X-ray emission of AGN

I. Papadakis
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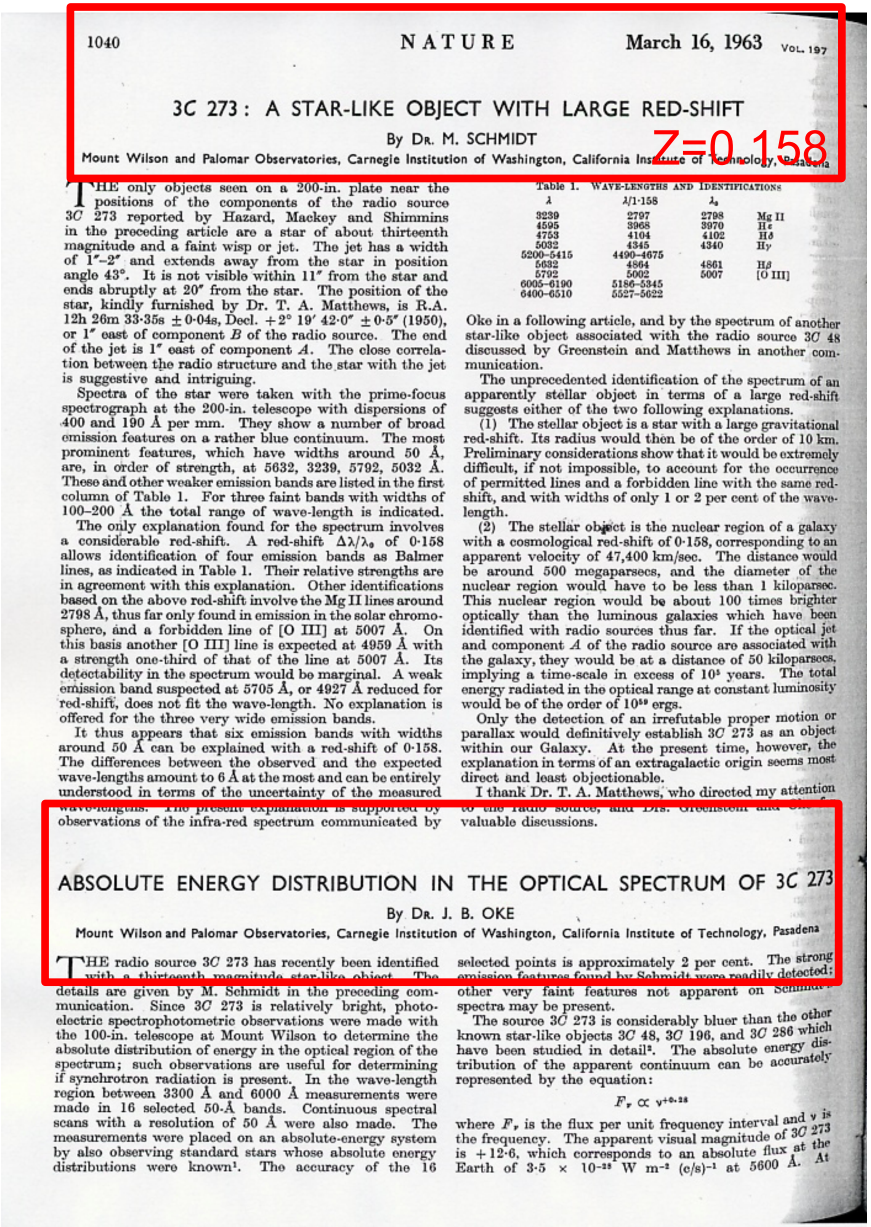

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT
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THE only objects seen on a 200-in. plate near the positions of the components of the radio source *3C* 273 reported by Hazard, Mackey and Shimmins in the preceding article are a star of about thirteenth magnitude and a faint wisp or jet. The jet has a width of 1″–2″ and extends away from the star in position angle 43°. It is not visible within 11″ from the star and ends abruptly at 20″ from the star. The position of the star, kindly furnished by Dr. T. A. Matthews, is R.A. 12h 26m 33·35s ± 0·04s, Decl. + 2° 19′ 42·0″ ± 0·5″ (1950), or 1″ east of component *B* of the radio source. The end of the jet is 1″ east of component *A*. The close correlation between the radio structure and the star with the jet is suggestive and intriguing.

Spectra of the star were taken with the prime-focus spectrograph at the 200-in. telescope with dispersions of 400 and 190 Å per mm. They show a number of broad emission features on a rather blue continuum. The most prominent features, which have widths around 50 Å, are, in order of strength, at 5632, 3239, 5792, 5032 Å. These and other weaker emission bands are listed in the first column of Table 1. For three faint bands with widths of 100–200 Å the total range of wave-length is indicated.

The only explanation found for the spectrum involves a considerable red-shift. A red-shift $\Delta\lambda/\lambda_0$ of 0·158 allows identification of four emission bands as Balmer lines, as indicated in Table 1. Their relative strengths are in agreement with this explanation. Other identifications based on the above red-shift involve the Mg II lines around 2798 Å, thus far only found in emission in the solar chromosphere, and a forbidden line of [O III] at 5007 Å. On this basis another [O III] line is expected at 4959 Å with a strength one-third of that of the line at 5007 Å. Its detectability in the spectrum would be marginal. A weak emission band suspected at 5705 Å, or 4927 Å reduced for red-shift, does not fit the wave-length. No explanation is offered for the three very wide emission bands.

It thus appears that six emission bands with widths around 50 Å can be explained with a red-shift of 0·158. The differences between the observed and the expected wave-lengths amount to 6 Å at the most and can be entirely understood in terms of the uncertainty of the measured wave-lengths. The present explanation is supported by observations of the infra-red spectrum communicated by Oke in a following article, and by the spectrum of another star-like object associated with the radio source *3C* 48 discussed by Greenstein and Matthews in another communication.

Table 1. Wave-lengths and Identifications

λ	$\lambda/1{\cdot}158$	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	Hϵ
4753	4104	4102	Hδ
5032	4345	4340	Hγ
5200–5415	4490–4675		
5632	4864	4861	Hβ
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

The unprecedented identification of the spectrum of an apparently stellar object in terms of a large red-shift suggests either of the two following explanations.

(1) The stellar object is a star with a large gravitational red-shift. Its radius would then be of the order of 10 km. Preliminary considerations show that it would be extremely difficult, if not impossible, to account for the occurrence of permitted lines and a forbidden line with the same red-shift, and with widths of only 1 or 2 per cent of the wave-length.

(2) The stellar object is the nuclear region of a galaxy with a cosmological red-shift of 0·158, corresponding to an apparent velocity of 47,400 km/sec. The distance would be around 500 megaparsecs, and the diameter of the nuclear region would have to be less than 1 kiloparsec. This nuclear region would be about 100 times brighter optically than the luminous galaxies which have been identified with radio sources thus far. If the optical jet and component *A* of the radio source are associated with the galaxy, they would be at a distance of 50 kiloparsecs, implying a time-scale in excess of 10^5 years. The total energy radiated in the optical range at constant luminosity would be of the order of 10^{59} ergs.

Only the detection of an irrefutable proper motion or parallax would definitively establish *3C* 273 as an object within our Galaxy. At the present time, however, the explanation in terms of an extragalactic origin seems most direct and least objectionable.

I thank Dr. T. A. Matthews, who directed my attention to the radio source, and Drs. Greenstein and Oke for valuable discussions.

ABSOLUTE ENERGY DISTRIBUTION IN THE OPTICAL SPECTRUM OF 3C 273

By Dr. J. B. OKE
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THE radio source *3C* 273 has recently been identified with a thirteenth magnitude star-like object. The details are given by M. Schmidt in the preceding communication. Since *3C* 273 is relatively bright, photoelectric spectrophotometric observations were made with the 100-in. telescope at Mount Wilson to determine the absolute distribution of energy in the optical region of the spectrum; such observations are useful for determining if synchrotron radiation is present. In the wave-length region between 3300 Å and 6000 Å measurements were made in 16 selected 50-Å bands. Continuous spectral scans with a resolution of 50 Å were also made. The measurements were placed on an absolute-energy system by also observing standard stars whose absolute energy distributions were known[1]. The accuracy of the 16 selected points is approximately 2 per cent. The strong emission features found by Schmidt were readily detected; other very faint features not apparent on Schmidt's spectra may be present.

The source *3C* 273 is considerably bluer than the other known star-like objects *3C* 48, *3C* 196, and *3C* 286 which have been studied in detail[2]. The absolute energy distribution of the apparent continuum can be accurately represented by the equation:

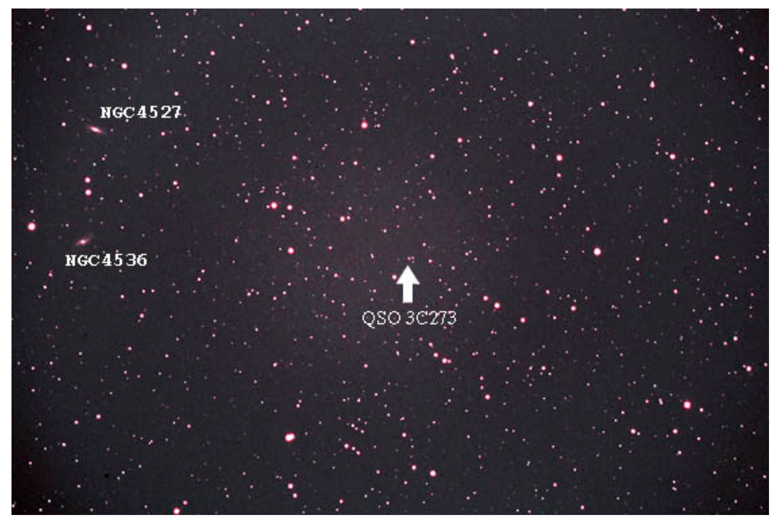
$$F_\nu \propto \nu^{+0.28}$$

where F_ν is the flux per unit frequency interval and ν is the frequency. The apparent visual magnitude of *3C* 273 is + 12·6, which corresponds to an absolute flux at the Earth of $3{\cdot}5 \times 10^{-28}$ W m^{-2} (c/s)$^{-1}$ at 5600 Å. At

March 16, 1963

The discovery of the extraordinary "quasars" ("active galactic nuclei"-AGN)

Quasar = quasi-stellar radio source



3C 273: $L_{bol} \simeq 10^{47}$ erg/s $\simeq 3 \times 10^{13}\ L_\odot$

THE ASTROPHYSICAL JOURNAL

VOLUME 140 JULY 1, 1964 NUMBER 1

THE QUASI-STELLAR RADIO SOURCES 3C 48 AND 3C 273

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Received April 18, 1964

ABSTRACT

The spectra of two quasi-stellar radio sources, 3C 48 and 3C 273, have been studied in detail. We present as full conclusions as we can derive from the redshift, luminosity, emission-line, and continuous spectra. Together with the radio-frequency data and the light variability, these indicate the presence of very large total energies in a relatively small volume of space. We deliberately have not attempted to discuss the origin of these large energies, nor do we discuss the numerous other physical problems concerned with suggested mechanisms in the quasi-stellar objects.

We first consider other explanations for the large redshifts, in particular the possibility of gravitational redshift. The presence of relatively narrow emission lines excludes objects near 1 $M_\odot$ which are stable because of the small emitting volume. The presence of forbidden lines sets an upper limit to the gas density. Together with a limit to gravitational perturbations on our Galaxy, this leads to a lower limit of 10^{11} $M_\odot$, condensed to a 10^{17}-cm radius. Whether such large masses can be even quasi-stable has not yet been demonstrated.

We then adopt the interpretation that the redshifts are cosmological in origin. The absolute visual magnitudes are about -26 for 3C 273 and -25 for 3C 48. The forbidden lines of high ionization potential are quite strong in 3C 48 relative to hydrogen. By analogy with planetary nebulae and assuming normal abundances, with astrophysical details given in the appendices, we derive the electron density, N_e, probably near to or less than 3×10^4 cm^{-3}; the electron temperature is not very high, and the mass is about 5×10^6 $M_\odot$ within a radius of 10 pc or more. The emitting volumes are obtained from N_e and the observed luminosity in Hβ and Mg II. The forbidden lines and the Balmer lines are optically thin, but Mg II is optically thick, leading to discussions in the appendices. For 3C 273, in which the forbidden lines are weaker, the surprising weakness of [O II] permits a closer estimate of N_e near 3×10^6 cm^{-3} and a mass of 6×10^5 $M_\odot$ within a radius of about 1 pc.

The light variations observed in both, with cycles of 10 years or less, suggest the presence of a source of optical continuum with a diameter of 1 pc, possibly much less. We urgently need continued observations of the absolute intensities of lines and continuum and their variations. The thermal energy supply in the H II region is small. The ionized gas must be of low density in the region in which the radio frequencies are generated, because of free-free absorption and Faraday rotation, i.e., $N_e < 10$ cm^{-3} if $R = 500$ pc for the radio source.

We explore models for synchrotron generation of radio and optical frequencies. If $R = 500$ pc, total energies required for radio emission are relatively low, about 10^{57} erg at equipartition. The lifetimes for exhausting the total energy supply are about 10^6 years. If we wish to obtain optical synchrotron from the same volume as produces radio frequencies, the equipartition energy reaches 10^{58} erg. If optical synchrotron radiation is to arise within a volume 1 pc^3, however, the total energy is small, 10^{54} erg, the life about a year, and serious problems arise, such as cosmic-ray proton collisional loss, and inverse-Compton effect electron loss. Models for the jet radio source 3C 273A offer no particular difficulty.

We review conditions under two possible age estimates of the inner components of the quasi-stellar objects. At 10^3 years, the object can be in expansion, with a velocity compatible with the emission-line width, about 1000 km/sec. The energy supply is sufficient for the radio spectrum, and the kinetic energy of the H II region is nearly enough to maintain the optical emission. On this hypothesis, the jet in 3C 273 and the nebular wisps in 3C 48, which are 150000 light-years in size, must have originated in a separate event.

If the age is 10^6 years, the H II region energy is much too small; in addition, its small radius and

"The light variations observed in both,
<u>with cycles of 10 years or less</u>,
suggest the presence of a source of
optical continuum
<u>with a diameter of 1pc</u>, possible much
less."

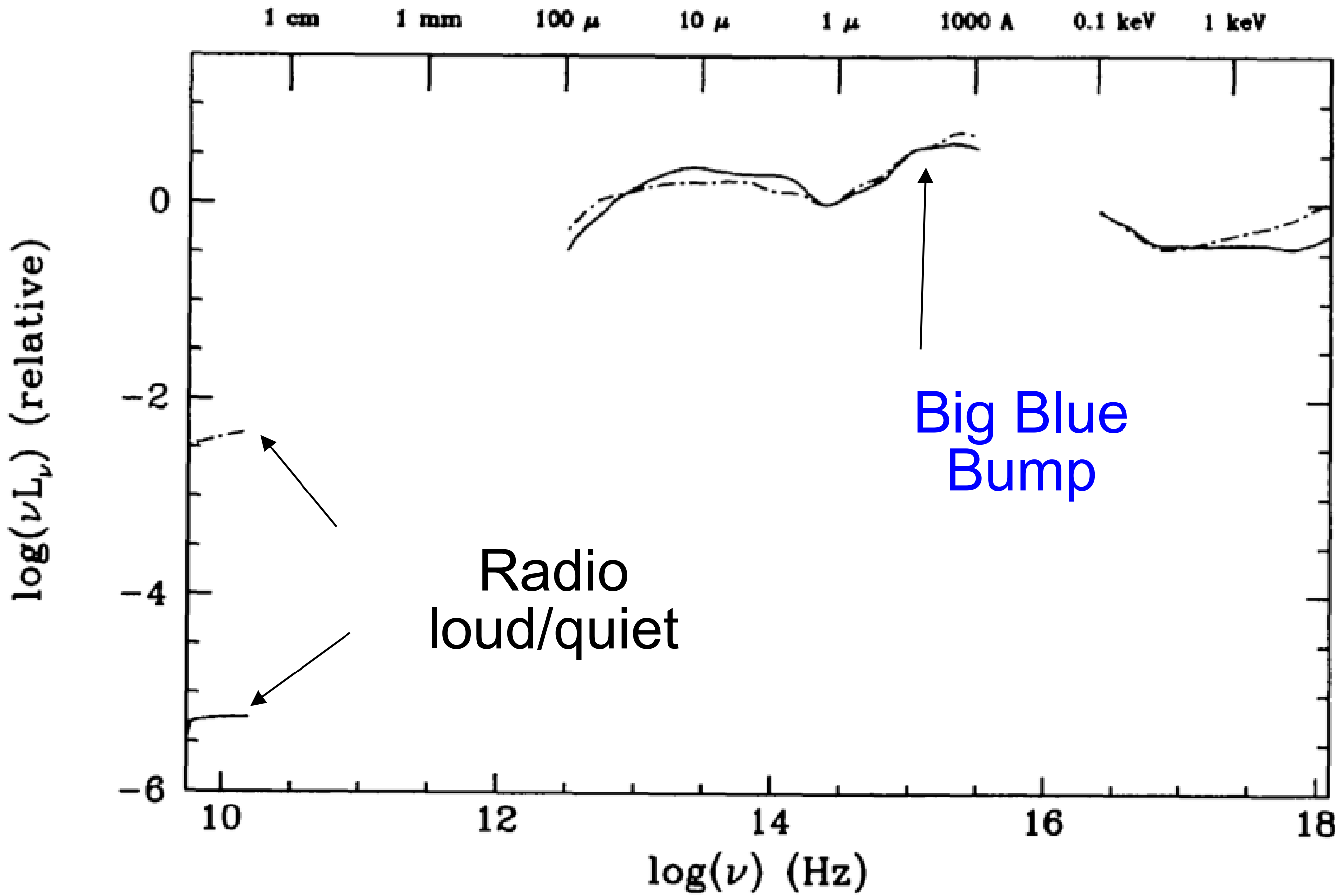
If true, then

"luminosity surface density" of 3C273

$\sim 10^{13}$ $L_\odot$/pc^2,

which is 10^6 times larger than the "nuclear surface density" of M32 (the highest among all normal galaxies).

By the late 1960's, we knew that the nuclear regions in a "few" nearby galaxies (~10% of all galaxies) are "highly unusual" (i.e. they exhibit phenomena which *cannot* be explained by the "normal" stellar processes) – Active Galaxies/AGN.

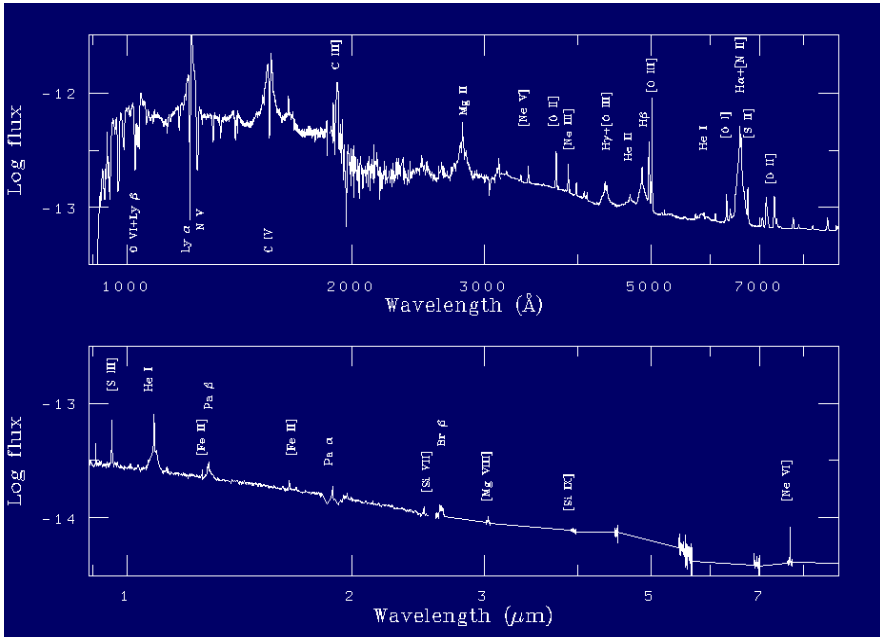


Elvis et al, 1994, ApJS, 95, 413

The central engine (Current Paradigm):

Accretion of matter into a Super-Massive Black Hole

Why “super-massive” black hole” ?



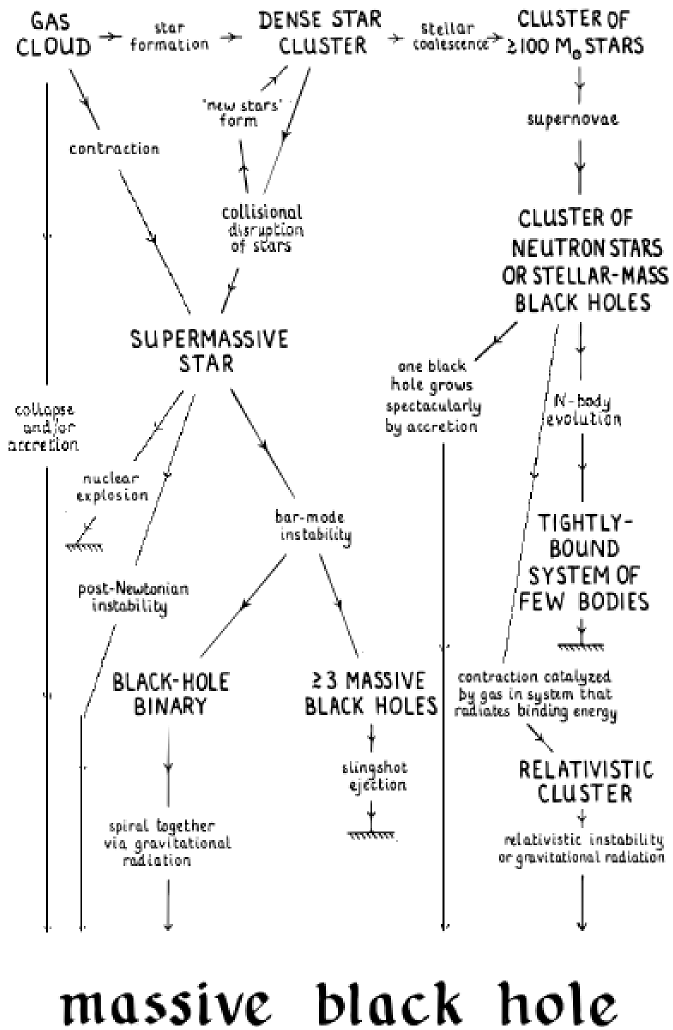
In “typical” AGN, FWHM ~ 10^3 – 10^4 km/sec.
If the line emission originates from clouds which rotate around the center, and are gravitationally bound, then:

$M \approx \upsilon^2 R/G$, and,
$M \approx 10^{6\text{-}8} M_\odot$ for R~5 light days

What could be this “massive object” in active nuclei?

A (very...) dense star cluster, with an (exceptionally) high rate of supernovae explosions

and/or (many...) stars with a mass > 100 $M_{\odot}$...



But:

"According to conventional Physics, the almost inevitable end point (of the above) will be the collapse of a large fraction of its total mass to a massive black hole."
(Rees, 1984, ARAA, 22, 471)

Why accretion of matter?

Accretion to a compact object is a very efficient mechanism to extract energy from a particle.

Suppose that mass falls onto an object of mass M with a rate of $\dot{m}=dm/dt$.

As the matter falls in, the rate of potential energy that is released at a distance r from the central object is:

$$dU/dt = -GM\dot{m}/r$$

If this energy is transformed into radiation (in some way...) then:

$$L=0.5\times(dU/dt) = 0.5\times G\dot{m}(M/r)$$

The ratio (M/r) is a measure of the compactness of the source and is maximum for a Black Hole. For example, if $r=3R_S$, then:

$$L=0.08\times\dot{m}c^2$$

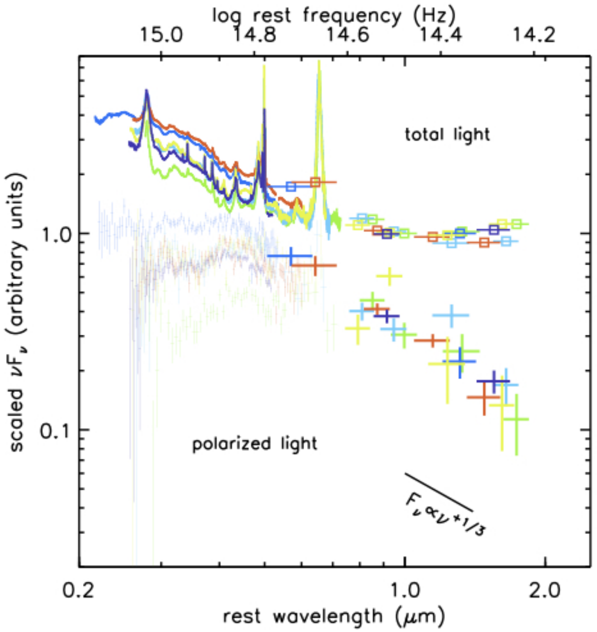
Accretion should proceed in a form of a disc.

Viscosity is necessary to accrete material (magnetic fields may be important; Balbus & Hawley, 1991, ApJ, 376, 214)

If the released energy is emitted as blackbody radiation, as material moves inwards from *R* to *R-ΔR*, then:

$$2\pi R\Delta R\sigma T^4 \propto G\dot{m}(M/R^2)\Delta R, \text{ or } T \propto (M\dot{m}/R^3)^4$$

The disc's emitted spectrum should be the sum of many black bodies, and $F(\nu) \propto \nu^{1/3}$ – Big Blue Bump



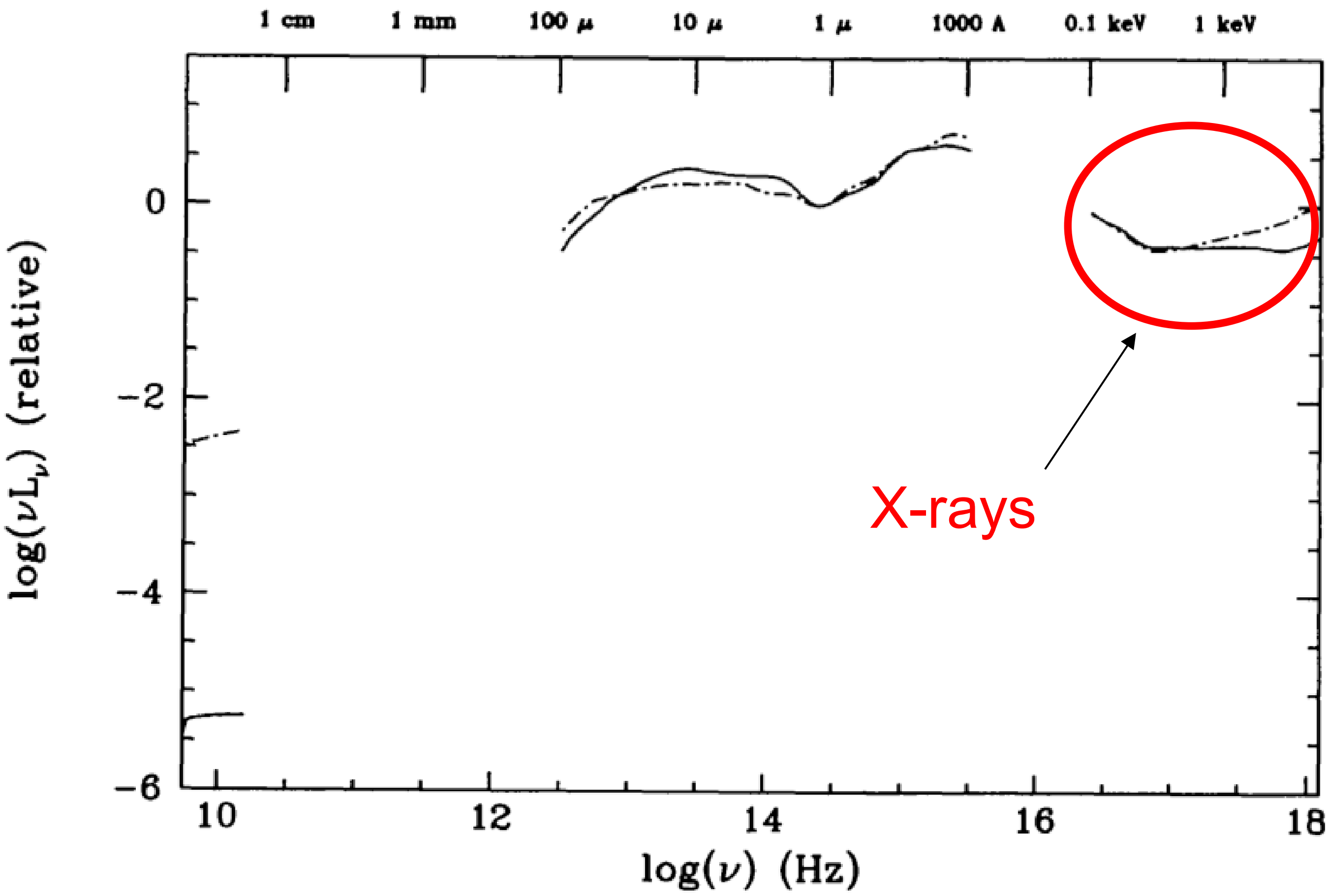
Shakura & Sunyaev, 1974, A&A, 24, 337

Pringle, J.E., 1981, ARA&A, 19, 137

Kishimoto et al, 2008, Narure, 454, 492

AGN emit X-rays

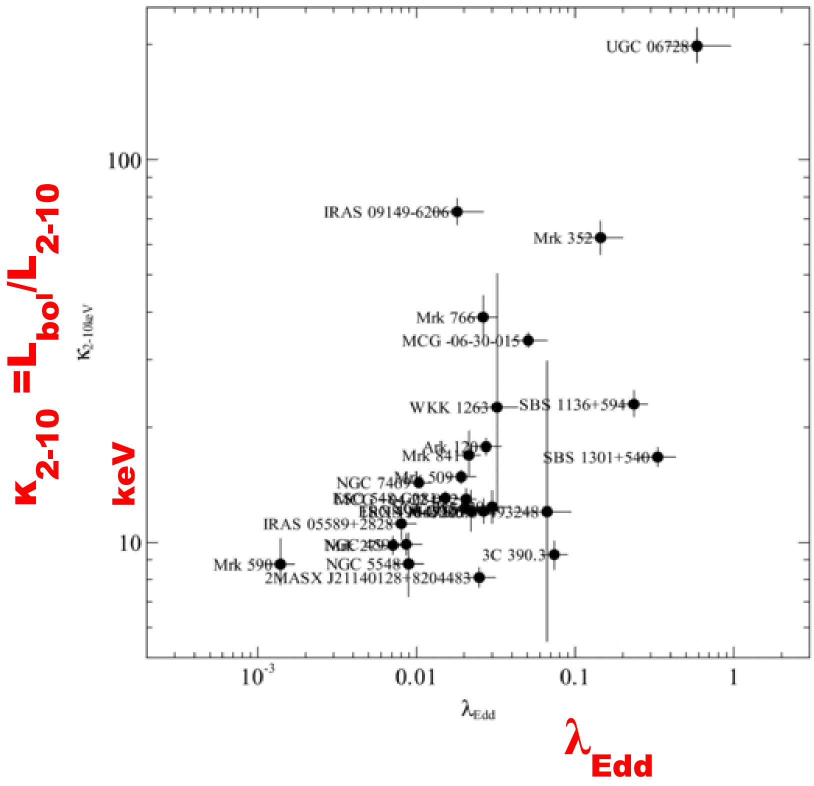
(Already known from the early/mid-70's)



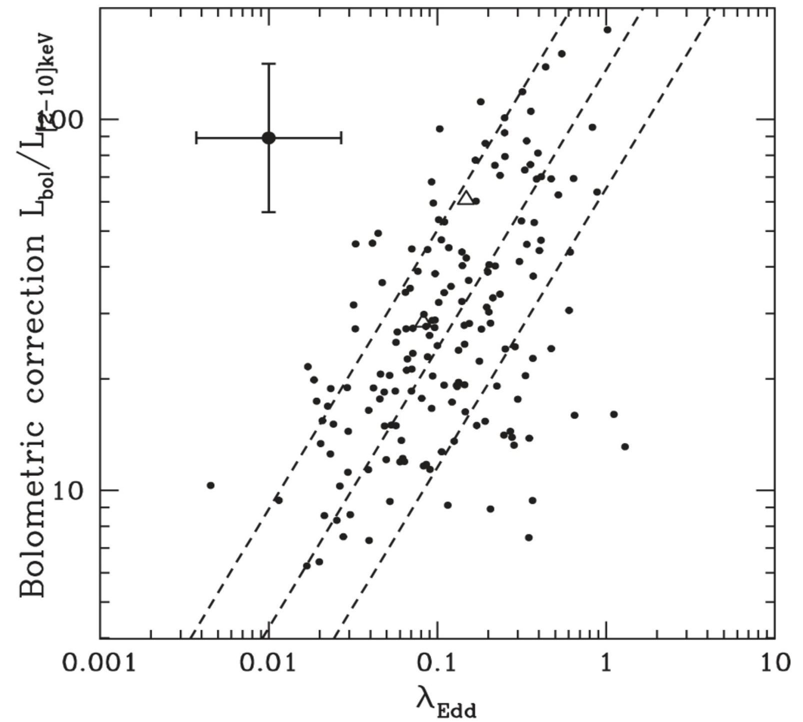
AGN are strong X-ray emitters.

Any galaxy emitting a luminosity $>10^{42}$ ergs/sec in the 2-10 keV band is considered to be an AGN.

X-ray luminosity is a sizeable fraction of L_{bol} in AGN



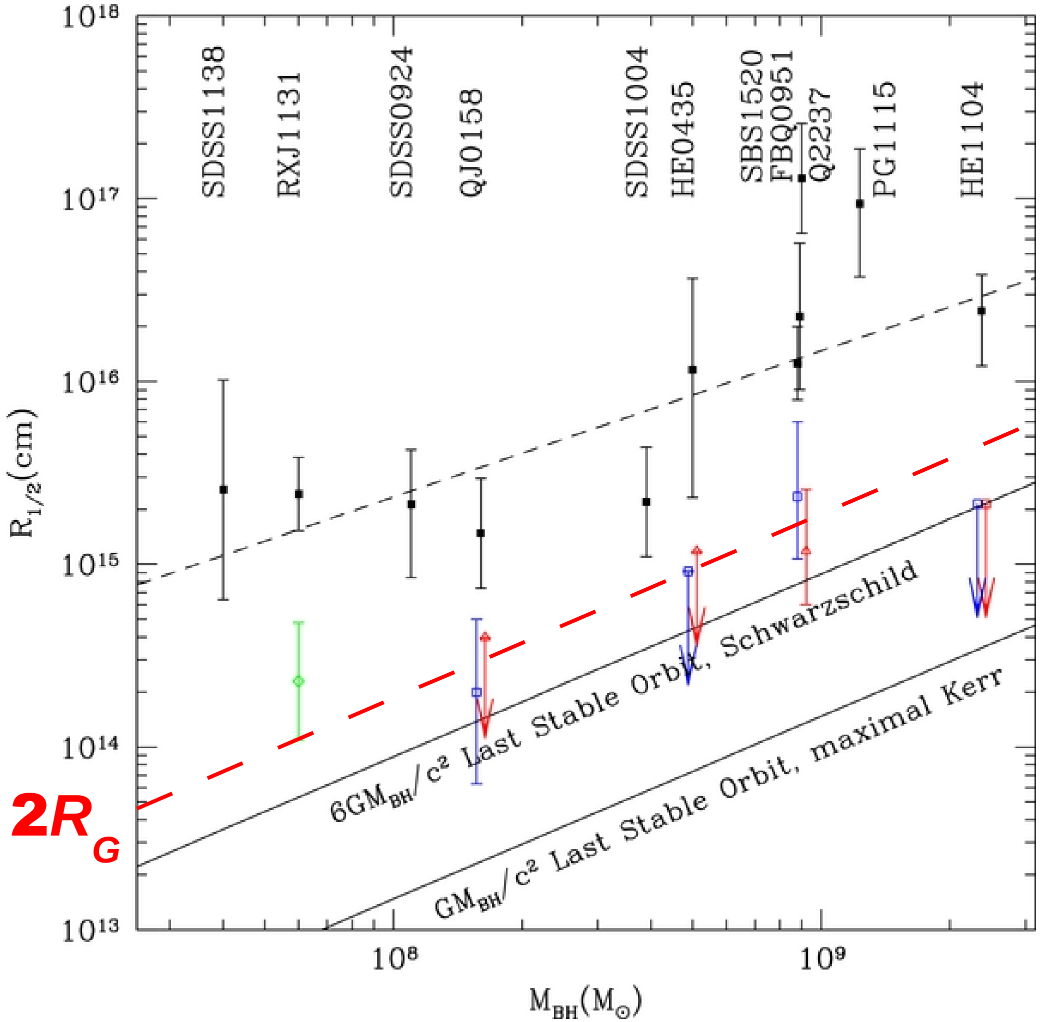
Vasudevan et al. 2009, MNRAS , 399, 1553



Lusso et al. 2012, MNRAS, 425, 623

Microlensing (and variability) studies suggest that the X-ray emitting source is "very small" in size.

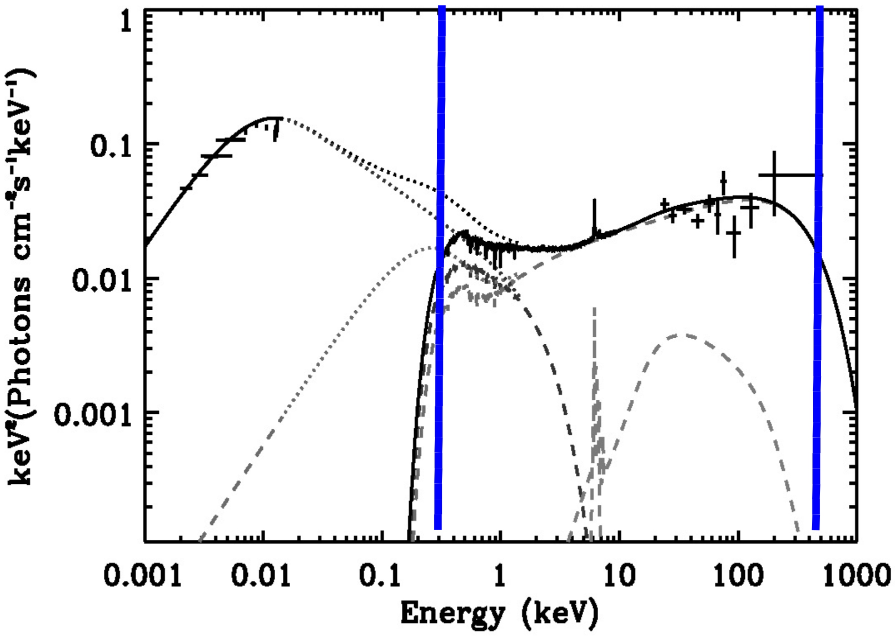
X-rays are produced very close to the central BH



$R_x \leq 12R_G$

Mosquera et al, 2013, ApJ, 769, 53

- ✓ <u>The X-ray spectrum</u> has a power-law like form, which “breaks” at high energies.
- ✓ The shape, and the energy break, are indicative of Compton up-scattering of “soft” photons by “energetic” electrons.
- ✓ At energies > 2 keV, a prominent emission line appears at ~ 6.4 keV



Mrk 506, Petrucci et al 2013, A&A, 549, 73

X-ray emission is highly variable

We observe large amplitude variations, on short time scales

NGC 4151 (Tananbaum et al, 1978, ApJ, 223, 74)

No. 1, 1978 *UHURU* OBSERVATIONS FR

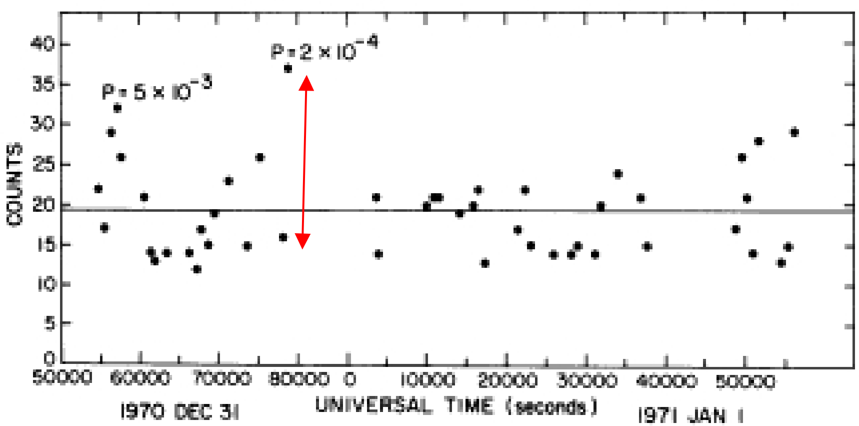
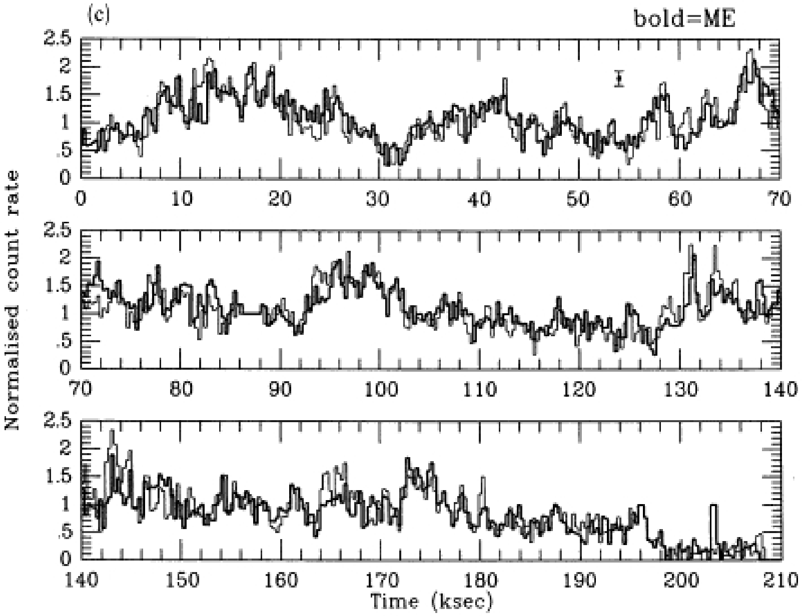


FIG. 1.—Counts observed for each 1.73 s observation for NGC 4151 for UT 1970 December 31 and 1971 January 1. The dots represent the observed source plus background counts for each pass, while the solid line indicates the average source plus background count level. The probabilities are calculated for large enhancements as described in the text and are indicated on the figure.

An increase of the emitted X-ray luminosity of the order of:

~ 5×10^{43} erg/sec in 10 min.

This fast & large amplitude X-ray variability is very common (at all time scales).



NGC4051
(Papadakis & Lawrence, 1995, MNRAS, 272, 161)

X-ray variability of NGC 4051

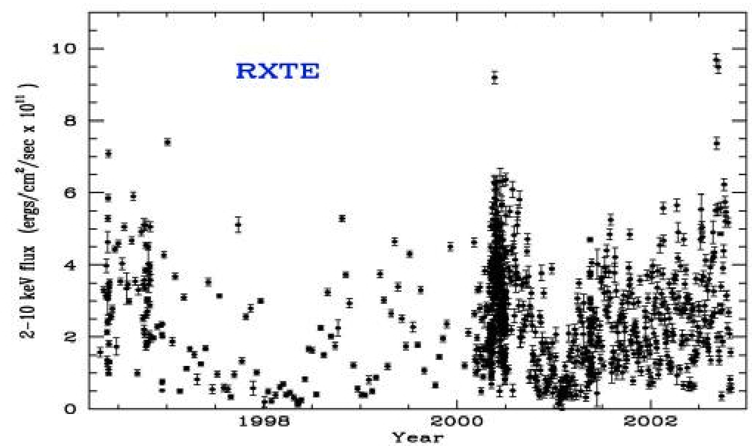
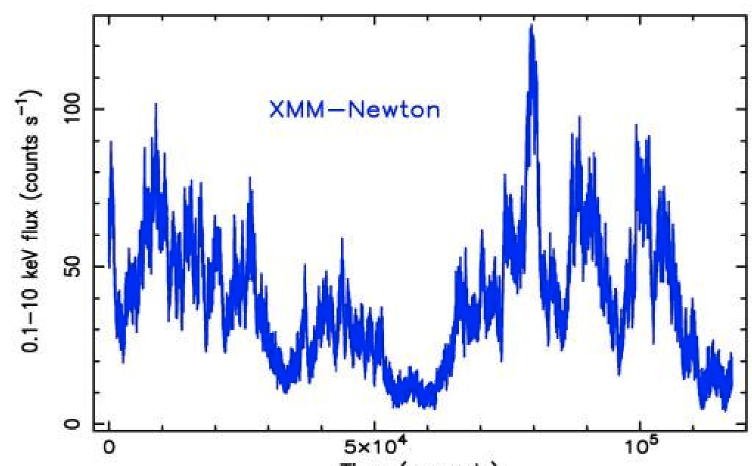
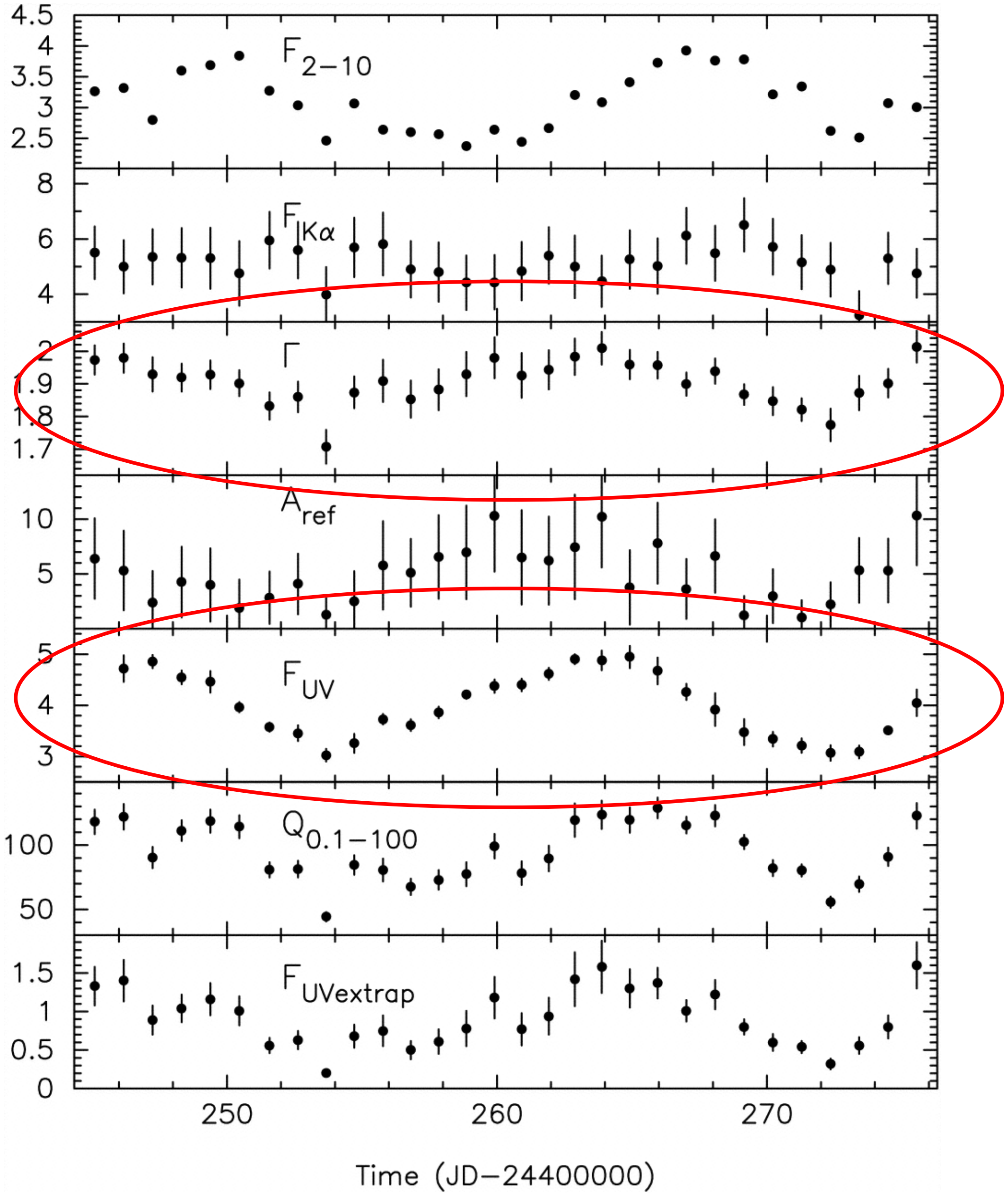


Figure 1. *RXTE* long-term 2–10 keV light curve of NGC 4051. Each data point represents an observation of ~1 ks.



NGC4051
(McHardy et al, 2004, MNRAS, 348, 783)

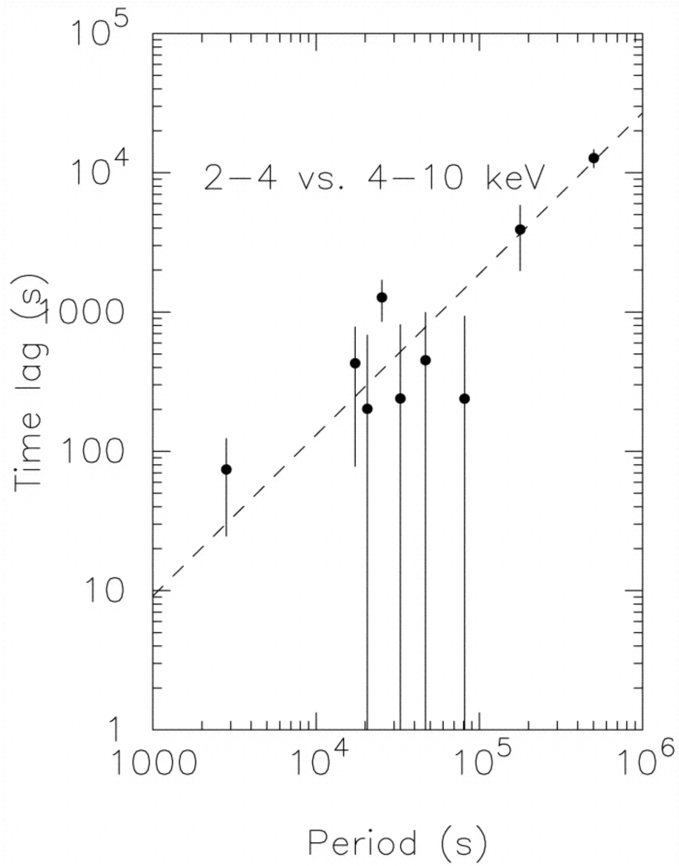
X-ray variability studies offer strong support to the Comptonization idea.

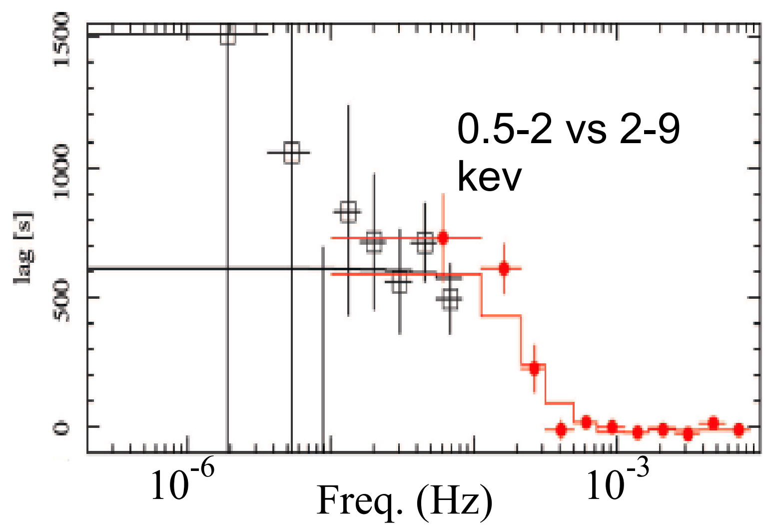


NGC 7469

Nandra et al, 2000, ApJ, 544, 734

The variations in the X-ray “hard” bands are delayed with respect to the variations observed in “softer” bands.





Ark 564

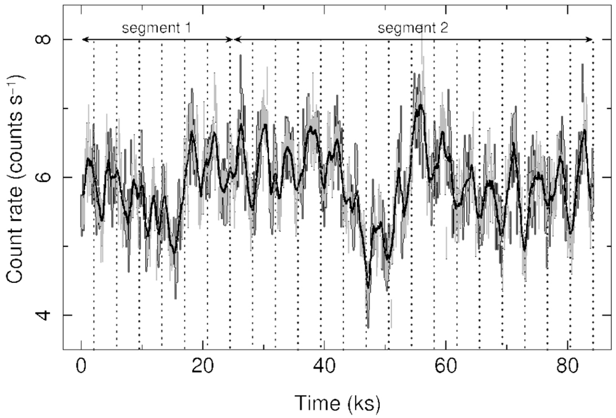
McHardy et al., 2007, MNRAS,382, 985

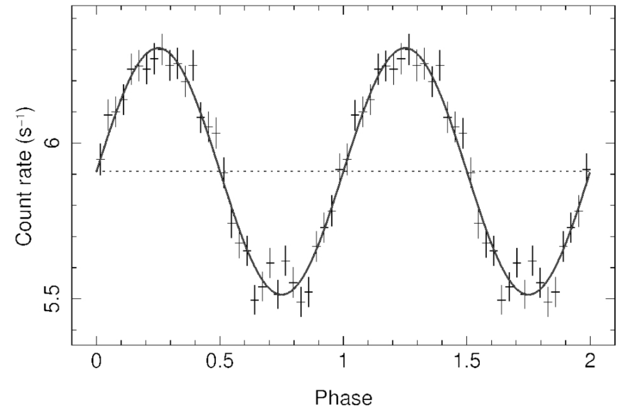
NGC7469

(Papadakis, Nandra & Kazanas, 2001, ApJ, 554, L133)

TX-ray variations are not periodic

Except from RE J1034+396 (Gierlinski et al., 2008, Nature, 455, 369).



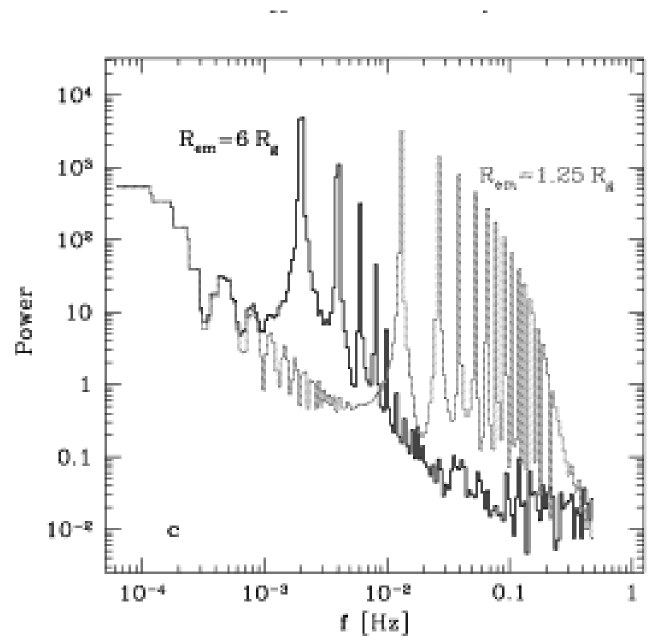


The absence of periodic variations is puzzling.

If X-rays were produced in compact regions co-rotating with a Keplerian accretion disc, concentrated toward the inner disc edge around the BH,

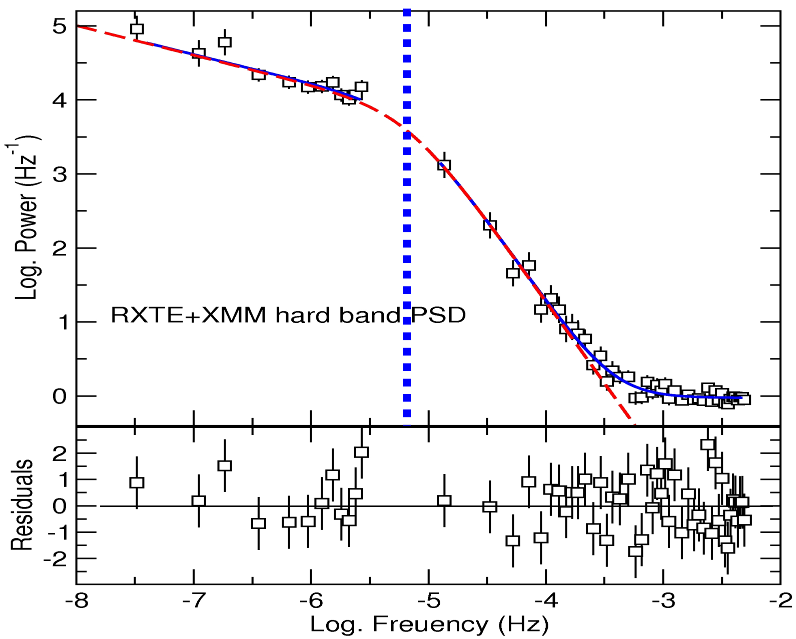
then

the X-ray emission should be modulated in time by strong Doppler effects.



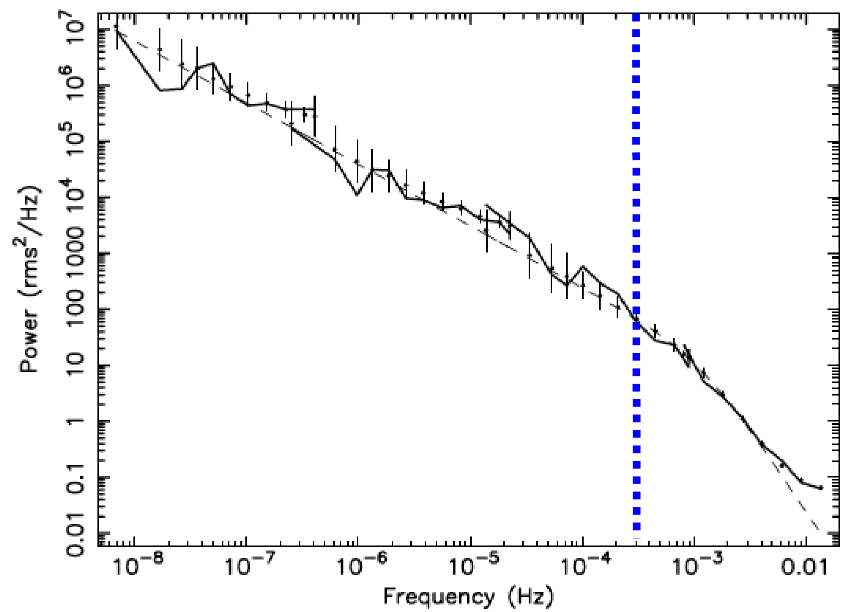
Życki & Niedźwiecki, 2005, MNRAS, 359, 308

Nevertheless, *'characteristic time scales'*, have been detected in ~20 AGN.



PKS 0558-504

(Papadakis et al, 2010 A&A, 518, 28)



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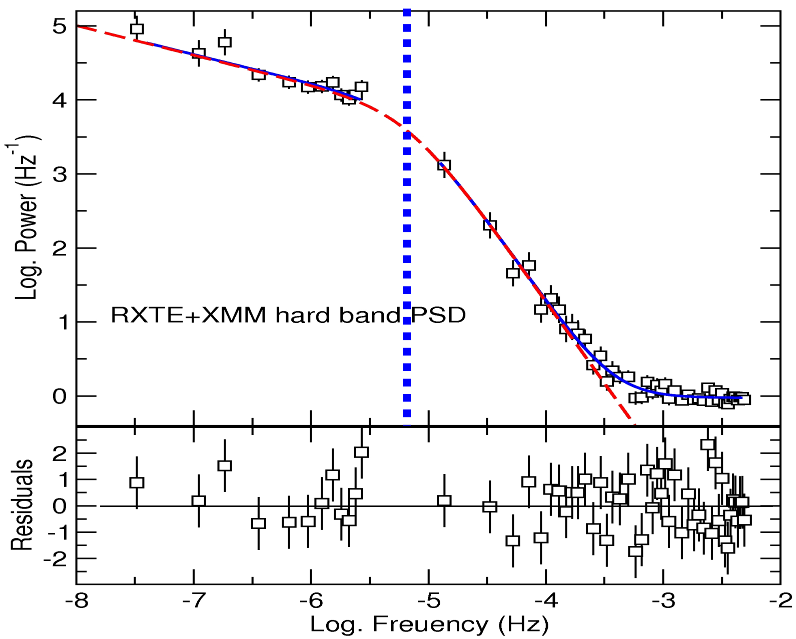

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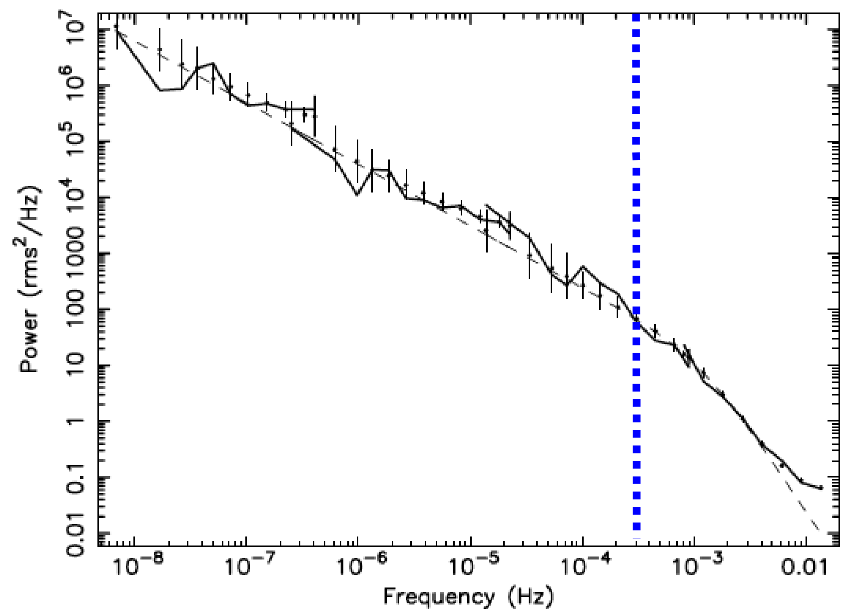
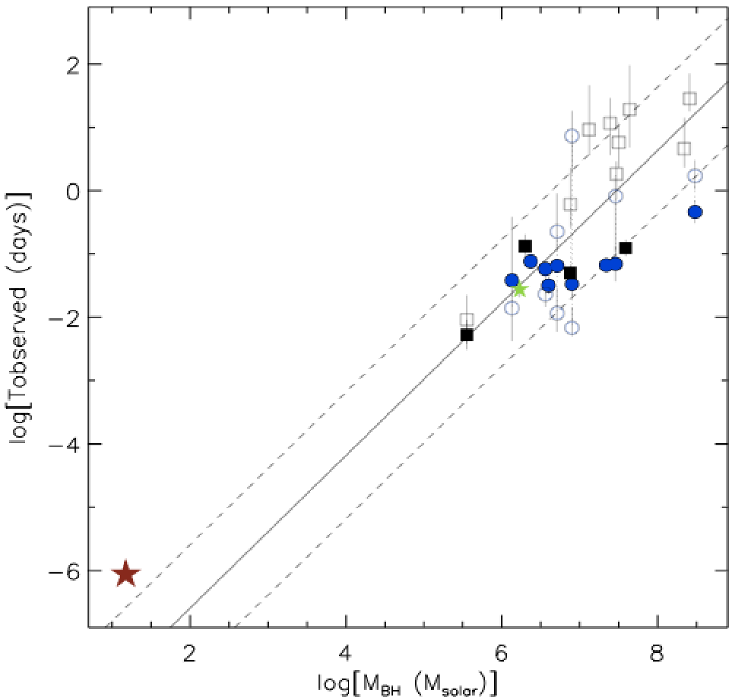
(Papadakis et al, 2010 A&A, 518, 28)



NGC4051
(McHardy et al, 2004, MNRAS, 348, 783)

T_{br} scales linearly with BH mass:

$$T_{br}(\text{days}) \sim 0.02(M_{BH}/10^6\ M_\odot)$$



(González-Martín & Vaughan, 2012, A&A, 544, 80)

It is also possible that:

$$T_{br} \propto \left(\dot{m}_E\right)^{-1}$$

(McHardy et al, 2006, Nature, 444, 730)

Thesee results can help us understand the physical processes in the innermost region of AGN

Is it possible that T_{br} is associated with one of the basic timescales for a Keplerian, geometrically-thin and optically-thick disc?

$$t_{dyn}(R_3)=10^4\, R_3^{3/2}\, M_8\ (s)$$
$$t_{sound\text{-}r}(R_3)=T_{dyn}\ (r/h_d)\ (s)$$
$$t_{th}(R_3)=10^5\ (\alpha_{0.1})^{-1} R_3^{\ 3/2}\, M_8\ (s)$$
$$t_{visc}(R_3)=10^7\ (\alpha_{0.1})^{-1}(r/h_d)^2 R_3^{\ 3/2}\, M_8\ (s)$$

(where R_3=(distance from the center)/3R_S, and $M_8=M_{BH}/10^8\ M_{sun}$).

All these time scales increase with increasing M_{BH}, hence we should expect : $T_{br} \propto M_{BH}$ (as observed).

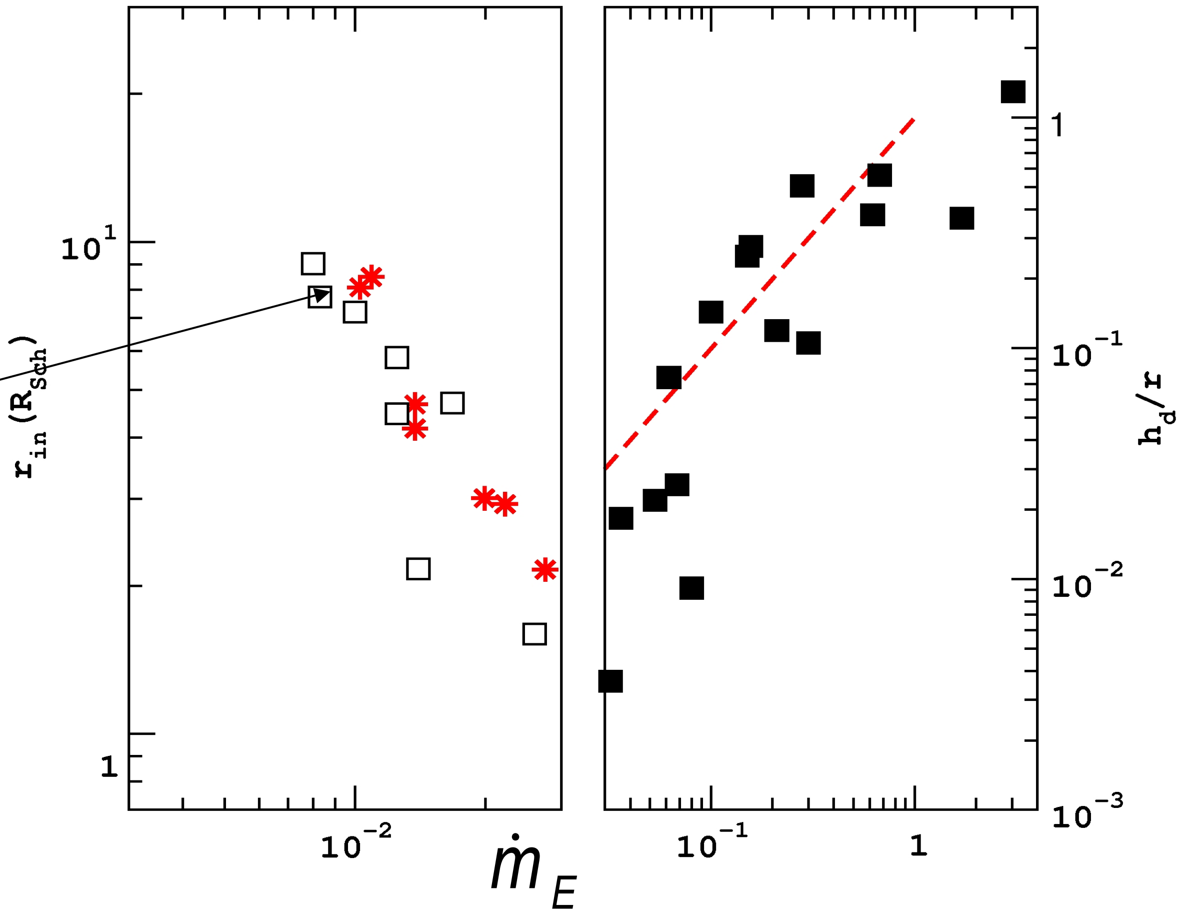
But why should, $T_{br} \propto \left(\dot{m}_E\right)^{-1}$ *(ie of the accretion rate normalized to Eddington units)* as well?

A possible scenario:

a) T_{br}=$T_{sound\text{-}r}$(r_{inner}) and r_{inner} decreases with increasing $\dot{m}_E$, up to $\dot{m}_E$ = 0.03, then

b) T_{br}~$T_{sound\text{-}r}$($5R_{SCH}$), and (h_d/r) ∝ $\dot{m}_E$

r_{inner} data for XTE J1817-330 (Cabanac et al, 2009)



After almost 40 years of intensive observational and theoretical effort, we know that:

There is a copious production of X-rays from AGN...

… in a “mysterious” source (how are the electrons heated/accelerated?)

… which is very small in size, and very close to the central source...

(almost certain of that)

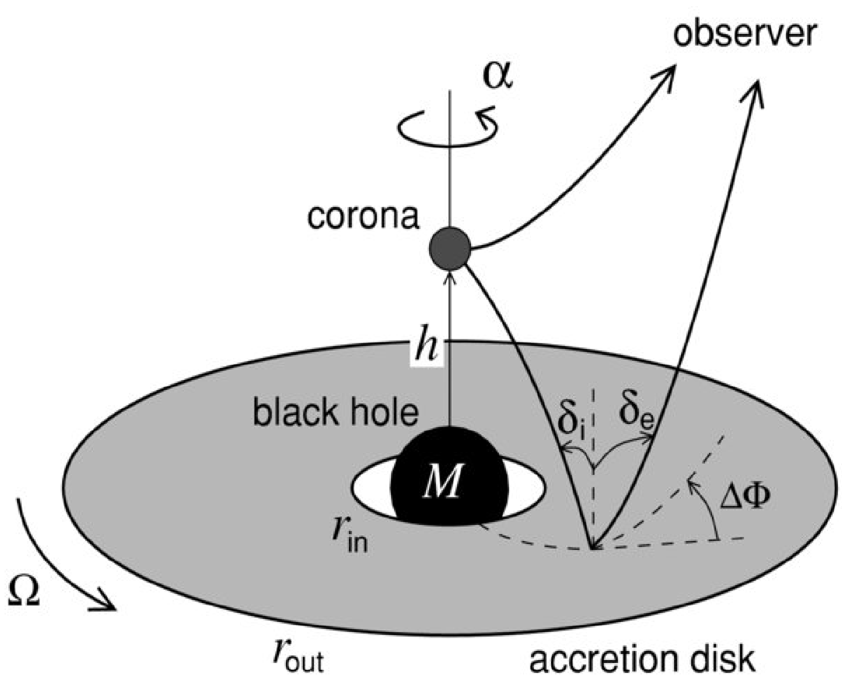
… located either above the disc, or

in the same plane with the disc ...

Is there a way to find out what is going on? Well...

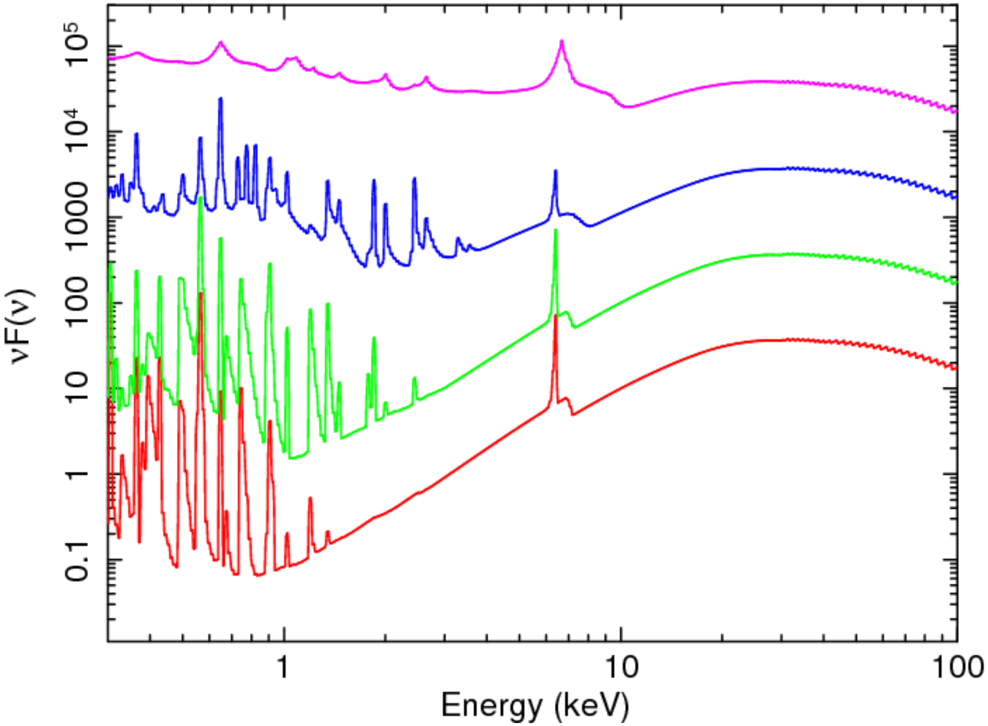
Suppose that:

- ✔The X-ray source is compact,
- ✔ it is located above the disc, on the axis of symmetry of the system, at height *h*, and
- ✔emits isotropically (in its rest-frame)



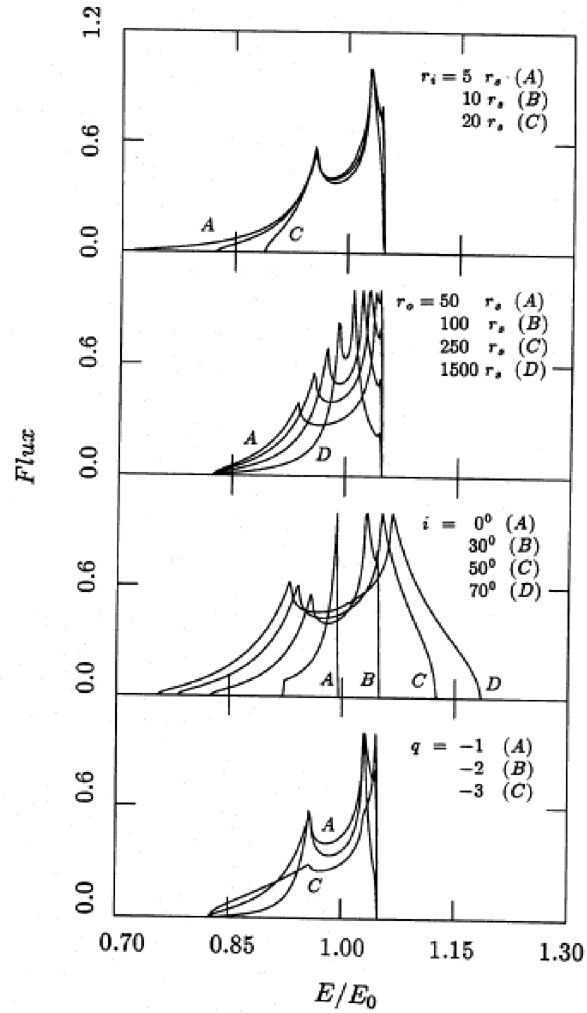
In this case,
the inner disc,
will be irradiated by the
X-ray source,
and will produce a
"reflection" spectrum

Which is rather complex



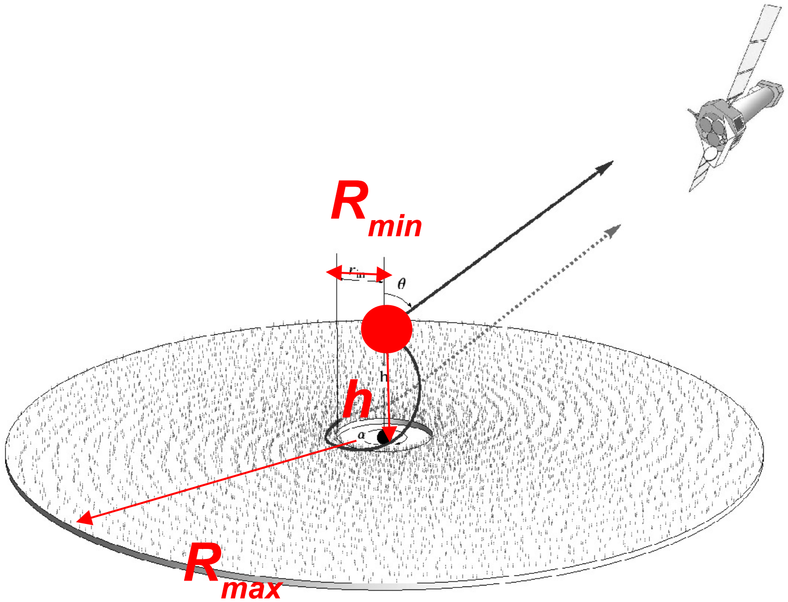
George & Fabian, 1991, MNRAS, 249, 352
Ross & Fabian, 2005, MNRAS, 358, 211

...which will become even more complex, due to GR ("gravitational redshift") and Doppler effects.



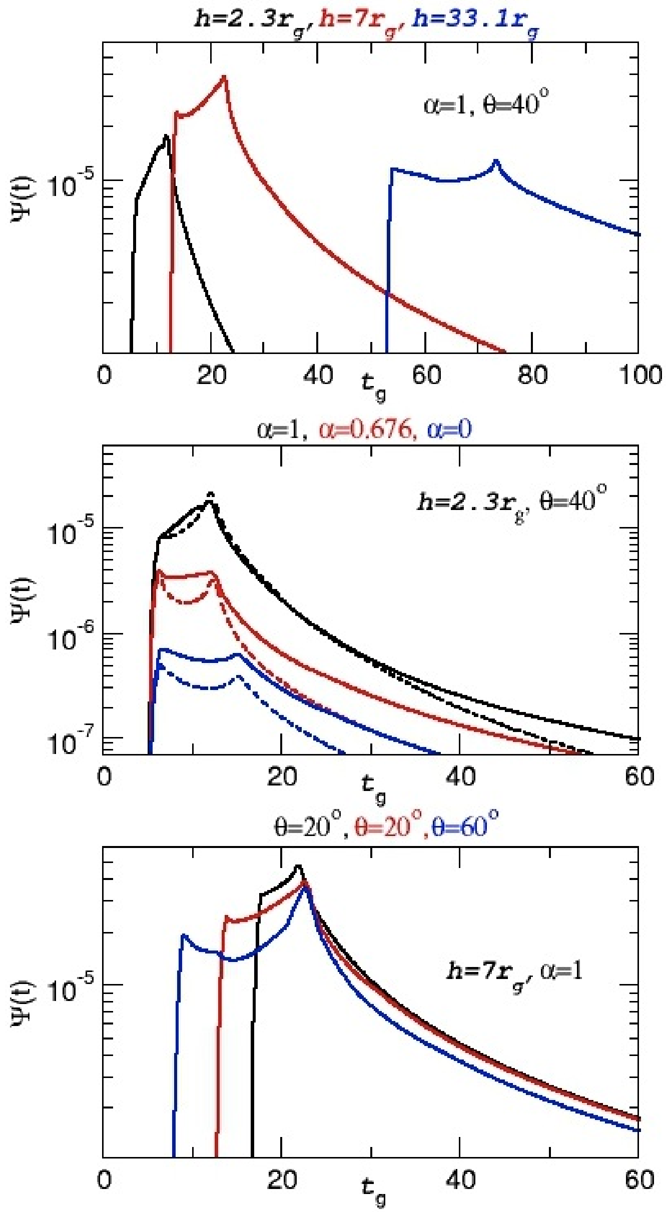
Fabian et al, 1989, MNRAS, 238, 729

Suppose now the X-ray source is also variable.



We expect in this case the disc to respond to the X-rays (with a delay).

The disc response should depend on: ***h, R_{min}***, ***BH mass***, and inclination.



Papadakis et al, 2016, A&A, 588, 13

In this case:

$$F_{obs,E}(t) = \int_{-\infty}^{\infty} \psi_E(t-\xi)\, N_{lamp}(\xi)\, d\xi$$

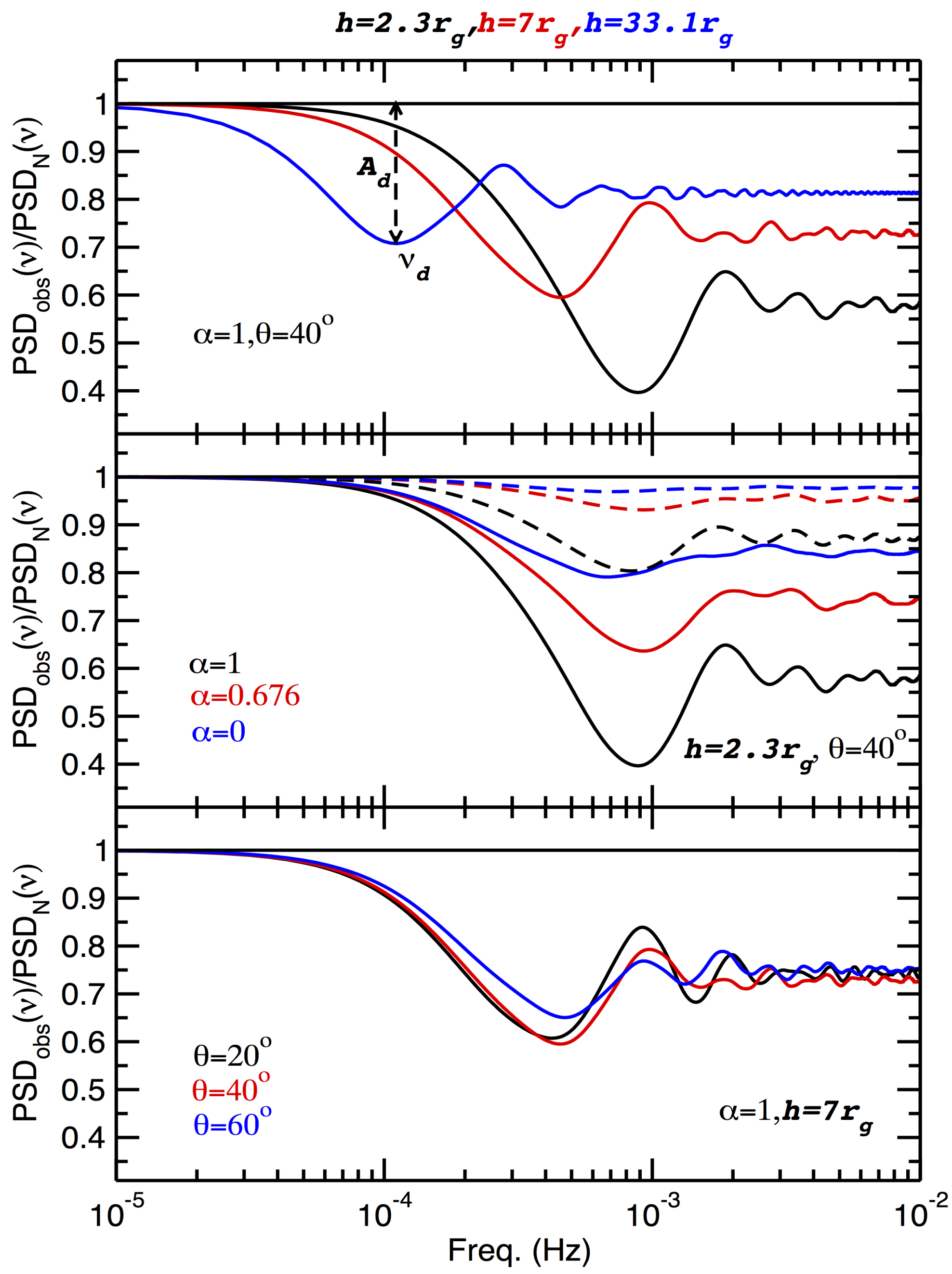
And, hence

$$PSD_{obs,E}(v) = |\Gamma(v)|^2\, PSD_N(v),$$

Where

$$\Gamma(v) = \int_{-\infty}^{\infty} \psi_E(t) \exp(-i2\pi v)\, dt.$$

Therefore,
by dividing the observed power-spectrum
with the intrinsic,
one can estimate the disc "transfer" function.



AGN are highly luminous in X-rays

Their X-ray emission is highly variable.

The study of the X-ray variability can help us understand *i)* the origin of the X-ray emission in AGN, and *ii)* the geometry in their innermost region.

It can provide conclusive evidence for the presence of the accretion disc close to the BH, and information regarding its structure.