The soft-to-hard X-ray time-lags in AGN

(constraints on the size of the X-ray corona due to Comptonisation)

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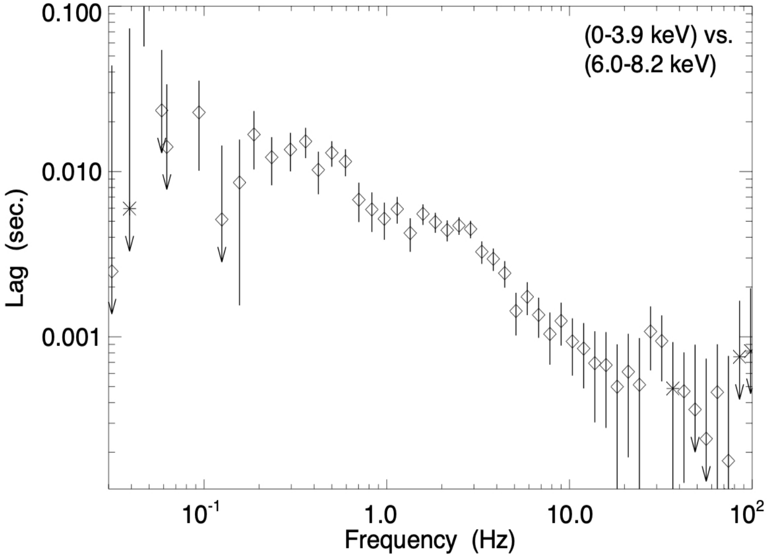
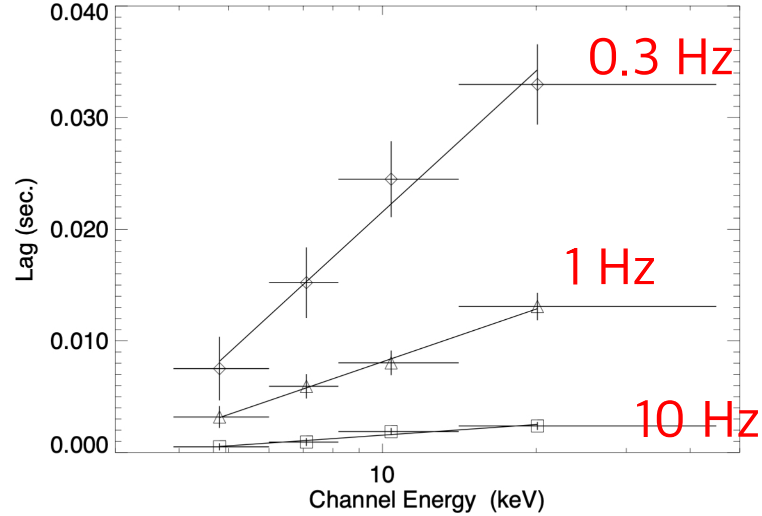
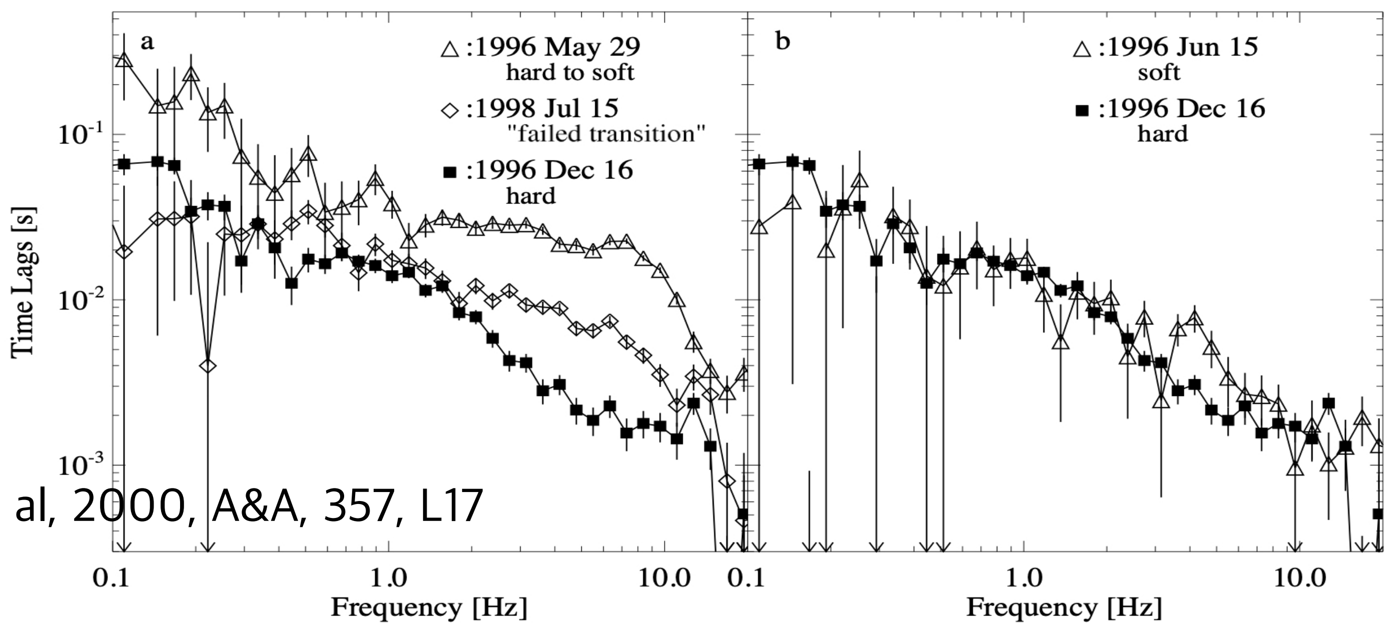
Time lag vs 2-4 keV

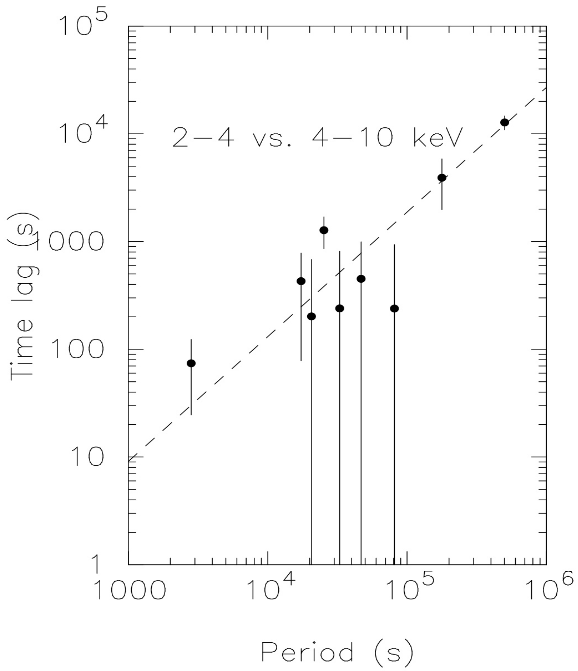




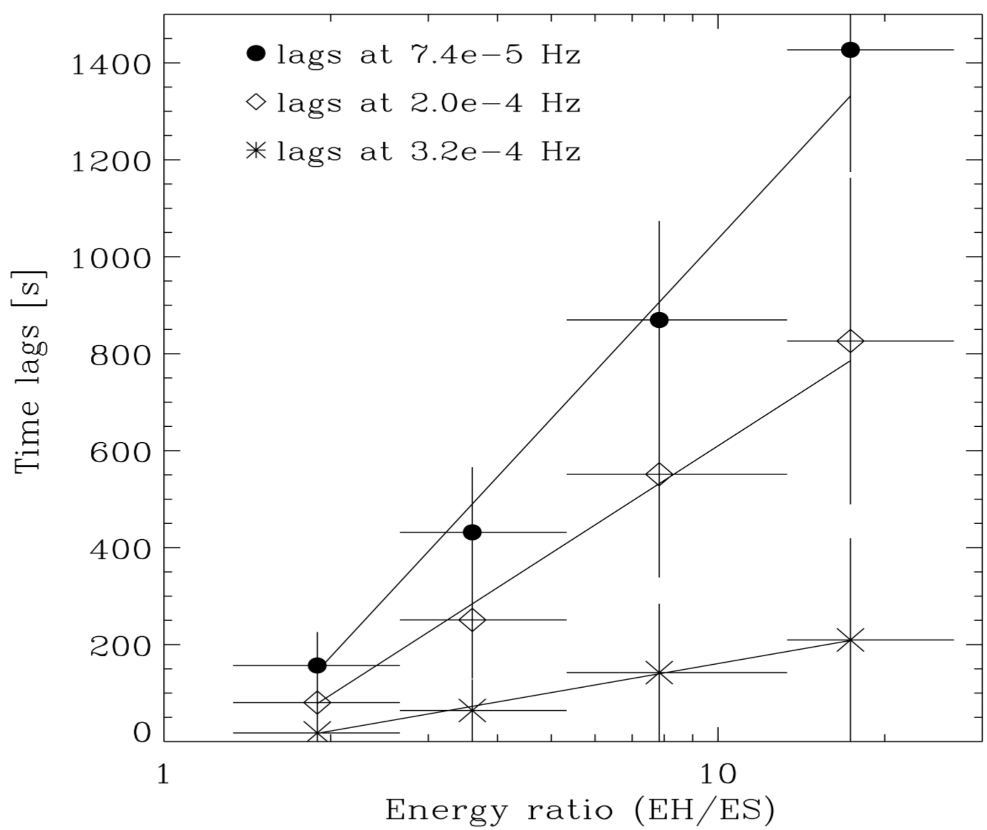
Cyg X-1 (Nowak et al 1999, ApJ, 510, 874)



Pottschmidt et al, 2000, A&A, 357, L17



NGC 7469: Papadakis et al, 2001, ApJ, 554, L133



Ark 564: Arevalo, et al, 2006, MNRAS, 372, 401

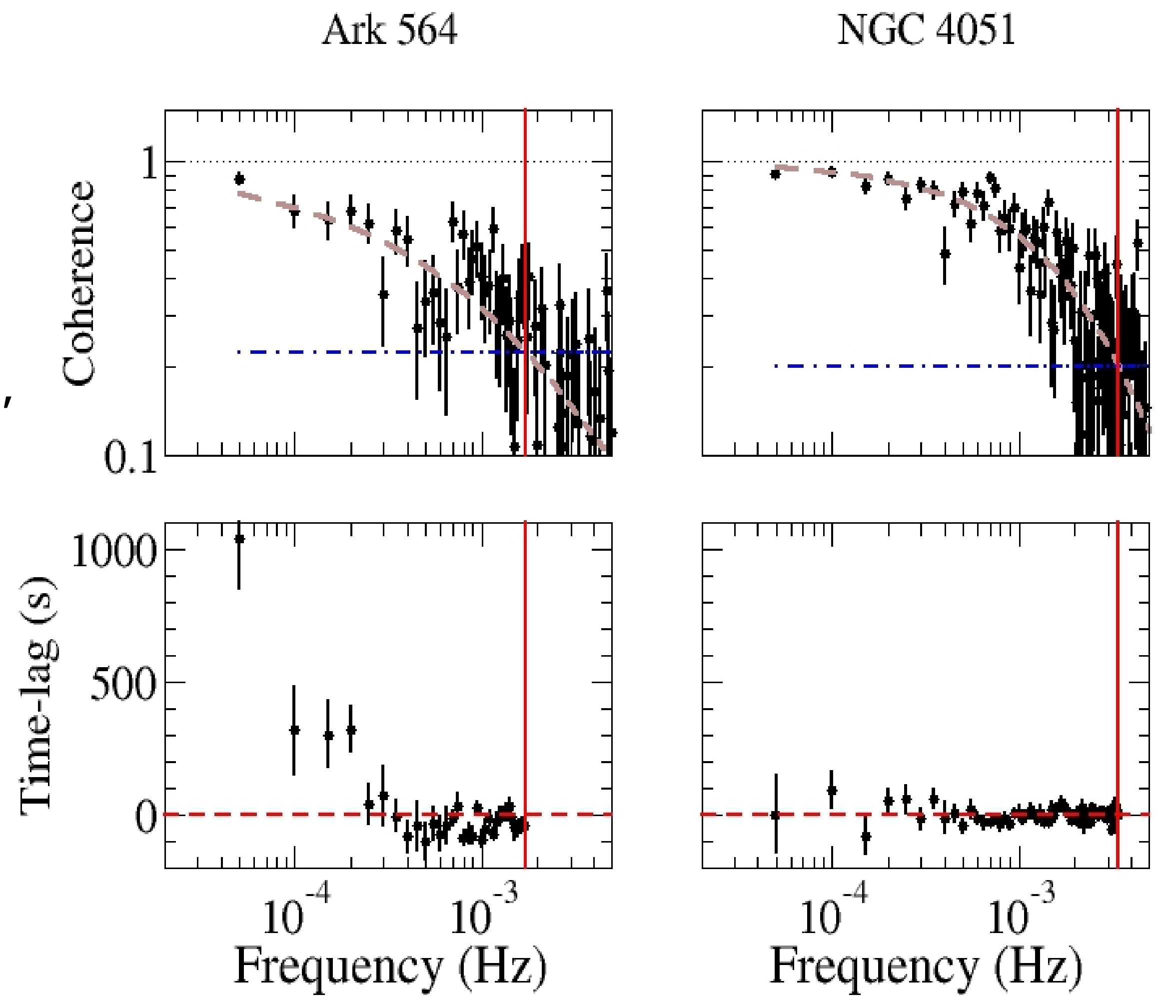
Systematic study of time lags + coherence in AGN

(Epitropakis & Papadakis, 2017, MNRAS, 468, 3568)

- We studied 10 AGN (X-ray bright, variable, with lots of data), using archival XMM-Newton data.
- We estimated time lags (and the coherence) between 2-4 keV (the reference band) and 7 other energy bands (0.3-0.5, 0.5-0.7, 0.7-1, 1-2, 4-5, 5-7 and 7-10 keV).
- We focused on the study of the continuum (low frequency) time lags.

We used the techniques of Epitropakis & Papadakis (2016, A&A, 591, 113), to estimate the time lags.

The resulting time lags estimates are unbiased, Gaussian, with known errors, so we can fit models to them using traditional χ^2 minim. techniques.



We fitted time lags in the frequency range ~ 5×10^{-5} - 5×10^{-4} Hz.

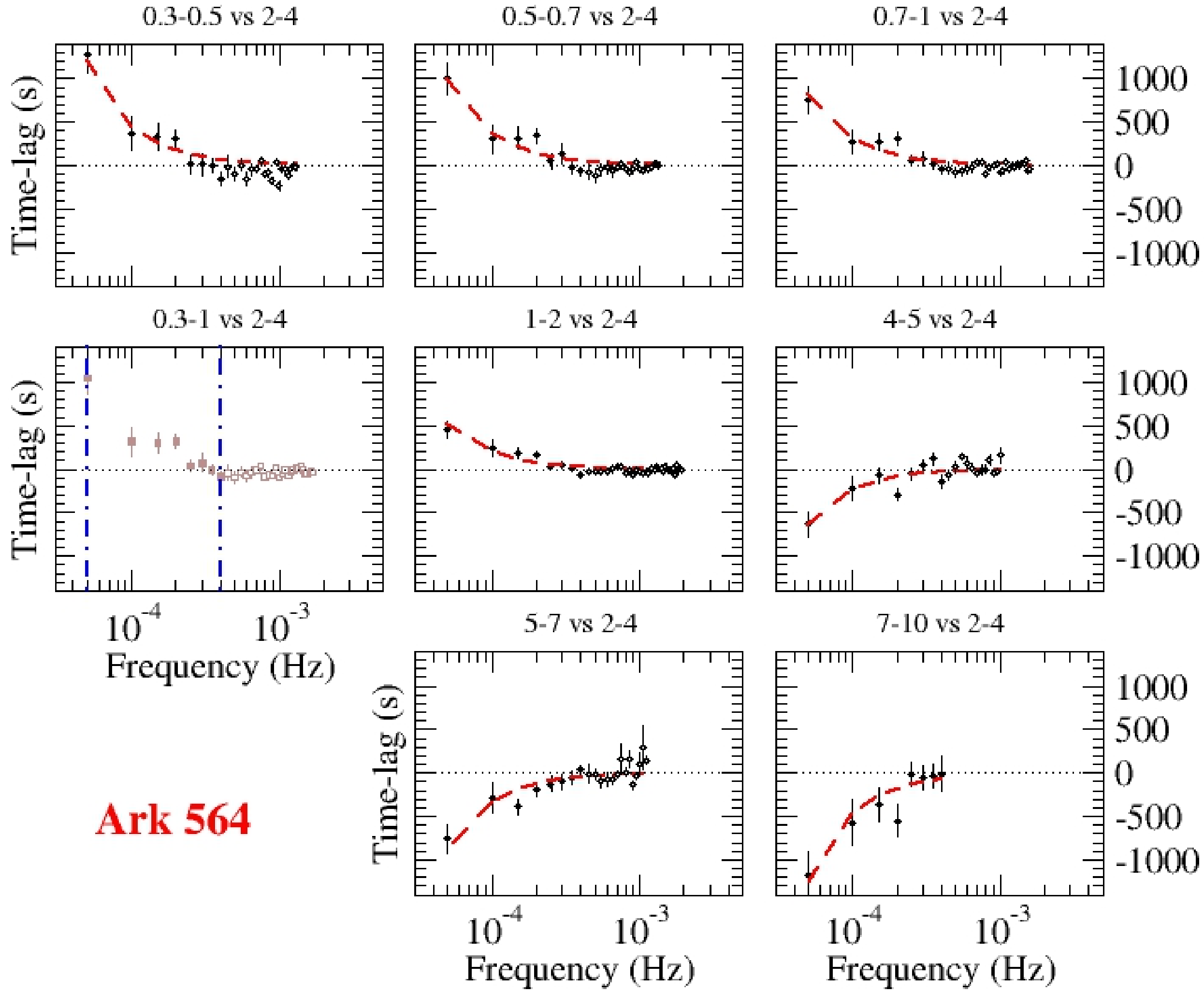
We used a model of the form:

$$\tau(\nu, E, 3\mathrm{keV}) = A(E, 3\mathrm{keV})\left(\frac{\nu}{1\mathrm{e}\text{-}4}\right)^{-s}(sec)$$

(time lag at $\nu=10^{-4}$ Hz)

We kept the slope, *s*, the same for the time lags spectra at all energies.

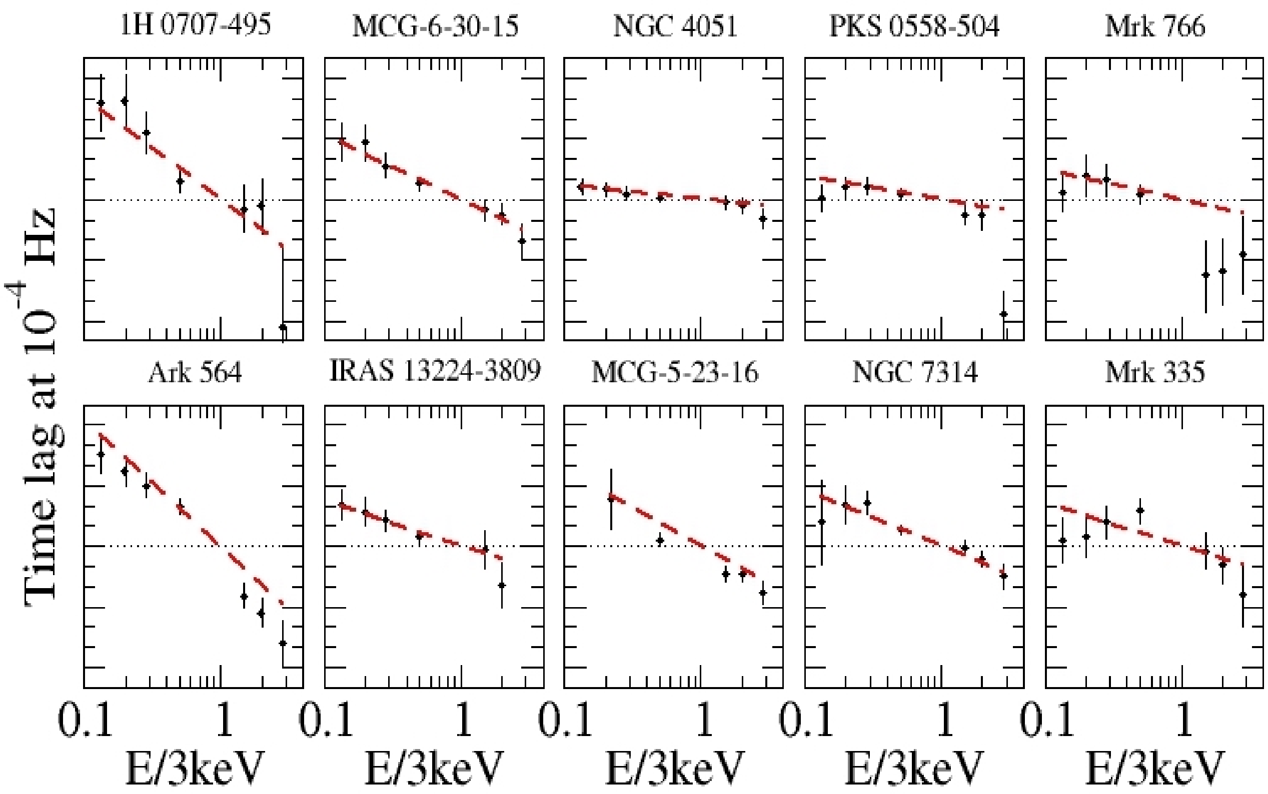
The power law model fits reasonably well the time lags between the reference band (2–4 keV) and all energy bands, in all objects.



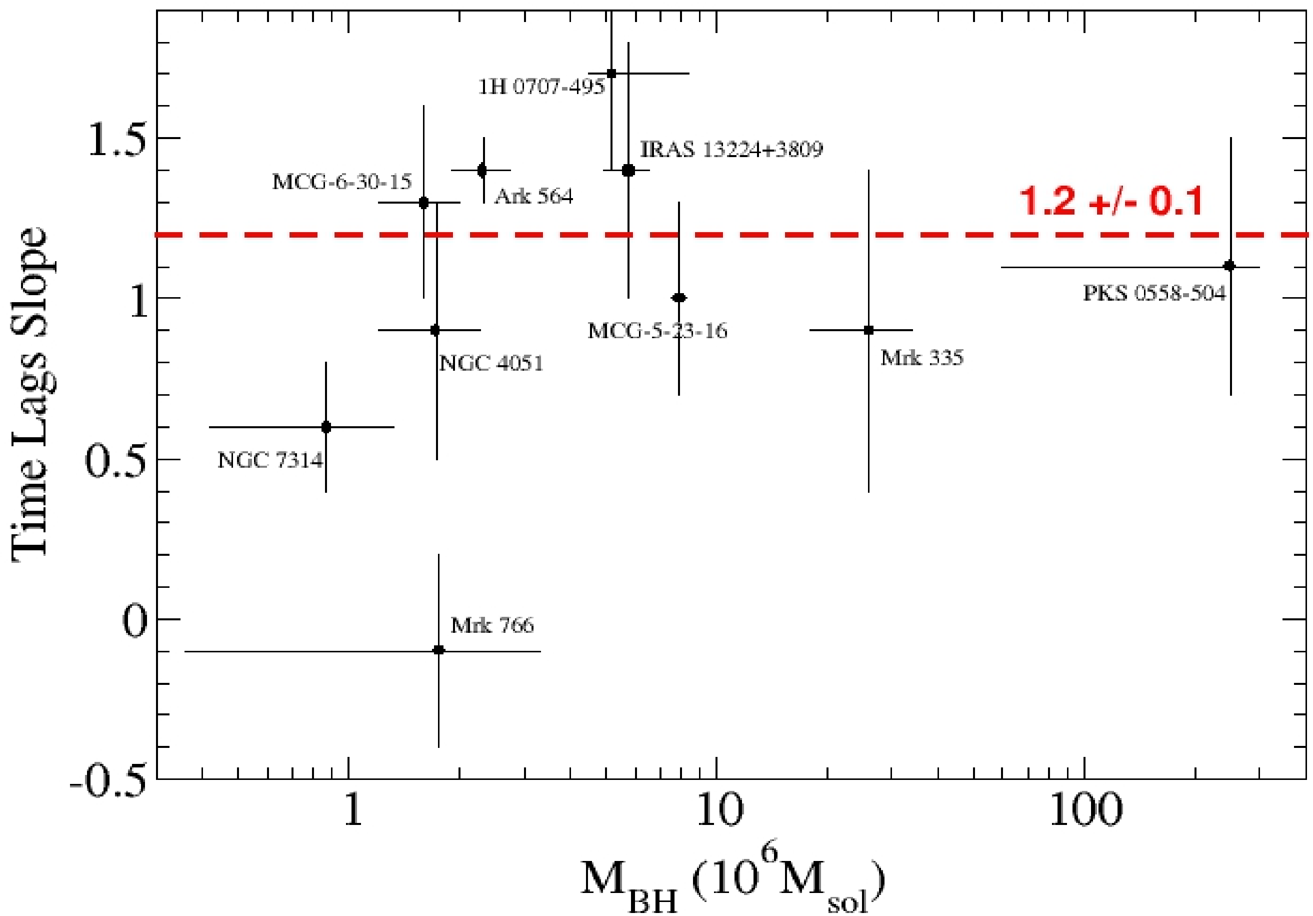
The time lags amplitude depends on the energy separation between the light curves,

$$A(E, E_{ref}) = A_0 \log\left(\frac{E}{E_{ref}}\right)$$

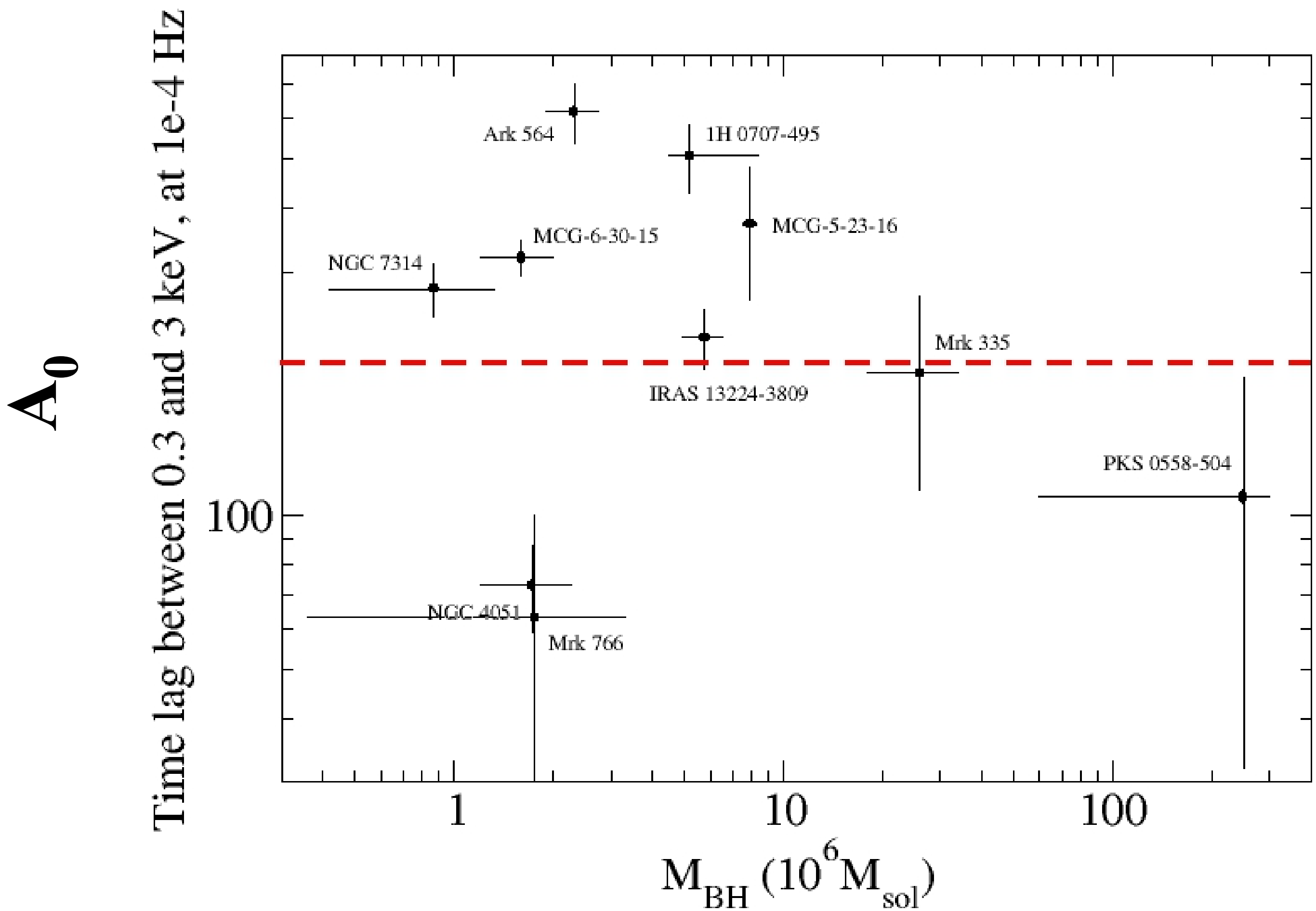
time lag at 10^{-4} Hz when $E_1 = 10E_2$



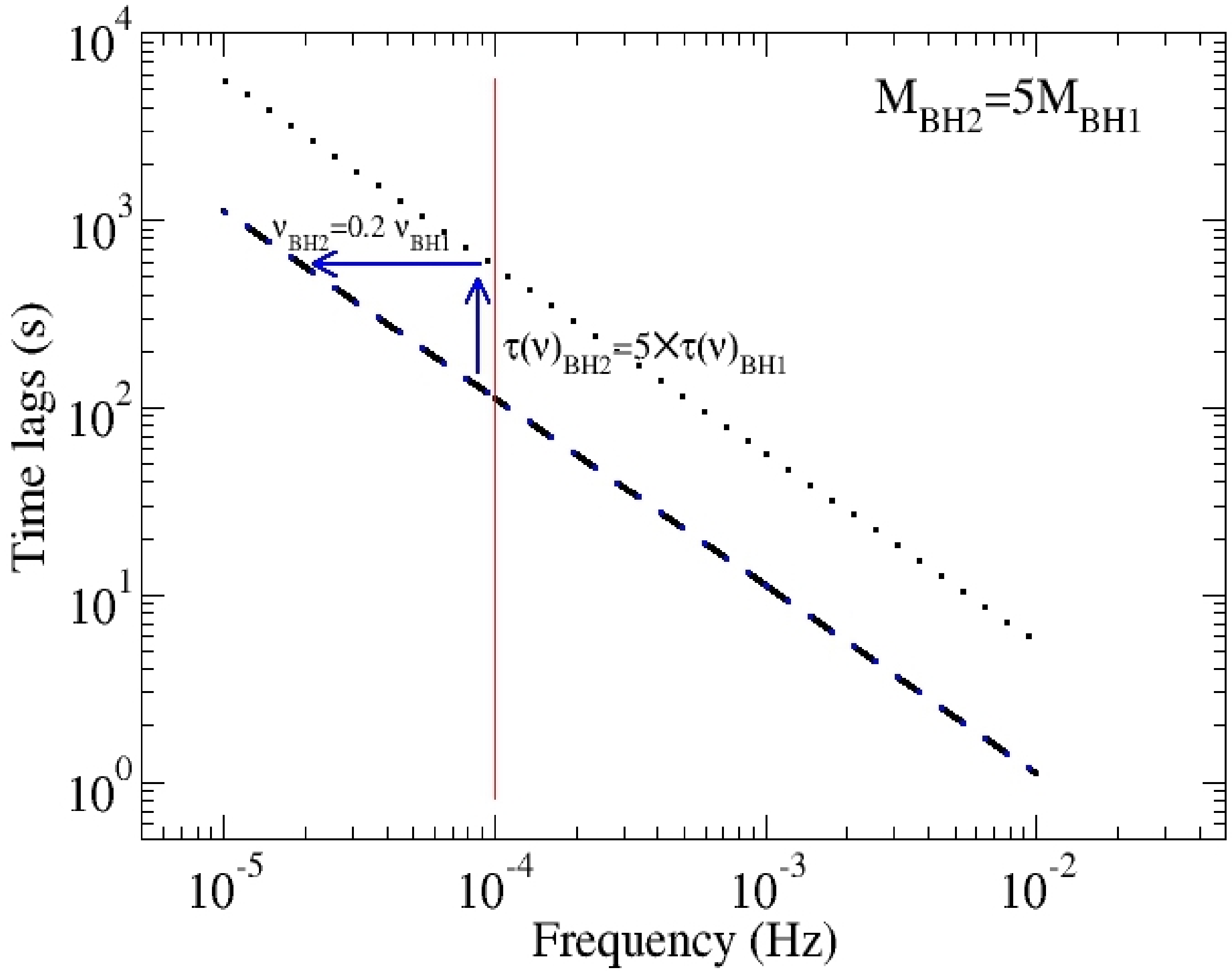
The best fit power law is ~ -1 at all energies, & all objects.



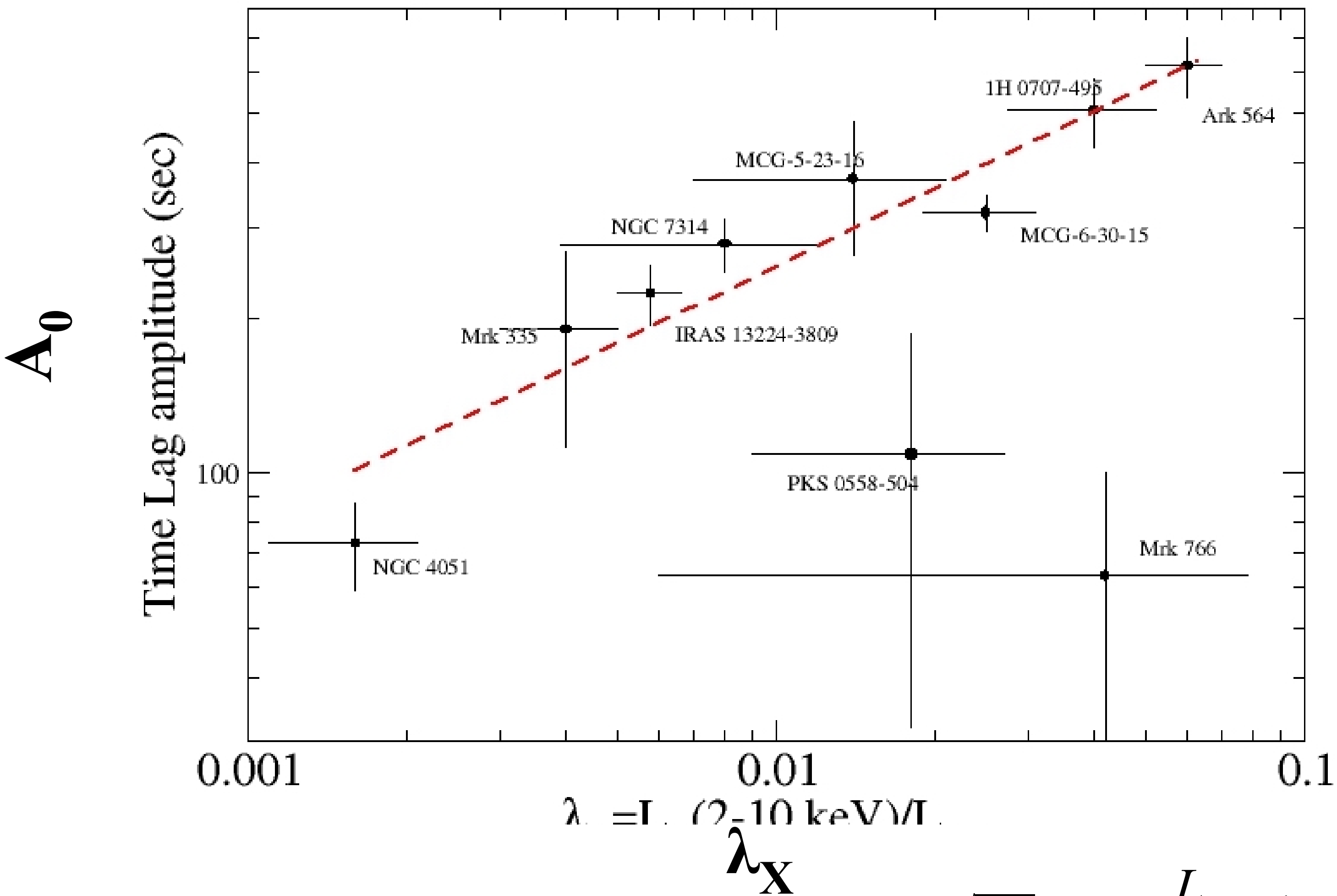
Time lags amplitude does not depend on BH mass.



Which is fine, if time scales/frequencies increase/decrease proportionally with BH mass.



The time lags amplitude depends on “accretion rate”



$$A_0 \propto \sqrt{\lambda_X},\ \lambda_X = \frac{L_{2-10\mathrm{keV}}}{L_{Edd}}$$

SUMMARY

- X-ray continuum time lags in AGN, are power-law like (in the 5×10^{-5}-5×10^{-4} Hz range), with a slope of ~ -1.
- Their amplitude depends on the logarithm of the ratio of the energy of the two light curves.

CONFIRM

- Their amplitude (at a fixed frequency) does not depend on BH mass, but
- it depends on the square root of L_x/L_{Edd}.

In principle, we can use these results to constrain theoretical models.

For example, to **constrain the X-ray source size** considering only **time lags due to thermal Comptonization**.

Time lags due to thermal Comtonization

(Zhang, Dovciak, & Bursa, 2019, ApJ, 875, 148).

Assume a thin, NT, disc which extends down to ISCO, and has an outer radius of 100 GM/c^2. Spin is 1, the BH mass is 10^7 solar, and the accretion rate is 0.1 of the Eddington limit.

Assume a spherical X-ray corona, located at $20r_g$ above the BH.

Assume a corona radius of: 2, 5 and $10r_g$

Assume a corona temperature of 50, 100 and 200 keV.

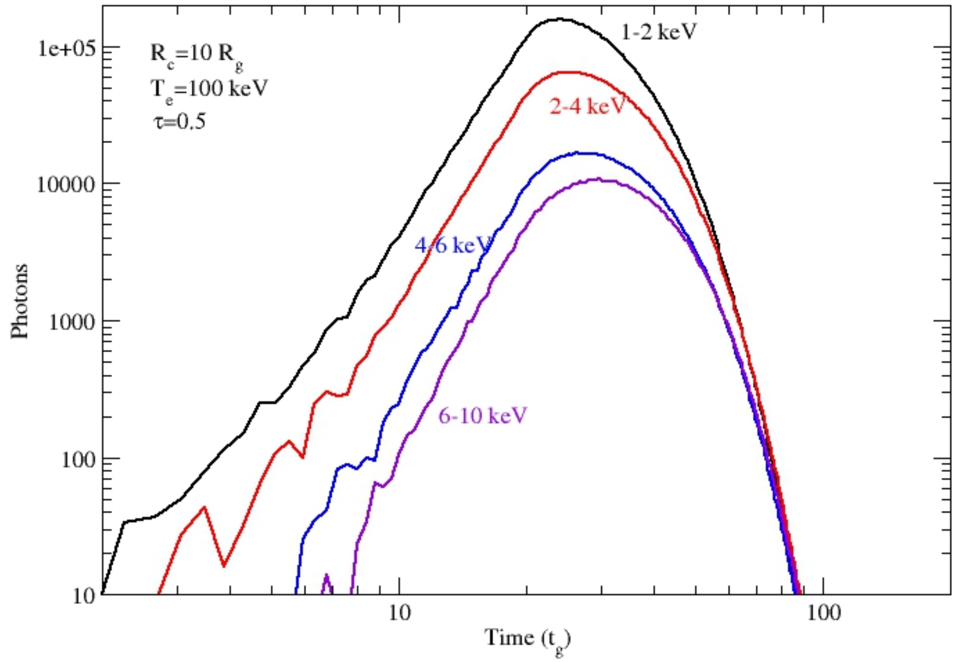
Assume a corona optical depth of τ=0.5

What are the delays that will be “introduced” to the X-ray photons, at various energies, as they emerge from the corona towards to the observer, just because of the Compton scattering of the photons by the hot electrons?

To find out....

We compute the response of the X-ray corona to a instantaneous flash of thermal disc emission, ie..

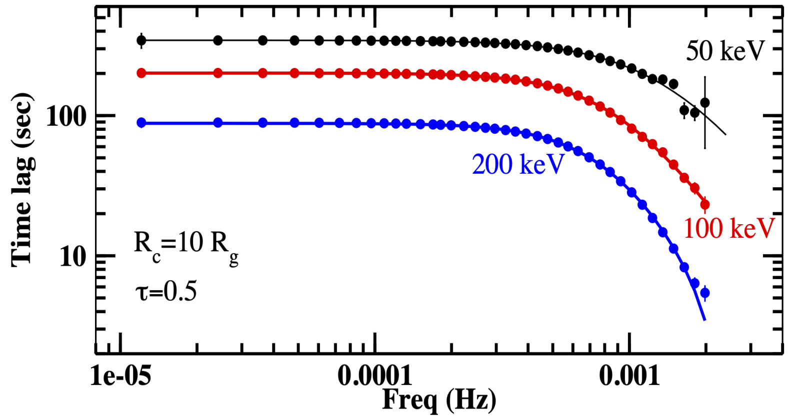
we compute the arrival time of the X-ray photons (as observed by a distant observer), in the case when a burst of soft photons (with the right spectrum, emitted from the entire disc) arrive on the corona surface simultaneously.

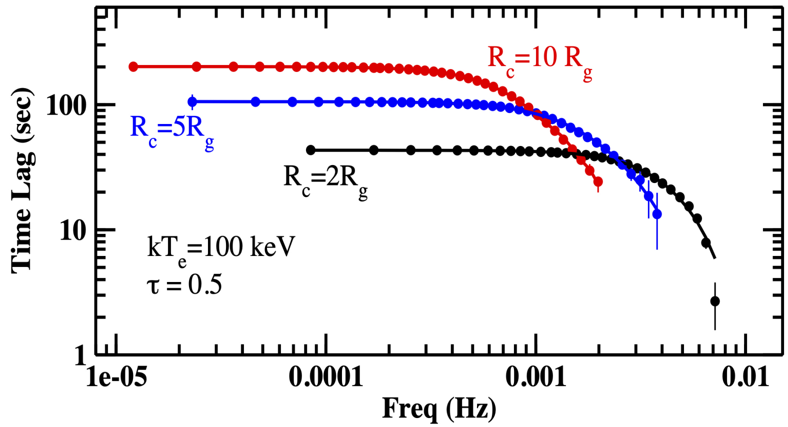


Using the corona response light curves, we can estimate the cross-spectrum, and hence the time lags, between the light curves in two energy bands (we can also estimate coherence, power spectra in various energy bands etc).

The time lags we compute are those due just to the (thermal) Comptonization process.

Results (for the 6-10 vs 2-4 keV band time-lags).

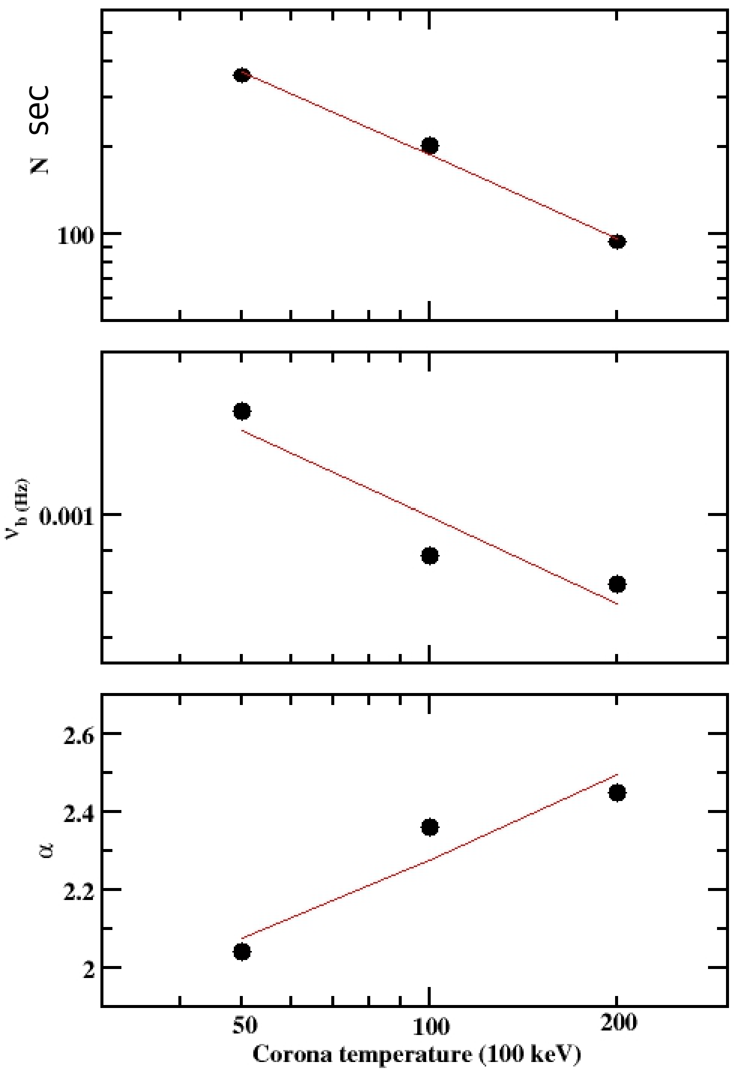




A function of the form: $\tau(\nu) = \dfrac{N}{1+(\dfrac{\nu}{\nu_b})^{\alpha}}$, fits the time-lags well.

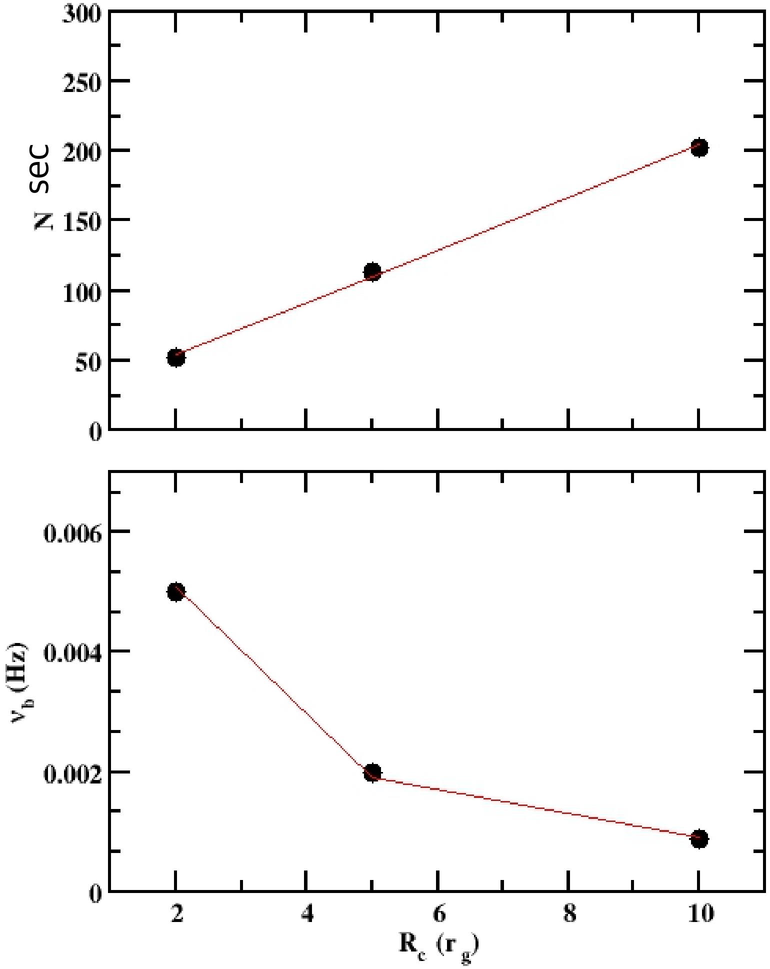
Dependance on electron temperature (R_c=10 r_g, τ=0.5)

$$\tau(\nu)=\frac{N}{1+\left(\frac{\nu}{\nu_b}\right)^{\alpha}}$$

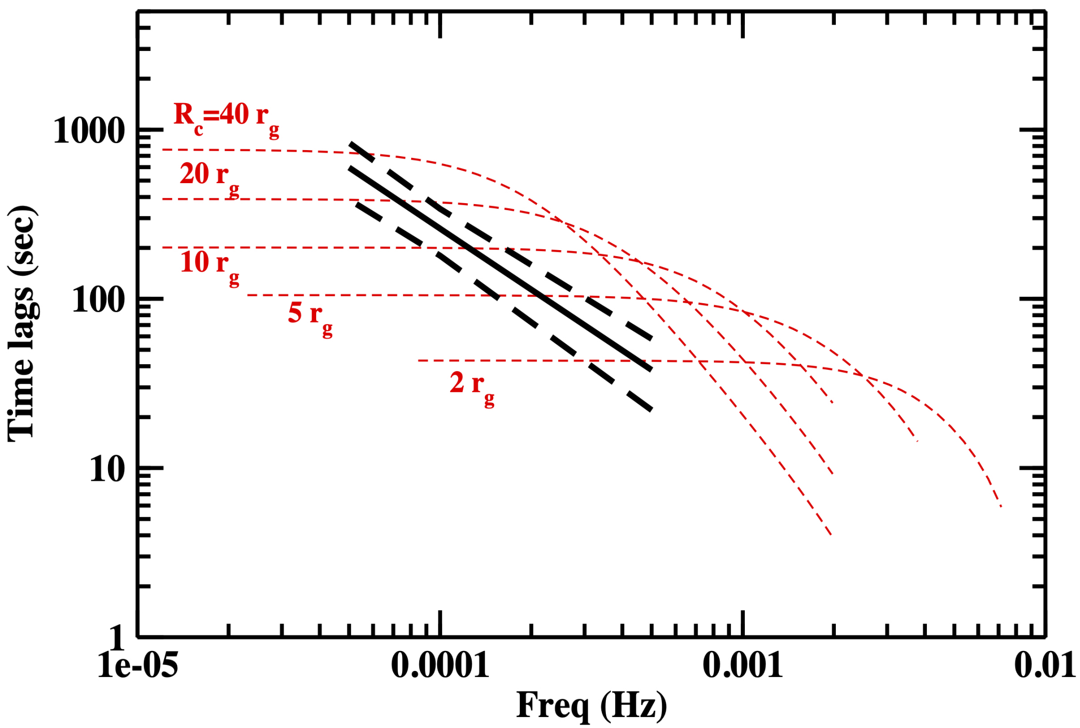


Dependance on corona radius (100 keV, τ=0.5)

$$\tau(\nu) = \frac{N}{1 + \left(\frac{\nu}{\nu_b}\right)^{\alpha}}$$



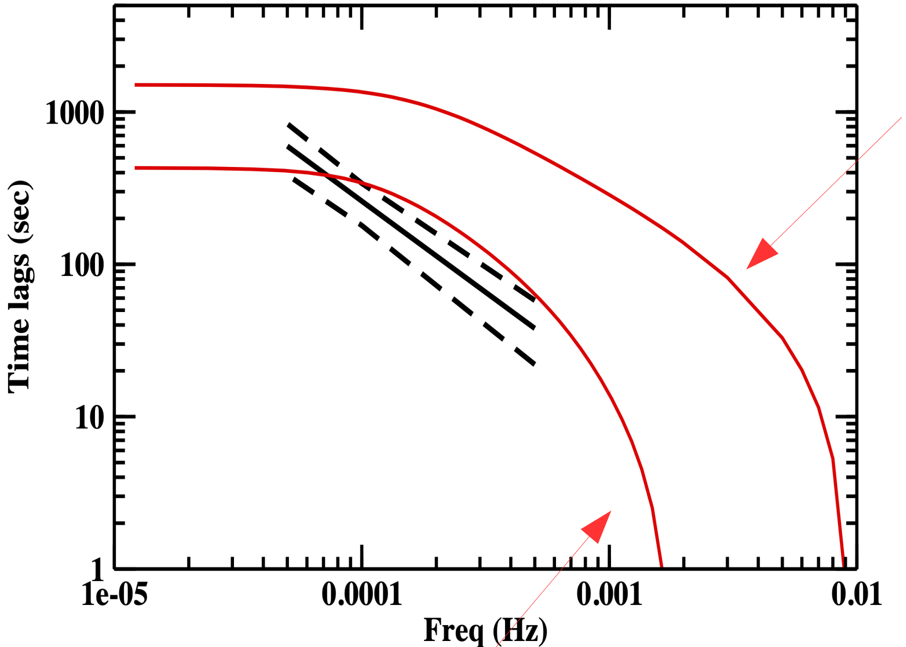
Comparison with observations (I).



Time lags from individual flares. They have different radius and the same temperature (100 keV) and optical depth (τ=0.5.)

Obviously, they have the wrong shape and amplitude.

Comparison with observations (II).



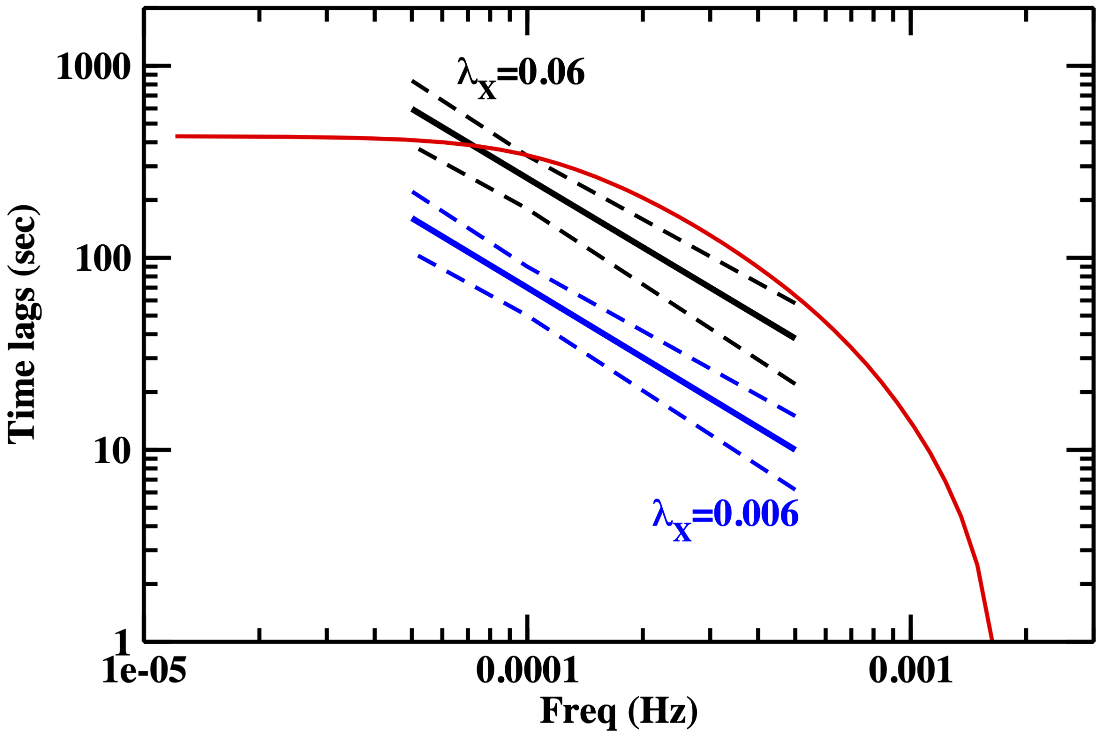
Time lags from a collection of flares, with radius R_c = 2, 5, 10, 20 and 40 r_g and kT_e=100 keV, τ=0.5.

We get power-law like time-lags.

Time lags from flares, with radius R_c = 10, 20 and 40 r_g (kT_e=300 keV, τ=0.5).

The amplitude is still too high, and this is for objects with high λ_x (=0.06).

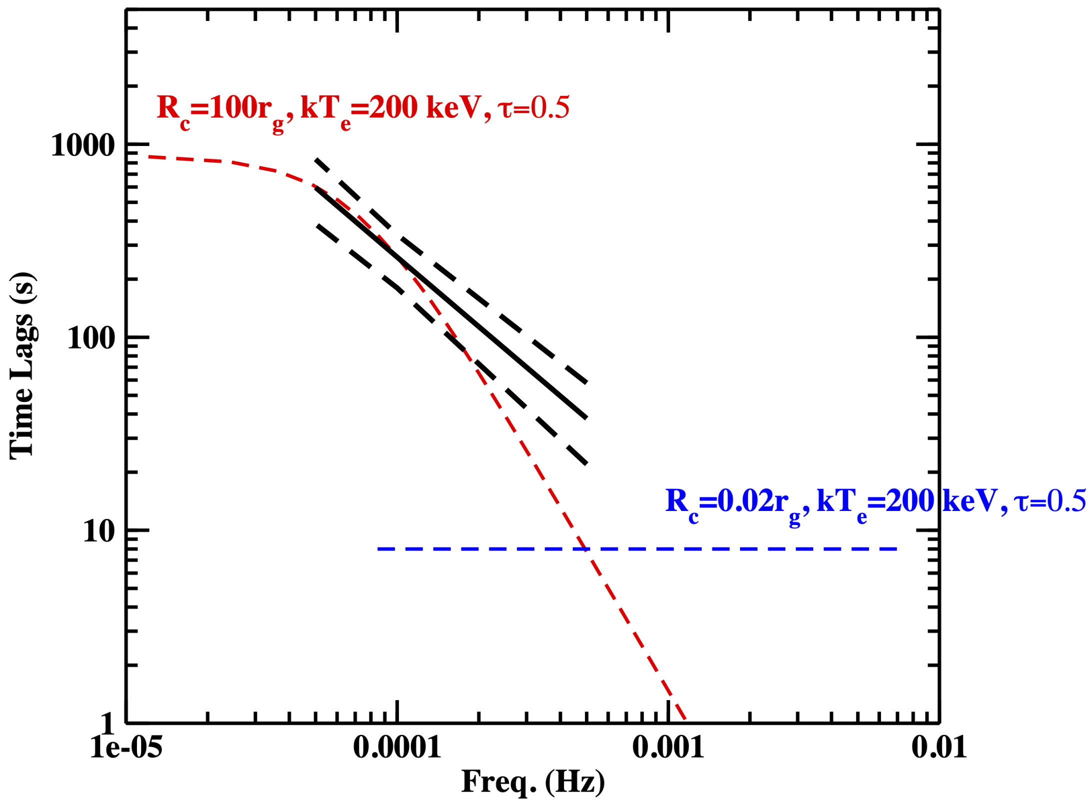
Comparison with observations (III).



The disagreement between model predictions and observations is more significant when we consider the observed time lags for objects with low λ_x (=0.006).

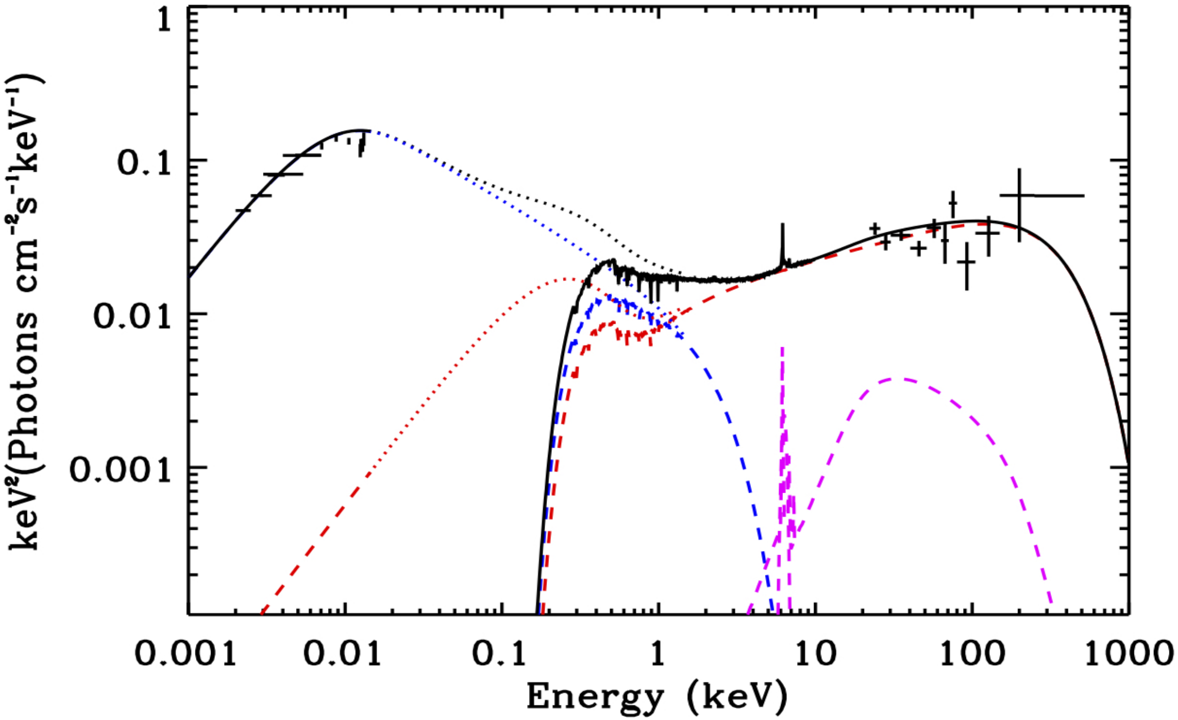
- If inverse Compton is the mechanism to produce X-rays, the observed time lags can place constrains on the size of the source.
- The delays due to Comptonization can be quite large (when compared to data).
- The results so far suggest it is difficult to have a single X-ray corona, with a radius 2-40 r_g.
- It is also difficult to assume that the corona radius varies (randomly) between 2 and 40 r_g. The model time lags in this case are significantly **larger** than the observed ones.

The corona can be either smaller than _0.02r_g or larger than 100r_g.



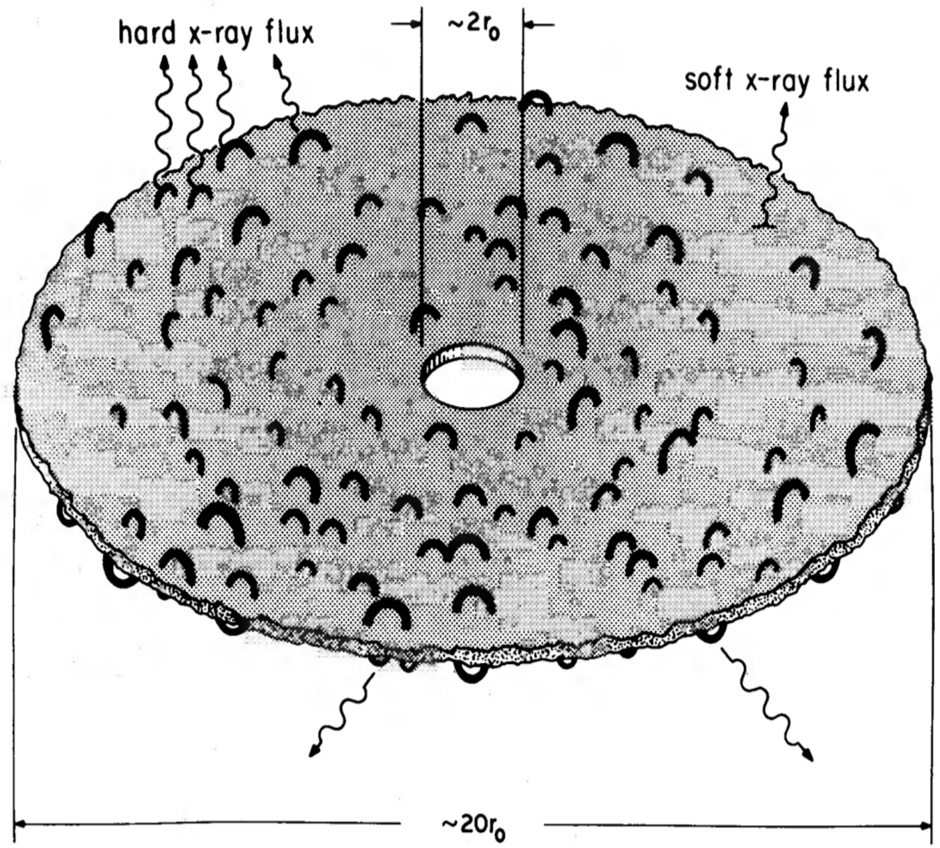
We avoid conflict with the data, but we cannot explain them.

But if there is a corona with a size larger than 100 r_g, above the disc, it is difficult to explain the broad band SED of some AGN.



Mrk 509: Petrucci et al, 2013, A&A, 549, 73

The case of the small radius corona



Galeev, Rosner & Vaiana, ApJ, 229, 318

Assume the Haardt, Maraschi & Ghisellini (1994, ApJ, 432, L95) model.

$R_b \alpha^{1/3} = z_0$,

Where z_0 is the disc height and α is the disc viscosity. According to Svensson & Zdziarski (1994, ApJ, 436, 599):

$$z_0(r) = \frac{3}{4}\left(\frac{\dot{M}}{\dot{M}_{Edd}}\right) S(r)(1-f) r_g ,$$

where, $S(r) = [1-(6r_g/r)^{1/2}]$. The eq. gives $R_b = 0.02 r_g$ (at $r = 10 r_g$, M_dot =0.055, f=0.09, α=0.1).

As for the luminosity of the blob,

$$L_b(r) = 1.7 \cdot 10^{44} \left(\frac{M_{BH}}{10^7 M_{sun}}\right)\left(\frac{f}{0.2}\right)\left(\frac{0.1}{\alpha}\right)\left(\frac{r}{r_g}\right)^{2/3}\left(\frac{\dot{M}}{\dot{M}_{Edd}}\right) S(r) \, erg/s ,$$

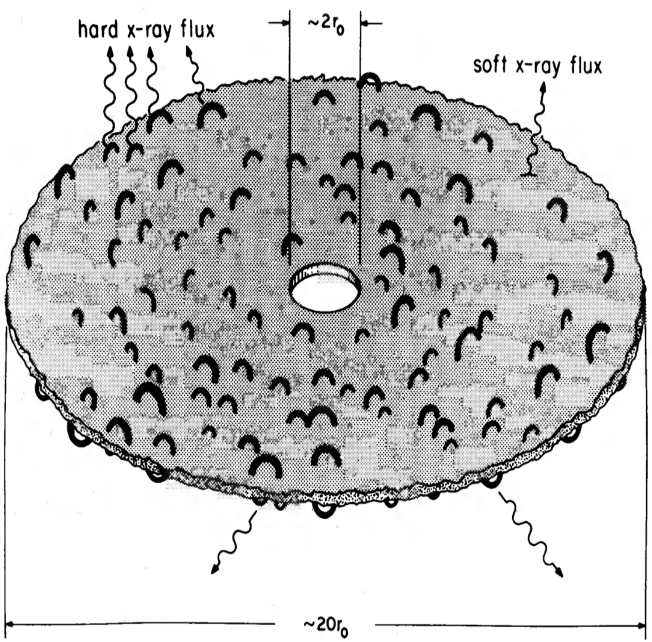
which implies, $L_b = 3 \cdot 10^{41} \, erg/s.$

Not much, so we need quite a few of these “blobs”.

For each blob:

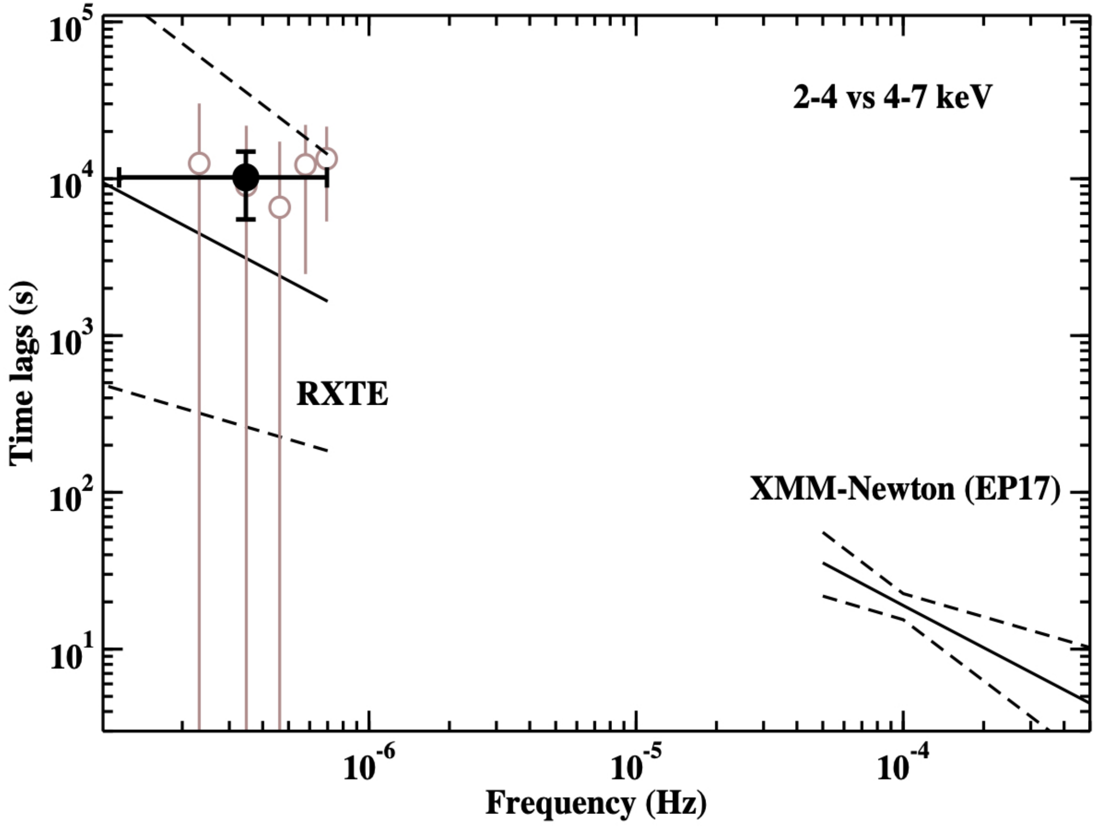
$$l_h = \frac{L_b}{R_b}\frac{\sigma_T}{m_e c^3} \sim 300,\ \ l_s \sim 30, \text{ and: } \ \frac{l_h}{l_s} = 10,$$

which implies a (maximum) corona temperature of ~130 keV.



If this is the case, the blobs should have softer temperatures at longer radii, to produce the soft-to-hard time lags through propagation of m_dot variations in the disc (Lyubarskii, 1997), which should also affect f.

What about the very-low frequencies?



Papadakis et al, 2019, MNRAS, 485, 1454

What do we plan to do in the future:

Check the dependance of time-lags on optical depth.

Check coronae in slab geometry, above the disc.

Different heights from the disc, different m_dot (so different input spectrum).

Different corona geometry: