
Errorbars - Optical data.
Dashed line – X-rays

See also Kelly et al 2010



Simulated optical and X-ray PSDs

Breedt et al in prep.



Simulated reprocessed optical PSD.

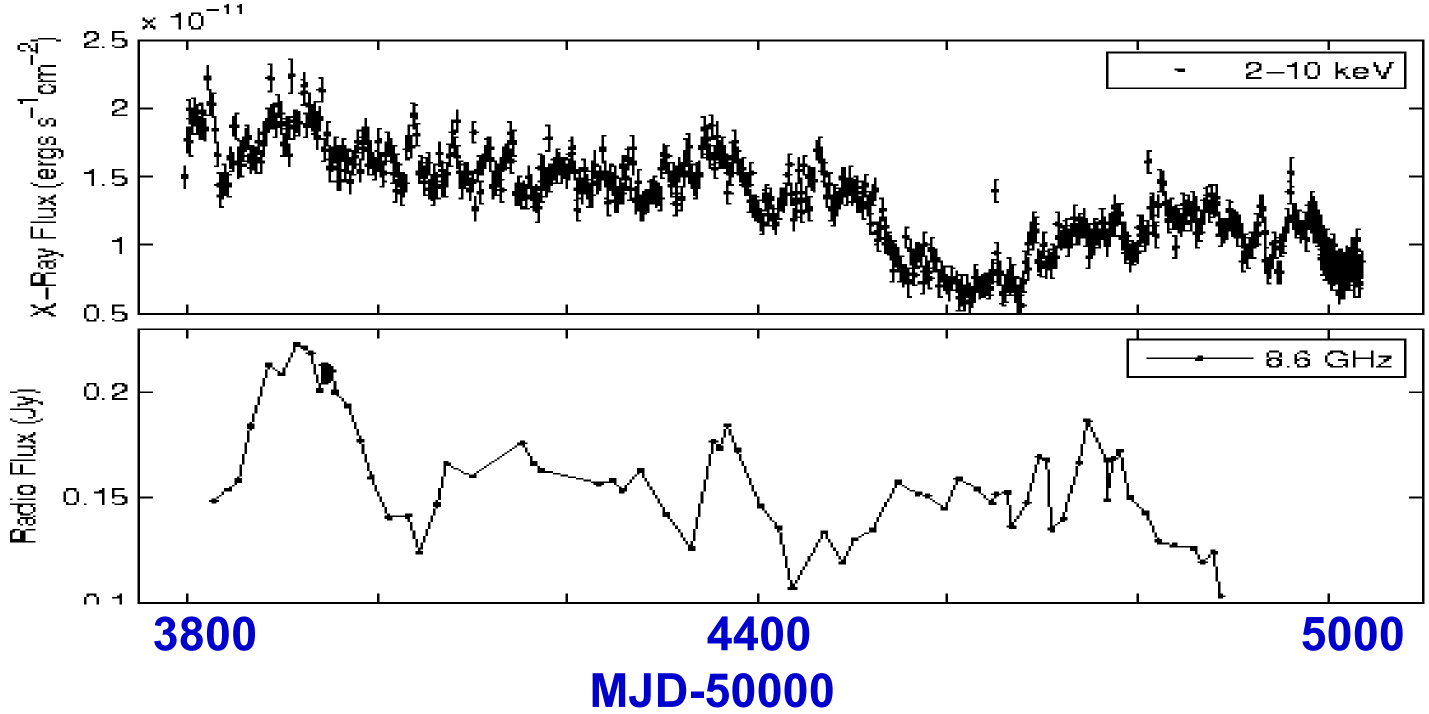
Some observed optical PSDs exceed the X-ray PSDs at low frequencies.
Requires additional intrinsic disc variability.

Radio/X-Ray Variability

1. Liners – NGC7213 and M81

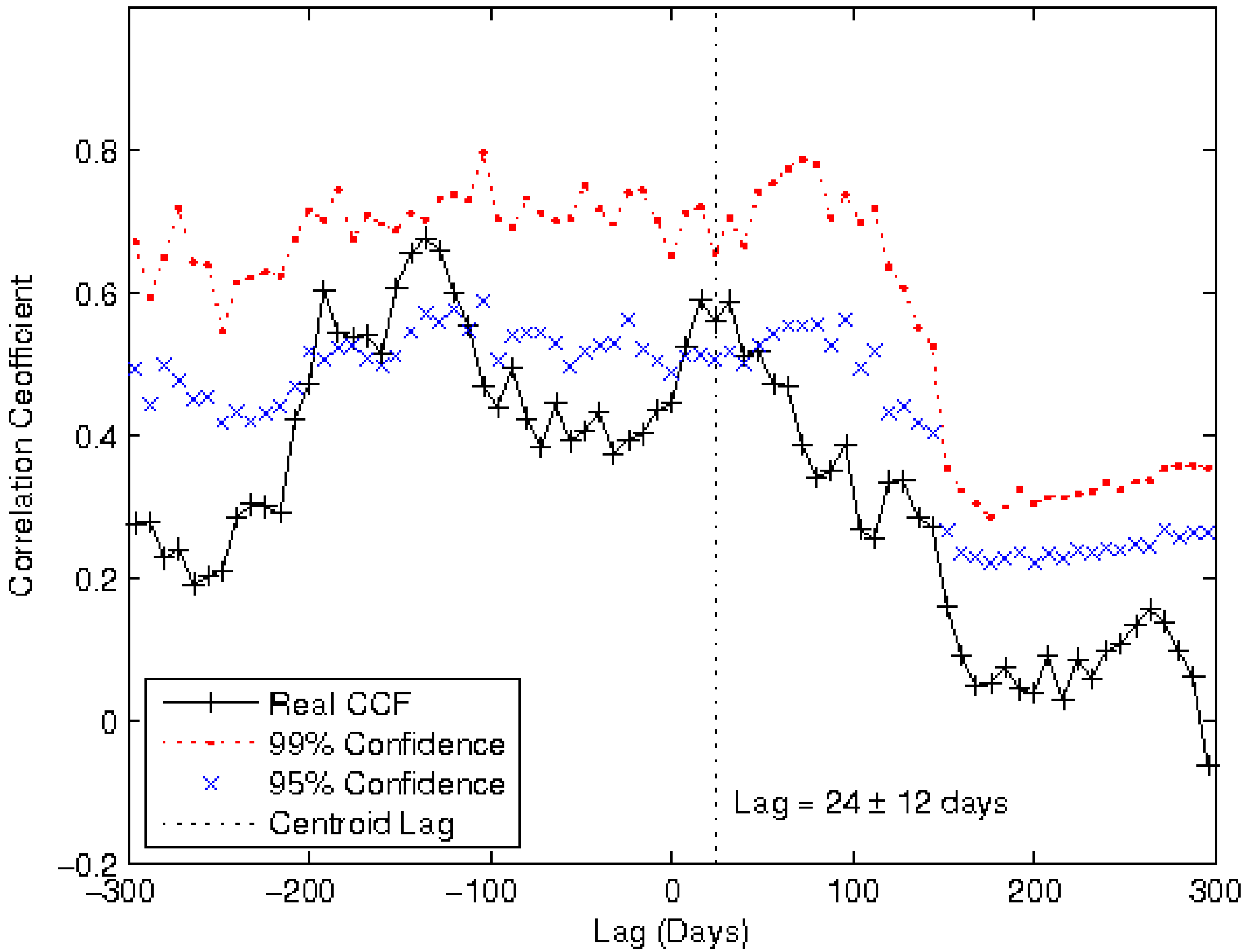
2. Seyfert – NGC4051

NGC7213 – X-RAY/RADIO



(Bell et al, 2010)

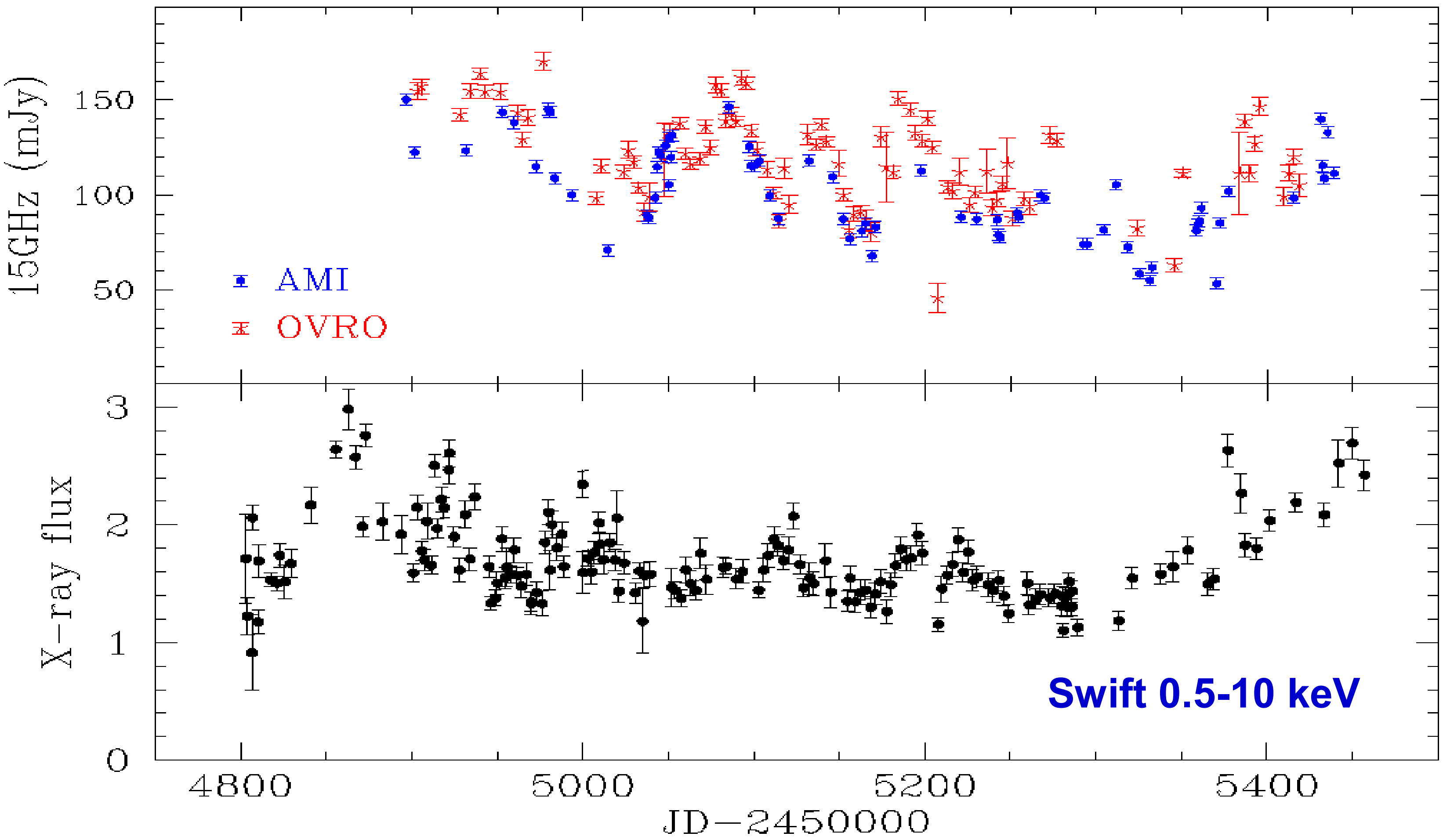
NGC7213 – X-RAY/RADIO



8 GHz lags X-rays by ~24 days
5 GHz lags X-rays by ~40 days

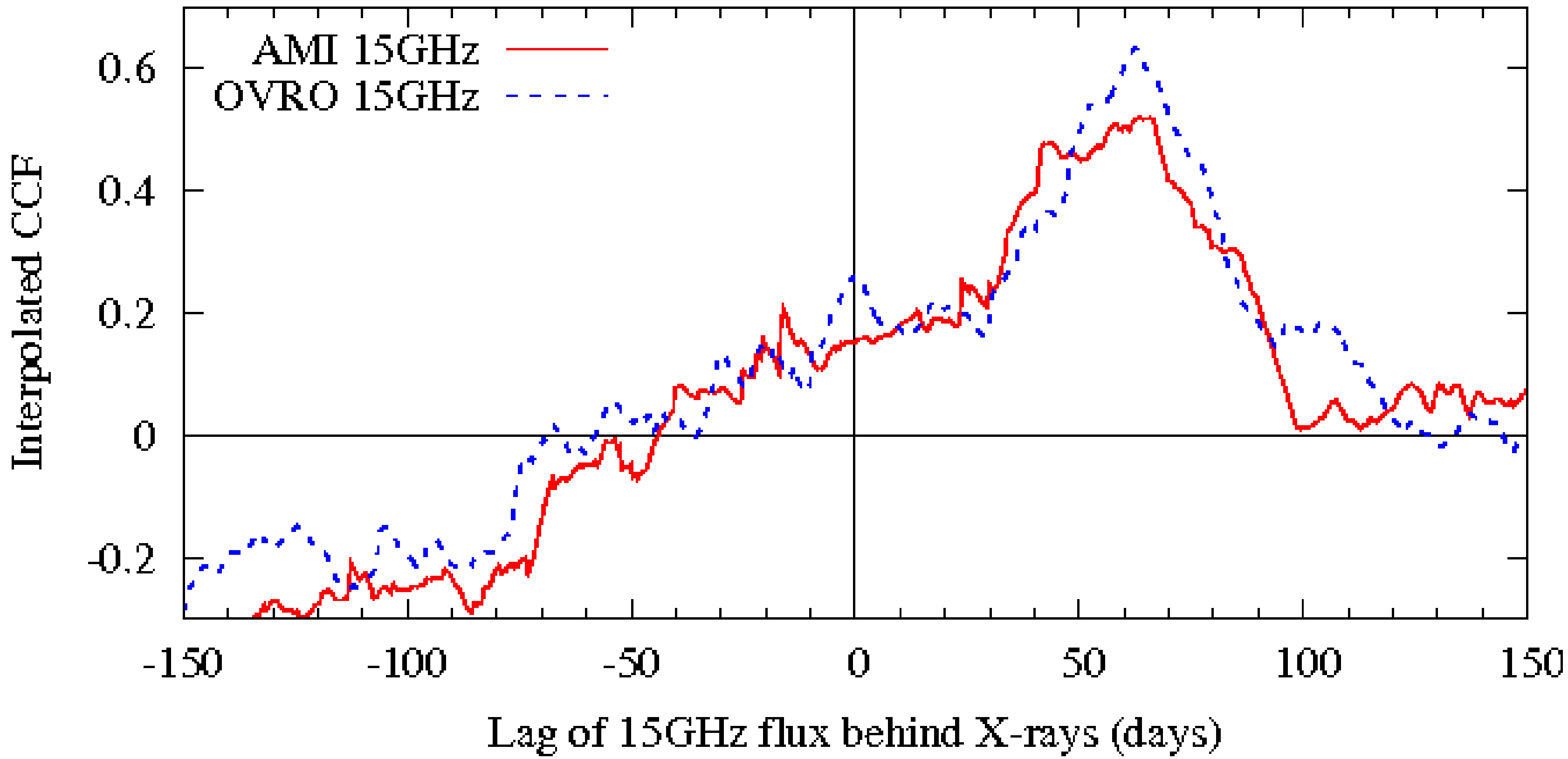
Southampton

M81 X-ray and 15GHz lightcurves

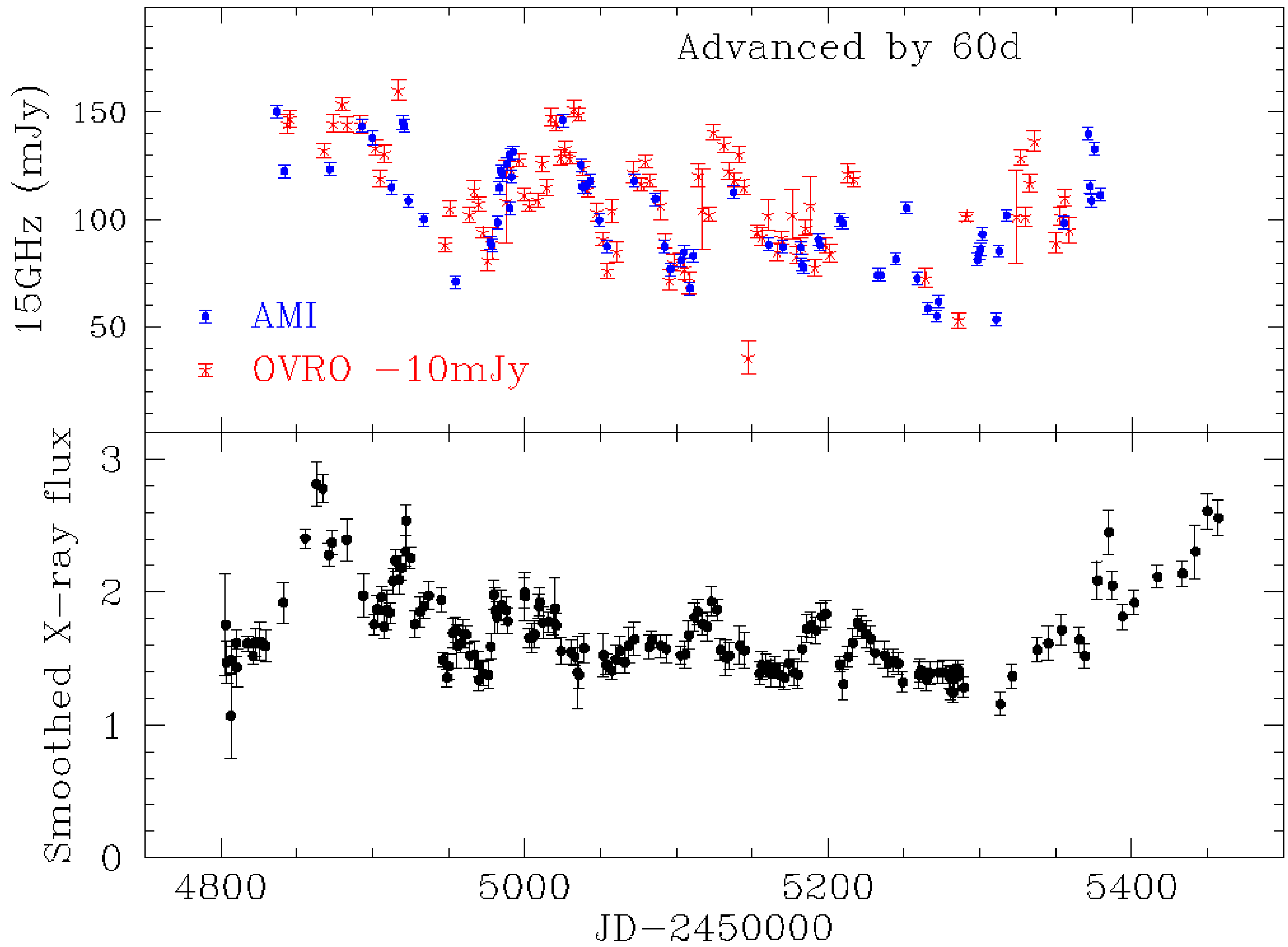


AMI – Pooley
OVRO – Richards, Readhead, Pearson

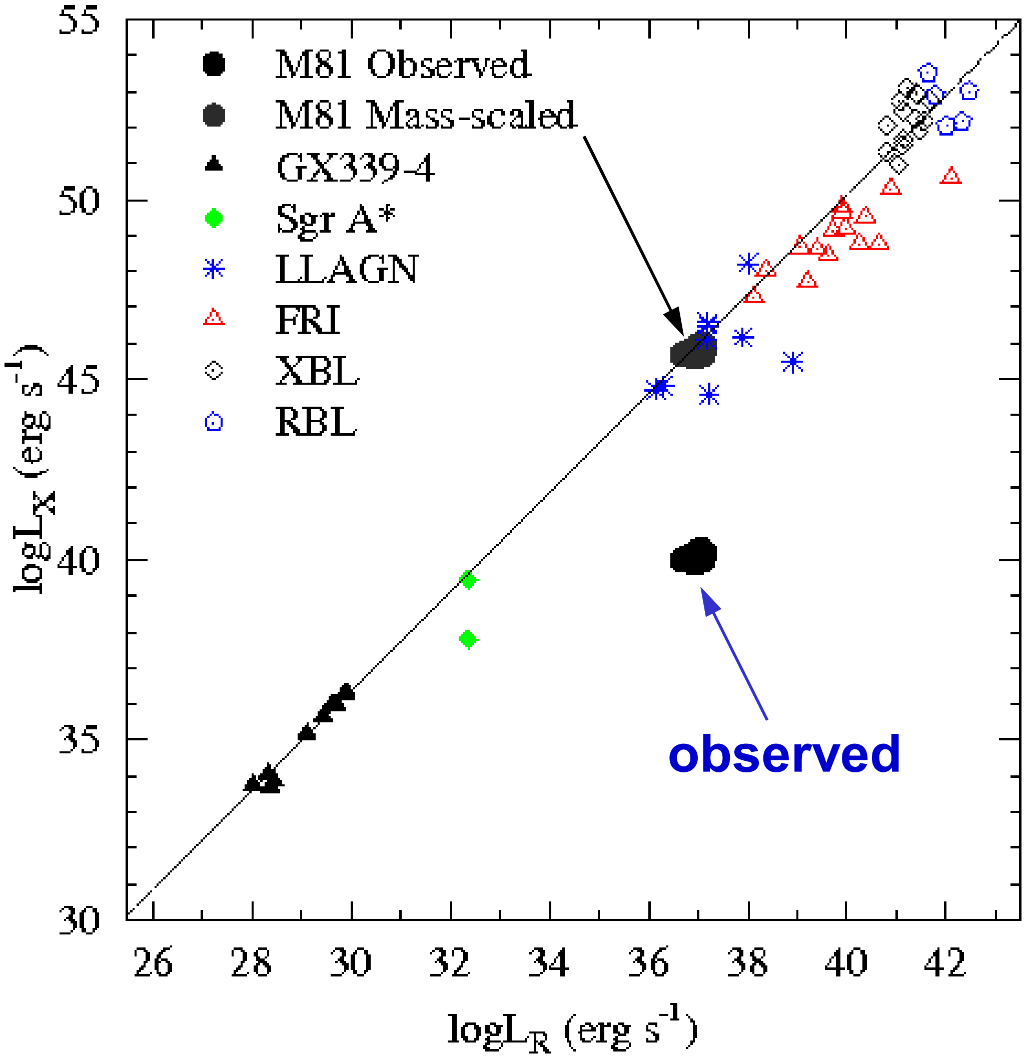
M81 X-ray and 15GHz Cross-correlation



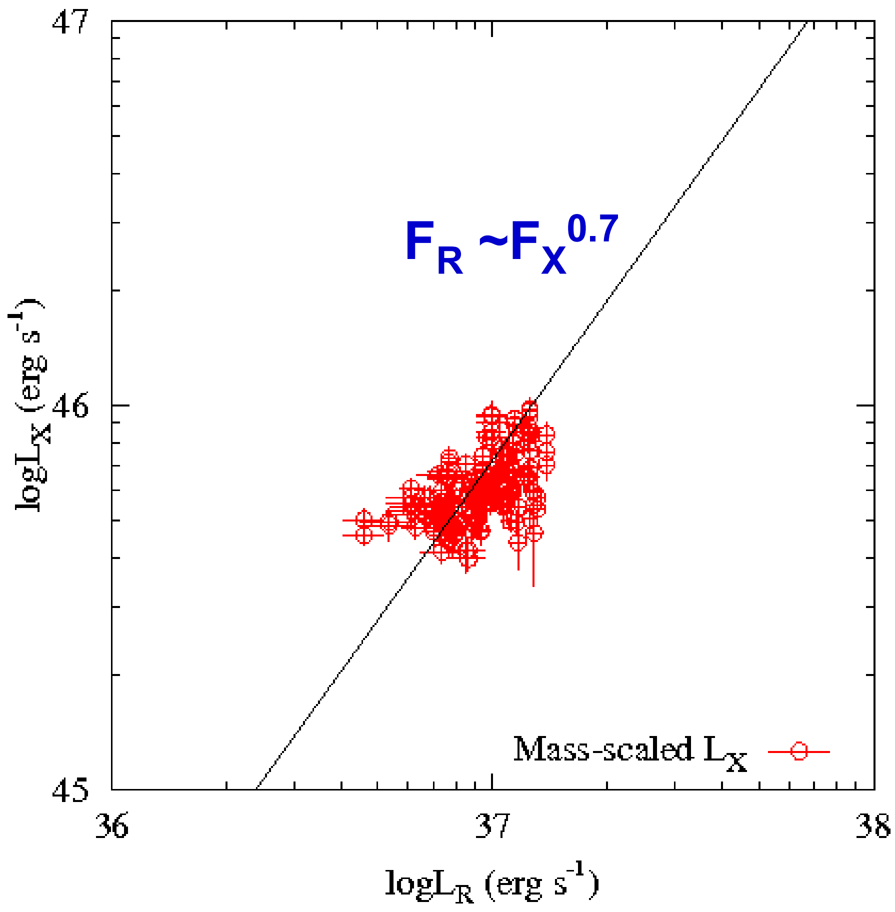
X-ray and 15GHz lightcurves of M81



M81 X-ray and 15GHz



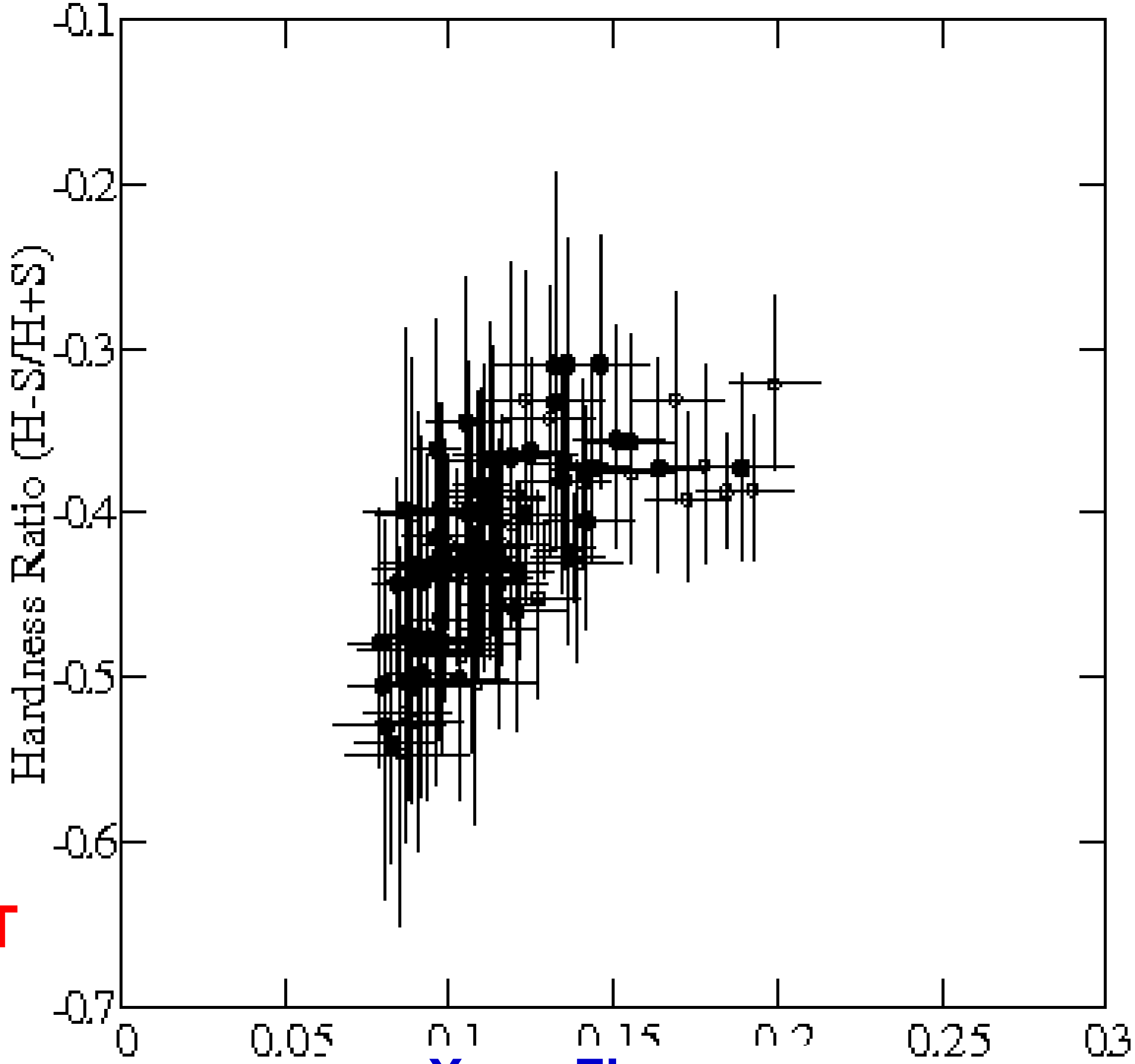
From Falcke et al 2004



Mass-scaling assuming Falcke's jet model

M81 X-ray spectra

HARD



SOFT

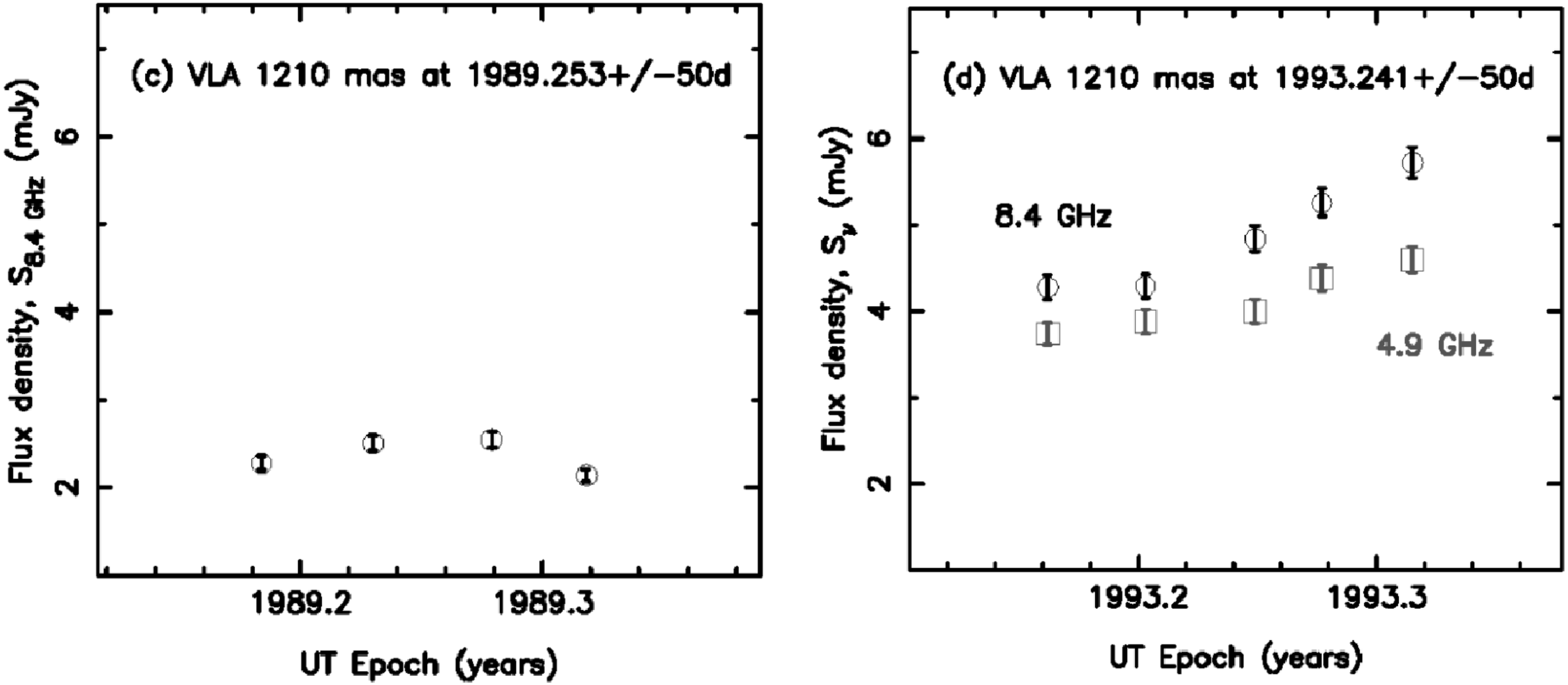
X-ray Flux

X-ray spectrum HARDENS as flux increases

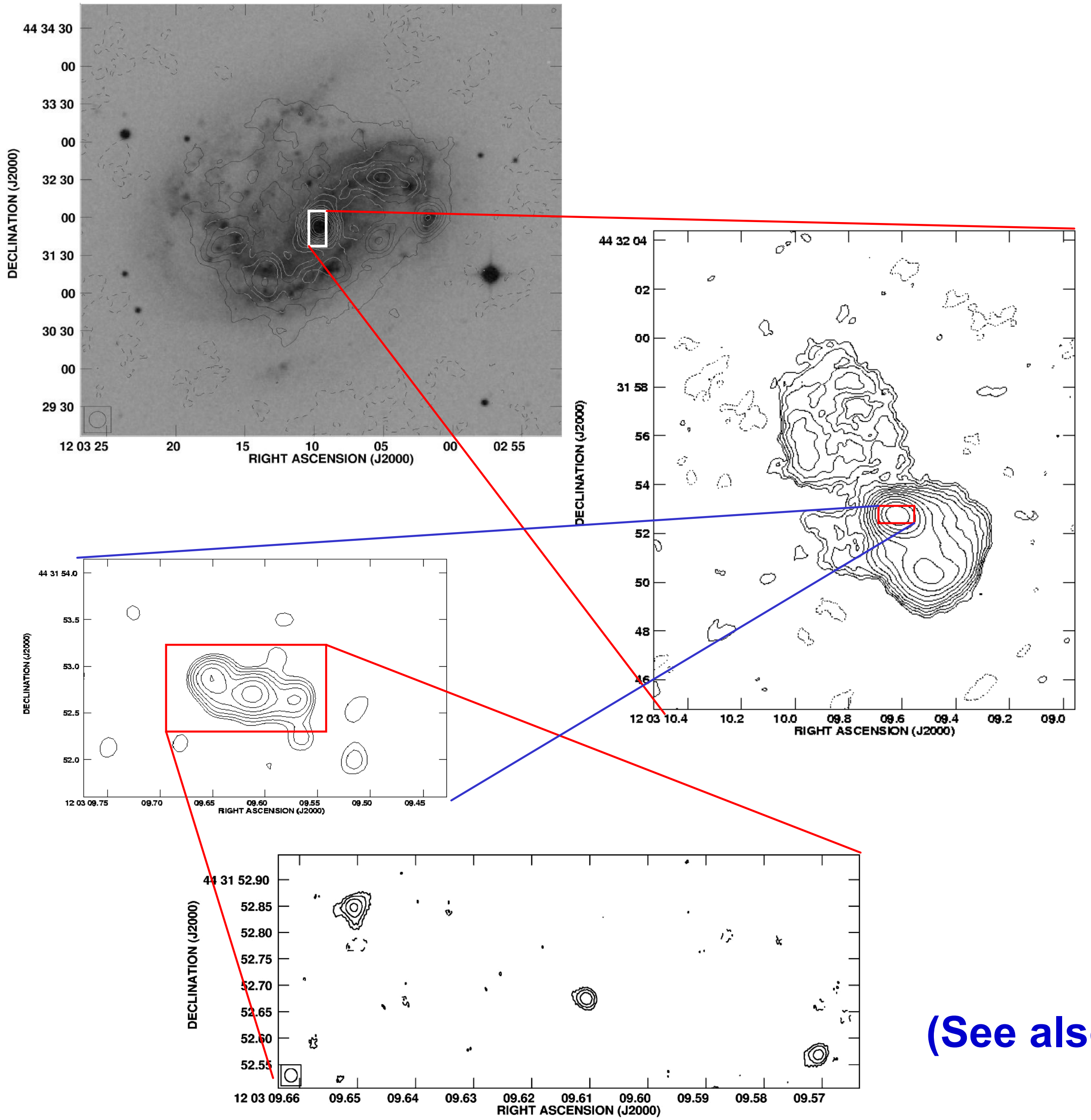
- Opposite to Seyfert galaxies

Radio variability from Seyferts, ie high accretion rate, Soft State, AGN

NGC5548 – Wrobel 2000 - no parallel X-ray observations



NGC4051

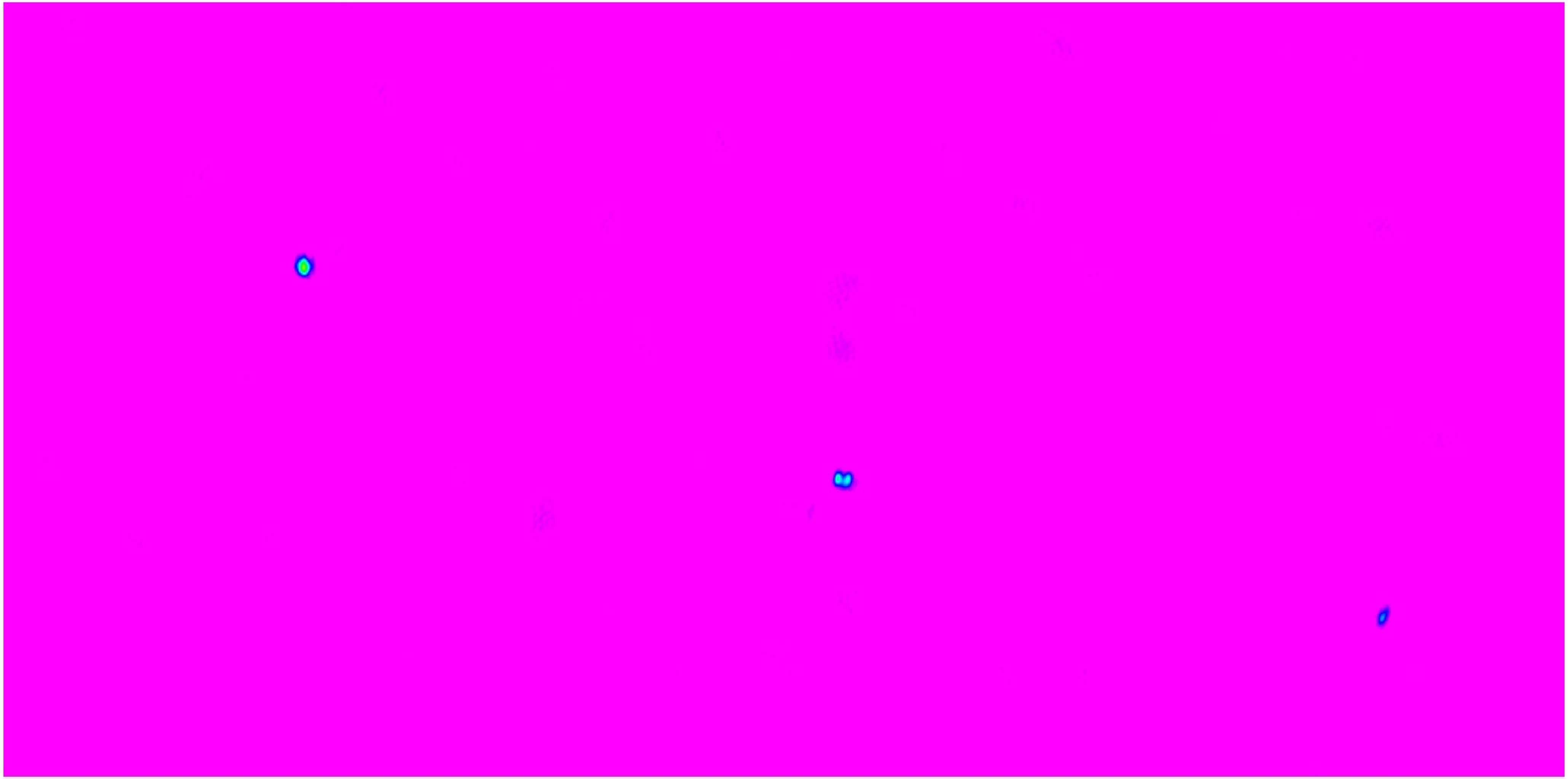


- Looks just like a classical radio galaxy – except much smaller and of much lower luminosity.

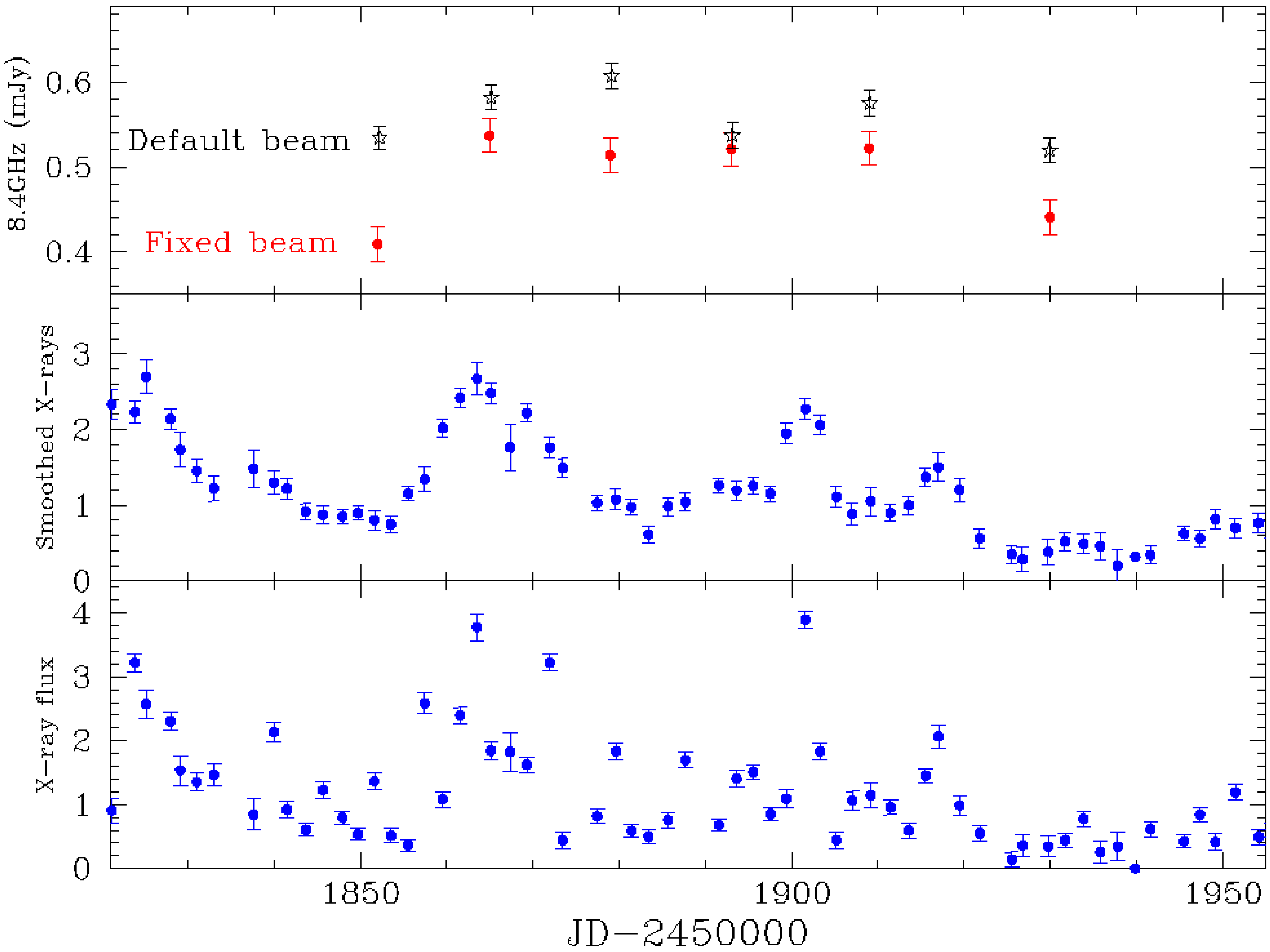
- Component separation is ~50 light years

(See also Girolleti and Panessa 2009)

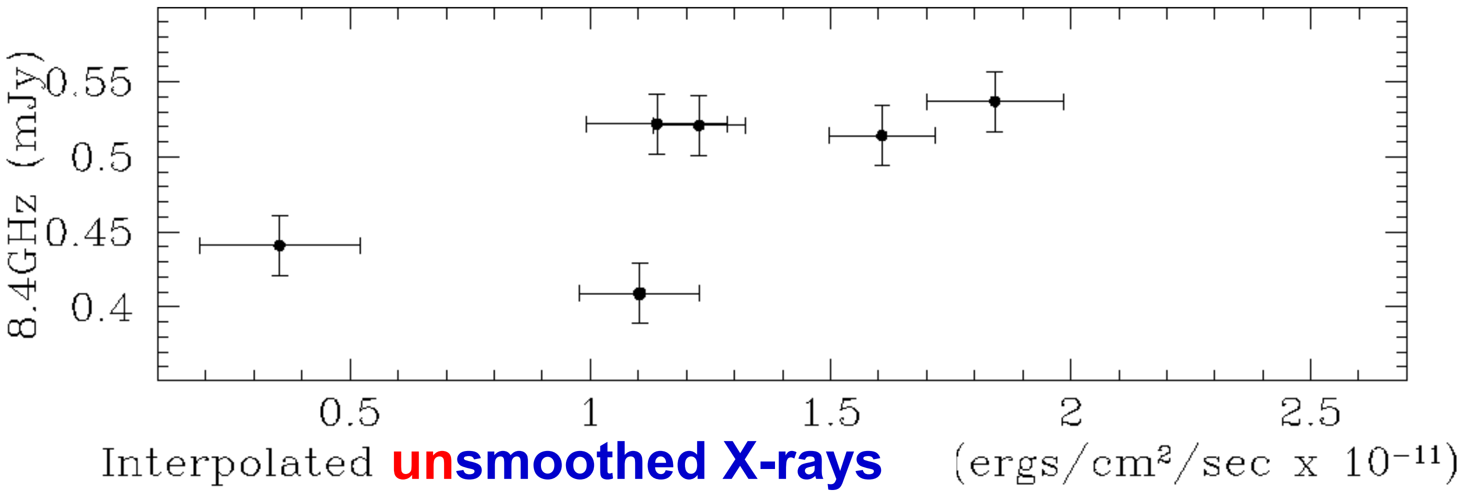
NGC4051 – Global VBLI

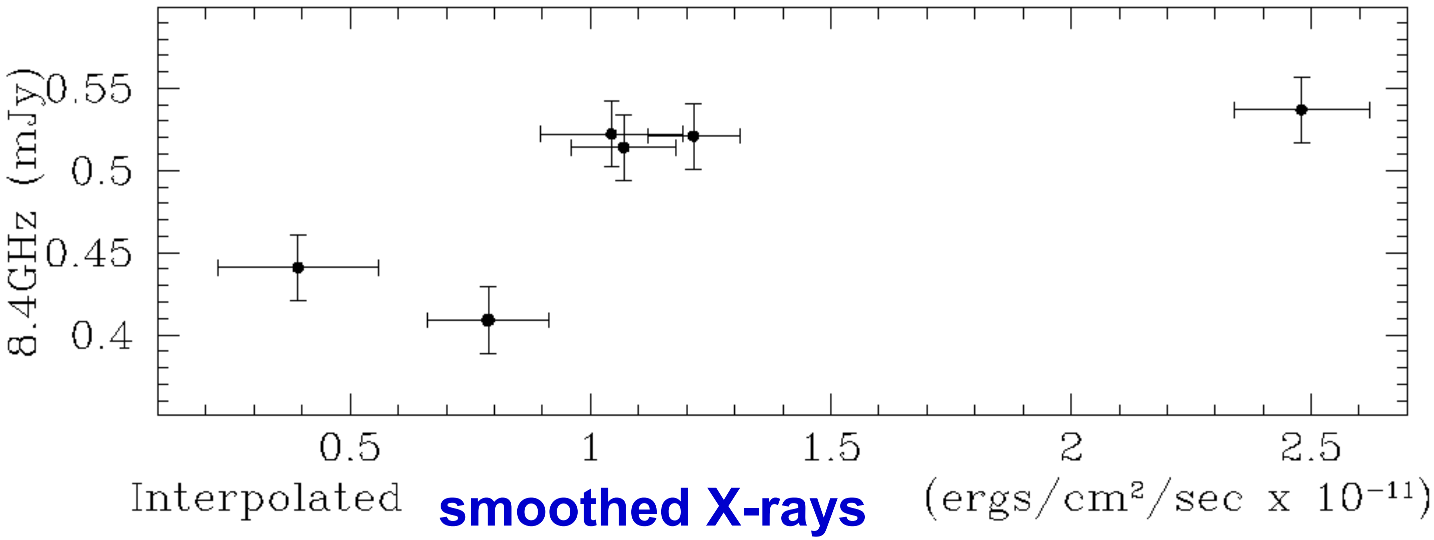


NGC4051 VLA A array observations



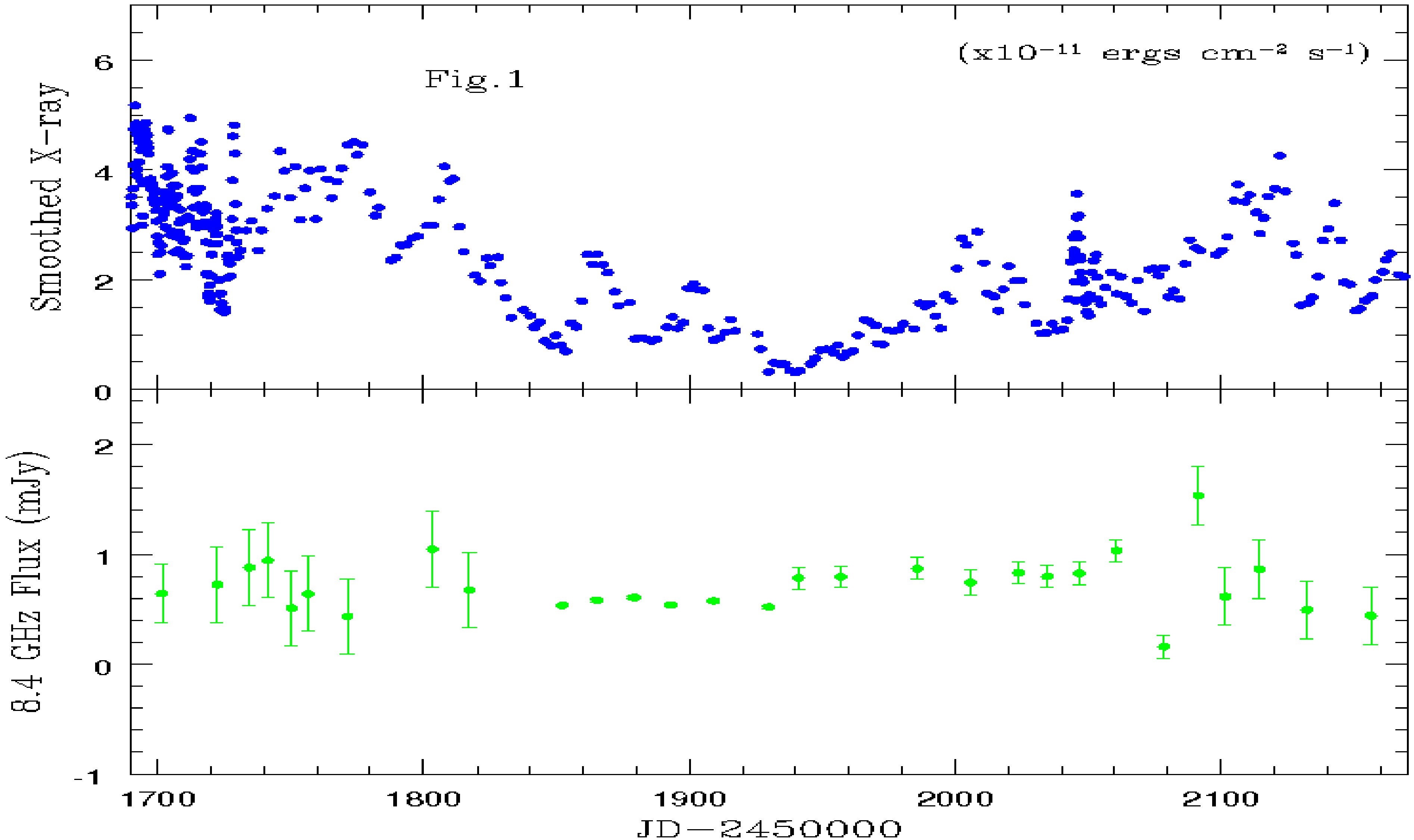
NGC4051 Radio vs. X-ray – A array





Weak correlation?

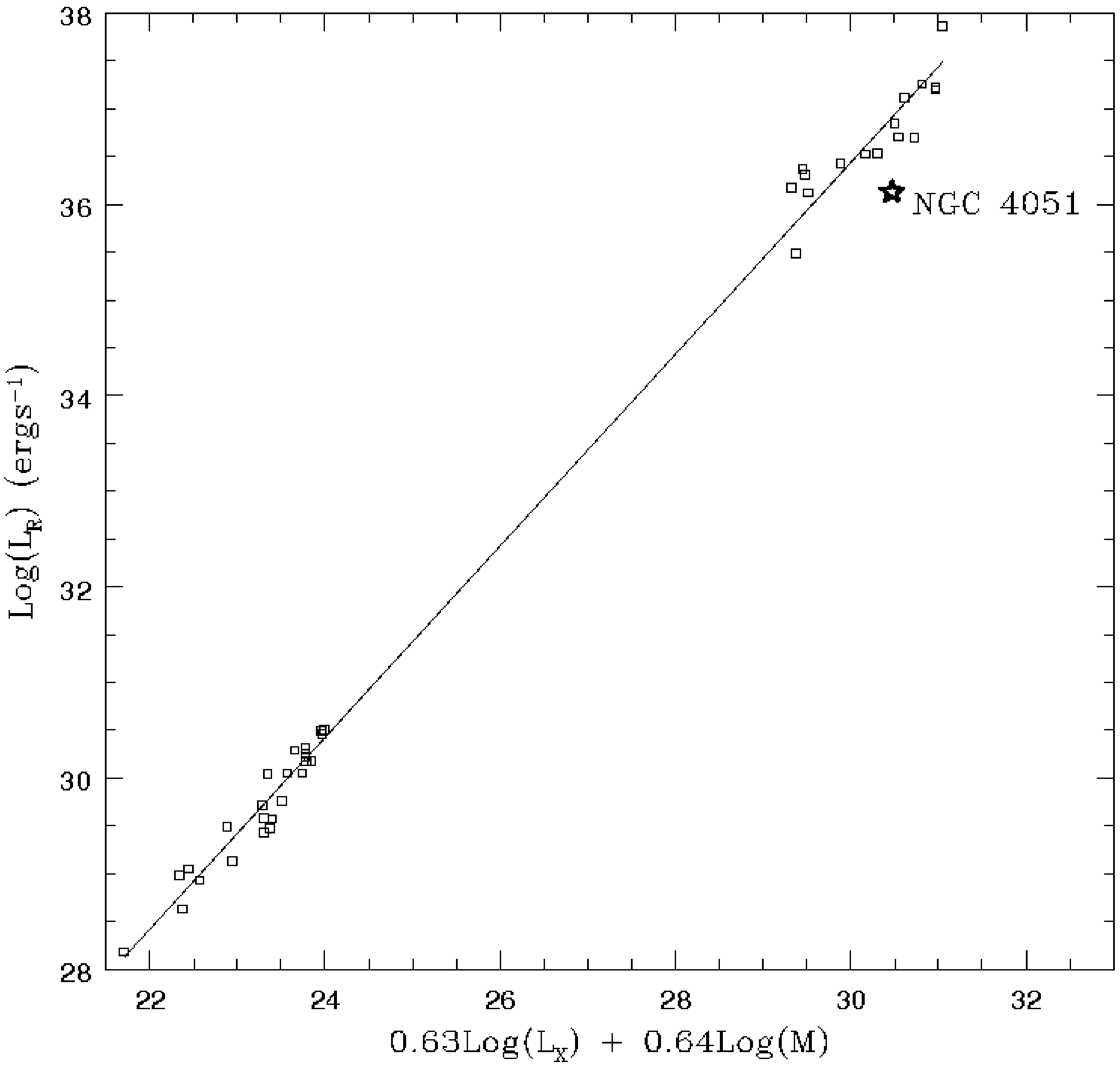
NGC4051 Radio vs. X-ray - all arrays



No strong evidence for large amplitude radio variability

(Jones et al, 2011)

NGC4051 on radio `fundamental plane' for jet-dominated sources



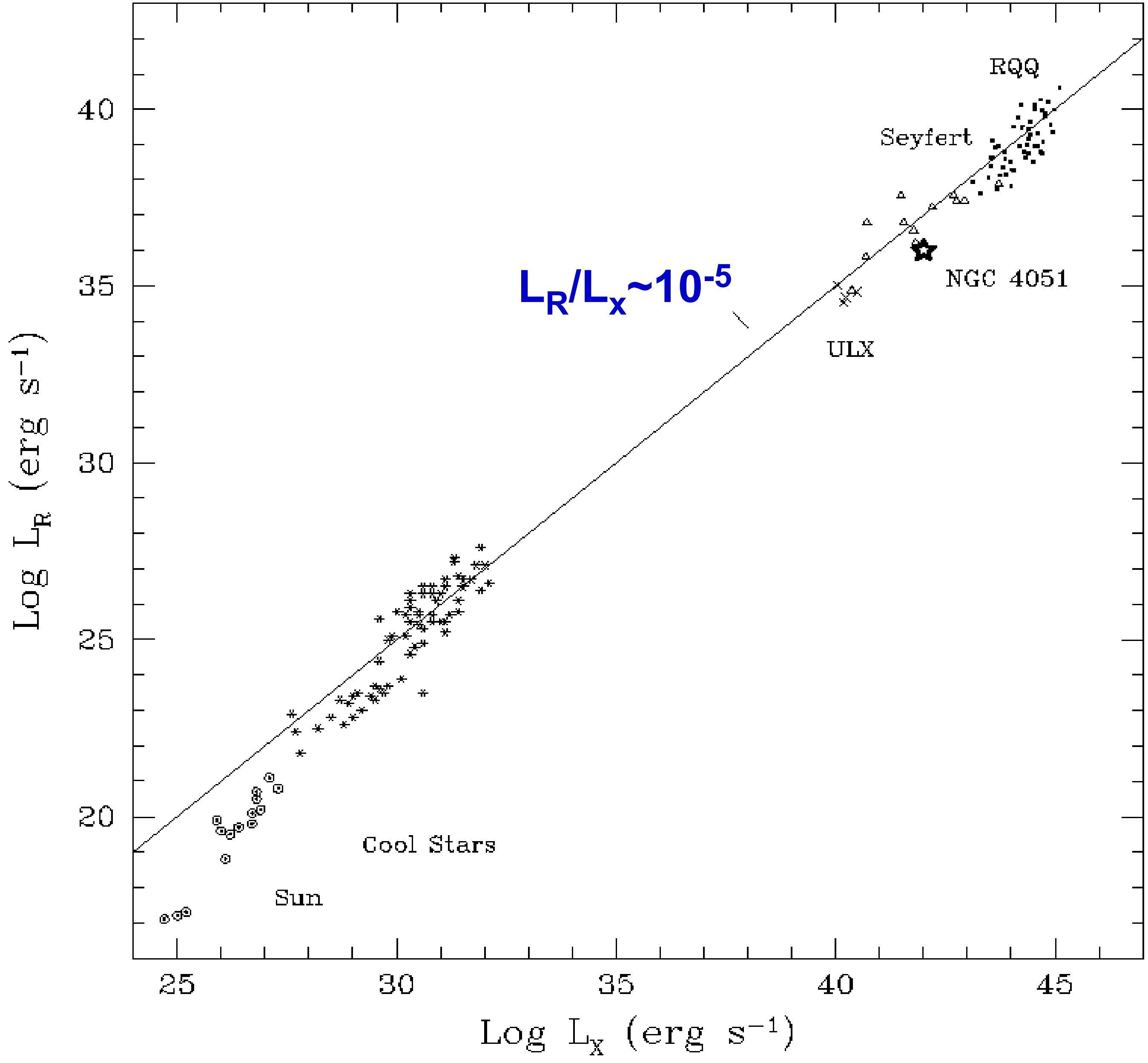
(Merloni et al 2003, Falcke et al 2004, Koerding et al 2006

Here plotting just hard state objects from Koerding etal

NGC4051 is slightly radio quiet

Southampton

NGC4051 as a coronal radio source?



From Fig.6 of Laor and Behar 2008

Maybe a combination of fast inner jets and slower, more diffuse, outflow, or corona

Or just jet orientation?

CONCLUSIONS

AGN probably occupy all the same spectral-timing states as GBHs.

PSD bend timescales scale with mass and accretion rate; high frequency PSD normalisation probably purely mass dependent.

Direct link between X-ray timing properties and host galaxy linewidth.

Short timescale optical variability in Seyferts dominated by reprocessing of X-rays, strength dependent on disc temperature.

Optical variability on longer timescales from intrinsic disc variability.

Good correlation between X-ray and radio in liners (~10^{-4} Eddington) consistent with jet emission

In higher accretion rate Seyferts, origin of radio emission is mystery.