X-ray reverberation studies of AGN

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Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο

ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
ΕΚΠΑΙΔΕΥΣΗ ΚΑΙ ΔΙΑ ΒΙΟΥ ΜΑΘΗΣΗ
επένδυση στην κοινωνία της γνώσης
ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ ΚΑΙ ΘΡΗΣΚΕΥΜΑΤΩΝ
ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ

ΕΣΠΑ
2007-2013
πρόγραμμα για την ανάπτυξη
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ

Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

Active Galactic Nuclei (AGN):

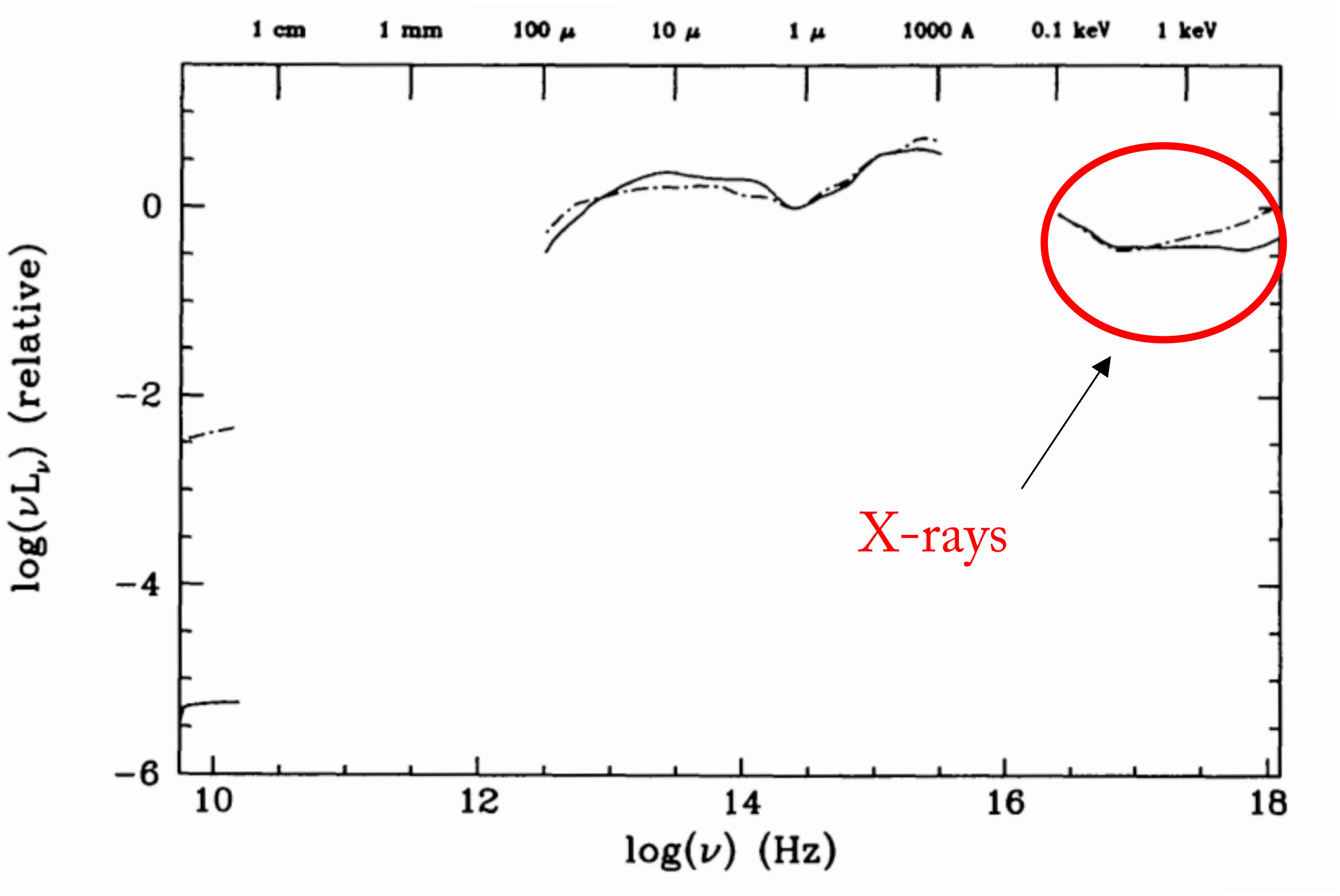
Nuclear regions in a “few” nearby galaxies (~10% of all nearby galaxies) which exhibit phenomena that *cannot* be explained by stellar processes (large luminosities at all wavelengths, fast and large amplitude variations, jets, strong and broad optical/UV emission lines).

Current Paradigm:

Central engine: accretion of matter onto Super-Massive Black Hole (10^6-10^7 solar mass), in the form of a geometrical thin, optically thick disc.

AGN emit X-rays

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

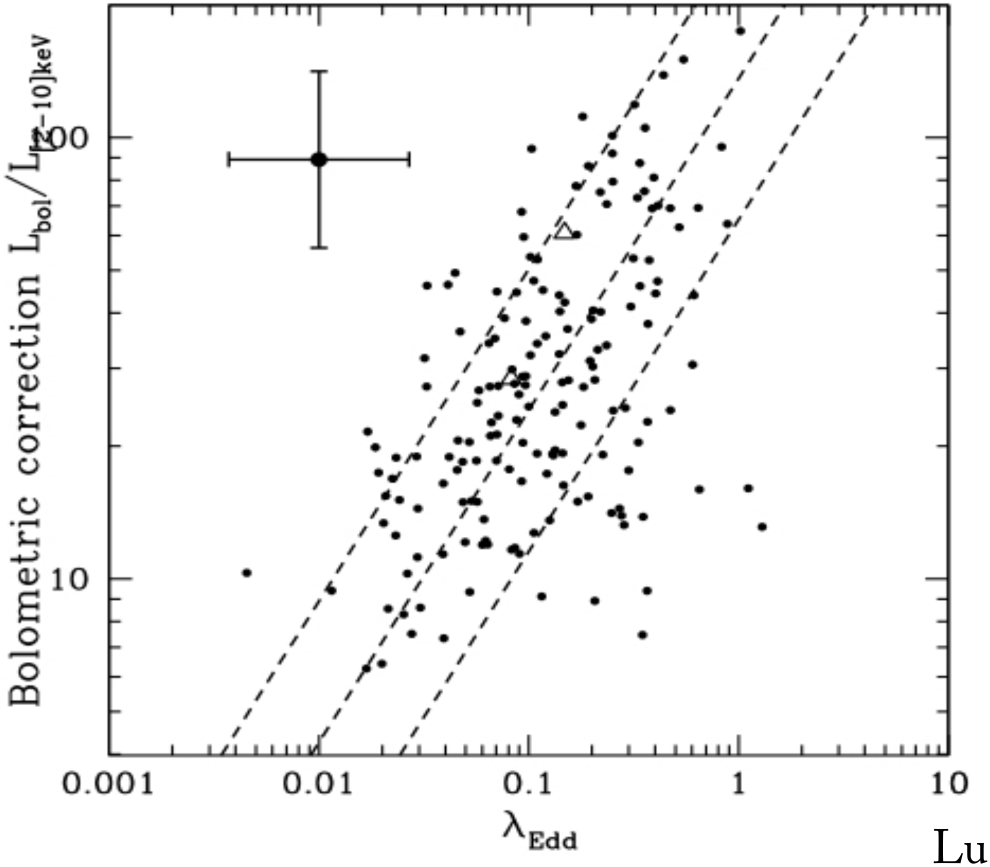


X-rays

Elvis et al, 1994, ApJS, 95, 413

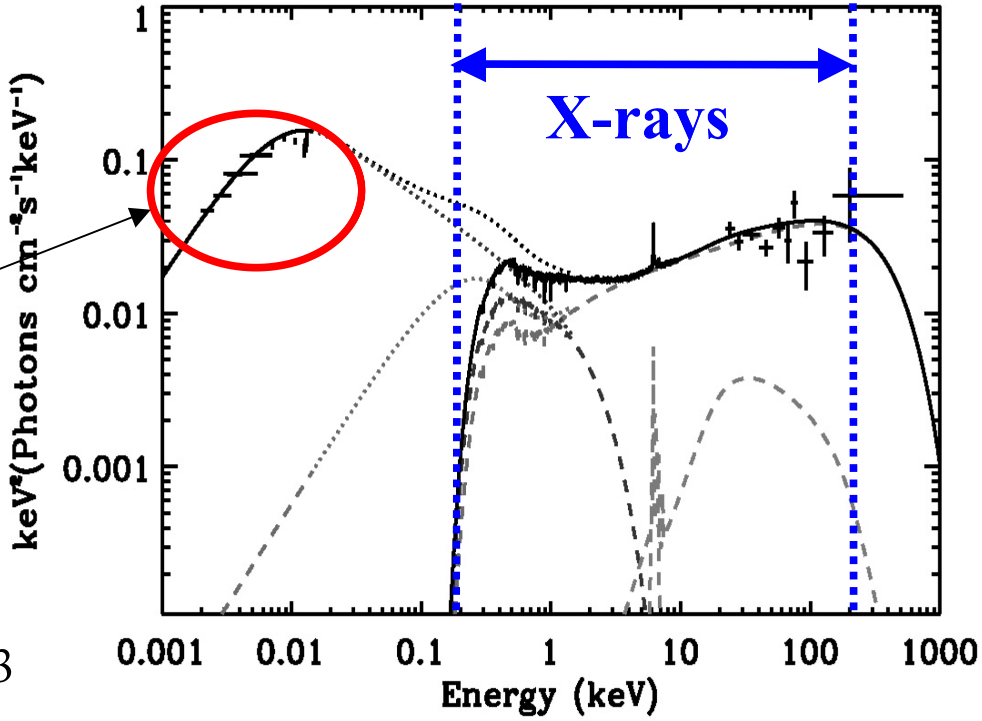
AGN are strong X-ray emitters.

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



Lusso et al, 2012, MNRAS, 425, 623

- ✓ The X-ray spectrum 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 in an “X-ray corona”.
- ✓ At energies > 2 keV, a prominent emission line appears at ~ 6.4 keV

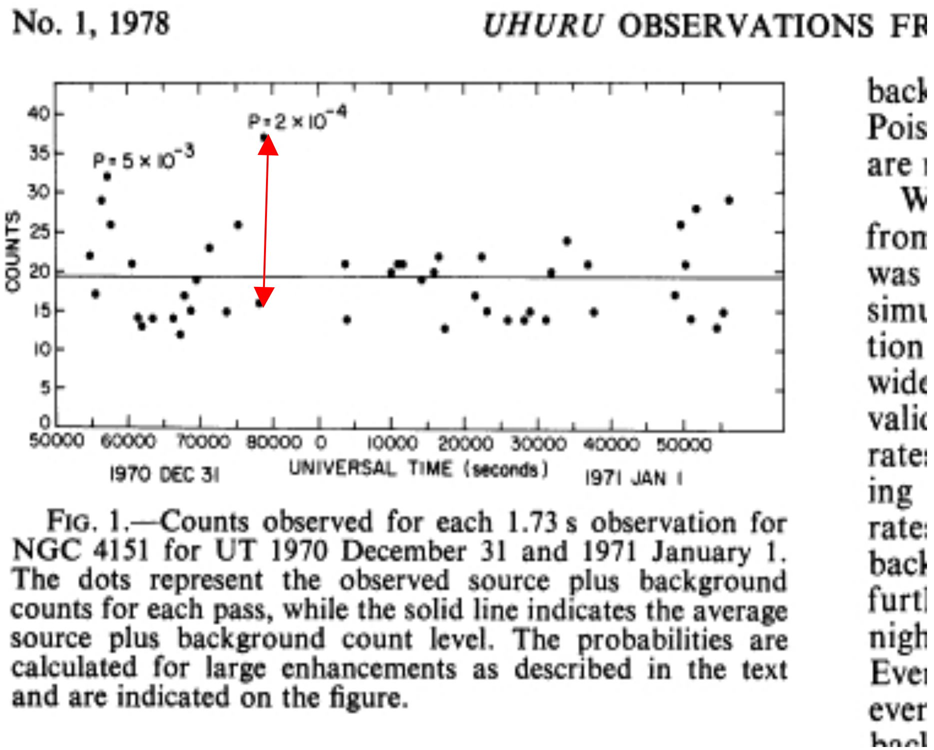


Disk emission

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



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.

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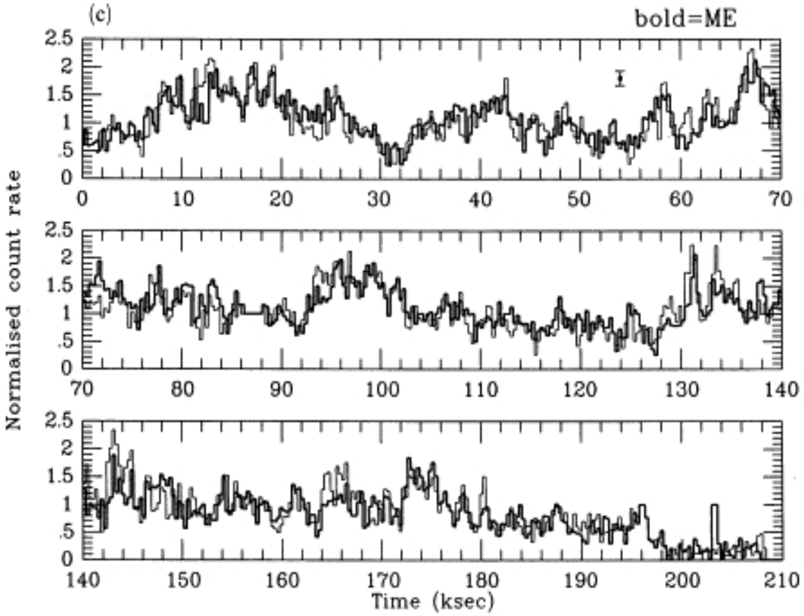
An increase of the emitted X-ray luminosity of the order of:

~ 5×10^{43} erg/sec in 10 min.

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

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

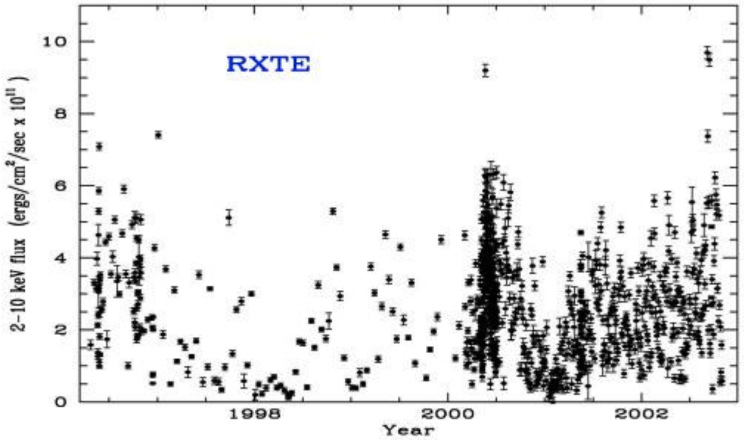
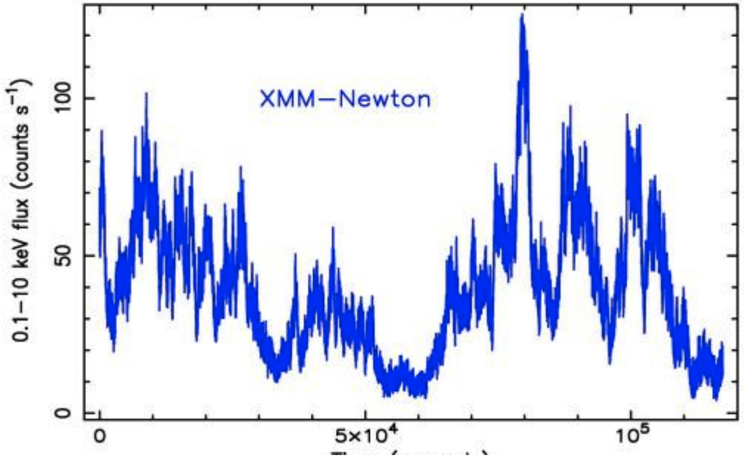


Figure 1. *RXTE* long-term 2–10 keV light curve of NGC 4051. Each data point represents an observation of ~1 ks.

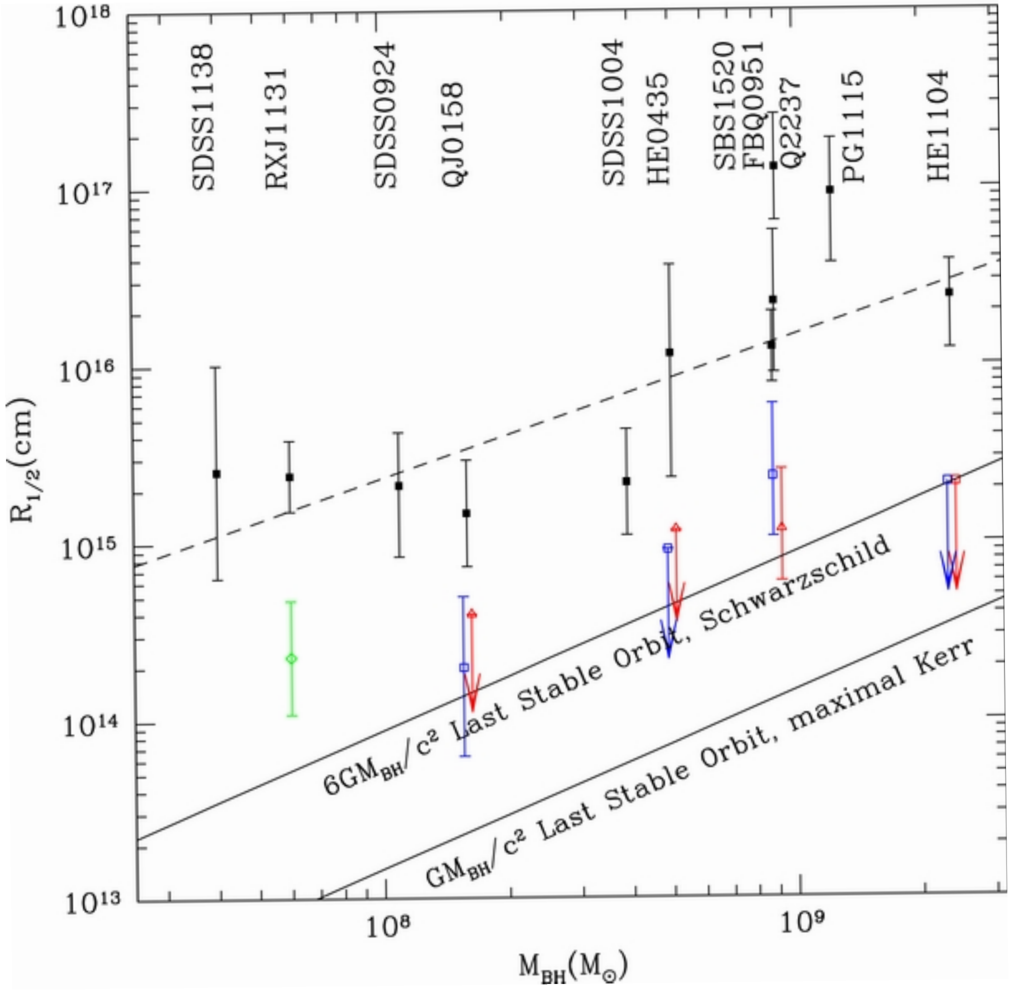


NGC4051

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

Variability studies suggest that the X-ray emitting source is “very small” in size.

This is verified by recent micro-lensing studies.



Mosquera et al, 2013, ApJ, 769, 53

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

But we still do not know:

✓The physical mechanism that powers the X-ray corona
✓The physical mechanism that is responsible for the X-ray variability
✓The "corona/disc" geometry

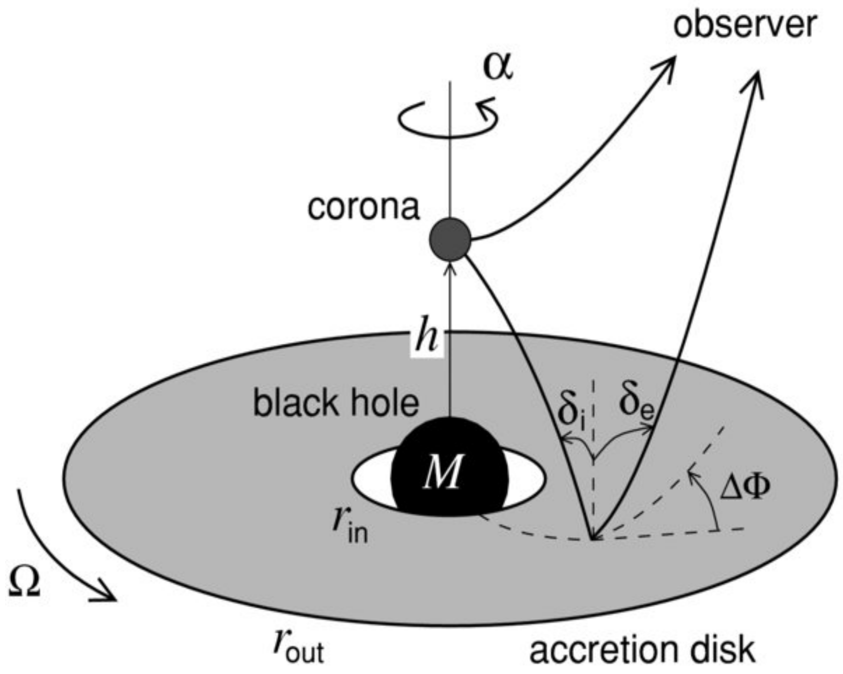
Is there a way to find out what is going on?
Well…

Suppose that:

✓ the X-ray source is compact,

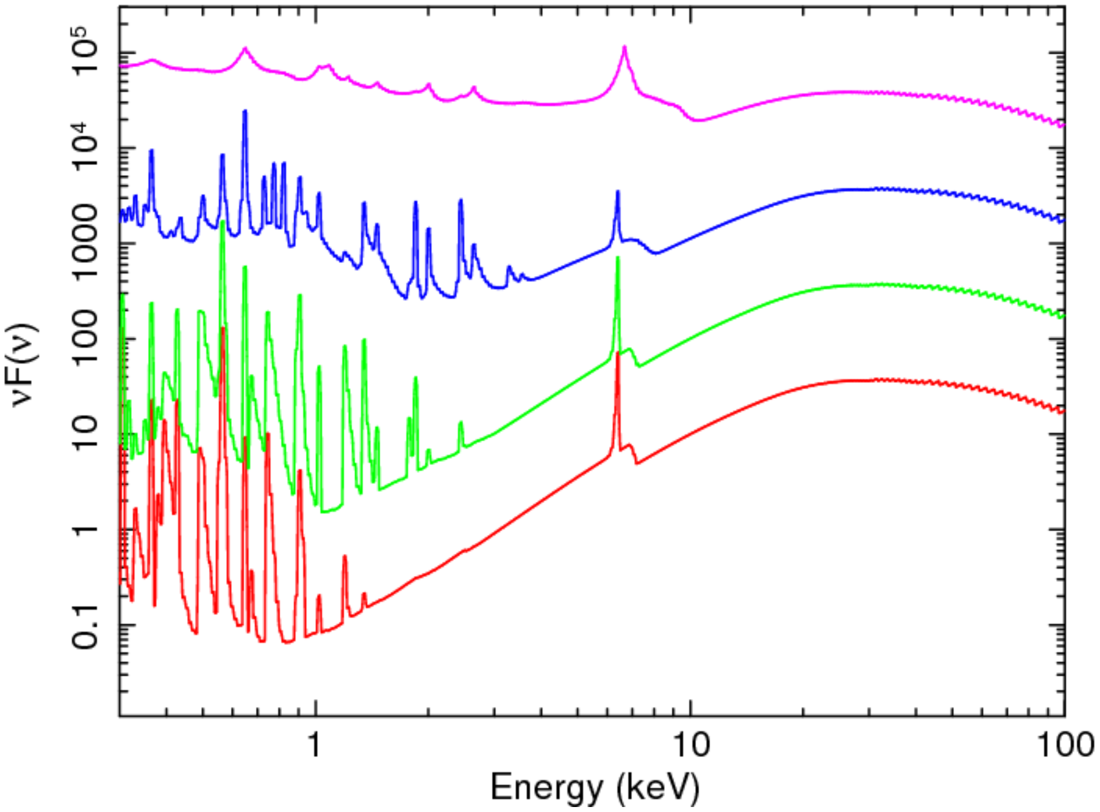
✓ it is located above the disc, on the axis of symmetry of the system, at height *h*, and

✓emits isotropically (in its rest-frame)



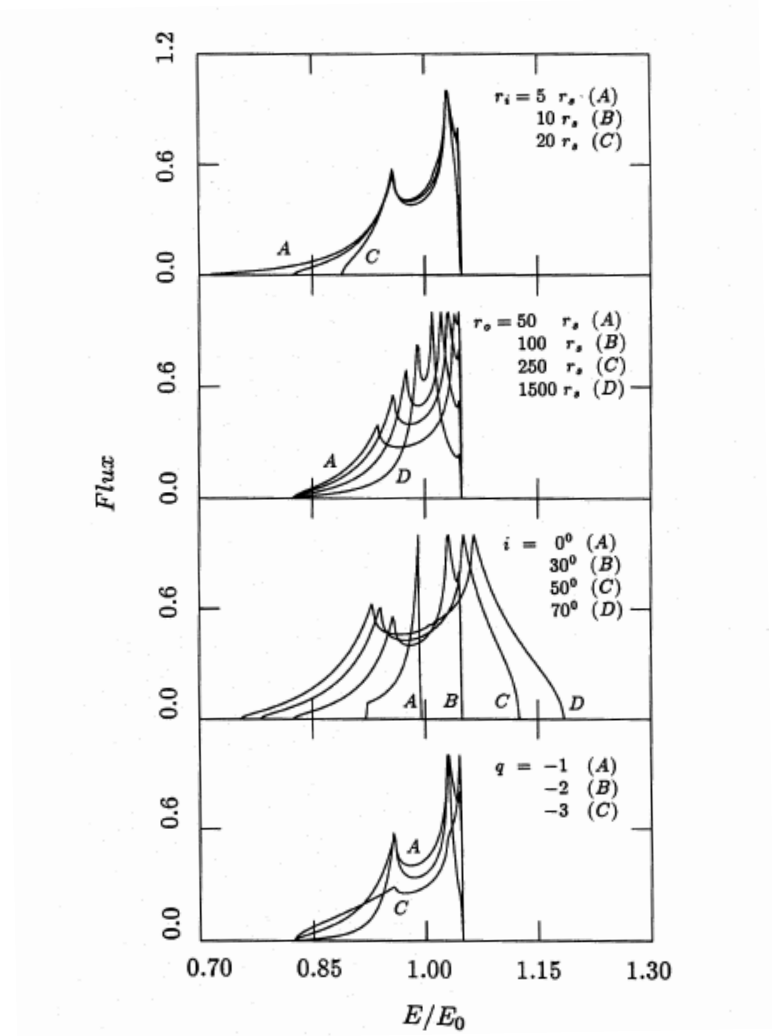
In this case,
the inner disc,
will be irradiated by the
X-ray source,
and will produce a
“reflection” spectrum

Which is rather complex



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

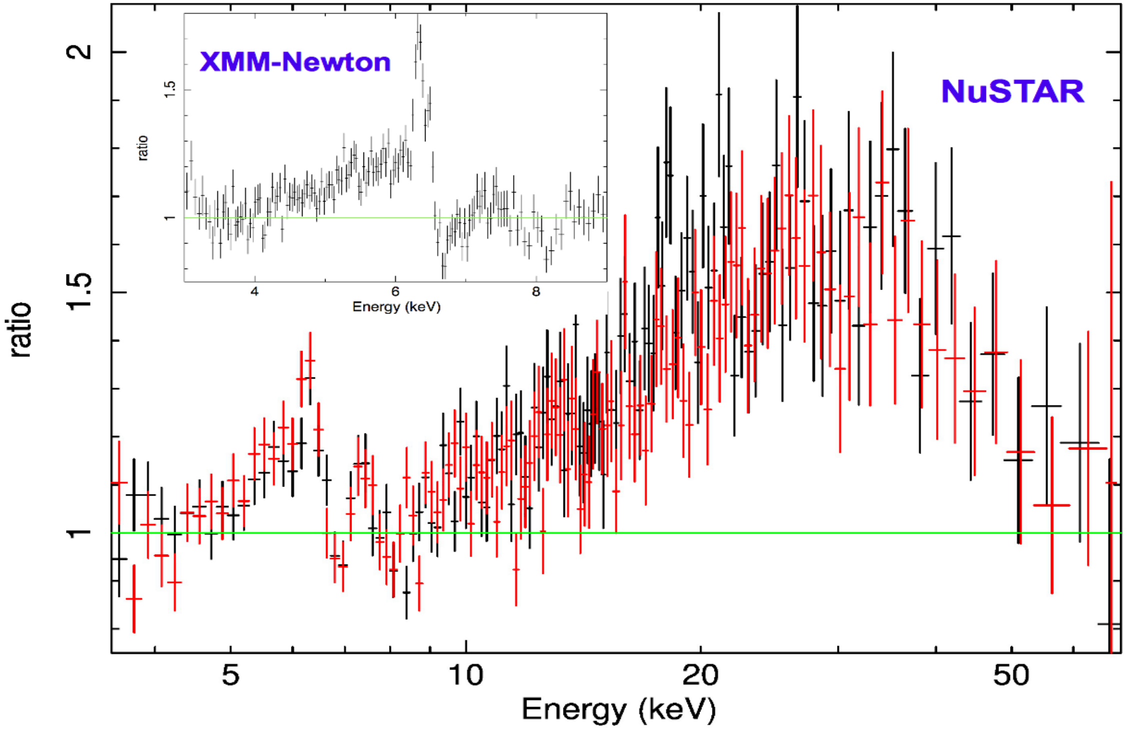
…which will become even more complex, due to GR (e.g. “gravitational redshift”) and Doppler effects.



Fabian et al, 1989, MNRAS, 238, 729

NGC 1365

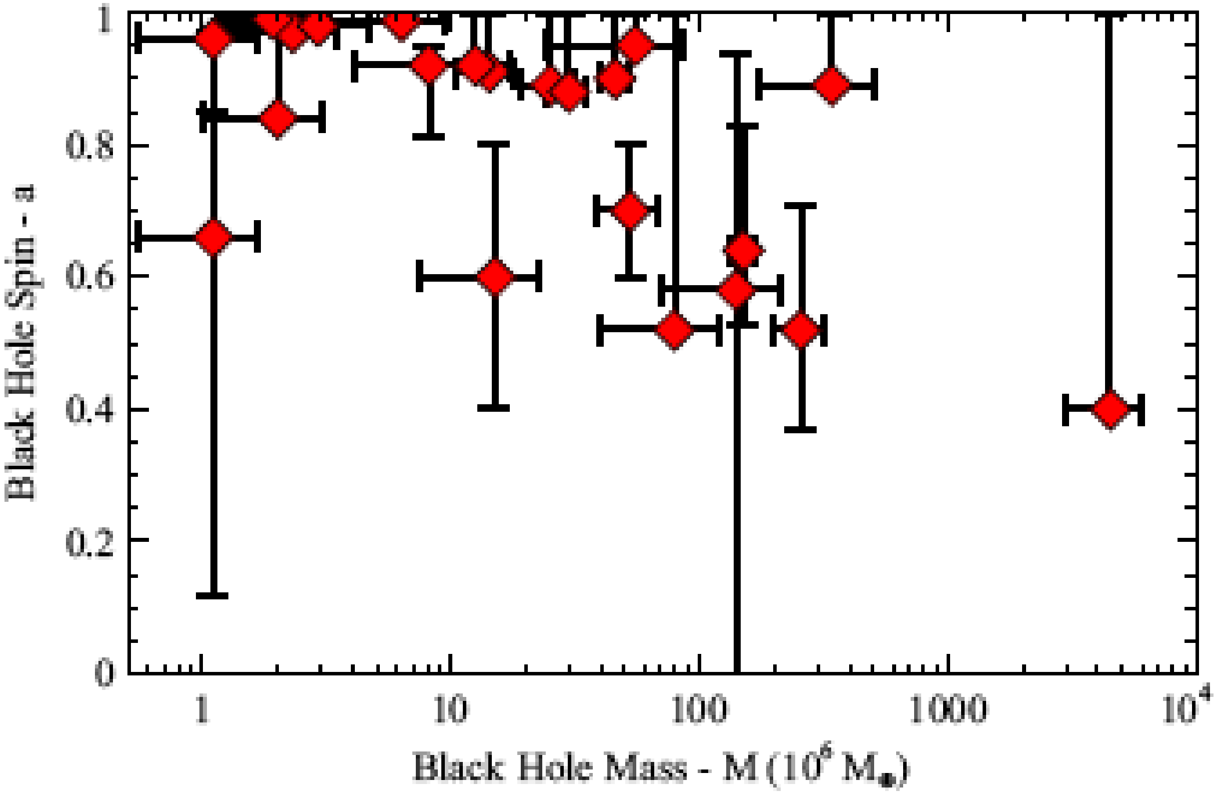
(Risaliti et al, 2013, Nature, 494, 449)



Spectral modeling of the iron Kα line in AGN has been a very active area of research the last 20 years. The aim is to:

a) confirm the presence of relativistic effects

b) estimate the black hole spin, and determine the disc/X-ray geometry.



Vasudevan et al, 2015 (in press)

X-ray reverberation

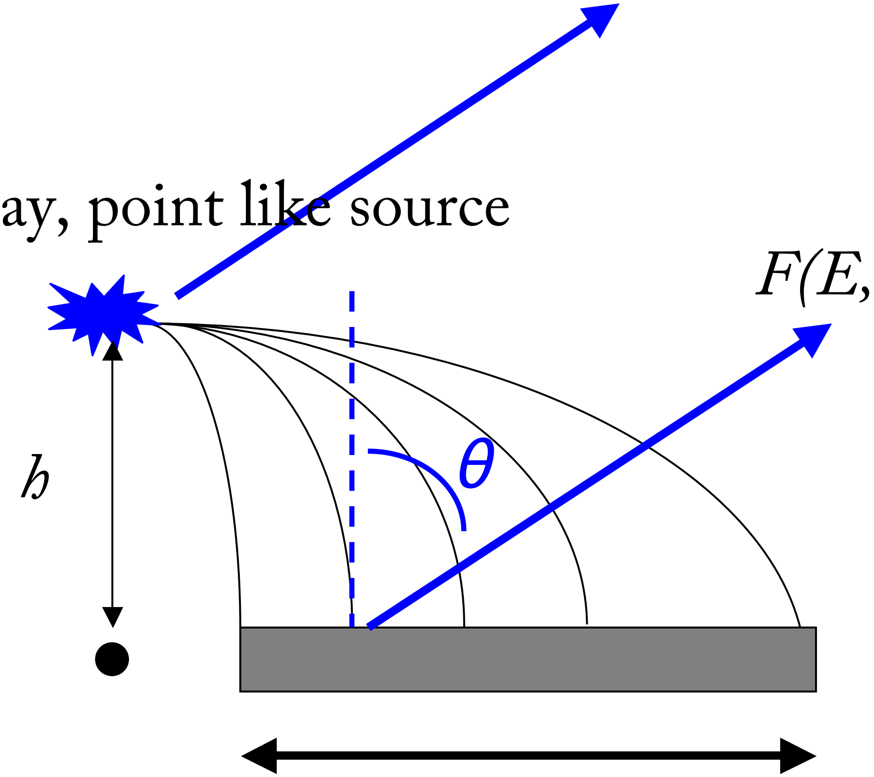
Suppose now the X-ray source is also variable.

We expect in this case the disc to respond to the X-rays

with a delay

which should depend on h, r_{min}, *BH mass*, and inclination

$$F(E,t)_{primary}=D(E)\times\underbrace{N(t)\times E^{-\Gamma}\exp(-E/300)\ \mathrm{keV})}_{F(E,t)_{intrinsic}}$$



X-ray, point like source

$$F(E,t)_{refl}=\int_0^\infty \boxed{\Psi_E(t-\xi)}F(E,t)_{intrinsic}d\xi$$

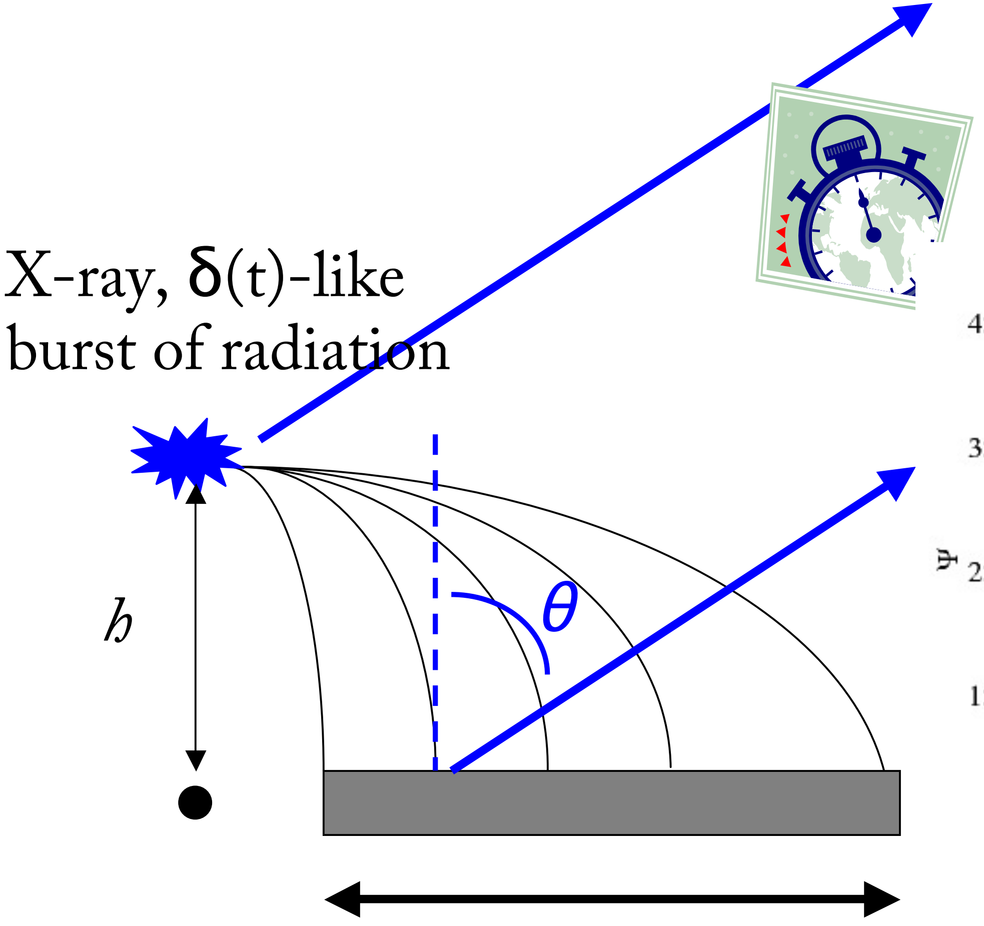
“disc response function”

$r_{in}=r(ISCO)=f(\alpha)$

$r_{out}=1000\ r_g$

Keplerian disc,
co-rotating with BH

The disc response function

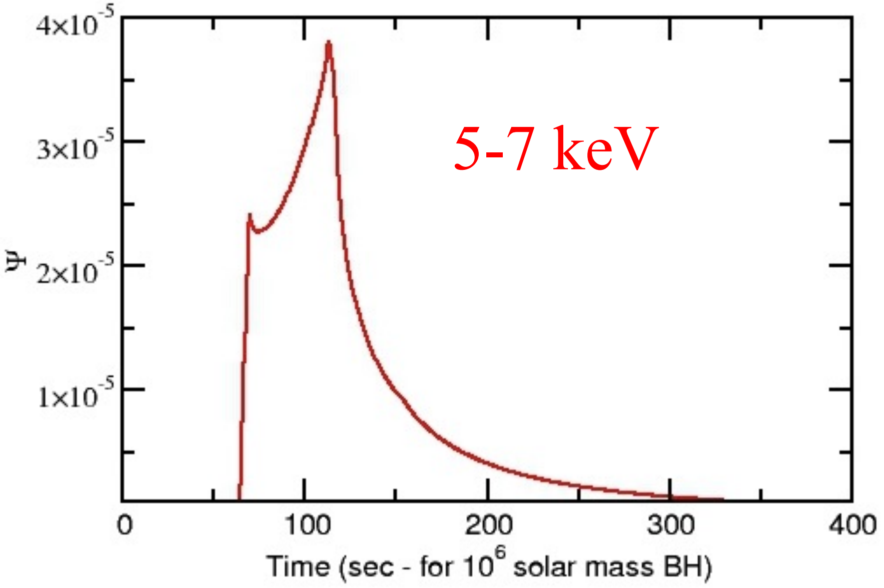


X-ray, δ(t)-like burst of radiation

$r_{in}=r(ISCO)=f(\alpha)$

$r_{out}=1000\ r_g$

$t_0=0$ is the time we detect the primary photons. After some time, we detect the reflection component photons as well.



$\Psi=f(h,r\text{-in},r\text{-out},\theta,E)$

The (first) idea now is the following:

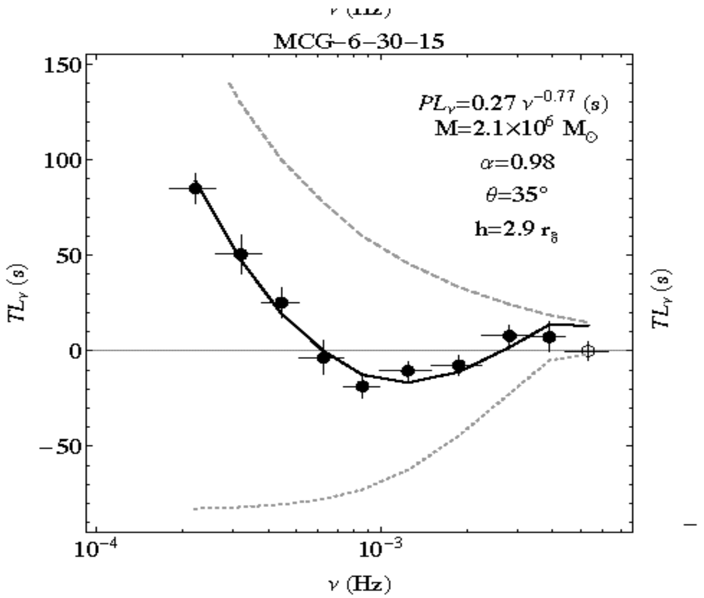
1) Choose an energy band which is dominated by the X-ray continuum (2-4 keV)

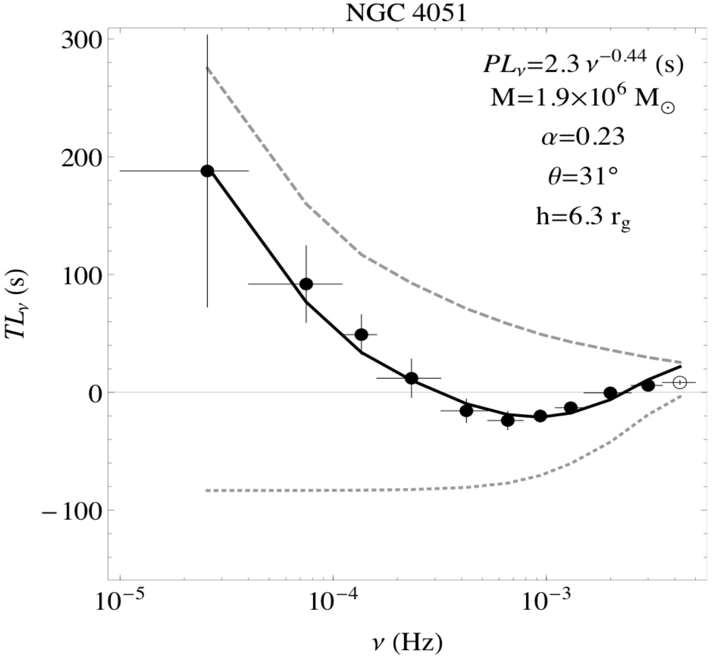
2) Choose a second energy band where the reflection spectrum from the disc contributes significantly to the observed flux (0.3-1 keV or 5-7 keV or 15-30 keV)

3) Estimate the “delays” between the variations observed in the light curves of the two energy bands, and

4) Compare what you observe with what you predict.

The aim is to:
a) confirm the presence of relativistic effects
b) estimate the black hole spin, and determine the disc/X-ray geometry.





Emmanoulopoulos et al
(2014,MNRAS, 439, 3931)
estimated the “time lags spectrum”, between “soft” and “continuum”, for 12 AGN, using all the available data to the XMM-Newton archive (~0.5-1 Msec for each one).

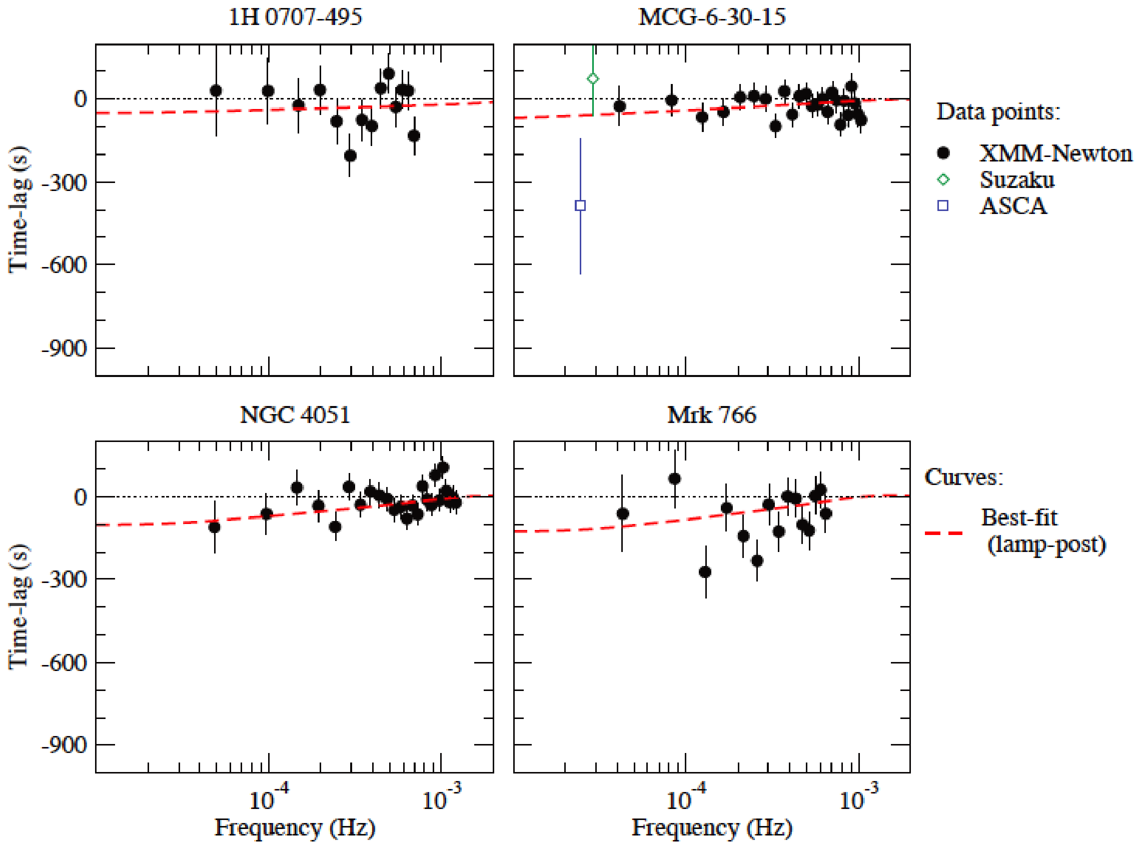
✓The “X-ray reflection” scenario of the inner is fully consistent with the observations.

✓X-ray source is point-like

✓Its height is less than a few r_g

We have studied the the iron line vs continuum time lags in 7 AGN using XMM-Newton (net exposure > 320 ks).

We have estimated the time lags as accurately as possible.



Epitropakis et al, in prep.

The data are consistent with:

Kerr BHs,

X-ray source compact

Source height small

We can also think as follows:

The observer detects the continuum from the source and the signal from the disc.

This is a smeared and delayed “echo” of the continuum.

Choose an energy band where the reprocessed signal from the disc is significant.

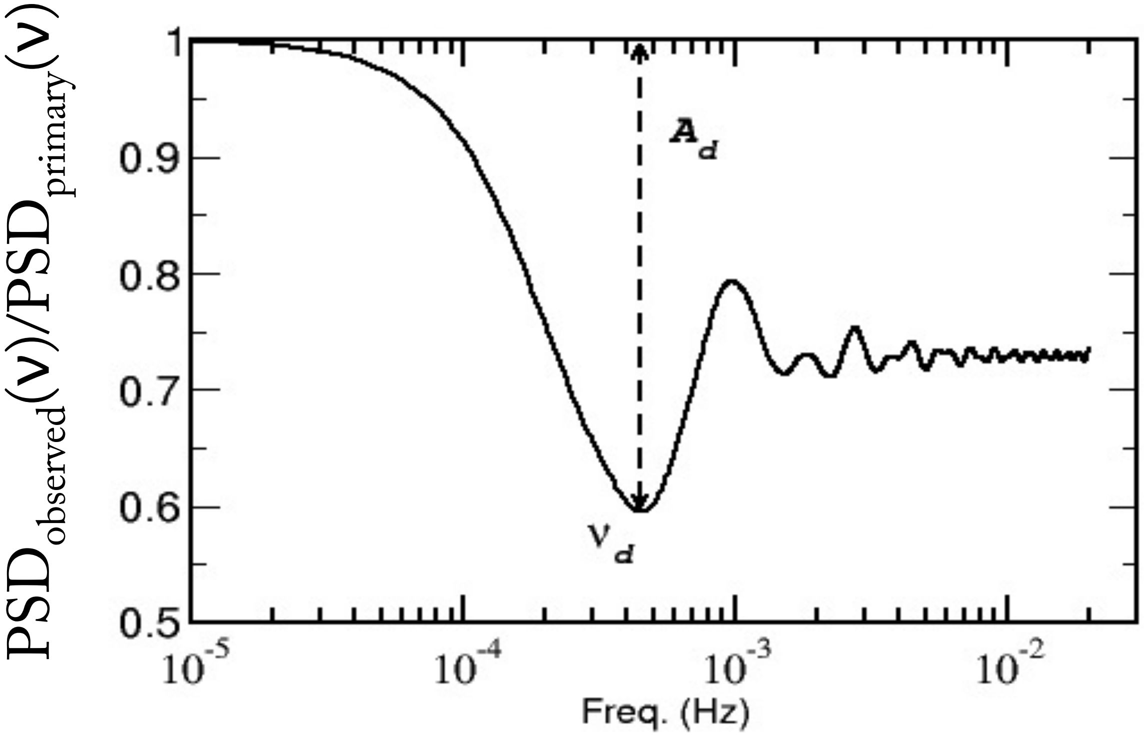
The observed variability must be reduced.

BY HOW MUCH?

$$F(E,t)_{\mathrm{total,observed}} = F(E,t)_{\mathrm{primary}} + \underbrace{F(E,t)_{\mathrm{reflection}}}_{\substack{\text{a delayed and “filtered” version} \\ \text{of the continuum}}}$$

$$\mathrm{PSD}_{\mathrm{total,observed}}(\nu)=\mathrm{PSD}_{\mathrm{primary}}(\nu)\times|\Gamma(E,\nu)|^2$$

$$\text{Where: } \underbrace{\Gamma(E,\nu)= \int_0^{\infty} \Psi_E(t-\xi)\exp(-i2\pi\nu\xi)\,d\xi}_{\text{is the transfer function of the system}}$$



5-7 keV

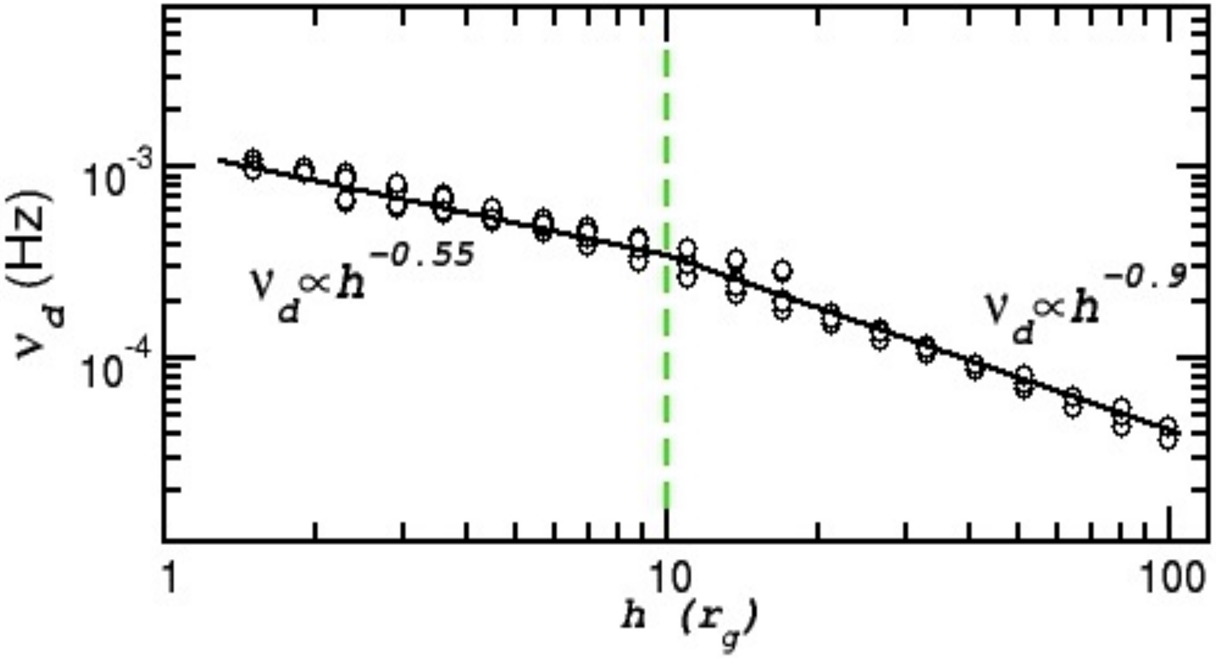
We expect the observed PSDs (in energy bands where the reflection component is expected to be strong) to show an “oscillatory” behaviour (with a decreasing amplitude) at high frequencies.

The amplitude and frequency of the first dip (A_d and ν_d) depend on:

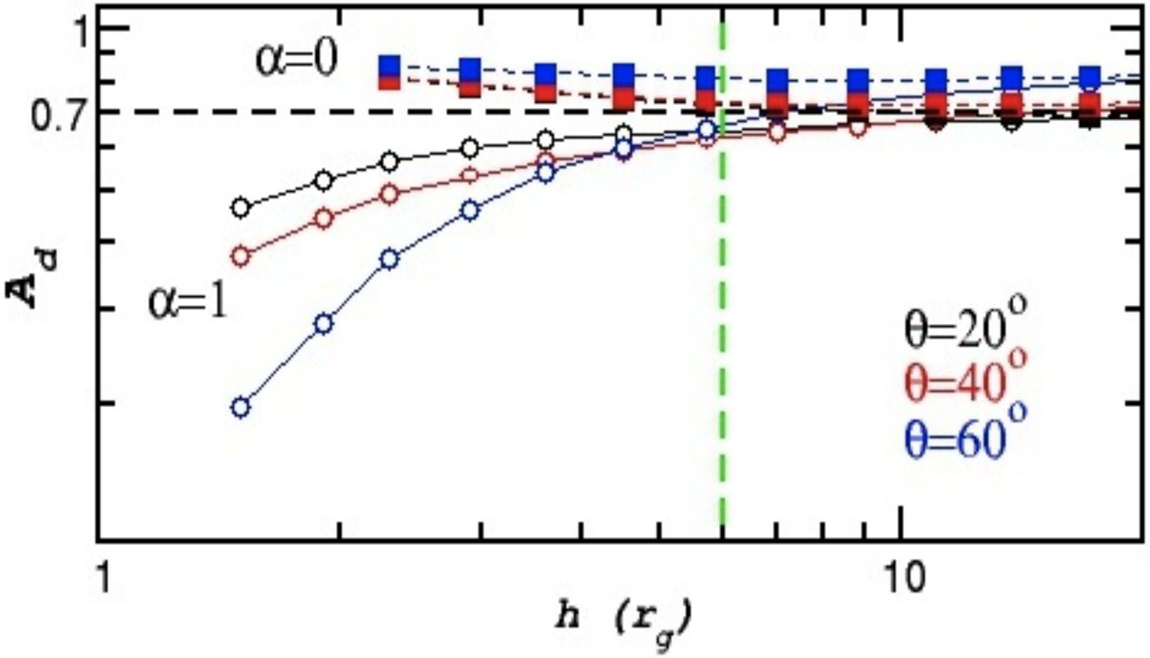
h, $r_{in}(\alpha)$, and θ

(for a given M_{BH}, ionization state of the disc, & iron abundance)

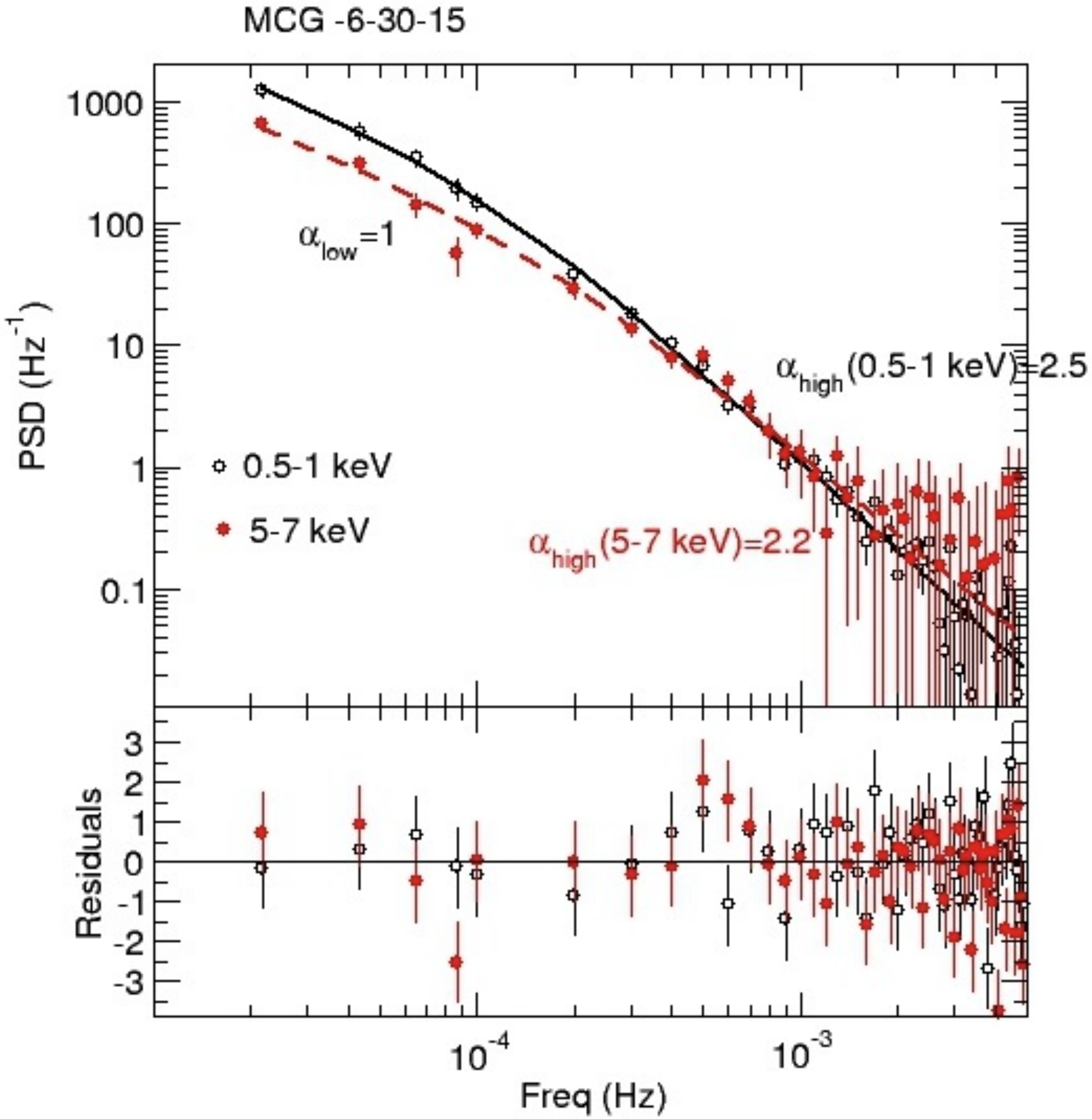
Results for:
5-7 keV PSDs,
in the case of
neutral material &
a 10^7 solar mass BH.



If one can detect the first "dip" in a PSD, then one can estimate h from ν_d, and then, α and θ from A_d.

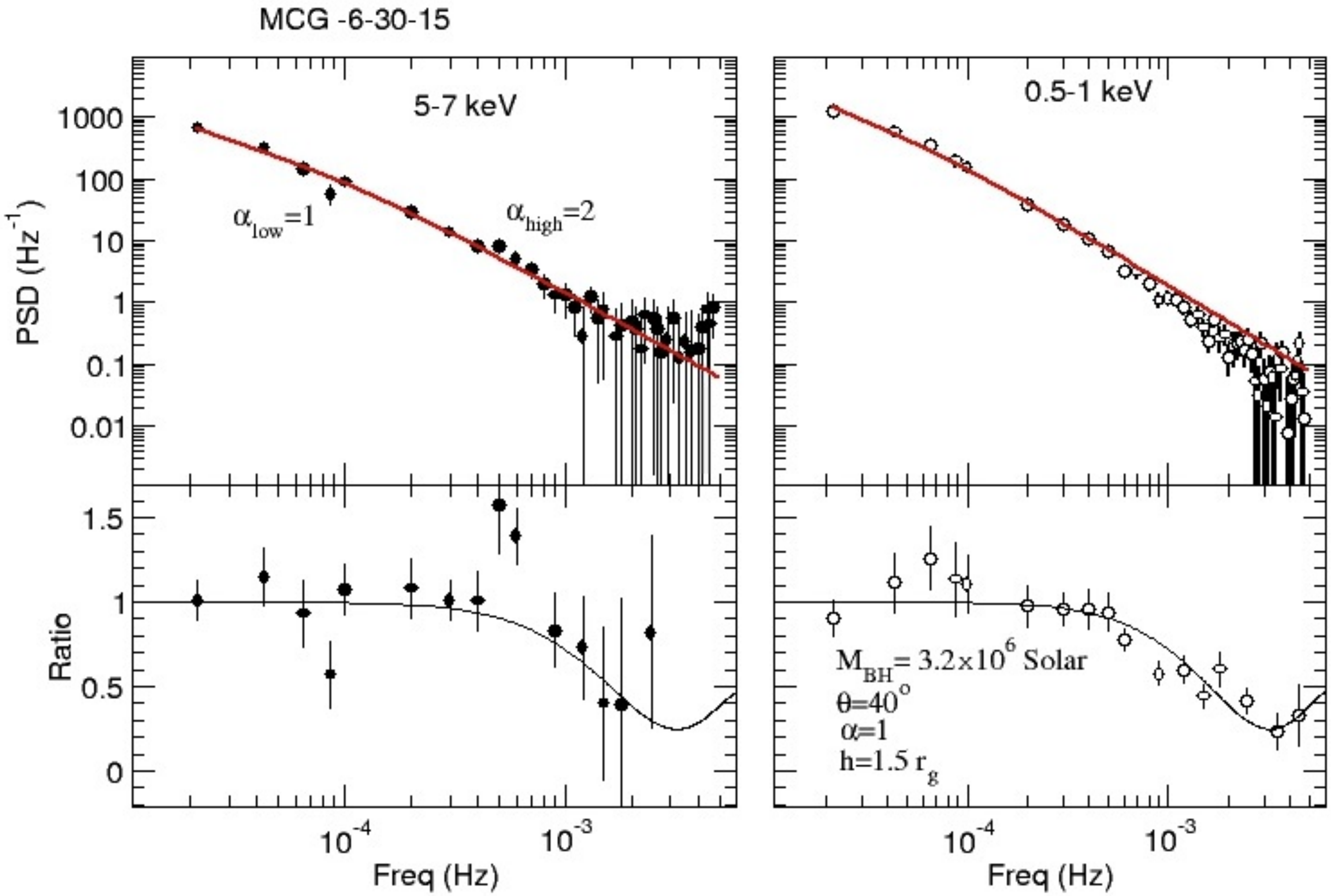


What do the data tell us?



“bending power-law” model fits the data well

“bending power-law” best-fit when α_{high} fixed at -2



X-ray studies can probe the geometry and the physical processes which operate in the innermost region of AGN.

✓ There has been an enormous effort to study the shape of the iron emission line in AGN, the last 20 years.

✓ There has been an enormous effort to study the delays between the X-ray continuum and the X-ray reprocessed emission from the disc in these objects, the last 5 years.

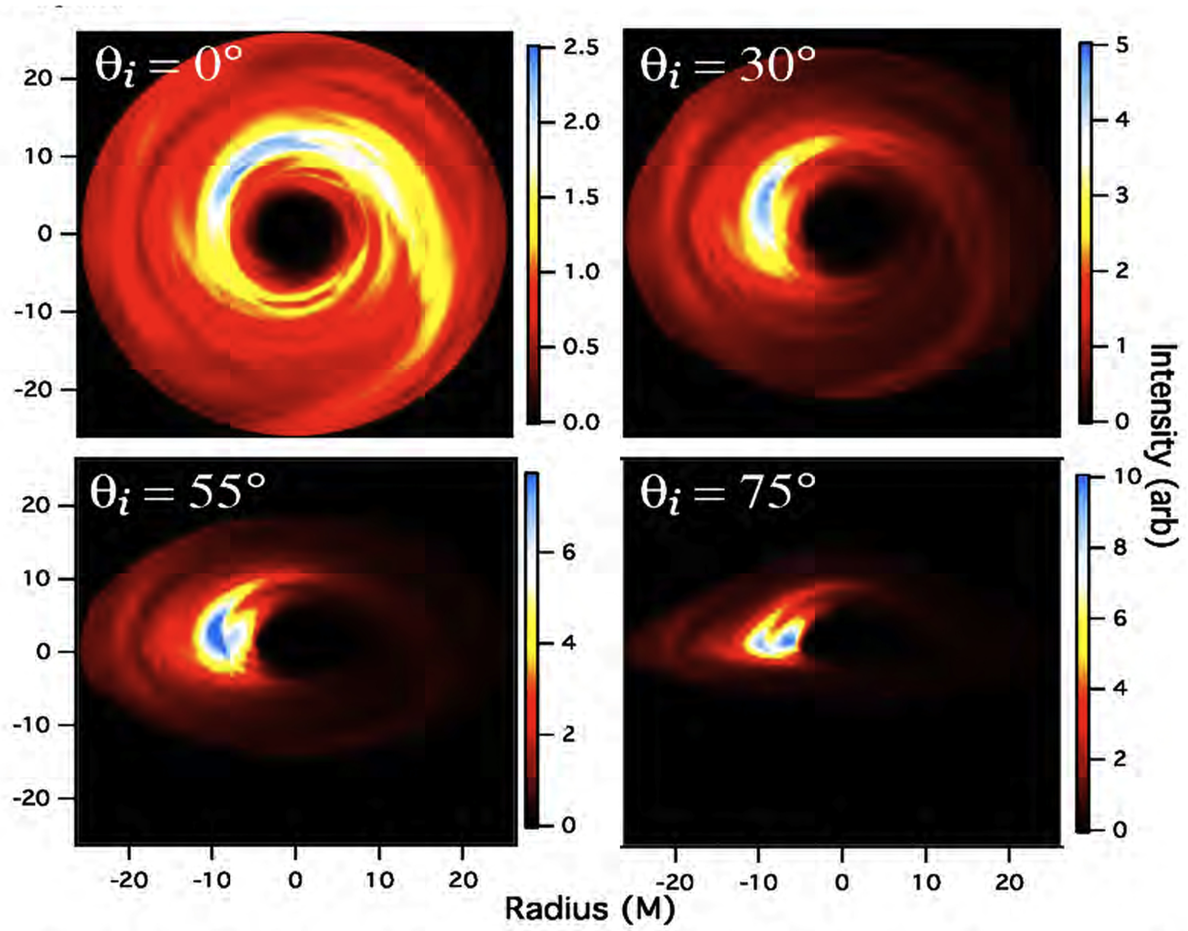
The results so far (for about ~20 AGN) have shown that:

The disc in many sources extends to 1 r_g, the X-ray source is compact, and no more than a few r_g.

X-ray reverberation also predicts PSD “echo”-features at high frequencies.

PSD modeling is “easy” - there is a hope we will be able to
characterized, quantitatively, the X-ray/disc geometry
(source height, size, disc inner radius, inclination angle)
and the BH parameters (mass and spin)
to a large samples of objects.

Recent studies of the variability properties of GR-MHD simulations of thin accretion discs around rotating and non-rotating BHs find temperature fluctuations, which lead to the formation of rotating hot "arcs" in the inner disc (Wellons, et al, 2014, ApJ, 785, 142)



If the accretion disc is inhomogeneous, and bright arcs rotate in its innermost region,

and,

If X-ray irradiation of the inner disc takes place,

and,

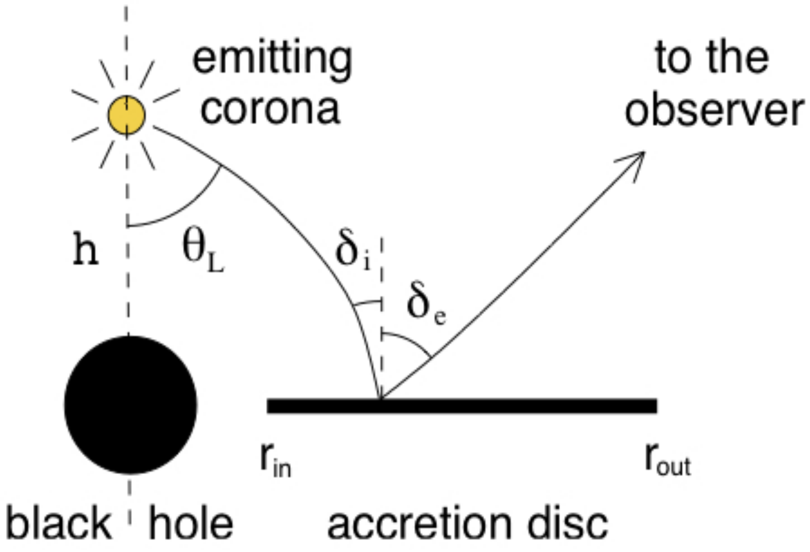
If the X-ray reflection spectrum coming from the surface of the disc is proportional to the local continuum intensity,

then

we may expect the X-ray iron line
to be periodically modulated.

We have recently started an investigation of this problem.
(Papadakis, Pechacek, & Dovciak, in prep).

a) We assume the “lamp-post” geometry, three inclinations: 20°, 40°, and 60°, for $M_{BH}=10^6$ and 10^7 solar masses.



In this geometry the disc irradiation decreases rapidly with the radius of the disc, and only the innermost part of the disc contributes significantly to to the reflection component in the spectrum.

Thus, although arc-like overdensed regions may exist on the disc surface even at large distances from the center, we need only to consider the ones in the innermost region.

b) Bright arcs appear randomly. They appear (and disappear) instantaneously (with an average rate of one arc/50 sec).

They are characterized by:

i) their average life time, $<t_l>$,
ii) average size, $<\phi_a>$, and
iii) “contrast, f_c, with respect to the local mean emission.

We have considered the cases of arcs at $3R_S$, and:

$f_c=5$

$<t_l>$	0.3(+/- 0.06) T_{orb}	1.2(+/- 6) T_{orb}	9.6(+/- 1.9) T_{orb}
$<\phi_a>$	3.6^o(+/- 0.7)	32.4^o(+/- 6)	291.6^o(+/- 60)

We created 50 sec binned light curves for each case, in the energy bands: 2-4, 5-6.3, 6.6-7, 5-7 (and 10-20) keV.

The observed count rate is equal to:

$$CR_{obs}(t) = CR_{cont}(t+delay)+f_b\times[CR_{ring}(t)+f_c\times CR_{arc}(t)]$$

$CR_{cont}(t)$ is the X-ray continuum count rate that the observer measures and the one that drives the reflection component variations as well.

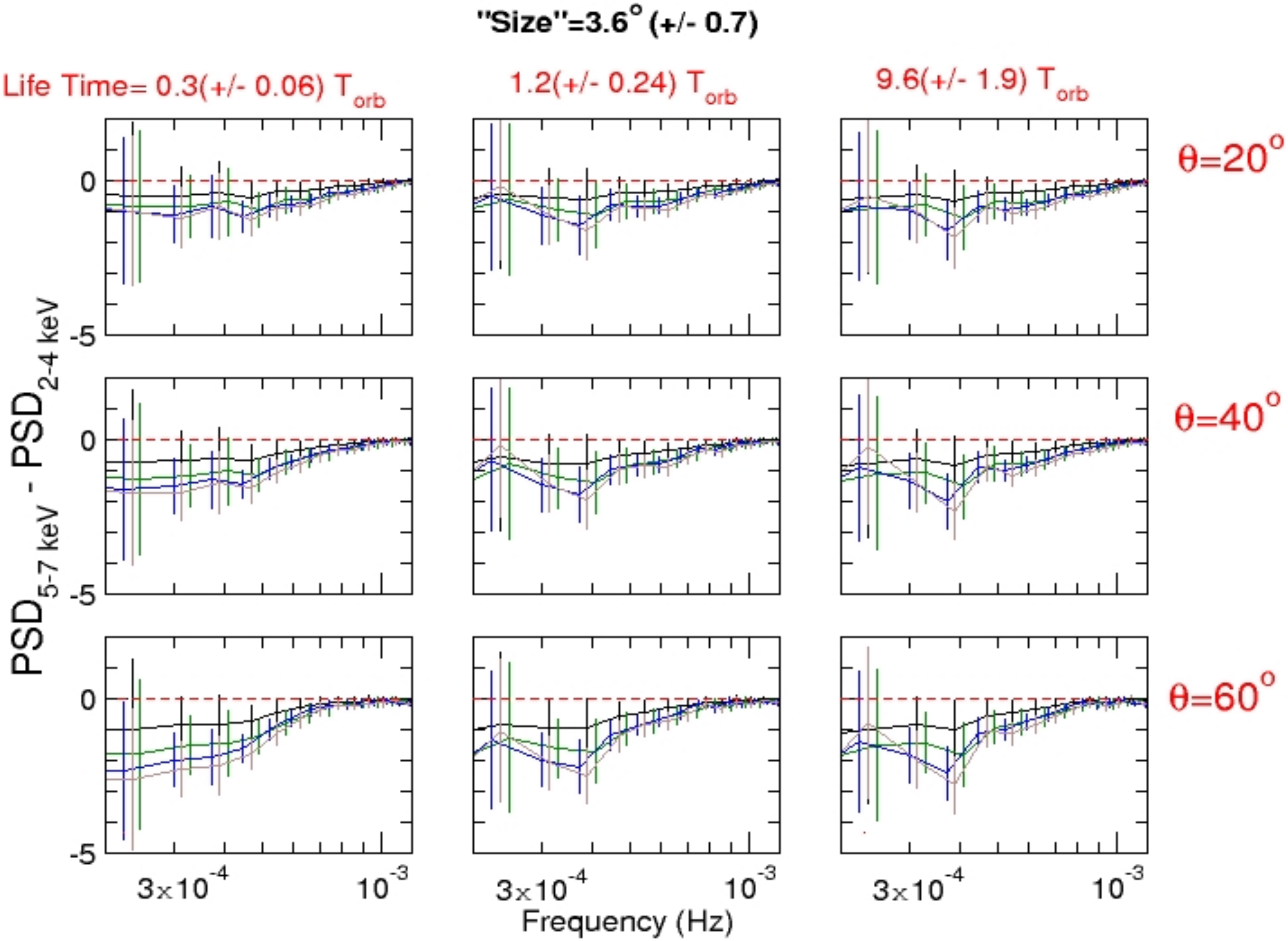
Our aim is to investigate whether the “signals” due to the rotating arcs can be detected using the existing data in the XMM-Newton (and Suzaku, and ASCA…) archives.

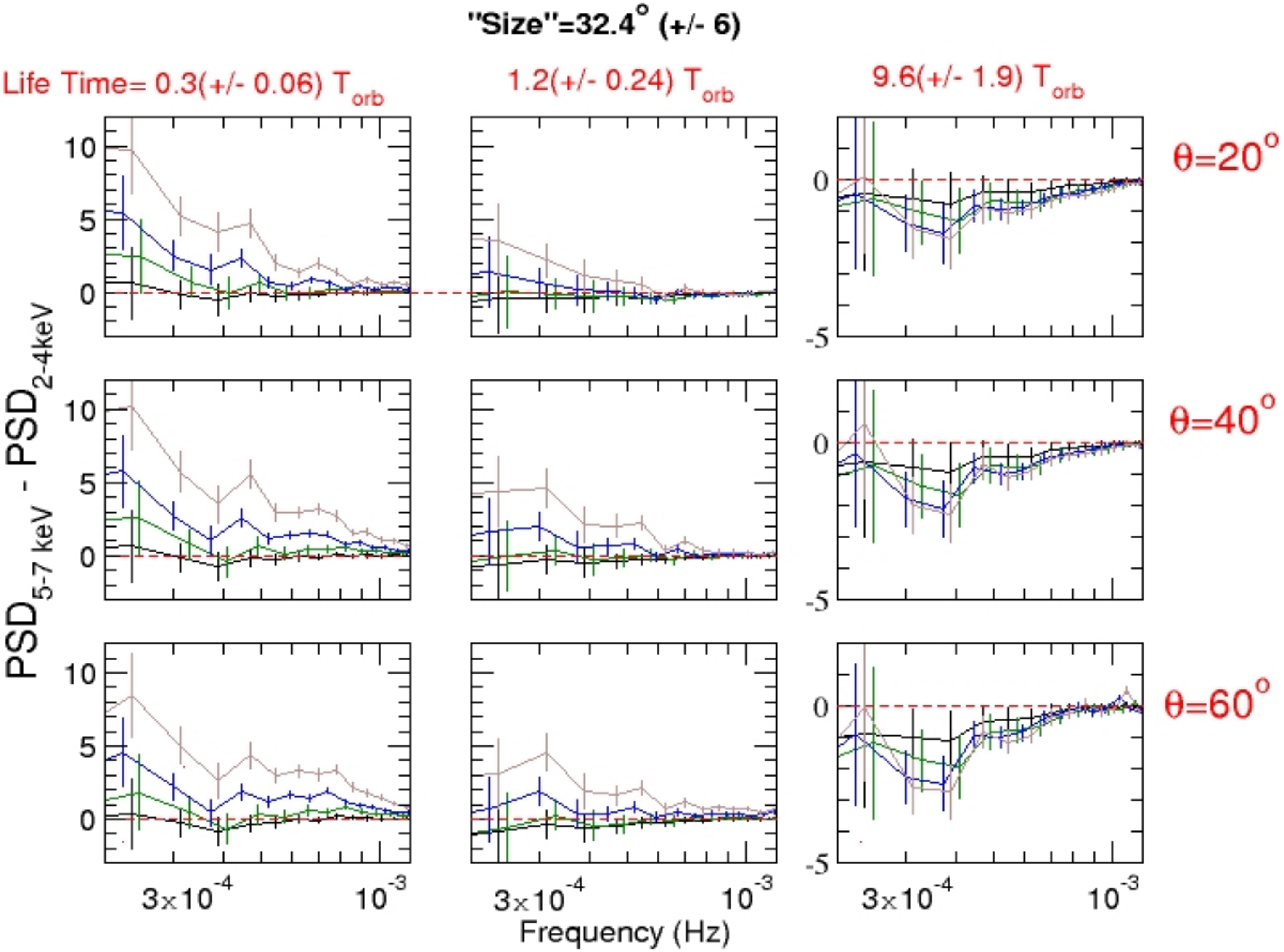
✓We considered 50, 12.8 ksec long light curves (256 points), and we averaged their PSDs in each energy band (such light curves do exist in the archives for a handful of objects).

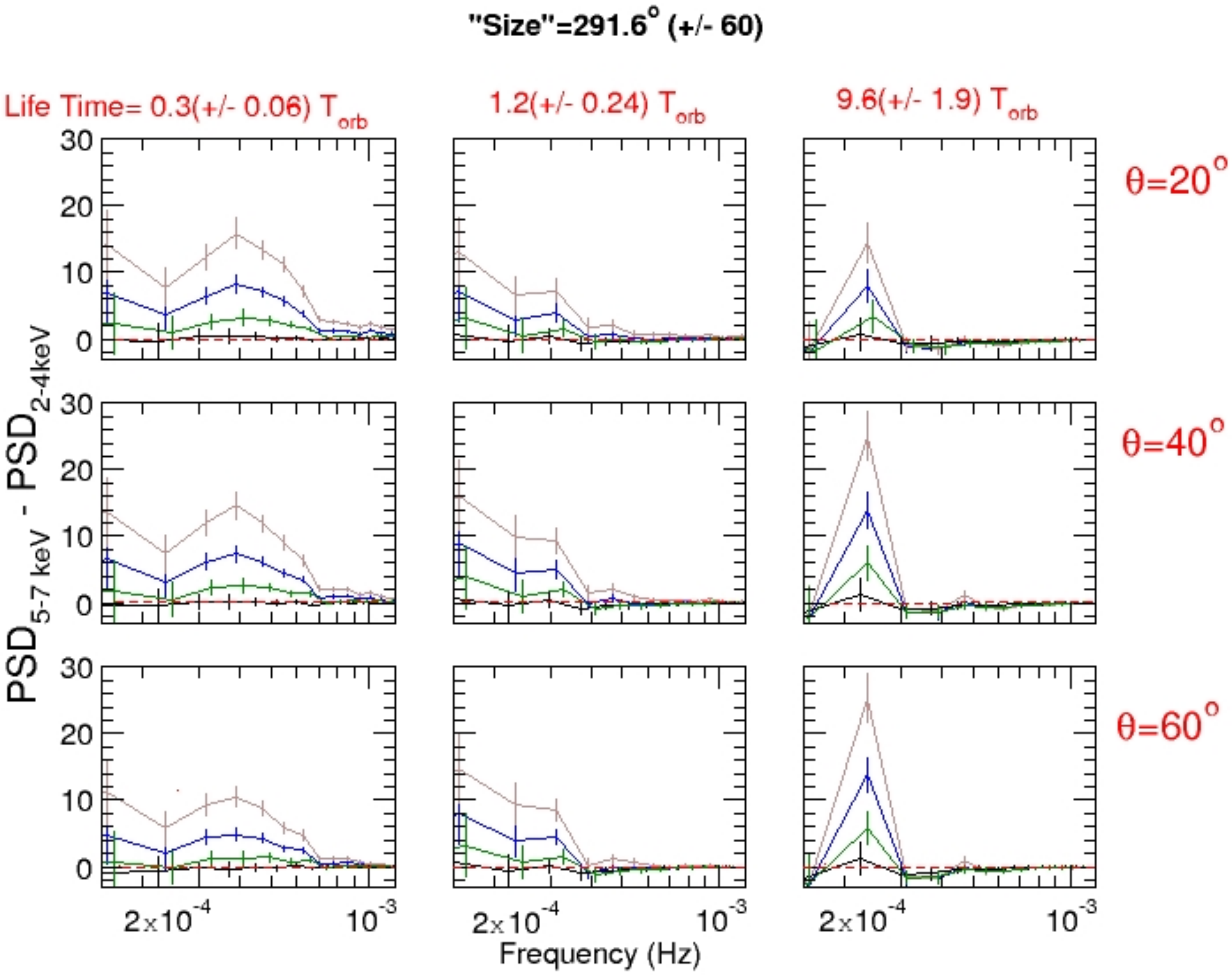
✓We estimated the average PSD in each band, and

✓We subtracted the PSDs in the “line” bands from the PSD in the 2-4 keV band.

The results (5-7 keV) band, for a BH of a 100 million solar masses:


"Size"=3.6° (+/- 0.7)
Life Time= 0.3(+/- 0.06) T_{orb}
1.2(+/- 0.24) T_{orb}
9.6(+/- 1.9) T_{orb}
θ=20°
θ=40°
θ=60°
$PSD_{5\text{-}7\,keV}$ - $PSD_{2\text{-}4\,keV}$
0
-5
0
-5
0
-5
3×10^{-4}
10^{-3}
3×10^{-4}
10^{-3}
3×10^{-4}
10^{-3}
Frequency (Hz)




"Size"=291.6° (+/- 60)
Life Time= 0.3(+/- 0.06) T_orb
1.2(+/- 0.24) T_orb
9.6(+/- 1.9) T_orb
θ=20°
θ=40°
θ=60°
PSD_5-7 keV - PSD_2-4keV
30
20
10
0
2×10^-4
10^-3
Frequency (Hz)

Model predictions are encouraging.

Have to reduce and analyze the data now
(perhaps I could report the new results in the next MEARIM)

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.